Local heat transition in the Netherlands

Exploring pathways towards a sustainable heating system at neighbourhood level for 2030 – a case study of Overvecht, Utrecht

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MSc Energy Science – Thesis
23 September 2019

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Foreword & Acknowledgements

For completion of the Master's programme Energy Science at Utrecht University, I have done a graduation project in the form of a Master's thesis, of which you see the product before you. This project is a combination of performing scientific research and writing a Master's thesis, covering the core areas of the field of Energy Science.

This research is executed in collaboration with the Municipality of Utrecht. Although this research is executed as a stand-alone scientific research, it is used to learn about the application of *Vesta MAIS* for a neighbourhood-level analysis and share the lessons learned to apply an analysis with this level of detail to the whole city of Utrecht. This will in turn contribute to the development of a 'Transitievisie Warmte', an obligatory plan that all municipalities in the Netherlands need to construct by 2021, which contains a neighbourhood-level plan to replace natural gas as heating source for buildings. This report aims to help the Municipality of Utrecht with achieving this goal.

I want to thank the following people, without whose help this project would not have been possible. First of all, I want to thank my supervisor Sara Herreras Martinez for her excellent guidance, commitment and shown interest in my work. Working with you has been an absolute pleasure. I hold your supervision in high regard. Secondly, I want to thank Wen Liu (Utrecht University) for her involvement and valuable feedback. Both of you really helped me to perform better. Thirdly, I want to thank Jesus Rosales Carreon (Utrecht University) for being my second reader. Next, I want to thank Folckert van der Molen (PBL) for his time to help me get started with the model and answering lots of questions. It helped to speed up the start of this project a lot. Next, I want to thank the Municipality of Utrecht for the opportunity of doing a graduation project at their organization and facilitating this research. I felt most welcome. The time I spend at the project was very educational, and a good first taste of what working as an energy system modelling specialist is like. In special, I want to thank the Data Brigade team members Ling-Po Shih and Dick Joosten for their trust in me and for providing a good research environment. I had a very pleasant time and was always happy to go to our meetings. Also, I want to thank Mirjam Harmelink and Dietje van Eif (both Municipality of Utrecht), for shown interest and practical uptake of my gained experience during this project. I have found our collaboration most valuable. Moreover, I want to thank Chris Vos (Eneco) for our valuable meeting regarding district heating. Finally, I want to thank Simone Borggreve (TU Delft) for exploring the *Vesta MAIS* model together with me, as it was really helpful to discuss the details and learn from each other.

Thank you all. I have cherished our collaboration. I have learned a lot.

Max Uyttewaal

Utrecht, 23 September 2019

Abstract

In order to contribute to the transition towards a carbon-neutral heating system and aid to reach the goals of the Paris Agreement, this research has investigated the optimal mix of sustainable heating technologies at the neighbourhood level. By using the neighbourhood Overvecht in Utrecht as a case study, the most optimal techno-economic pathways at local scale towards a sustainable heating system by 2030 are established per district, based on the lowest societal costs. Herein, the *Vesta MAIS* model was used to assist with the analysis.

Identifying the most techno-economic pathway included a three-phase method. Phase I consisted of collecting data and making adjustments to the *Vesta MAIS* model to allow a neighbourhood-level analysis. In the second phase, several scenarios to achieve a sustainable heating system by 2030 were calculated with *Vesta MAIS,* and the energy demand, emissions and societal costs were extracted. Phase III consisted of an analysis of the output parameters, and the determination of the optimal pathway towards a sustainable heating system by 2030. In addition, a sensitivity analysis investigated the robustness of the optimal pathway for various societal discount rates, learning curves and building improvement costs.

The optimal pathway for Overvecht showed that for 14 districts a high temperature (HT) heat network is more attractive, while for 3 districts a low temperature (LT) heat network is optimal, and for 1 district individual heat pumps are the optimal option. For the districts with a LT heat network and individual heat pumps as the optimal option, the buildings' energy labels are upgraded to A+ to account for the LT heat supply at building level. The buildings which have a HT heat network as optimal pathway do not require an upgrade to a higher energy label. Within this optimal pathway, an energy demand reduction of 20% (to 687 TJ/year) and an emission reduction of 70% (to 19 kt CO_2/year) can be achieved, while the societal costs show an increase of 34% to 28 M€/year.

In general, this study found that the expansion of a HT heat network to surrounding districts is the optimal option for districts with a high heat demand density and a dominance of average energy labels (C and D) present in these districts. The LT heat network is the optimal option for districts with a high heat demand density and low energy labels (E or lower), as these buildings require the implementation of insulation to reduce the high heat demand, which is economically attractive to combine with LT district heating. For areas with a low heat demand density, individual heat pumps are found to be the optimal option.

To conclude, this research has shown that the optimal pathways towards a sustainable heating system consist of a combination of different system adjustments, including the expansion of the HT heat network, the instalment of LT heat networks, the implementation of individual heat pumps and the upgrade of a limited share of buildings to energy label A+. The heat demand density and the energy label are driving factors behind the optimal pathway for a district. A neighbourhood-level analysis with *Vesta MAIS* proved to be a useful tool to identify the most optimal techno-economic pathways at local scale towards a sustainable heating system by 2030. However, this research produced only a part of the required information to actually start the heat transition at neighbourhood-level and realize a sustainable heating system by 2030, as social and political factors also need to be taken into account.

Keywords: heat transition, sustainable heating, energy system modelling, neighbourhood-level, techno-economic pathways

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1. Introduction

This first chapter presents the general introduction to the subject, which includes the societal background, scientific relevance, case study introduction and research questions, as well as the outline for the rest of this research.

1.1 Societal background and problem

With the adoption of the Paris Agreement in 2015, the Netherlands has committed itself to reduce emissions by 95% in 2050, compared to 1990 levels (UNFCCC, 2015). With this, the Netherlands aims to deliver its contribution to reach the goal of limiting global warming to 1.5 degrees Celsius, and avoid the most destructive consequences of global warming.

In the Netherlands, 53% of total final energy is used for heating purposes, where 80% is still covered by natural gas (RIVM, 2018). Therefore, making the transition to a carbon neutral heating system is essential to reach the goals of the Paris Agreement. Additionally, the prominent use of natural gas in the Netherlands has raised, next to the environmental concerns, also social and economic concerns, of which the earthquakes in Groningen and gas import dependencies are important examples (Rijksoverheid, 2017). For these reasons, the Dutch government has set the goal to remove the gas supply from all buildings by 2050.

As contribution to reach the stated goal and reduce the natural gas use, the Dutch government has changed a law which now forbids the connection of newly built homes to the gas grid (Rijksoverheid, 2018b). Although this is a good first step, the majority of the building stock and emissions in 2050 will still consist of, and originate from the currently existing building stock. Therefore, the current Dutch government has set the ambition to remove 30,000 to 50,000 existing homes from the natural gas grid per year (starting in 2021), or at least improve the energy efficiency that allows decoupling from the gas grid (Rijksoverheid, 2017). With this, a first step will be made towards removing 200,000 homes per year from the natural gas grid. This pace is required to renovate the whole building stock of 7 million existing homes in 30 years until 2050.

This transition, also known as the 'heat transition', is one of the biggest challenges that the Netherlands is facing towards realizing a more sustainable building sector. There are for instance high investment costs associated with the transition to other heating technologies (e.g. for insulation measures, heat pumps, heat networks and reinforcement of electricity grids), spatial restrictions (e.g. existing infrastructure and buildings) and limited experience or even uncertainty related to the implementation of sustainable technologies (e.g. capacity and availability of geothermal resources) (Deason, Wei, Leventis, Smith, & Schwartz, 2018; Lomas, 2009). These difficulties vary greatly on a local scale, which indicates the need of sufficient knowledge of potential solutions at the local level. For these reasons, the Dutch government has decided to use a neighbourhood approach to take on this challenge (Sectortafel Gebouwde omgeving, 2018). Additionally, compared to a lower level (e.g. building level) analysis, a neighbourhood-level approach allows a better analysis of collective systems, such as district heating (Walker, Labeodan, Boxem, Maassen, & Zeiler, 2018).

Furthermore, the variety of stakeholders including municipalities, energy suppliers, grid operators, building owners, housing associations and residents indicates the presence of different interests (e.g. heat suppliers prefer district heating and lower insulation levels for a better business case, while for instance homeowners and insulation manufacturers may prefer high insulation levels for higher comfort and lower monthly heating costs). Here, municipalities have a central role in communicating clearly to all stakeholders what the best options are, reducing resistance and achieving a desirable outcome (Giebels-Westhuis, 2016).

To start the transition, the Dutch government has issued municipalities to develop a 'Transitievisie Warmte' by 2021, which should provide an outline for the local, neighbourhood-level transition towards a sustainable heating system (Rijksoverheid, 2017). However, due to the complex nature of this transition, municipalities require more knowledge to determine what technologies are the best to implement (van den Wijngaart, van Polen, van Bemmel, & Harmelink, 2017). Continuing without this knowledge could result in slow progress, lack of stakeholder support or sub-optimal choices. Therefore, there is a need to provide suitable insights to municipalities into the local future possibilities by outlining the available mix and the costs involved of the most optimal sustainable heating options for buildings at neighbourhood level.

1.2 Scientific background and existing literature gap

This section focuses on the scientific background of this research and identifies the existing gap in literature. For this, first the scientific background of the heat transition and the associated technological changes are discussed. Next, it is explained how these technological changes can be analysed with energy system models. Finally, arguments are provided for the selection of the energy system model used for this analysis, the existing gap in literature is identified and it is explained how the use of this model can help to fill the gap.

The heat transition and associated technological changes

Previous studies have identified that there are at least three technological changes involved in the transition to a sustainable heating system for buildings (Giebels-Westhuis, 2016; Leibowicz et al., 2018). First, implementing energy saving measures – such as insulation – to reduce the heat demand. Second, implementing efficiency improvements for the supply and distribution of heat. Finally, replacing natural gas by climate-neutral energy carriers for providing heating such as electricity from renewable sources, collective heat systems (industrial waste heat, geothermal or biomass) or other gasses such as hydrogen and biogas.

Depending on the local characteristics regarding the availability of renewable resources and the potential of efficiency improvements and demand reduction, different pathways towards a sustainable heating system exist. In general, a distinction can be made between the following types (Leibowicz et al., 2018; Wang, 2018):

- 'All-electric'[1] individual heating (with high insulation levels and individual heat pumps)
- High temperature (HT) collective heating (with relatively lower insulation level combined with centralized heat generation and district heating)
- Low temperature (LT) collective heating (with high insulation levels combined with local collective heat generation and district heating)
- Heating by alternative gasses (with relatively lower insulation levels combined with replacing natural gas in individual boilers by hydrogen or biogas)

All these options have their benefits and drawbacks. For example, All-electric and LT collective heating options require high insulation levels and LT heat distribution equipment (e.g. LT radiators or floor/wall heating) to account for the lower temperature water, which together with a heat pump (All-electric) or a heat and cold storage system (LT collective heating) requires significant investments (Knobloch, Pollitt, Chewpreecha, Daioglou, & Mercure, 2019; H. Li & Nord, 2018; Vijay & Hawkes, 2017). However, these investments result in a greatly reduced energy demand (and therefore lower operational costs), low emissions and increased comfort in the building (Bloess, Schill, & Zerrahn,

[1] Buildings with a completely electric heat supply are also called 'All-Electric' buildings, as these buildings only have a connection to the electrical grid and no other energy carriers are supplied.

2018; Qadrdan, Fazeli, Jenkins, Strbac, & Sansom, 2019; Vijay & Hawkes, 2017). HT collective heating and heating by alternative gasses require less adjustments to a building as HT heat is delivered, which does not require high insulation levels or different radiators (H. Li & Nord, 2018; Vijay & Hawkes, 2017). HT heating does require the connection of the building to a HT heat source, which require limited investment in the case of expanding an existing HT network to significant investments in case a new HT network needs to be installed (Dochev, Peters, Seller, & Schuchardt, 2018; Vijay & Hawkes, 2017). Heating by alternative gasses can to a certain extent use the existing infrastructure and heat delivery systems, but may have limited availability as these technologies are still relatively immature (hydrogen) or have availability issues due to policies and natural availability (biogas) (Vijay & Hawkes, 2017). Compared to the LT alternatives described above, these HT options results in a relatively higher energy demand, higher emissions and do not increase comfort in a building (Dochev et al., 2018). However, HT heat networks deliver heat more efficiently to buildings than individual gas-fired boilers, which are currently dominant in the Netherlands (Arnaudo, Zaalouk, Topel, & Laumert, 2018; Giebels-Westhuis, 2016).

To find the optimal solution for a neighbourhood, comparing and assessing all these different benefits and drawbacks is essential. While additional analyses (e.g. analysis of social factors) may be required to assess other factors, such as the social acceptance of the different sustainable heating options, an energy system model is a very useful tool to assess the different sustainable heating options in terms of energy savings potentials, emissions and costs (Giebels-Westhuis, 2016; Vijay & Hawkes, 2017).

Previous literature on the assessment of optimal heating options per building type describe that district heating is best applied to areas with high- and low-rise apartments, as these building together form an area with a high heat demand density, while heat pumps combined with the required heavy insulation are generally best suited for areas with detached and duplex houses, as these buildings often together form an area with a low heat demand density (Dochev et al., 2018; Giebels-Westhuis, 2016; H. Li & Nord, 2018).

Energy system models

Possible pathways can be constructed and analysed using energy system models. Energy system models are widely used tools to gain a better understanding of an energy or heating system, its potential evolution, or its optimal configuration (Müller, Gardumi, & Hülk, 2018). However, many of these models use coarse spatial resolution, often analysing energy systems at national or regional level, such as Dido and MARKAL (Hall & Buckley, 2016; Jalil-Vega & Hawkes, 2018b; P. Li, Keppo, & Strachan, 2018; Ringkjøb, Haugan, & Solbrekke, 2018). While these models contribute greatly to research in sustainable energy futures (e.g. determining capacity of energy production facilities to satisfy demand at lowest costs), a more detailed approach is required to find the optimal solutions for the built environment at the local level (Jalil-Vega & Hawkes, 2018a; van den Wijngaart et al., 2017).

Models that can be applied to more detailed levels such as cities also exist, such as CitySIM (Leibowicz et al., 2018). CitySIM is a model that can be applied to cities in any given country, as it allows the choice and adjustment of default datasets for the types and age categories of buildings to be studied (Robinson et al., 2009). However, as the scope of this research is within the Netherlands, it is particularly useful to have existing Dutch datasets in place, which most accurately reflect the actual situation in the Netherlands. Additionally, models which already use datasets specific to the Netherlands require less time to set-up and run the model. The *Energie Transitie Atlas (ETA)*, *Heat*, *Energy Transition Model (ETM)*, *CEGOIA* and *Vesta MAIS* model all offer this (Netbeheer Nederland, 2019; van den Wijngaart et al., 2017), as for example the models use the 'Basisregistratie Adressen en Gebouwen' (BAG) to include the built environment (e.g. location, size, type and age of buildings) in the models and a database from RVO to include all the energy labels of the buildings, which reflect their energetic performance (PDOK, 2019; RVO, 2019a). A model that is not specifically focussed on the Netherlands would require the inclusion of these databases in the model, as well as adjustments to the calculation rules of the model, which may be a very time consuming process.

However, these models themselves have different characteristics, which influences their suitability for a neighbourhood-level analysis (see Table 1). First of all, while allowing lower than city-level analyses, these models have a different degree of geographical detail. The *ETA*, *Heat* and *Vesta MAIS* model can produce all output parameters (e.g. optimal heating option) per district, and some parameters even per building (e.g. insulation costs), while the *CEGOIA* and *ETM* model produce results with a more coarse resolution (per district and neighbourhood, respectively). Secondly, the models offer a different level of adjustability, which is defined here as the possibility to adjust the operation and input data of the model. The *ETA* model has limited adjustability, as it displays maps (e.g. of technological potentials) through a user interface without the ability to adjust input data or the operation of the model. The *Heat*, *ETM* and *CEGOIA* model show results through a user interface which allows the adjustment of input data (e.g. costs of technologies) and limited adjustment of the model operation (e.g. choice of technologies). The *Vesta MAIS* model is highly adjustable and not limited by a user interface with limited options. For example the building stock, energy prices, heat sources and heat network can all be adjusted to reflect the actual situation in a neighbourhood accurately (Brouwer, 2019). While the models with a lower level of adjustability are less time intensive and operated more easily, a higher level of adjustability is preferred for a neighbourhood-level analysis.

Table 1: Overview of energy system model characteristics and suitability for a neighbourhood-level analysis of the heating sector in the built environment (Netbeheer Nederland, 2019)

Model	Owner	Geographical detail	Adjustability	Sectoral coverage	Focus	Optimal pathway	Availability
Energie Transitie Atlas (ETA)	**Over Morgen**	District/Building	Low	Heat	Built environment	Yes	Commercial
Heat	**Alliander**	District/Building	Medium	Heat	Heat infrastructure	No	Commercial
Energy Transition Model (ETM)	**Quintel Intelligence**	Neighbourhood	Medium	Heat Electricity Gas	Built environment	Yes	Open source
CEGOIA	**CE Delft**	District	Medium	Heat Electricity Gas	Built environment	Yes	Commercial
Vesta MAIS	**PBL**	District/Building	High	Heat	Built environment	Yes	Open source

Furthermore, several characteristics of these model results in a different suitability for this analysis (see Table 1). First of all, the models have different degrees of sectoral coverage. While the *ETM* and *CEGOIA* model simulate the heat, electricity and gas energy system, the *ETA*, *Heat* and *Vesta MAIS* model solely focus on the heat sector. While the modelling of different sectors in a model offers the implementation of cross-sector interactions, and therefore more accurately reflects an actual energy system, the generally higher level of detail of a model focused on the heat sector is preferred, due to the low spatial level of this analysis. Secondly, the *Heat* model differs from the other models in its focus and its ability to analyse optimal pathways. The Heat model is particularly suited to determine the individual and collective business cases of developing new heat infrastructures (Alliander, 2016). As this research focuses on determining optimal pathways for the whole built environment, the *Heat* model is less suitable for this study. Finally, the *ETA*, *Heat* and *CEGOIA* model are not open source and were therefore not available for this study.

As the *Vesta MAIS* model provides a high geographical detail, is focused on the built environment and the heating system, can analyse optimal pathways, is highly adjustable and is open source, this research uses *Vesta MAIS* to take into account local characteristics and investigate the most optimal sustainable heating options at neighbourhood level.

The *Vesta MAIS* model and its application at various scales

In 2010, the 'Vesta Multi Actor Impact Simulation' (*Vesta MAIS*) spatial energy system model is developed by the 'Planbureau voor de Leefomgeving' (PBL) to explore the possibilities to heat the built environment of the Netherlands in a climate-neutral way against the lowest possible costs (van den Wijngaart et al., 2017). *Vesta MAIS* does this by calculating the techno-economic potential of sustainable heating technologies; calculating the effects of policy instruments on national costs, energy use and emissions; calculating business cases of heat suppliers and building owners, as well as the financial consequences for energy users; and displaying the consequences for the infrastructure of heat, gas and electricity networks (van den Wijngaart et al., 2017).

However, the *Vesta MAIS* model is often used to explore these issues on a national to regional level. With this, it is especially useful for analysing the effect of national policies. For instance, in 2012 PBL used the model to explore four investment routes to a climate-neutral building stock for the Netherlands (van den Wijngaart, Folkert, & van Middelkoop, 2012). In addition, *Vesta MAIS* was also used at regional scale to calculate the techno-economic potential of sustainable heating options for the region of the Drechtsteden (van der Molen, van den Wijngaart, van Polen, & van Bemmel, 2018). Finally, at its smallest scale, the model was applied to the municipality of Utrecht for an initial study to explore the potential of different sustainable heating technologies (van den Wijngaart, van Polen, van Bemmel, & Harmelink, 2018). However, it has not been applied yet at smaller scale such as a neighbourhood, which generally contains around 2,000 – 20,000 houses (CBS, 2018). Therefore, there exists a research gap at the required information for the desired neighbourhood approach of the Dutch government. Applying *Vesta MAIS* at neighbourhood level can help to address this research gap.

1.3 Case study: Overvecht, Utrecht

In order to investigate the most optimal sustainable heating options at neighbourhood level, an area to analyse is required. This research selects Overvecht – a neighbourhood in the North of Utrecht (see Chapter 2 for a more detailed description) – for three main reasons:

First of all, the Municipality of Utrecht is one of the municipal front-runners of the energy transition. The municipality has announced they want to achieve climate neutrality as soon as possible (Gemeente Utrecht, 2017a). One of the largest sectors that has to undergo a transition to achieve this is the built environment. Therefore, as part of this ambition, the Municipality of Utrecht have set the goal to remove 40,000 of their 108,000 homes from the gas grid and sustainably heat them by 2030. As a start the municipality wants to sustainably heat the around 18,000 buildings in Overvecht (Gemeente Utrecht, 2017b).

Secondly, Overvecht-Noord – the Northern half of Overvecht - has been selected as a pilot area within the Green Deals agreement (Green Deals, 2019). In this agreement the Dutch government announced to invest 120 million Euro in removing 27 existing (sub-)neighbourhoods from the natural gas grid by 2030 and replacing it with sustainable heating options, in order to gain knowledge and experience on how to sustainably heat existing neighbourhoods in a feasible and affordable way (Rijksoverheid, 2018a). The selection of Overvecht-Noord raises the need for the investigation of the optimal sustainable heating alternative and increases the viability of implementation of these measures due the available funds.

Thirdly, Overvecht is an interesting neighbourhood of Utrecht to analyse due to its variety of building types, energy profiles and heat sources (see Chapter 2 for a more detailed description) (Gemeente Utrecht, 2017b). Due to its many different characteristics, it can serve as an example for showing solutions for the complexities of the heat transition for (parts of) neighbourhoods with similar characteristics. Furthermore, there is a natural gas grid present which was installed in the 1960s, and that needs replacement in the near future. As the lifetime of a new natural gas grid exceeds the foreseen use of natural gas, there is a need for information regarding what alternative options are, which this analysis can contribute to. Moreover, 70% of the buildings in the neighbourhood is owned by corporations. Here, implementation of sustainable heating options is deemed easier compared to neighbourhoods with a higher share of private ownership. This fact may increase the practical applicability of this analysis, as an identified optimal solution can be implemented more easily.

For all the reasons above, this research has selected Overvecht as a case study to investigate the optimal mix of sustainable heating technologies at neighbourhood level.

1.4 Research aims and research questions

The aim of this research is two-fold. First, as a contribution to solving a big societal problem, this research aims to supply detailed knowledge for Overvecht with respect to the optimal mix of sustainable heating technologies. Consequently, this knowledge and derived experience can be used to ease the challenge of removing the gas grid and implement sustainable heating in Overvecht as well as other neighbourhoods with similar characteristics. This knowledge can be useful for policy makers at municipal level, as well as energy companies and network operators. Secondly, this research aims to fill the scientific gap by assessing the ability of *Vesta MAIS* to determine the optimal mix of sustainable heating technologies on a local scale. With this, the question can be answered how well the model is suited to contribute to supply the required knowledge on making the existing building stock's heating systems sustainable. This knowledge can be useful for researchers aiming to perform a neighbourhood level analysis, as well as researchers studying the heat transition in a broader perspective. This research aims to achieve these goals by answering the following research question (RQ) and associated sub-questions (SQ):

RQ: How to identify the most optimal techno-economic pathways at local scale towards a sustainable heating system by 2030?

SQ1: What are the energy savings of different pathways?
SQ2: What are the emissions of different pathways?
SQ3: What are the societal costs of different pathways?
SQ4: What is the most optimal techno-economic pathway?

These questions are addressed by constructing several scenarios with different sustainable heating technologies and different extends of building improvements (e.g. increased insulation levels). First, this research analyses the impact of energy savings measures on the energy demand, and on the heat demand in particular (SQ1). Here, no other developments are considered in order to isolate the effect of these measures. Secondly, the pathways are analysed in order to determine how much emissions can be reduced by the different sustainable heating options (SQ2). Similarly, the scenarios are run to determine the societal costs of the different pathways (SQ3). The societal costs are defined as system costs for the whole society, and therefore do not included taxes, subsidies or cash flows between parties, as these all are redistributions of money and not an actual cost for society. From the different scenarios, the optimal option is chosen for each district in the neighbourhood (SQ4). Here, optimal is defined as locally (i.e. at building level) natural gas free, achieving large emission reductions and having the lowest societal costs. The lowest societal costs are used as criteria, because it reflects the most economic option for society to transition toward a sustainable heating system, which is desirable as there are many concerns regarding the affordability of this transition (Sectortafel Gebouwde omgeving, 2018). In order to determine the robustness of the optimal option per district a sensitivity analysis is performed. Together, this leads to identifying the most optimal techno-economic pathway towards a sustainable heating system by 2030 (RQ).

1.5 Outline

Following the general introduction to the subject in Chapter 1, which includes the societal background, scientific relevance, problem statement, case study introduction and research questions, this report presents five additional chapters. Chapter 2 provides a description of the general characteristics of Overvecht, as well as the current heating system. Chapter 3 contains the used methodology to answer the research questions, which consists of a description of the system boundaries, operation of the *Vesta MAIS* model, data collection, scenarios, output parameters, selecting the optimal procedure and sensitivity analysis. Chapter 4 shows the results of the different output parameters for each of the scenarios, the resulting optimal pathway and the outcome of the sensitivity analysis. Chapter 5 discusses the theoretical and societal implications of the results, discusses the limitations of this study and provides recommendations for further research. Finally, Chapter 6 summarizes this research, answers the research question and draws the main conclusions.

2. Description of Overvecht: characteristics and current heating system

This chapter provides a description of the general characteristics of Overvecht (Section 2.1), as well as the current heating system (Section 2.2).

2.1 Neighbourhood characteristics

Overvecht is one of the ten neighbourhoods in Utrecht, the fourth largest city in the Netherlands. Overvecht is located in the north of the city, and the neighbourhood consists of ten districts (see Figure 1), including a polder area with a single inhabited dike ('Poldergebied Overvecht'), a business area ('Bedrijventerrein en omgeving'), and eight residential districts. The residential districts 'Vechtzoom-noord, Klopvaart', 'Vechtzoom-zuid', 'Tigrisdreef en omgeving' and 'Zambesidreef en omgeving' are together known as Overvecht-Noord (displayed in red in Figure 1). The residential districts 'Zamenhofdreef en omgeving', 'Taag- en Rubicondreef en omgeving', 'Neckardreef en omgeving' and 'Wolga- en Donaudreef en omgeving' are together known as Overvecht-Zuid (displayed in blue in Figure 1). In total the neighbourhood encompases an area of 8.48 square kilometres.

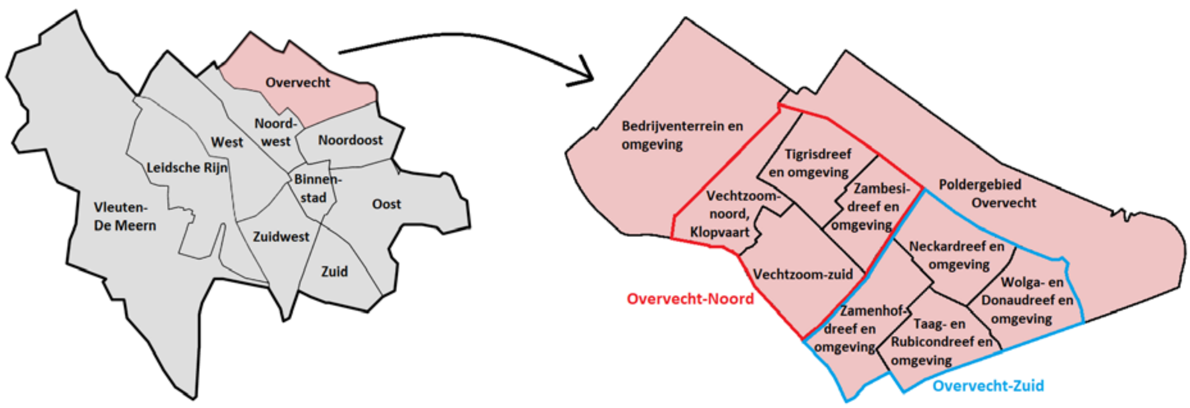

Figure 1: The ten neighbourhoods of Utrecht with Overvecht highlighted (left) and the ten districts of Overvecht (right)

As of 1 January 2019, the neighbourhood has 34,293 inhabitants across 15,884 residences, averaging at 2.16 person per household and 4,044 persons per square kilometre (Gemeente Utrecht, 2019b). 22% of these buildings are privately owned, which is the lowest percentage in Utrecht, which has an average of 47%. The neighbourhood has a low social-economic status, with 38 jobs per 100 inhabitants as compared to the average of 75 jobs per 100 inhabitants in Utrecht. Furthermore, a total of 1,925 utility buildings are present, which are defined as having a different use than housing people (Gemeente Utrecht, 2019b). The amount of buildings per district can be found in Table 2.

Table 2: Number of residences and utility buildings in each of the districts in Overvecht (Gemeente Utrecht, 2019b)

District	Residences	Utilities
'Taag- en Rubicondreef en omgeving'	1994	360
'Wolga- en Donaudreef en omgeving'	2162	82
'Zamenhofdreef en omgeving'	1466	350
'Neckardreef en omgeving'	2020	262
'Vechtzoom-zuid'	2499	191
'Vechtzoom-noord, Klopvaart'	1480	149
'Bedrijventerrein en omgeving'	41	125
'Zambesidreef en omgeving'	2219	211
'Tigrisdreef en omgeving'	1910	179
'Poldergebied Overvecht'	93	16
Total	**15884**	**1925**

Until 1960, the area of what is now Overvecht was mainly a pasture. Only a limited amount of mostly detached and duplex houses existed along the Gageldijk in the north of the area, and next to the river Vecht along the south-western border of Overvecht. In 1961 the construction of large amounts of apartment buildings (as well as some terraced houses) in the neighbourhood started and was finished by 1970 (Gemeente Utrecht, 2015). These low- and high-rise apartments still form the majority of buildings in the neighbourhood, and strongly influence the typical image of the neighbourhood, together with its green and spacious set-up (see cover page). From 1970, the neighbourhood was expanded several times with mostly terraced houses and low-rise apartments, as well as some high-rise apartments. An overview of the year when the buildings were built and types of residences can be found in Figure 2. The building period 1965 to 1974 and high-rise apartments are dominant. However, it can be seen that also a variety of other building years and buildings types are present in the neighbourhood.

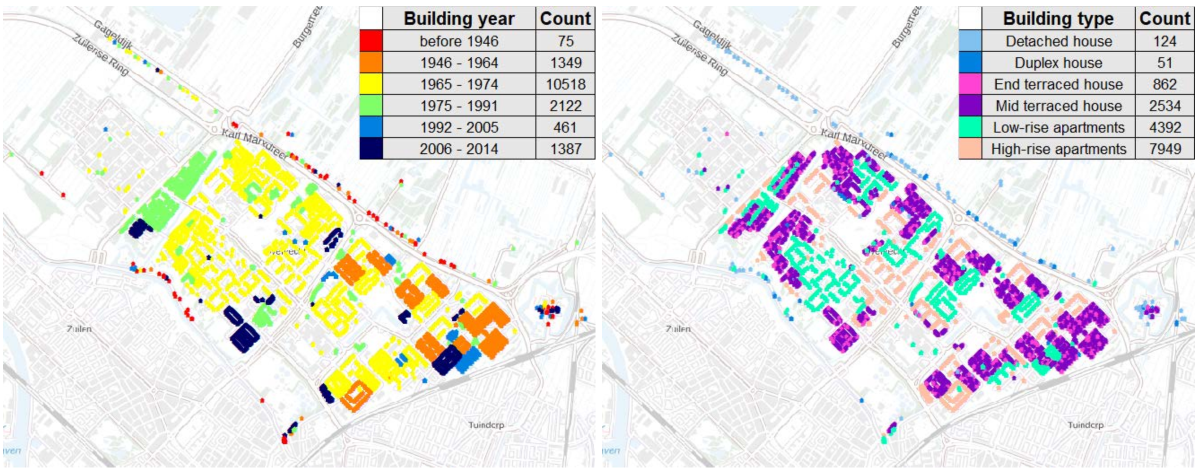

Figure 2: Building years (left) and building types (right) of residences in Overvecht (PDOK, 2019)

The utility buildings present in Overvecht include offices and stores, and health care, education, industry, conference and sports buildings. Figure 3 provides an overview of the building years and types of utility buildings in Overvecht. Here, it can be seen that also utility buildings were mainly built in the period up to 1975 (note: building years are clustered differently than with residences due to data availability), although a considerable amount of buildings have also been constructed from 1995 to 2015. The right map of Figure 3 shows that the neighbourhood contains variety of utility buildings. Here, it can be seen that a major share of 873 utility buildings is undefined in the category 'Other'. This category contains all other types of utility buildings, including for example restaurants, repair shops and libraries. Note that in the map there is some overlap between certain markers, which makes especially the 411 industry buildings hard to see. However, the table in the figure shows the presence of each type of utility building.

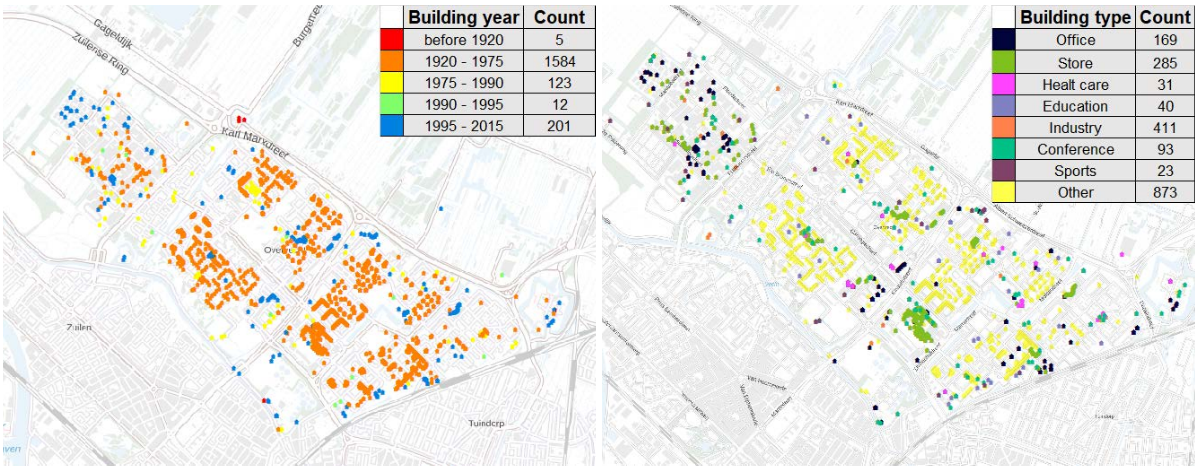

Figure 3: Building years (left) and building types (right) of utility buildings in Overvecht (PDOK, 2019)

2.2 Current heating system

The amount of heat that is required to heat the building stock described in Section 2.1 strongly depends on the energy labels of the buildings. The lower the energy label is, the higher the heat demand. The energy labels are highly influenced by the construction year of the building, as shown on the left map of Figure 4. In Overvecht, energy labels for residences range from G to B, and energy labels for utility buildings from E to B (see tables in Figure 4). As 76% of the buildings in Overvecht have low energy labels (D or lower), it is clear that there is a large potential to increase the insulation levels of the building stock and reduce the heat demand.

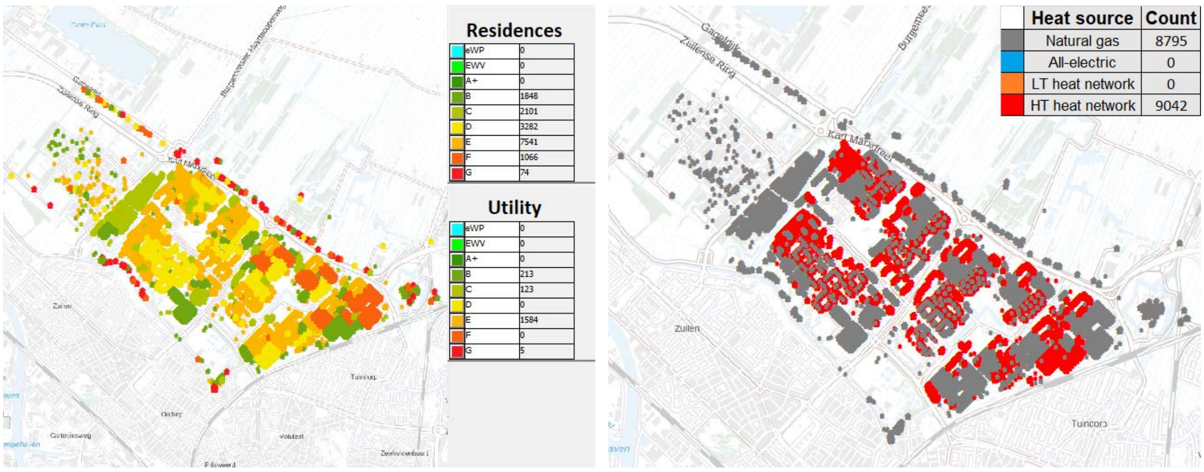

Figure 4: Energy labels of 01-01-2019 (left) and heating technologies (right) of residences and utility buildings in Overvecht (CBS, 2018; RVO, 2019b)

The map on the right side of Figure 4 displays the technologies by which the buildings are heated. It can be seen that 49% of the buildings are heated by burning natural gas in individual boilers (displayed in grey), while 51% is heated by a HT heat network (displayed in red). This HT heat is supplied by the largest and oldest district heating network in the Netherlands, connecting around 50,000 buildings in Utrecht and the south-bordering municipality of Nieuwegein (Eneco, 2014). The left map of Figure 5 provides an overview of the district heating system. The heat sources of this network are the facilities 'Centrale Merwede' and 'Centrale Lage Weide', which are located on both sides of the Amsterdam–Rhine Canal (see left map of Figure 5). As the Merwede facility is located on the eastern side of the canal and closer to Overvecht, these plants produce the heat that is used in Overvecht. The Merwede facility consists of two combined cycle gas turbine (CCGT) plants: Merwede-11 and Merwede-12. Table 3 provides the construction years and electric/thermal capacities of these plants.

Table 3: Characteristics of HT heat sources which deliver heat to Overvecht (Arcadis, 2013)

Plant	Construction year	Fuel source	Electric capacity (MWe)	Thermal capacity (MWth)
Merwede-11	1985	Natural gas	103	110
Merwede-12	1990	Natural gas	225	180
Auxiliary boiler	1995	Natural gas	-	25

From the Merwede plants, primary heat transport pipes run towards a heat transfer station (HTS) in Overvecht. From there, distribution pipes distribute heat towards the different districts in Overvecht. Finally, branches of the distribution pipes are connected to buildings to supply heat. The majority of the heat is delivered this way by the Merwede plants. However, the amount of electricity and heat which the Merwede plants delivers depends on energy market strategies, as the attractiveness of producing more electricity or more heat depends on for instance the electricity price. This means that in some cases (e.g. when the electricity price is high) it is more interesting to produce more electricity and less heat and the plants will not deliver sufficient heat for Overvecht. Therefore, there is a gas-fired auxiliary boiler located next to the HTS which can provide heat for a deficit in the heat supply (see Figure 5 and Table 3).

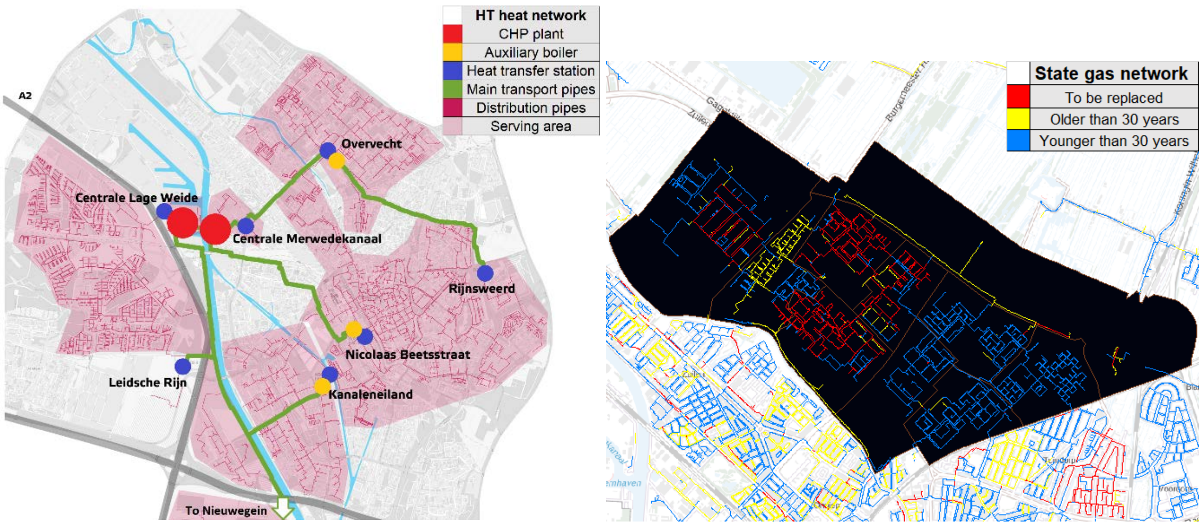

Figure 5: Overview of district heating in Utrecht (left) and natural gas network in Overvecht (right) (Eneco, 2019; Stedin, 2019). *Left map adapted from* (Eneco, 2019)

Furthermore, as the right map of Figure 5 shows, there is a natural gas network present in Overvecht of which large parts need to be placed now (red), or in in the near future (yellow). These parts are largely located in Overvecht-Noord, the business area (top left) and the polder area (top right). The network in Overvecht-Zuid and small parts of Overvecht-Noord and the business area is younger than 30 years (blue), and therefore does not demand replacement in the near future.

3. Methodology

To answer the research questions three phases are designed. Each phase consists of a number of steps that contribute to answer the research questions. The first Phase consists of establishing the system boundaries and taking the preparation steps in order to run *Vesta MAIS* at neighbourhood level. For this, the operation of the model is explored to determine what data needs to be gathered, and which adjustments need to be made to the model. In Phase II multiple scenarios are constructed and calculated with *Vesta MAIS*. For each scenario output parameters are selected that allow comparison between the different scenarios. As a result, Phase II provides answer to SQ1-3. Phase III consists of an analysis of the output parameters and the selection of the *Optimal pathway*, which provides an answer to SQ4. Also, a sensitivity analysis is performed to test the robustness of the 'optimal' final route. Consequently, these steps answer the main research question. The used methodological framework is provided in Figure 6 and further elaborated in the next paragraphs.

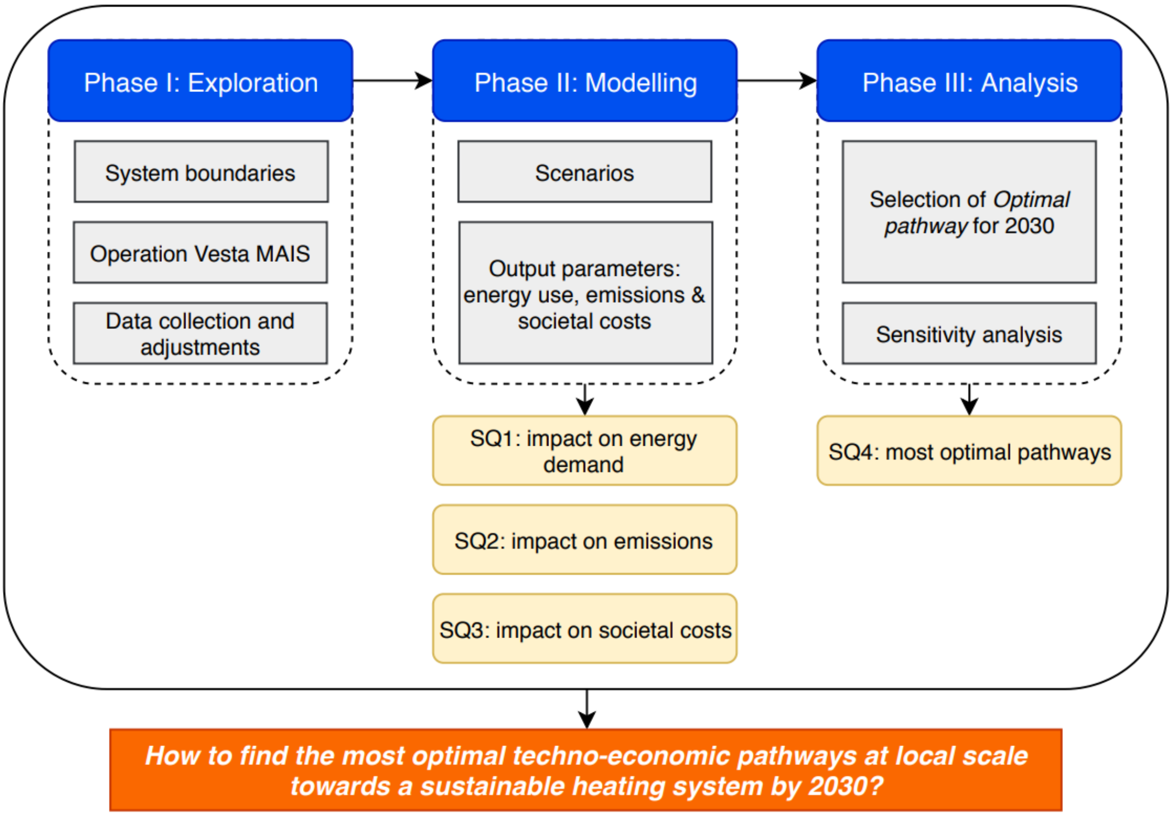

Figure 6: The methodological framework that is used for this research

3.1 Phase I: Exploration

This study is performed with *Vesta MAIS* version 3.3, of which the existing set of input data is created to calculate at national level with district-level detail. To apply the model at a specific region such as Overvecht, more specific data are necessary and model adjustments are required. In order to execute this type of analysis, first the system boundaries are determined, which is explained in Section 3.1.1. Next, the operation of *Vesta MAIS* is explained and the adjustments that are made for this analysis are described in Section 3.1.2.

3.1.1 System boundaries

The geographical boundaries of the studied area (Overvecht) in this research have been taken from the boundaries defined by the Municipality of Utrecht (Gemeente Utrecht, 2015). Moreover, the period up to 2030 is used as time horizon, as the goal of the Municipality of Utrecht is to remove Overvecht from the gas grid and sustainably heat the neighbourhood by 2030.

Furthermore, by using the *Vesta MAIS* model this research is solely modelling the heating sector. Although various components of the electricity sector are used to model the heat transition (e.g. electricity prices for heat pumps), the transport of electricity and the power producing sector are not modelled and do not interact with the heating sector, but solely parts are used as fixed inputs, such as electricity prices and grid reinforcements costs.

3.1.2 Operation of *Vesta MAIS* and adjustments for neighbourhood-level analysis

This section gives a general description of the relevant parts of *Vesta MAIS* for this research. A more detailed description of the model can be found in functional design report of the *Vesta MAIS* model from CE Delft, and the general description of *Vesta MAIS* from PBL (CE Delft, 2017; van den Wijngaart et al., 2017). Figure 7 provides an overview of the operation of *Vesta MAIS*.

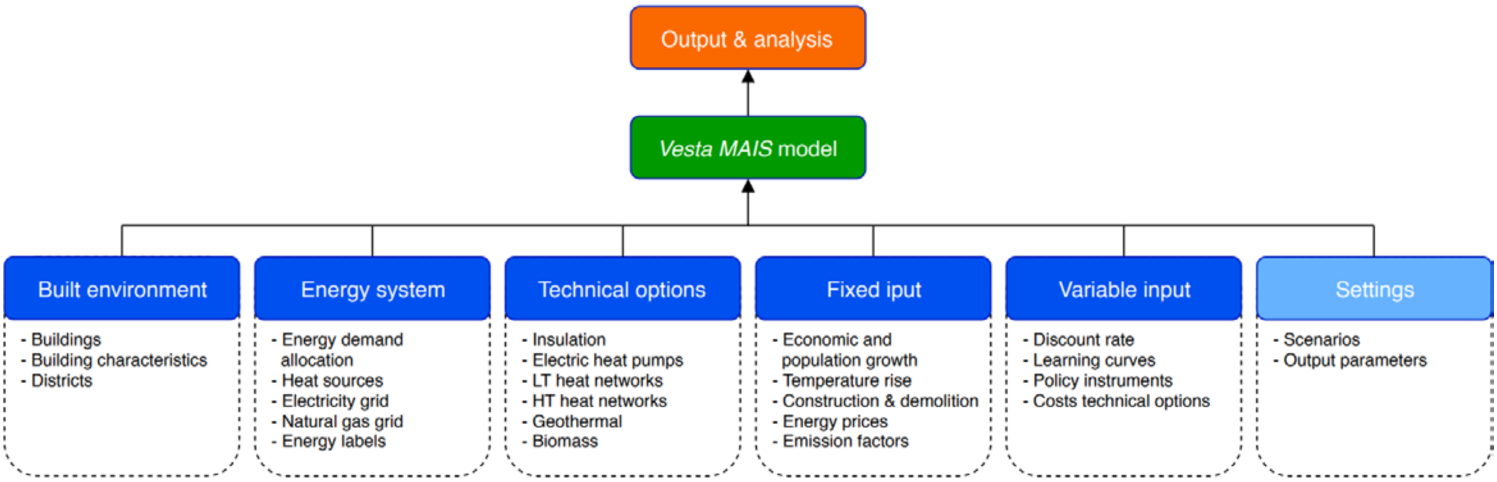

Figure 7: Overview of the operational approach of the Vesta MAIS model

As the standard model operation and existing set of input data in *Vesta MAIS* are created to calculate at national level, several adjustments and the inclusion of specific local data are required to analyse a specific region such as Overvecht. In each of the following paragraphs, first the operation of Vesta MAIS in the standard configuration is described, followed by the adjustments that are made to adjust the model for this analysis.

3.1.2.1 Built environment

Buildings and buildings characteristics

Vesta MAIS simulates the heat supply as a spatial system. For this study this simulation is limited to the heat supply in the built environment of the neighbourhood Overvecht in Utrecht, but in its standard configuration *Vesta MAIS* models the heat supply in the built environment of the whole of the Netherlands. The built environment is defined as a collection of model objects which correspond with a residence or utility building. *Vesta MAIS* extracts the existing building stock from the 'Basic registrations Addresses and Buildings' (BAG) of 01-01-2019, as it is updated regularly (PDOK, 2019). From this database all residences, utility buildings and greenhouses are extracted and included in the input database of *Vesta MAIS*. Industry is not taken into account, as the energy demand and technical possibilities for industrial complexes are too specific to model with *Vesta MAIS*. For each building the location, construction year, building type and floor area are included in the model. More specific building characteristics such as the monumental status are not included.

Districts

In addition, *Vesta MAIS* adds different layers of spatial regions to the model such as provinces, municipalities, neighbourhoods and neighbourhood districts. In the standard configuration of the model, neighbourhood districts as defined by the Central Bureau of Statistics (CBS) are used (CBS, 2018). This is done to be able to aggregate results to the desired spatial level. Furthermore, *Vesta MAIS* uses neighbourhoods as the spatial border to determine where collective technologies are applied. Therefore, collective technologies such as district heating are applied to all buildings in a neighbourhood, even if not all buildings are connected to that heating network.

Adjustments for this analysis

To adjust the *Vesta MAIS* model to the local level, the built environment in the model needs to be adjusted to fit the area for local analysis. Otherwise, the buildings which are located in the rest of the country will also be included in the model run. Therefore, the building stock in the BAG database is sorted on municipality, and consequently all buildings in other municipalities than Utrecht are removed. Similarly, the database is sorted on neighbourhood and all buildings in other neighbourhoods than Overvecht are removed.

The same is done for the CBS districts which are included in the model. Here, the GIS software QGIS is used to remove all districts other than the ten districts of Overvecht from the model, by filtering the attribute table on neighbourhoods and removing all districts that belong to other neighbourhoods than Overvecht. A final adjustment is required, as 12 buildings of the BAG database are not located in the defined CBS districts of Overvecht. Therefore, these 12 buildings are removed from the BAG database. As a result, only buildings that are registered to Overvecht and are located in the by CBS defined area of Overvecht remain in place for the analysis. An additional adjustment to these districts is made to make Vesta MAIS more suitable for the analysis of Overvecht. However, as first the operation of the model regarding district heating needs to be explained, this adjustment is addressed in Section 3.1.2.2.

Finally, it is also required that the building categories that are not used in the area of analysis are turned off, as otherwise the model gives an error. As Overvecht does not contain greenhouses, the category is turned off by adjusting the *Vesta MAIS* code which includes greenhouses in the analysis.

3.1.2.2 Energy system

Energy demand allocation and energy labels

Once the built environment is included in the model, *Vesta MAIS* assigns a heat demand to each of the buildings based on its year of construction, energy label and building type. The building type can be different types of residences (e.g. detached house or high-rise apartment) or utility buildings (e.g. office or school). Table 4 shows the energy demand that is allocated to each type of residential building, while Table 5 shows this for utility buildings. Here, the heat demand of both space heating and warm water is determined by the functional heat demand divided by the heating efficiency of the present heating technology. The functional heat demand is defined as the heat that is required for heating at the building level, which means that efficiency losses to supply this demand are not taken into account yet. Next, based on the same criteria as for heating, the electricity demand is assigned per object. This includes the electricity required for all electrical equipment (appliances and lighting) in a building, as well as electrical pump energy for the distribution of warm water through a building. These inputs result in a spatial distribution of natural gas, heat and electricity demand. *Vesta MAIS* assumes that there is currently no demand for cold.

The energy demand allocated to these building strongly relates to the energy label, which is a representation of the energetic performance of a building (RVO, 2019a). Energy labels range from G to A, where G represents a building that has no or very poor insulation, and A represent a building that is very well insulated. The energy labels of existing buildings in the area are extracted by *Vesta MAIS* from the database of the 'Rijksdienst voor Ondernemend Nederland' (RVO), which contains definitive energy labels, up to 01-01-2019. *Vesta MAIS* uses these energy labels to determine the energetic performance of the building, based on the building type and year of construction (Agentschap NL, 2011). Therefore, Table 4 and Table 5 also show the energetic performance of buildings for different energy labels (see column on the right). For all other building for which no definitive label was available, an estimation is made based on the building type and year of construction. Based on the available data, it is difficult to estimate which renovations have already taken place in specific building, especially when the construction year is long past. As a result, it is possible that specific buildings are better insulated than assumed based on year of construction and building type. On the contrary, it is also possible that *Vesta MAIS* estimates the insulation levels of certain building types too high or too low. Therefore, a comparison of the modelled energy demand in the starting year with actual energy demand is required to ensure the model calculates from a reasonable starting point, which can be seen at the end of this section.

Table 4: Overview of energy demand allocation to the residential building stock as considered in the Vesta MAIS model

			Current building performance										
			Heating and cooling							Electricity use			Energy label
			Space heating			Warm water			Cold				
			Functional demand	Heating efficiency		Functional demand	Heating efficiency		Functional demand	Functional demand	Appliance efficiency	Pump demand	
		Area		Gas	Heat network		Gas	Heat network					
Building type	**Building year**	**m2**	**GJ/jr**	**η**	**η**	**GJ/jr**	**η**	**η**	**GJ/jr**	**GJ/jr**	**η**	**GJ/jr/m2**	
Detached house	before 1946	130	61.63	0.99	1	6.95	0.72	1	0	9.70	1	0.01	G
	1946 - 1964	130	61.63	0.99	1	6.95	0.72	1	0	9.70	1	0.01	G
	1965 - 1974	144	62.47	0.97	1	7.53	0.72	1	0	9.56	1	0.01	F
	1975 - 1991	154	55.86	1.00	1	7.94	0.72	1	0	9.46	1	0.01	D
	1992 - 2005	172	47.76	1.01	1	8.67	0.72	1	0	9.28	1	0.01	B
	2006 - 2014	172	48.64	1.05	1	8.67	0.72	1	0	9.28	1	0.01	A
Duplex	before 1946	110	47.79	0.98	1	6.14	0.72	1	0	9.90	1	0.01	F
	1946 - 1964	110	47.79	0.98	1	6.14	0.72	1	0	9.90	1	0.01	F
	1965 - 1974	123	47.26	0.98	1	6.67	0.72	1	0	9.77	1	0.01	E
	1975 - 1991	123	39.27	0.99	1	6.67	0.72	1	0	9.77	1	0.01	C
	1992 - 2005	132	33.97	1.00	1	7.04	0.72	1	0	9.68	1	0.01	B
	2006 - 2014	132	33.73	1.05	1	7.04	0.72	1	0	9.68	1	0.01	A
Mid terraced house	before 1946	102	37.89	0.95	1	5.81	0.72	1	0	9.98	1	0.01	G
	1946 - 1964	87	35.52	0.95	1	5.20	0.72	1	0	10.13	1	0.01	F
	1965 - 1974	106	35.84	0.96	1	5.97	0.72	1	0	9.94	1	0.01	E
	1975 - 1991	106	30.07	0.97	1	5.97	0.72	1	0	9.94	1	0.01	C
	1992 - 2005	114	26.90	1.00	1	6.30	0.72	1	0	9.86	1	0.01	B
	2006 - 2014	114	29.07	1.05	1	6.30	0.72	1	0	9.86	1	0.01	A
End terraced house	before 1946	102	37.89	0.95	1	5.81	0.72	1	0	9.98	1	0.01	G
	1946 - 1964	87	35.52	0.95	1	5.20	0.72	1	0	10.13	1	0.01	F
	1965 - 1974	106	35.84	0.96	1	5.97	0.72	1	0	9.94	1	0.01	E
	1975 - 1991	106	30.07	0.97	1	5.97	0.72	1	0	9.94	1	0.01	C
	1992 - 2005	114	26.90	1.00	1	6.30	0.72	1	0	9.86	1	0.01	B
	2006 - 2014	114	29.07	1.05	1	6.30	0.72	1	0	9.86	1	0.01	A
Low-rise apartment	before 1946	59	22.86	0.90	1	4.05	0.72	1	0	8.41	1	0.01	G
	1946 - 1964	66	20.57	0.82	1	4.34	0.72	1	0	8.34	1	0.01	E
	1965 - 1974	71	21.16	0.93	1	4.54	0.72	1	0	8.29	1	0.01	D
	1975 - 1991	70	19.41	0.94	1	4.50	0.72	1	0	8.30	1	0.01	C
	1992 - 2005	74	19.59	0.98	1	4.66	0.72	1	0	8.26	1	0.01	B
	2006 - 2014	74	21.50	1.05	1	4.66	0.72	1	0	8.26	1	0.01	A
High-rise apartment	before 1946	72	21.12	0.94	1	4.58	0.72	1	0	8.28	1	0.01	D
	1946 - 1964	72	21.12	0.94	1	4.58	0.72	1	0	8.28	1	0.01	D
	1965 - 1974	82	20.48	0.90	1	4.99	0.72	1	0	8.18	1	0.01	E
	1975 - 1991	68	20.50	0.95	1	4.42	0.72	1	0	8.32	1	0.01	C
	1992 - 2005	79	16.78	1.01	1	4.87	0.72	1	0	8.21	1	0.01	B
	2006 - 2014	79	20.77	1.05	1	4.87	0.72	1	0	8.21	1	0.01	A

Table 5: Overview of energy demand allocation to the utility building stock as considered in the Vesta MAIS model

		Current building performance											
		Heating and cooling								Electricity use			Energy label
		Space heating			Warm water			Cold					
		Functional demand	Heating efficiency		Functional demand	Heating efficiency		Functional demand	Cooling efficiency	Functional demand	Appliance efficiency	Pump demand	
			Gas	Heat network		Gas	Heat network						
Building type	**Building year**	**GJ/jr/m2**	**η**	**η**	**GJ/jr/m2**	**η**	**η**	**GJ/jr/m2**	**η**	**GJ/jr/m2**	**η**	**GJ/jr/m2**	
Office	before 1920	0.98	0.83	1	0.004	0.72	1	0.09	1.56	0.45	1	0.01	G
	1920 - 1975	0.77	0.94	1	0.004	0.72	1	0.09	1.56	0.45	1	0.01	E
	1975 - 1990	0.39	1.00	1	0.004	0.72	1	0.09	1.56	0.45	1	0.01	C
	1990 - 1995	0.36	1.02	1	0.004	0.72	1	0.09	1.56	0.45	1	0.01	B
	1995 - 2015	0.30	1.07	1	0.004	0.72	1	0.09	1.56	0.45	1	0.01	B
	unknown	0.49	1.01	1	0.004	0.72	1	0.09	1.56	0.45	1	0.01	D
Store	before 1920	0.49	0.83	1	0.004	0.72	1	0.04	1.56	0.57	1	0.01	G
	1920 - 1975	0.39	0.93	1	0.004	0.72	1	0.04	1.56	0.57	1	0.01	E
	1975 - 1990	0.20	1.01	1	0.004	0.72	1	0.04	1.56	0.57	1	0.01	C
	1990 - 1995	0.19	1.06	1	0.004	0.72	1	0.04	1.56	0.57	1	0.01	B
	1995 - 2015	0.15	1.07	1	0.004	0.72	1	0.04	1.56	0.57	1	0.01	B
	unknown	0.29	0.99	1	0.004	0.72	1	0.04	1.56	0.57	1	0.01	D
Health care	before 1920	1.12	0.83	1	0.038	0.72	1	0.03	1.56	0.23	1	0.01	G
	1920 - 1975	0.82	0.87	1	0.038	0.72	1	0.03	1.56	0.23	1	0.01	E
	1975 - 1990	0.46	0.97	1	0.038	0.72	1	0.03	1.56	0.23	1	0.01	C
	1990 - 1995	0.45	1.04	1	0.038	0.72	1	0.03	1.56	0.23	1	0.01	B
	1995 - 2015	0.38	1.07	1	0.038	0.72	1	0.03	1.56	0.23	1	0.01	B
	unknown	0.62	0.97	1	0.038	0.72	1	0.03	1.56	0.23	1	0.01	D
Education	before 1920	0.52	0.83	1	0.005	0.72	1	0.00	1.56	0.15	1	0.01	G
	1920 - 1975	0.39	0.91	1	0.005	0.72	1	0.00	1.56	0.15	1	0.01	E
	1975 - 1990	0.21	1.00	1	0.005	0.72	1	0.00	1.56	0.15	1	0.01	C
	1990 - 1995	0.20	1.07	1	0.005	0.72	1	0.00	1.56	0.15	1	0.01	B
	1995 - 2015	0.16	1.07	1	0.005	0.72	1	0.00	1.56	0.15	1	0.01	B
	unknown	0.28	0.98	1	0.005	0.72	1	0.00	1.56	0.15	1	0.01	D
Industry	before 1920	0.42	0.83	1	0.004	0.72	1	0.01	1.56	0.09	1	0.01	G
	1920 - 1975	0.32	0.94	1	0.004	0.72	1	0.01	1.56	0.09	1	0.01	E
	1975 - 1990	0.17	1.00	1	0.004	0.72	1	0.01	1.56	0.09	1	0.01	C
	1990 - 1995	0.15	1.02	1	0.004	0.72	1	0.01	1.56	0.09	1	0.01	B
	1995 - 2015	0.13	1.07	1	0.004	0.72	1	0.01	1.56	0.09	1	0.01	B
	unknown	0.21	1.00	1	0.004	0.72	1	0.01	1.56	0.09	1	0.01	D
Conference	before 1920	0.56	0.83	1	0.033	0.72	1	0.18	1.56	0.13	1	0.01	G
	1920 - 1975	0.81	0.91	1	0.033	0.72	1	0.18	1.56	0.13	1	0.01	E
	1975 - 1990	0.61	1.01	1	0.033	0.72	1	0.18	1.56	0.13	1	0.01	C
	1990 - 1995	0.62	1.06	1	0.033	0.72	1	0.18	1.56	0.13	1	0.01	B
	1995 - 2015	0.44	1.07	1	0.033	0.72	1	0.18	1.56	0.13	1	0.01	B
	unknown	0.63	0.96	1	0.033	0.72	1	0.18	1.56	0.13	1	0.01	D
Sport	before 1920	0.72	0.83	1	0.004	0.72	1	0.09	1.56	0.45	1	0.01	G
	1920 - 1975	0.54	0.85	1	0.004	0.72	1	0.09	1.56	0.45	1	0.01	E
	1975 - 1990	0.33	0.97	1	0.004	0.72	1	0.09	1.56	0.45	1	0.01	C
	1990 - 1995	0.33	1.04	1	0.004	0.72	1	0.09	1.56	0.45	1	0.01	B
	1995 - 2015	0.28	1.07	1	0.004	0.72	1	0.09	1.56	0.45	1	0.01	B
	unknown	0.39	0.98	1	0.004	0.72	1	0.09	1.56	0.45	1	0.01	D
Other	before 1920	0.23	0.83	1	0.004	0.72	1	0.09	1.56	0.45	1	0.01	G
	1920 - 1975	0.17	0.85	1	0.004	0.72	1	0.09	1.56	0.45	1	0.01	E
	1975 - 1990	0.09	0.97	1	0.004	0.72	1	0.09	1.56	0.45	1	0.01	C
	1990 - 1995	0.09	1.04	1	0.004	0.72	1	0.09	1.56	0.45	1	0.01	B
	1995 - 2015	0.07	1.07	1	0.004	0.72	1	0.09	1.56	0.45	1	0.01	B
	unknown	0.11	0.99	1	0.004	0.72	1	0.09	1.56	0.45	1	0.01	D

Heat sources

In the starting situation (e.g. 2019), *Vesta MAIS* assumes that the heat supply is fulfilled by individual gas-fired boilers, unless it is known that a heating network is present in a neighbourhood. In this version of the model it is not possible yet to indicate the presence of other heating technologies, such as heat pumps or heat and cold storage systems.

The presence of a heat network in *Vesta MAIS* is determined by the percentage of buildings that are connected to a heating network, as registered by the CBS (CBS, 2018). Here, the model uses a simplification. If in the CBS data less than 50% of the buildings in a district is connected to a heat network, *Vesta MAIS* assumes that <u>none</u> of the buildings in the district are connected. On the other hand, if in the CBS data more than 50% of the buildings in a district is connected to a heat network, *Vesta MAIS* assumes that <u>all</u> buildings in the district are connected to a heat network. In this case, *Vesta MAIS* also assumes that the heat network supplies both space heating and warm water. Furthermore, as the model's goal of locally gas-free is already achieved when a HT heat network supplies the heat to the buildings in a district, *Vesta MAIS* does not allow the implementation of other heating technologies in this district. In this case, it is only possible in Vesta to upgrade the building's energy label.

Next, *Vesta MAIS* simulates the heat sources that can supply heat to an existing heat network. PBL periodically collects the data of these sources, including location, construction and demolition year, fuel source, thermal (and possibly electrical) capacity and emission factors from utilities and energy companies (PBL, 2019). Also, in *Vesta MAIS* the heat sources are coupled to the neighbourhoods they supply heat to by geographical proximity, for which information is at this point already in the model.

Electricity & natural gas grid

Vesta MAIS includes the electricity and natural gas grid in order to determine the costs for maintenance, replacement or removal (gas grid), or reinforcements (electricity grid). *Vesta MAIS* uses data from gas grid operators such as Stedin to include the length of the pipes in the gas grid in the model, as well as its age (see Figure 5 in Section 2). *Vesta MAIS* assumes replacement or removal is always necessary for the category 'needs to be removed', and necessary for the category 'older than 30 years' before 2050. The category 'younger than 30 years' is assumed to be usable beyond 2050. *Vesta MAIS* uses fixed costs per length of natural gas grid for the maintenance, replacement and removal costs, which can be found in the model documentation (CE Delft, 2017). Similarly, the length of the electricity grid is included in the model, in order to calculate the costs for grid reinforcements. Here, the amount of heat pumps that are installed in a district determines the costs for grid reinforcements, as it is multiplied by a fixed cost factor per length of electricity grid, as well as the length of the grid in the district (CE Delft, 2017).

Adjustments for this analysis

Adjusting neighbourhood districts for connections to HT heat network

The simplification for the presence of a heat network in the starting year results in the fact that in the standard configuration, *Vesta MAIS* assumes that 7 of the 10 districts of Overvecht are completely heated by the HT heat network (see left part of Figure 8). This does not accurately reflect the actual situation as depicted by the right part of Figure 4 in Chapter 2. This results in that in the standard configuration only the 2 districts without existing districts heating ('Poldergebied' and 'Bedrijventerrein en omgeving') can be analysed correctly (see Table 6), as for these districts the modelled district heating connections reflect the actual situation. This research adjusted the shape of the standard CBS districts to account for the simplification.

Table 6: Comparison of buildings connected to district heating in reality and in Vesta MAIS (CBS, 2018). *In the figure, red numbers reflect data which does not accurately represent the actual situation, while green numbers reflect data which does represent the actual situation accurately.*

District	Buildings connected to district heating		Deviation
	Actual	Vesta	
'Taag- en Rubicondreef en omgeving'	58%	100%	+42%
'Wolga- en Donaudreef en omgeving'	72%	100%	+28%
'Zamenhofdreef en omgeving'	81%	100%	+19%
'Neckardreef en omgeving'	68%	100%	+32%
'Vechtzoom-zuid'	55%	100%	+45%
'Vechtzoom-noord, Klopvaart'	22%	0%	-22%
'Bedrijventerrein en omgeving'	0%	0%	0%
'Zambesidreef en omgeving'	67%	100%	+33%
'Tigrisdreef en omgeving'	50%	100%	+50%
'Poldergebied Overvecht'	0%	0%	0%
Total	**59%**	**89%**	**+30%**

The following method is applied to adjust the shape of the standard CBS districts to account for the simplification. The standard CBS districts are represented in *Vesta MAIS* by a shapefile, which is a polygon with coordinates reflecting the geographical location of district borders as defined by the CBS. The polygons representing the districts where district heating is present are split up into two separate polygons: a polygon which represents the part of the district which has district heating, and a polygon which represents the part of the district which does not have district heating. The geographic information system (GIS) application QGIS is used for this process (QGIS, 2019). Additionally, the percentages of district heating connections in a district in the CBS database are adjusted to account for the new polygons, as this determines which districts are heated by district heating in the starting situation in *Vesta MAIS* (CBS, 2018). As a result, Overvecht now consists of 18 districts: the 2 districts which do not have district heating ('Poldergebied' and 'Bedrijventerrein en omgeving'), plus the 8 standard CBS districts which have district heating, split up into the part that has district heating and the part that does not have district heating. The right part of Figure 8 shows the presence of district heating in the 18 new districts.

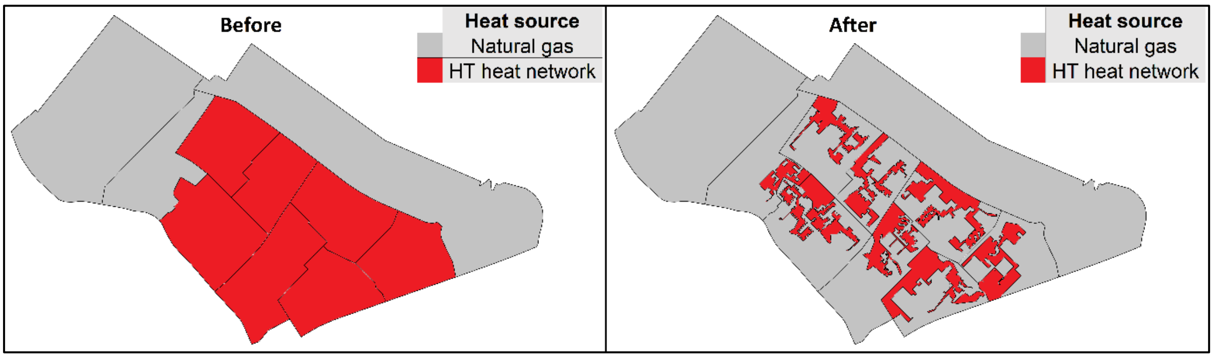

Figure 8: Heat sources of districts before (left) and after district adjustments (right)

Adjusting heat sources and development of HT district heating

To adjust the *Vesta MAIS* model to the studied area, the heat sources in the model need to be adjusted to fit the area for local analysis. Otherwise, the heat sources which are located in the rest of the country (i.e. outside Utrecht) will also be included in the model run. Therefore, the heat sources in *Vesta MAIS* which do not serve as source for the district heating in Overvecht are removed. As a result, only the Merwede plants (as described in Chapter 2) remain in place in the model.

In the standard configuration, *Vesta MAIS* assumes that the Merwede plants remain the primary sources for the HT heat network in Utrecht and that therefore the fuel sources used are largely fossil-fuel based. However, Eneco has recently published a roadmap for increasing the sustainability of their HT heat network in Utrecht, of which the first stage – a biomass plant – is currently nearing completion and will deliver heat to the network by the end of 2019 (Eneco, 2018). Additionally, in the roadmap Eneco announces plans to extract heat from a sewage treatment plant combined with an industrial heat pump by 2021, and they expect to be able to extract heat from two large geothermal sources by 2025 and 2030, as well as from other sources (e.g. industrial waste heat). Due to these developments, Eneco wants to reduce the heat supplied by the CCGTs in the coming years, and eventually close these plants by 2030. Therefore, the characteristics of the HT heat network in *Vesta MAIS* are updated to reflect the developments of the HT heat sources and the expected decrease in emission factors (see Table 7).

Table 7: Overview of HT heat network development according to the latest Eneco Roadmap (Eneco, 2018)

HT heat network		2018	2020	2025	2030
Share of heat supply	CCGTs	80%	50%	20%	0%
	Auxiliary boiler	20%	10%	10%	10%
	Biomass plant	0%	40%	40%	30%
	Sewage treatment plant	0%	0%	10%	10%
	Geothermal plants	0%	0%	20%	40%
	Other	0%	0%	0%	10%
Emission factor (kg CO_2 / GJ)	HT heat network (without auxiliary boiler)	40.0	27.8	23.9	20.0

Validation energy demand

In order to check if the energy demand modelled with *Vesta MAIS* accurately reflects the actual energy use, the modelled values are compared to the actual energy use of electricity and natural gas. It was not possible to check the energy demand from HT heat networks, due the limited data availability. For the comparison the interactive energy platform PICO is used. Here, the selection of Overvecht results in the display of electricity and natural gas use for 18,203 addresses in Overvecht (PICO, 2019). This deviates 2% from the 17,809 which are modelled with *Vesta MAIS*, which may be caused by different building definitions or the use of a different database. The results of the comparison are displayed in Table 8. Here, it can be seen that *Vesta MAIS* accurately simulates the electricity demand in the starting year, as it only deviates by 3% from the actual electricity use. The natural gas demand modelled with *Vesta MAIS* deviates significantly more from the actual natural gas use with 16%. This may be caused by that buildings are in practice better insulated than *Vesta MAIS* assumes. Combined, the modelled electricity and natural gas use deviate 11% from the actual use, which should be kept in mind during the analysis.

Table 8: Comparison of measured (PICO) and modelled (Vesta MAIS) energy use of buildings in Overvecht in 2018 (PICO, 2019)

Energy demand	PICO	Vesta MAIS	Deviation
Buildings	18,203	17,809	-2%
Electricity (GJ)	216,803	223,445	+3%
Natural gas (GJ)	299,718	348,727	+16%
Total (GJ)	**516,521**	**572,172**	**+11%**

3.1.2.3 Technical options

Vesta MAIS is able to assess six different technical measures that might replace the current heat supply: insulation, individual heat pumps (i.e. ‘All-electric’), collective LT heat networks, collective HT heat networks, geothermal and biomass plants. Here, individual means that a technology is installed per building, while collective entails that these technologies are applied to a group of buildings. In the following paragraphs the details of the technical measures are further elaborated.

Insulation

Vesta MAIS models energy savings as improvement to a higher energy label. Here, an improvement is realized regarding the building efficiency for heat use, so that less heat or natural gas is needed to fulfil the heat demand. *Vesta MAIS* assumes that buildings with an energy label lower than A+ cannot be heated by All-electric or LT heat networks. This is because the energy source for electric heating is of low-temperature, it is required to install LT radiators or underfloor heating systems to effectively distribute the supplied heat, as traditional HT radiators, present in most Dutch buildings, have a smaller area and cannot emit sufficient heat. In reality the applicability of different heating technologies depends on multiple factors, and energy label B may be sufficient for LT heating. However, *Vesta MAIS* simplifies this to a hard boundary at which buildings with energy label G to B require HT heating (70 to 90 °C) and building which are insulated to label A+ are able to be heated with LT heat of maximum of 60 °C. *Vesta MAIS* allows three types of insulation measures:

- Smallest label upgrade: The smallest upgrade that can be made is to an 'intermediate label', which is an upgrade to an energy label two labels higher (e.g. F to D). This corresponds with a minimal saving where relatively small and low-cost measures are taken which slightly improve the energy performance of a building, and from which it is possible to later upgrade to a higher energy label.
- Medium label upgrade: The next upgrade that can be made is to label B. Here, the building is relatively well insulated because of e.g. the implementation of HR++ glass and wall insulation. *Vesta MAIS* assumes that the energy label B is equivalent to insulation with an RC value of 2.5 m^2K/W (CE Delft, 2014).
- Highest label upgrade: The largest upgrade that can be made is to label A+. For this the building requires insulation in the floors, roofs and walls of the building. *Vesta MAIS* assumes that the energy label A+ is equivalent to 'low temperature' space heating and insulation with an RC value of 5.0 m^2K/W (CE Delft, 2014).

The costs of implementing these three label upgrades to a higher energy label, as well as the costs to install a LT heat supply system (e.g. LT radiators or floor heating) which are required for the All-electric and LT heat network heating options, are displayed in Table 9 for residential buildings and Table 10 for utility buildings. In the standard configuration, *Vesta MAIS* assumes the average of the displayed minimal and maximal investments costs as the costs for building improvements to a higher energy label. The rebound factor that is displayed entails the difference between the theoretical and actual energy savings that can be achieved by energy label improvements. For example, a factor of 0.25 means that 25% of the theoretical energy savings will in practice not be achieved, as people will start to use more energy when their building is more efficient, which is also known as the 'rebound effect', and entails an increase in comfort (CE Delft, 2017).

Table 9: Building improvement costs of upgrading a residential building to a higher energy label, as well as the costs to install a LT heat system, which is required for the All-electric and LT heat network heating options

			Building improvements															
			Energy label												LT heat		
			Current → Intermediate				Current → B				Current → A+				Space heating	LT supply system	
			Functional demand	rebound	Investment costs		Functional demand	rebound	Investment costs		Functional demand	rebound	Investment costs		Heating efficiency	Investment costs	
		Area			min	max			min	max			min	max	LT heat	min	max
Building type	**Building year**	**m2**	**GJ/jr**	**factor**	**€**	**€**	**GJ/jr**	**factor**	**€**	**€**	**GJ/jr**	**factor**	**€**	**€**	**η**	**€**	**€**
Detached house	before 1946	130	55.56	0.5	2441	2755	34.86	0.5	12690	14318	20.88	0.25	26296	29120	1.07	1511	1511
	1946 - 1964	130	59.31	0.5	839	946	34.86	0.5	12690	14318	20.88	0.25	26296	29120	1.07	1511	1511
	1965 - 1974	144	60.50	0.5	864	981	38.62	0.5	13803	15668	23.12	0.23	28765	31963	1.07	1674	1674
	1975 - 1991	154					41.30	0.5	13492	15317	24.73	0.19	27432	30487	1.07	1790	1790
	1992 - 2005	172					46.13	0.5	2111	2643	27.62	0.04	17070	18894	1.07	2000	2000
	2006 - 2014	172									27.62	0.00	14959	16251	1.07	2000	2000
Duplex	before 1946	110	41.03	0.5	3133	3505	26.94	0.5	10964	12265	16.13	0.25	20911	23039	1.07	1279	1279
	1946 - 1964	110	45.65	0.5	870	973	26.94	0.5	10964	12265	16.13	0.25	20911	23039	1.07	1279	1279
	1965 - 1974	123	44.56	0.5	1471	1657	30.13	0.5	11447	12895	18.04	0.23	21775	24090	1.07	1429	1429
	1975 - 1991	123					30.13	0.5	11643	12993	18.04	0.18	21910	24110	1.07	1429	1429
	1992 - 2005	132					32.33	0.5	3011	3780	19.36	0.05	13962	15650	1.07	1534	1534
	2006 - 2014	132									19.36	0.00	10951	11870	1.07	1534	1534
Mid terraced house	before 1946	102	33.26	0.5	2734	3639	23.34	0.5	9761	12993	13.97	0.23	17314	21134	1.07	1186	1186
	1946 - 1964	87	30.40	0.5	1993	2284	19.90	0.5	6873	7879	11.92	0.25	13340	14868	1.07	1011	1011
	1965 - 1974	106	30.64	0.5	3207	3683	24.25	0.5	7814	8976	14.52	0.21	14508	16211	1.07	1232	1232
	1975 - 1991	106					24.25	0.5	7167	8157	14.52	0.16	13972	15511	1.07	1232	1232
	1992 - 2005	114					26.08	0.5	818	1023	15.62	0.03	8421	9155	1.07	1325	1325
	2006 - 2014	114									15.62	0.00	7603	8132	1.07	1325	1325
End terraced house	before 1946	102	33.26	0.5	2734	3639	23.34	0.5	9761	12993	13.97	0.23	17314	21134	1.07	1186	1186
	1946 - 1964	87	30.40	0.5	1993	2284	19.90	0.5	6873	7879	11.92	0.25	13340	14868	1.07	1011	1011
	1965 - 1974	106	30.64	0.5	3207	3683	24.25	0.5	7814	8976	14.52	0.21	14508	16211	1.07	1232	1232
	1975 - 1991	106					24.25	0.5	7167	8157	14.52	0.16	13972	15511	1.07	1232	1232
	1992 - 2005	114					26.08	0.5	818	1023	15.62	0.03	8421	9155	1.07	1325	1325
	2006 - 2014	114									15.62	0.00	7603	8132	1.07	1325	1325
Low-rise apartment	before 1946	59	17.12	0.5	2636	2888	14.32	0.5	4099	4492	8.57	0.23	8942	9571	1.07	556	556
	1946 - 1964	66	20.20	0.5	390	421	16.02	0.5	6366	6873	9.59	0.17	11501	12266	1.07	622	622
	1965 - 1974	71					17.23	0.5	6881	7413	10.32	0.15	12221	13026	1.07	669	669
	1975 - 1991	70					16.99	0.5	5793	6226	10.17	0.12	10951	11640	1.07	659	659
	1992 - 2005	74					17.96	0.5	2021	2299	10.75	0.08	7510	8071	1.07	697	697
	2006 - 2014	74									10.75	0.00	5489	5772	1.07	697	697
High-rise apartment	before 1946	72					14.55	0.5	5817	6292	8.71	0.21	10088	10746	1.07	678	678
	1946 - 1964	72					14.55	0.5	5817	6292	8.71	0.21	10088	10746	1.07	678	678
	1965 - 1974	82	18.08	0.5	3215	3518	16.57	0.5	5547	6071	9.92	0.16	10074	10793	1.07	773	773
	1975 - 1991	68					13.74	0.5	6472	6897	8.23	0.22	10889	11512	1.07	641	641
	1992 - 2005	79					15.96	0.5	630	712	9.56	0.05	5371	5668	1.07	745	745
	2006 - 2014	79									9.56	0.00	4741	4956	1.07	745	745

Table 10: Building improvement costs of upgrading a utility building to a higher energy label, as well as the costs to install a LT heat system, which is required for the All-electric and LT heat network heating options

		Building improvements										
		Energy label								LT heat		
		Current → B				Current → A+				Space heating	LT supply system	
		Functional demand	rebound	Investment costs		Functional demand	rebound	Investment costs		Heating efficiency	Investment costs	
				min	max			min	max	LT heat	min	max
Building type	**Building year**	**GJ/jr/m2**	**factor**	**€/m2**	**€/m2**	**GJ/jr**	**factor**	**€**	**€**	**η**	**€/m2**	**€/m2**
Office	before 1920	0.21	0	101	144	0.15	0.00	135	215	1.07	7	7
	1920 - 1975	0.21	0	100	143	0.15	0.00	135	214	1.07	7	7
	1975 - 1990	0.21	0	93	139	0.15	0.00	127	209	1.07	7	7
	1990 - 1995	0.21	0	91	135	0.15	0.00	125	206	1.07	7	7
	1995 - 2015	0.21	0	87	132	0.15	0.00	121	203	1.07	7	7
	unknown	0.22	0	92	137	0.15	0.00	127	208	1.07	7	7
Store	before 1920	0.11	0	119	175	0.07	0.00	157	260	1.07	7	7
	1920 - 1975	0.11	0	118	174	0.07	0.00	157	260	1.07	7	7
	1975 - 1990	0.11	0	108	167	0.07	0.00	146	253	1.07	7	7
	1990 - 1995	0.11	0	106	164	0.07	0.00	144	250	1.07	7	7
	1995 - 2015	0.11	0	100	160	0.07	0.00	138	246	1.07	7	7
	unknown	0.11	0	110	168	0.08	0.00	148	254	1.07	7	7
Health care	before 1920	0.28	0	116	172	0.19	0.00	158	251	1.07	7	7
	1920 - 1975	0.27	0	116	171	0.19	0.00	158	250	1.07	7	7
	1975 - 1990	0.27	0	106	165	0.19	0.00	148	244	1.07	7	7
	1990 - 1995	0.28	0	104	161	0.19	0.00	146	241	1.07	7	7
	1995 - 2015	0.28	0	98	158	0.20	0.00	140	237	1.07	7	7
	unknown	0.29	0	107	164	0.20	0.00	149	244	1.07	7	7
Education	before 1920	0.11	0	110	175	0.08	0.00	148	272	1.07	7	7
	1920 - 1975	0.11	0	110	174	0.08	0.00	147	271	1.07	7	7
	1975 - 1990	0.11	0	98	168	0.08	0.00	136	265	1.07	7	7
	1990 - 1995	0.11	0	96	164	0.08	0.00	134	261	1.07	7	7
	1995 - 2015	0.11	0	90	160	0.08	0.00	127	257	1.07	7	7
	unknown	0.12	0	100	168	0.08	0.00	138	265	1.07	7	7
Industry	before 1920	0.09	0	76	105	0.06	0.00	101	157	1.07	7	7
	1920 - 1975	0.09	0	76	104	0.06	0.00	101	156	1.07	7	7
	1975 - 1990	0.09	0	70	100	0.06	0.00	95	152	1.07	7	7
	1990 - 1995	0.09	0	69	98	0.06	0.00	94	150	1.07	7	7
	1995 - 2015	0.09	0	66	96	0.06	0.00	91	148	1.07	7	7
	unknown	0.09	0	70	100	0.06	0.00	95	152	1.07	7	7
Conference	before 1920	0.15	0	102	147	0.11	0.00	140	210	1.07	7	7
	1920 - 1975	0.27	0	102	146	0.19	0.00	139	210	1.07	7	7
	1975 - 1990	0.37	0	94	141	0.26	0.00	131	204	1.07	7	7
	1990 - 1995	0.38	0	92	138	0.27	0.00	129	201	1.07	7	7
	1995 - 2015	0.33	0	87	135	0.23	0.00	125	198	1.07	7	7
	unknown	0.26	0	96	142	0.18	0.00	134	205	1.07	7	7
Sport	before 1920	0.21	0	166	241	0.15	0.00	233	358	1.07	7	7
	1920 - 1975	0.21	0	165	240	0.15	0.00	233	357	1.07	7	7
	1975 - 1990	0.21	0	149	229	0.15	0.00	217	346	1.07	7	7
	1990 - 1995	0.21	0	145	222	0.15	0.00	212	340	1.07	7	7
	1995 - 2015	0.21	0	137	216	0.15	0.00	204	334	1.07	7	7
	unknown	0.22	0	149	227	0.16	0.00	217	345	1.07	7	7
Other	before 1920	0.05	0	105	167	0.03	0.00	152	259	1.07	7	7
	1920 - 1975	0.05	0	104	166	0.03	0.00	151	259	1.07	7	7
	1975 - 1990	0.05	0	91	159	0.03	0.00	138	251	1.07	7	7
	1990 - 1995	0.05	0	89	154	0.03	0.00	136	247	1.07	7	7
	1995 - 2015	0.05	0	82	150	0.03	0.00	129	243	1.07	7	7
	unknown	0.05	0	91	157	0.04	0.00	138	249	1.07	7	7

All-electric

Vesta MAIS defines buildings with individual heat pumps installed in the building as being All-electric. As mentioned before, *Vesta MAIS* only allows the implementation of this option in case the building has or it upgraded to energy label A+. The standard heat pump that *Vesta MAIS* considers is an air-sourced heat pump, which transfers heat from the outside air (i.e. the heat source) to the inside air by utilizing a reversed refrigeration cycle. *Vesta MAIS* assumes that the heat pumps operates with a coefficient of performance (COP) of 4, meaning that for each unit of electricity that is required for operation of the heat pump (mainly for the compressor), four units of heat are supplied to the building (CE Delft, 2017). The costs input data to install the All-electric option is displayed in Table 11. More detailed information regarding the costs and used formula's for this heating option can be found in the model documentation (CE Delft, 2017).

Table 11: Cost input data for All-electric (CE Delft, 2014; RVO, 2019c)

Component	Costs
Fixed investment costs residences	Ground-sourced heat pump: 8,826 €/residence Air-sourced heat pump: 3,652 €/residence
Variable investment costs residences	Ground-sourced heat pump: 65 €/kW Air-sourced heat pump: 281 €/kW
Investment costs utilities	Ground-sourced heat pump: 203 €/kW Air-sourced heat pump: 1,925 €/kW
Fixed maintenance costs	50 €/year
Variable maintenance costs	2% of investment costs
LT supply system	See Insulation costs
Economy of scale for apartments	34%

LT collective heat networks

Next to the previous individual options, several collective options are modelled in *Vesta MAIS*. Many different types of LT heat networks exist, with different sources (e.g. supermarkets, data centres) and temperature levels (more or less between 40 and 60 °C). For the future it is likely that more types will be developed that suit local conditions. To simplify this, *Vesta MAIS* grouped these different types under one conventional type of LT heat network. *Vesta MAIS* defines a LT network as local heat supply up to 60 °C with a double source heat and cold storage (HCS) as primary source and central upgrading using a collective industrial ground-sourced heat pump (CE Delft, 2017). Additionally, like with All-electric heating, *Vesta MAIS* assumes that only buildings can be heated with this technology that are very well insulated up to label A+ and where a LT heat delivery system is installed in the building.

Whereas in *Vesta MAIS* insulation and heat pumps can be installed for individual buildings, LT heat networks are installed in clusters. Here, it is possible that different neighbouring clusters are collectively connected to one LT heat network. In practice this would be around 200 to 5,000 residences per heat network, but smaller is also possible. One large utility building can for example have its own LT heat network, if the demand is sufficient. In the *Vesta MAIS* calculations a LT heat network is simulated with a source of a shallow ground system for HCS. In practice it is also possible to combine this system with a supplementary source, such as surface waters or waste water, but this is not yet possible to consider with the current model (CE Delft, 2017). *Vesta MAIS* assumes the source system delivers water at a base temperature, which is consequently electrically upgraded to around 60 °C by a collective central water-water heat pump, which is then used to heat buildings and supply warm water. This additional electrical heating can in some cases be done with individual heat pumps, but *Vesta MAIS* assumes this is done by a collective central heat pump. Because LT heat networks are local and at smaller scale, *Vesta MAIS* does not require the instalment of large transport pipes in these heat networks, but only local distribution pipes and possibly internal pipes for high-rise buildings. Because in this study LT heat networks use a shallow ground system, a map is incorporated into *Vesta MAIS* with restriction areas where it is not allowed to install a system in the shallow ground, due to for example drinking water extraction areas. As a results, *Vesta MAIS* does not allow the implementation of a LT heat network in the district 'Poldergebied Overvecht'. The used model approach for the cost estimation of LT heat networks is relatively uncertain, because there is limited practical experience in the Netherlands with the application of this technology (van der Molen et al., 2018). The costs input data of *Vesta MAIS* to install a LT heat network is displayed in Table 12. More detailed information regarding the costs and used formula's for this heating option can be found in the model documentation (CE Delft, 2017).

Table 12: Cost input data for LT heat networks (CE Delft, 2014)

Component	Costs
HCS source	Houses: 1,400 €/residence Apartments: 1,400 €/residence Utilities: 26 €/m^2
Generation	Houses: 2,000 €/residence Apartments: 1,800 €/residence Utilities: 28 €/m^2
Distribution	Houses: 6,000 €/residence Apartments: 2,000 €/residence Utilities: 0 €/m^2
LT heat supply	See Insulation (Table 9 and Table 10)

HT collective heat networks

HT heat networks are the most mature alternative for individual gas-fired boilers, as the technique is already being used for decades in cities. *Vesta MAIS* defines HT heat networks as heat supply up to 90 °C. Sources which deliver heat at 70 or 80 °C are also included here, possibly with central upgrading to a higher temperature. Currently, sources for HT heat networks are often power stations, incineration plants, or industrial companies that produce heat as by-product from their company operation. Alternatively, sustainable sources such as geothermal energy or biomass can be used. It is also possible that multiple different sources feed-in to the same HT heat network.

A HT heat network consists of primary transport pipes, which transport heated water from the source to a neighbourhood, and distribution pipes which distribute the heat to individual buildings in a neighbourhood. Furthermore, also internal building pipes are required for high-rise buildings. Combined, these pipes form a major share of the investments costs of HT heat networks. Therefore, the financial attractiveness of a HT heat network is highly affected by the spatial distribution of the heat demand and the distance to the source. A high heat demand density at short distance from a HT heat source means that a relatively small amount of infrastructure needs to be constructed to supply a large amount of heat, which greatly increases the financial attractiveness, and vice versa.

The operational costs per produced unit of heat are also very important for the financial attractiveness, and amongst others depends on the type of source, while the investment costs are considered to be the same by *Vesta MAIS*, as displayed in Table 13. Geothermal sources can for instance have much higher costs than waste heat from incineration plants. Also, strong fluctuations can exist for the heat demand in a HT heat network, especially when they need to heat poorly insulated buildings. Therefore, HT heat networks also use auxiliary boilers which can supply the peak demand above the capacity of the primary source, to ensure a continuous heat supply. These auxiliary boilers are common natural gas-fired, which also makes the natural gas price important for the financial attractiveness, as well as affect the sustainability of HT heat networks.

Table 13: Investment costs input data for HT heat networks (CE Delft, 2014)

Component	Description	Costs
Heat transfer station (HTS)	Auxiliary boiler Building Heat exchanger	125,000 €/MW
Distribution station	For around 150 residences. Heat exchanger	100 €/kW
Main network	Pipes between HT source and HTS	Min. curve: 215.5 * (P^0.4828) Max. curve: 379.29 * (P^0.4739) P = Power (MW)
Distribution network	Pipes between HTS and distribution station	See Main network pipes
Connection costs	Connection of the building to the distribution network. Assumed 15m per connection	Houses: 5,000 €/residence Apartments: 2,700 €/residence Utilities: 125 €/kW
Internal building distribution	Installing heat station Installing distribution pipes ground floor Installing vertical pipes Radiators Removing old boiler	Houses: Installing: 0 €/residence Removing: 500 €/residence Apartments without collective heating: Installing: 5,308 €/residence Removing: 500 €/residence Apartments with collective heating: Installing: 4,523 €/residence Removing: 500 €/residence

In the standard configuration of *Vesta MAIS* there are multiple types of HT heat sources available. Next to existing heat sources (e.g. power plants) of which the location and characteristics are known, it is possible to model the implementation of new HT sources, such as a geothermal source or a biomass plant. This way it is possible to dynamically simulate the development of a HT heat network and its sources. The various costs components of HT heat sources, which *Vesta MAIS* uses, are displayed in Table 14. More detailed information regarding the costs and used formula's for this heating option can be found in the model documentation (CE Delft, 2017).

Table 14: Cost components of HT heat sources

Plant type	Investment	Minimal capacity	Minimal costs	Fixed costs	Variable costs
	(€/kW_{th},output)	(MW_{th})	(M€)	(% of investment)	(€$_{2010}$/GJ_{th})
CCGT	150 - 175	10.0	1.50 - 1.75	5%	4.94
Coal	150 - 175	20.0	3.00 - 3.50	5%	2.38
Gas motor	800 - 1,800	0.5	0.40 - 0.90	1%	3.71
Gas turbine	175 - 185	6.0	1.05 - 1.11	5%	4.94
Industry	100 - 275	6.0	0.60 - 1.65	5%	0.000237
Refinery	225 - 275	6.0	1.35 - 1.65	5%	0.000237
Waste incineration	150 - 175	3.0	0.45 - 0.53	5%	2.67
Biomass plant	175 - 185	3.0	0.53 - 0.56	5%	6.94
Nuclear	-	-	-	5%	0.000237
Local CHP	800 - 1,800	0.5	0.40 - 0.90	1%	3.71
Bio-CHP	750 - 1,000	0.5	0.38 - 0.50	5%	
Geothermal	1,750 - 2,000	3.0	5.25 - 6.00	1%	0.000237

Adjustments for this analysis

In this analysis it is chosen to include the heating options biomass and geothermal in the category HT heat network, instead of modelling them separately. This is due to the fact that the information provided by the Enenco roadmap aggregates these three heating options, as they all will feed-in into the same HT heat network (Eneco, 2018). However, the characteristics of these technologies and the resulting HT heat network are incorporated into the model, as described in Section 3.1.2.2.

3.1.2.4 Fixed input

Economic growth, population growth and temperature rise

The effects of climate change, which will likely occur in the coming decades, are incorporate in *Vesta MAIS* in the form of assuming a climate scenario as presented by the WLO report of PBL (PBL, 2015). Here, the scenario 'WLO Hoog' is used as standard scenario, which is associated with the global climate scenario that assumes an average temperature increase of 2.5 to 3 °C in 2100, as a result of, amongst others, high economic growth and population growth (PBL, 2015). As a results, *Vesta MAIS* assumes that the annual heating demand will decrease in the future by around 10% in 2030, as the warmer climate results in a reduced demand for heat.

Energy prices

Vesta MAIS uses energy prices by multiplying them with the appropriate energy demand to determine operational energy costs. The development of the energy prices used in *Vesta MAIS* is based on the WLO report of PBL (PBL, 2015). Here, *Vesta MAIS uses* the scenario 'WLO Hoog' as standard scenario. Practically, this means that the commodity price (i.e. price at production point, without taxes, etc.) for natural gas (which also affects the heat price) is assumed to decrease from 0.206 €/m^3 in 2019 to 0.134 €/m^3 in 2030 while the commodity price for electricity will increase form 0.061 €/kWh in 2019 to 0.083 €/kWh in 2030. Table 15 shows an overview of the development of energy prices in *Vesta MAIS*.

Table 15: Development of energy prices in Vesta MAIS

Year	Heat (€/GJ)	Electricity (€/kWh)	Natural gas (€/m^3)
2010	6.900	0.048	0.246
2020	7.180	0.063	0.200
2030	6.420	0.083	0.134

Construction and demolition

Next, to simulate the development of the building stock over time, *Vesta MAIS* includes plans for construction and demolition. Construction is simulated as the addition of model objects to the existing building stock. The amount of construction is determined by currently known and available plans at national level (PBL, 2019). Therefore, periodic updating of these data is required to reflect the actual development of the building stock, and more specific plans for construction are desirable. Demolition is simulated as the removal of existing model objects of the building stock. In the standard configuration *Vesta MAIS* uses the construction year and expected lifetime of the building to determine the demolition date.

Emission factors

Vesta MAIS uses emission factors to determine the amount of emissions that results from the consumption of different types of heat or energy sources. The emission factors that *Vesta MAIS* uses are displayed in Table 16.

Table 16: Overview of emission factors of the different energy carriers (CE Delft, 2017)

Emission factor (kg CO_2/GJ)	Individual gas-fired boilers	Electricity	LT heat	HT heat
2019	50.6	126.1	-	53.7
2030	50.6	16.9	8.6	53.7

The emission factor for individual gas-fired boilers remains the same, as this results from the burning of natural gas, which is still the case in the future if the type of gas is not changed. *Vesta MAIS* assumes a very strong 86% reduction in the emission factor of electricity by 2030, as a results of the deep decarbonisation of the electricity sector in the 'WLO Hoog' scenario (PBL, 2015). Currently, there is only 13.8% renewable electricity present in the Dutch electricity mix in 2017 (CBS, 2019). The emission factor of LT heat is related to the emission factor of electricity, as in *Vesta MAIS* LT heat networks are using collective industrial heat pumps. However, as *Vesta MAIS* assumes this is a more efficient system, the resulting emission factor is significantly lower. In the standard configuration, *Vesta MAIS* assumes that the current HT heat sources remain unaltered in the period up to 2030.

Adjustments for this analysis

As this study investigates the optimal pathway to remove the existing buildings in a neighbourhood from the natural gas grid and sustainably heat the building stock, construction and demolition are turned off in the model. Newly constructed buildings are strongly regulated by new laws to be well insulated, are not connected to the gas grid and have an alternative heating technology in place. Also, as these buildings will already achieve the objective of being locally gas-free, *Vesta MAIS* will not implement different heating technologies for these buildings. In addition, the available area for construction within the modelling area is limited, and 2030 is a limited time horizon to build new buildings. Therefore, construction is less interesting to look at in this analysis. Construction is turned off by adjusting the code section in *Vesta MAIS* that adds new buildings to the neighbourhood.

Similarly, demolition is turned off as there are very limited plans for demolition in this area (Gemeente Utrecht, 2019a). Also, as 2030 is limited time horizon, there is a smaller chance buildings in the neighbourhood will be demolished in the near future. Also, this research investigates what the best alternatives are for natural gas heating for a certain existing building stock, therefore the results are also relevant for replaced homes, as the optimal connection (i.e. electricity only, or heat network + electricity) is also determined by this study.

Finally, the emission factor of 53.7 kg CO_2/GJ for HT heat in 2030 is adjusted to 33.7 kg CO_2/GJ, to incorporate the developments of the HT heat network of Eneco (Eneco, 2018). This value is different from the emission factor presented in Section 3.1.2.2, as this value includes the emissions from the auxiliary boiler.

3.1.2.5 Variable input

Societal costs and discount rate

Vesta MAIS can determine costs for end-users, as well as societal costs. As described in Section 1.4, this research uses societal costs for the analysis. While the analysis of end-user costs is very important to determine the affordability of a pathway to sustainable heating system, it is not included due to time constraints. Societal costs are calculated by adding yearly fixed and variable operational expenditures (e.g. plant maintenance and heat production costs) and annualized investment costs. To annualize investment costs, *Vesta MAIS* uses a societal discount rate of 4%, which is the discount rate to determine societal costs (CE Delft, 2017).

Learning curves

In *Vesta MAIS*, the development of the costs of technical measures follow learning curves that are developed by CE Delft (CE Delft, 2014). Here, it is assumed that the costs of technical measures decline following a fixed curve. This assumed decline is caused by the assumption that costs of materials and labour will decline following a fixed pattern. The used learning curves have a bandwidth between most optimistic and most pessimistic expectations. In the most optimistic case, the costs of for instance heat pumps will substantially decrease in the future, whereas the most pessimistic scenarios has no or a minimal decline. In the standard configuration of *Vesta MAIS*, the average between the minimum and maximum is taken as learning effect, as displayed by Table 17.

Table 17: Learning curve values for Vesta MAIS measures (CE Delft, 2014)

Component		2010	2020	2030
Building improvements	Min Max	100 100	85 101	72 105
Ground-sourced heat pump	Min Max	100 100	81 88	69 80
Air-sourced heat pump	Min Max	100 100	72 80	58 70
Heat networks – Curve 1	Min Max	100 100	87 92	77 87
Heat networks – Curve 2	Min Max	100 100	72 80	58 70

For heat networks, *Vesta MAIS* assumes that different components will follow a different learning curve, as these technologies have different potentials to reduce in costs. Table 18 displays which of the learning curves for heat networks is used for the various components. More detailed information regarding the construction and use of these learning curves can be found in the model documentation (CE Delft, 2014).

Table 18: Used learning curves for heat network cost components (CE Delft, 2014)

Heat network component	Used learning curve
Heat transfer station (HTS)	2
Distribution station	1
Main network	2
Distribution network	2
Connection costs	1

Costs technical options

The costs of technical options, such as building improvement costs can in *Vesta MAIS* be varied between a maximum and minimum value, as displayed by Table 9 and Table 10**.** In the standard configuration, *Vesta MAIS* calculates with the average between these values.

Adjustments for this analysis

Adjustments to the parameters in this section are made solely for the sensitivity analysis, as described in Section 3.3.2.

3.1.2.6 Settings

In *Vesta MAIS*, several settings are required in order to run the model. First of all, the user needs to determine what the year of analysis will be. In the standard configuration, it is possible to extract data at 10 year intervals starting at 2020, up to 2050. Next, the user needs to determine in which year certain measures will be installed. *Vesta MAIS* allows instalments of measures in the same years as the years of analysis. It is possible to take different measures a specific time period (e.g. first insulating buildings in 2020, and then installing heat pumps in 2030). Moreover, the user can choose to implement measures based on a positive business case, or apply measures regardless or financial attractiveness, which is an important choice for scenario development (PBL, 2019). As there are no standard scenarios present in the model, the user needs to develop and input the scenarios. Scenarios can include different levels of insulation, as well as different choices in heating technologies. Finally, the user needs to determine which output parameters will be extracted from each model run in order to perform the analysis.

Adjustments for this analysis

For this analysis, all measures are set to be installed in 2030, as it is impossible to take all measures by 2020. Although in practice not all measure can and will be installed in 2030, this is the most suitable choice in the model. Furthermore, in this study, all constructed scenarios are based on the implementation of measures regardless of financial attractiveness. Section 3.2.1 gives a detailed description of the 5 scenarios studied, as well as of the output parameter that are extracted from the model.

3.2 Phase II: Scenarios modelling

Several scenarios are constructed based on the available technologies described in Section 3.1. Table 19 shows an overview of the calculated scenarios and are further elaborated in Section 3.2.1. In the table, the blue colour represents the current situation, the orange colour represents the scenarios which are used as reference or comparison (and still have natural gas consumption at building level), and the green colour represents the 'gas-free' scenarios from which the *Optimal pathway* is selected. Furthermore, the brackets in the scenario names contain the energy labels to which buildings are upgraded in a scenario. Here, '(A+)' and '(B)' mean that buildings are upgraded to energy label A+ and B, respectively, while '(-)' means that no upgrades take place. Section 3.2.2 describes which output parameters are produced for each of the stated scenarios. The results are produced for each of the 18 new districts of the neighbourhood. Note that the outcome of individual scenarios will most likely not be the actual situation that will be implemented, as here all district are forced to one heating option and therefore undermine where preferable characteristics are located for a specific heating option.

Table 19: Overview of characteristics of the Baseline and all calculated scenarios

Scenario	*Baseline*	*Reference (-)*	*Insulation (B)* *Insulation (A+)*	*All-electric (A+)*	*LT collective (A+)*	*HT collective (-)*
Target year	2019	2030	2030	2030	2030	2030
Energy label upgrade to	None	None	B A+	A+	A+	None
Heating technologies	Current	Current	Current	Heat pumps	HCS + Collective heat pumps	CHP, Biomass, Industrial heat pump, Geothermal
Natural gas grid	Current	Partly renewed	Partly renewed	Removed	Removed	Removed
Electricity grid	Current	Current	Current	Reinforced	Reinforced	Current
LT heat network	None	None	None	None	Installed	None
HT heat network	Current	Current	Current	Current	Current	Expanded
HT heat sources	Current	Development according to plans of Eneco	Development according to plans of Eneco	Development according to plans of Eneco	Development according to plans of Eneco	Development according to plans of Eneco

3.2.1 Scenarios

Baseline

First, the *Baseline* is established to allow comparison between the calculated scenarios and the current system. Here, the building stock has energy labels according to the BAG. The buildings are heated with HT heat networks (with existing HT heat network connection) and individual gas-fired boilers. A LT heat network is currently not in place. Figure 9 shows an overview of the energy labels per building and installed heating technologies per district.

Figure 9: Energy labels of buildings (left) and installed heating technologies in the Baseline (right)

***Reference (-)* scenario**

The *Reference (-)* scenario is constructed to investigate the effects besides the implementation of technical measures, such as the warming of the climate, energy price developments and increasing sustainability of the HT heat network and electricity grid by 2030, as described in Section 3.1. Therefore, it is assumed here that no buildings are further insulated, and all the current building connections (electricity, natural gas and HT heat networks) remain in place (see Figure 10). Part of the natural gas network is renewed due to aging, as described in Section 2.

Figure 10: Energy labels of buildings (left) and installed heating technologies in the Reference (-) scenario (right)

Insulation (B) **and** ***Insulation (A+)*** **scenarios**

The *Insulation (B)* and *Insulation (A+)* scenarios are constructed to analyse the effects of insulation measures, and allow the comparison with other scenarios which have the same insulation measures, but different heating options. In the *Insulation (B)* and *Insulation (A+)* scenarios the current heating technologies stay in place, but all building are strongly insulated in 2030 (see Figure 11 and Figure 12). Accordingly, this scenario still has a natural gas demand and only displays the effect of different extends of insulating. Therefore, two variants are calculated. In the scenario *Insulation (B)*, all buildings are upgraded to energy label B, except for the 2,061 buildings which already have energy label B (see Figure 9). In the scenario *Insulation (A+)*, all buildings are insulated to energy label A+. Furthermore, this scenario resembles the *Reference (-)* scenario, as current grid connections stay in place, part of the natural gas grid (see Section 2) is renewed and all other mentioned developments of the *Reference (-)* scenario take place.

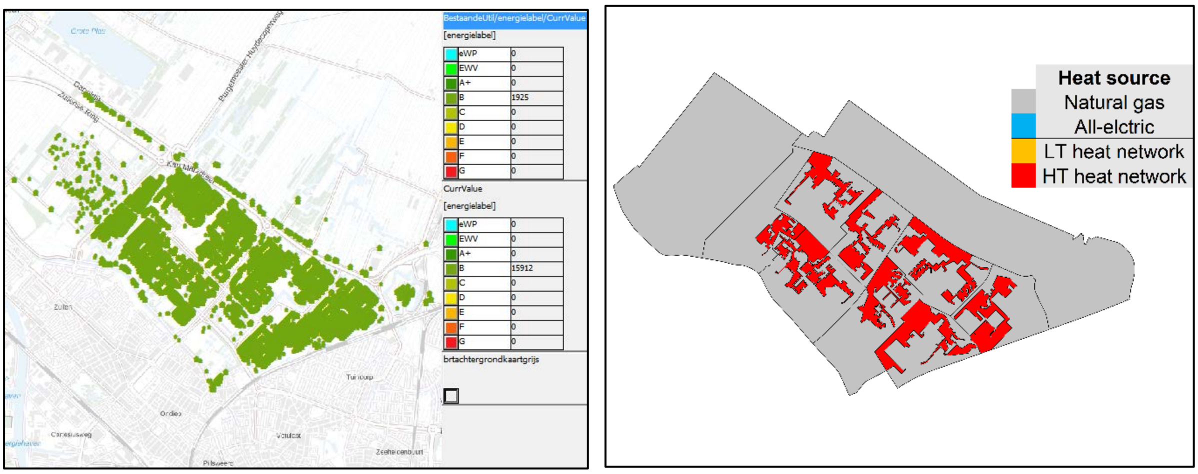

Figure 11: Energy labels of buildings (left) and installed heating technologies in the Insulation (B) scenario (right)

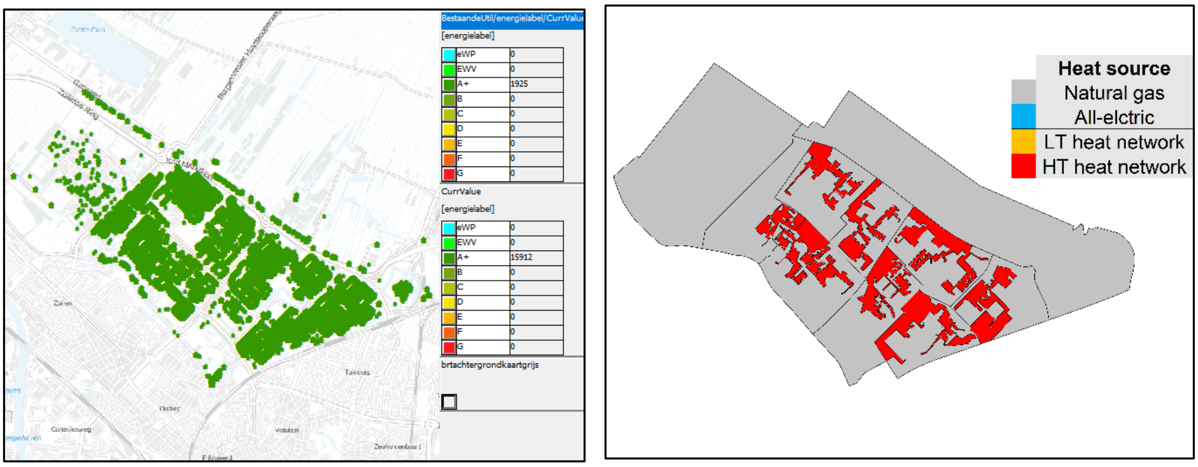

Figure 12: Energy labels of buildings (left) and installed heating technologies in the Insulation (A+) scenario (right)

All-electric (A+) scenario

In order to determine for which districts the optimal option is to be heated by individual heat pumps, this scenario is constructed. The *All-electric (A+)* scenario is the first scenario which achieves a locally sustainable heating system by 2030, as all buildings are removed from the gas grid. Here, all buildings that are not originally connected to the HT heat network are insulated to label A+ and individual heat pumps and internal LT heat supply equipment (e.g. LT radiators or floor heating) are installed (see Figure 13). However, the buildings that were already connected to the HT heat network remain unchanged due to model limitations. For these buildings, no insulation is installed and the current connection to the HT heat network remains (see Figure 13). Furthermore, the natural gas network is removed completely, as there are no longer buildings connected to this grid. Also, the electricity grid is reinforced in the districts with All-electric heating to account for the increased electricity demand due to the instalment of heat pumps (see Appendix E).

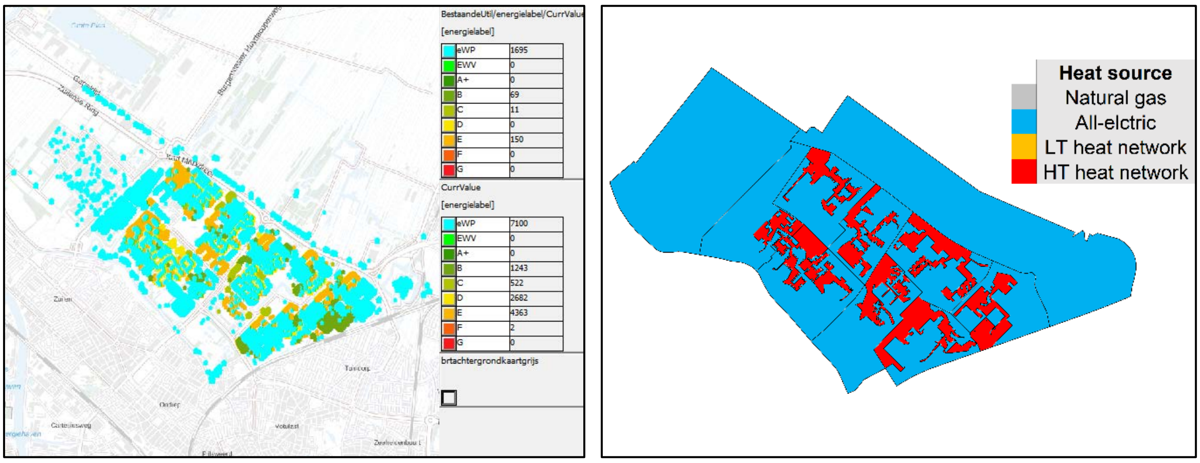

Figure 13: Energy labels of buildings (left) and installed heating technologies in the All-electric (A+) scenario (right). In the left map and tables, the light blue colour represents buildings with energy label A+ and an installed electrical heat pump.

LT collective (A+) scenario

The *LT collective (A+)* scenario is constructed to analyse for which districts the optimal pathway consist of heating by a LT heat network. In this scenario, all buildings are insulated to energy label A+. Furthermore, collective HCS systems with auxiliary collective heat pumps are installed in clusters for all buildings that were not originally connected to the HT heat network (see Figure 14). Additionally, these buildings are equipped with LT supply systems (i.e. LT radiators or floor heating) and in high-rise buildings LT internal distribution pipes are installed. The natural gas grid is removed completely, as there are no longer buildings connected to this grid. The electricity grid also needs to be reinforced to account for the instalment of collective heat pumps (note: the location of these heat pumps is not determined by Vesta MAIS). Buildings that were already connected to the HT heat network remain connected to this grid.

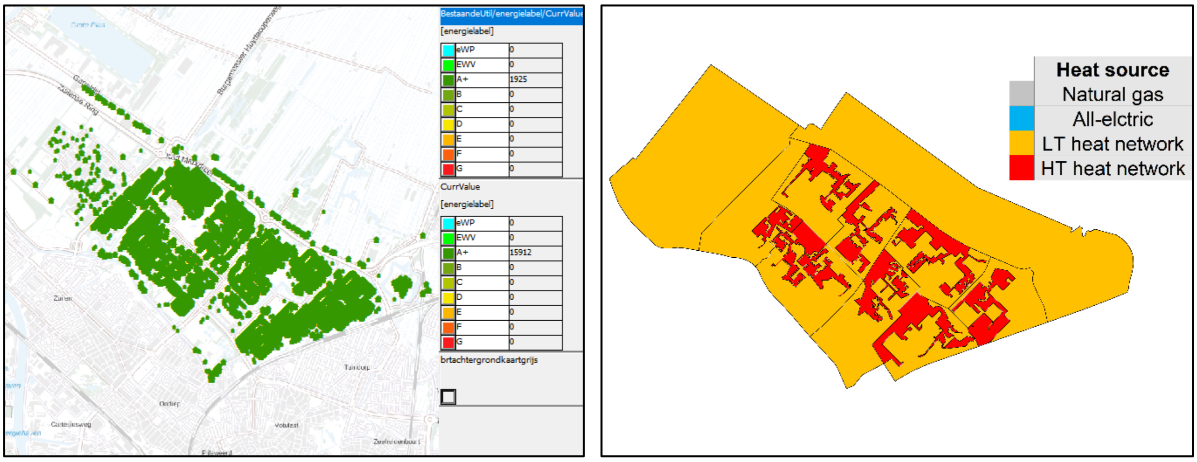

Figure 14: Energy labels of buildings (left) and installed heating technologies in the LT collective (A+) scenario (right)

***HT collective (-)* scenario**

In order to determine for which districts the optimal option is to be heated by a HT heat network, the *HT collective (-)* scenario is constructed. In this scenario, the HT heat network is expanded to all neighbourhood districts and all buildings are connected to the HT heat network (see Figure 15). The installed capacity of the HT sources is sufficient to fulfil the heat demand, while the composition of the heat sources which feed-in to this network reflect the composition as describe by Eneco's roadmap (see Table 7). In the *HT collective (-)* scenario all buildings are not further insulated and therefore remains in the same condition as in the Baseline (see Figure 15). The natural gas grid is removed, as all individual gas-fired boilers are removed. Furthermore, electricity grid reinforcements are not required, as no heat pumps are installed.

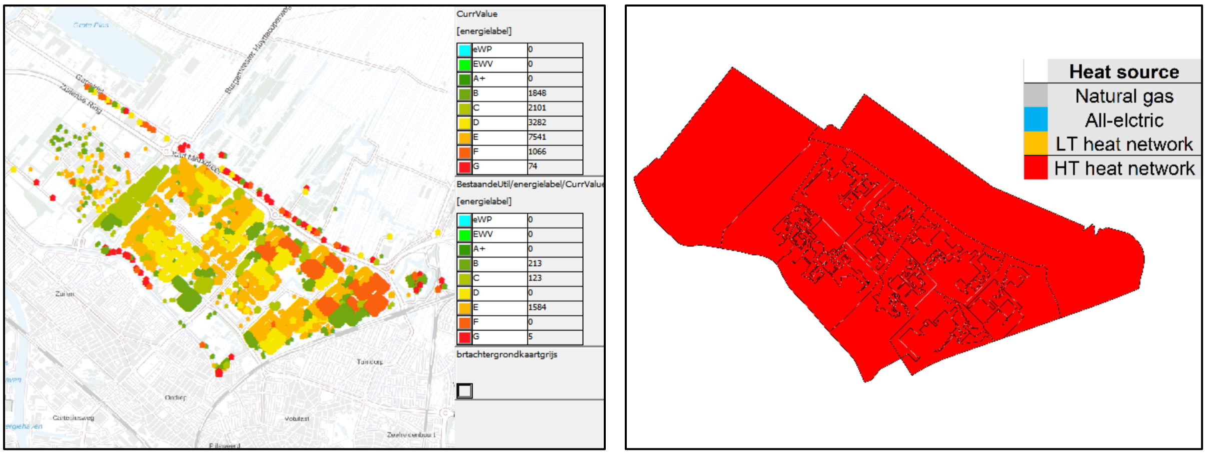

Figure 15: Energy labels of buildings (left) and installed heating technologies in the HT collective (-) scenario (right)

3.2.2 Output parameters

For each of the scenarios the following output parameters are used to compare the different scenarios and their effects, and in turn determine the *Optimal pathway*.

Energy demand
In order to analyse the impact of energy savings measures and the switch to sustainable heating options on the energy demand – and on the heat demand in particular – the energy demand is the first output parameter. Here, a distinction is made between energy from district heating, electricity and natural gas.

- The label 'district heating' demand in the results includes the heat demand of buildings from HT or LT district heating networks, including network losses. As this parameter shows a building-level perspective, natural gas used for the HT heat sources of the district heating network, as well as the electricity consumption of collective heat pumps, are included under 'district heating', as these systems are located at district level and not at building level.
- The energy demand with the label 'electricity' in the results reflects the electricity that is consumed at building-level for the use of appliances (e.g. lighting and electrical equipment) and heat pumps, in case these are present.
- The label 'natural gas' demand in the results reflects the amount of natural gas that is required to heat the buildings with individually gas-fired boilers.

The energy demand of each of these three categories displayed in the results is end-use energy, and not primary energy. Therefore, the electricity demand needs to be converted to primary energy, in case a comparison of this factor is desired. The results of this parameter, as displayed in Section 4.1.1, answer SQ1.

Emissions
In order to establish the impact of the different scenarios on the emissions of the energy system and provide an answer to SQ2, emissions are chosen as second output parameter. Similar to the output parameter of the energy demand, emissions are disaggregated into emissions from district heating, electricity and natural gas. For these parameters, the same building-level perspective applies as for the energy demand described above. The emissions here reflect the emissions that originate from the direct use of technologies and consumption of energy, multiplied by an emission factor. Therefore, emissions that arise from the installation of technologies are not included.

Societal costs
In order to answer SQ3, the societal costs are calculated for each of the scenarios. These costs reflect the costs for society of installing, using and maintaining the energy system in the different scenarios. Therefore, taxes, subsidies and cash flows between actors (e.g. what a consumer pays a heat supplier) are excluded, as these are all redistributions of money and not actual costs for the society as a whole. All investment costs are annualized with a societal discount rate and all costs – investment costs and operation and maintenance (O&M) costs – are presented in Euro2010 to allow comparison. In the results, a distinction is made between the following labels:

- 'District heating' include the societal costs of the O&M of heating technologies (including fuel costs), as well as costs required for network expansion, and the instalment of collective heat pumps, as they are used to upgrade the LT district heating temperature.
- 'Electricity use' displays the costs of consuming electricity at building level.
- 'Electricity grid' shows the costs for operating and maintaining the electricity grid, as well costs for potential grid reinforcements.
- 'Natural gas use' displays the costs of consuming natural gas at building level in individual gas-fired boilers.
- 'Natural gas grid' costs include the operation and maintenance costs, renewal costs and removal costs of the natural gas grid.

- 'Insulation' costs entail the investment costs of building improvements to a higher energy label.
- 'Heat pumps' contain the costs for the instalment and maintenance of individual heat pumps at building level.

For the starting year and for each scenario the energy demand, emissions and societal costs are extracted from *Vesta MAIS* and exported to Excel. From here, the analysis takes place as described in Section 3.3.

3.3 Phase III: Analysis

This phase consists of an analysis of the output parameters and the selection of the *Optimal pathway* in Section 3.3.1, followed by the description of the sensitivity analysis in Section 3.3.2.

3.3.1 Determining the *Optimal pathway*

The *Optimal pathway* represents the pathway with the lowest societal costs to remove Overvecht from the gas grid and sustainably heat the buildings in the neighbourhood. Therefore, for each district the scenario with the lowest societal costs is selected from the calculated scenarios. Here, to reduce emissions, only 'gas-free' scenarios are allowed. Additionally, in this way developments on a higher level can take care of reducing the emission further by decarbonising the electricity and heat grid further. This selection results in the most 'optimal' combination of the different scenarios and forms what is defined in this research as the most *Optimal pathway*, which provides the answer to SQ4. Here, it is possible that certain technologies have constraints in certain areas, such as HCS that is not allowed in areas where drinking water is extracted. These constraints are taken into account by removing this option as input for the *Optimal pathway*. Table 20 show an example for how the *Optimal pathway* is constructed.

Table 20: Example of constructing the optimal pathway from different scenarios

District		**Societal costs**			**Optimal**
	Scenario A	Scenario B	Scenario C		
1	High	Low	Mid	→	Scenario B
2	Mid	High	Low	→	Scenario C
3	Low	Mid	High	→	Scenario A
4	Mid	Low	High	→	Scenario B

Furthermore, energy labels and used heating technologies in the *Baseline* of 2019 and *Optimal pathway* for 2030 are shown in figures to clearly show the impact on the neighbourhood and what measures need to be taken per district in order to reach the objective.

3.3.2 Sensitivity analysis

To determine the robustness of the results a sensitivity analysis is performed. The criteria used to select the input parameters are either a high uncertainty, or the fact that they strongly influence the output. The results of this analysis show the turning point when the optimal heating option identified per district changes when an input parameter is changed, and thereby show the robustness of the identified *Optimal pathway*. For this analysis, the societal discount rate, learning curves and building improvement costs are varied. Additionally, the reason why energy prices are not included in the sensitivity analysis is explained.

Societal discount rate

The societal discount rate has a significant influence on the total annual societal costs, as it discounts investment costs to annual societal costs. The discount rate that is used depends on the type of actor by which the investments are done (CE Delft, 2017). For societal investments, a standard discount rate of 4% is used by Vesta MAIS, while for end-users generally a discount rate of 6% is used (PBL, 2019). This is done as investments for society are considered to have a lower risk and costs of capital. However, as the investments eventually need to be paid by end-users, an increase in discount rate may be possible (Knobloch et al., 2019). Therefore, in the sensitivity analysis, the societal discount rate is increased from the standard 4%, to 5% and 6%, to establish its effect on the *Optimal pathway*.

Energy prices

As a large part of the societal costs in the future scenarios consist of expenditures for energy consumption, the energy prices are of great importance for the *Optimal pathway*. Especially the Dutch natural gas prices are uncertain for the future, as the gas fields in Groningen are closing down and the country has started a transition to a natural gas-free society (Sectortafel Gebouwde omgeving, 2018). Therefore, the investigation of the effect of varying natural gas prices is desirable for the sensitivity analysis.

However, because of the modelling approach used in this research to address the developments of Eneco's district heating in Vesta MAIS, varying the natural gas price affects the HT heat network price more than it should. A completely different modelling approach has to be used to allow a sensitivity analysis of natural gas prices. Therefore, natural gas prices are not included in this analysis.

Learning curves

The future development of investment costs of heating options have a large impact on the total costs of the heat transition. As the actual path of the development of these costs are also uncertain (e.g. it is uncertain when a technological development is made which will decrease for instance the amount of labour required to produce a heat pump), the influence of different extend of costs development is examined. For the sensitivity analysis, the learning curves are varied to both the minimum and the maximum values, as depicted in Table 17. In the results the minimum learning effect is displayed as ‘0’, while the maximum learning effect is displayed as ‘1’. The learning effects ‘0.25’, ‘0.5’ (standard) and ‘0.75’ represent a learning effect between the minimum and maximum learning effect, based on a linear trend. For example, the standard learning effect of ‘0.5’ equals the average learning effect between the minimum and the maximum. Additionally, in the sensitivity analysis the learning curves are turned off, to display the *Optimal pathway* against current prices, as it is also possible that technologies will not reduce in costs due to the limited time horizon up to 2030.

Building improvement costs

For the costs of building improvements, Vesta MAIS uses general costs as displayed by Table 9 and Table 10**,** ranging from minimum to maximum costs. In the standard configuration, Vesta MAIS uses the average between the minimum and maximum. It may be possible that actual costs to improve buildings may be higher, for instance when difficulties arise during renovation (e.g. limited accessibility to walls or roofs for applying extra insulation due to the way it is built), or lower, when for example a whole street can be insulated at the same time to benefit from a project approach. As these costs are specific to a building and Vesta MAIS uses a general approach to these costs, these costs are relatively uncertain. Therefore, in the sensitivity analysis, the building improvement costs are varied between the minimum and maximum as displayed by Table 9 and Table 10. Similar to the learning effects, the building improvement costs with label ‘0.25’, ‘0.5’ (standard) and ‘0.75’ represent the costs between the minimum and maximum, based on a linear trend. For example, ‘0.25’ entails the minimum costs plus 0.25 times the difference between the minimum and the maximum building improvement costs.

4. Results

This chapter presents the results following from the methodology of this research.

4.1 Scenario outputs

This section respectively shows the results of the energy demand, emissions and societal costs for the different scenarios. All the neighbourhood districts are aggregated and the total results for Overvecht are shown in Figure 16, Figure 17 and Figure 18. In these figures the characteristics of the *Optimal pathway* are also included to allow comparison with the other scenarios. However, the *Optimal pathway* itself is discussed in Section 4.2. More detailed results can be found in Appendices A-H, which contain data tables with the results for each scenario disaggregated to neighbourhood districts.

4.1.1 Energy demand

Figure 16 shows the energy demand of the different scenarios. In the starting situation (*Baseline*) approximately 33% (282 TJ/year) of the energy demand is supplied by district heating, while 26% (223 TJ/year) is supplied by electricity and 41% (349 TJ/year) by natural gas. In total, this accumulates to an energy use of 854 TJ per year. In the following paragraphs, first the energy demand of the *Reference* is compared to the *Baseline*, followed by the comparison of the other scenarios to the *Reference*.

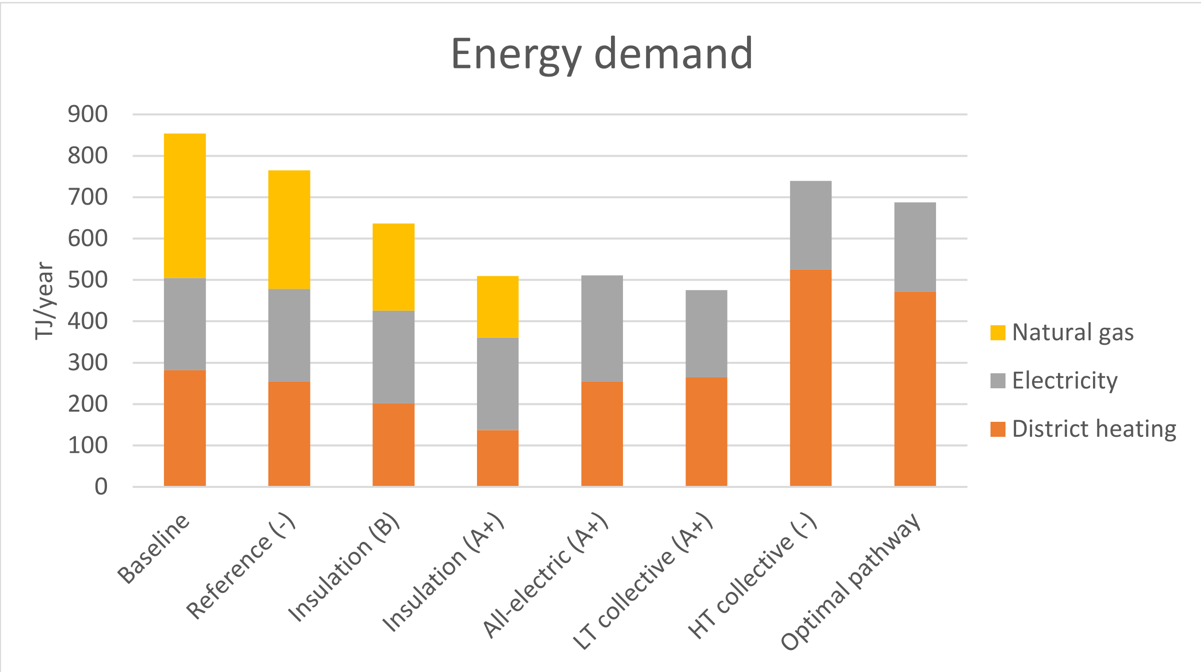

Figure 16: Overview of energy demands in the different scenarios

In the *Reference (-)* a decline of 10% compared to the *Baseline* of the total energy demand can be seen, which is caused by the warming of the climate. This is explained by progressively warmer winters in the studied period, where less heat is required to keep the buildings at a comfortable temperature and therefore the heat demand decreases. However, as this only reduces the heat demand, the electricity demand remains the same.

In the *Insulation (B)* scenario the total energy demand decreases by 17% compared to the *Reference*. Here, the upgrading of the energy labels to label B reduces the heat demand for both buildings connected to the natural gas grid as well as the HT heat network, while electricity demand remains the same. The *Insulation (A+)* scenario achieves nearly double the reduction of the *Insulation (B)* scenario, with a 33% decrease in energy demand compared to the *Reference*.

The *All-electric (A+)* scenario shows the same district heating demand as the *Reference (-)* as the buildings that are connected to the existing HT heat network are not further insulated. Electricity demand in this scenario increases by 15%. This is because all the buildings that currently do not use district heating will start using electricity for heating via air-based heat pumps. The heating demand for these buildings sharply decreases in compared to the *Reference (-)* due to the strong insulation up to energy label A+, and the fact that considered heat pumps supply heat with a COP of 4. This means that the natural gas demand for buildings with the same amount of insulation can be heated with a quarter of this amount in electricity. In total, the *All-electric (A+)* scenario shows a 33% decrease in energy demand compared to the *Reference*, which is roughly the same reduction that can be achieved through insulating all buildings to energy label A+.

Similar to *All-electric (A+)*, the *LT collective (A+)* scenario shows a strong reduction (38%) in energy demand compared to the *Reference*, since here all buildings are insulated to energy label A+. While this scenario has the same amount of HT district heating demand as *Insulation (A+)*, a large share of LT district heating is implemented. Furthermore, the electricity demand remains similar, as the output parameter displays the electricity demand at building level. Therefore, the electricity demand of the collective heat pumps is included in the energy demand for district heating.

The *HT collective (-)* scenario shows roughly the same total energy demand as the *Reference (-)*, as buildings are not further insulated. The natural gas demand is replaced by the expansion of the district heating demand. However, as district heating delivers the heat demand more efficiently than individual gas-fired boilers, a small decrease in energy demand is achieved.

4.1.2 Emissions

The emissions of the different scenarios are displayed in Figure 17. In the starting situation (*Baseline*) approximately 25% of the 61 kt CO_2/year emissions originate from district heating, while 46% is from electricity and 29% by natural gas use. Here, it can be seen that the emissions from the district heating and individual gas-fired boilers are proportionate to their energy demands, as they have a similar emission factor in the starting year. The electricity emissions are relatively high due to the current fuel mix of the Dutch electricity sector and resulting high emission factor in the starting year, as described in Section 3.1.2.4.

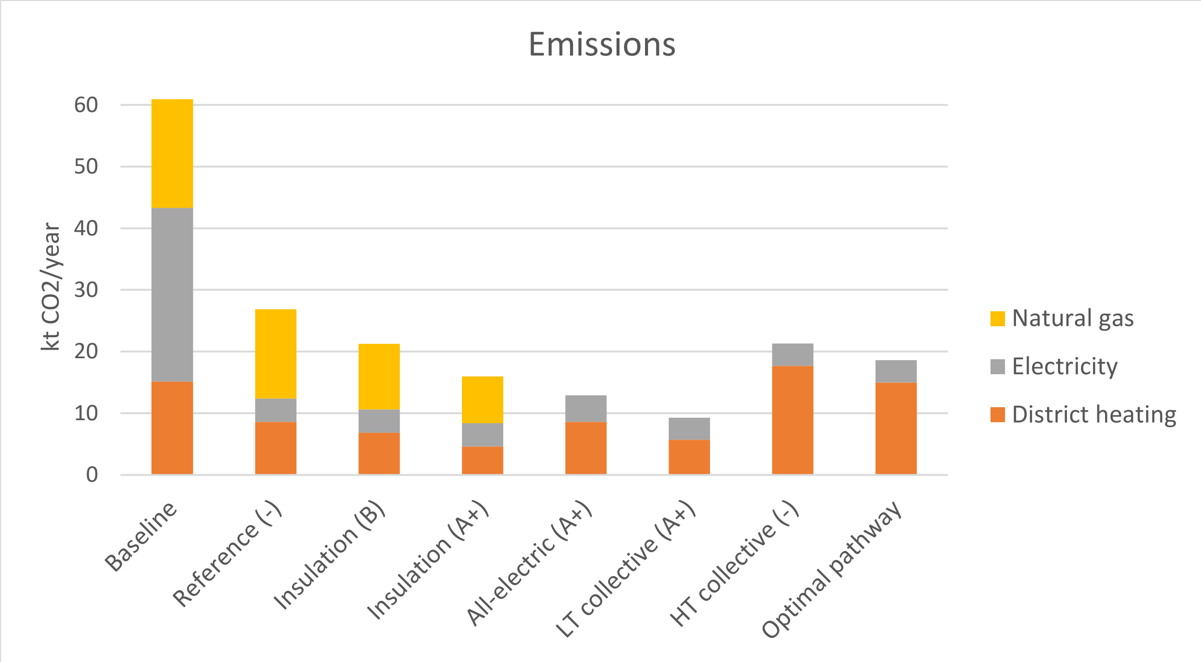

Figure 17: Overview of emissions in the different scenarios

In the *Reference (-)* scenario a 56% decline to 27 kt CO_2/year can be seen in the total emissions, due to several developments. First of all, the lower energy demand due to the warming of the climate also reduces the emissions accordingly, as less energy has to be produced. Secondly, the considered sustainable energy developments in the Dutch electricity mix, including shutting down coal-fired power plants and installing significantly more renewable power capacity, greatly reduces the emission factor of electricity, leading to a 86% reduction in electricity emissions. Thirdly, the emission from the HT district heating network decline by 43%, as a result of the decarbonisation of the district heating network by Eneco. However, the emissions related to the focus area of this research – achieving locally gas-free buildings with sustainable heating technologies – remain high, as natural gas emission account for 54% of the total emissions in the *Reference (-)* scenario. Therefore, a major share of the challenge to decarbonise the heat supply remains, for which the scenarios provide possible pathways.

In the *Insulation* scenarios a similar effect can be seen as in the *Reference (-)* scenario, with a higher decline in heat-related emissions due to the reduction of the energy demand as consequence of insulation measures. As a result, the total emissions of the *Insulation (B)* and *Insulation (A+)* scenarios decline by 21% and 41% respectively, compared to the *Reference (-)* scenario.

The *All-electric (A+)* scenario shows a 52% reduction compared to the *Reference (-)* scenario. Here, it should be noted that the district heating emissions are the same as in the *Reference (-)* scenario, as the district heating energy demand is equal and the buildings with HT heating are not further insulated. The emissions from electricity increase by 15% due to the increase in electricity demand caused by the instalments of heat pumps to replace individual gas-fired boilers, while having the same emission factor as in the *Reference (-)* scenario.

Similar to *All-electric (A+)*, the *LT collective (A+)* scenario displays a strong decline in emissions due to the reduced heat demand due to the insulation of buildings. However, with a 66% decrease compared to the *Reference (-)* scenario, the effect is stronger as in this scenario all buildings are upgraded to energy label A+, including the buildings connected to a HT heat network. Furthermore, it can be seen that the emissions from LT district heating only account for a small share of the emissions, as there is only a 23% increase in district heating emissions compared to the *Insulation (A+*) scenario, which represents the heating emissions of all building connected to the existing HT heat network. This is caused by the fact that the LT heat network has a much lower emission factor than the HT heat network. The electricity emissions are similar to the *Reference (-)* scenario, as the emissions of the electricity required to operate the collective heat pumps are included under district heating here.

The *HT collective (-)* scenario shows relatively high emissions compared to the other 'gas-free' alternatives, due to the fact that there are no insulation measures installed. A 21% decrease of total emissions compared to the *Reference (-)* scenario can be achieved through this scenario, due to the fact that natural gas demand for individual boilers is replaced by HT district heating, which has a lower emission factor. However, the HT district heating emissions double compared to the *Reference (-)* scenario due to the expansion of the HT heat network to all buildings, while electricity emissions are similar.

4.1.3 Societal costs

In Figure 18, the societal costs of the different scenarios can be seen. In the starting situation (*Baseline*) 69% of the 21.0 M€/year costs are associated with the consumption of energy (i.e. district heating 32%, electricity 17% and natural gas 20%). The other 31% of the costs are associated with maintaining the electricity (23%) and natural gas grid (8%), of which the electricity grid costs are much higher.

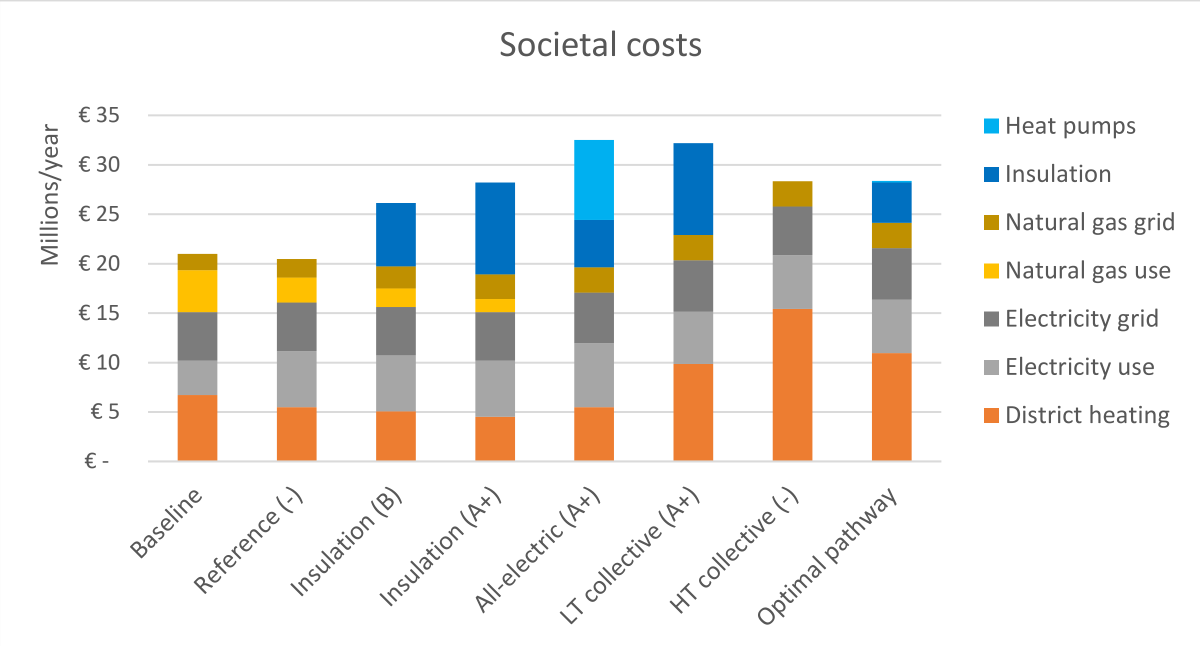

Figure 18: Overview of societal costs in the different scenarios

In the *Reference (-)* scenario the heat related (i.e. district heating and natural gas use) costs decline by 27% due to the warming of the climate, and the decrease of the natural gas price. On the other hand, the electricity costs increase by 62% as a result from the increasing electricity prices to 2030. Furthermore, the electricity grid costs remain the same, while the natural gas grid costs increase by 12% due the fact that part of the natural gas grid needs to be replaced in Overvecht-Noord. In total, these developments lead to a 3% decrease of societal costs compared to the *Baseline*.

In the *Insulation (B)* and *Insulation (A+)* scenarios the same developments as for the *Reference (-)* scenario occur. However, the addition of the large share of insulation costs lead to an increase of 28% and 38% for the total costs of the *Insulation (B)* and *Insulation (A+)* scenario, respectively. Here, it should be noted that insulation costs for an building upgrade to energy label A+ are 45% more expensive than for an upgrade to energy label B, while this reduces double (i.e. 100% more) of the energy demand and emissions than an upgrade to label B. Additionally, an upgrade to energy label A+ reduces operational costs by 1.5 M€/year compared to the *Reference (-)* scenario, while an upgrade to energy label B does this by 0.75 M€/year.

In the *All-electric (A+)* scenario the district heating costs are equal to the *Reference (-)*, as the buildings with an existing HT heat network connection remain the same. The costs for electricity use increase by 14% due to the added electricity consumption of the installed heat pumps at individual level. With 8.1 M€/year, the heat pumps themselves account for the largest share of the costs of the *All-electric (A+)* scenario, while the required insulation of these building also makes up a significant share with 4.8 M€/year. The costs for the electricity grid increase by 5% due to required reinforcements. The cost for the natural gas grid also increase by 37% due to the fact that the whole network needs to be removed. In total, this scenario shows a 59% increase of societal costs compared to the *Reference (-)* scenario.

The *LT collective (A+)* scenario shows a near to doubling (+79%) of district heating costs compared to the *Reference (-)* scenario. This is caused by the instalment of LT heat networks with HCS systems and collective heat pumps (note: due aggregation of the Vesta MAIS model all these factors are included under district heating costs). For the same reason, the electricity costs remain similar. The largest added cost in the LT collective scenario is caused by insulating all buildings to label A+, for which 9.3 M€/year is needed. Similar to the *All-electric (A+)* scenario, the electricity grid costs are a little higher (+6%) due the need of grid reinforcements to account for the collective heat pumps. The natural gas grid costs are equal to the *All-electric (A+)* scenario, as in this case the whole gas infrastructure is also removed. Combined, these characteristics show a 57% increase of societal costs for this scenario compared to the *Reference (-) scenario*.

With an total increase of 38% compared to the *Reference (-)* scenario, the *HT collective (-)* scenario shows relatively low total costs due to the fact that only the HT heat network is expanded, and no extra insulation is installed. However, by comparing the *HT collective (-)* and the *LT collective (A+)* scenario, it can be seen that LT heat networks are less costly to install and operate (see share of orange bar). Natural gas grid costs are the same as for the *All-electric (A+)* scenario, as the grid is completely removed, while electricity grid costs are 5% lower as no reinforcements are required. Electricity costs are similar to the *Reference (-) scenario*, as no electrical equipment such as heat pumps are installed.

4.2 Optimal pathway 2030

From the figures in the previous section, Figure 16 shows that in the *Optimal pathway* 69% of the remaining 687 TJ/year energy demand is supplied by a heat network and 31% by electricity. Here, it can be seen that while this pathway is identified to be the most optimal in economic sense, it does not have lowest energy demand and shows only a 10% decrease compared to the *Reference (-)* scenario. Similarly, Figure 17 displays the emissions of the *Optimal pathway*, where 80% originates from district heating and 20% is from electricity production. Here, the 31% decline of emissions compared to the *Reference (-)* scenario is only larger than the *Insulation (B)* and *HT collective (-)* scenarios, while the other scenarios display higher reductions. This clearly shows that the selection of an optimal pathway strongly depends on what is defined as ‘optimal’, as for instance the *LT collective (A+)* scenario would be the *Optimal pathway* in case the largest emission or energy demand reductions were defined as ‘optimal’. Furthermore, of the societal costs in the *Optimal pathway,* 39% originates from district heating, 19% from electricity use, 18% from the electricity grid, 9% to remove the natural gas grid, 14% for insulation and 1% for heat pumps, as displayed by Figure 18. Here, it can be seen that the *Optimal pathway* has the lowest societal costs of the ‘gas-free’ scenarios, but that the

Insulation (A+) scenario has lower costs, while achieving a larger emission reduction (see Figure 17). Therefore, the importance of the definition of the 'optimal' should be kept in mind while assessing optimal pathways, as it strongly influences the outcome of an analysis.

The *Optimal pathway* for 2030 of this study consists of a mix of different heating options. Figure 19 and Figure 20 show that for one district *All-electric* is the optimal option, for 3 districts a LT heat network is the optimal option and for 14 districts a HT heat network without insulation measures is the optimal option (of which 8 districts already had a HT heat network). It can be seen that for none of the districts, it is financially attractive to insulate the buildings when HT heat is applied. In total, the societal costs for the most optimal pathway are 28,216,439 €/year. Appendix H provides all the results per district for the *Optimal pathway*, including a disaggregation of the various components of the costs.

'Optimal' final image 2030					All-electric (A+) Societal costs Euro2010/year	LT collective (A+) Societal costs Euro2010/year	HT collective (-) Societal costs Euro2010/year		Optimal pathway Societal costs Euro2010/year		Optimal pathway Scenario
id	Neighbourhood district	Residences	Utility	Existing HT-DH?							
0	'Taag- en Rubicondreef en omgeving'	895	336	No	€ 2,832,707	€ 2,355,680	€ 2,259,105	>	€ 2,259,105	=	HT collective (-)
1	'Wolga- en Donaudreef en omgeving'	1305	14	Yes	€ 1,410,047	€ 1,782,193	€ 1,389,893	>	€ 1,389,893	=	HT collective (-)
2	'Zamenhofdreef en omgeving'	294	258	No	€ 1,302,271	€ 1,111,917	€ 1,083,582	>	€ 1,083,582	=	HT collective (-)
3	'Neckardreef en omgeving'	697	229	No	€ 2,196,397	€ 1,805,722	€ 1,808,490	>	€ 1,805,722	=	LT collective (A+)
4	'Vechtzoom-zuid'	1190	155	No	€ 3,089,535	€ 2,451,050	€ 2,448,768	>	€ 2,448,768	=	HT collective (-)
5	'Bedrijventerrein en omgeving'	41	125	No	€ 2,074,782	€ 1,985,362	€ 1,796,033	>	€ 1,796,033	=	HT collective (-)
6	'Zambesidreef en omgeving'	763	188	No	€ 2,093,242	€ 1,682,804	€ 1,715,741	>	€ 1,682,804	=	LT collective (A+)
7	'Tigrisdreef en omgeving'	1000	172	No	€ 2,589,647	€ 2,074,304	€ 2,064,461	>	€ 2,064,461	=	HT collective (-)
8	'Poldergebied Overvecht'	93	16	No	€ 573,151	€ 514,253	€ 579,376	>	€ 573,151	=	All-electric (A+)
9	'Taag- en Rubicondreef en omgeving'	1099	24	Yes	€ 1,535,218	€ 2,096,774	€ 1,514,123	>	€ 1,514,123	=	HT collective (-)
10	'Vechtzoom-noord, Klopvaart'	238	1	Yes	€ 314,400	€ 414,499	€ 307,555	>	€ 307,555	=	HT collective (-)
11	'Tigrisdreef en omgeving'	910	7	Yes	€ 975,741	€ 1,321,961	€ 960,349	>	€ 960,349	=	HT collective (-)
12	'Zambesidreef en omgeving'	1456	23	Yes	€ 1,534,726	€ 2,071,561	€ 1,516,230	>	€ 1,516,230	=	HT collective (-)
13	'Neckardreef en omgeving'	1323	33	Yes	€ 1,588,295	€ 2,160,515	€ 1,565,054	>	€ 1,565,054	=	HT collective (-)
14	'Zamenhofdreef en omgeving'	1172	92	Yes	€ 1,471,438	€ 1,972,326	€ 1,453,003	>	€ 1,453,003	=	HT collective (-)
15	'Wolga- en Donaudreef en omgeving'	857	68	No	€ 2,238,193	€ 1,772,366	€ 1,851,317	>	€ 1,772,366	=	LT collective (A+)
16	'Vechtzoom-noord, Klopvaart'	1242	148	No	€ 3,162,643	€ 2,522,719	€ 2,499,010	>	€ 2,499,010	=	HT collective (-)
17	'Vechtzoom-zuid'	1309	36	Yes	€ 1,541,345	€ 2,095,794	€ 1,525,230	>	€ 1,525,230	=	HT collective (-)
	Total Overvecht	15884	1925		€ 32,523,777	€ 32,191,800	€ 28,337,320		**€ 28,216,439**		

Figure 19: Selection of Optimal pathway per neighbourhood district. Here, the yellow highlighting represents the lowest societal costs options, which are selected and combined into one highlighted yellow column to display the optimal pathway. In the far right column, in red, orange and blue is the identification of the most optimal pathway depending on the heat technology chosen.

Figure 20 provides an overview of the heating technologies in the *Baseline* and the *Optimal pathway*. Here, it can be seen that the *Optimal pathway* means that the existing HT heat network will need to be expanded to the business area and to 5 residential districts (displayed in red), the buildings in the polder area will be heated by individual heat pumps (displayed in blue), and the buildings in 3 of the residential districts that did not originally have a connection to the HT heat network (displayed in grey) will be heated by a LT heat network (displayed in orange). The LT heat source will in this case be located somewhere in the orange area, but this is not specified by Vesta MAIS.

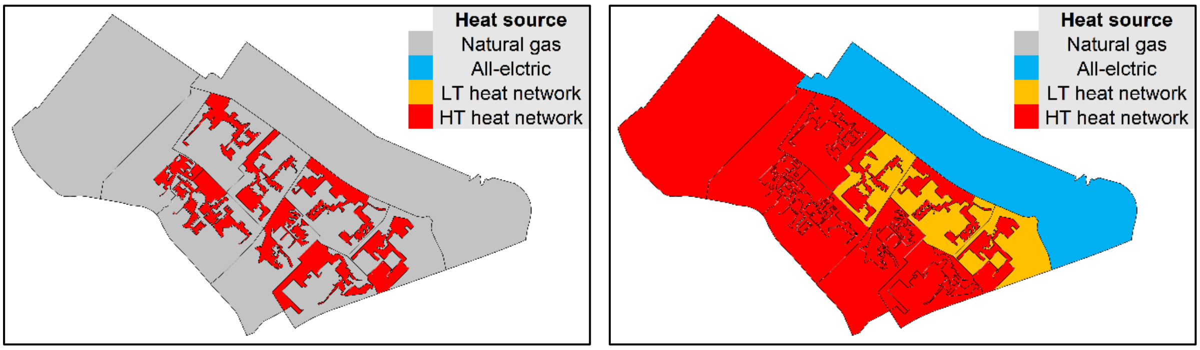

Figure 20: Installed heating technologies in the Baseline scenario (left) and Optimal pathway (right)

Additionally, the *Optimal pathway* requires the insulation of the polder area, and the 3 residential districts that will have a LT heat network, to energy label A+ to account for the LT heat supply. The 8 residential districts with an existing HT heat network connection, the business area and the 5 district that will have a HT heat network in the *Optimal pathway* do not require building improvements to a higher energy label, neither to change the original heating distribution system (e.g. HT radiators). Figure 21 provides an overview of the energy labels in the *Baseline* and the *Optimal pathway*.

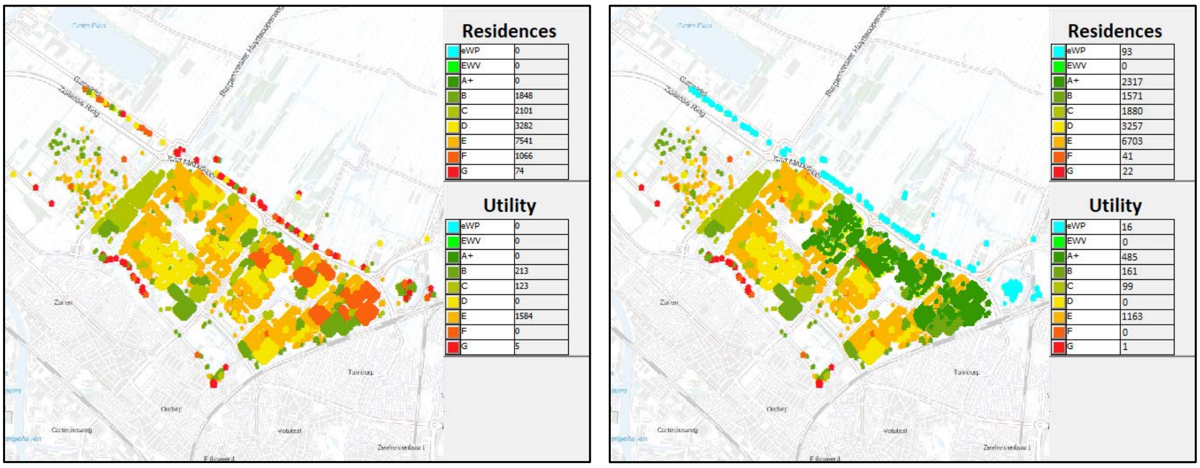

Figure 21: Energy labels of buildings in the Baseline (left) and the 'Optimal' pathway (right)

Here, combined with the results displayed in Figure 20, it can be seen that All-electric is only interesting in areas with a low heat demand density (e.g. an area with many detached and duplex houses), as this technology is only applied along the inhabited dike in the polder area. Also, it can be seen that LT heat networks are more attractive when the energy labels are very low, because the figure for instance shows many F labels (dark orange) changing to A+ (dark green) for transition to a LT heat network. Finally, the combination of the figures shows that a HT heat network is most attractive in areas with a high heat demand density (e.g. an area with many apartments) and medium energy labels (C to E).

4.3 Sensitivity analysis

This section presents the results of the sensitivity analysis that was executed to analyse the impact of changing some of the variables. First, the impact of a higher interest rate is analysed. Furthermore, the influence of varying learning curves and building improvement costs were investigated.

4.3.1 Societal discount rate

Figure 22 shows the *Optimal pathway* for a societal discount rate of 4% (standard), 5% and 6%. Here, it can be seen that the number of neighbourhoods which have the *LT collective (A+)* scenario as optimal decreases when the societal discount rate increases (displayed in orange). In turn, the *HT collective (-)* scenario becomes the most optimal for these neighbourhoods (see Appendix I to see which). This is because a higher interest rate will results in higher annual investment costs due to a larger interest payment. As the discount rate is used to distribute the investment over the total lifetime of a technology, it does not affect the yearly variable costs such as fuel or operation and maintenance costs. As the *LT collective (A+)* and *All-electric (A+)* scenarios rely more on large investments – such as insulation measures and (collective) heat pumps – their total costs increase more compared to the *HT collective (-)* scenario which has higher operational costs, but has lower investment costs. However, even with a societal discount rate of 6%, the *All-electric (A+)* scenario remains the most optimal option in the polder area. This is because the financial attractiveness of the *HT collective (-)* scenario in the polder area remains low due to a very low heat demand density.

Appendix I shows the optimal pathways and societal costs per neighbourhood district for the different societal discount rates.

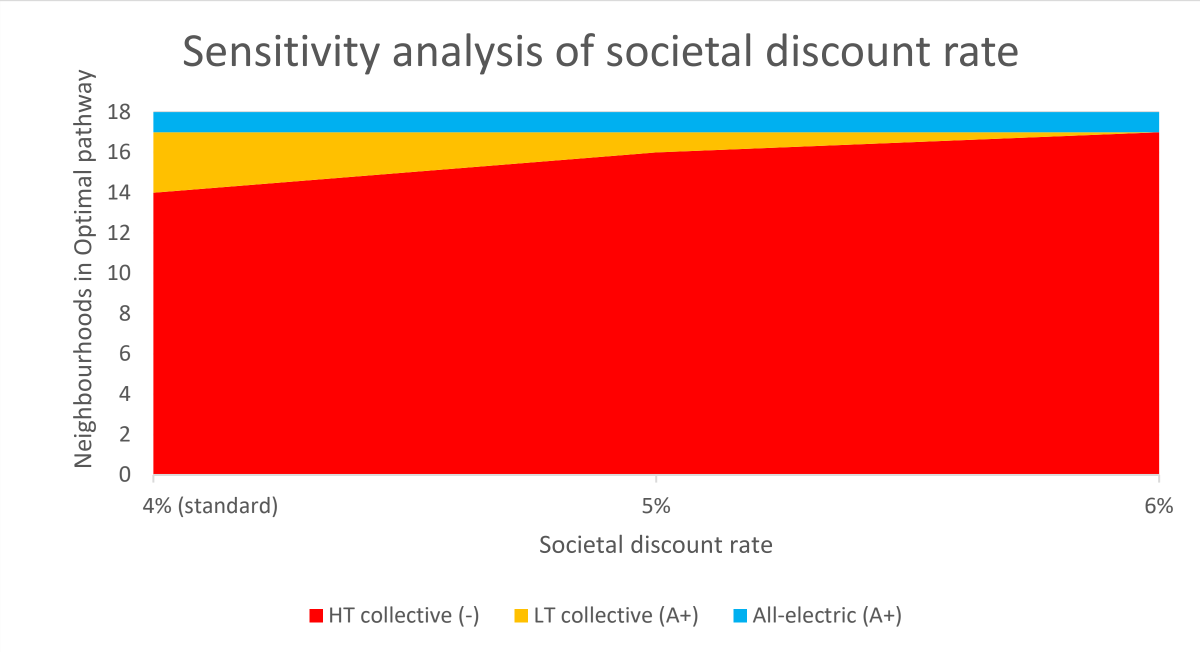

Figure 22: Sensitivity of the optimal pathway by varying the societal discount rate

The *Optimal pathway* is very robust for 15 of the 18 districts, as the optimal outcome for these districts does not change when the societal discount rate increases. However, the *Optimal pathway* is less robust for the districts 'Neckardreef en omgeving', 'Zambesidreef en omgeving' and 'Wolga- en Donaudreef en omgeving' without an original HT heat network, as they favour a HT heat network instead of an LT heat network when the societal discount rate is increased (see Appendix I).

4.3.2 Learning curves

The effect of changing the learning curves in *Vesta MAIS* on the *Optimal pathway* is displayed in Figure 23 . The figure shows that when the learning effect increases, the number of neighbourhoods with the *LT collective (A+)* scenario as optimal pathway increases. Vice versa is also true, as the share of the *LT collective (A+)* scenario in the *Optimal pathway* becomes smaller when the learning effect is less. This is caused by the fact that the *LT collective (A+)* scenario requires more investments (e.g. costs of building improvements such as retrofitting measures and collective heat pumps) compared to the *HT collective (-)* scenario. As a result, these high investment costs are expected to decline more following a fixed curve than technologies with lower required investments, which leads to more significant changes in case the learning effect is varied. This assumed decline is caused by the assumption that costs of materials and labour will decline following a fixed pattern. For the same reason, the share of *All-electric (A+)* decreases to zero in case of a minimal learning effect, as in this case the large investment for All-electric heating decrease less. When the learning effect is increased, the share of All-electric heating does not increase, as the high heat demand density of the districts still results in lower costs for a collective heating network option (see Appendix J). Furthermore, it can be seen that – based on learning curves – currently it is more attractive to install HT heat networks for 17 of the 18 districts, as installing heating technologies in the present day corresponds to not having a learning effect, as it takes time for developments to decrease costs of technologies. Likewise, further in the future it can be seen that LT heat networks become more interesting, as this corresponds to a stronger learning effect.

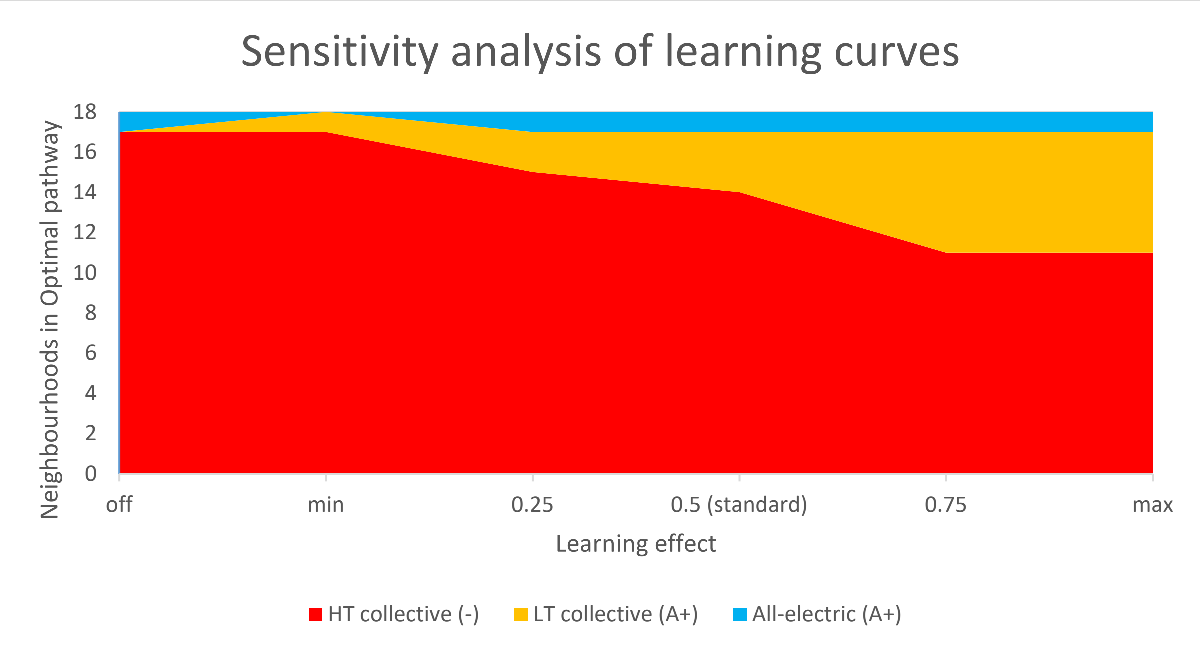

Figure 23: Sensitivity of the optimal pathway by varying the learning curves

The *Optimal pathway* is very robust for 11 of the 18 districts, as the optimal outcome for these districts does not change when the building improvement costs are varied. However, the *Optimal pathway* is less robust for the districts 'Neckardreef en omgeving', 'Vechtzoom-zuid', 'Zambesidreef en omgeving', 'Tigrisdreef en omgeving', 'Poldergebied Overvecht', 'Wolga- en Donaudreef en omgeving' and 'Vechtzoom-noord, Klopvaart' without an original HT heat network (see Appendix J). When the learning effect is stronger than standard (i.e. 0.75 or higher), the optimal scenario for the districts 'Vechtzoom-zuid', 'Tigrisdreef en omgeving' and 'Vechtzoom-noord, Klopvaart' without an original HT heat network, changes from *HT collective (-)* to *LT collective (A+)*.

On the contrary, a weaker learning effect shows a change from *LT collective (A+)* to *HT collective (-)* as optimal scenario for the districts 'Neckardreef en omgeving' (at a learning effect of 0.25), 'Zambesidreef en omgeving' (at a minimum learning effect) and 'Wolga- en Donaudreef en omgeving' (at no learning effect). The *Optimal pathway* of the districts that point out a different optimal scenario than in the reference situation at a relatively small change (e.g. 0.25 or 0.75) are less robust than the *Optimal pathway* of districts that have a different optimal scenario at a relatively large change (e.g. min, max or even no learning effect). This means that for example the optimal pathway for the district 'Wolga- en Donaudreef en omgeving' is more robust than for the district 'Neckardreef en omgeving'.

Finally, it can be seen that the optimal pathway for the district 'Poldergebied Overvecht' only changes from *All-electric (A+)* to *HT collective (-)* in case of a minimal learning effect. This is causes by the fact that, with a minimal learning effect, the costs for a HT heat network decrease more than the costs for All-electric. An overview of the *Optimal pathways* and societal costs per neighbourhood district for the different learning effects can be found in Appendix J.

4.3.3 Building improvement costs

Varying the building improvement costs in *Vesta MAIS* leads to a change in the *Optimal pathway*, as displayed by Figure 24. Here, it can be seen that the share of *LT collective (A+)* in the *Optimal pathway* increases at the expense of the *HT collective (-)* share for a reduction in building improvement costs (towards the minimum). Vice versa, but to a lesser extend this is true in case of increasing building improvement costs. This is causes by the fact that the *LT collective (A+)* and *All-electric (A+)* scenarios have large building improvement costs due to the high level of insulation required for LT heating, whereas the *HT collective (-)* scenario does not, as it does not require building improvements. The share of All-electric heating remains the same for all examined building improvement costs, as the high heat demand density in many of the districts favour collective heating by a HT or LT heat network in economic terms.

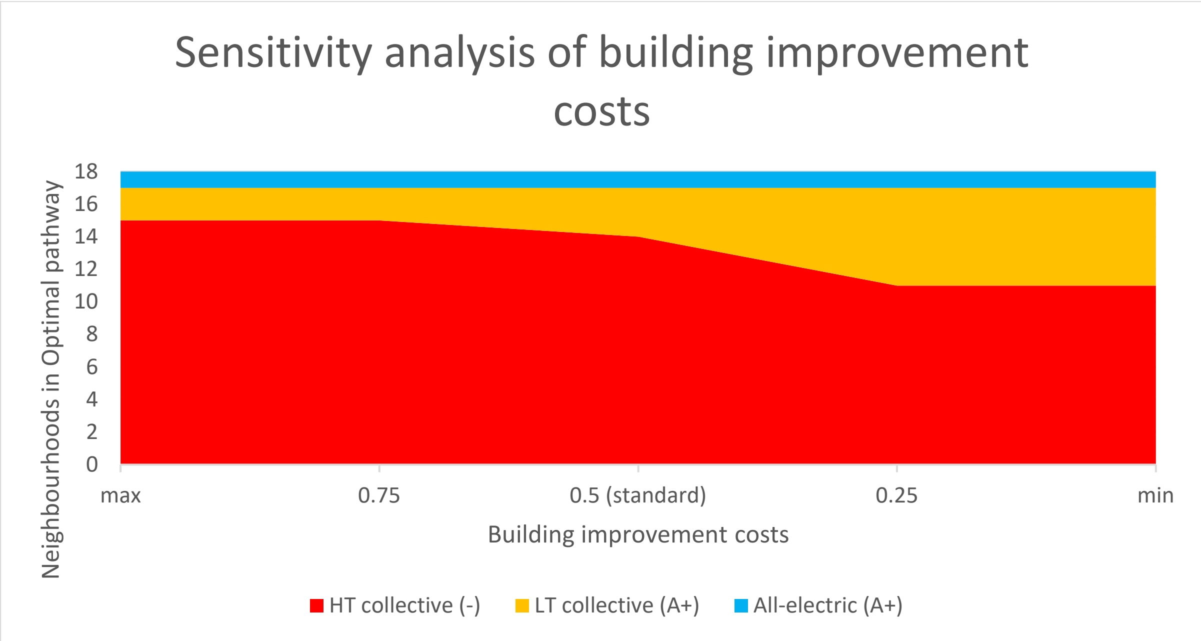

Figure 24: Sensitivity of the optimal pathway by varying building improvement costs. Here, '0.5' equals the average between the minimum and maximum building improvement costs as displayed by Table 9 and Table 10. Likewise, '0.75' equals the average between the maximum and the average of the building improvement costs, and '0.25' equals the average between the minimum and the average of the building improvement costs.

The *Optimal pathway* is very robust for 14 of the 18 districts, as the optimal outcome for these districts does not change when the building improvement costs are varied. However, the *Optimal pathway* is less robust for the districts 'Neckardreef en omgeving', 'Vechtzoom-zuid', 'Tigrisdreef en omgeving' and 'Vechtzoom-noord, Klopvaart' without an original HT heat network (see Appendix K). When the building improvement costs are increased the optimal scenario for the district 'Neckardreef en omgeving', without an original HT heat network, changes from *LT collective (A+)* to *HT collective (-)*. On the contrary, the optimal scenario changes from *HT collective (-)* to *LT collective (A+)* for the districts 'Vechtzoom-zuid', 'Tigrisdreef en omgeving' and 'Vechtzoom-noord, Klopvaart' without an original HT heat network, when the building improvement cost are decreased, as the costs for the building upgrade to energy label A+ required for a LT heat network decline, while the costs for implementing a HT heat network remain constant. Appendix K shows the *Optimal pathways* and societal costs per neighbourhood district for the different building improvement costs.

5. Discussion

This chapter focuses on discussing the implications of the results of this analysis and the applicability of *Vesta MAIS* for an analysis at neighbourhood-level. Furthermore, the limitations of Vesta MAIS and the applied method of this research are discussed as well as recommendations for future research.

Note that for a better understanding of the results, some points of discussion are already incorporated in the results in Chapter 4.

5.1 Scientific implications

This research extends current theoretical insights, and adds to scientific literature through the developed methodology, as well as with the produced results. Additionally, with this research the ability of Vesta MAIS to perform a neighbourhood-level analysis is established, which fills a gap in literature.

Contributions of developed methodology to scientific literature

To start with, the methodology developed for this research adds to existing methodologies in two ways. First of all, due to the simplification in the standard configuration of *Vesta MAIS* regarding the presence of HT heat network in a district, the model could produce reliable results for only 2 of the 10 standard districts of Overvecht as is shown in Section 3.1.2.2. To address this issue, this study developed a method to increase the applicability of *Vesta MAIS* to neighbourhoods with existing HT district heating, by dividing the standard CBS districts into two sections (based on where HT district heating is present or not) to depict a more accurate picture of the starting situation when an existing HT district heating network is present in the neighbourhood. It is greatly advised to incorporate this or a method with the same effect into analyses of neighbourhoods that have currently district heating, as it greatly increases the reliability of the results. However, the required alterations to the model to achieve this are time intensive. Although this is a known problem, the next Vesta MAIS version (3.4) is not yet able to address this issue (van den Wijngaart, 2019).

Secondly, this research developed an alternative approach to the development of scenarios and determination of an optimal pathway. Previous PBL studies use different rankings of technological preferences to form scenarios (see for example (van der Molen et al., 2018)). These scenarios are fed-in to *Vesta MAIS* and the scenario with the lowest societal costs represents the optimal pathway. On the contrary, this research developed scenarios which contain one dominant technology, and from these scenarios the districts are selected that have the lowest societal costs, which together form the optimal pathway. While the method of previous PBL studies is more elegant, as it does not require the manual selection of the optimal pathway from scenarios, the method of this study facilitated the assessment of all possible combinations of technological options per district. However, due to the required manual selection of the optimal pathway from the different scenarios, this method is more time consuming.

Contributions of produced results to scientific literature

Furthermore, this research adds to the following findings to existing theory. First of all, this research has found that All-electric is only interesting in areas with a low heat demand density. However, it is identified to be a very robust option for districts with this characteristic, as it remains the optimal option for all, except one (for a minimal learning effect), variations in the sensitivity analysis.

Secondly, it is found that LT heat networks are the most economically interesting heating technology for buildings with low energy labels (E or lower), as long as it is in an area with a high heat demand density. This is due to the fact that currently no buildings are present in Overvecht with energy label A+, which also are economically interesting to heat with LT heat. Therefore, insulation measures are always required in this analysis before a building can be connected to a LT heat network. As HT heating does not require further insulation, this option is often more financially attractive. However, for buildings with very low energy labels (E or lower) the operational heating costs become very high, as they are poorly insulated and therefore have a high heat demand. As a result, these buildings are very expensive to heat without further insulating them. Therefore, for these buildings it is interesting to insulate the building. This analysis shows that when building in areas with a high heat demand density are poorly insulated (energy label E or lower), it is economically more interesting to insulate them very well to energy label A+, than to not insulate the building and install a HT heating network. However, the robustness of this result is limited for parameters affecting the investment costs, such as the discount rate.

Thirdly, this study found that expanding the HT heat network is financially attractive in neighbourhoods with an existing HT heat network, as long as there is a high heat demand density. This is especially the case for buildings with medium level energy labels (C to E), as for buildings with high insulation levels are better suited for LT heating, and buildings with very low energy labels (E or lower) favour insulation combined with a LT heat network, as described in the previous paragraph.

The final finding is that although *Vesta MAIS* does not calculate alternative options for neighbourhood districts with an existing HT heat network in place, it can still be seen that this is the lowest societal cost option when comparing similar neighbourhood districts without an existing HT heat network. For example, 'Vechtzoom-zuid' with an existing HT heat network has in all cases lower societal costs than the 'Vechtzoom-Noord, Klopvaart' without an existing HT heat network (see Appendix H).

***Vesta MAIS* as modelling tool for a neighbourhood-level analysis**

The application of *Vesta MAIS* during this research has served to try out the model for a neighbourhood-level analysis. During this investigation a number of advantages and disadvantages have been identified:

In a practical sense, it was difficult to learn how to use the model for a new type of analysis such as this research, as the model documentation available is more suitable for the execution of analyses which focus more on the regional or national level. For more specific analyses, such as the one carried out in this research, technical support of model experts is desirable. PBL offers to a certain extent this support by training sessions and being available for general questions. However, these forms of support are more suitable to carry out a broader type of analysis. Therefore, more frequent and in-depth technical support is desirable to increase the applicability of *Vesta MAIS* for a neighbourhood-level analysis in a practical sense.

The difficulty of using the model originates from the open type of model structure. This entails that hard coding lines of the model need to be changed in order to perform specific types of analyses. However, a major advantage of this is that the model is highly adjustable and not limited by a user interface with limited options. For example the building stock, energy labels, heat sources and heat network can all be adjusted to reflect the actual situation in a neighbourhood most accurately. This characteristic makes the model very well suited to perform a neighbourhood-level analysis. However, due to the high adjustability it is relatively easy to make an error in the model. Therefore, checking intermediate results (e.g. energy demand per building) after changing a parameter is strongly advised to ensure the model is working as desired.

Furthermore, as the model is designed to perform a national analysis with district level detail, trimming down the area of analysis to one neighbourhood greatly reduces the calculation time. As many trials and errors may be required to adjust the model for a specific neighbourhood analysis, the short calculation time is an advantage.

Considering the aspects mentioned before and the applicability of this study of *Vesta MAIS* which has shown to display both the outcome per districts of a neighbourhood and high adjustability by the model user, it can be concluded that the *Vesta MAIS* model is well suited to perform a neighbourhood-level analysis.

5.2 Societal implications

The results of the *Optimal pathway* of this research can be used as starting point for the discussion on what technologies should be installed in the various districts of Overvecht in the coming years towards a sustainable heating system. Especially the districts for which the results are very robust, the established optimal pathway provides a founded base for what measures should be taken to transition to a sustainable heating system. For example the districts 'Taag- en Rubicondreef en omgeving', 'Zamenhofdreef en omgeving' and 'Bedrijventerrein en omgeving' show a HT heat network as the optimal option in all cases of the sensitivity analysis. Similarly, the districts 'Poldergebied Overvecht' and 'Wolga- en Donaudreef en omgeving' respectively show All-electric and a LT heat network as a very robust optimal pathway. Therefore, for these district there is a strong argument to implement these options. However, the limitations of this research and applying Vesta MAIS – as described in Section 5.3 – should be noted when considering the implementation of the results of this study.

Additionally, the results of this research that apply to certain districts, can be used as reference for districts with similar characteristics, as it is very likely these district will have the same optimal pathway. This is especially useful for municipalities which have limited means or time to perform a detailed neighbourhood-level analysis, as this requires either energy modelling experts to perform the analysis, or significant funds to outsource the analysis, as well as that it is a very time intensive process. Here, the general conclusions for districts with certain characteristics can be used (e.g. for areas with a low heat demand density, All-electric is found to be the optimal option).

Finally, this research can serve as a guideline for executing a neighbourhood-level analysis for other neighbourhoods. It is especially suited as guideline to perform neighbourhood-level analyses in neighbourhoods with a HT heat network present, as it includes a method to address the modelling simplification regarding existing district heating. Therefore, this study is best applied as guideline to neighbourhoods in for example Almere, Amsterdam, The Hague, Rotterdam and Utrecht, which all have HT district heating present in one or more neighbourhoods (CE Delft, 2009).

5.3 Limitations and significance for this research

***Vesta MAIS* limitations**

Vesta MAIS has several limitations inherently to the model. First of all, the model has no automatic optimization, as it solely calculates the scenarios that are constructed by the user. Therefore, the method of determining the optimal pathway towards a sustainable heating system needs to be determined by the user. While this allows flexibility in the determination of what the optimal pathway is, it is an additional and therefore more time consuming process. However, this research was able to define and construct an optimal pathway at neighbourhood level.

Secondly, *Vesta MAIS* can determine the optimal pathway per district, and not per building. Therefore, it may be the case that buildings with characteristics that are ideal for the all-electric heating option, are located in a district with many apartments which favour a HT heat network (e.g. buildings along the river Vecht show similar characteristics to the building in the polder area and may be ideal for all-electric heating, but are part of the residential districts and thus are assigned a HT heat network). Therefore, the building composition in a district is always important to keep in mind and a building-level analysis is recommended. However, this research still provides meaningful results as it determined the optimal pathway at lower than district level, as 8 of the 10 districts are split up into 2 smaller sections.

Thirdly, a limited amount of technologies are assessed with the model. Technologies such as thermal energy storage or heating by alternative heating gasses such as biogas and hydrogen are not included in the model. Also, the LT heat network is currently represented by one type of LT heat, namely HCS combined with auxiliary collective heat pumps. Due to these limitations, technologies that have better characteristics (e.g. lower costs) may not be presented as optimal technology, as they are not included in the analysis. The 4.0 version of *Vesta MAIS,* which will be released in October 2019, includes more technologies, such as thermal energy storage and different types of LT heating (van den Wijngaart, 2019). However, the results produced with this study still offer insight in which of the available technologies in version 3.3 form the most optimal pathway at neighbourhood level.

Furthermore, *Vesta MAIS* considers that all investments take place in the current year or in the year of analysis (e.g. 2030). However, both do not accurately reflect the reality, as it might take several years to implement all the technologies required for the transition to a sustainable heating system. As a result, the costs of the technologies are estimated too high in case the technologies are considered to be installed in the current year, as no learning effect is able to take place to reduce the costs. On the other hand, if technologies are modelled to be installed in the target year (e.g. 2030) such as in this study, the learning effect may be too large as technologies are in practice installed also before the target year, in order to complete the transition to a sustainable heating system by the target year. Therefore, investments in this research might be underestimated. However, the results of this study still provide meaningful insights as all of the technologies are affected by this limitation.

Moreover, the model incorporates the need for electricity grid reinforcements, but only to account for the increase in electricity consumption due to heat pumps. Here, the developments in the electricity sector (e.g. higher share of renewables and therefore higher intermittency) and transportation sector (e.g. more EVs) are not taken into account. As these developments may have a larger effect on the required grid reinforcements than heat pumps, reinforcement costs may need to be left out of the equation when comparing different pathways. Due to this issue, the way the electricity grid is modelled in the 3.4 version of Vesta MAIS is adjusted to account for these developments (van den Wijngaart, 2019). However, as the differences in costs associated with the electricity grid have a very limited influence on the results, the optimal pathway will not change in case the electricity grid reinforcements are left out of the analysis.

Finally, *Vesta MAIS* only allows the implementation of All-electric heating and LT heat networks in case a building is upgraded to energy label A+. However, in practice it may be sufficient to have an energy label B, or even C. As lower energy labels require lower investment costs, *Vesta MAIS* may show too high requirements on and costs for the implementation of these technologies, limiting their financial attractiveness compared to HT heat networks. Therefore, an additional analysis can be performed in order to determine the economic attractiveness of LT heating with lower insulation levels than energy label A+. However, the results of this study still provide meaningful insights for the combination of LT heating with energy label A+.

Limitations of the method of this research

First of all, this study aimed to address the simplification of Vesta MAIS regarding the presence of existing HT district heat by splitting up the districts as defined by the CBS into two section. However, ideally a modeller would adjust the districts to form separate clusters with similar characteristics (e.g. building type), in order to make the optimal outcome as specific as possible. However, the great number of adjustment that is required to achieve this, makes performing a neighbourhood-level analysis at this level of detail a very time intensive process. Therefore, the chosen method to split up the CBS district into two sections is found to be a major improvement from the standard configuration of *Vesta MAIS*.

Secondly, this research only investigates the costs of the different alternative heating options and defines optimal as bearing the lowest societal costs. However, potential benefits of the different options (e.g. increased value of a building in case of high insulation levels and higher comfort levels) may lead to a different definition of what the optimal outcome is. However, this study still provides valuable insights through the analyses of the three output parameters: energy demand, emissions and societal costs.

Thirdly, the emission reductions shown by the pathways in this research assume a strong decarbonisation of the fuel mix by 2030 for both the electricity grid and the HT district heating system. Actual emissions may however vary from this, which may change the optimal outcome when a certain emission reduction is mandatory or valuated with a CO_2-price. However, as the assumed developments are likely to take place as concrete plans are available (e.g. the roadmap from Eneco), the results produced by this analysis with these assumptions are relatively certain.

Finally, it is good to realize that the application of a different energy system model than *Vesta MAIS* may lead to a different optimal outcome (e.g. different optimal heating options and insulation levels per district, or even per building), as different models may utilize different calculation rules, assumptions, include different aspects of an energy system or consider different sustainable heating technologies. However, as the *Vesta MAIS* model is one of the best suited models to perform a neighbourhood analysis (as established in Section 1.2), the results of this analysis are highly relevant.

5.4 Recommendations for further research

The chosen method of this research has the following main limitations, from which recommendations for future research are derived. Most importantly, the composition of the optimal pathway is largely based on the selection of scenarios that show the lowest societal costs for districts. Although several other criteria (e.g. natural gas-free) have been incorporated by the careful construction of the scenarios, the incorporation of these criteria may be better served as modelled constraints (e.g. the incorporation of an emission cap for the total neighbourhood in 2030). Alternatively, it is also meaningful to optimize for a different parameter (e.g. lowest emissions) to allow comparison between different optimization methods. From this, depending on the desired goal, the optimal pathway can be chosen. Additionally, although it is a very time consuming process, it is recommended to disaggregate the districts even further into clusters of buildings which have similar characteristics. This way, an analysis will produce results which more accurately reflect the optimal pathway in practice.

Moreover, the sensitivity analysis of this study is limited to three factors that influence the investment costs of a scenario. However, factors that include the operational costs are also of great importance. It is suggested that the energy price is used in the sensitivity analysis of further research, as it has large impact on the total societal costs, and has a significant uncertainty. Additionally, this study recommends the incorporation of a CO_2 price in the sensitivity analysis of future research, as it has a high impact on the optimal pathway. The inclusion of this will increase the costs of options with relatively higher emissions, such as HT heat networks, which is in favour of lower emission options such as LT heat networks or All-electric with high insulation levels.

Another main limitation of this research is that it only focuses on societal costs. However, the costs for the end-user costs are also highly important. From this the affordability of the different technological options can be determined, which is very important for the actual realization of the heat transition. Also, the determination of end-user cost is required in order to determine which policies need to be created to realize the heat transition. Therefore, this study recommends to include the end-user costs in a next neighbourhood-level analysis, which is also possible with Vests MAIS version 3.3.

Finally, this analysis determines the optimal pathway towards a sustainable heating system by using only techno-economic criteria. For the actual heat transition to occur also social (e.g. social acceptance of pathways) and political criteria (e.g. nationally desired emission reductions) should be assessed. Therefore, the final recommendation of this research is to include social and political criteria in a future neighbourhood-level analysis.

6. Conclusions

In order to contribute to the transition towards a carbon-neutral heating system and to reaching the goals of the Paris Agreement, this research investigated the optimal mix of sustainable heating technologies at the neighbourhood level by 2030. By using the neighbourhood Overvecht in Utrecht as a case study, the following research question was addressed: *How to identify the most optimal techno-economic pathways at local scale towards a sustainable heating system by 2030?* Herein, the *Vesta MAIS* model was used to assist with the analysis.

Identifying the most techno-economic pathway included a three-phase method. Phase I consisted of collecting data and making adjustment to the *Vesta MAIS* model. From the collected data on technological options for the heat transition, several scenarios were formed. In the second phase of this research, the constructed scenarios were calculated with *Vesta MAIS* and the energy demand, emissions and societal costs were extracted. Phase III consisted of the analysis of the output parameters and the determination of the optimal pathway towards a sustainable heating system by 2030. In addition, a sensitivity analysis investigated the robustness of the optimal pathway for a various societal discount rates, learning curves and building improvement costs.

The optimal pathway for Overvecht showed that for 14 districts a HT heat network is more attractive, while for 3 districts a LT heat network and for 1 district All-electric is the optimal option. For the districts with LT heat network and All-electric, the buildings' energy labels are upgraded to A+ to account for the LT heat supply at building level. The buildings which have a HT heat network as optimal pathway do not require an upgrade to a higher energy label. Within this optimal pathway, an energy demand reduction of 20% (to 687 TJ/year) and an emission reduction of 70% (to 19 kt CO_2/year) can be achieved compared to the *Baseline*, while the societal costs show an increase of 34% to 28 M€/year. Of the remaining energy demand, 69% is supplied by a heat network and 31% by electricity. For emissions 80% originates from district heating, while 20% is from electricity production. Of the societal costs 39% originates from district heating, 19% from electricity use, 18% from the electricity grid, 9% to remove the natural gas grid, 14% for insulation and 1% for heat pumps. The HT heat network is dominant in the *Optimal pathway* due to the presence of an existing HT heat network in the neighbourhood, the resulting lower cost (compared to a neighbourhood without an existing HT heat network) for expanding this network to surrounding districts with a high heat demand density and the dominance of average energy labels (C and D) present in these districts. The LT heat network is the optimal option for districts with a high heat demand density and low energy labels (E or lower), as these buildings require the implementation of insulation to reduce the high heat demand, which is economically attractive to combine with LT district heating. For areas with a low heat demand density, All-electric is the optimal option.

From the sensitivity analysis is can be concluded that the results are robust for the majority of the districts. A few of the districts with a LT heat network as optimal option switch to a HT heat network as optimal solution when the investment cost are expected to increase. The investment costs can be increased by a higher societal discount rate, a smaller learning effect and higher building improvement costs. The opposite has as result that some of the HT heat networks are replaced by a LT heat network in the optimal solution. The All-electric heating option is very robust as the optimal heating technology for areas with a low heat demand density, as it only changes when the learning effect is at its minimum.

This research contributes to scientific literature by the development of a method to increase the applicability of *Vesta MAIS* to neighbourhoods with existing HT district heating, as well as with a method to establish the optimal pathway based on lowest societal costs per district. The produced results add to theory by establishing that individual heat pumps are only interesting in areas with a low heat demand density; LT heat networks are the most economically interesting heating technology for buildings with low energy labels (E or lower), as long as it is in an area with a high heat demand density; and expanding the HT heat network is financially attractive in neighbourhoods with an existing HT heat network, as long as there is a high heat demand density. Additionally, *Vesta MAIS* is established as a model that is well suited to perform a neighbourhood-level analysis, as it displays both the optimal outcome per districts of a neighbourhood and high adjustability by the model user. Furthermore, this research contributes to society as it can be used as starting point for the discussion on what technologies should be installed in the various districts of Overvecht and in districts with similar characteristics, as well as serve as a guideline for executing a neighbourhood-level analysis for other neighbourhoods.

Limitations of the *Vesta MAIS* model are that it does not automatically optimizes, can display optimal pathways only per district, assesses a limited amount of technologies, assumes all investments take place within one year, determines electricity grid reinforcement costs based on a fixed costs per installed heat pump, and requires very high insulation levels for HT heating. The main limitations of the chosen methodology arise from the choice to determine the optimal pathway per district (based on the presence of HT district heating), and not based on smaller clusters with similar characteristics, and to determine the optimal pathway based on the lowest societal costs without the inclusion of modelled emission constraints. Additionally, this research is limited by the fact that only *Vesta MAIS* is used for the analysis, as a different model may lead to a different outcome. Despite these limitations, the *Vesta MAIS* model is identified as one of the best suited models to perform a neighbourhood analysis and therefore the results of this analysis are highly relevant. The further investigation of 1) different definitions of what an optimal pathway is, 2) disaggregating districts into smaller clusters of buildings with similar characteristics, 3) a sensitivity analysis of energy prices, and 4) taking into account social and political criteria, are all recommended for future research.

To conclude, this research has shown that the pathways towards a sustainable heating system consist of a combination of different system adjustments, including the expansion of the HT heat network, the instalment of LT heat networks, the implementation of individual heat pumps and the upgrade of a limited share of buildings to energy label A+. The heat demand density and the energy label are driving factors behind the optimal pathway for a district. A neighbourhood-level analysis with *Vesta MAIS* proved to be a useful tool to identify the most optimal techno-economic pathways at local scale towards a sustainable heating system by 2030. However, this research is only a part of the required information to actually start the heat transition at neighbourhood-level and realize a sustainable heating system by 2030, as social and political factors also need to be taken into account.

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Appendices

In this section the following appendices can be found:

- Appendices A-G: output parameters per neighbourhood district for each scenario
- Appendix H: output parameters per neighbourhood district for the *Optimal* pathway
- Appendices I-K: results sensitivity analysis per neighbourhood district

Appendix A: Baseline – output parameters per neighbourhood district

Baseline (-)					Energy demand				Emissions			
					Total	District heating	Electricity	Natural gas	Total	District heating	Electricity	Natural gas
id	Neighbourhood district	Residences	Utility	Existing HT-DH?	GJ/year	GJ/year	GJ/year	GJ/year	kg CO2/year	kg CO2/year	kg CO2/year	kg CO2/year
0	'Taag- en Rubicondreef en omgeving'	895	336	No	57642	0	16336	41306	4150901	0	2060153	2090748
1	'Wolga- en Donaudreef en omgeving'	1305	14	Yes	49153	36600	12553	0	3547766	1964675	1583091	0
2	'Zamenhofdreef en omgeving'	294	258	No	25794	0	8453	17341	1943789	0	1066060	877729
3	'Neckardreef en omgeving'	697	229	No	50513	0	13258	37255	3557666	0	1671985	1885681
4	'Vechtzoom-zuid'	1190	155	No	61330	0	14835	46495	4224242	0	1870824	2353417
5	'Bedrijventerrein en omgeving'	41	125	No	64092	0	20447	43645	4787771	0	2578635	2209135
6	'Zambesidreef en omgeving'	763	188	No	43025	0	11244	31781	3026677	0	1418039	1608638
7	'Tigrisdreef en omgeving'	1000	172	No	49268	0	12015	37252	3400835	0	1515269	1885566
8	'Poldergebied Overvecht'	93	16	No	12703	0	3118	9585	878332	0	393190	485142
9	'Taag- en Rubicondreef en omgeving'	1099	24	Yes	59700	43616	16085	0	4369766	2341282	2028484	0
10	'Vechtzoom-noord, Klopvaart'	238	1	Yes	12478	10024	2454	0	847592	538076	309516	0
11	'Tigrisdreef en omgeving'	910	7	Yes	34454	26129	8325	0	2452449	1402589	1049860	0
12	'Zambesidreef en omgeving'	1456	23	Yes	53659	40054	13605	0	3865813	2150098	1715716	0
13	'Neckardreef en omgeving'	1323	33	Yes	57622	42358	15263	0	4198660	2273795	1924865	0
14	'Zamenhofdreef en omgeving'	1172	92	Yes	56696	42108	14588	0	4100105	2260363	1839742	0
15	'Wolga- en Donaudreef en omgeving'	857	68	No	49600	0	10619	38980	3312253	0	1339228	1973025
16	'Vechtzoom-noord, Klopvaart'	1242	148	No	59632	0	14545	45087	4116392	0	1834247	2282145
17	'Vechtzoom-zuid'	1309	36	Yes	56552	40852	15700	0	4172878	2192924	1979955	0
	Total Overvecht	15884	1925	0	853912	281740	223445	348727	60953885	15123801	28178858	17651226

Baseline (-)					Societal costs							
					Total	District heating	Electricity use	Natural gas use	Heat pumps	Insulation	Electricity grid	Natural gas grid
id	Neighbourhood district	Residences	Utility	Existing HT-DH?	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year
0	'Taag- en Rubicondreef en omgeving'	895	336	No	€ 1,321,784	€ -	€ 254,233	€ 502,511	€ -	€ -	€ 329,784	€ 235,256
1	'Wolga- en Donaudreef en omgeving'	1305	14	Yes	€ 1,440,646	€ 897,825	€ 183,393	€ -	€ -	€ -	€ 359,428	€ -
2	'Zamenhofdreef en omgeving'	294	258	No	€ 643,104	€ -	€ 137,576	€ 210,013	€ -	€ -	€ 160,238	€ 135,277
3	'Neckardreef en omgeving'	697	229	No	€ 1,064,407	€ -	€ 213,725	€ 452,595	€ -	€ -	€ 243,025	€ 155,063
4	'Vechtzoom-zuid'	1190	155	No	€ 1,417,715	€ -	€ 220,702	€ 565,924	€ -	€ -	€ 377,744	€ 253,345
5	'Bedrijventerrein en omgeving'	41	125	No	€ 959,819	€ -	€ 407,842	€ 520,420	€ -	€ -	€ 31,488	€ 69
6	'Zambesidreef en omgeving'	763	188	No	€ 1,000,077	€ -	€ 170,856	€ 386,592	€ -	€ -	€ 260,777	€ 181,851
7	'Tigrisdreef en omgeving'	1000	172	No	€ 1,193,327	€ -	€ 172,865	€ 454,094	€ -	€ -	€ 334,095	€ 232,273
8	'Poldergebied Overvecht'	93	16	No	€ 305,568	€ -	€ 55,959	€ 115,882	€ -	€ -	€ 73,998	€ 59,728
9	'Taag- en Rubicondreef en omgeving'	1099	24	Yes	€ 1,586,805	€ 1,034,690	€ 263,900	€ -	€ -	€ -	€ 288,215	€ -
10	'Vechtzoom-noord, Klopvaart'	238	1	Yes	€ 329,063	€ 223,971	€ 34,972	€ -	€ -	€ -	€ 70,120	€ -
11	'Tigrisdreef en omgeving'	910	7	Yes	€ 1,002,264	€ 629,826	€ 119,174	€ -	€ -	€ -	€ 253,264	€ -
12	'Zambesidreef en omgeving'	1456	23	Yes	€ 1,567,751	€ 968,421	€ 197,532	€ -	€ -	€ -	€ 401,799	€ -
13	'Neckardreef en omgeving'	1323	33	Yes	€ 1,634,863	€ 1,035,909	€ 235,825	€ -	€ -	€ -	€ 363,129	€ -
14	'Zamenhofdreef en omgeving'	1172	92	Yes	€ 1,506,710	€ 948,377	€ 227,222	€ -	€ -	€ -	€ 331,110	€ -
15	'Wolga- en Donaudreef en omgeving'	857	68	No	€ 1,040,186	€ -	€ 154,582	€ 474,807	€ -	€ -	€ 265,065	€ 145,732
16	'Vechtzoom-noord, Klopvaart'	1242	148	No	€ 1,427,659	€ -	€ 208,728	€ 549,256	€ -	€ -	€ 397,189	€ 272,486
17	'Vechtzoom-zuid'	1309	36	Yes	€ 1,563,520	€ 963,923	€ 246,657	€ -	€ -	€ -	€ 352,940	€ -
	Total Overvecht	15884	1925	0	€ 21,005,268	€ 6,702,942	€ 3,505,744	€ 4,232,093	€ -	€ -	€ 4,893,408	€ 1,671,081

Appendix B: Reference (-) – output parameters per neighbourhood district

Reference (-)					Energy demand				Emissions			
					Total	District heating	Electricity	Natural gas	Total	District heating	Electricity	Natural gas
id	Neighbourhood district	Residences	Utility	Existing HT-DH?	GJ/year	GJ/year	GJ/year	GJ/year	kg CO2/year	kg CO2/year	kg CO2/year	kg CO2/year
0	'Taag- en Rubicondreef en omgeving'	895	336	No	50505	0	16336	34169	2006310	0	276805	1729506
1	'Wolga- en Donaudreef en omgeving'	1305	14	Yes	45756	33203	12553	0	1330994	1118288	212706	0
2	'Zamenhofdreef en omgeving'	294	258	No	22697	0	8453	14243	864186	0	143237	720949
3	'Neckardreef en omgeving'	697	229	No	43730	0	13258	30472	1767026	0	224650	1542377
4	'Vechtzoom-zuid'	1190	155	No	53240	0	14835	38405	2195272	0	251366	1943906
5	'Bedrijventerrein en omgeving'	41	125	No	55126	0	20447	34678	2101754	0	346469	1755285
6	'Zambesidreef en omgeving'	763	188	No	37699	0	11244	26454	1529544	0	190529	1339015
7	'Tigrisdreef en omgeving'	1000	172	No	42444	0	12015	30429	1743786	0	203593	1540192
8	'Poldergebied Overvecht'	93	16	No	11130	0	3118	8012	458359	0	52829	405529
9	'Taag- en Rubicondreef en omgeving'	1099	24	Yes	55386	39301	16085	0	1596221	1323671	272550	0
10	'Vechtzoom-noord, Klopvaart'	238	1	Yes	11499	9045	2454	0	346211	304624	41587	0
11	'Tigrisdreef en omgeving'	910	7	Yes	31997	23672	8325	0	938345	797285	141060	0
12	'Zambesidreef en omgeving'	1456	23	Yes	49923	36318	13605	0	1453709	1223183	230526	0
13	'Neckardreef en omgeving'	1323	33	Yes	53561	38298	15263	0	1548496	1289869	258627	0
14	'Zamenhofdreef en omgeving'	1172	92	Yes	52568	37980	14588	0	1526349	1279159	247190	0
15	'Wolga- en Donaudreef en omgeving'	857	68	No	42558	0	10619	31939	1796543	0	179940	1616603
16	'Vechtzoom-noord, Klopvaart'	1242	148	No	52337	0	14545	37792	2159358	0	246452	1912906
17	'Vechtzoom-zuid'	1309	36	Yes	52610	36910	15700	0	1509169	1243139	266029	0
	Total Overvecht	15884	1925	0	764766	254727	223445	286594	26871631	8579218	3786146	14506267

Reference (-)					Societal costs							
					Total	District heating	Electricity use	Natural gas use	Heat pumps	Insulation	Electricity grid	Natural gas grid
id	Neighbourhood district	Residences	Utility	Existing HT-DH?	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year
0	'Taag- en Rubicondreef en omgeving'	895	336	No	€ 1,304,221	€ -	€ 413,056	€ 303,791	€ -	€ -	€ 329,784	€ 257,590
1	'Wolga- en Donaudreef en omgeving'	1305	14	Yes	€ 1,410,047	€ 745,181	€ 305,438	€ -	€ -	€ -	€ 359,428	€ -
2	'Zamenhofdreef en omgeving'	294	258	No	€ 650,811	€ -	€ 219,761	€ 125,391	€ -	€ -	€ 160,238	€ 145,421
3	'Neckardreef en omgeving'	697	229	No	€ 1,032,756	€ -	€ 342,622	€ 270,475	€ -	€ -	€ 243,025	€ 176,634
4	'Vechtzoom-zuid'	1190	155	No	€ 1,363,154	€ -	€ 364,929	€ 342,065	€ -	€ -	€ 377,744	€ 278,416
5	'Bedrijventerrein en omgeving'	41	125	No	€ 966,203	€ -	€ 606,636	€ 295,922	€ -	€ -	€ 31,488	€ 32,158
6	'Zambesidreef en omgeving'	763	188	No	€ 974,380	€ -	€ 280,177	€ 235,258	€ -	€ -	€ 260,777	€ 198,168
7	'Tigrisdreef en omgeving'	1000	172	No	€ 1,149,429	€ -	€ 289,681	€ 271,834	€ -	€ -	€ 334,095	€ 253,819
8	'Poldergebied Overvecht'	93	16	No	€ 295,303	€ -	€ 86,271	€ 70,387	€ -	€ -	€ 73,998	€ 64,646
9	'Taag- en Rubicondreef en omgeving'	1099	24	Yes	€ 1,535,218	€ 826,722	€ 420,281	€ -	€ -	€ -	€ 288,215	€ -
10	'Vechtzoom-noord, Klopvaart'	238	1	Yes	€ 314,400	€ 185,447	€ 58,833	€ -	€ -	€ -	€ 70,120	€ -
11	'Tigrisdreef en omgeving'	910	7	Yes	€ 975,741	€ 522,366	€ 200,110	€ -	€ -	€ -	€ 253,264	€ -
12	'Zambesidreef en omgeving'	1456	23	Yes	€ 1,534,726	€ 803,127	€ 329,801	€ -	€ -	€ -	€ 401,799	€ -
13	'Neckardreef en omgeving'	1323	33	Yes	€ 1,588,295	€ 840,948	€ 384,218	€ -	€ -	€ -	€ 363,129	€ -
14	'Zamenhofdreef en omgeving'	1172	92	Yes	€ 1,471,438	€ 771,275	€ 369,053	€ -	€ -	€ -	€ 331,110	€ -
15	'Wolga- en Donaudreef en omgeving'	857	68	No	€ 975,678	€ -	€ 257,826	€ 284,896	€ -	€ -	€ 265,065	€ 167,891
16	'Vechtzoom-noord, Klopvaart'	1242	148	No	€ 1,378,630	€ -	€ 350,135	€ 337,071	€ -	€ -	€ 397,189	€ 294,235
17	'Vechtzoom-zuid'	1309	36	Yes	€ 1,541,345	€ 789,108	€ 399,297	€ -	€ -	€ -	€ 352,940	€ -
	Total Overvecht	15884	1925	0	€ 20,461,775	€ 5,484,176	€ 5,678,123	€ 2,537,091	€ -	€ -	€ 4,893,408	€ 1,868,978

Appendix C: Insulation (B) – output parameters per neighbourhood district

Insulation (B)					Energy demand				Emissions			
					Total	District heating	Electricity	Natural gas	Total	District heating	Electricity	Natural gas
id	Neighbourhood district	Residences	Utility	Existing HT-DH?	GJ/year	GJ/year	GJ/year	GJ/year	kg CO2/year	kg CO2/year	kg CO2/year	kg CO2/year
0	'Taag- en Rubicondreef en omgeving'	895	336	No	42497	0	16336	26161	1600975	0	276805	1324170
1	'Wolga- en Donaudreef en omgeving'	1305	14	Yes	42479	29926	12553	0	1220600	1007894	212706	0
2	'Zamenhofdreef en omgeving'	294	258	No	18871	0	8453	10418	670547	0	143237	527310
3	'Neckardreef en omgeving'	697	229	No	33807	0	13258	20549	1264782	0	224650	1040132
4	'Vechtzoom-zuid'	1190	155	No	46382	0	14835	31547	1848158	0	251366	1596791
5	'Bedrijventerrein en omgeving'	41	125	No	35843	0	20447	15396	1125735	0	346469	779267
6	'Zambesidreef en omgeving'	763	188	No	32863	0	11244	21619	1284785	0	190529	1094255
7	'Tigrisdreef en omgeving'	1000	172	No	37000	0	12015	24984	1468204	0	203593	1264611
8	'Poldergebied Overvecht'	93	16	No	9012	0	3118	5894	351162	0	52829	298333
9	'Taag- en Rubicondreef en omgeving'	1099	24	Yes	44095	28010	16085	0	1215925	943376	272550	0
10	'Vechtzoom-noord, Klopvaart'	238	1	Yes	9012	6558	2454	0	262457	220870	41587	0
11	'Tigrisdreef en omgeving'	910	7	Yes	27816	19491	8325	0	797521	656460	141060	0
12	'Zambesidreef en omgeving'	1456	23	Yes	44237	30632	13605	0	1262225	1031700	230526	0
13	'Neckardreef en omgeving'	1323	33	Yes	46027	30764	15263	0	1294750	1036123	258627	0
14	'Zamenhofdreef en omgeving'	1172	92	Yes	41489	26901	14588	0	1153210	906020	247190	0
15	'Wolga- en Donaudreef en omgeving'	857	68	No	32684	0	10619	22065	1296768	0	179940	1116828
16	'Vechtzoom-noord, Klopvaart'	1242	148	No	46688	0	14545	32143	1873405	0	246452	1626953
17	'Vechtzoom-zuid'	1309	36	Yes	45766	30065	15700	0	1278634	1012605	266029	0
	Total Overvecht	15884	1925	0	636567	202347	223445	210776	21269845	6815048	3786146	10668651

Insulation (B)					Societal costs							
					Total	District heating	Electricity use	Natural gas use	Heat pumps	Insulation	Electricity grid	Natural gas grid
id	Neighbourhood district	Residences	Utility	Existing HT-DH?	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year
0	'Taag- en Rubicondreef en omgeving'	895	336	No	€ 1,663,307	€ -	€ 413,056	€ 232,427	€ -	€ 392,991	€ 329,784	€ 295,049
1	'Wolga- en Donaudreef en omgeving'	1305	14	Yes	€ 1,634,652	€ 718,483	€ 305,438	€ -	€ -	€ 251,304	€ 359,428	€ -
2	'Zamenhofdreef en omgeving'	294	258	No	€ 796,303	€ -	€ 219,761	€ 92,150	€ -	€ 161,689	€ 160,238	€ 162,465
3	'Neckardreef en omgeving'	697	229	No	€ 1,336,543	€ -	€ 342,622	€ 182,751	€ -	€ 345,798	€ 243,025	€ 222,348
4	'Vechtzoom-zuid'	1190	155	No	€ 1,745,963	€ -	€ 364,929	€ 282,080	€ -	€ 411,843	€ 377,744	€ 309,367
5	'Bedrijventerrein en omgeving'	41	125	No	€ 1,421,241	€ -	€ 606,636	€ 133,115	€ -	€ 536,677	€ 31,488	€ 113,325
6	'Zambesidreef en omgeving'	763	188	No	€ 1,197,935	€ -	€ 280,177	€ 192,956	€ -	€ 244,028	€ 260,777	€ 219,997
7	'Tigrisdreef en omgeving'	1000	172	No	€ 1,492,399	€ -	€ 289,681	€ 223,152	€ -	€ 366,021	€ 334,095	€ 279,451
8	'Poldergebied Overvecht'	93	16	No	€ 348,153	€ -	€ 86,271	€ 51,770	€ -	€ 61,817	€ 73,998	€ 74,297
9	'Taag- en Rubicondreef en omgeving'	1099	24	Yes	€ 1,939,892	€ 734,749	€ 420,281	€ -	€ -	€ 496,647	€ 288,215	€ -
10	'Vechtzoom-noord, Klopvaart'	238	1	Yes	€ 398,305	€ 165,192	€ 58,833	€ -	€ -	€ 104,161	€ 70,120	€ -
11	'Tigrisdreef en omgeving'	910	7	Yes	€ 1,263,606	€ 488,309	€ 200,110	€ -	€ -	€ 321,923	€ 253,264	€ -
12	'Zambesidreef en omgeving'	1456	23	Yes	€ 1,956,112	€ 756,817	€ 329,801	€ -	€ -	€ 467,696	€ 401,799	€ -
13	'Neckardreef en omgeving'	1323	33	Yes	€ 2,007,822	€ 779,580	€ 384,218	€ -	€ -	€ 480,895	€ 363,129	€ -
14	'Zamenhofdreef en omgeving'	1172	92	Yes	€ 1,899,520	€ 681,033	€ 369,053	€ -	€ -	€ 518,324	€ 331,110	€ -
15	'Wolga- en Donaudreef en omgeving'	857	68	No	€ 1,274,663	€ -	€ 257,826	€ 197,123	€ -	€ 340,789	€ 265,065	€ 213,859
16	'Vechtzoom-noord, Klopvaart'	1242	148	No	€ 1,798,703	€ -	€ 350,135	€ 286,815	€ -	€ 443,992	€ 397,189	€ 320,573
17	'Vechtzoom-zuid'	1309	36	Yes	€ 1,949,906	€ 733,354	€ 399,297	€ -	€ -	€ 464,315	€ 352,940	€ -
	Total Overvecht	15884	1925	0	€ 26,125,027	€ 5,057,518	€ 5,678,123	€ 1,874,339	€ -	€ 6,410,909	€ 4,893,408	€ 2,210,731

Appendix D: Insulation (A+) – output parameters per neighbourhood district

Insulation (A+)					Energy demand				Emissions			
					Total	District heating	Electricity	Natural gas	Total	District heating	Electricity	Natural gas
id	Neighbourhood district	Residences	Utility	Existing HT-DH?	GJ/year	GJ/year	GJ/year	GJ/year	kg CO2/year	kg CO2/year	kg CO2/year	kg CO2/year
0	'Taag- en Rubicondreef en omgeving'	895	336	No	34749	0	16336	18413	1208778	0	276805	931973
1	'Wolga- en Donaudreef en omgeving'	1305	14	Yes	32390	19837	12553	0	880824	668118	212706	0
2	'Zamenhofdreef en omgeving'	294	258	No	15481	0	8453	7028	498956	0	143237	355719
3	'Neckardreef en omgeving'	697	229	No	27993	0	13258	14735	970478	0	224650	745828
4	'Vechtzoom-zuid'	1190	155	No	37446	0	14835	22611	1395862	0	251366	1144495
5	'Bedrijventerrein en omgeving'	41	125	No	30804	0	20447	10357	870696	0	346469	524228
6	'Zambesidreef en omgeving'	763	188	No	26239	0	11244	14995	949507	0	190529	758977
7	'Tigrisdreef en omgeving'	1000	172	No	30164	0	12015	18149	1122201	0	203593	918608
8	'Poldergebied Overvecht'	93	16	No	6782	0	3118	3665	238317	0	52829	185488
9	'Taag- en Rubicondreef en omgeving'	1099	24	Yes	34873	18788	16085	0	905322	632772	272550	0
10	'Vechtzoom-noord, Klopvaart'	238	1	Yes	6961	4507	2454	0	193382	151795	41587	0
11	'Tigrisdreef en omgeving'	910	7	Yes	21797	13472	8325	0	594802	453741	141060	0
12	'Zambesidreef en omgeving'	1456	23	Yes	34748	21144	13605	0	942644	712118	230526	0
13	'Neckardreef en omgeving'	1323	33	Yes	35997	20734	15263	0	956956	698329	258627	0
14	'Zamenhofdreef en omgeving'	1172	92	Yes	33285	18697	14588	0	876896	629706	247190	0
15	'Wolga- en Donaudreef en omgeving'	857	68	No	26538	0	10619	15919	985698	0	179940	805758
16	'Vechtzoom-noord, Klopvaart'	1242	148	No	37517	0	14545	22972	1409209	0	246452	1162757
17	'Vechtzoom-zuid'	1309	36	Yes	35627	19926	15700	0	937154	671125	266029	0
	Total Overvecht	15884	1925	0	509392	137105	223445	148843	15937680	4617704	3786146	7533830

Insulation (A+)					Societal costs							
					Total	District heating	Electricity use	Natural gas use	Heat pumps	Insulation	Electricity grid	Natural gas grid
id	Neighbourhood district	Residences	Utility	Existing HT-DH?	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year
0	'Taag- en Rubicondreef en omgeving'	895	336	No	€ 1,857,607	€ -	€ 413,056	€ 164,142	€ -	€ 620,096	€ 329,784	€ 330,529
1	'Wolga- en Donaudreef en omgeving'	1305	14	Yes	€ 1,782,193	€ 636,310	€ 305,438	€ -	€ -	€ 481,018	€ 359,428	€ -
2	'Zamenhofdreef en omgeving'	294	258	No	€ 907,338	€ -	€ 219,761	€ 62,444	€ -	€ 287,077	€ 160,238	€ 177,818
3	'Neckardreef en omgeving'	697	229	No	€ 1,438,874	€ -	€ 342,622	€ 131,212	€ -	€ 472,745	€ 243,025	€ 249,269
4	'Vechtzoom-zuid'	1190	155	No	€ 1,873,735	€ -	€ 364,929	€ 202,180	€ -	€ 577,448	€ 377,744	€ 351,435
5	'Bedrijventerrein en omgeving'	41	125	No	€ 1,569,834	€ -	€ 606,636	€ 89,980	€ -	€ 706,602	€ 31,488	€ 135,128
6	'Zambesidreef en omgeving'	763	188	No	€ 1,304,489	€ -	€ 280,177	€ 133,981	€ -	€ 378,626	€ 260,777	€ 250,928
7	'Tigrisdreef en omgeving'	1000	172	No	€ 1,598,481	€ -	€ 289,681	€ 162,276	€ -	€ 501,045	€ 334,095	€ 311,385
8	'Poldergebied Overvecht'	93	16	No	€ 427,840	€ -	€ 86,271	€ 32,406	€ -	€ 150,943	€ 73,998	€ 84,222
9	'Taag- en Rubicondreef en omgeving'	1099	24	Yes	€ 2,096,774	€ 659,630	€ 420,281	€ -	€ -	€ 728,648	€ 288,215	€ -
10	'Vechtzoom-noord, Klopvaart'	238	1	Yes	€ 414,499	€ 148,486	€ 58,833	€ -	€ -	€ 137,060	€ 70,120	€ -
11	'Tigrisdreef en omgeving'	910	7	Yes	€ 1,321,961	€ 439,282	€ 200,110	€ -	€ -	€ 429,305	€ 253,264	€ -
12	'Zambesidreef en omgeving'	1456	23	Yes	€ 2,071,561	€ 679,528	€ 329,801	€ -	€ -	€ 660,434	€ 401,799	€ -
13	'Neckardreef en omgeving'	1323	33	Yes	€ 2,160,515	€ 697,886	€ 384,218	€ -	€ -	€ 715,283	€ 363,129	€ -
14	'Zamenhofdreef en omgeving'	1172	92	Yes	€ 1,972,326	€ 614,207	€ 369,053	€ -	€ -	€ 657,956	€ 331,110	€ -
15	'Wolga- en Donaudreef en omgeving'	857	68	No	€ 1,368,705	€ -	€ 257,826	€ 142,219	€ -	€ 460,850	€ 265,065	€ 242,744
16	'Vechtzoom-noord, Klopvaart'	1242	148	No	€ 1,938,910	€ -	€ 350,135	€ 205,154	€ -	€ 623,027	€ 397,189	€ 363,406
17	'Vechtzoom-zuid'	1309	36	Yes	€ 2,095,794	€ 650,769	€ 399,297	€ -	€ -	€ 692,789	€ 352,940	€ -
	Total Overvecht	15884	1925	0	€ 28,201,436	€ 4,526,097	€ 5,678,123	€ 1,325,994	€ -	€ 9,280,952	€ 4,893,408	€ 2,496,863

Appendix E: All-electric (A+) – output parameters per neighbourhood district

All-electric (A+)

id	Neighbourhood district	Residences	Utility	Existing HT-DH?	Energy demand: Total GJ/year	District heating GJ/year	Electricity GJ/year	Natural gas GJ/year	Emissions: Total kg CO2/year	District heating kg CO2/year	Electricity kg CO2/year	Natural gas kg CO2/year
0	'Taag- en Rubicondreef en omgeving'	895	336	No	20412	0	20412	0	345874	0	345874	0
1	'Wolga- en Donaudreef en omgeving'	1305	14	Yes	45756	33203	12553	0	1330994	1118288	212706	0
2	'Zamenhofdreef en omgeving'	294	258	No	9823	0	9823	0	166446	0	166446	0
3	'Neckardreef en omgeving'	697	229	No	16560	0	16560	0	280607	0	280607	0
4	'Vechtzoom-zuid'	1190	155	No	19986	0	19986	0	338660	0	338660	0
5	'Bedrijventerrein en omgeving'	41	125	No	21693	0	21693	0	367570	0	367570	0
6	'Zambesidreef en omgeving'	763	188	No	14638	0	14638	0	248033	0	248033	0
7	'Tigrisdreef en omgeving'	1000	172	No	16198	0	16198	0	274474	0	274474	0
8	'Poldergebied Overvecht'	93	16	No	3858	0	3858	0	65367	0	65367	0
9	'Taag- en Rubicondreef en omgeving'	1099	24	Yes	55386	39301	16085	0	1596221	1323671	272550	0
10	'Vechtzoom-noord, Klopvaart'	238	1	Yes	11499	9045	2454	0	346211	304624	41587	0
11	'Tigrisdreef en omgeving'	910	7	Yes	31997	23672	8325	0	938345	797285	141060	0
12	'Zambesidreef en omgeving'	1456	23	Yes	49923	36318	13605	0	1453709	1223183	230526	0
13	'Neckardreef en omgeving'	1323	33	Yes	53561	38298	15263	0	1548496	1289869	258627	0
14	'Zamenhofdreef en omgeving'	1172	92	Yes	52568	37980	14588	0	1526349	1279159	247190	0
15	'Wolga- en Donaudreef en omgeving'	857	68	No	14292	0	14292	0	242176	0	242176	0
16	'Vechtzoom-noord, Klopvaart'	1242	148	No	19942	0	19942	0	337907	0	337907	0
17	'Vechtzoom-zuid'	1309	36	Yes	52610	36910	15700	0	1509169	1243139	266029	0
	Total Overvecht	15884	1925	0	510704	254727	255977	0	12916608	8579218	4337390	0

All-electric (A+)

id	Neighbourhood district	Residences	Utility	Existing HT-DH?	Societal costs: Total Euro2010/year	District heating Euro2010/year	Electricity use Euro2010/year	Natural gas use Euro2010/year	Heat pumps Euro2010/year	Insulation Euro2010/year	Electricity grid Euro2010/year	Natural gas grid Euro2010/year
0	'Taag- en Rubicondreef en omgeving'	895	336	No	€ 2,832,707	€ -	€ 511,047	€ -	€ 997,186	€ 620,096	€ 370,219	€ 334,159
1	'Wolga- en Donaudreef en omgeving'	1305	14	Yes	€ 1,410,047	€ 745,181	€ 305,438	€ -	€ -	€ -	€ 359,428	€ -
2	'Zamenhofdreef en omgeving'	294	258	No	€ 1,302,271	€ -	€ 252,977	€ -	€ 418,439	€ 287,077	€ 174,975	€ 168,803
3	'Neckardreef en omgeving'	697	229	No	€ 2,196,397	€ -	€ 423,127	€ -	€ 771,168	€ 472,745	€ 274,280	€ 255,077
4	'Vechtzoom-zuid'	1190	155	No	€ 3,089,535	€ -	€ 487,649	€ -	€ 1,233,403	€ 577,448	€ 423,865	€ 367,170
5	'Bedrijventerrein en omgeving'	41	125	No	€ 2,074,782	€ -	€ 643,129	€ -	€ 610,840	€ 706,602	€ (31,138)	€ 145,349
6	'Zambesidreef en omgeving'	763	188	No	€ 2,093,242	€ -	€ 361,460	€ -	€ 798,803	€ 378,626	€ 296,606	€ 257,745
7	'Tigrisdreef en omgeving'	1000	172	No	€ 2,589,647	€ -	€ 388,666	€ -	€ 1,003,964	€ 501,045	€ 377,765	€ 318,207
8	'Poldergebied Overvecht'	93	16	No	€ 573,151	€ -	€ 104,054	€ -	€ 164,726	€ 150,943	€ 72,349	€ 81,081
9	'Taag- en Rubicondreef en omgeving'	1099	24	Yes	€ 1,535,218	€ 826,722	€ 420,281	€ -	€ -	€ -	€ 288,215	€ -
10	'Vechtzoom-noord, Klopvaart'	238	1	Yes	€ 314,400	€ 185,447	€ 58,833	€ -	€ -	€ -	€ 70,120	€ -
11	'Tigrisdreef en omgeving'	910	7	Yes	€ 975,741	€ 522,366	€ 200,110	€ -	€ -	€ -	€ 253,264	€ -
12	'Zambesidreef en omgeving'	1456	23	Yes	€ 1,534,726	€ 803,127	€ 329,801	€ -	€ -	€ -	€ 401,799	€ -
13	'Neckardreef en omgeving'	1323	33	Yes	€ 1,588,295	€ 840,948	€ 384,218	€ -	€ -	€ -	€ 363,129	€ -
14	'Zamenhofdreef en omgeving'	1172	92	Yes	€ 1,471,438	€ 771,275	€ 369,053	€ -	€ -	€ -	€ 331,110	€ -
15	'Wolga- en Donaudreef en omgeving'	857	68	No	€ 2,238,193	€ -	€ 344,962	€ -	€ 878,950	€ 460,850	€ 298,779	€ 254,651
16	'Vechtzoom-noord, Klopvaart'	1242	148	No	€ 3,162,643	€ -	€ 478,283	€ -	€ 1,237,286	€ 623,027	€ 446,117	€ 377,930
17	'Vechtzoom-zuid'	1309	36	Yes	€ 1,541,345	€ 789,108	€ 399,297	€ -	€ -	€ -	€ 352,940	€ -
	Total Overvecht	15884	1925	0	€ 32,523,777	€ 5,484,176	€ 6,462,382	€ -	€ 8,114,765	€ 4,778,460	€ 5,123,821	€ 2,560,173

Appendix F: LT collective (A+) – output parameters per neighbourhood district

LT collective (A+)					Energy demand				Emissions			
					Total	District heating	Electricity	Natural gas	Total	District heating	Electricity	Natural gas
id	Neighbourhood district	Residences	Utility	Existing HT-DH?	GJ/year	GJ/year	GJ/year	GJ/year	kg CO2/year	kg CO2/year	kg CO2/year	kg CO2/year
0	'Taag- en Rubicondreef en omgeving'	895	336	No	30617	15977	14641	0	376990	128913	248077	0
1	'Wolga- en Donaudreef en omgeving'	1305	14	Yes	32390	19837	12553	0	880824	668118	212706	0
2	'Zamenhofdreef en omgeving'	294	258	No	13789	6094	7695	0	179260	48880	130380	0
3	'Neckardreef en omgeving'	697	229	No	24394	12549	11845	0	312405	111697	200708	0
4	'Vechtzoom-zuid'	1190	155	No	32799	19373	13426	0	383280	155784	227497	0
5	'Bedrijventerrein en omgeving'	41	125	No	27201	9668	17533	0	368630	71543	297087	0
6	'Zambesidreef en omgeving'	763	188	No	22991	12840	10151	0	276313	104303	172010	0
7	'Tigrisdreef en omgeving'	1000	172	No	26386	15497	10889	0	311157	126650	184507	0
8	'Poldergebied Overvecht'	93	16	No	5732	2631	3101	0	84847	32296	52551	0
9	'Taag- en Rubicondreef en omgeving'	1099	24	Yes	34873	18788	16085	0	905322	632772	272550	0
10	'Vechtzoom-noord, Klopvaart'	238	1	Yes	6961	4507	2454	0	193382	151795	41587	0
11	'Tigrisdreef en omgeving'	910	7	Yes	21797	13472	8325	0	594802	453741	141060	0
12	'Zambesidreef en omgeving'	1456	23	Yes	34748	21144	13605	0	942644	712118	230526	0
13	'Neckardreef en omgeving'	1323	33	Yes	35997	20734	15263	0	956956	698329	258627	0
14	'Zamenhofdreef en omgeving'	1172	92	Yes	33285	18697	14588	0	876896	629706	247190	0
15	'Wolga- en Donaudreef en omgeving'	857	68	No	23166	13351	9815	0	289481	123168	166313	0
16	'Vechtzoom-noord, Klopvaart'	1242	148	No	33027	19674	13352	0	384958	158711	226248	0
17	'Vechtzoom-zuid'	1309	36	Yes	35627	19926	15700	0	937154	671125	266029	0
	Total Overvecht	15884	1925	0	475781	264759	211022	0	9255301	5679649	3575652	0

LT collective (A+)					Societal costs							
					Total	District heating	Electricity use	Natural gas use	Heat pumps	Insulation	Electricity grid	Natural gas grid
id	Neighbourhood district	Residences	Utility	Existing HT-DH?	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year
0	'Taag- en Rubicondreef en omgeving'	895	336	No	€ 2,355,680	€ 657,648	€ 369,878	€ -	€ -	€ 620,096	€ 373,898	€ 334,159
1	'Wolga- en Donaudreef en omgeving'	1305	14	Yes	€ 1,782,193	€ 636,310	€ 305,438	€ -	€ -	€ 481,018	€ 359,428	€ -
2	'Zamenhofdreef en omgeving'	294	258	No	€ 1,111,917	€ 280,318	€ 199,903	€ -	€ -	€ 287,077	€ 175,816	€ 168,803
3	'Neckardreef en omgeving'	697	229	No	€ 1,805,722	€ 496,318	€ 303,124	€ -	€ -	€ 472,745	€ 278,457	€ 255,077
4	'Vechtzoom-zuid'	1190	155	No	€ 2,451,050	€ 751,381	€ 329,016	€ -	€ -	€ 577,448	€ 426,036	€ 367,170
5	'Bedrijventerrein en omgeving'	41	125	No	€ 1,985,362	€ 609,867	€ 519,297	€ -	€ -	€ 706,602	€ 4,247	€ 145,349
6	'Zambesidreef en omgeving'	763	188	No	€ 1,682,804	€ 496,090	€ 251,261	€ -	€ -	€ 378,626	€ 299,081	€ 257,745
7	'Tigrisdreef en omgeving'	1000	172	No	€ 2,074,304	€ 615,331	€ 262,506	€ -	€ -	€ 501,045	€ 377,215	€ 318,207
8	'Poldergebied Overvecht'	93	16	No	€ 514,253	€ 133,235	€ 74,289	€ -	€ -	€ 150,943	€ 74,706	€ 81,081
9	'Taag- en Rubicondreef en omgeving'	1099	24	Yes	€ 2,096,774	€ 659,630	€ 420,281	€ -	€ -	€ 728,648	€ 288,215	€ -
10	'Vechtzoom-noord, Klopvaart'	238	1	Yes	€ 414,499	€ 148,486	€ 58,833	€ -	€ -	€ 137,060	€ 70,120	€ -
11	'Tigrisdreef en omgeving'	910	7	Yes	€ 1,321,961	€ 439,282	€ 200,110	€ -	€ -	€ 429,305	€ 253,264	€ -
12	'Zambesidreef en omgeving'	1456	23	Yes	€ 2,071,561	€ 679,528	€ 329,801	€ -	€ -	€ 660,434	€ 401,799	€ -
13	'Neckardreef en omgeving'	1323	33	Yes	€ 2,160,515	€ 697,886	€ 384,218	€ -	€ -	€ 715,283	€ 363,129	€ -
14	'Zamenhofdreef en omgeving'	1172	92	Yes	€ 1,972,326	€ 614,207	€ 369,053	€ -	€ -	€ 657,956	€ 331,110	€ -
15	'Wolga- en Donaudreef en omgeving'	857	68	No	€ 1,772,366	€ 522,001	€ 236,449	€ -	€ -	€ 460,850	€ 298,414	€ 254,651
16	'Vechtzoom-noord, Klopvaart'	1242	148	No	€ 2,522,719	€ 755,129	€ 321,273	€ -	€ -	€ 623,027	€ 445,359	€ 377,930
17	'Vechtzoom-zuid'	1309	36	Yes	€ 2,095,794	€ 650,769	€ 399,297	€ -	€ -	€ 692,789	€ 352,940	€ -
	Total Overvecht	15884	1925	0	€ 32,191,800	€ 9,843,415	€ 5,334,027	€ -	€ -	€ 9,280,952	€ 5,173,234	€ 2,560,173

Appendix G: HT collective (-) – output parameters per neighbourhood district

HT collective (-)					Energy demand				Emissions			
					Total	District heating	Electricity	Natural gas	Total	District heating	Electricity	Natural gas
id	Neighbourhood district	Residences	Utility	Existing HT-DH?	GJ/year	GJ/year	GJ/year	GJ/year	kg CO2/year	kg CO2/year	kg CO2/year	kg CO2/year
0	'Taag- en Rubicondreef en omgeving'	895	336	No	47342	32100	15242	0	1339404	1081144	258260	0
1	'Wolga- en Donaudreef en omgeving'	1305	14	Yes	45756	33203	12553	0	1330994	1118288	212706	0
2	'Zamenhofdreef en omgeving'	294	258	No	21509	13616	7893	0	592325	458577	133748	0
3	'Neckardreef en omgeving'	697	229	No	41414	28956	12458	0	1186338	975237	211102	0
4	'Vechtzoom-zuid'	1190	155	No	49200	35609	13591	0	1429601	1199302	230299	0
5	'Bedrijventerrein en omgeving'	41	125	No	53946	34853	19092	0	1497370	1173862	323508	0
6	'Zambesidreef en omgeving'	763	188	No	35058	24635	10423	0	1006325	829708	176617	0
7	'Tigrisdreef en omgeving'	1000	172	No	39135	28087	11048	0	1133177	945975	187202	0
8	'Poldergebied Overvecht'	93	16	No	10595	7757	2838	0	309356	261265	48091	0
9	'Taag- en Rubicondreef en omgeving'	1099	24	Yes	55386	39301	16085	0	1596221	1323671	272550	0
10	'Vechtzoom-noord, Klopvaart'	238	1	Yes	11499	9045	2454	0	346211	304624	41587	0
11	'Tigrisdreef en omgeving'	910	7	Yes	31997	23672	8325	0	938345	797285	141060	0
12	'Zambesidreef en omgeving'	1456	23	Yes	49923	36318	13605	0	1453709	1223183	230526	0
13	'Neckardreef en omgeving'	1323	33	Yes	53561	38298	15263	0	1548496	1289869	258627	0
14	'Zamenhofdreef en omgeving'	1172	92	Yes	52568	37980	14588	0	1526349	1279159	247190	0
15	'Wolga- en Donaudreef en omgeving'	857	68	No	39839	30065	9774	0	1178205	1012596	165610	0
16	'Vechtzoom-noord, Klopvaart'	1242	148	No	48331	34930	13401	0	1403501	1176427	227073	0
17	'Vechtzoom-zuid'	1309	36	Yes	52610	36910	15700	0	1509169	1243139	266029	0
	Total Overvecht	15884	1925	0	739670	525335	214335	0	21325096	17693310	3631786	0

HT collective (-)					Societal costs							
					Total	District heating	Electricity use	Natural gas use	Heat pumps	Insulation	Electricity grid	Natural gas grid
id	Neighbourhood district	Residences	Utility	Existing HT-DH?	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year
0	'Taag- en Rubicondreef en omgeving'	895	336	No	€ 2,259,105	€ 1,207,948	€ 385,877	€ -	€ -	€ -	€ 331,121	€ 334,159
1	'Wolga- en Donaudreef en omgeving'	1305	14	Yes	€ 1,389,893	€ 725,028	€ 305,438	€ -	€ -	€ -	€ 359,428	€ -
2	'Zamenhofdreef en omgeving'	294	258	No	€ 1,083,582	€ 548,002	€ 205,494	€ -	€ -	€ -	€ 161,283	€ 168,803
3	'Neckardreef en omgeving'	697	229	No	€ 1,808,490	€ 986,644	€ 321,740	€ -	€ -	€ -	€ 245,028	€ 255,077
4	'Vechtzoom-zuid'	1190	155	No	€ 2,448,768	€ 1,368,282	€ 334,040	€ -	€ -	€ -	€ 379,276	€ 367,170
5	'Bedrijventerrein en omgeving'	41	125	No	€ 1,796,033	€ 1,044,555	€ 565,180	€ -	€ -	€ -	€ 40,950	€ 145,349
6	'Zambesidreef en omgeving'	763	188	No	€ 1,715,741	€ 936,427	€ 259,428	€ -	€ -	€ -	€ 262,141	€ 257,745
7	'Tigrisdreef en omgeving'	1000	172	No	€ 2,064,461	€ 1,145,318	€ 266,493	€ -	€ -	€ -	€ 334,443	€ 318,207
8	'Poldergebied Overvecht'	93	16	No	€ 579,376	€ 344,628	€ 78,445	€ -	€ -	€ -	€ 75,221	€ 81,081
9	'Taag- en Rubicondreef en omgeving'	1099	24	Yes	€ 1,514,123	€ 805,627	€ 420,281	€ -	€ -	€ -	€ 288,215	€ -
10	'Vechtzoom-noord, Klopvaart'	238	1	Yes	€ 307,555	€ 178,602	€ 58,833	€ -	€ -	€ -	€ 70,120	€ -
11	'Tigrisdreef en omgeving'	910	7	Yes	€ 960,349	€ 506,975	€ 200,110	€ -	€ -	€ -	€ 253,264	€ -
12	'Zambesidreef en omgeving'	1456	23	Yes	€ 1,516,230	€ 784,631	€ 329,801	€ -	€ -	€ -	€ 401,799	€ -
13	'Neckardreef en omgeving'	1323	33	Yes	€ 1,565,054	€ 817,707	€ 384,218	€ -	€ -	€ -	€ 363,129	€ -
14	'Zamenhofdreef en omgeving'	1172	92	Yes	€ 1,453,003	€ 752,840	€ 369,053	€ -	€ -	€ -	€ 331,110	€ -
15	'Wolga- en Donaudreef en omgeving'	857	68	No	€ 1,851,317	€ 1,093,743	€ 237,338	€ -	€ -	€ -	€ 265,585	€ 254,651
16	'Vechtzoom-noord, Klopvaart'	1242	148	No	€ 2,499,010	€ 1,400,760	€ 322,778	€ -	€ -	€ -	€ 397,543	€ 377,930
17	'Vechtzoom-zuid'	1309	36	Yes	€ 1,525,230	€ 772,993	€ 399,297	€ -	€ -	€ -	€ 352,940	€ -
	Total Overvecht	15884	1925	0	€ 28,337,320	€ 15,420,709	€ 5,443,842	€ -	€ -	€ -	€ 4,912,596	€ 2,560,173

Appendix H: 'Optimal' pathway 2030 – output parameters per neighbourhood district

'Optimal' pathway 2030					Energy demand				Emissions			
					Total	District heating	Electricity	Natural gas	Total	District heating	Electricity	Natural gas
id	Neighbourhood district	Residences	Utility	Existing HT-DH?	GJ/year	GJ/year	GJ/year	GJ/year	kg CO2/year	kg CO2/year	kg CO2/year	kg CO2/year
0	'Taag- en Rubicondreef en omgeving'	895	336	No	47342	32100	15242	0	1339404	1081144	258260	0
1	'Wolga- en Donaudreef en omgeving'	1305	14	Yes	45756	33203	12553	0	1330994	1118288	212706	0
2	'Zamenhofdreef en omgeving'	294	258	No	21509	13616	7893	0	592325	458577	133748	0
3	'Neckardreef en omgeving'	697	229	No	24394	12549	11845	0	312405	111697	200708	0
4	'Vechtzoom-zuid'	1190	155	No	49200	35609	13591	0	1429601	1199302	230299	0
5	'Bedrijventerrein en omgeving'	41	125	No	53946	34853	19092	0	1497370	1173862	323508	0
6	'Zambesidreef en omgeving'	763	188	No	22991	12840	10151	0	276313	104303	172010	0
7	'Tigrisdreef en omgeving'	1000	172	No	39135	28087	11048	0	1133177	945975	187202	0
8	'Poldergebied Overvecht'	93	16	No	3858	0	3858	0	65367	0	65367	0
9	'Taag- en Rubicondreef en omgeving'	1099	24	Yes	55386	39301	16085	0	1596221	1323671	272550	0
10	'Vechtzoom-noord, Klopvaart'	238	1	Yes	11499	9045	2454	0	346211	304624	41587	0
11	'Tigrisdreef en omgeving'	910	7	Yes	31997	23672	8325	0	938345	797285	141060	0
12	'Zambesidreef en omgeving'	1456	23	Yes	49923	36318	13605	0	1453709	1223183	230526	0
13	'Neckardreef en omgeving'	1323	33	Yes	53561	38298	15263	0	1548496	1289869	258627	0
14	'Zamenhofdreef en omgeving'	1172	92	Yes	52568	37980	14588	0	1526349	1279159	247190	0
15	'Wolga- en Donaudreef en omgeving'	857	68	No	23166	13351	9815	0	289481	123168	166313	0
16	'Vechtzoom-noord, Klopvaart'	1242	148	No	48331	34930	13401	0	1403501	1176427	227073	0
17	'Vechtzoom-zuid'	1309	36	Yes	52610	36910	15700	0	1509169	1243139	266029	0
	Total Overvecht	0	0	0	687173	472662	214511	0	18588437	14953673	3634764	0

'Optimal' pathway 2030					Societal costs							
					Total	District heating	Electricity use	Natural gas use	Heat pumps	Insulation	Electricity grid	Natural gas grid
id	Neighbourhood district	Residences	Utility	Existing HT-DH?	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year	Euro2010/year
0	'Taag- en Rubicondreef en omgeving'	895	336	No	€ 2,259,105	€ 1,207,948	€ 385,877	€ -	€ -	€ -	€ 331,121	€ 334,159
1	'Wolga- en Donaudreef en omgeving'	1305	14	Yes	€ 1,389,893	€ 725,028	€ 305,438	€ -	€ -	€ -	€ 359,428	€ -
2	'Zamenhofdreef en omgeving'	294	258	No	€ 1,083,582	€ 548,002	€ 205,494	€ -	€ -	€ -	€ 161,283	€ 168,803
3	'Neckardreef en omgeving'	697	229	No	€ 1,805,722	€ 496,318	€ 303,124	€ -	€ -	€ 472,745	€ 278,457	€ 255,077
4	'Vechtzoom-zuid'	1190	155	No	€ 2,448,768	€ 1,368,282	€ 334,040	€ -	€ -	€ -	€ 379,276	€ 367,170
5	'Bedrijventerrein en omgeving'	41	125	No	€ 1,796,033	€ 1,044,555	€ 565,180	€ -	€ -	€ -	€ 40,950	€ 145,349
6	'Zambesidreef en omgeving'	763	188	No	€ 1,682,804	€ 496,090	€ 251,261	€ -	€ -	€ 378,626	€ 299,081	€ 257,745
7	'Tigrisdreef en omgeving'	1000	172	No	€ 2,064,461	€ 1,145,318	€ 266,493	€ -	€ -	€ -	€ 334,443	€ 318,207
8	'Poldergebied Overvecht'	93	16	No	€ 573,151	€ -	€ 104,054	€ -	€ 164,726	€ 150,943	€ 72,349	€ 81,081
9	'Taag- en Rubicondreef en omgeving'	1099	24	Yes	€ 1,514,123	€ 805,627	€ 420,281	€ -	€ -	€ -	€ 288,215	€ -
10	'Vechtzoom-noord, Klopvaart'	238	1	Yes	€ 307,555	€ 178,602	€ 58,833	€ -	€ -	€ -	€ 70,120	€ -
11	'Tigrisdreef en omgeving'	910	7	Yes	€ 960,349	€ 506,975	€ 200,110	€ -	€ -	€ -	€ 253,264	€ -
12	'Zambesidreef en omgeving'	1456	23	Yes	€ 1,516,230	€ 784,631	€ 329,801	€ -	€ -	€ -	€ 401,799	€ -
13	'Neckardreef en omgeving'	1323	33	Yes	€ 1,565,054	€ 817,707	€ 384,218	€ -	€ -	€ -	€ 363,129	€ -
14	'Zamenhofdreef en omgeving'	1172	92	Yes	€ 1,453,003	€ 752,840	€ 369,053	€ -	€ -	€ -	€ 331,110	€ -
15	'Wolga- en Donaudreef en omgeving'	857	68	No	€ 1,772,366	€ 522,001	€ 236,449	€ -	€ -	€ 460,850	€ 298,414	€ 254,651
16	'Vechtzoom-noord, Klopvaart'	1242	148	No	€ 2,499,010	€ 1,400,760	€ 322,778	€ -	€ -	€ -	€ 397,543	€ 377,930
17	'Vechtzoom-zuid'	1309	36	Yes	€ 1,525,230	€ 772,993	€ 399,297	€ -	€ -	€ -	€ 352,940	€ -
	Total Overvecht	0	0	0	€ 28,216,439	€ 13,573,676	€ 5,441,779	€ -	€ 164,726	€ 1,463,165	€ 5,012,922	€ 2,560,173

Appendix I: Results sensitivity analysis – Societal discount rate

Optimal pathways for different societal discount rates (4% = standard):

		Societal discount rate		
id	Neighbourhood district	4%	5%	6%
0	'Taag- en Rubicondreef en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)
1	'Wolga- en Donaudreef en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)
2	'Zamenhofdreef en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)
3	'Neckardreef en omgeving'	LT collective (A+)	HT collective (-)	HT collective (-)
4	'Vechtzoom-zuid'	HT collective (-)	HT collective (-)	HT collective (-)
5	'Bedrijventerrein en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)
6	'Zambesidreef en omgeving'	LT collective (A+)	HT collective (-)	HT collective (-)
7	'Tigrisdreef en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)
8	'Poldergebied Overvecht'	All-electric (A+)	All-electric (A+)	All-electric (A+)
9	'Taag- en Rubicondreef en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)
10	'Vechtzoom-noord, Klopvaart'	HT collective (-)	HT collective (-)	HT collective (-)
11	'Tigrisdreef en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)
12	'Zambesidreef en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)
13	'Neckardreef en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)
14	'Zamenhofdreef en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)
15	'Wolga- en Donaudreef en omgeving'	LT collective (A+)	LT collective (A+)	HT collective (-)
16	'Vechtzoom-noord, Klopvaart'	HT collective (-)	HT collective (-)	HT collective (-)
17	'Vechtzoom-zuid'	HT collective (-)	HT collective (-)	HT collective (-)

Societal costs per neighbourhood district for different societal discount rates (4% = standard):

		All-electric (A+)			LT collective (A+)			HT collective (-)		
id	Neighbourhood district	4%	5%	6%	4%	5%	6%	4%	5%	6%
0	'Taag- en Rubicondreef en omgeving'	€ 2,832,707	€ 2,955,752	€ 3,084,394	€ 2,355,680	€ 2,499,067	€ 2,651,688	€ 2,259,105	€ 2,334,183	€ 2,415,181
1	'Wolga- en Donaudreef en omgeving'	€ 1,410,047	€ 1,410,047	€ 1,410,047	€ 1,782,193	€ 1,842,259	€ 1,905,453	€ 1,389,893	€ 1,389,893	€ 1,389,893
2	'Zamenhofdreef en omgeving'	€ 1,302,271	€ 1,357,259	€ 1,414,769	€ 1,111,917	€ 1,177,312	€ 1,246,904	€ 1,083,582	€ 1,119,150	€ 1,157,522
3	'Neckardreef en omgeving'	€ 2,196,397	€ 2,290,704	€ 2,389,295	€ 1,805,722	€ 1,913,161	€ 2,027,492	€ 1,808,490	€ 1,867,389	€ 1,930,934
4	'Vechtzoom-zuid'	€ 3,089,535	€ 3,218,061	€ 3,352,274	€ 2,451,050	€ 2,597,938	€ 2,754,479	€ 2,448,768	€ 2,536,241	€ 2,630,612
5	'Bedrijventerrein en omgeving'	€ 2,074,782	€ 2,190,958	€ 2,312,686	€ 1,985,362	€ 2,142,822	€ 2,310,336	€ 1,796,033	€ 1,854,114	€ 1,916,775
6	'Zambesidreef en omgeving'	€ 2,093,242	€ 2,177,060	€ 2,264,593	€ 1,682,804	€ 1,779,082	€ 1,881,687	€ 1,715,741	€ 1,775,813	€ 1,840,623
7	'Tigrisdreef en omgeving'	€ 2,589,647	€ 2,698,137	€ 2,811,459	€ 2,074,304	€ 2,198,183	€ 2,330,156	€ 2,064,461	€ 2,139,977	€ 2,221,448
8	'Poldergebied Overvecht'	€ 573,151	€ 599,535	€ 627,158	€ 514,253	€ 546,822	€ 581,454	€ 579,376	€ 603,292	€ 629,095
9	'Taag- en Rubicondreef en omgeving'	€ 1,535,218	€ 1,535,218	€ 1,535,218	€ 2,096,774	€ 2,187,761	€ 2,283,488	€ 1,514,123	€ 1,514,123	€ 1,514,123
10	'Vechtzoom-noord, Klopvaart'	€ 314,400	€ 314,400	€ 314,400	€ 414,499	€ 431,613	€ 449,620	€ 307,555	€ 307,555	€ 307,555
11	'Tigrisdreef en omgeving'	€ 975,741	€ 975,741	€ 975,741	€ 1,321,961	€ 1,375,569	€ 1,431,970	€ 960,349	€ 960,349	€ 960,349
12	'Zambesidreef en omgeving'	€ 1,534,726	€ 1,534,726	€ 1,534,726	€ 2,071,561	€ 2,154,030	€ 2,240,795	€ 1,516,230	€ 1,516,230	€ 1,516,230
13	'Neckardreef en omgeving'	€ 1,588,295	€ 1,588,295	€ 1,588,295	€ 2,160,515	€ 2,249,834	€ 2,343,805	€ 1,565,054	€ 1,565,054	€ 1,565,054
14	'Zamenhofdreef en omgeving'	€ 1,471,438	€ 1,471,438	€ 1,471,438	€ 1,972,326	€ 2,054,486	€ 2,140,926	€ 1,453,003	€ 1,453,003	€ 1,453,003
15	'Wolga- en Donaudreef en omgeving'	€ 2,238,193	€ 2,335,945	€ 2,438,072	€ 1,772,366	€ 1,880,470	€ 1,995,559	€ 1,851,317	€ 1,917,774	€ 1,989,471
16	'Vechtzoom-noord, Klopvaart'	€ 3,162,643	€ 3,297,037	€ 3,437,423	€ 2,522,719	€ 2,675,295	€ 2,837,821	€ 2,499,010	€ 2,589,015	€ 2,686,118
17	'Vechtzoom-zuid'	€ 1,541,345	€ 1,541,345	€ 1,541,345	€ 2,095,794	€ 2,182,304	€ 2,273,319	€ 1,525,230	€ 1,525,230	€ 1,525,230
	Total Overvecht	**€ 32,523,777**	**€ 33,491,657**	**€ 34,503,332**	**€ 32,191,800**	**€ 33,888,007**	**€ 35,686,950**	**€ 28,337,320**	**€ 28,968,385**	**€ 29,649,216**

Appendix J: Results sensitivity analysis – Learning curves

Optimal pathways for different learning curves (off = no learning effect, 0 = minimal learning effect, 0.5 = standard, 1 = maximal learning effect):

		Learning curves (off=const. costs, 0=min. learning effect, 1=max. learning effect)					
id	Neighbourhood district	off	min	0.25	0.5	0.75	max
0	'Taag- en Rubicondreef en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)
1	'Wolga- en Donaudreef en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)
2	'Zamenhofdreef en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)
3	'Neckardreef en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)	LT collective (A+)	LT collective (A+)	LT collective (A+)
4	'Vechtzoom-zuid'	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	LT collective (A+)	LT collective (A+)
5	'Bedrijventerrein en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)
6	Zambesidreef en omgeving'	HT collective (-)	HT collective (-)	LT collective (A+)	LT collective (A+)	LT collective (A+)	LT collective (A+)
7	'Tigrisdreef en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	LT collective (A+)	LT collective (A+)
8	Poldergebied Overvecht'	All-electric (A+)	HT collective (-)	All-electric (A+)	All-electric (A+)	All-electric (A+)	All-electric (A+)
9	'Taag- en Rubicondreef en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)
10	'Vechtzoom-noord, Klopvaart'	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)
11	'Tigrisdreef en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)
12	'Zambesidreef en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)
13	'Neckardreef en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)
14	'Zamenhofdreef en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)
15	Wolga- en Donaudreef en omgeving'	HT collective (-)	LT collective (A+)	LT collective (A+)	LT collective (A+)	LT collective (A+)	LT collective (A+)
16	'Vechtzoom-noord, Klopvaart'	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	LT collective (A+)	LT collective (A+)
17	'Vechtzoom-zuid'	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)

Societal costs per neighbourhood district for different learning curves (off = no learning effect, 0 = minimal learning effect, 0.5 = standard, 1 = maximal learning effect):

		All-electric (A+)					
id	Neighbourhood district	off	min	0.25	0.5	0.75	max
0	'Taag- en Rubicondreef en omgeving'	€ 3,181,511	€ 2,984,327	€ 2,908,517	€ 2,832,707	€ 2,756,896	€ 2,681,086
1	'Wolga- en Donaudreef en omgeving'	€ 1,482,602	€ 1,423,454	€ 1,416,750	€ 1,410,047	€ 1,403,343	€ 1,396,640
2	'Zamenhofdreef en omgeving'	€ 1,463,751	€ 1,368,413	€ 1,335,342	€ 1,302,271	€ 1,269,200	€ 1,236,129
3	'Neckardreef en omgeving'	€ 2,462,316	€ 2,313,014	€ 2,254,706	€ 2,196,397	€ 2,138,089	€ 2,079,780
4	'Vechtzoom-zuid'	€ 3,414,350	€ 3,259,303	€ 3,174,419	€ 3,089,535	€ 3,004,652	€ 2,919,768
5	'Bedrijventerrein en omgeving'	€ 2,472,246	€ 2,198,292	€ 2,136,537	€ 2,074,782	€ 2,013,027	€ 1,951,272
6	'Zambesidreef en omgeving'	€ 2,306,219	€ 2,203,626	€ 2,148,434	€ 2,093,242	€ 2,038,050	€ 1,982,858
7	'Tigrisdreef en omgeving'	€ 2,871,485	€ 2,730,742	€ 2,660,195	€ 2,589,647	€ 2,519,100	€ 2,448,553
8	'Poldergebied Overvecht'	€ 658,057	€ 602,745	€ 587,948	€ 573,151	€ 558,355	€ 543,558
9	'Taag- en Rubicondreef en omgeving'	€ 1,645,574	€ 1,555,379	€ 1,545,298	€ 1,535,218	€ 1,525,137	€ 1,515,057
10	'Vechtzoom-noord, Klopvaart'	€ 330,592	€ 317,332	€ 315,866	€ 314,400	€ 312,934	€ 311,468
11	'Tigrisdreef en omgeving'	€ 1,025,767	€ 984,968	€ 980,355	€ 975,741	€ 971,127	€ 966,513
12	'Zambesidreef en omgeving'	€ 1,612,217	€ 1,549,159	€ 1,541,942	€ 1,534,726	€ 1,527,510	€ 1,520,294
13	'Neckardreef en omgeving'	€ 1,689,509	€ 1,606,837	€ 1,597,566	€ 1,588,295	€ 1,579,023	€ 1,569,752
14	'Zamenhofdreef en omgeving'	€ 1,554,600	€ 1,486,859	€ 1,479,149	€ 1,471,438	€ 1,463,728	€ 1,456,017
15	'Wolga- en Donaudreef en omgeving'	€ 2,497,421	€ 2,363,799	€ 2,300,996	€ 2,238,193	€ 2,175,390	€ 2,112,586
16	'Vechtzoom-noord, Klopvaart'	€ 3,513,095	€ 3,337,047	€ 3,249,845	€ 3,162,643	€ 3,075,440	€ 2,988,238
17	'Vechtzoom-zuid'	€ 1,625,542	€ 1,556,943	€ 1,549,144	€ 1,541,345	€ 1,533,546	€ 1,525,747
	Total Overvecht	**€ 35,806,853**	**€ 33,842,238**	**€ 33,183,008**	**€ 32,523,777**	**€ 31,864,547**	**€ 31,205,316**

		LT collective (A+)					
id	Neighbourhood district	off	min	0.25	0.5	0.75	max
0	'Taag- en Rubicondreef en omgeving'	€ 2,870,774	€ 2,415,303	€ 2,366,593	€ 2,355,680	€ 2,330,170	€ 2,278,566
1	'Wolga- en Donaudreef en omgeving'	€ 2,125,321	€ 1,840,696	€ 1,811,445	€ 1,782,193	€ 1,752,942	€ 1,723,691
2	'Zamenhofdreef en omgeving'	€ 1,323,348	€ 1,158,238	€ 1,135,078	€ 1,111,917	€ 1,088,757	€ 1,066,373
3	'Neckardreef en omgeving'	€ 2,257,268	€ 1,878,147	€ 1,840,343	€ 1,805,722	€ 1,764,735	€ 1,771,036
4	'Vechtzoom-zuid'	€ 2,995,986	€ 2,553,281	€ 2,502,166	€ 2,451,050	€ 2,389,042	€ 2,338,412
5	'Bedrijventerrein en omgeving'	€ 2,454,018	€ 2,049,768	€ 2,041,913	€ 1,985,362	€ 1,928,811	€ 1,872,260
6	'Zambesidreef en omgeving'	€ 2,010,638	€ 1,749,852	€ 1,716,328	€ 1,682,804	€ 1,649,280	€ 1,615,755
7	'Tigrisdreef en omgeving'	€ 2,521,916	€ 2,160,640	€ 2,117,472	€ 2,074,304	€ 2,011,115	€ 1,968,792
8	'Poldergebied Overvecht'	€ 584,605	€ 531,865	€ 520,204	€ 514,253	€ 496,880	€ 485,218
9	'Taag- en Rubicondreef en omgeving'	€ 2,616,994	€ 2,185,246	€ 2,141,010	€ 2,096,774	€ 2,052,538	€ 2,008,302
10	'Vechtzoom-noord, Klopvaart'	€ 507,786	€ 430,280	€ 422,389	€ 414,499	€ 406,608	€ 398,717
11	'Tigrisdreef en omgeving'	€ 1,613,472	€ 1,371,436	€ 1,346,699	€ 1,321,961	€ 1,297,224	€ 1,272,486
12	'Zambesidreef en omgeving'	€ 2,520,545	€ 2,147,909	€ 2,109,735	€ 2,071,561	€ 2,033,387	€ 1,995,213
13	'Neckardreef en omgeving'	€ 2,664,077	€ 2,246,116	€ 2,203,316	€ 2,160,515	€ 2,117,715	€ 2,074,915
14	'Zamenhofdreef en omgeving'	€ 2,425,588	€ 2,049,431	€ 2,010,878	€ 1,972,326	€ 1,933,774	€ 1,895,222
15	'Wolga- en Donaudreef en omgeving'	€ 2,216,252	€ 1,840,614	€ 1,802,866	€ 1,772,366	€ 1,727,371	€ 1,689,623
16	'Vechtzoom-noord, Klopvaart'	€ 3,081,883	€ 2,604,861	€ 2,582,649	€ 2,522,719	€ 2,469,543	€ 2,416,367
17	'Vechtzoom-zuid'	€ 2,569,684	€ 2,176,341	€ 2,136,067	€ 2,095,794	€ 2,055,521	€ 2,015,247
	Total Overvecht	**€ 39,360,155**	**€ 33,390,023**	**€ 32,807,150**	**€ 32,191,800**	**€ 31,505,411**	**€ 30,886,195**

		HT collective (-)					
id	Neighbourhood district	off	min	0.25	0.5	0.75	max
0	'Taag- en Rubicondreef en omgeving'	€ 2,446,423	€ 2,292,500	€ 2,275,783	€ 2,259,105	€ 2,242,468	€ 2,225,870
1	'Wolga- en Donaudreef en omgeving'	€ 1,451,112	€ 1,401,411	€ 1,395,652	€ 1,389,893	€ 1,384,134	€ 1,378,376
2	'Zamenhofdreef en omgeving'	€ 1,211,356	€ 1,106,192	€ 1,094,875	€ 1,083,582	€ 1,072,313	€ 1,061,068
3	'Neckardreef en omgeving'	€ 1,953,101	€ 1,834,239	€ 1,821,352	€ 1,808,490	€ 1,795,653	€ 1,782,843
4	'Vechtzoom-zuid'	€ 2,612,875	€ 2,478,169	€ 2,463,452	€ 2,448,768	€ 2,434,118	€ 2,419,501
5	'Bedrijventerrein en omgeving'	€ 2,184,966	€ 1,863,475	€ 1,829,717	€ 1,796,033	€ 1,762,424	€ 1,728,890
6	'Zambesidreef en omgeving'	€ 1,841,867	€ 1,738,233	€ 1,726,976	€ 1,715,741	€ 1,704,529	€ 1,693,340
7	'Tigrisdreef en omgeving'	€ 2,211,063	€ 2,090,518	€ 2,077,476	€ 2,064,461	€ 2,051,472	€ 2,038,511
8	'Poldergebied Overvecht'	€ 698,073	€ 599,620	€ 589,492	€ 579,376	€ 569,272	€ 559,180
9	'Taag- en Rubicondreef en omgeving'	€ 1,612,613	€ 1,532,306	€ 1,523,214	€ 1,514,123	€ 1,505,031	€ 1,495,939
10	'Vechtzoom-noord, Klopvaart'	€ 319,895	€ 309,845	€ 308,700	€ 307,555	€ 306,410	€ 305,264
11	'Tigrisdreef en omgeving'	€ 1,001,718	€ 968,134	€ 964,241	€ 960,349	€ 956,457	€ 952,564
12	'Zambesidreef en omgeving'	€ 1,583,316	€ 1,528,929	€ 1,522,579	€ 1,516,230	€ 1,509,881	€ 1,503,532
13	'Neckardreef en omgeving'	€ 1,653,195	€ 1,581,417	€ 1,573,235	€ 1,565,054	€ 1,556,872	€ 1,548,690
14	'Zamenhofdreef en omgeving'	€ 1,525,795	€ 1,466,696	€ 1,459,849	€ 1,453,003	€ 1,446,157	€ 1,439,310
15	'Wolga- en Donaudreef en omgeving'	€ 1,996,686	€ 1,876,895	€ 1,864,094	€ 1,851,317	€ 1,838,566	€ 1,825,839
16	'Vechtzoom-noord, Klopvaart'	€ 2,664,684	€ 2,528,500	€ 2,513,739	€ 2,499,010	€ 2,484,314	€ 2,469,650
17	'Vechtzoom-zuid'	€ 1,600,362	€ 1,539,317	€ 1,532,274	€ 1,525,230	€ 1,518,187	€ 1,511,143
	Total Overvecht	**€ 30,569,100**	**€ 28,736,397**	**€ 28,536,700**	**€ 28,337,320**	**€ 28,138,257**	**€ 27,939,511**

Appendix K: Results sensitivity analysis – Building improvement costs

Optimal pathways for different building improvement costs (1 = maximum costs, 0.5 = standard costs, 0 = minimum costs):

		Building improvement Costs (1=max, 0=min)				
id	Neighbourhood district	max	0.75	0.5	0.25	min
0	'Taag- en Rubicondreef en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)
1	'Wolga- en Donaudreef en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)
2	'Zamenhofdreef en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)
3	'Neckardreef en omgeving'	HT collective (-)	HT collective (-)	LT collective (A+)	LT collective (A+)	LT collective (A+)
4	'Vechtzoom-zuid'	HT collective (-)	HT collective (-)	HT collective (-)	LT collective (A+)	LT collective (A+)
5	'Bedrijventerrein en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)
6	'Zambesidreef en omgeving'	LT collective (A+)	LT collective (A+)	LT collective (A+)	LT collective (A+)	LT collective (A+)
7	'Tigrisdreef en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)	LT collective (A+)	LT collective (A+)
8	'Poldergebied Overvecht'	All-electric (A+)	All-electric (A+)	All-electric (A+)	All-electric (A+)	All-electric (A+)
9	'Taag- en Rubicondreef en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)
10	'Vechtzoom-noord, Klopvaart'	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)
11	'Tigrisdreef en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)
12	'Zambesidreef en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)
13	'Neckardreef en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)
14	'Zamenhofdreef en omgeving'	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)
15	'Wolga- en Donaudreef en omgeving'	LT collective (A+)	LT collective (A+)	LT collective (A+)	LT collective (A+)	LT collective (A+)
16	'Vechtzoom-noord, Klopvaart'	HT collective (-)	HT collective (-)	HT collective (-)	LT collective (A+)	LT collective (A+)
17	'Vechtzoom-zuid'	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)	HT collective (-)

Societal costs per neighbourhood district for different building improvement costs (1 = maximum costs, 0.5 = standard costs, 0 = minimum costs):

		All-electric (A+)					LT collective (A+)					HT collective (-)				
id	Neighbourhood district	1	0.75	0.5	0.25	0	1	0.75	0.5	0.25	0	1	0.75	0.5	0.25	0
0	'Taag- en Rubicondreef en omgeving'	€ 3,178,939	€ 3,005,823	€ 2,832,707	€ 2,659,590	€ 2,486,474	€ 2,429,374	€ 2,392,527	€ 2,355,680	€ 2,318,833	€ 2,281,986	€ 2,292,623	€ 2,275,864	€ 2,259,105	€ 2,242,346	€ 2,225,587
1	'Wolga- en Donaudreef en omgeving'	€ 1,357,580	€ 1,383,813	€ 1,410,047	€ 1,436,280	€ 1,462,514	€ 1,756,780	€ 1,769,487	€ 1,782,193	€ 1,794,900	€ 1,807,606	€ 1,331,861	€ 1,360,877	€ 1,389,893	€ 1,418,909	€ 1,447,925
2	'Zamenhofdreef en omgeving'	€ 1,438,703	€ 1,370,487	€ 1,302,271	€ 1,234,054	€ 1,165,838	€ 1,158,823	€ 1,135,370	€ 1,111,917	€ 1,088,464	€ 1,065,011	€ 1,129,784	€ 1,106,683	€ 1,083,582	€ 1,060,481	€ 1,037,381
3	'Neckardreef en omgeving'	€ 2,457,309	€ 2,326,853	€ 2,196,397	€ 2,065,941	€ 1,935,486	€ 1,851,206	€ 1,826,873	€ 1,805,722	€ 1,778,206	€ 1,753,873	€ 1,829,266	€ 1,818,878	€ 1,808,490	€ 1,798,101	€ 1,787,713
4	'Vechtzoom-zuid'	€ 3,492,667	€ 3,291,101	€ 3,089,535	€ 2,887,969	€ 2,686,403	€ 2,491,814	€ 2,471,432	€ 2,451,050	€ 2,430,669	€ 2,398,909	€ 2,444,322	€ 2,446,545	€ 2,448,768	€ 2,450,992	€ 2,453,215
5	'Bedrijventerrein en omgeving'	€ 2,239,263	€ 2,157,022	€ 2,074,782	€ 1,992,541	€ 1,910,301	€ 2,137,358	€ 2,061,360	€ 1,985,362	€ 1,909,364	€ 1,833,366	€ 1,992,128	€ 1,894,081	€ 1,796,033	€ 1,697,986	€ 1,599,938
6	'Zambesidreef en omgeving'	€ 2,359,404	€ 2,226,323	€ 2,093,242	€ 1,960,160	€ 1,827,079	€ 1,716,624	€ 1,699,714	€ 1,682,804	€ 1,665,894	€ 1,648,984	€ 1,724,613	€ 1,720,177	€ 1,715,741	€ 1,711,305	€ 1,706,869
7	'Tigrisdreef en omgeving'	€ 2,929,094	€ 2,759,371	€ 2,589,647	€ 2,419,924	€ 2,250,200	€ 2,109,239	€ 2,091,771	€ 2,074,304	€ 2,056,836	€ 2,018,503	€ 2,065,686	€ 2,065,073	€ 2,064,461	€ 2,063,848	€ 2,063,236
8	'Poldergebied Overvecht'	€ 622,877	€ 598,014	€ 573,151	€ 548,288	€ 523,425	€ 529,948	€ 519,245	€ 514,253	€ 497,839	€ 487,135	€ 629,141	€ 604,258	€ 579,376	€ 554,493	€ 529,610
9	'Taag- en Rubicondreef en omgeving'	€ 1,527,785	€ 1,531,501	€ 1,535,218	€ 1,538,934	€ 1,542,650	€ 2,189,370	€ 2,143,072	€ 2,096,774	€ 2,050,476	€ 2,004,178	€ 1,500,906	€ 1,507,515	€ 1,514,123	€ 1,520,731	€ 1,527,339
10	'Vechtzoom-noord, Klopvaart'	€ 303,994	€ 309,197	€ 314,400	€ 319,603	€ 324,807	€ 411,928	€ 413,213	€ 414,499	€ 415,784	€ 417,069	€ 295,218	€ 301,386	€ 307,555	€ 313,723	€ 319,892
11	'Tigrisdreef en omgeving'	€ 938,609	€ 957,175	€ 975,741	€ 994,307	€ 1,012,873	€ 1,306,486	€ 1,314,224	€ 1,321,961	€ 1,329,699	€ 1,337,437	€ 918,947	€ 939,648	€ 960,349	€ 981,050	€ 1,001,751
12	'Zambesidreef en omgeving'	€ 1,477,478	€ 1,506,102	€ 1,534,726	€ 1,563,350	€ 1,591,975	€ 2,055,026	€ 2,063,293	€ 2,071,561	€ 2,079,828	€ 2,088,096	€ 1,453,884	€ 1,485,057	€ 1,516,230	€ 1,547,404	€ 1,578,577
13	'Neckardreef en omgeving'	€ 1,556,528	€ 1,572,411	€ 1,588,295	€ 1,604,178	€ 1,620,061	€ 2,201,425	€ 2,180,970	€ 2,160,515	€ 2,140,061	€ 2,119,606	€ 1,526,901	€ 1,545,978	€ 1,565,054	€ 1,584,130	€ 1,603,206
14	'Zamenhofdreef en omgeving'	€ 1,439,698	€ 1,455,568	€ 1,471,438	€ 1,487,308	€ 1,503,178	€ 1,998,536	€ 1,985,431	€ 1,972,326	€ 1,959,221	€ 1,946,116	€ 1,416,188	€ 1,434,596	€ 1,453,003	€ 1,471,410	€ 1,489,818
15	'Wolga- en Donaudreef en omgeving'	€ 2,532,816	€ 2,385,504	€ 2,238,193	€ 2,090,881	€ 1,943,570	€ 1,798,775	€ 1,781,947	€ 1,772,366	€ 1,748,290	€ 1,731,462	€ 1,858,948	€ 1,855,133	€ 1,851,317	€ 1,847,502	€ 1,843,687
16	'Vechtzoom-noord, Klopvaart'	€ 3,579,463	€ 3,371,053	€ 3,162,643	€ 2,954,232	€ 2,745,822	€ 2,561,336	€ 2,542,027	€ 2,522,719	€ 2,503,410	€ 2,484,102	€ 2,489,808	€ 2,494,409	€ 2,499,010	€ 2,503,611	€ 2,508,212
17	'Vechtzoom-zuid'	€ 1,500,801	€ 1,521,073	€ 1,541,345	€ 1,561,617	€ 1,581,889	€ 2,113,974	€ 2,104,884	€ 2,095,794	€ 2,086,704	€ 2,077,614	€ 1,480,253	€ 1,502,742	€ 1,525,230	€ 1,547,719	€ 1,570,208
	Total Overvecht	**€ 34,933,009**	**€ 33,728,393**	**€ 32,523,777**	**€ 31,319,161**	**€ 30,114,546**	**€ 32,818,021**	**€ 32,496,840**	**€ 32,191,800**	**€ 31,854,478**	**€ 31,501,052**	**€ 28,380,479**	**€ 28,358,899**	**€ 28,337,320**	**€ 28,315,741**	**€ 28,294,162**