GIMA

Geographical Information Management and Applications

HEATING AMSTERDAM: NETWORK SOLUTIONS

Master thesis

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Abstract

This master thesis is about district heating in Amsterdam. In the context of climate change, the research looks at alternative ways to heat up buildings. One of the alternatives is a heat distribution network. A very efficient however costly way of relocating excess heat throughout the city. This research studies this potential alternative for gas heating. It focusses on the city of Amsterdam with a lot of infrastructure already in place and a wish to get rid of gas heating.

In the first research question it looks at the most well known alternatives for gas heating and ranks them. District heating is thought to be one of the best solutions next to better isolation, however isolation does mean that gas still is used. The downside to district heating is the high investment cost. The second research question looks into the demand in the neighboured the Rivierenbuurt, Amsterdam. Overall, demand is above average in this particular area. The building year is one of the factors that influence the demand for energy.

The third research question calculates the least cost pathway for district heating using the spanning tree algorithm. As well as the spanning tree, a number of hydrological tools are used to calculate the cost for a new network in the research area. Also benefits were calculated using the CO_2 emission multiplied by the emission trading price. In the fourth question the model is tested in three different demand scenarios. This results into the insight that the cost are non-linear related to the demand points. For every connection more the cost do not increase linearly.

Overall, the cost are many times higher than the overall benefits on yearly basis. However, this does not mean that district heating should be completely written off. One of the advantages of district heating is its compatibility with different heat sources and therefore small scale solutions can be profitable. Seen in a broader social perspective, this solution should be considered by policy makers because as a society we have try to stop climate change.

Glossary

HDN	**Heat distribution network**	A network that disperses heat to houses
DH	**District heating**	An area in which energy is disseminated. network that disperses heat to houses.
HE	**Housing equivalent**	the average amount of energy used by a household expressed for one building.
HP	**Heat pumps**	An alternative system of heating. This system uses electricity to move the heat, that is absorbed from the air, inside.
PC6	**Postal code 6**	postal code level which uses four numbers and two letters as geographic reference.
BGT	**Basisregistratie Grootschalige Topografie**	A very accurate dataset of the public spaces in the Netherlands.
BAG	**Basisregistratie Adressen en Gebouwen**	A accurate dutch dataset about all the buildings in the Netherlands.
OSM	**Open Street Map**	Open source dataset of buildings and roads.

Contents

1. Introduction

Since 2012 we are officially living in a new geological era called the Anthropocene. After the Holocene, the new era is defined by mankind as having a severe effect on the planet (Luttikhuis P. , 2012). The effects of a changing world are now tangible with for instance record heat in Australia and also record braking storms in the Caribbean (Luttikhuis P. , 2017). Organisations are trying to push-back on climate change with treaties such as: The Kyoto Protocol (United Nations, 2014), The Lisbon Strategy (European Commission, 2000) and Europe 2020 (European Commission, 2010).

Furthermore the Dutch government signed multiple international agreements on CO_2 reduction to reduce climate change. However, in a recent lawsuit by “Urgenda” the judge urged the government to increase their efforts because they were not compliant to treaties they signed (Schreuder, 2015). Accordingly, the national government sharpened the Dutch agenda for energy transition; the “Energieagenda”, in which the vision on sustainability for 2050 is described in order to be compliant to the treaties. (Ministerie van Economische Zaken, 2016).

Parallel to the push for sustainability, there is also a change in demand for energy. In the Netherlands we see a decrease in household size and an increase in the absolute amount of households. In fact, the amount of households has risen with 143% since the 1960’s. This can be explained by the average household size which has dropped from 3.6 inhabitants per household to 2.2 inhabitants per household (Moetekoe, 2016). With an increase in absolute amount of households, the demand rises.

The total amount of energy used in the Netherlands in 2016 was 800 PJ. Almost 30% of this energy is used for the heating of buildings which is created by every household on itself. Heat was traditionally produced using wood, peat and charcoal in a fire. However, this changed quickly when in 1948 a major gas field was found in Coevorden. The municipality invested in a gas network that delivered natural gas instead of light gas to the front door. Until this day, households burn natural gas to create heat and cook with (NAM, 2018).

Mining of gas is heavily debated in the Netherlands. Gas is mined in Groningen and in the North Sea, however not without consequences. In January 2018 an earthquake, with the magnitude of 3,4 on the Richter scale, caused damage in the province. Also, earthquakes are becoming more frequent and stronger the last years (Leijten, 2018).

Energy consumption per household is largely spent on heating. In the Netherlands, the most common way to heat a building is with natural gas. On average, a household uses 1.500 m^3 of natural gas which can be split into 80% for heating and 20% for heating of water (Milieucentraal, 2016). To comply to the agreements made in Paris, heating of housing shows great possibilities on national and local scale. There are multiple ways to realize energy-use reduction. According to research, almost 350 PJ of heat can be delivered by district heating(DH) in 2050 (Planbureau voor de leefomgeving , 2017).

Alliander, a net provider in the Netherlands, is researching the possibilities in district heating. This is not new in the Netherlands. Rotterdam for instance is a city that makes use of this system. It is seen as a system that can help to heat housing in a more sustainable way. Excess heat or green gas can be used to heat buildings in a village or city. This system is applicable in different ways, as shown in figure 1.

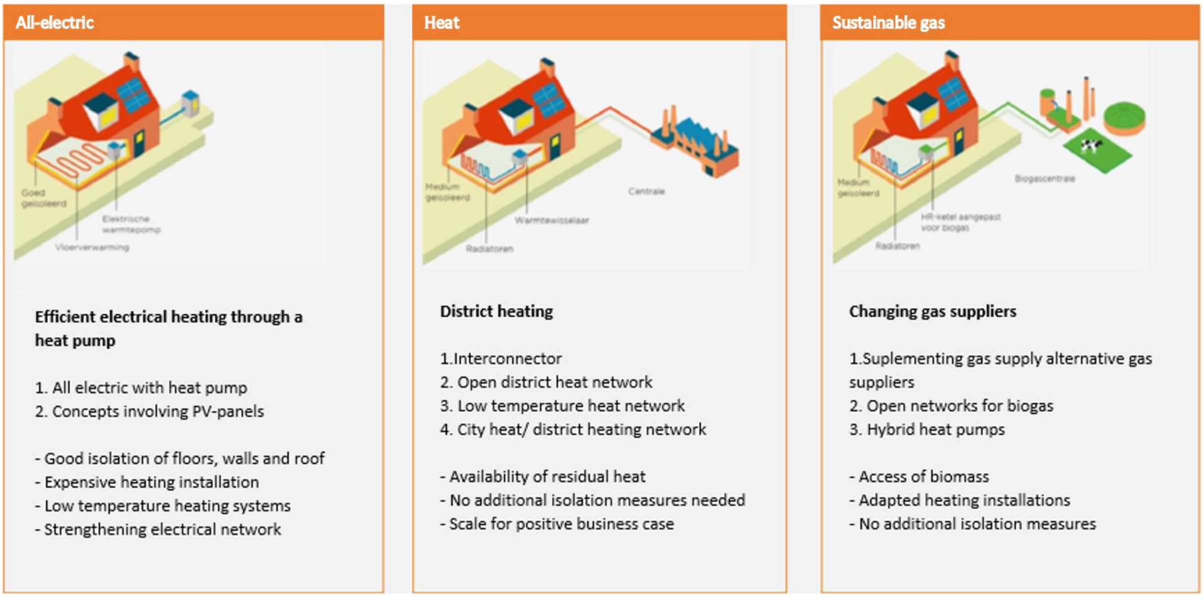


Figure 1 Future heating systems, **(Alliander, 2017)**

1.1 Problem statement

For the city of Amsterdam the "Energieagenda" was not enough. That is why alderman Choho published the cities vision for 2050, where the city will be heated without the use of natural gas (Oosterbaan, 2016). Excess heat produced as a residual product by the industry will be distributed through district heating in this vision.

The city is taking the matter seriously and started initiatives such as 'Westpoort Warmte' in Amsterdam, which makes use of decentralised district heating (Nuon, 2014). These initiatives are with local parties and are not interconnected throughout the city. As stated before, net provider Alliander is exploring the possibilities of district heating (Alliander, 2017). They own and maintain the electrical and gas network of the municipality of Amsterdam. To maintain the network, certain connections need to be renewed every so many years. Combining these activities with the ambitions on heating of the municipality may open up new opportunities.

Building a heat distribution network bares high initial costs. There are a lot of factors that come in to play when constructing a network, such as: groundwork, heat loss, distance to heat source, number of users, amount of crossroads and financial depreciation of the existing net.

Location is key when it comes to district heating. Therefore, an optimisation can make the difference to reach the goal set by the municipality. Which costs and which stakeholders are important, and is district heating a good solution to fulfil the goals set?

1.2 Research objective & questions

As explained in the introduction, there is an inevitable change in the energy market worldwide. Every energy market and governmental body acts on its own way. This particular research will focus on the energy market in Amsterdam.

Goal of this report is: " ***develop a model that finds the optimal location for district heating and calculates the social cost and benefits, at street level in a research area."***

This will result in a map with the best potential route for district heating in one of the neighbourhoods in Amsterdam.

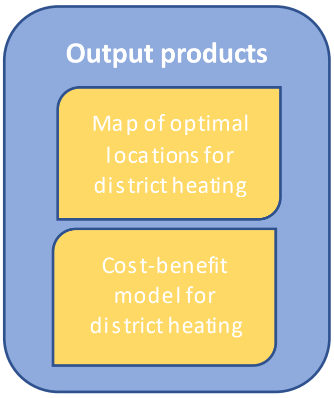


Figure 2 Output products of research

In order to answer the research objective four questions have been formulated:

1. ***What are possible heating systems in the near future?***

This question has to identify different ways to make the city more sustainable and point out potential candidates for research. Also, it should identify potential competitors for district heating. This is based on a literature study and will result in a table.

2. ***How is heat disseminated in the present?***

How is the current network constructed, and where are the large stakeholders located? These questions will be answered to form the groundworks for the network analysis later on in the research. This question looks into heat demand because it is one of the key factors for district heating.

3. ***How can heat be disseminated in the future?***

In this question the following three components will treated: the network will be constructed using GIS, the constructed network will be translated into cost and following the cost and benefit ratio will be constructed.

4. ***How robust is the approach?***

The last question will develop three different demand scenarios for the research area. They will be compared with each other to get an insight into what demand does with the model.

1.3 Reading guide

The research is constructed in such a way that the reader is able to follow every step in the process. First the concept chapter explains the larger concepts that are used in the report. The methodology forms the base for the research questions. It explains how the research was done and it handles the different algorithms that are used.

The fourth chapter shows all the results per research question. Which is followed up by the conclusion and later the discussion. The latter being the chapter where the report will be reviewed critically by the researcher.

2. Concepts

This research focusses on heating of buildings and different ways of heating. Before going into further detail, some general concepts have to be explained.

2.1 Network

In the context of this Geo-Information research a network is: *"A collection of topologically connected network elements (edges, junctions, and turns) that are derived from network sources, typically used to represent a linear network, such as a road or subway system. Each network element is associated with a collection of network attributes. Network datasets are typically used to model undirected flow systems"* (ESRI, 2016).

Net provider Alliander is owner of an energy transportation network, which is able to transport different kinds of energy, such as natural gas and electricity. This report focusses on an alternative energy network in the future.

2.2 Net provider

The net provider is a utility company and is responsible for delivering energy to clients. Costs are paid by the clients via the electricity company.

Amsterdam, the research area, is within the service area of net provider Alliander. This company is split into three important subcompanies of interest for this thesis: Liander the net provider, Liandon technical support and Alliander DGO sustainable development organisation (Alliander, 2017).

During the research there was extensive contact with the net provider Liander because of the shared interest in the subject.

2.3 Smallest primitive

As stated earlier in the research objective, this research focusses on district heating at street level. The research will focus on the city of Amsterdam. This has to do with the vision of the municipality and because it is the care area of net provider Alliander.

The level of detail is directed by the level of detail in de datasets. District heating is implementable at an even smaller scale. However, in reality it is more common to implement district energy supply on neighbourhood level.

The energy model is graphically shown in figure 3. A HDN can be decentral and circular where a gas network is linear. With HDN heat can be delivered back into the system. Energy storage is possible in both systems, however this is not within the scope of the research and therefore is left out of the illustration.

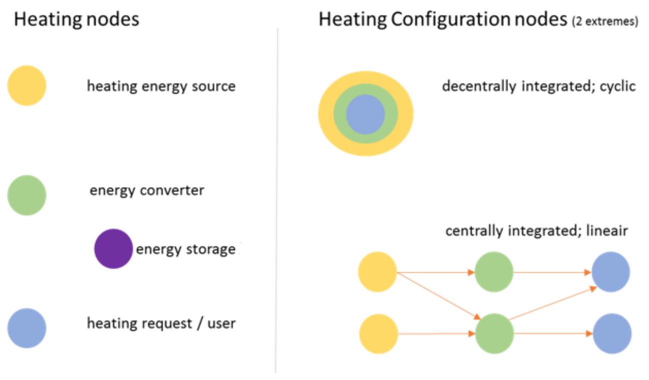


Figure 3 Theoretical illustation of heating network

2.4 District Heating

District Heating is not a new technology in the world. Countries like Iceland, Norway and Denmark have been using it for decades. In Denmark this technology came into play during the oil crisis of 1973 when they needed to increase the efficiency of the whole energy system in the country (Bühler, Petrocvic, Karlsson, & Elmegaard, 2017). Therefore, this system has proven its potential in the past.

The system is a network of pipes that are isolated very well in order to transport heat from a source to a boiler or heating element. Vice versa for transport of cooling energy. Traditionally the heat source is a power plant. However, the system is versatile and because it is not dependent upon just one heat source it is able to combine different heat sources with different temperatures. The versatility is shown in the figure 4. For instance, Excess Heat (EH) of industrial processes can be a heat source to the network. Not only EH is a heat source, biogas and solar energy can also be heat sources. As well as thermal heat, which can be won in the ground.

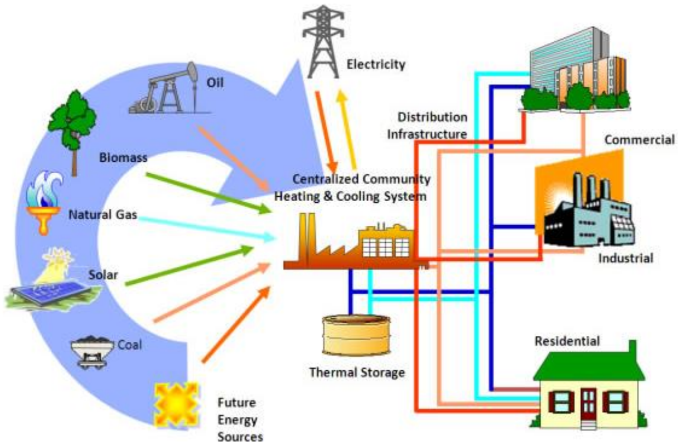


Figure 4 District heating inputs, **(FVB Energy Inc., 2017)**

The different stages of district heating are illustrated in figure 5. This research focusses on 4th generation district heating, because it is the most eco-friendly and future proof version. Remarkable trends illustrated in figure 5 are: the energy efficiency that keeps rising, the temperature at which the heat is distributed is gradually dropping and also the amount of different heat sources has increased. Interesting as well is the capability to connect future energy sources to the system as well.

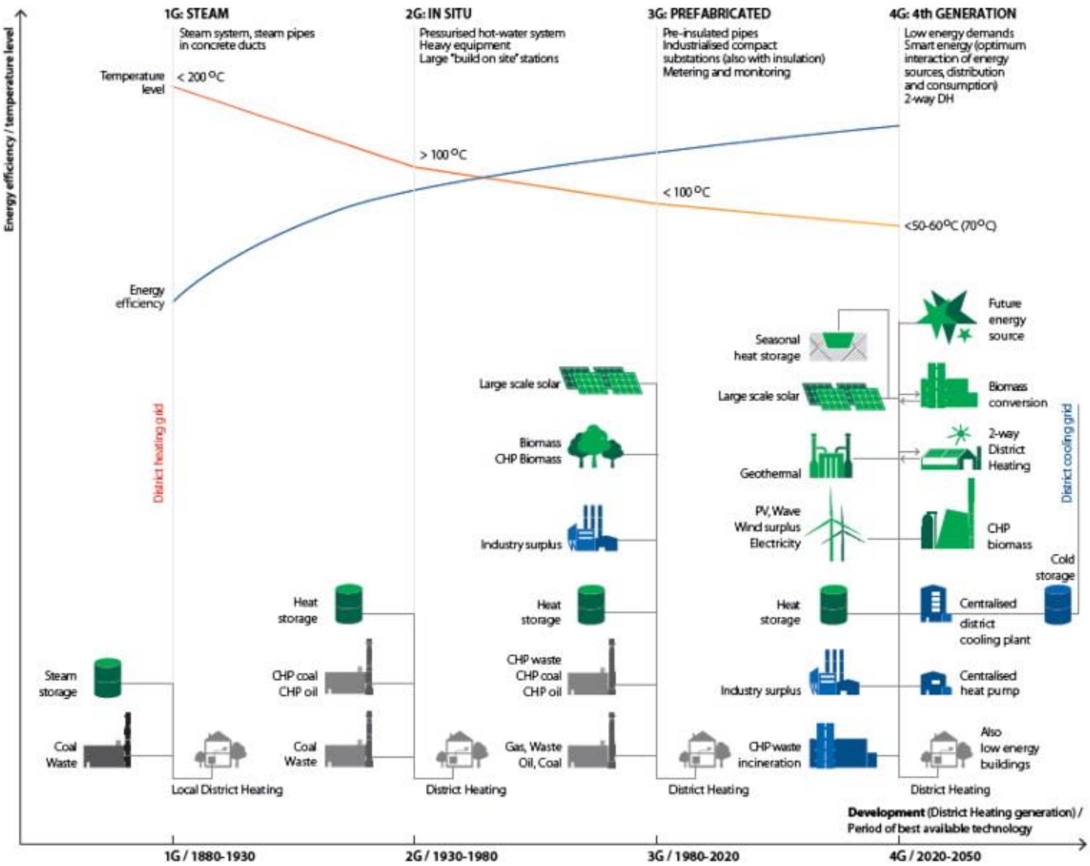


Figure 5 Generations of district heating, **(Lund, et al., 2014)**

2.5 Heating

In order to find a good heating system, it is essential to understand what the desired temperature is. Each person's preference is different when it comes to temperature of a living space. However, the rule of thumb, according to the World Health Organisation literature, is 18-22 degrees Celsius (WHO, 2007). Heating of housing is important because this temperature assures low risk of illness for young and elderly people.

The need for heating is commonly referred to as gas units, which is expressed in cubic metres. This is done because gas is most often used to create heating in the Netherlands. Another way of expressing the demand is in GigaJoule.

3. Methodology

3.1 Research steps

The research questions are constructed in such a way that there is a logical build up to the conclusion. It forms context for the analysis and explains certain choices that have been made. The two flow diagrams (figure 7 & appendix 1) shows the skeleton of the research.

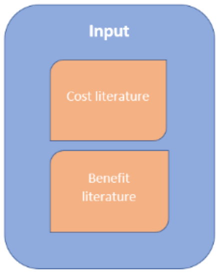


Figure 6 theoretical input of research

3.1.1 Literature

There are two kinds of inputs for this research. Input from literature and from data. Figure 6 illustrates that cost and benefit literature is studied not only to identify the cost and benefits but also the different heat sources. During this part of the research general knowledge was also gathered by speaking to experts at Alliander. This approach is mainly used to answer the first research question.

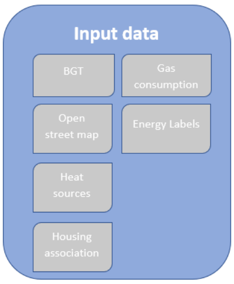


Figure 7 input data of model

3.1.2 Input data

Figure 7 shows the different dataset that will be used for the data analysis. Data about demand and efficiency is studied to identify the demand for heat in Amsterdam. Furthermore Open Street Map is used for roadmaps and centroids of houses. Lastly the Basisregistratie Grootschalige Topografie (BGT) is used for the cost analysis on street level.

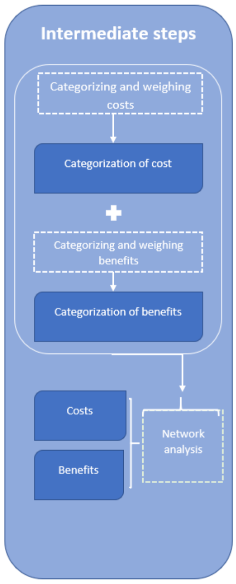


Figure 8 process steps data anlysis and model

3.1.3 Processing steps

Then the intermediate steps are taken to answer all the questions. This is the analysis part of the report. Categorizing and weighting of cost and benefits are the basis to the network analysis. A cost map is constructed on which a network is constructed. This will form the cost part of the analysis. The benefits are calculated by computing the reduction of emissions. Both functions will be illustrated during the methodology in a table.

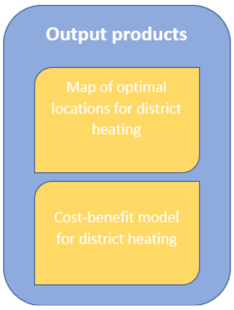


Figure 9 ouputs of research

3.1.4 Output products

Figure 9 shows the outputs of the report. The model is the most important part of the research. It will exist out of several parts in order to perform the analysis. The resulting map is a product of the model to show the calculations.

Questions are formulated to form the context of the larger research question in order to answer it correctly. The questions follow up one and other and bear different kinds of information needs

3.1.5 Input chart

Input for each question is ordered into three categories. These inputs differ per nature of the question. For instance the first question is a literature study; therefore it does not need an open dataset shown in figure 10.

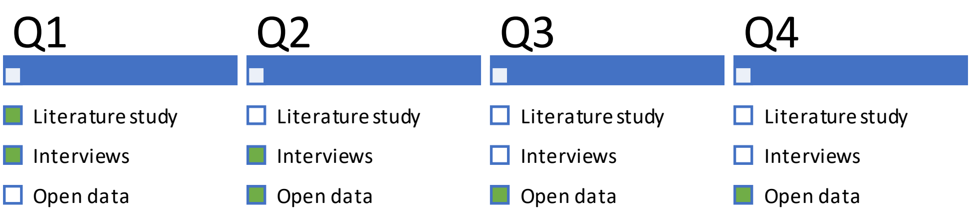


Figure 8 inputs per research question

3.2 Literature Study

The base of the study will be conducted through a literature study, following the book: “Key methods in geography” (Clifford & Valentine, 2003). Academic resources like reports, journals and books will be sought after on the subject District heating. Knowledge on the technical part of the subject will become indispensable further on during the research. A better understanding of the matter constructs the context in which the research will be embedded (Blaxter, Hughes, & Tight, 2001). Several keywords in the search for literature are: heat distribution networks, district heating and heat storage. For each keyword multiple sources have been consulted to develop a critical point of view upon the matter (Blaxter, Hughes, & Tight, 2001).

Identifying different solutions for global warming related to heating of housing is especially important for the first question. District heating is dependent upon different variables which make or break its success.

3.3 GIS Analysis

3.3.1 Method per research question

Question 1: upon the numbers found in the literature an economic analysis will be preformed of the different heating systems (Varian, 2010). Literature should yield enough data to plot the efficiency of different heating systems. This will form the bases for later GIS analysis.

Question 2: Data about the network, owned by Alliander, is used during this part of the research. A network analysis will be one of the tools used. To be more specific, a selection of features will be made to identify the age of the existing energy network. Furthermore, sources of heat will be identified in the data using open source data from the municipality (Municipality Amsterdam, 2017). And lastly, maps will be constructed to identify the demand throughout the city with the aim of identifying opportunities within the net using GIS (Huang, 2017).

Question 3: Open source data such as the Basisregistratie Grootschalige Topografie (BGT), Basisregistratie Adressen en Gebouwen (BAG) and Open Street Map (OSM) will be used to assess the different cost on street level. Using GIS tools a cost map will be constructed (Douglas, 2016). Using the principal of a minimum spanning tree the route will be constructed and demand will be calculated. The tools that will be used are discussed in the chapter “Tools”.

Question 4: The model constructed and used in the third research question will be tested with three different scenario’s. One scenario with only half of the points, one realistic scenario and one scenario with twice as much points. These points will be selected randomly after which the results are displayed in the report.

Flow chart methods

This research identified two different methods to model the least cost paths. The first method is demand driven. Polygons and polylines will be retained and demand points are used as input for the spanning tree function from GRASS GIS.

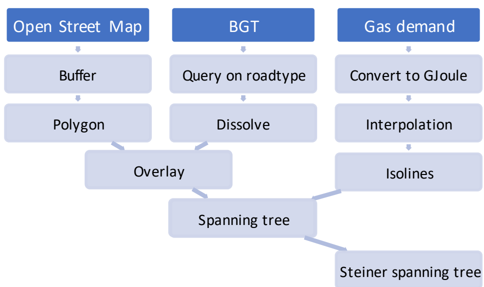


Figure 9 Flowchart model polyline method

The second method is supply driven. Where the first method calculates the pipe routes with demand as the main variable, the second method calculates the least cost path. Polygons must be converted into a raster file. Hereafter, there are two methods that are able to construct a least costs path. One uses the cost connectivity tool and the second method uses a stream model to calculate the cost and demand. Unfortunately, there will be a loss in accuracy when using this method, however this method is less complicated and uses less assumptions about for instance the surface material. Therefore, the raster methods are used in this research. Where the cost connect method produces the cost path and the stream method can be used to determine the demand per polyline.

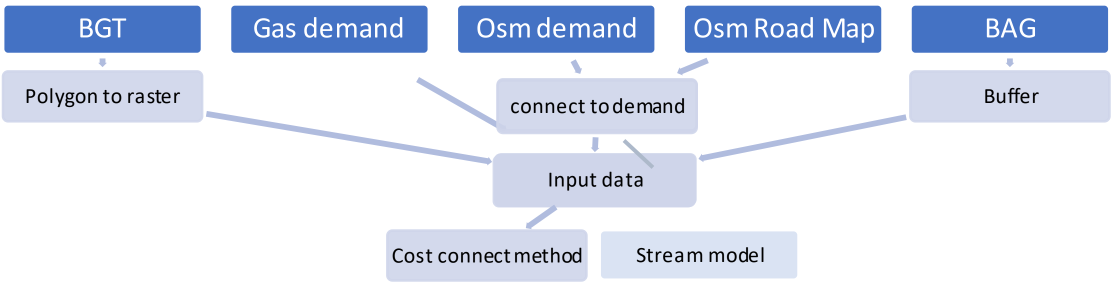


Figure 10 Flowchart model raster method

3.3.2 Tools

The analysis part is split into statistics and GIS functions and tools. All the concepts in this chapter are used at the last two research questions. The following functions are applied:

Algorithm

To optimise the service area and minimalize the costs for district heating, the research needs an algorithm. For such geo-information problems there are algorithms that focus on the cost of edges between nodes. A solution for this problem is described in literature on spanning trees. This research looks at three different algorithms that may form a solution.

Minimum spanning tree

This method is a graph that connects all edge-weighted vertices together, without making cycles while maintaining minimum costs. A spanning tree whose length is the shortest of all spanning trees is called the minimum spanning tree (MST). This method is one of the classic methods invented by Boruvka in 1929, and is still used to solve coverage problems for telecom companies (Nesetril, Milkova, & Nesetrillova, 2001). The figure illustrates a MST solution.

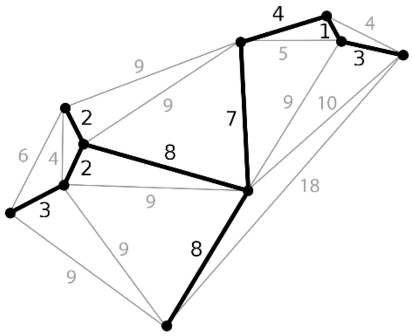


Figure 11 Minimum spanning tree, **(Wikipedia, 2017)**

Kruskal's algorithm

The basics of the Kruskal's algorithm is identifying the least cost weight of an edge as a starting point. The greedy algorithm asses each edge at ascending order, and checks whether the edge will form a cycle if it was added to the tree. If this is not the case, the edge will be added to the tree until every edge is assessed (Katsigiannis, Anastopoulos, Nikas, & Koziris, 2012). This algorithm is not the quickest way to solving the minimum spanning tree because it needs to assess all edges one by one.

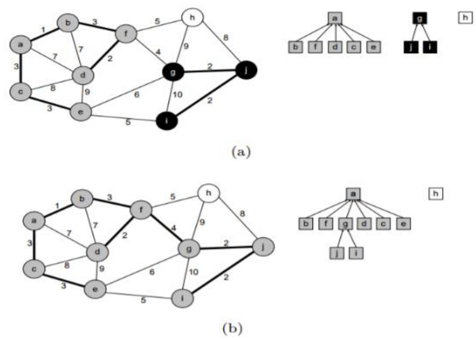
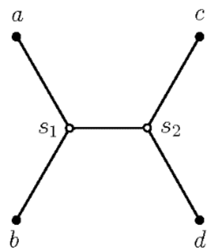


Figure 12 Kruskal's algorithm, **(Katsigiannis, Anastopoulos, Nikas, & Koziris, 2012)**

Prim's algorithm

This algorithm starts at a given point and will calculate the minimum spanning tree from this point. It is a greedy algorithm that finds the MST for a undirected graph. The algorithm grows one edge at a time picking the least cost path (Pettie & Ramachandran, 2002).



Steiner's algorithm

Figure 13 Steiner's algorithm, (Brazil, Graham, Thomas, & Zachariasen, 2013)

Steiner's algorithm is a minimum spanning tree which can be used to calculate the minimum-cost vector network connecting a number of nodes in a network framework. It connects the demand points a, b, c and d using the shortest path. Therefore, it introduces two extra nodes in order to keep the edges as short as possible (Winter, Richards, & Hwang, 1992). This method is used in geographical information software for the planning of fibre optic cables to provide a service area.

Stream model

Strahler's model is commonly used in the science of hydrology, this model was built to identify stream orders. Next to Strahler's model there is the Scheidegger's stream magnitude function. It accumulates different streams into one main stream (Radinger & Gebbert, 2016). This function can be used on raster data to identify possible pipe routes throughout the city.

However, this research uses Shreve's model illustrated in figure 14. This algorithm accounts for all links in the method. The difference with the Strahler model lies in the way the interior links are calculated. It adds the order numbers up from previous links.

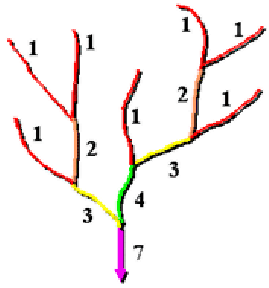


Figure 14 Shreve's model, (Esri, 2017)

Cost back link

This tool is used in the model before the cost connectivity tool. The function defines the neighbour cell with the lowest value. This way it is able to determine the least accumulative cost path to the source. Inputs of this tool are the source and cost both in a raster format as illustrated in figure 15 (Esri, n.d.).

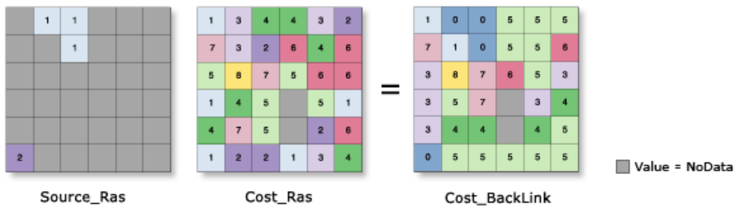


Figure 15 Cost back link illustration, (Esri, n.d.)

Cost connectivity

The cost connectivity tool produces the least-cost connectivity network connecting multiple regions. Again the cost raster is a input and is combined with the polygons of the regions the function needs to connect (Esri, n.d.). Before constructing the cost connect path the functions connect all regions to each other in a network graph. Then it uses a minimum spanning tree to construct the cost connect map illustrated in figure 16.

Figure 16 cost connectivity illustration, (Esri, n.d.)

Watershed

The watershed tool is well known in the scientific field of hydrology. It computes the area that generates a glow to a common outlet point or pour point. Within the larger watershed there are smaller sub basins that contributed to the larger watershed (Esri, n.d.). Combined with Shreve's stream model the demand of a sub basin can be calculated.

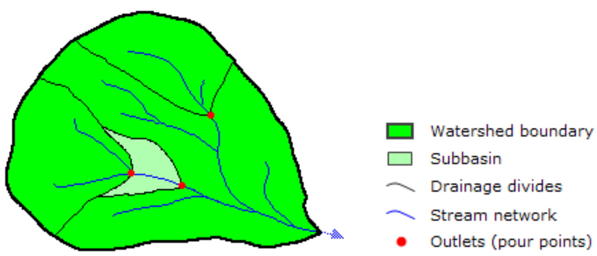


Figure 17 Watershed, (Esri, n.d.)

Align features

This function is able to match lines within a search distance and align them with the target feature. This way polylines constructed from a raster dataset can be snapped to target polylines. (Esri, n.d.)

3.4 Cost function

To calculate the cost, we have to identify different cost factors before apprehending them in a methodology. The cost functions are used in the third and fourth research question.

Nielsen & Möller show that there is a method for calculating the potential of DH on national scale in Denmark (Nielsen & Möller, 2013).

$$C_{DH} = C_{Prod} + C_{Tr} + C_{di} \tag{1}$$

This equation sums up the total cost for district heating by adding up the production, transmission and distribution cost.

Production cost

Traditionally heat sources are heated by burning fuel to produce heat. This traditional method was used by Nielsen & Möller to formulate the production cost (C_{Prod}) equation (Nielsen & Möller, 2013).

$$\frac{Total\ energy\ heat\ cost}{Total\ heat\ deliv + 20\%\ heatloss} * [EUR/GJ] \tag{2}$$

However, because excess heat is a residual product of a production process, the cost are close to none existent. Therefore, the production cost will be null in the cost function (C_{DH}).

Heat transmission cost

For the model it is not desirable to place pipes in unrealistic places. Therefore, the pipes follow the road network of Amsterdam, in the model. However, in reality transmission pipes may be located else for economic reasons, the model will hereby represent a conservative estimate of the length of pipes.

Using a minimal network spanning tree algorithm in GIS, the minimal pipe length will be calculated to the closest demand area for DH. To carry out this analysis the polygons will be converted into centroids within the GIS tooling. Henceforth calculating the capacity of the pipes by dividing the annual energy demand of the area, in MWh per year, by 3000 full-load hours, which determines the capacity in MW. Temperature difference of 55 ^{0}C and water flow rate are specified in the table. In order to calculate the transmission line cost, the following equation has been formulated:

$$C_{transmission} = Q_{length\ of\ trajectory} * P_{cost\ per\ metre} \tag{3}$$

$$\alpha = I_{total\ cost} * \frac{i_{discount\ rate}}{1-(1-i)^{-n}} \tag{4}$$

The total cost of transmission lines is calculated by multiplying length and cost per meter for the trajectory. Cost per metre is estimated to be around € 250,-. This estimate was based upon cost per metre for a new gas network. The cost for new pipes underneath a crossing is € 5000,- (Liander, 2018).

Next the transmission cost is annualized (α) with a lifetime of 30 years (n) and a discount rate (i) of 6%. Finally the cost is divided by the heat demand in each area to give the annual EUR/GJ cost for the transmission of the area.

Cost heat distribution

Multiple cost factors are associated with the distribution of heat. Based on Persson & Werner this research identified four cost factors for cost distribution: capital cost, heat loss cost, pressure loss cost, service and maintenance cost (Persson & Werner, 2011). Where the capital cost is the largest contributor, because its is the investment cost of constructing the network in the ground.

$$Q_{dist} = \frac{a \cdot (C1 + C2 \cdot d_a)}{\frac{Q_s}{L}} \cdot [EUR/GJ] \tag{5}$$

The equation C_{dist} represents the annual distribution capital cost. Where the annuity (a) is multiplied by the investment $(C1 + C2 \cdot d_a)$ and divided by the annual heat sold ($\frac{Q_S}{L}$). Where C1 is the construction cost constant (EUR/M), C2 is the construction cost coefficient (EUR/M^2), d_a is the pipe diameter, $\frac{Q_S}{L}$ is the annual heat sold divided by the length of the trench.

The annual heat sold (Q_s) can also be denoted as $[p \cdot q \cdot w]$, where p is the plot area, q the specific demand in GJ/M^2 building area and w is the effective width. W can be calculated as followed:

$$w = 80.144 \cdot e^{-0.744 \cdot p}$$

3.5 Benefits function

The benefit functions is used in the third and fourth research question. The benefits can be deduced into cost reduction and a reduction on CO_2 pollution.

CO_2 reduction district heating

The nature of this research is district heating with excess heat. Therefore, the CO_2 pollution is considered to be null. Being CO_2 neutral is the biggest selling point of DH. However, it is hard to express this monetary. The reduction of CO_2 can be expressed in the following function:

$$Reduction\ [EUR] = DH - Alternative \tag{6}$$

$$Red\ [EUR] = DH - \left(\frac{Q_{CO_2\,per\,unit}[kg\ CO_2] * Q_{consumed\ gas} * P_{ETS}[tCO_2]}{1000}\right) \tag{7}$$

For this research the reduction of CO_2 will be expressed in EUR using European Union Emission Trading Scheme as reference. One emission certificate at the end of 2017 was 7 EUR.

Air pollution

Another large factor is the particulate matter nuisance when burning gas, caused by particulate matter (PM10) . A large amount of particulate matter can cause smog in a city. This is proven to be harmful to the lungs of people and therefore forms a threat to public health (Kampa & Castanas, 2008). Therefore, it is beneficial to reduce this pollutant. The following equation is used to calculate the amount of pollution.

$$Reduction\ = DH - (Gas\ PM10\ pollution + \mathrm{NOx}) \tag{8}$$

$$Gas\ PM10\ pollution = (Average\ PM10\ per\ unit * Q_{Dwellings}) \tag{9}$$

3.6 Cost-benefit table

Cost	Benefit
Total cost: $C_{DH} = C_{Prod} + C_{Tr} + C_{di}$	Total benefits: $B = Red_{CO_2} + Red_{PM}$
Production cost: $\frac{\textbf{Total energy heat cost}}{\textbf{Tot heat deliv} + 20\% \textbf{ heatloss}} * [EUR/GJ]$	Reduction CO_2: $Reduction\ [EUR] = DH - Alternative$
Transmission cost $C_{transmission} = Q_{length\ of\ trajectory} * P_{cost\ per\ metre}$	Reduction particulate matter (PM): $Reduction = DH - Gas\ PM_{10}\ pollution$
Cost distribution $Q_{dist} = \frac{a \cdot (C1 + C2 \cdot d_a)}{\frac{Q_s}{L}} \cdot [EUR/GJ]$	

Table 1 Cost-benefit table

4. Research results

The results out of four chapters. First the different heat system will be identified, secondly the heat demand in the city will be identified, thirdly the model will calculate the route and cost for the Rivierenbuurt after which the model will be tested in different scenario's.

4.1 Heating systems

Identifying all heat sources is essential to this research, because delivering the right energy source to the client is crucial for implementation. This chapter is dedicated to answering the first research question, and will sum up the different results in sub-chapters. The table illustrates the ranking of heating systems based on found literature.

Cost	District Heating	Infrared		
		Heat pumps		
	Solar water heating			
				HR Kettle
		Isolation		
	Environmental impact			

Table 2 Ranking of energy systems

4.1.1. Housing heating systems

There are two main consumers of heat in a building. One is tap water for the shower and the dishes. The second consumer of energy is for the heating of rooms in the house. This is distributed through heating elements.

Conventionally heat in the Netherlands is produced by a gas heated boiler, a common and relatively efficient device is a "HR ketel". The basic gas heated boiler is depicted in figure 18.

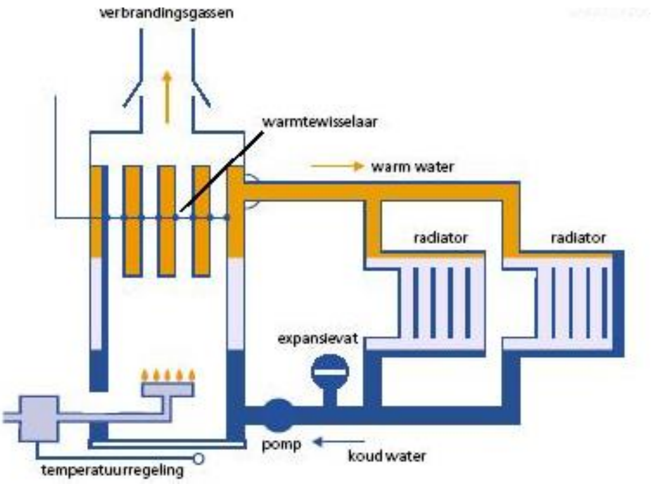


Figure 18 Traditional gas heating system, (Atho, sd)

Also, figure 19 indicates that 5,5% of the Netherlands makes use of renewable heat sources (CBS, 2017). So the Netherlands is heated for 95% by either district heating or the conventional HR kettle that is fuelled by gas. Alternative systems like heat pumps have not penetrated the market in a significant way.

	1990	1995	2000	2005	2010	2014	2015	2016**
	TJ							
Zonnewarmte	100	211	454	719	994	1 128	1 137	1 147
Aardwarmte					318	1 502	2 448	2 843
Bodemenergie	.	31	156	628	2 183	3 404	3 634	3 855
Buitenluchtwarmte	.	7	23	81	536	1 592	2 019	2 635
Biomassa, wv.	19 125	20 550	24 153	29 264	36 648	46 300	50 179	50 541
afvalverbrandingsinstallaties	2 203	1 770	4 548	5 241	7 708	11 757	13 523	13 060
meestoken in elektriciteitscentrales	0	1	15	693	1 267	.	.	.
biomassaketels voor warmte bedrijven	1 725	1 946	2 212	4 105	5 477	7 558	9 034	9 611
houtkachels huishoudens	12 949	13 540	14 187	15 857	16 859	18 111	18 368	18 766
houtskool	270	270	270	270	270	270	270	270
decentrale wkk met vaste en vl. biomassa	233	247	188	468	784	.	.	.
stortgas[2]	157	705	475	351	267	233	202	159
biogas uit rioolwaterzuiveringsinstallaties	1 142	1 278	1 361	1 306	1 258	1 288	1 205	1 296
biogas, co-vergisting van mest[1]				18	1 333	2 014	2 300	2 340
overig biogas[2]	446	792	897	954	1 424	2 724	3 065	3 107
vloeibare biotransportbrandstoffen						1 011	923	700
Totaal hernieuwbaar	19 226	20 798	24 785	30 691	40 679	53 927	59 417	61 022
Totaal eindverbruik voor verwarming	1 863 632	1 236 853	1 212 131	1 265 269	1 300 649	1 045 416	1 077 130	1 116 651**
Aandeel hernieuwbare warmte (%)	1,8	1,7	2	2,4	3,1	5,2	5,5	5,5**

Bron: CBS.
[1] Tot en met 2004 onderdeel van overig biogas.
[2] Inclusief indirect eindverbruik van warmte uit groen gas (biogas dat na opwaardering is geïnjecteerd in aardgasnet).

Figure 19 Use of energy sources Netherlands, **(Centraal Bureau voor de Statistiek, 2017)**

In Amsterdam 90% of the households still use gas as primary heat source, as illustrated in the figure below. However, district heating is growing the last years in Amsterdam as well. A fluctuation in gas consumption is visible in the figure 20. Temperatures in the winter are a variable which have a large effect on the gas consumption. Therefore it is impossible to describe the average use with a trendline.

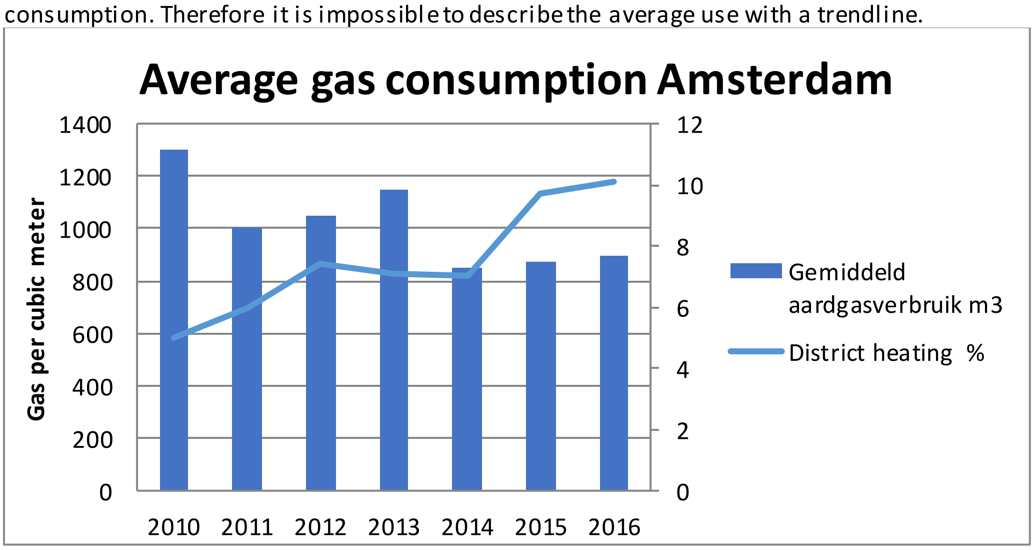


Figure 20 Average gas consumption Amsterdam, **(Centraal Bureau voor de Statistiek, 2017)**

4.1.2. Future heating systems

In the future it is possible that we are going to switch to alternative methods for heating. In the following sub-chapter several alternatives are explored.

District Heating

A network that provides heat is another way of heating buildings. This system makes use of existing hardware inside the building. Only to replace the heat element in the old situation and fill the pressure vessel with warm water.

District heating was invented in the United States of America in the 19th century and has widely spread in Europe ever since (National Research Council, 1985). An advantage of this system is that it is not dependable on one heat source, instead it can be fed with different heat sources to provide high and low temperature heat. Heat sources for district heating will be discussed in chapter 4.1.3. A distinction between high energetic heat and low energetic heat has been made in district heating. Both energetic levels can be used in different ways.

High temperature DH

High energetic heat is commonly water with a temperature of 90°C that is transported to a consumer. The heat is exchanged and the cooled water is transported back to the heat source to start the cycle again.

High energetic heat can be a product of a waste burning process or as by-product from industrial processes, which is called residual heat. It can also be a by-product of electricity generating by a gas or coal energy plant. This process is called combined heat and power (CHP).

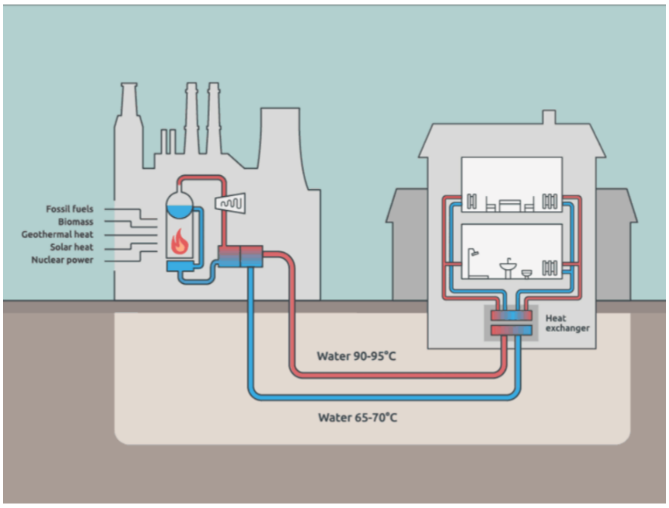


Figure 21 High temperature district heating, **(Wikipedia, 2017)**

Low temperature DH

Low energetic heat can form a base load in the conventional boiler. Heating up the base load has a direct positive influence on the energy that is needed to heat up a building.

The energy level needed for this kind of heating is upwards of 30°C. This level of heat can commonly be found as a by-product. An example is the residual heat of large datacentres. Also PV-panels can provide heat as a baseload. This energy level opens up the potential of multiple low energetic heat sources in an open HDN.

Isolation

Isolation might be an easy solution to save energy. Cheap isolation solutions are offered on the market to start off with. However, the city will not become CO_2 neutral when only this method is applied. Still, energy is needed to meet the demand for heat in a building.

Heat pumps

A technique that was discovered by R. Webber in America when he was experimenting with his deep freezer (The Renewable Energy Hub, sd). The outlet pipes where very hot, so he connected them with a water heater. He later designed a system that heated the air of a whole building. Nowadays a heat pump is considered to be highly cost effective.

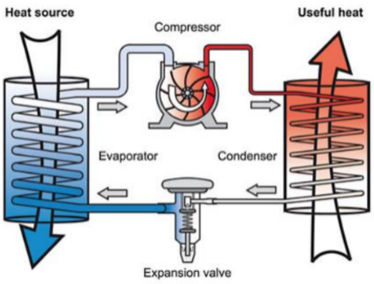


Figure 22 Heat pump, **(Veolia, 2017)**

Infrared

Another heating system is being experimented with by the Massachusetts Institute of Technology, this system is locally warming buildings. A system that addresses the fact that a step in efficiency can be made by only heating the part of the building where there are people instead of the whole building. Researchers make use of local Wi-Fi signal to identify the location of a person to turn on the infrared heating system in the ceiling (Ekstrom, 2014). However, there is a lot of debate about the efficiency and the cost of this new system. It is not easy applicable to monumental buildings in Amsterdam.

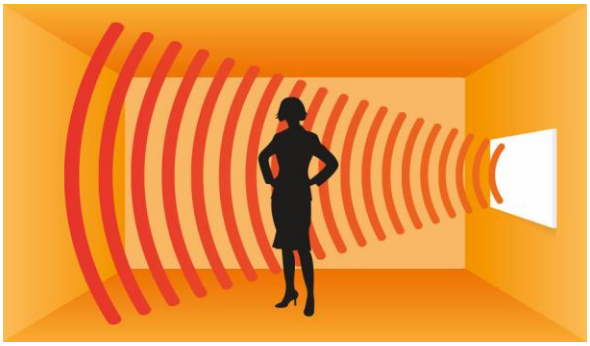


Figure 23 Infrared local heating **(Logicor, 2017)**

Solar water heater

This system makes use of the energy from the sun and it is applicable on large and small scale cooling and heating of housing. Photovoltaic panels on the roof collect energy to heat or cool a storage tank during the day (Buonomano, Calise, & Palombo, 2018).

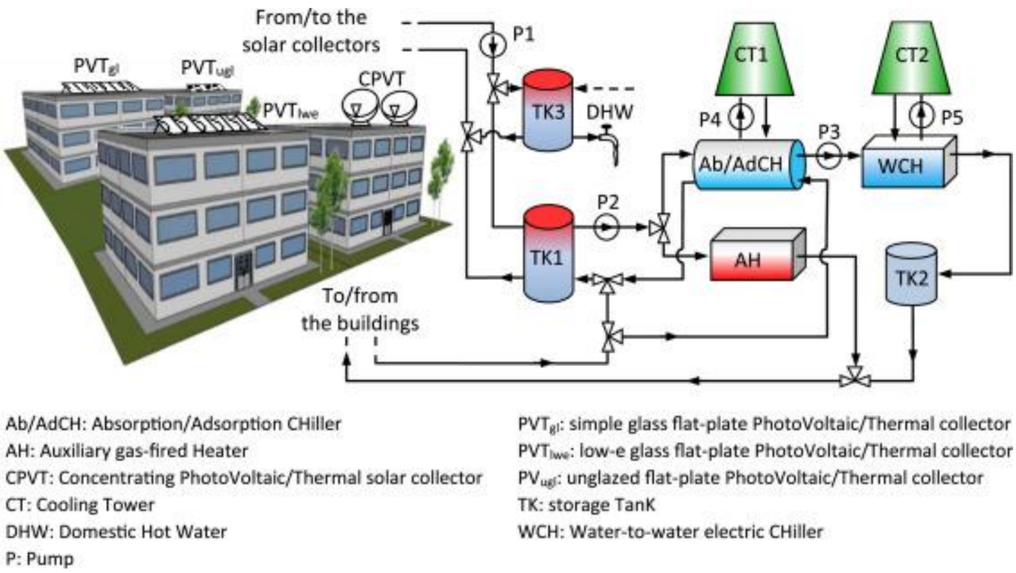


Figure 24 Solar water heating system, **(Buonomano, Calise, & Palombo, 2018)**

The advantage of solar water heating is that it can be installed upon the roof and it can cool and heat housing. Furthermore it can be connected with other heating systems to form one larger complimentary system. Therefore, it is very suitable to adopt this system in large DH networks, especially when this network is heated by fossil fuels (Winterscheid, Dalenbäck, & Holler, 2017).

4.1.3. Efficiency of fuel in district heating

District heating can be produced using different kinds of fuel. Figure 25 illustrates the emissions per fuel alternative.

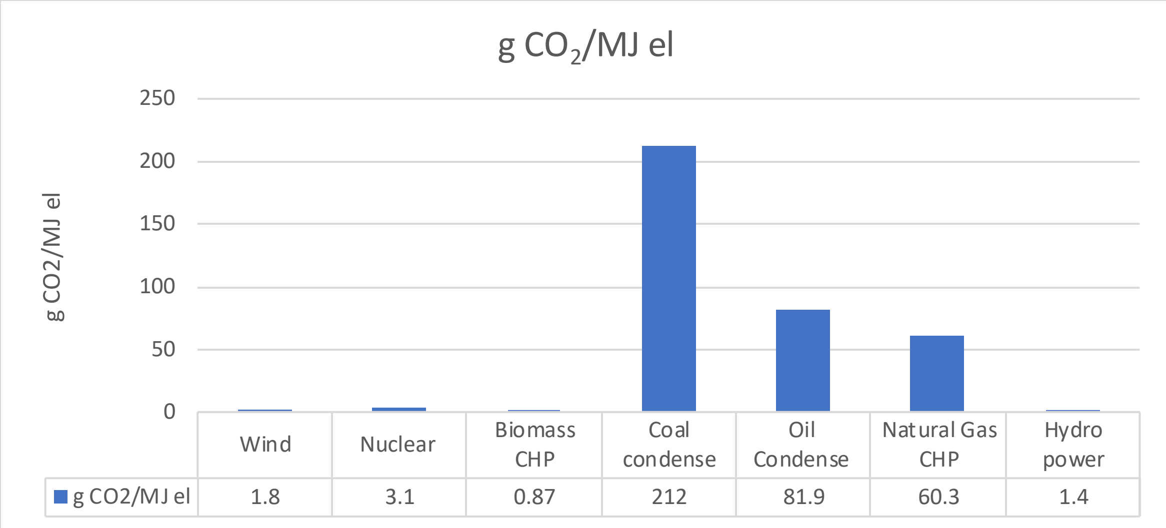


Figure 25 Efficiency of fuel for district heating networks, **(Eriksson, Finnveden, Ekvall, & Björklund, 2007)**

Laws

There are laws in the Netherlands to which an energy network has to obey. Next to the normal regulations of spatial and subterranean planning, there are the following laws that apply to DH:

- Warmtewet; it assures better protection for the consumers from a monopolist heat distributer (Ministerie van Economische Zaken, 2016).
- Wijzingingsbesluit bodemenergiesystemen; it determines the regulations of subterranean systems like geothermal heat. Also, it makes a distinction between a closed system, geothermal heat, and an open system for instance DH (RVO, 2017).
- Mijnbouwwet: this law restricts geothermal heat winning deeper than 500 meters without informing the ministry of Economic affairs (RVO, 2017).

4.2 Heat distribution Amsterdam

This chapter identifies the current heat demand situation as a frame of reference for later analysis. It is possible to distinguish two main ways of delivering resources for heating in Amsterdam. Gas and district heating deliver to larger part of the energy that is used for heating.

4.2.1 Demand

Construction year

According to M. Aksoezen et al, there is a non-linear relation between the construction year and energy consumption for a building (Aksoezen, Daniel, Hassler, & Kohler, 2015). Figure 26 shows that buildings from the 19th century are more energy efficient than for instance 20th century buildings.

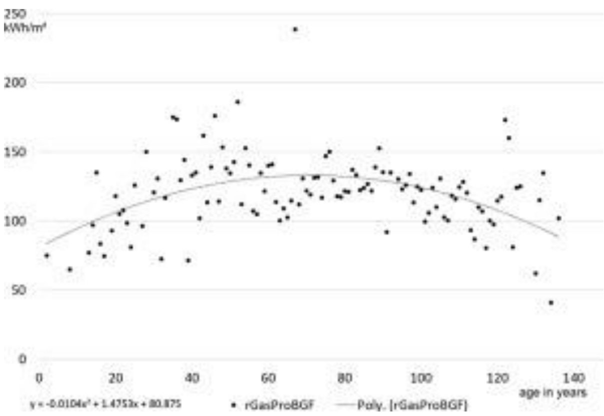


Figure 26 Construction year and energy efficiency, **(Aksoezen, Daniel, Hassler, & Kohler, 2015)**

This observation is important when analysing the cities demand for energy. Figure 27 shows that the inner part of the city, being the part within the ring road, mostly date from 1900 until the sixties. The light green and yellow colours indicate buildings the latter named buildings years. The centre of the city, is more historic and built in as far back as the 14th century. This clear pattern can be recognized in more historic cities.

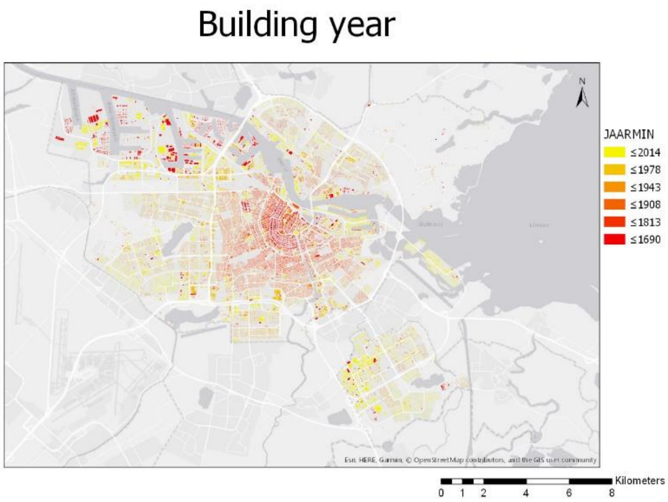


Figure 27 Building year

Energy label

The energy label has been introduced in the Netherlands since 2011. Not all parcels have been labelled because it is only obligatory since 2012 for houses that are sold and have been built before the year 2000 (RVO, 2017).

The pattern shown in figure 28 shows that neighbourhoods in the east slightly tend to consume more energy which correlates with figure 27.

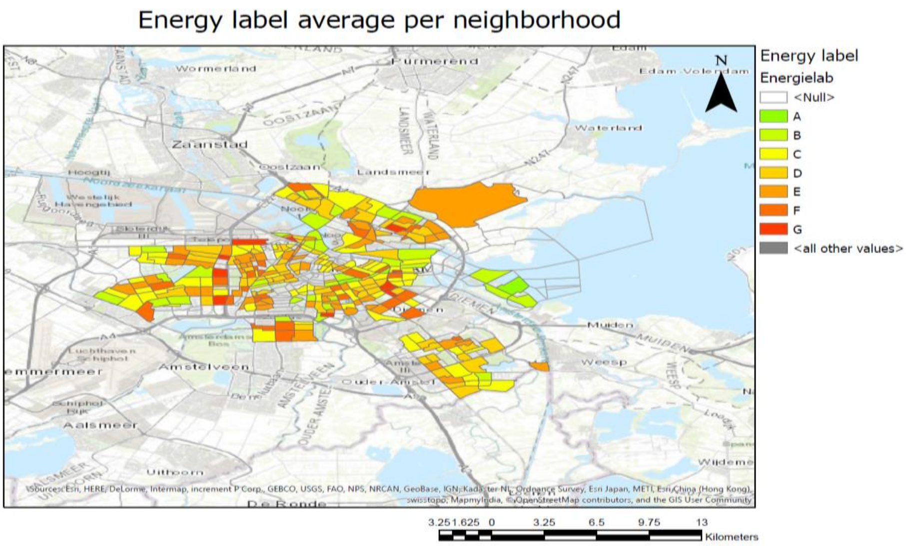


Figure 28 Energy label average per neigborhood, **(Municipality of Amsterdam, 2016)**

Some houses of housing associations have energy labels. On average these associations own houses with energy label D. Label D means that the energy consumption of a house is average. However, there is room for improvement.

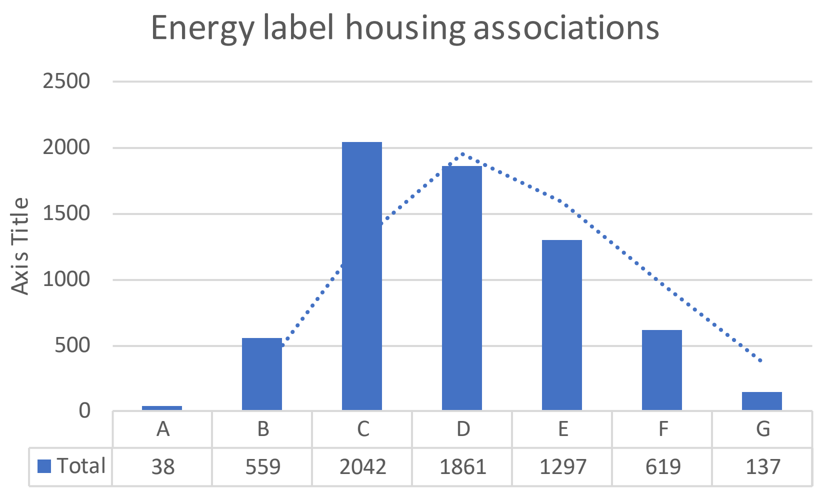


Figure 29 Energy label of housing associations, **(CBS, 2017)**

Consume per neighbourhood

The average use of gas in Amsterdam is 900m^3 per building (CBS, 2017). This amount is the equivalent of 31.65 GJ, because 1 m^3 is 0.035 GJ (Gasunie, n.d.). Using GI software the average consume per neighbourhood was calculated. A pattern occurs within the ring road of Amsterdam. Elderly buildings tend to have a higher consumption of gas on average.

There are some interesting outliers. For instance the part in the Markermeer uses a high amount of gas. Furthermore in the southern business part of the city the average gas consumption is also high. This correlates with the age of the buildings.

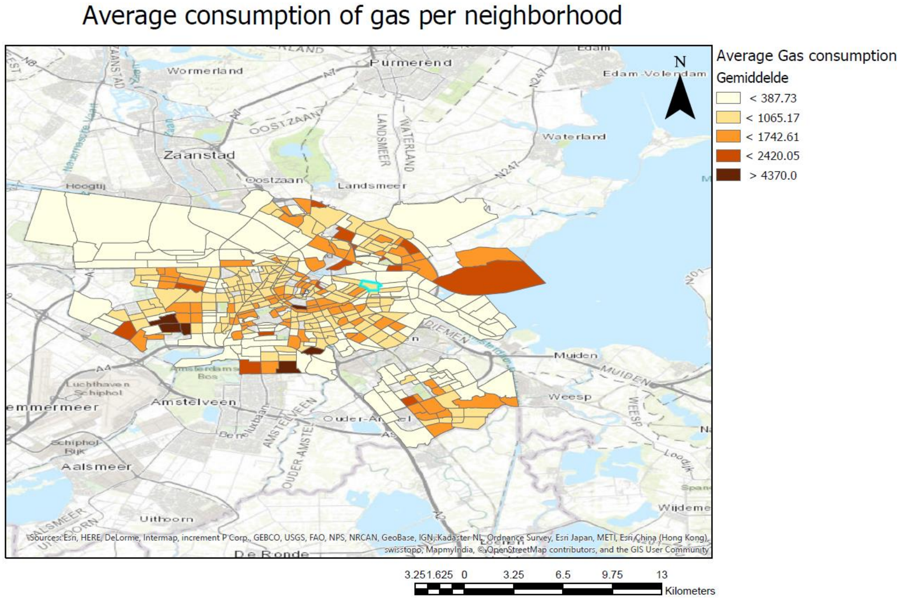


Figure 30 average gas consumption per neighborhood, **(CBS, 2017)**

Large consumers

Using gas consumption data on postal code 6 (PC6) level, large consumers can be identified. The map shows that most of the buildings in Amsterdam consume average or above average amounts of gas.

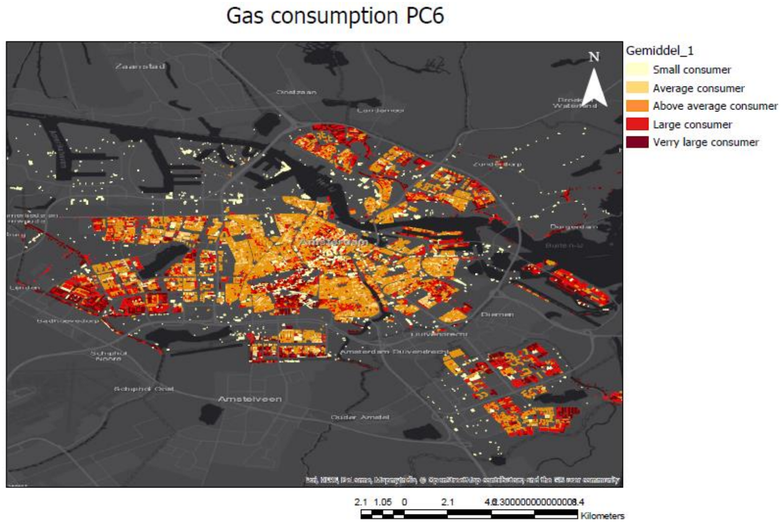


Figure 31 Gas consumption on PC6 level, **(Municipality Amsterdam, 2017)**

Amsterdam tries to provide housing for every income. That is why there are housing associations located throughout the city. These associations are regulated strictly through the Woningwet (Rijksoverheid, 2017). The buildings of these housing associations are heated with gas. Figure 32 shows the gas consumption per PC6 for the associations. Most of the buildings consume an average amount of gas, about 900 m^3 of gas.

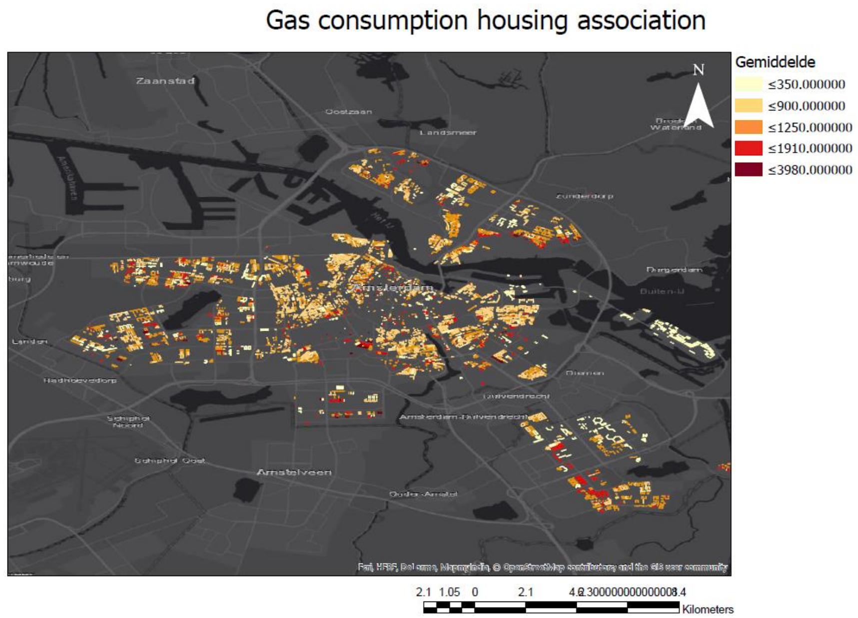


Figure 32 Gas consumption of housing associations, **(Municipality Amsterdam, 2017)**

4.2.2 Supply

Gas

In Amsterdam 90% of the residents use gas as fuel for their boiler. Water and the residence is heated by burning gas. The first gas subterranean infrastructure in Amsterdam was installed in 1816. This network was introduced for gas lighted street lights. At the end of the 19th century the demand for gas grew exponentially in the city due to several innovations and a peak in coal prices (Lintsen, 1993).

Nowadays the net provider Alliander is responsible for the gas and electric infrastructure in Amsterdam. The use of gas is an indicator of the amount of energy used for heating.

A distinction in infrastructure can be made between the main pipes and the distribution pipes. The difference is in pressure and functionality of the pipes. Main pipes are subsequent to a higher pressure and are used to transport large quantities of gas on a larger distance. These pipes are located in every street. To transport gas to the customer the main pipes are tapped by smaller distribution pipes in the street. Distribution pipes go all the way into the houses of the costumer to the boiler.

The high pressure gas infrastructure of Amsterdam is illustrated in figure 33. Figure 34 shows the low pressure gas infrastructure. It is visible that most of the streets have a low pressure gas pipe present, and almost every building in Amsterdam is connected to this network.

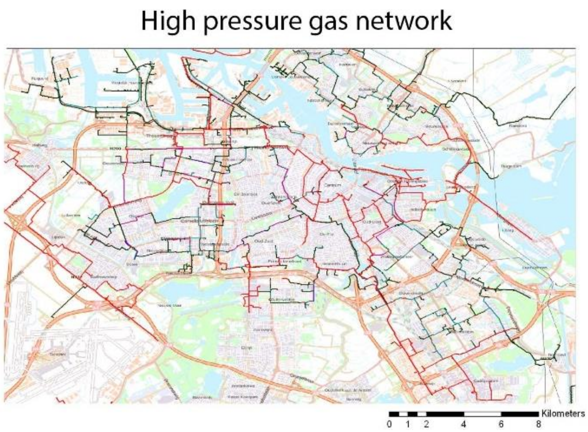


Figure 33 High pressure gas network, (Alliander, 2017)

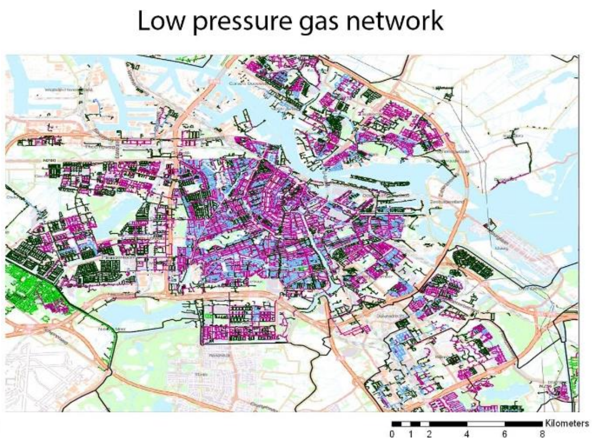


Figure 34 Low pressure gas network, (Alliander, 2017)

District Heating

Another way of energy distribution in Amsterdam is by DH. This is done by energy company Nuon in collaboration with other companies. According to the municipality of Amsterdam the two main heat sources, in the north west and south east of the city, are able to deliver heat to 325.000 housing equivalents (HE) (Municipality of Amsterdam, 2016).

Figure 35 shows a remarkable pattern throughout the city. The infrastructure for DH is located around the city centre outside of the ring road. Amsterdam has been build up from the centre outwards over years. Therefore, buildings in the inner part are on average older than on the outside of the city, this is demonstrated in colour in figure 36.

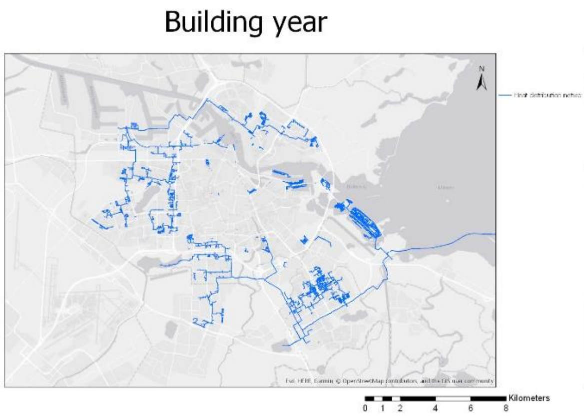


Figure 35 District heating network, (Nuon, 2018)

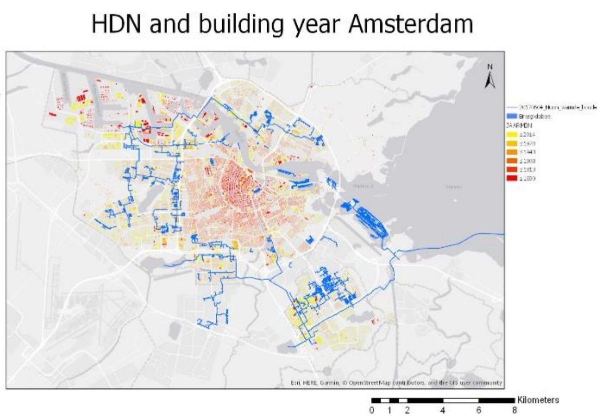


Figure 36 District heating network and age of buildings

Heat sources

Supply of heat is not dependent on only one kind of heat source. As explained in the previous chapter, heat can be delivered by more than one process. Excess heat from for instance energy plants and waste incinerators are common and popular heat sources in the Netherlands. They generate high energetic heat as residual product.

On national level potential heat sources have been identified in Amsterdam, illustrated in figure 37 with a star. In the north the harbour with its chemistry plants, in the east the hospital along with the energy plant and in the south the airport.

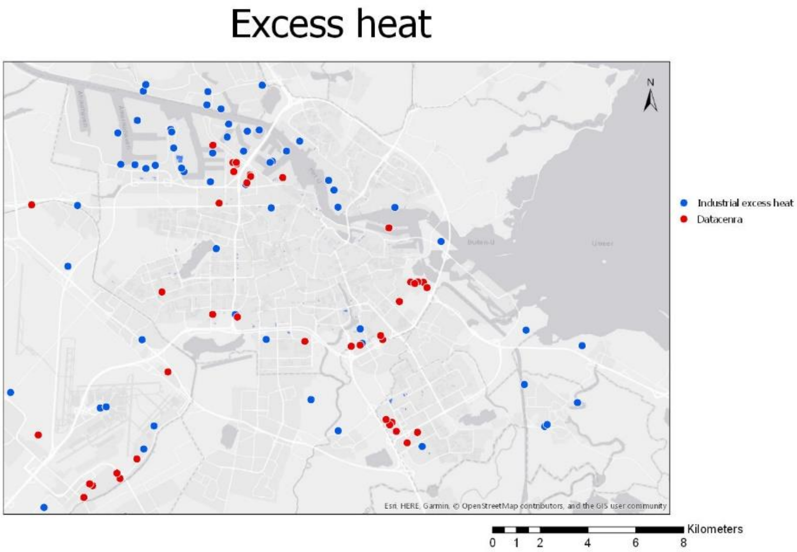


Figure 37 Heatsources in Amsterdam

However, these examples are only identified by the net provider. Low energetic and smaller heat sources are not taken into account. Heat sources like large boilers from hospitals or roof mounted PV-panels are also able to deliver a base load of heat.

Also geothermal heat can be exploited in Amsterdam. As shown in figure 38 the western part is more suited according to the university of Delft (Municpality of Amsterdam, n.d.).

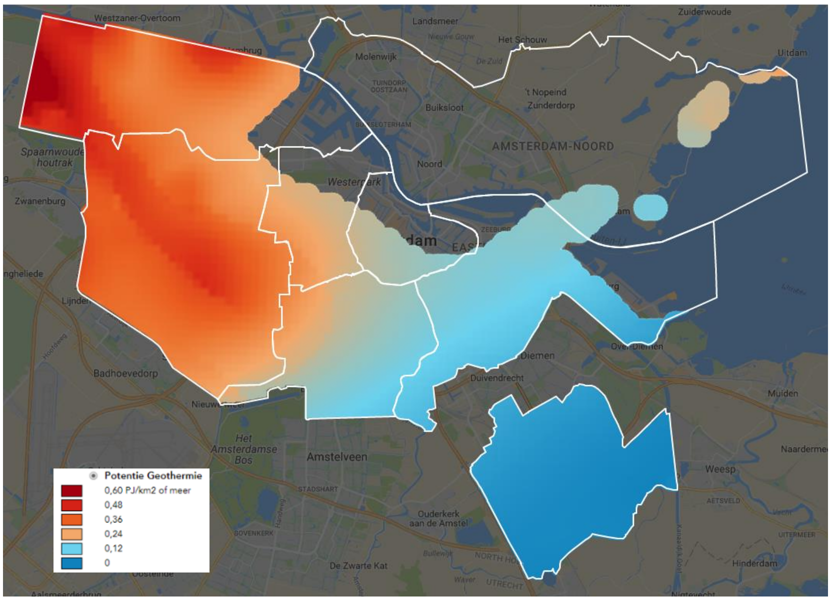


Figure 38 Geothermal heat in Amsterdam, **(Municipality Amsterdam, 2017)**

A HDN can also potentially be fed by heat form photovoltaic panels on rooftops. The system can be connected to the open network, for instance to deliver heat to the neighbour. Data about rooftops are freely available in the Netherlands. Companies make maps of the potential for PV-panels, like figure 39, shows this potential. It is clear that the potential is very high in Amsterdam, according to this source. Almost every building in

Amsterdam is in a way suited for PV-panels. However, this figure may be exaggerated because and the tool does not take into account installed pv-panels or limiting factors on the roofs.

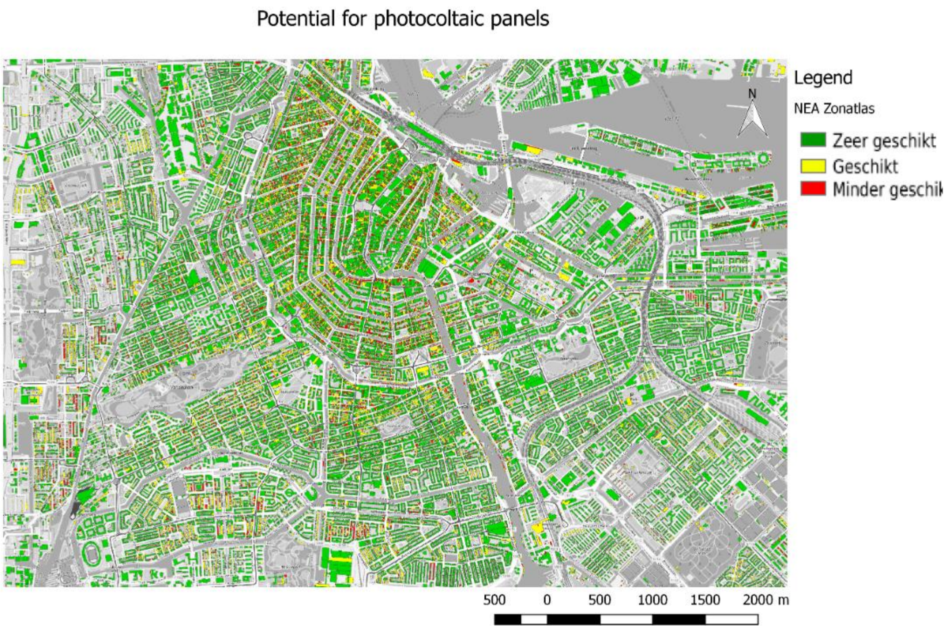
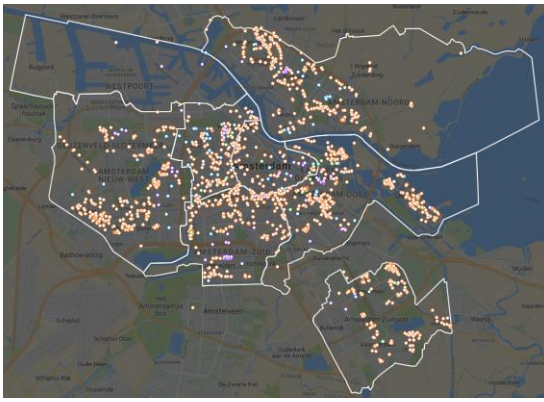


Figure 39 Potential of pv-panels in amsterdam, **(Zonatlas Amsterdam, 2017)**

There is also data available about the amount of installed PV-panels. All these dots are installed PV-panels either owned by housing associations or private persons. Figure 40 shows that there are already some PV-panels installed. However, it doesn't fulfil the potential of the city. Figure 41 shows the amount of 28 locations with installed PV-panels owned by housing associations.



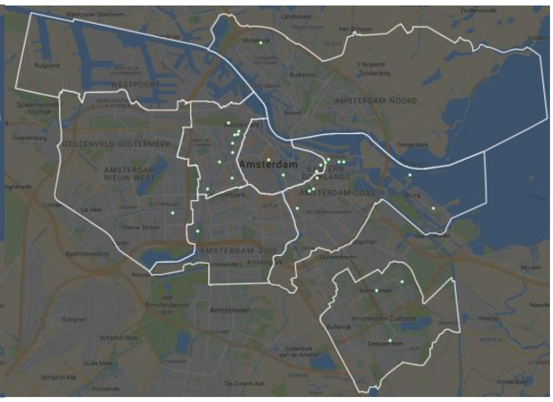


Figure 40 Installed PV-panels, **(Municpality of Amsterdam, n.d.)** **Figure 41** PV-panels on housing associations, **(Municpality of Amsterdam, n.d.)**

Cooling sources

The city of Amsterdam is built on clay and has a close relationship with water. Commerce started with trade over the main water bodies. Ships brought goods from the North Sea into Amsterdam. Nowadays these waters can provide cooling water for the city. Because DH is also able to provide cooling for the residents during the summer or for industrial purposes. The Nieuwe Meer is a lake that is already used by energy company Nuon for cooling water.

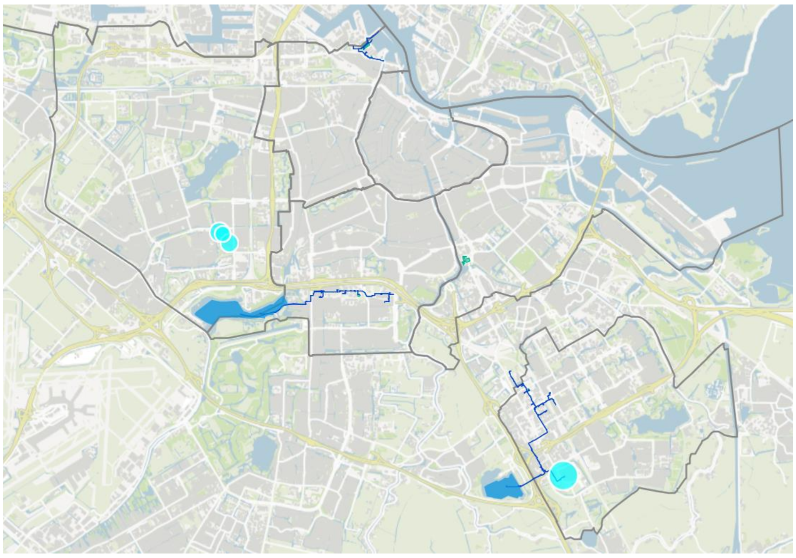


Figure 42 Couling sources

Heat storage

Heat can also be stored at larger facilities like the boilers of the city hall. The heat can be tapped during peak consumer moments in the morning for instance.

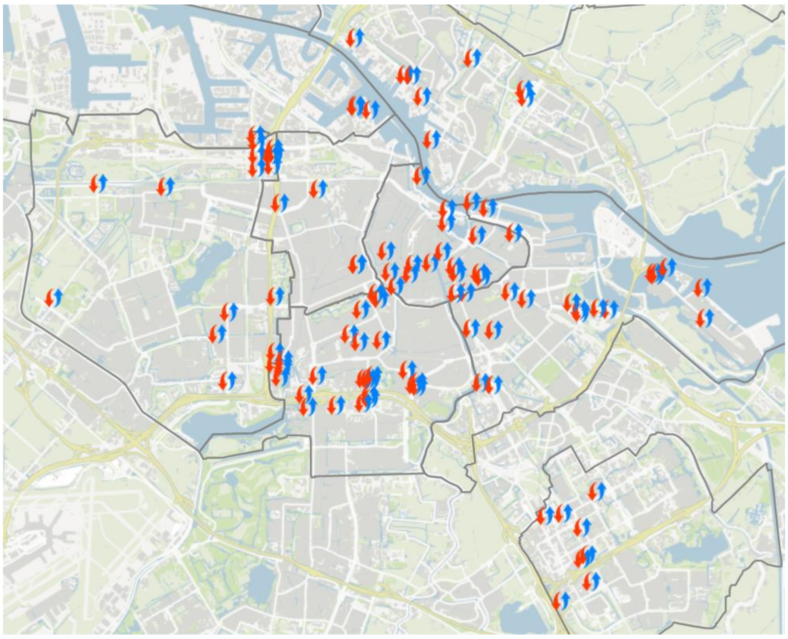


Figure 43 Heat storage

4.3 Future heat distribution Rivierenbuurt

This chapter will focus upon the potential of DH in the Rivierenbuurt. Constructing a cost route map and calculating cost and benefit for the neighbourhood.

When looking at the demand for gas at postal code 4 level in Amsterdam there are some neighbourhoods that use more energy than others. The centre uses more energy than other parts of the city. This research will focus on the neighbourhood the Rivierenbuurt located in the southern part of the city because it uses more energy than other neighbourhoods.

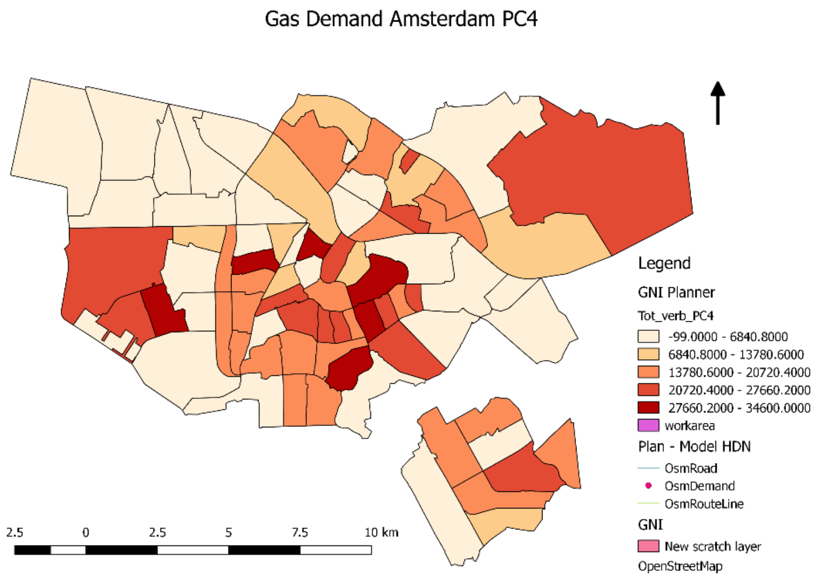


Figure 44 Gas demand on neigbourhood level

4.3.1 Benefits

CO_2

One m^3 of gas emits 1,8 kg CO_2 (Wageningen UR Livestock, 2007). The current gas network in Amsterdam had 527.864 houses in 2012 which consume on average 900 m^3 gas per year. One tenth of the buildings use district heating, so the rest of the buildings emit approximately 403.815.960 m^3 of CO_2 annually. Which amounts to € 5,088,081.10 EUR a year for the whole city. For the Rivierenbuurt with 15.525 houses the benefits amounts to € 166,272.75 a year (Municipality of Amsterdam South, 2014).

PM_{10}

The particulate matter pollution of DH is considered to be null, because the system uses residual heat. According to the data set: “Amsterdam IRC Residential Gas Emissions per Dwelling” the average PM10 pollution is 0.003 Mm^3/mg (ClairCity, 2017).

Next to PM10 the combustion of gas produces NO_x as residual product. According to CBS 75% of the households use HR-kettle in 2008. Unfortunately there are no up-to-date numbers about the installed amount of HR-kettles in Amsterdam, therefore we assume that the amount has risen to 100% (SenterNovem, 2009). There are different ways of burning gas, the most efficient way is with a premixed burner. This system only emits 70 [mg/Nm^3] of NO_x (Roeterdink & Kroon, 2010). Still the NO_x pollution of gas in the Rivierenbuurt is 92373.75 ton NO_x a year.

Unfortunately both kinds of pollutions cannot be expressed in monetary funds. However, this does not mean it could benefit public health and therefore save money on health insurance in the long term.

4.3.2 Cost

As explained in the methodology the cost raster is constructed on which further analysis can be done. The cost raster has been constructed on the BGT and the BAG which results in figure 45. When the figure is inspected closely the larger streets stand out with a high value. This can be explained by the weight that has been given in the model. Larger streets that have been asphalted are more expensive to break open for the construction than smaller streets consisting of tiles.

Because the raster size is 0,5m the values in the legend are half the price that is given in the methode.

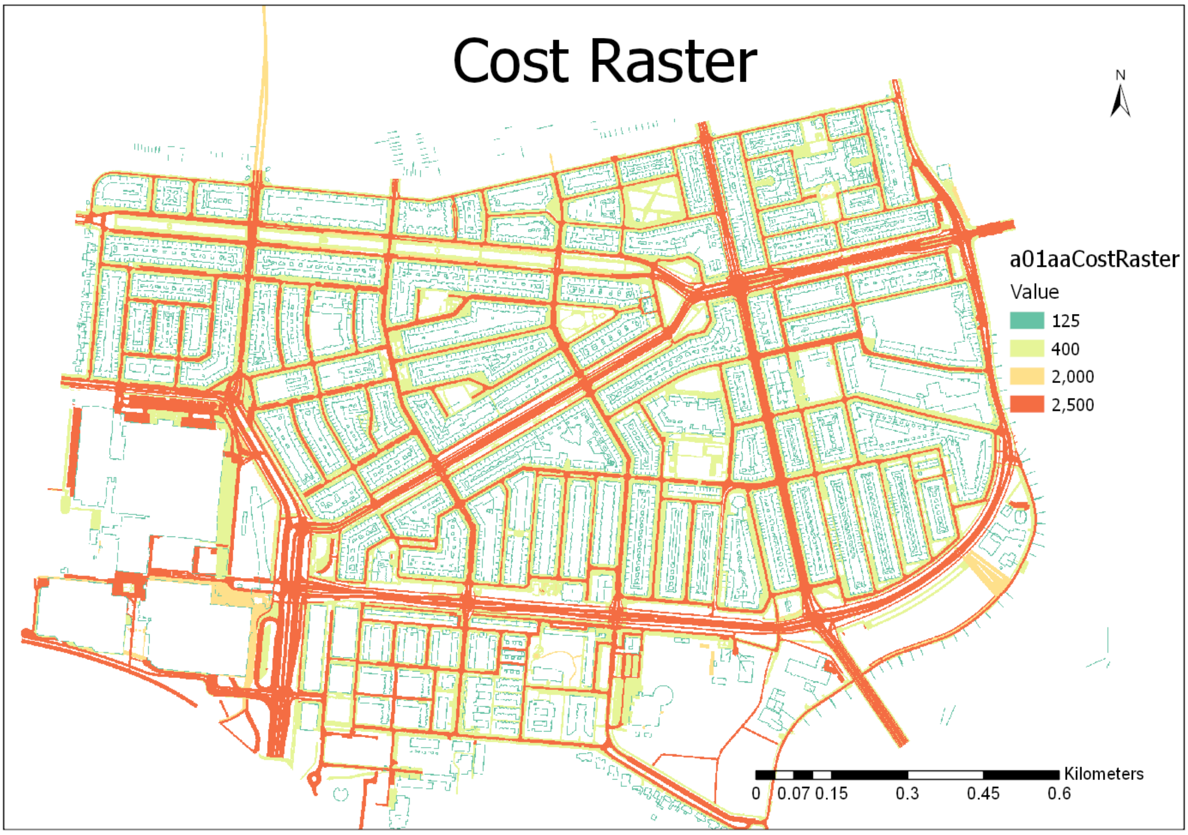
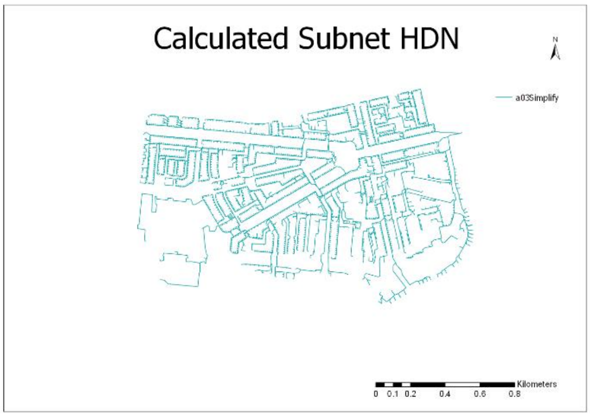


Figure 45 Cost raster created by model

The local loop that brings the energy or heat to the houses is constructed in figure 46. There is not a large notable difference in the calculated subnet and the current gas network. The connections between housing blocks are sometimes located a bit further up the road. A large outlier is the difference in the source. The source that has been used for the calculated subnet is located at the Berlage bridge, in the east of the research area, where the gas source is located 200 meters to the south.



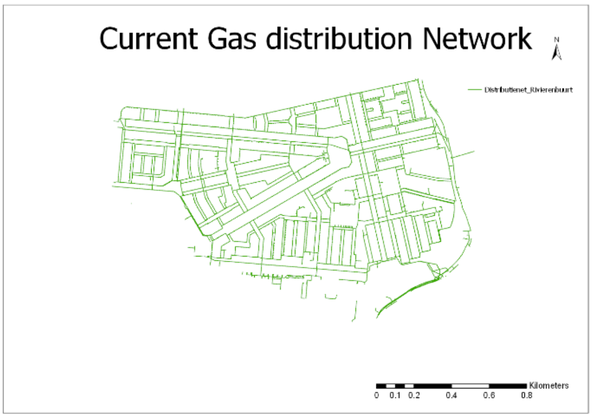


Figure 46 Calculated subnet district heating

Figure 47 Current gas distribution network

There is a difference between the subnet and the distribution network. The subnet connects the house to the heat network. Where the distribution network are the larger pipes that transport the heat through the neighbourhood. These figures do not differ significantly because the gas network has been constructed efficiently as well.

Table 3 has been calculated using statistic tools in GIS. The sum of the cost is very high, however when the cost are annualized it is more manageable with €4,6 million a year.

Total Cost	Length	Cost per meter	Annualized cost total
€ 64,661,604.37	63662.18 m	€ 1,015.70	€ 4,598,189.08

Table 3 Calculated cost table

To check whether the estimated total cost is realistic the research used Alliander's internal rules of thumb for constructing heat distribution networks in rural areas. Constructing a distribution network for 2500 buildings costs around €10 million (Liandon, 2018). Since the Rivierenbuurt has six times more houses to connect, the price rises to €60 million. More or less near the estimated cost by the model.

Figure 48 is a representation of the subnet aligned with the distribution network in order to inherit data from the gas network. With the colours the ages are illustrated. The as infrastructure has been categorized on upcoming renovations (Akkerman, 2018). Every so many years gas pipes have to be replaced. With the colours red and yellow the oncoming renovation is illustrated. This is important when constructing a new network, because a hole needs to be dug when renovating the network. This is expensive, so if a HDN pipe can be installed in the same hole a lot of expenses could be avoided. This map is especially interesting for the construction planners at Alliander.

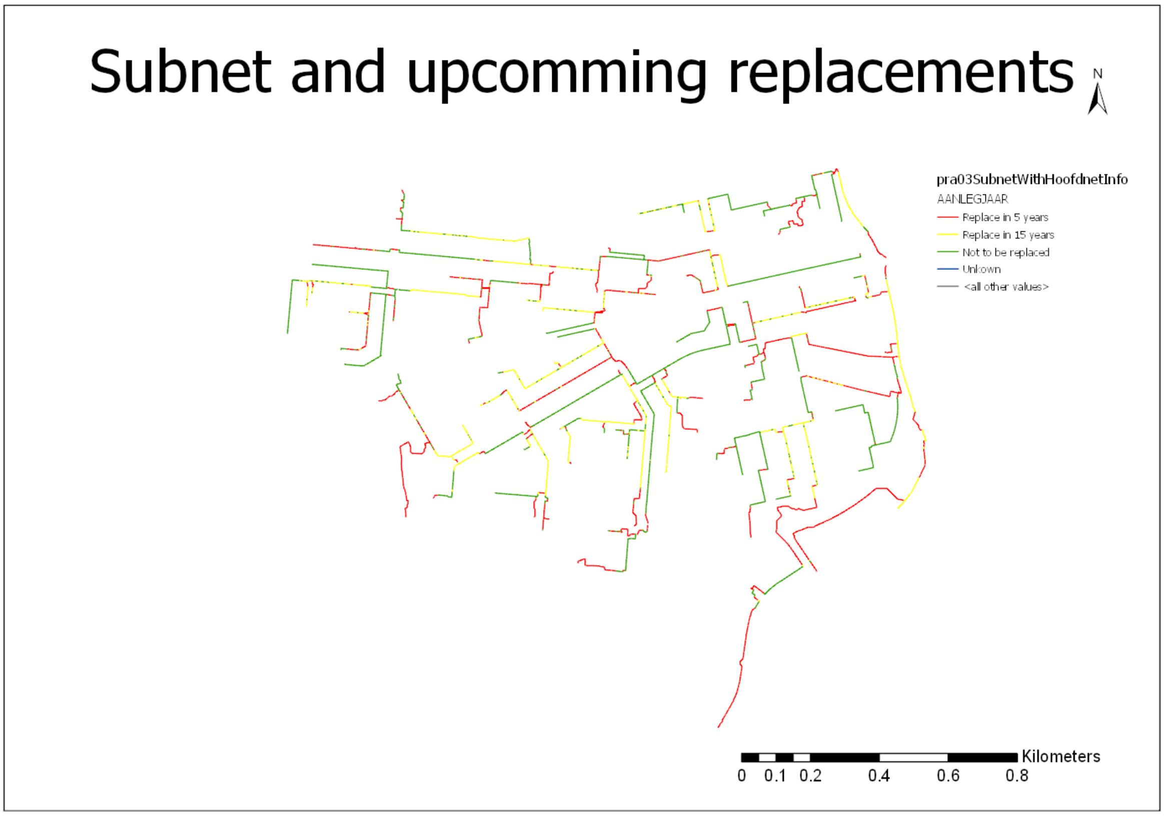


Figure 48 Calculated subnet and upcomming replacements of gas network

In order to come to a good estimate about the demand per pipe segment, a model has been constructed using hydrological tools in GIS. The stream order map is a result of the Shreve algorithm where the watershed streams are ordered. And the demand per line map is a result of an accumulation function in GIS.

Difference in the calculated pipeline routes from the subnet can be explained in the difference in tooling. There are some gaps that in the routing that are still inexplicable. However, the map can still be used to illustrated the demand pressure on the pipes. The pipes that have the most demand, illustrated in red, are more close to the source. Which can be explained by the accumulation of demand from the watersheds. With data about demand per household this function can be used to determine the distribution cost.

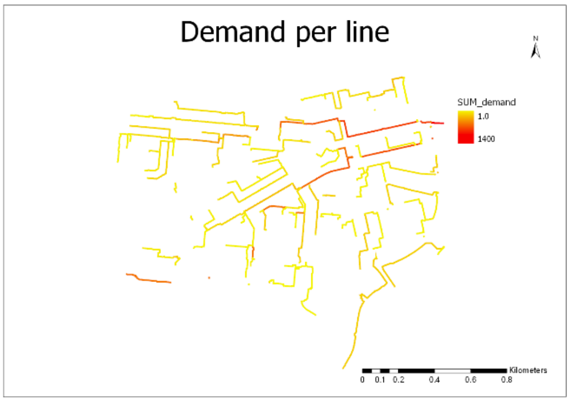
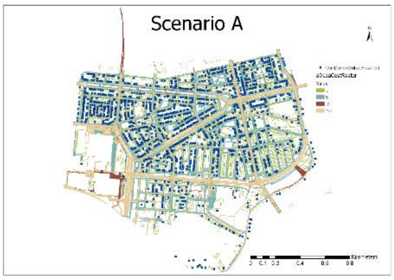


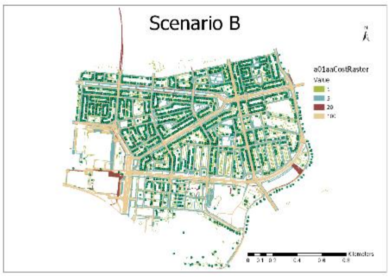
Figure 49 Stream order map

Figure 50 Demand per pipeline

4.4 Cost and demand scenario's

In this chapter different scenarios are constructed to test the model and to test the calculated cost. The point data set is decreased by 50% in scenario A and in scenario B by 25% using the subnet feature tool. Scenario C is the realistic scenario used in the previous chapter.





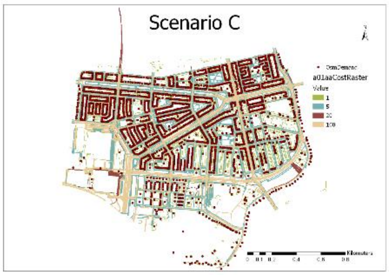
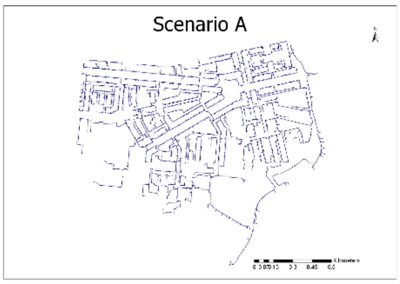
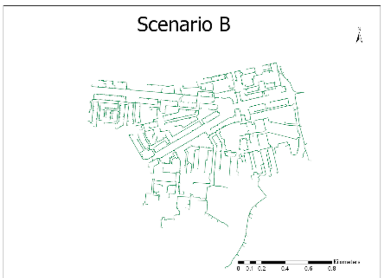


Figure 51 Cost raster & demand points A **Figure 52** Cost raster & demand points B **Figure 53** Cost raster & demand points C

To compare the different scenario's it is especially interesting to look at the constructed subnet. The figures below is an illustration of these scenario's. The trend which can be seen is the amount of detail. Scenario A and B have less detail than scenario C because there are less points to connect towards.





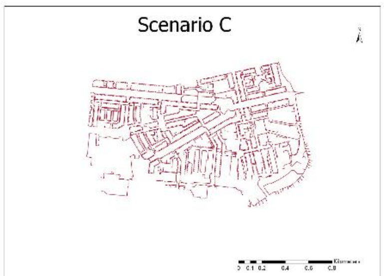


Figure 54 Calculated subnet A **Figure 55** Calculated subnet B **Figure 56** Calculated subnet C

The cost and length of the different scenarios have been plotted in table 4. Looking at the total cost of the three different scenario's an increase can be noted. However when looking at scenario b and c, the decrease of 25% of the points does not translate to the same decrease in cost. Less connections towards the houses have to be constructed in scenario A and B hence the absolute decrease in cost. However, the distribution net still has to be constructed. When the cost are extrapolated linearly to 1%, according to the model, there should be a certain amount of fixed cost.

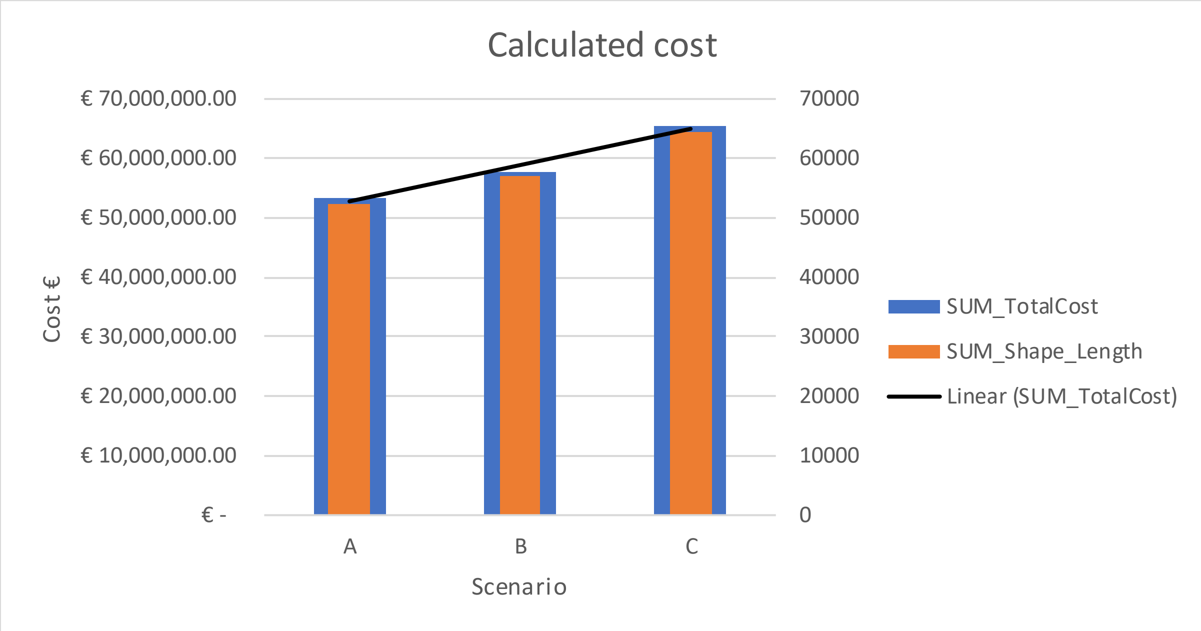


Table 4 Calculated cost and length per scenario

However when a closer look is taken at the cost per meter in the three scenarios a non-linear relation can be noted. This could have to do with the fact that the distribution net is already in place, and an extra house connection would use the existing network. An interesting effect that could be optimized by network providers.

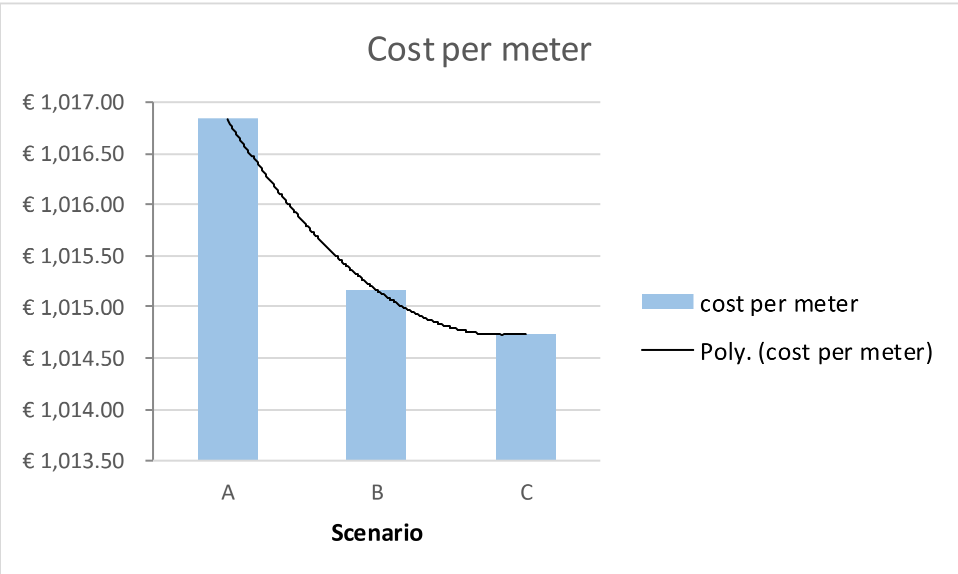


Figure 57 cost per meter

5.Conclusion

On the outset of this research the objective was*; develop a model that finds the optimal location for district heating and calculates the social cost and benefits, at street level in a research area*. This has been done by assessing the alternative methods of heat transportation and calculating costs and benefits of district heating for the Rivierenbuurt. Four research questions were formulated in order to solve the main objective.

The first research question focussed on future heating systems, in which different competitors of district heating were addressed. Cost and environmental impact were weight for each of the competitors. One of the biggest competitors is isolation. It is cheap and it is able to save a lot of heat loss in buildings. However, gas is still used for heating and that does not strike with the vision of the municipality. Heat pumps and solar water heating are also good alternatives. High initial costs, of these alternatives, for civilians prevented a large market penetration of these competitors. The advantage of district heating is the fact that it can use excess heat and distribute it to the demand areas. However, it also bares a high initial cost. Not for the civilians themselves, but the investment cost are done by net provider Alliander. Because this company is able to do this kind of investment with the way payment is done every year, the alternative can be a good alternative for future heating system in a built up areas.

The second research question studied the way in which heat was disseminated in the present. Demand for heat is not equal throughout the city. It has shown that older buildings tend to be less efficient with energy than newer buildings and that housing associations could save a lot of energy. The way in which the heat is disseminated is through a large subterranean gas network and a small percentage of the outer parts of the city makes use of district heating. Furthermore, the potential of energy sources, high as well as low energetic, is present. This is can form the basis of a 4th generation open district heating network.

The third research question was about the heat distribution in the future. A cost and benefit analysis was done with GIS tooling. The benefits were calculated to be €166,272.75. With a total cost amounting to €65 million in total for one neighbourhood. The cost were annualized which amounted to €4,5million every year therefore the benefits did not weigh up against the cost.

The fourth and final question was to test the robustness of the model. Three different scenarios were tested on the model. Interesting is the cost and length of the pipes. There is a threshold value when constructing a HDN. Also with a decrease of 25% of the points the cost did not decrease with the same amount. This has to do with the main infrastructure that has to be constructed nevertheless.

After all the research question the conclusion is that the cost <u>do not</u> weigh up against the benefits of district heating. When comparing the cost of the model and the cost predicted by the net provider Alliander itself there is no big difference between them which validates the model. If the cost are projected for other neighbourhoods, or the whole city, the cost will most likely not weigh up against the benefits.

However, as stated in the introduction, the world is inevitably changing due to climate change. The initial investment costs are high, but the mitigation cost of climate change and the health cost as a result of pollution in the long run are far greater. If the country decides to invest substantially, the question of cost benefits will change into cost optimisation. The government is capable to force investments in alternative energy sources by larger parties such as housing associations through altering laws. The costs for a new connection drop radically with new infrastructure already in place. Also, expertise on energy efficiency creates jobs and it could become an export product, these benefits are not taken into account in this research but they can be significant in the larger picture.

Application of district heating on small scale in combination with for instance solar heating might be an even better solution on locations where Alliander needs to renovate the gas network. Using a data driven model for estimating the cost of district heating can help future planners to decide on the best solution. If we don't react to the signs of climate change, we might be too late and we have to deal with the consequences. For a country that lives beneath sea level and strives to be innovative, this is a chance to take the lead and show how old European cities can change and become a healthier place. Therefore, district heating must be considered by the municipality of Amsterdam.

6. Discussion

The discussion is split into an internal and an external part. Where the internal part discusses the method and the results. And the external part the discussion reviews the academical context of the research.

Internal discussion

The research has shown some interesting results. The GIS model granted an insight into the costs in different scenarios and calculated the ideal route, which was not far of from the existing network. However the benefits did not weigh up against the cost in this research. However, as explained in the conclusion, this alternative should not be written of directly by policy makers.

Unfortunately, the research is not inclusive enough to have touched every alternative heating system and to compare all the cost and benefits of the best alternatives. If the net provider or government foresees other trends in the future, the results may be drastically different. Also, when parameters such as cost per meter or price for CO2 change, the results may alter. Furthermore, not all the benefits such as health could be expressed monetary, this has a negative effect on the results.

When a closer look is taken at the model it is possible to find weak spots. A buffer had to be constructed around the houses in order to create a single polyline. Despite tooling that should simplify the resulting polyline, there are some places where the line is interwoven. Also, we see that a street is crossed more than once within 50 meters. These kind of imperfections should be edited by hand to make the model more exact.

Additionally, the model only calculated the cost for the Rivierenbuurt. This does not yield enough empirical proof that the model is statistically solid. Adding to that, the fact that multiple heat sources is not taken into account in the model, which may distort the results as well. Therefore further research needs to be done on more neighbourhoods to prove the robustness of the model. For instance, the model should be subject to a large number of test on neighbourhoods in rural and built up areas.

In fact, the model should be seen as a proof of concept. It is possible to plan a new network on street level using GIS tooling. Factors like politics, heat loss, roots of trees and the dynamics of an open head distribution network are not taken in to account. Therefore, resulting costs should not be taken to literally, because in the real world there are more factors that have an effect on the construction and maintenance of a heat distribution network.

External discussion

The external discussion looks at the research from a wider academic and societal perspective. When comparing this research to others it is possible to find similarities as well as differences. Looking at the research in a broader perspective namely energy transition, the trend is to reach 100% change to renewable energy sources. However, as stated by Lund and Mathiesen, countries do have to make choices when they want to solely rely on renewable energy (Lund & Mathiesen, 2009). Which may mean that gas will still be there the coming years. This is not denied by this research, only the cost benefit analysis and the model can help in speeding up the transitional phase.

In the research area of energy transitions, most studies focus on the theoretical part and calculations on electricity production and consumption in general. Large studies on the efficiency of competing energy solutions are performed in detail. However most of the literature studies a certain object in a laboratory, which are not always applicable in this research.

However, a similar approach to district heating has been performed by (Nielsen & Möller, 2013). Studies that use GIS data are performed using large study areas. Their approach is on a more macro level, as they look at interconnecting cities on national scale. An example of a study that also looks at the cost and benefits, however it does this from an economic point of view and due to its scale it lacks detail which may effect cost and benefit estimations.

Combining multiple datasets in a large and compact city, on this precise scale is new for calculating the potential of district heating. Also, the model of this research is responsive to new input so policymakers can interact with different projections of contractors and new regulations. Moreover, this model can be adjusted from micro energy network analysis to macro energy network analysis. Also, extra subterranean data can be added to provide an even more exact cost indication.

A shortcoming in this research is the lack of hydrodynamics and cost differentiation. Where Nielsen and Möller do succeed in the differentiation of cost factors such as heat loss, this research did not. Hydrodynamics do play a large role in the construction of district heating networks. If the model is to be perfected, factors like heat loss should be taken into account. A suggestion for an economic feasibility study would be, to develop the stream methodology and implement a heat loss and a subterranean parameter which results in a better estimation of the total cost and benefits.

As discussed in the last part of the discussion the energy market is changing, and according to the Kyoto protocol we, as mankind, must change our behaviour (United Nations, 2014). This research has tried to help in the discussion around district heating. According to the PBL we can distribute vast amounts of heating through district heating (Planbureau voor de leefomgeving , 2017). However, this research shows that it is expensive to install district heating. In order to speed up the transitional phase in which our society finds itself, it might be helpful to create an oversight of all small scale solutions, which enables policy makers to substantiates their choice for a solution.

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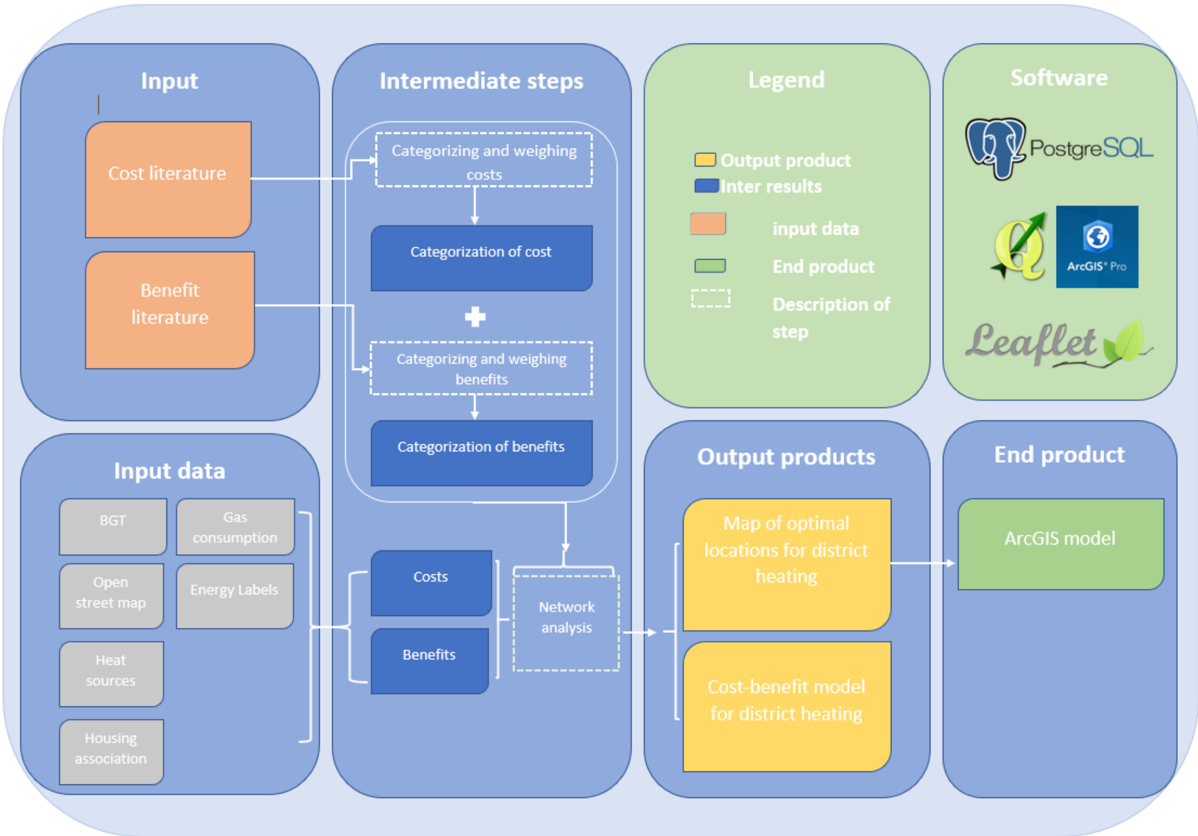
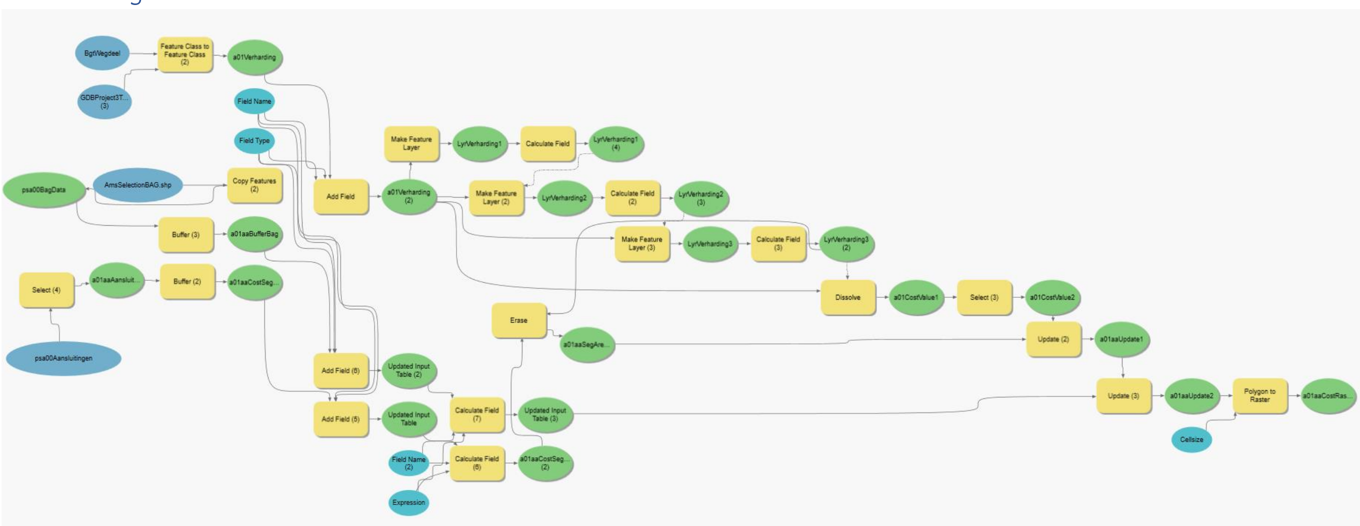
Appendix

1. Flowchart

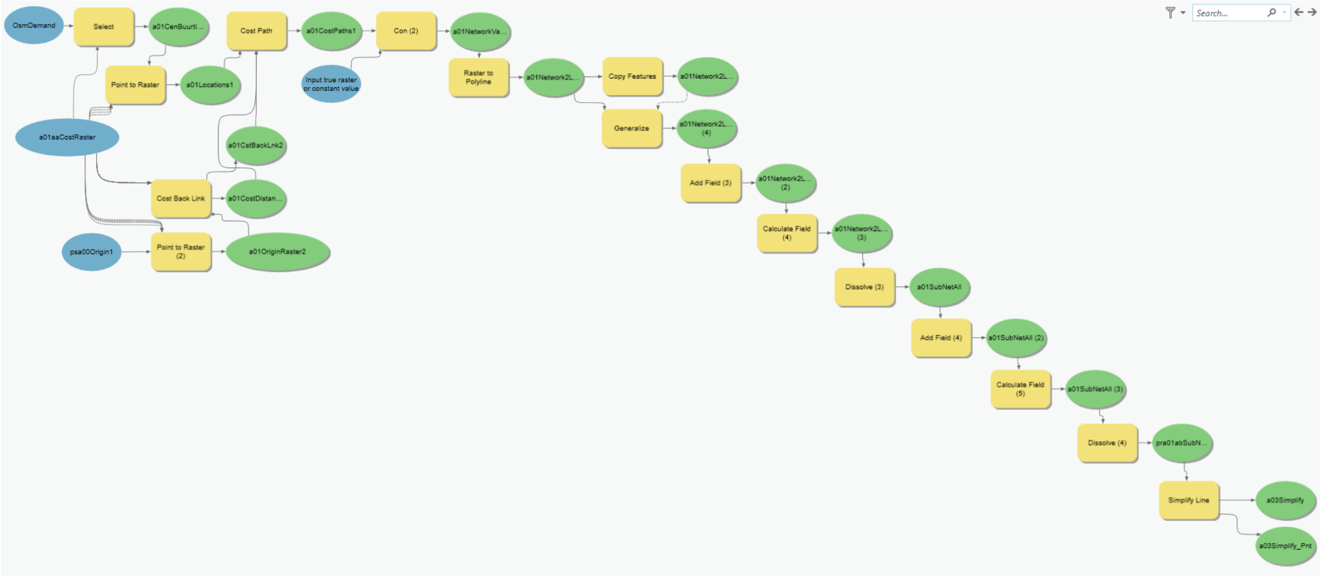


2. Models

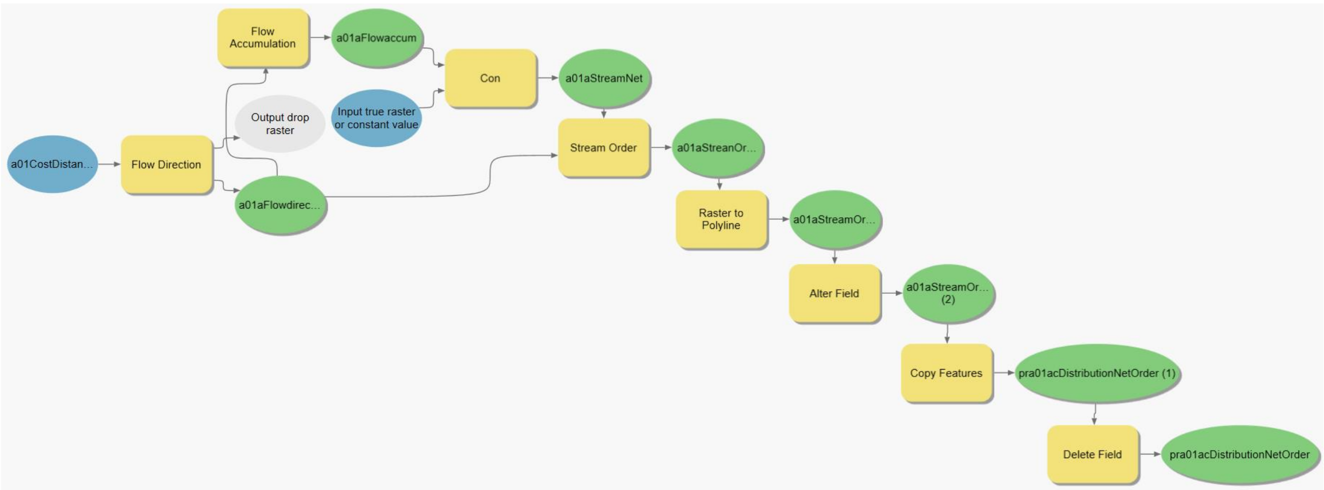
2.1Creating a cost raster



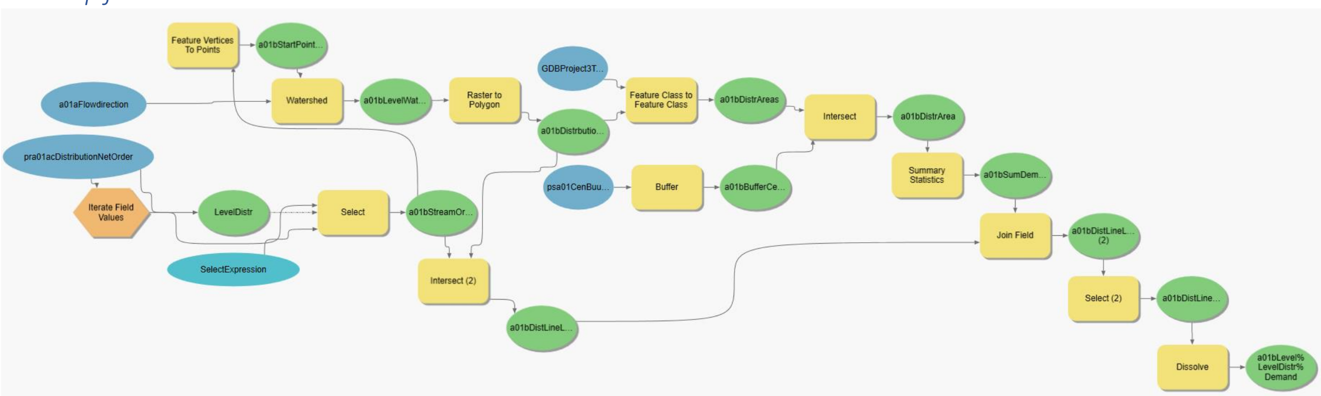
2.2 Creating a subnet polyline



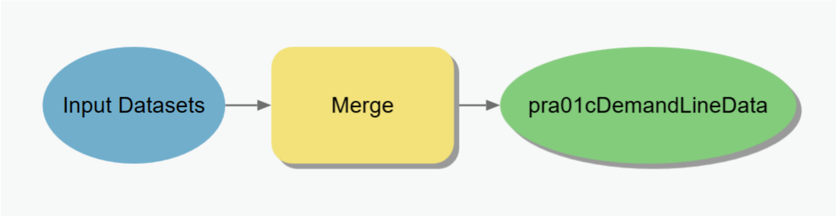
2.3 Creating a streamorder



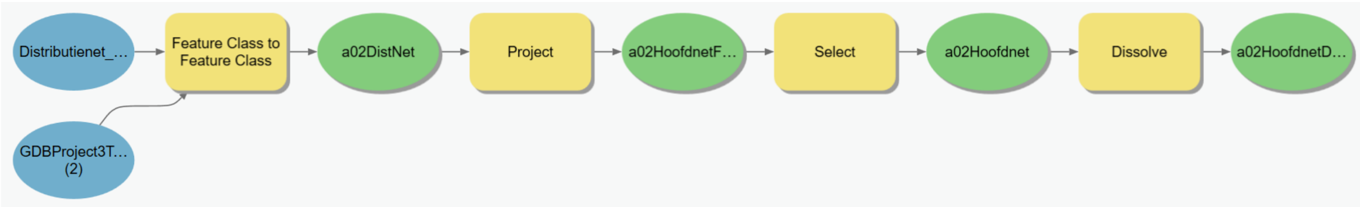
2.4 Loop for distribution level



2.5 Merge the loop



2.6 Creating a distribution net



2.7 Aligning distribution net with gas network