Design of Integrated Electricity and Heating Systems

An Optimization Study for the Netherlands

by

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Associated codes of the modelling practice are available at
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Preface

With this thesis, my adventure of MSc Engineering and Policy Analysis at the faculty of Technology, Policy and Management at the Delft University of Technology reaches an end. I have enjoyed even the most stressful moments of these two years full of learning, joy, and excitement. I have had the privilege of meeting many brilliant, hard-working, and maybe more importantly, friendly people during this journey. While finishing my student days with this research and opening a new page in my life, I would like to thank a number of important people who supported me to reach this point.

Firstly, I would like to express my gratitude to my supervisor Jan Kwakkel, for all the eye-opening moments and for all the questioning that enlightens the path of graduation. It has been a really intense 6 months with full of learning points and thank you for your contribution. Next, I would like to thank Emile Chappin for his detailed feedback and comforting suggestions when I needed them the most. It would be a shame if I skip mentioning it, thank you Emile for convincing me to give another chance to dropjes! I would also like to thank Zofia Lukszo for her precious feedback during the meetings, and all the convenience that she has provided me with.

I conducted this study in cooperation with one of the private energy companies operating in the Netherlands, Uniper. This thesis would not be able to reach an end without the support of Rick van Staveren. Thank you, Rick, for being there and spending your time to clarify even the silliest concerns I have had during the last 6 months. Thanks to your guidance, I have realized many mistakes, missing points, or shortcuts which I would not notice they exist without you. Most of the times, your suggestions were beyond this thesis, and they have become learning points for my whole career that lie ahead of me.

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Besides working hard, learning a lot, and experiencing new things, I have been laughing a lot during the last 2 years, and this joy was there thanks to my friends. I would like to thank the brilliant members of “Support Group”, I cannot even imagine the last two years without the memes sent to this group. Special thanks to Mikhail for the countless coffee breaks, Shajeeshan for his puzzling questions, and Ammar for just being himself.

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Kind regards,

Merih Koray Karabulut
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Executive Summary

Due to the fact that the electricity and heat production sectors have a high share of emitted greenhouse gases, many countries have started developing transition plans towards renewable technologies to reduce their emissions. However, most of the large-scale renewable energy development plans overlook a certain link between electricity and heating sector. Conventional electricity and/or heat energy generation systems which are based on fuel combustion can generate each others' primary output as the secondary output of their processes. Current efforts to reduce greenhouse gas emissions endanger this relation between heat and electricity generation systems because most of the renewable technologies are not capable of generating electricity and heat simultaneously, specifically, wind turbine applications exemplifies this situation.

This decoupling of electricity and heating sectors due to the integration of renewable sources generate many ambiguities. Whether the existing co-generation facilities will function as a part of the future energy systems, the existing heat networks will be of any use, or power-to-heat conversion will take place to strengthen the link between electricity and heat generation are points which are waiting to be clarified.

In line with the above-mentioned concerns, the target of this research is set as to explore how the electricity and heat generation facilities are installed and heating transmission networks are expanded to achieve minimum system cost under the effect of emission reduction targets. Specifically, the emphasis is put on the power-to-heat conversion technologies, co-generation facilities, and thermal grids.

The research is conducted for the Netherlands which is one of the European countries with a high share of fossil fuel-based electricity and heat generation system and also with ambitious climate targets for its future. Based on its current position, it is foreseeable that the Netherlands will undergo a series of drastic infrastructural changes to comply with the emission targets, and the above-mentioned ambiguities are quite valid for the country since onshore and offshore wind production possesses a significant share in the future development plans.

To explore the future conditions of generation and transmission capacity expansions in the Netherlands, an optimization model is designed. This created model approaches the Netherlands as an isolated country by excluding the regional energy transmissions, and it concentrates on the design of an integrated electricity and heating system. For the research, a greenfield approach is adopted which evaluates the future systems as if they are built from scratch. Also, the electricity transmission network is excluded by making a "copper-plate" assumption. The model is set to explore capacity investment decisions over 30 years in 355 municipalities, whereas operational decisions like unit commitment are made 3-hourly. A set of representative days which minimizes the time series distance for input data sets are used in the model to represent a decade.

For the analysis of the system, the reference scenario is set to represent emission targets imposed by the Dutch government for 2030 and 2050, and district heating share of the Dutch municipalities calculated based on heat density of them. While, experimental scenarios are set to explore changing emission targets, changing costs for power-to-heat technologies, and changing costs for the pipeline installations.

The findings indicate that the electricity sector maintains a fossil-fuel dominated generation scheme in between 2020 and 2030, while wind energy is utilized with a relatively small share. As the emission targets are imposed, the generation mix undergoes drastic shifts towards renewables. It is observed that the years between 2030 and 2040 witness a jump in the

installed wind power capacity, and for the last decade the investments shift to the biomass facilities.

Similarities are observed in the heat generation sector. Besides the industrial waste heat which is utilized as much as possible, for the years between 2020 and 2030, a major part of the generated heat energy comes from natural gas boilers, and a small share is fulfilled by power-to-heat technologies. As the emission reductions are imposed, this generation mix shifts to the major use of heat pumps in between 2030 and 2040, and biomass co-generation facilities in the years between 2040 and 2050. It is observed that the pipeline installations between municipalities take place mostly in the province of Zuid-Holland. While, the overall thermal grid indicates clusters around municipalities with available industrial waste heat.

It is found that the power-to-heat technologies are helpful to reach emission targets when there are investments made for the electricity generation systems based on renewable sources. One positively affects another, increases the system efficiency, and together they help the energy systems to reach their emission targets.

From the experiments, it is observed that imposing more restricting climate targets leads the system to invest more in the power-to-heat conversion technologies and thermal grid expansions. As the policies target further reductions in the emissions, the investments made for the renewable sources show incremental behaviour. As a result of the increased capacity of renewable sources, the investments for power-to-heat conversion technologies become more preferable to generate clean heat energy. Therefore, stricter climate targets make the shift from natural gas boilers to heat pumps sharper.

The findings indicate that biomass co-generation systems exist in the future energy sector as a base-load alternative. Due to the relatively higher cost values, the installation of biomass facilities is delayed until it becomes an obligation because of the emission reduction targets.

Lastly, it is observed that the thermal grid expansions occur, first, with the purpose of utilizing industrial waste heat as much as possible. Secondly, several pipeline installations are realized to decrease peak demand of municipalities by utilizing heat pumps while the wind energy is abundant. As a result, fewer capacity installations are needed in the overall system, and the electricity and heat demands can be fulfilled while yielding less total cost.

Contents

List of Figures

List of Tables

Nomenclature

A_{y,m_1,m_2}^{pipe} additional capacity between municipalities m_1 and m_2 in year y

$A_{y,m,f}$ additional capacity installation for facility type f in municipality m during the year y

$AF_{y,d,h,m,f}$ amount of fuel used by facility type f in municipality m during the hour h of day d of year y

C^{fuel} total fuel cost

C_f^{fuel} cost of fuel for facility type f

C^{inv} total investment cost

C_f^{inv} total investment cost of facility type f

C_{pipe}^{inv} total investment cost of pipe installations

C^{om} total annual O&M cost

C_f^{om} annual O&M cost of facility type f

C_{y,m_1,m_2}^{pipe} existing pipeline capacity between municipalities m_1 and m_2 in year y

C^{vom} total variable O&M cost

C_f^{vom} variable O&M cost of facility type f

$C_{y,m,f}$ installed capacity of facility type f in municipality m during the year y

D days

d_{m_1,m_2} distance between municipalities

$dh_{y,m}$ district heating share of municipality m in year y

e_f electrical efficiency of facility type f

E_y yearly emission value of year y

$ed_{y,d,h}$ electricity demand during hour h of day d of year y

$emission^{ref}$ emission value of the reference year

F fuels

fc_f fuel cost for the related fuel of facility type f

fcv_f calorific value of related fuel of facility type f

FE facilities which generate electricity

FFB fossil fuel based facilities

$fom_{y,f}$ unit fixed O&M cost of facility type f during year y

FT facilities which generate heat energy

$G^{e}_{y,d,h,f}$ generated amount of electricity by facility type f during the hour h of day d of year y

$G^{po}_{y,d,h,m,f}$ generated amount of primary output of facility type f in municipality m during the hour h of day d of year y

$GT^{e}_{y,d,h}$ total generated amount of electricity during the hour h of day d of year y

$GT^{t}_{y,d,h,m}$ generated amount of heat in municipality m during the hour h of day d of year y

H hours

$hd_{y,d,h,m}$ heat demand of municipality m during hour h of day d of year y

hl heat loss coefficient

HOF facilities which generate only heat energy

HP heat pumps

$ic^{pipe}_{m_1,m_2}$ initial capacity between municipalities m_1 and m_2

$ic_{m,f}$ initial generation capacity of facility type f in municipality m

$inv_{y,f}$ unit investment cost of facility type f in year y

$inv_{y,pipe}$ unit investment cost of pipeline installations in year y

M municipalities

$o_{y,d,h,m,f}$ output of facility type f in municipality m during hour h of day d of year y

r^{dec}_{y} coefficient of interest for 10 years starting from year y

r_y coefficient of interest rate until 2050 starting from year y

RE renewable energy facilities

$SE_{y,d,h}$ spilled electricity during hour h of day d of year y

$SH_{y,d,h,m}$ spilled heat energy in municipality m during hour h of day d of year y

$target_y$ emission reduction target in year y

TH_{y,d,h,m_2,m_1} transferred heat from municipality m_1 to m_2 in hour h of day d of year y

$vom_{y,f}$ unit variable O&M cost of facility f in year y

wh_m industrial waste heat capacity of municipality m

Y years

1

Introduction

The Blue Marble that hosts human beings has been undergoing a series of changes related to its climate. There has been a 0.8°C increase in Earth's average surface temperature since 1880 (NASA Earth Observatory, 2014). Two-thirds of this increase happened with a rate of 0.15°C to 0.20°C per decade since the late 1970s (Hansen, Ruedy, Sato, & Lo, 2010). This rapid increase might result in serious changes in the climate system such as rise in sea levels and extreme weather events like floods and droughts (IPCC, 2014a).

The high concentration of greenhouse gases causes a positive total radiative force leading to an increase in average temperature values. The atmospheric concentrations of CO_2, CH_4, and N_2O, which are categorized as the greenhouse gases, have reached their all-time high for the last 800,000 years (IPCC, 2014b). IPCC's 2014 Climate Change Report (2014b) identifies the "extremely likely" cause of these observed changes as greenhouse gas emissions due to anthropogenic activities.

Reducing greenhouse gas emissions is critically important to limit the increase in global average temperatures (IPCC, 2014a). To mitigate the effects of climate change, 195 countries have agreed on 2°C as the critical threshold for the global average temperature increase in the Paris Agreement (UNFCCC, 2015). The European Union has endorsed key targets such as a 40% reduction in greenhouse gas emissions with respect to 1990 levels by 2030 (European Council, 2014). Also, around 80-95% reduction in the emissions is targeted by 2050 (European Commission, 2012).

1.1. Problem Orientation

Greenhouse gas emissions can be caused by natural systems as well as anthropogenic activities (Yue & Gao, 2018). CO_2 emissions due to oceans or volcanoes, released gases from the Earth's crust due to tectonic activities, forest fires, and simply the breathing of living creatures are examples of natural sources. These natural greenhouse gas emissions were in action well before the humankind has reached to the industrial era. Later on, the increasing anthropogenic activities have resulted in emissions due to transportation, electricity and heat generation, or industrial activities.

Anthropogenic activities require further attention to mitigate the effects of climate change. These activities are responsible for 55.46% of the total greenhouse gases emitted in 2016, slightly more than the natural systems (Yue & Gao, 2018). The Earth is capable of balancing the natural emissions out by its sinks under normal circumstances. However, human activities put extra pressure on the Earth's balance (Yue & Gao, 2018). The accumulation of additional emissions from human activities should be kept under control to stay within the threshold value set by the Paris Agreement.

Fossil fuel combustion and industrial processes are the main anthropogenic activities which lead to an increase in global greenhouse gas emissions since the 1970s (IPCC, 2014b). Within fossil fuel combustion, electricity and heat production sectors were solely responsible for 40.8% of global CO_2 emissions in 2008 (Karl & Lippelt, 2011). This means that a reduction in emissions of electricity and heat generation processes can have significant effects on reducing greenhouse gas emissions.

Due to the high share of electricity and heat production sectors in greenhouse gas emissions, many countries have started developing plans to reduce their emissions. As a part of these plans, carbon sequestration techniques, which absorb CO_2 from the atmosphere, have become one of the focusing points during recent years. Although they sound promising, Moriarty and Honnery (2016) indicate that these techniques have low efficiency values which interfere with their widespread use. Therefore, more fundamental changes are sought for the energy sector. Decreasing the fossil-fuel dominance by shifting to other energy options can reduce emissions, too. Nuclear power has become one of the prominent discussion points for this reason. However, especially after the Fukushima accident in 2011, the global perception towards nuclear technologies was negatively affected (Ming, Yingxin, Shaojie, Hui, & Chunxue, 2016). As a result, renewable energy technologies such as wind turbines, solar panels, hydropower turbines, biomass plants, and geothermal energy applications have gained a considerable amount of attention during the recent decades as options to reduce dependency on fossil fuels.

Renewable energy sources have the potential to mitigate the effects of climate change by replacing fossil fuels but they come with certain trade-offs. Solar and wind differentiate from hydro, bioenergy, and geothermal energy because of their intermittent nature (Moriarty & Honnery, 2016). The latter group can have lower technical potential because of geographical limitations and environmental concerns (Moriarty & Honnery, 2016). Besides, the low cost-effectiveness of certain renewable technologies challenge the governments on the integration of renewable energy sources (Ellabban, Abu-Rub, & Blaabjerg, 2014).

One of the subtle trade-offs for an energy transition towards renewable sources comes to the light when the link between heat and electricity generation systems is considered. This is a link that has not been looked into in most of the large-scale renewable energy development studies but an important one (Jacobson & Delucchi, 2011). In conventional heat and electricity generation systems, the combustion of fossil fuels releases heat which can be used for heating purposes. Electricity and heat generation systems can produce each other's primary output as a by-product, and such coupling of two sectors results in high efficiency values.

The transition towards renewable sources endangers the relation between heat and electricity generation systems. Decoupling of electricity and heat generation can prevent the systems from reaching high-efficiency values as they do with the conventional systems. Also, such decoupling can result in decreased heat generation capacity because some of the renewable sources can be utilized to generate electricity, but not heat. For example, offshore wind parks are considered as a possible main electricity source for the future, but heat is not a by-product of these electricity generation facilities. The same situation is valid for hydropower facilities which generate only electricity, or photovoltaic systems which do not have installed thermal collectors.

Several applications are proposed to compensate for the loss of integration between electricity and heating sectors due to the transition towards renewable technologies. District heating networks require some attention in this respect. District heating is regarded as a way to achieve further reductions in fossil fuel consumption (Lund et al., 2014; Quiquerez, Lachal, Monnard, & Faessler, 2017). These networks can benefit from the economies of scale, especially when the heat energy is produced via co-generation facilities where electricity and heat are generated simultaneously. Co-generation leads the facilities to reach high efficiency values (Secretariat, 2006). Since the emission reduction efforts can restrict the use of fossil-fuels, co-generation based on biomass can emerge as a renewable option which can also be utilized together with the existing heat networks.

Barring the biomass co-generation, electrification of the heating system can be considered as another concept to compensate for the missing link between electricity and heat generation processes due to the energy transition. Electrification of heating systems means the use of ”Power-to-Heat” conversion technologies to generate heat energy by consuming electricity and this electricity can come from renewable sources. Similar to the biomass co-generation, large-scale heat pumps can supply heat to the district heating networks. It should be noted that such an application means drastic increases in electricity demand. Therefore, capacity increase for the electricity generation systems can be needed to fulfill the additional load. This, however, requires extra investment. Covering the heat demand by using electricity can get too costly and this can make the electrification of heating systems infeasible for many cases.

When above-mentioned concerns are considered together, the following points slowly come to light. Changing climate requires restrictions on greenhouse gas emissions, and this leads to an energy transition towards renewable sources. With such a transition, fossil-fuel dependence can be reduced, but it can also lead to unintended outcomes such as decoupling of electricity and heat generation. In order to avoid the effects of this decoupling, biomass can take over a certain share as a ”carbon-free” option which can be combusted like fossil-fuels, but this can lead to higher costs since biomass is relatively more expensive than fossil-fuels (Caputo, Palumbo, Pelagagge, & Scacchia, 2005). As another solution to compensate for the missing link between electricity and heat generation, Power-to-Heat technologies can supply heat to existing district heating networks. However, extensive use of these technologies can create unprecedented peak values as a huge burden on electricity generation systems. Shortly, the transition towards renewable technologies yields certain trade-offs and applicability of these technologies for future energy systems contains uncertainties.

1.2. Literature Review

As stated in the previous section, there are emerging uncertainties and trade-offs for certain technologies due to the decoupling of electricity and heat generation, which is argued as an unintended result of the transition towards renewable sources. This section presents the literature on these technologies, shares various standpoints for the future use of them, and discusses the findings.

Section 1.2.1 reviews the integration of wind and solar energy to the existing energy systems. Section 1.2.2 discusses the district heating networks. Section 1.2.3 reviews the co-generation facilities, while section 1.2.4 shares findings about power-to-heat technologies. Finally, Section 1.2.5 examines the generation expansion planning studies to discuss the integration of these technologies and their effect on future energy systems.

1.2.1. Integration of wind and solar energy

The electricity and heat generation sectors carry a considerable amount of responsibility for greenhouse gas emissions. Therefore, the transition towards renewable energy sources takes place to reduce emissions. This transition leads to the use of variable renewable energy sources such as wind or solar. Integration of these variable renewable energy sources requires further attention due to their intermittent nature.

Sharma and Balachandra (2019) call attention to the transition of energy generation systems from supply-chain influenced conventional types to nature influenced renewable types, and examine the effects of such a transition on the energy system's expansion schemes. Differentiation is based on the fact that the supply side of the fuel-based conventional energy generation systems are controlled by human-beings, whereas the use of renewable sources means the loss of human-control over the supply of energy and nature takes control (Sharma & Balachandra, 2019). An optimization model is created to evaluate the effects of this change on the energy systems expansion over time. When the model is used to represent Indian electricity system, the findings indicate that required installed capacity of electricity generation systems increases from 534 GW to 1135 GW as the renewable share increases from 0% to 40% (Sharma & Balachandra, 2019). Their findings indicate that high renewable penetration brings high level of redundancy in its train and this causes higher costs together with lower capacity utilization. In the same manner, it can be concluded that the use of renewable sources is quite advantageous for emission mitigation effort. However, the need for a balanced electricity generation mix which involves certain share of fuel-based systems is perspicuous for the sake of system's budget and reliability.

Zappa and van den Broek (2018) conduct an extensive study about the use of wind and solar energy in Europe based on spatial distribution of these sources. Temporal scope of their analysis is determined as 2050, and an optimization model is used to calculate the capacity mix of generation types while minimizing the residual demand (Zappa & van den Broek, 2018). The output of default scenario of this research is quite in line with the findings of Sharma and Balachandra (2019), which indicates the need for dispatchable energy generation systems to ensure long-term reliability of the system. It is presented that minimum total residual demand is achieved when the share of variable renewable energy sources hits 82% (Zappa & van den Broek, 2018).

1.2.2. District heating networks

District heating is a centralized way of providing with heat energy to the dwellings, office environments, greenhouses or industrial facilities. In these systems, heat is produced by single or multiple generation facilities and it is transmitted to the demand points through a pipeline network. Producers can vary by generation type. Co-generation facilities, heat-only boilers or large-scale heat-pumps constitute a part of the examples for district heating applications. Waste heat from industrial processes can be utilized, or heat from the incineration of fossil fuels, wood pellets, or municipal waste can be supplied to the network. Ability to provide cheaper heat production is one of the most prominent positive sides of district heating applications, while distribution losses are examples for the negative sides of them (IEA-ETSAP, 2013b).

Lund et al. (2014) discuss the future integration of smart thermal grids with sustainable energy systems, and indicate that district heating has an important role to play in energy transition, but whether this role is realized successfully depends on the network's ability to supply low-temperature heat with decreased losses, ability to integrate renewable heat sources, ability to integrate with other energy systems, and compatibility of existing institutional frameworks. Quiquerez et al. (2017) analyze the applicability of different heat strategies for both demand and supply aspects, and they conclude that district heating is helpful to reach low CO_2 emission levels which would be achievable by imposing strict isolation techniques in the absence of district heating. They indicate that when district heating applications are supported by a slight decrease in heat demand of the households, reaching target emission levels is socio-economically more preferable. Both studies indicate that district heating applications are useful for a better climate change response. They also point out that using better isolation methods to reduce heat losses is a must to acquire better performing thermal grids. It is an understandable discussion because better isolation leads to lower heat demand values, and this reduces the burden on the thermal systems.

Romanchenko, Odenberger, Göransson, and Johnsson (2017) design a mixed-integer linear programming model to find the optimal operational decisions for a district heating system. The study specifically focuses on the impacts of electricity prices on the decisions made for the district heating system and indicates that the share of heat pumps and CHP plants can change significantly with respect to the electricity prices (Romanchenko et al., 2017). Their results indicate that with the increasing electricity prices, the heat generated by heat pumps can decrease by 20% while CHP facilities' contribution can increase up to 25%. They also state that the future role of CHP facilities can be more focused on electricity generation, and heat can be seen as a secondary business.

Lastly, the future of heat generation is examined in the report called "Heat Roadmap Netherlands" and it is stated that the covered heat demand by district heating should reach 56% by 2050 in the Netherlands (Paardekooper et al., 2018). The current value is indicated as around 7% and this means the report suggests eight times bigger district heating applications for the Netherlands. For the share of generation units, it is stated that the boilers should not generate more than 8% of the heat demand of district heating networks to open space for low-carbon solutions which help to comply with European Union's 2050 targets.

1.2.3. Co-generation facilities

Co-generation facilities, or combined heat and power facilities, are generation units which supply both electricity and heat simultaneously (Rosen, Le, & Dincer, 2005). The use of co-generation technologies allow the producers to utilize the waste heat via heat recovery systems and this makes such applications reach much higher efficiency values when compared to single-output facilities (IEA-ETSAP, 2010c).

Kang, Lu, Li, and Zhang (2017) focus on the coupling of combined heating and power systems (CHP) with heat pumps and indicate that the coupling leads to an increase in the efficiency of the system. Li, Zou, Zhu and, Fu (2018) design two-stage optimal planning method for a "combined cooling, heat and power system". A genetic algorithm is utilized for this study and it is indicated that using an optimized operation strategy can reduce the annual costs significantly (Li et al., 2018).

Wang, Yin, Abdollahi, Lahdelma, and Jiao (2015) study a combined heat and power system together with renewable energy sources by also including storage facilities. A linear programming model is used to minimize the overall costs of the net acquisition for heat and power in deregulated markets (Wang et al., 2015). They state that the future energy systems will utilize co-generation based district heating applications together with renewable energy sources and they conclude that the use of thermal energy storage applications will be more intensive in the future scenarios with high renewable integration and fluctuating co-generation loads.

1.2.4. Power-to-heat technologies

In order to meet the heat demand in a future with intermittent renewable energy sources, technologies like power-to-heat which convert electricity to heat can be utilized. These technologies can be divided into centralized and decentralized systems. In centralized systems, the conversion of electricity to heat is often at a different location than where the heat demand is occurring. In decentralized systems, flats, houses, or blocks make the conversion at a much closer location to the heat demand point. The centralized systems for power-to-heat technologies in the form of district heating have the storage options which might be more preferable in some cases whereas decentralized options might use direct heating approach (Bloess, Schill, & Zerrahn, 2018).

Power-to-heat systems might help with the decarbonization goals and provide flexibility options for the integration of renewables (Bloess et al., 2018). It is also stated that the power-to-heat technologies can be utilized cost-effectively as they can replace fossil fuels when they get expensive, decrease the required capacity to fulfill peak heat demand, reduce the need for power storage technologies, comply with existing thermal grids, and reduce spilled electricity which comes from abundance of renewable energy (Bloess et al., 2018). These arguments are supported by indicating that these power-to-heat systems have significantly lower costs than power storage facilities as a flexibility option (Bloess, 2019).

In another study which indicates the role of power-to-heat technologies to reach decarbonization goals, Mikkola (2016) states that replacing fossil fuels in the merit order with wind power requires options like power-to-heat with pumps. The systems with power-to-heat technologies yields lower CO_2 emissions in comparison to the systems without these technologies (Bloess et al., 2018). Yilmaz (2018) states that power-to-heat technologies reached the technical maturity to play a significant role in future European energy markets to reach climate targets.

1.2.5. Generation expansion planning

Besides the studies related to individual technologies and their performances, a part of the literature which examines how the energy systems evolves and expands in the future was found useful for this research.

In his study, Ugranli (2019) analyses the effects of renewable sources on distribution network expansions and it is indicated that the introduction of distributed renewable generation yields a decrease in the overall system costs, while total energy prices increase.

As an example for large-scale energy network studies, Abbasi and Seifi (2014) focus on the optimization of expansion planning for energy systems which covers electricity and heat simultaneously. They develop a method which integrates power-only units, heat-only units, CHP units and includes transmission line calculations to the system while optimizing with respect to objectives such as cost, energy losses and voltage deviation. They suggest this method can be used to indicate the expansion of generation capacities and introduction of new transmission lines to a system (Abbasi & Seifi, 2014).

Lastly, Bagheri, Monsef and Lesani (2015) conduct an integrated dynamic distribution network expansion study where renewable power generation is also included. It is indicated that introducing distributed generation units to the networks decreases the costs together with the pollutant emissions (Bagheri et al., 2015).

1.3. Research gap and research questions

From the conducted literature study, it can be concluded that the use of district heating systems contribute to the race of energy transition towards lower emissions levels. Use of co-generation facilities can help an energy system to decrease its fuel use by the help of increasing efficiency values. A co-generation facility can also run with biomass sources which makes it emission-free and so, a directly available option for emission reduction processes. The use of power-to-heat technologies can generate emission-free heat energy if the power source is also emission free. Also, power-to-heat technologies increase the flexibility of systems and helps to achieve better utilization of renewable sources. It is also observed that despite of their intermittent nature, integration of renewable sources is one of the most prominent solutions to the energy transition problems.

These technologies are claimed useful to reach a greener future, but a system which includes them all poses new questions. Whether the fossil fuels will still be in use dominantly, biomass facilities will substitute the fossil fuel facilities, or electric heating which uses sustainable sources will take place are relevant points for discussion. The role of these technologies in the future's energy systems remains uncertain.

In order to explore the role of these technologies in the future, this thesis adopts a quantitative approach which integrates heating and electricity generation and looks for the optimal expansion planning of these generation capacities together with heat transmission networks. It is believed that with such a study, one can shed some light on the mentioned uncertainties. As a result, the main research question can be formed in the following way:

How should the electricity and heat generation facilities be installed and heat transmission networks be expanded to achieve an energy system which yields minimum system costs under the effect of emission reduction targets?

The main research question can be divided into sub-questions:

- ***To what extent do the energy conversion technologies help to reach the emission targets?***
- ***What is the effect of renewable integration on heat transmission systems?***

- ***What is the role of co-generation facilities in the future energy systems?***
- ***What are the dominant factors leading to the installation of new pipelines between cities?***

1.4. Thesis outline

Chapter 2 explains the electricity and heating systems and policies for CO_2 emission reductions in the Netherlands. Chapter 3 presents the model description which covers the domain of the model, the mathematical formulation, used input data and applied speed-up methods. In Chapter 4, the model verification based of certain tests is presented, the reference scenario and its findings are shared and it is validated by evaluating its fitness to the purpose. Chapter 5 gives an overview of the scenarios that are analyzed and presents their results. In Chapter 6, the results of the modeling study are discussed. Lastly, Chapter 7 draws conclusions, provides recommendations for policymakers and insights for future research.

2

Domain of the study

The Netherlands is one of the countries which has a fossil fuel driven energy system and currently undergoing severe changes to acquire a renewable-dominant energy system. The Netherlands signed the Paris Agreement on keeping the average global warming increase at 2°C in 2016. With the Climate Act, the country aims for a 49% reduction in greenhouse gas emissions by 2030 compared to 1990 levels and 95% reduction by 2050 (*Climate policy*, n.d.). These developments and policy discussions make the Netherlands a perfect candidate to evaluate the identified research targets in the first chapter.

This chapter is used to explain the functioning of electricity and heating systems in the Netherlands in a very brief way. Before diving into the mathematical model in Chapter 3, it is crucial to grasp the fundamental mechanisms of the real electricity and heating systems of the Netherlands. By doing so, the reasoning behind choices made for the mathematical formulation of the model can be understood in a better way.

2.1. Electric power system of the Netherlands

The electric power system can be described in three components in general. These components can be listed as generation systems, transmission systems, and distribution systems (Pérez-Arriaga, 2014).This description applies to the Netherlands as well because the need to instantly balance the supply and demand at all times makes the power systems across different countries similar. Electricity is produced in generation plants, and then it is transferred to the substations by using the transmission systems, and finally it is distributed to the consumers by distribution systems. A general scheme for the electric power systems is provided in Figure 2.1.

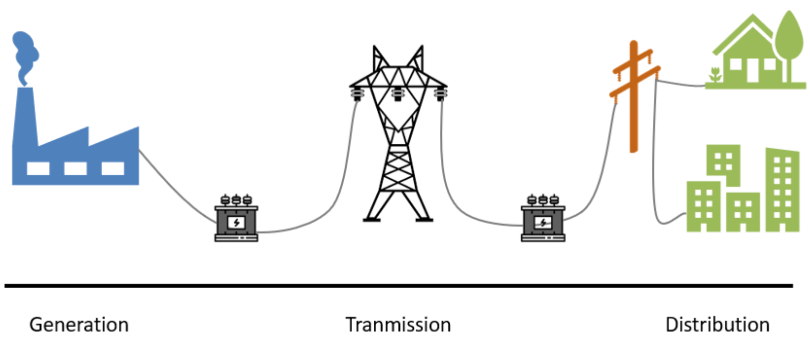


Figure 2.1: A simple descriptive scheme of a generic electric power system

Table 2.1: Shares of different energy sources for the total electricity generation in the Netherlands in 2017 (CBS, 2019a)

Natural gas	49.36%
Hard coal	26.67%
Wind energy	9.01%
Biomass	3.92%
Other fossil fuels	3.31%
Nuclear energy	2.90%
Other energy commodities	2.85%
Solar PV	1.88%
Hydro-power	0.05%
Fuel oil	0.05%

2.1.1. Electricity generation

There are millions of appliances or machines which use a certain amount of electricity to perform their tasks, and this electric energy needs to be supplied to these gadgets whenever they need it. Generation processes represent the first step of the supply side for the electric power system. Electricity is produced by utilizing various generation types, which are explained in the following sections.

In 2017, the amount of supplied electricity to the grid in the Netherlands has reached 120.766 TWh, while 117.260 TWh of this amount is produced within the country, and the rest is provided by the surplus of imported electricity (CBS, 2019c). The share of each energy source which is used to generate electricity in the Netherlands in 2017 is represented in Table 2.1.

As it can be seen from Table 2.1, the electricity generation in the Netherlands is dominantly based on fossil-fuels. The share of renewable sources has been showing an increasing trend during the recent years as shown in Figure 2.2. However, there are still many steps to take for the pursuit of an almost emission-free energy system in 2050.

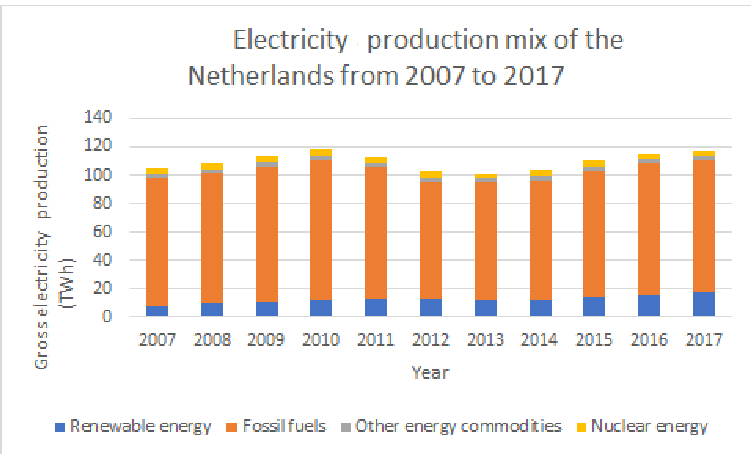


Figure 2.2: The electricity generation by different energy types in the Netherlands between 2007-2017 (CBS, 2019a)

There are several types of electricity generation facilities based on their energy source which will be elaborated in the following paragraphs.

Natural gas, hard coal, and nuclear energy

Natural gas can be considered as a transition fuel because of its low environmental pollution rates and greenhouse gas emissions. Since the exploration of Groningen gas field, natural gas has been an important source for electricity generation in the Netherlands (Prieto, Correljé, & Ascari, 2012). The gas network in Europe has been developed following the exploration and utilization of the Groningen gas field (Correljé, Van der Linde, & Westerwoudt, 2003). As of 2019, the installed capacity of natural gas is 15.57 GW in the Netherlands (2019a). In 2017, 49.4% of the electricity consumption is met by natural gas plants (CBS, 2019a). However, the earthquakes in the fields and renewable energy movement decreased the popularity of natural gas in the country. Currently, some of the gas power plants will be decommissioned.

As of 2019, the installed capacity of hard coal is 4.63 GW in the country (2019a). The Dutch government announced that they will be decommissioning all coal-fired power plants by 2030, which was responsible for supplying 26.7% of the electricity consumption in 2017 (Banja, Sikkema, Jégard, Motola, & Dallemand, 2019). This phase-out process puts an extra pressure to integrate significant shares of renewable energy sources to the power system in the next ten years.

Nuclear has a rather small share (2.9% of the electricity production in 2017) in the energy mix of the Netherlands with an installed capacity of 0.49 GW as of 2019 (2019a). There is only a single reactor actively used and it is placed close to the city called Borssele. Nuclear power generation has been a discussion point in the Netherlands due to its risks and waste management processes. Governmental sources indicate that no expansion is being planned for the existing nuclear power capacity in the country (*Nuclear energy*, n.d.).

Bioenergy

Biomass is the collection of organic materials like plants, trees, and crops. Biomass energy, or bioenergy, is produced by converting this biomass into biofuels, heat, or electricity (Ellabban et al., 2014). Bioenergy has a huge potential in energy transition since it is renewable but carries the characteristics of fossil fuel. It can be easily stored and transported as biofuels, which is important to balance out the growing share of intermittent energy sources like solar and wind. Another advantage of bioenergy is that the crops used for biomass create new jobs in the agriculture sector and support the security of supply since most countries have the land for its production (Faaij et al., 1998).

In the Netherlands, biomass powered plants have a total installed capacity of 0.49 GW as of 2019 (ENTSO-E, 2019a). In recent years, the Dutch government started to support the investments for biomass energy projects via feed-in-tariffs and research and development activities about large-scale utilization of bioenergy (Faaij et al., 1998; Junginger, Agterbosch, Faaij, & Turkenburg, 2004).

Solar energy

Solar power is the conversion of the energy of the sun to electricity through solar photovoltaic (PV) systems. The fundamental element of a PV system is the PV (or solar) cell, which converts the solar energy into direct-current (DC) electricity. Several PV cells are brought together in an environmentally protective seal to form a PV module. Several PV modules connected via wires in series and/or in parallel is called PV panels.

Solar PV systems can be connected to the electricity grid or off-grid stand-alone systems. The grid-tied PV system feeds into the inverter to convert direct current to alternating current, which is used by the electric grid. The system feeds electricity to the grid in times of excess supply and draws from it when in need. The off-grid systems generally have higher costs because of the need for battery or diesel generator to balance supply and demand.

The Netherlands has an installed solar PV generation capacity of 3.94 GW (ENTSO-E, 2019a). The Klimaatmonitor published by Rijkswaterstaat, The Ministry of Infrastructure and Water Management (2019) shows that the solar PV systems have a considerably homogeneous distribution for provinces in the country. The solar energy produced by each province is shown in Table 2.2.

There has been a 50% increase in solar energy production in the Netherlands in 2018, from 2.2 TWh to 3.47 TWh CBS (2019e). This increase in the solar power generation is partly due to the SDE+ (in Dutch: Stimulering Duurzame Energieproductie), an operating grant for the companies, institutions, and non-profit organizations (voor Ondernemend Nederland, 2018).

Table 2.2: The solar energy produced by each province in the Netherlands in 2018 (Klimaatmonitor, 2019)

North Brabant	15.81%
Gelderland	12.52%
South-Holland	11.18%
North Holland	10.99%
Overijssel	8.36%
Limburg	8.22%
Friesland	6.40%
Groningen	5.98%
Utrecht	5.84%
Drenthe	5.44%
Zealand	5.09%
Flevoland	4.17%

According to Zonopkaart.nl database, the largest solar parks are in Borsele (55 MWp), Delfzijl (30.8 MWp), Emmen (30.69 MWp), Veendam (15.8 MWp) and Haarlemmermeer (14.98 MWp) (2019). There are also future projects with higher generation capacities such as the one in Hoogezand-Sappemeer (103 MWp), Menterwolde (56.18 MWp), Steenwijkerland (51.3 MWp), Heerenveen (51.3 MWp), and Vlagtwedde (48.74 MWp) (ROM3D, 2019). The increase in the capacity also stems from the growth of the residential rooftop solar PV systems, which set a new record in 2018 (Kippzonen, 2018). With the existing subsidy schemes, the solar energy can be expected to continue to increase in size to help the Netherlands reach its emission reduction targets.

Wind energy

Wind energy has become one of the most prominent renewable energy sources to meet global energy demand. Wind turbines are connected to a power grid and convert the mechanical energy to electrical energy (Manwell, McGowan, & Rogers, 2010). The wind energy projects differ as onshore and offshore wind turbines. Onshore wind power is produced by the wind turbines located on land. The wind turbines are generally grouped together to form wind farms which have 5 to 300 MW of capacity (Ellabban et al., 2014). The offshore wind power is produced by the wind farms established in a body of water. The offshore wind farms have higher capacity because they can be built more and larger than the onshore counterparts.

In the Netherlands, the installed capacity to utilize wind energy does not show a homogeneous distribution over the country in contrast to the solar PV systems. According to ENTSO-E's database, the installed wind power in the Netherlands is 4.63 GW (2019a). Windstats.nl's statistics present a detailed list of 2324 wind turbine installations which have 4.43 GW capacity in total (2019). 3.47 GW of the total capacity is in the form of onshore wind turbine installations, while the rest is the contribution of the offshore projects.

In the current situation, wind turbine installations are dominantly concentrated in several provinces, and the other provinces have just a few installations. According to windstats.nl's statistics (2019), Flevoland, Zeeland, Groningen, Zuid-Holland, Noord-Holland, Noord-Brabant, and Fryslân provinces have the 95.81% of the total number of installations in the Netherlands, whereas Gelderland, Overijssel, Utrecht, Drenthe, and Limburg have only 4.19% of the total installations. It should be noted that 8 installations are not included in the calculations for these distributions since they are shown as 0 capacity turbine installations. Therefore, the related values show the overall situation of 2316 wind turbine installations.

Although the wind turbine installations are clustered in several provinces, this does not mean that the total generation capacity of these installations is also distributed in a similar way. When it is checked, however, it is seen that the situation is the same for the Netherlands. Installed capacity in Flevoland, Zeeland, Groningen, Zuid-Holland, Noord-Holland, Noord-Brabant, and Fryslân provinces have the 94.39% of the total share, while, Gelder-

Table 2.3: The wind energy produced by each province in the Netherlands in 2018 (Klimaatmonitor, 2019)

Flevoland	35.89%
Zealand	14.75%
Groningen	14.09%
South-Holland	9.70%
North Holland	8.34%
Friesland	5.90%
North Brabant	5.72%
Gelderland	2.22%
Utrecht	1.46%
Overijssel	1.02%
Drenthe	0.61%
Limburg	0.30%

land, Overijssel, Utrecht, Drenthe, and Limburg have only 5.61% of it. Table 2.3 presents the overall share of wind energy in each province.

Average wind turbine capacity for the installations in Flevoland, Zeeland, Groningen, Zuid-Holland, Noord-Holland, Noord-Brabant, and Fryslân is around 1.7 MW. This average value increases to 2.2 MW for the other provinces in the Netherlands, but since the number of installations is quite small when it is compared to the number of installations in the whole country, this value does not affect the overall average significantly. The overall average value of wind turbine capacity for the onshore installations is found around 1.7 MW. On the other hand, for offshore installations in the Netherlands, the values are different. There are in total of 289 offshore wind turbine installations in the Netherlands, and the average wind turbine capacity is 3.3 MW.

2.1.2. Electricity transmission and distribution

The main responsibility of the transmission system operator is to transport the electricity at high voltages over large distances. TenneT is the transmission system operator (TSO) in the Netherlands. The responsibilities of TenneT are to maintain a reliable grid at the right voltage and frequency level, balance the power injections and withdrawals in the transmission network, and supervise import capacity by organizing auctions (TenneT, 2019b). The electricity is imported when it is cheaper to buy from another country than national production. The TSO is responsible for maintaining the interconnections between countries to ensure the security of supply and coordination among countries. TenneT works with the distribution network operators (DNO) to make the connection with the distribution system network where the high-voltage is converted to the medium and low voltage. TenneT is obliged to make the connections to the power grid wherever needed. In the Netherlands, the transmission grid uses four voltage levels: 380 kV, 220 kV, 150 kV, and 110 kV (TenneT, 2019a). Distribution is the next step to deliver high, medium, or low voltage electricity to the consumers, whose medium voltage is around 50 kV (TenneT, 2019b).

The energy transition results in a re-evaluation of roles and responsibilities of the TSO. In an integrated power system with high renewable energy share, the TSO should deal with the intermittency of solar and wind energy production to maintain the balance between supply and demand at all times. TenneT should connect new producers, consumers, and prosumers to the electric grid. The increased complexities in the system should be managed to ensure the security of supply. Traditionally, the balancing of supply and demand is done at high voltage, transmission, level. However, with the growth of rooftop solar which is fed directly to the medium and low-voltage grids, there will be issues of balancing the grid at distribution level as well. The cooperation and coordination between the TSO and DNO should be improved to keep up with the changes in the power grid.

The distribution system is responsible for delivering the high, medium, or low-voltage electricity to the end-users like large industries, consumers, prosumers, and other countries as exports. In the Netherlands, each consumer is supplied by the distribution network operator (DNO) closest to them automatically. The DNO is responsible for electricity and gas connections. There are several DNOs operating in different provinces in the Netherlands. Liander is responsible for Flevoland, electricity of Friesland, Gelderland, Noord-Holland, and Zuid-Holland, Enexis operates Drenthe, gas of Friesland, Groningen, Limburg, Noord-Brabant, and Overijssel. Stedin manages Zuid-Holland, Utrecht, and some places in Gelderland. Finally, Delta is responsible for the distribution network of Zeeland.

Looking into the electricity system in the Netherlands, it is seen that the electricity system is inextricably linked to the heating system. Heat networks and electric heating will become more important to reach the emission reduction targets (van Vuuren, Boot, Ros, Hof, & den Elzen, 2017). The co-generation, or combined heat and power (CHP), has constituted a significant share of the electricity generation in the Netherlands. In 2012, 51.8% of the electricity was generated in co-generation facilities. However, the share of the electricity production in CHP plants decreased in the last five years as shown in Figure 2.3. The report prepared by Co-generation Observatory and Dissemination Europe (2019) suggests that the CHP production is expected to decrease in the Netherlands as the necessary financial support for the investments is lacking since 2011. This raises concerns for the district heating systems which should adapt to using renewable heat as input instead of combustion of fossil fuels because of the emission targets.

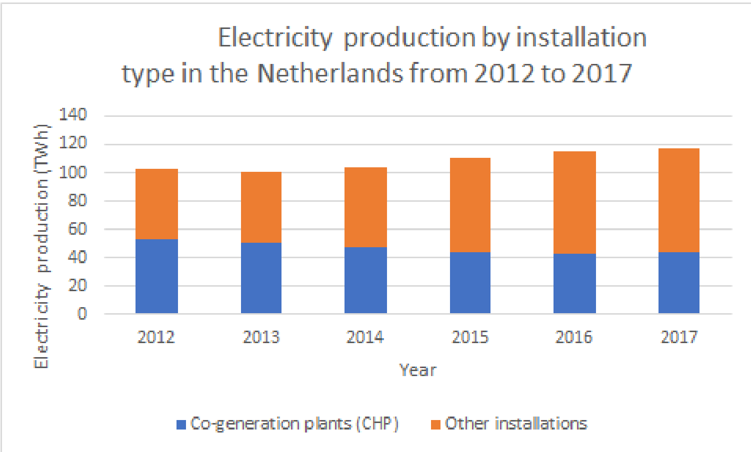


Figure 2.3: Shares of CHP and other installations for the total electricity generation in the Netherlands between 2012-2017 (CBS, 2019b)

2.2. Heating system of the Netherlands

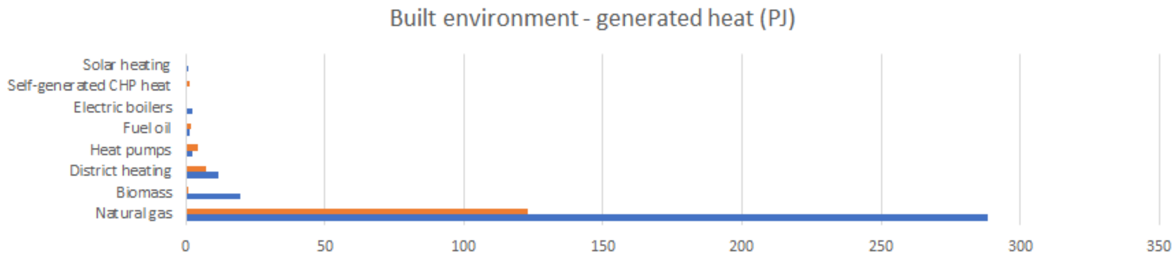
In 2017, more than half of the total energy consumption of the Netherlands was used for heating purposes (Segers et al., 2019). Around 47% of this heat energy is consumed by the households and offices, 42% is used in industry, 10% is used for agricultural purposes, and last 1% is utilized for waste related processes (Segers et al., 2019).

Heat energy is either generated by the individual consumers in a decentralized way, or consumers can be connected to district heating networks and heat is supplied to these networks via centralized facilities. Natural gas boilers, electric boilers, biomass sources, CHPs, or heat pumps constitute of the examples for decentralized heat generation types, whereas the same facilities with larger scales and waste heat from industrial processes can be used to fulfill the heat demand of district heating networks (Segers et al., 2019).

Like electric power systems, heat networks are composed of generation, transportation (primary network), distribution (secondary network), and consumption. The heat produced from different sources is transported to substations where the heat exchange occurs. Following that, the steam or hot water is distributed to consumers. District heating networks supply hot water to dwellings and businesses from a centralized location, while industrial consumers are mostly supplied with steam (Segers et al., 2019).

2.2.1. Heat generation

Major part of the heat demand in the built environment is fulfilled by the use of natural gas boilers; then wood consumption is used the most to generate heat energy for the households; it is followed by the use of district heating networks, electric heating, fuel oil, and solar energy (Segers et al., 2019). The distribution of generated heat via different sources for built environment in 2017 is presented in Figure 2.4.



	Natural gas	Biomass	District heating	Heat pumps	Fuel oil	Electric boilers	Self-generated CHP heat	Solar heating
Offices	122.8	0.9	7.4	4.6	2	0	1.4	0.2
Households	288.3	19.5	11.9	2.5	1.5	2.5	0	0.9

Figure 2.4: Generated heat via different sources for built environment (in PJ) (Segers et al., 2019)

The shares of different generation types are distributed quite heterogeneously for the generated heat which is used for agricultural purposes. As shown in Figure 2.5, heat generation is dominated by the use of natural gas together with CHP installations which also use natural gas (Segers et al., 2019). Geothermal heating, biomass sources, district heating, petroleum products and heat pumps constitute the remaining 10% of the heat sources.

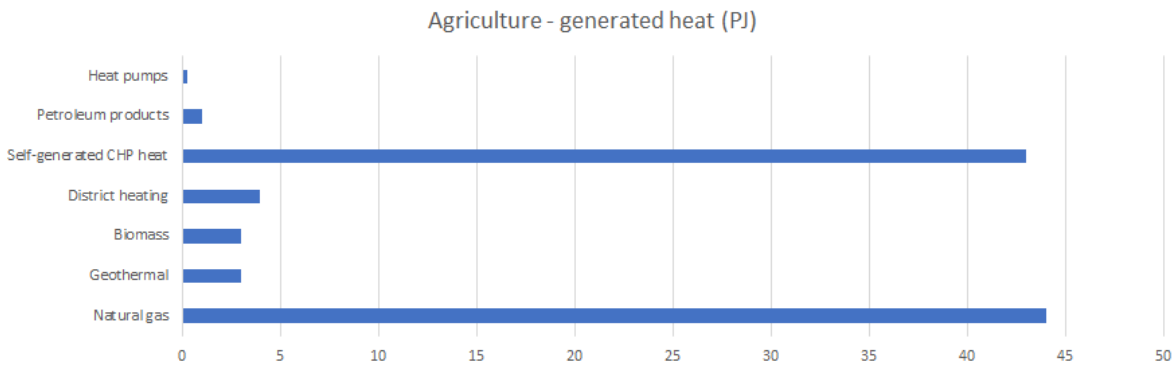


Figure 2.5: Generated heat via different sources for agricultural purposes (in PJ) (Segers et al., 2019)

Unlike the built environment and agricultural facilities, industrial demand requires much higher temperatures. As shown in Figure 2.6, generated heat energy is mainly based on fossil fuels. Besides the natural gas, industrial heat demand in the Netherlands is supplied by a significant amount of petroleum products, which is mostly the residual gases from oil (Segers et al., 2019).

Heat generation networks make use of different sources such as natural gas, biomass, electricity, or waste heat to maintain the security of supply. The CHP facilities can also produce

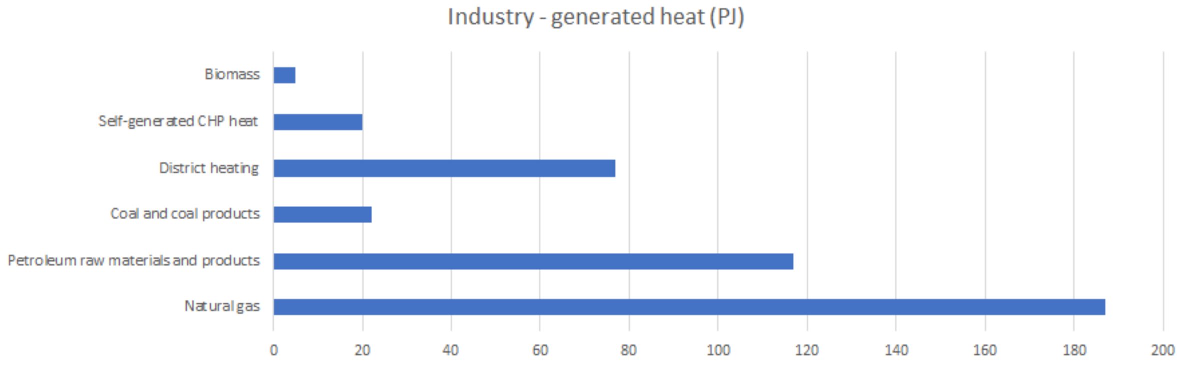


Figure 2.6: Generated heat via different sources for industry (in PJ) (Segers et al., 2019)

heat next to their electricity generation, and this heat can be supplied to the networks. The main motivation behind this study is seen more clearly after breaking down the supplied heat to the networks by energy sources, which is presented in Figure 2.7.

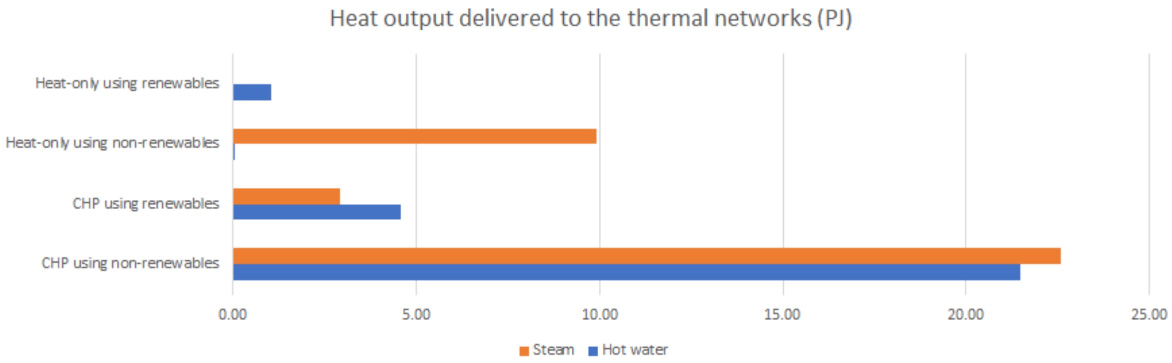


Figure 2.7: Sources of delivered heat to the thermal grids (in PJ) (Segers et al., 2019)

Although the current heat generation is dominantly based on the fossil fuels, the share of renewable sources for heating purposes has been increasing during the last years. The shift from fossil fuels to renewables is clear from Figure 2.8, where it can be observed that the share of heat production from renewable energy sources increased whereas the share of fossil fuels decreased in the past years. The conventional and CHP plants that use fossil fuels will be decommissioned in the future to reach emission reduction targets and the integration of renewables will pose challenges to meet the heat demand (Niessink R., 2015).

2.2.2. Heat transportation and distribution

After heat is generated, it is transported and distributed through pipes to reach the consumers. Out of the gross heat production, 80% was delivered as steam and 20% was delivered as hot water (CBS, 2015). The heat delivery network consists of primary and secondary networks, divided a substation where the heat exchange takes place (de Boer, 2018). The pipelines connecting the generation facility and consumers vary in pumping speed to maintain the pressure and temperature, making sure that each customer receives the same service quality (Scown & Regen, 2017).

The primary heat network is where the heat transportation between cities occurs. The generated heat is transported from the generation facility to the substations. The large heat distribution networks are located in the municipalities of Rotterdam, Almere, Utrecht, Amsterdam, Purmerend, Tilburg, Den Haag, Nieuwegein, Breda, Duiven - Westervoort, Capelle

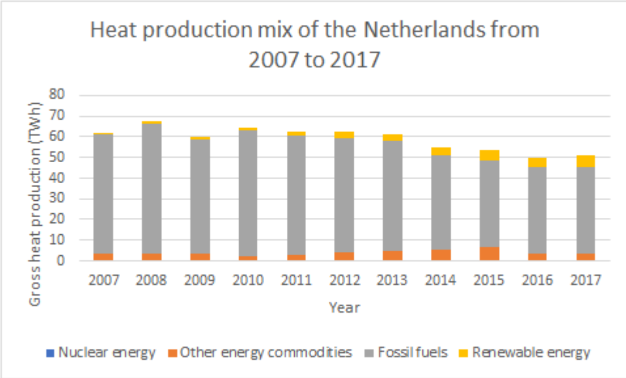


Figure 2.8: The heat generation by different energy types in the Netherlands between 2007-2017 (CBS, 2019a)

aan den IJssel, Leiden, Enschede, Helmond, and Lelystad (Niessink & Rösler, 2015). Traditionally, the temperature of the heat is around 130°C which is decreased to 90°C, ready to be delivered to households in a distribution network. Here, the secondary network is used for distributing the heat from the substations to the customers.

Realizing the need for innovation in heating systems with the energy transition, the Netherlands initiated the Heat Roundabout project for Zuid-Holland which aims to connect greenhouses, industrial buildings, and dwellings in cities like Den Haag, Rotterdam, Dordrecht, Leiden, and Zoetermeer (Madsen, 2015). The Port of Rotterdam produces 150 PJ of residual heat which can be utilized for heating purposes (Zuid-Holland, 2016). In order to make the most of this heat produced, an underground heat network transport hot water to the houses and businesses and collect the cooled water back to the system to be heated (of Rotterdam, 2019). The Heat Roundabout project aims to reduce greenhouse gas emissions by one million tons by making use of renewable energy sources and reducing heat waste.

3 Model description

As described in the previous section, the coupling of electricity and heating systems of the Netherlands is a vast domain which makes it hard to conduct some real-time experiments. Decision-makers can use several different methods to gain insights. To evaluate the effect of certain changes on such a system, it is preferable to convert the real system into an artificial representation, a computer model. This chapter is used to describe the transformation of the previously mentioned real system to a computer model.

The first subsection describes the modelling approach used to help decision-makers gain insight about the system. In subsection 3.2, the model domain is described in terms of the temporal and spatial resolution. In subsection 3.3, the decision variables, objective function, and constraints of the mathematical model are presented. In subsection 3.4, The data used as input for the model are provided and explained in detail. In the last subsection, the methods to decrease computational time are presented.

3.1. Modelling approach

While modelling the electricity and heating systems, it is important to choose the correct modelling approach. Energy systems modelling is used for ”the design, planning and implementation of future energy systems” (Lund et al., 2017). The modelling paradigms can be classified as simulation or optimization and top-down or bottom-up (Després et al., 2015). The simulation models present information about the behaviour of the system under a set of conditions for a certain period of time. The optimization models provide the set of decision variables which give the optimal objective function under a set of constraints. The simulation models give the performance of a system while optimization models give the optimal design under certain assumptions and constraints (Lund et al., 2017). The top-down models illustrates the economic relationships between different parts of a national or regional system whereas bottom-up models stems from the technological details to match the supply and demand of a system (Després et al., 2015). Considering this typology for energy systems modelling, least cost way to realize energy transition for the electricity and heating systems of the Netherlands is studied through a bottom-up optimization model.

Following the general scheme for the model created by the Després et al. shown in 3.1, the structure of the model is defined by answering several questions. The first question is about the which energy carriers are included in the system. This study is concerned with power and heat in terms of energy carriers excluding hydrogen. The second one is concerned with whether the system evolves in time. In this study, the parameters regarding the investment costs and efficiencies are changing over time. The third question is concerned with the reasoning behind the modelling. Since this study aims to find the least cost design for the energy system under emission target constraints, the optimization is selected as the appropriate logic. The fourth question is about the perspective of analysis. This study is taking a system approach which aims to minimize the costs of the energy transition from a societal point of view. Lastly, the dynamics of the model is what differentiates this study from the many studies in literature because both operational and investment planning decisions are taken into account.

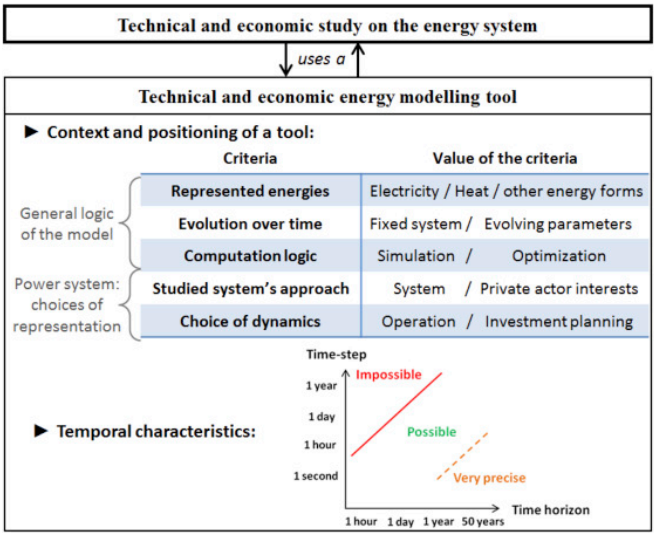


Figure 3.1: Questions to answer while formulating a model (Després et al., 2015)

This study is concerned with national electricity and heating system of the Netherlands. An optimization model is considered as an appropriate tool to conduct this study. At the beginning of the research period, the research question is determined in a way that the study aims to identify the future capacities of integrated electricity and heating systems, and heating transmission network. This research aims to shed some light on these future capacity values which yield minimum system costs, and this exploration is conducted under the effect of emission targets. In order to utilize an optimization model which artificially represents a real system, certain components of an optimization model should be determined. As one of these components, decision variables are the quantities which are controlled and changed by the people or systems which are in charge of that particular quantity. Similar to the decision variables, there are parameters in an optimization model to represent the quantities which are either fixed or out of reach for the represented decision-makers and systems by the modeling study.

As another component of an optimization model, objective functions are used to describe the target variables whose optimal value is searched by the model and also the direction of the search which is conducted by the model. It basically indicates whether the target variables need to reach a lower value or a higher value with respect to changing decision variable values. Lastly, an optimization model cannot reach a solution if the solution space of the model is not determined by using certain mathematical formulations. Constraints, as the final part of optimization models, are used to formulate the relations between real system components which are represented in the model. Constraints describe the feasible solutions in the model, so that the optimal solution can be searched respectively.

In the following sections, first the connection between the real system and the model is evaluated, then the identified objective function and constraints are presented. It should be noted that the domain of the model which is presented in the following section and the domain of the study, which is presented in the previous chapter 2, are different from each other. Domain of the study presents the features of the real electricity and heating systems which are related to this study's research targets, whereas the domain of the model presents the features of the designed optimization model which is used to represent the real system.

3.2. Domain of the model

This study concentrates on the design of an integrated electricity and heating system in the Netherlands. It aims to come up with the expansion planning of the electricity and heating system over years where electricity and heat generation facilities are installed and the heat transmission network is constructed with minimum cost. Therefore, fundamentally it is a strategical decision-making model where the ultimate target is to provide decision support related to future conditions of these systems. However, due to the included technologies, there are also operational decisions which are considered to grasp the detailed structure of integrated electricity and heating systems.

In their study, Zappa and van den Broek (2018) discusses that treating the electricity system as a copper-plate can be considered as an acceptable assumption to reduce the computational heaviness of a model. In line with their approach, a copper-plate electricity system is assumed for the Netherlands. This means that the losses due to the transmission of electricity and also the limitations on the transmission of the electricity due to the capacity of transmission lines are neglected. Similarly, it is assumed that there is no transmission line between the Netherlands and other countries. It is regarded as an isolated system, so imports and exports are also neglected in this study.

For the modeling of the energy systems, a greenfield approach is adopted. This means that the Netherlands' energy system is assumed to be constructed from scratch. No existing electricity or heat generation facility is assumed in the model. Also, existing pipeline installations for the transmission of heat energy is excluded. There is a single but quite binding reason behind such a decision. Instead of a greenfield approach, if a brownfield approach was adopted, it would require to use data related to existing systems. Existing conventional electricity generation facilities, wind turbine installations, or solar panel farms in the Netherlands are listed on several sources such as ENTSO-E (2019b), Open Power Systems Data (2018), WindStats (2019), and ZonOpKaart (2019). However, data related to district heating networks and the technologies which are used in these networks is quite limited. It is considered that representing the integrated electricity and heating systems by using such limited data would degrade the model quality, and so the clarity of the results in the end. Therefore, a greenfield approach is used to model the system at hand.

As described in the previous chapters, there is a variety of energy generation technologies. It is quite critical to select the right set of technologies in the model to be able to represent the dynamics of the real system. With these in mind, co-generation facilities, power plants which generate only electricity, large-scale boilers which generate only heat energy, heat pumps, solar PV installations, and finally onshore and offshore wind turbines are included in the model as available technologies to generate electricity and/or heat. Also, industrial waste heat is included as a source of heat energy. It is assumed as a steady source of heat energy. Coal, natural gas, and biomass, more specifically wood pellets, are included in the model as the fuels which are consumed by the fuel-based plants.

3.2.1. Temporal resolution

Both the European Union and the Netherlands, have endorsed emission targets for 2030 and 2050. Since the main purpose of this study is to present the system design which is compatible with emission targets while spending the minimum amount of money, setting the temporal resolution based on these targets is considered as a starting point. Therefore, it is assumed that the model duration can be 30 years which represents the years between 2020 and 2050.

30 years is not a long-time period for strategical decisions. However, as mentioned before, this study also includes operational decisions which are related to the integration of renewable energy sources. As presented in Figure 3.2 and Figure 3.3, their intermittent nature within a day mandates the use of a temporal resolution which is higher than daily resolution. As a result of the renewable resources' intermittent nature, the model is designed to be capable

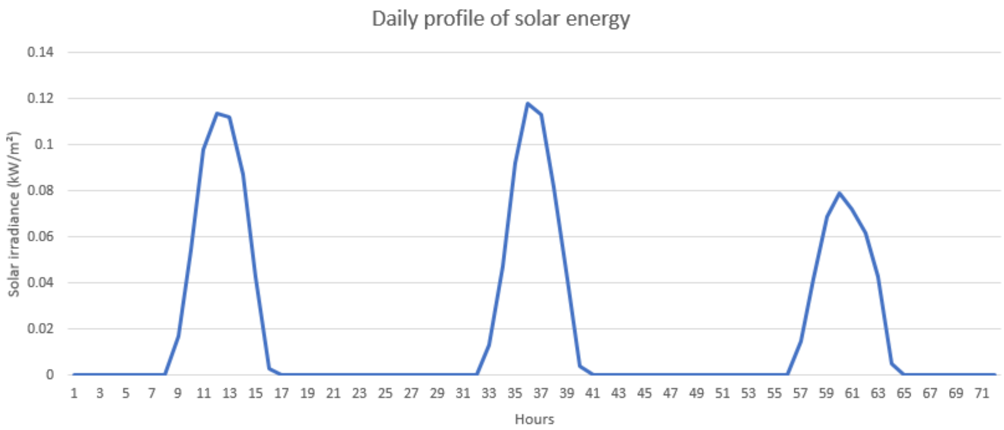


Figure 3.2: Sample daily profiles for The Hauge's solar irradiance in 2005

of representing hourly decisions.

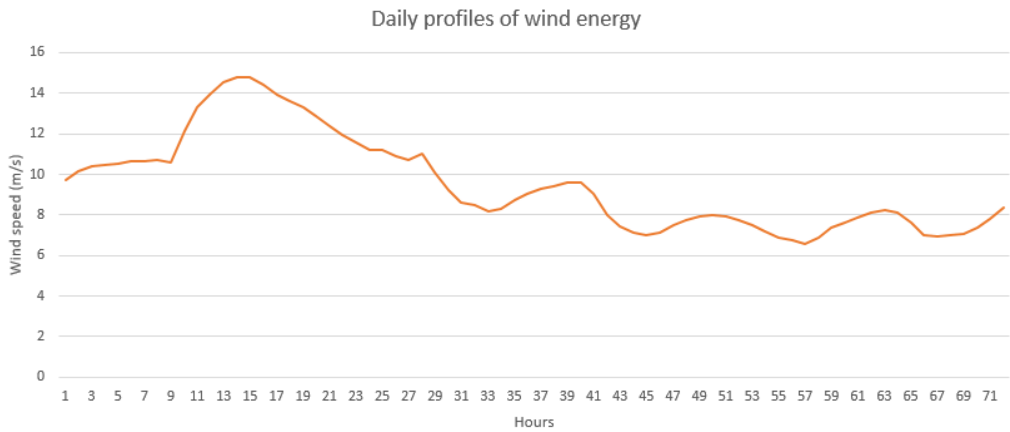


Figure 3.3: Sample daily profiles for The Hauge's wind speed in 2005

3.2.2. Spatial resolution

Since this study's scope is the whole country, it is crucial to set the boundaries in a way that the computational heaviness can be prevented while the model still represents the reality sufficiently. The inner-city district heating is not included in the scope of this study due to the reason shared above, computational heaviness. Such a study would require each municipality's dwellings exist on a network. However, since it is a country-wide study, it would not be applicable to run a related optimization model while maintaining the same level of detail.

On the other hand, NUTS3 classification of the Netherlands which is also known as COROP regions are considered as another candidate scope for the study. This classification divides the Netherlands into 40 regions which is much lower than the number of municipalities. Therefore, it would be easier to reach a result by using the model. However, aggregating municipalities in this way makes the model lose the pipeline construction opportunities between close municipalities, and it is considered that this is a piece of valuable information which can be gathered from this modeling study. As a result, it is decided that the municipal level has enough detail when it comes to the availability of renewable sources or demand and supply of electricity and heat. 355 municipalities are assumed to be the "nodes" in this study. A comparison between the municipal borders and COROP regions classification can be seen in Figure 3.4.

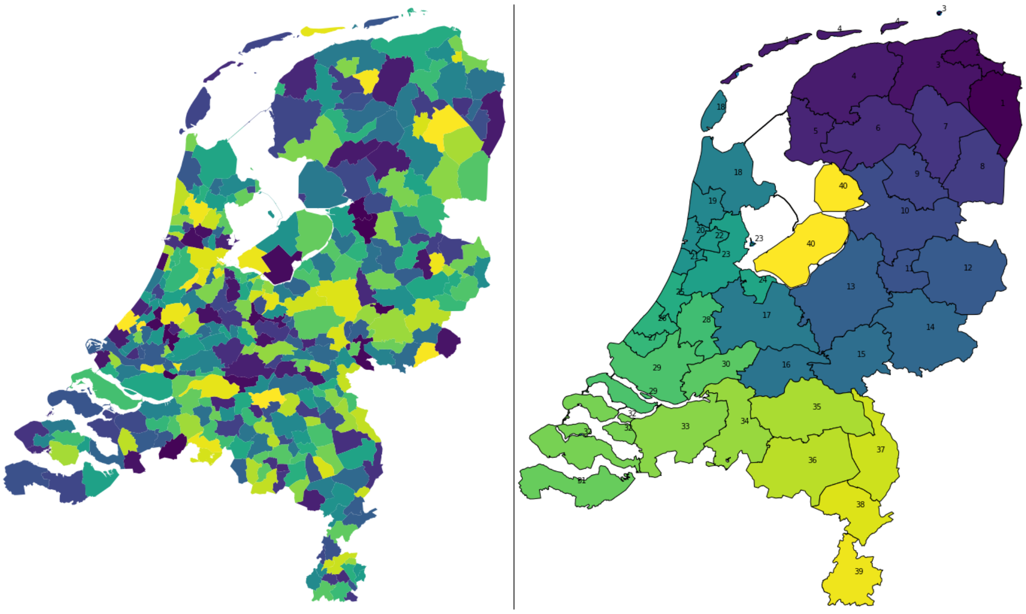


Figure 3.4: Municipal borders (left), from (Imergis Organisatiebloei, 2019). Borders with respect to COROP classification (right), from (Jasper Dekkers , 2017)

3.2.3. Electricity and heat demand

It is assumed that the generation of electricity and heat, and consumption of them take place on the same set of nodes. In other words, since each municipality can have a set of energy generation facilities as well as consumption points within its borders, the chosen spatial resolution makes it possible to evaluate the generation and consumption together on the same node.

Electricity demand is aggregated to the country level instead of municipalities. The assumption which is made for electricity transmission system makes a further aggregation of electricity demand be possible. As stated before, it is assumed that the electricity is transmitted without any transmission loss, and all the electricity is assumed to be accumulated in a pool node. It is considered that the generated electricity is going to be distributed to the demand points which are also artificially aggregated in a single node. Therefore, the hourly electricity demand of the country is considered as one of the input parameters to the system.

On the other hand, heat demand requires higher spatial resolution since a subset of the municipalities can have no district heating network available. It makes it meaningless to fulfill these municipalities' heat demand which is satisfied by the heat generation technologies of individual consumers. The system should supply heat to the municipalities which can make use of this supplied heat energy with a district heating network. Therefore, municipal level is considered as a relevant spatial resolution for heating related decisions.

It is considered that three types of heat demand can be included in this system, namely the offices, greenhouses, and households. Industrial heat demand is not covered since industrial temperatures are on a different scale than the heat networks which serve households, offices or greenhouses. Also, the buildings which are not connected to a district heating network are excluded from the study's scope. This study only covers low-temperature heating networks. Therefore, hourly heat demand of municipalities, together with the share of district heating networks in each municipality constitutes two of the input parameters for such a study.

3.3. Mathematical model

Previous sections are used to explain the motivation behind the use of an optimization model, the description of an optimization model, and lastly the domain of the model. This section presents the mathematical formulation of the designed model. Detailed variable and parameter descriptions are shared in the Nomenclature. In the following paragraphs, first, the objective function of the model is explained. Then the constraints which connect the model to the reality are identified in detail.

Shared mathematical model in this section is translated into a computer model by using Python (Van Rossum & Drake Jr, 1995). The parameters and decision variables are contained in specialized data structures, specifically dataframes and matrices (McKinney et al., 2010; Oliphant, 2006). The optimization process is conducted by utilizing another specialized Python library which is called ”PuLP” (Mitchell & Dunning, 2011).

When the model whose mathematical formulation is shared in the following sections is formed, two points grab attention. First, the model is structured as a Mixed-Integer Linear Programming (MILP) model due to the use of integer values for wind turbine installations. Second, certain operational decisions such as the decisions related to heat transfer between two cities make the model have a high number of decision variables, which makes it computationally too heavy to reach a solution.

3.3.1. Decision variables

Since the model represents the real electricity and heating systems for 30 years with an hourly scope, and since the spatial resolution is determined as municipalities, an operational decision about the amount of heat energy transferred from a municipality to another at an hour in a day in a year requires 33,119,370,000 decision variables, considering that the number of municipalities is 355. Including the other decision variables as shown in the Nomenclature, the total number of decision variables reaches 33,781,694,460. When this number is evaluated by also taking the integer values into account, it becomes quite clear that the computer implementation of the model gets problematic due to computational shortages. In the next sections, the model is explained in detail, while the last section of this chapter is used to introduce the methods used to overcome the computational shortages.

3.3.2. Objective function

The objective function of the model is formulated to minimize the total cost of electricity and heating systems. This total cost value includes the investment cost of the electricity and heat generation facilities, annual operating and maintenance cost of them, variable operating and maintenance cost of them and cost of fuel which is used to generate electricity and heat.

$$\text{minimize} \quad TotalCost$$

The above-mentioned total cost objective is calculated as the sum of investment costs, fixed O&M costs, variable O&M costs, and fuel costs:

$$TotalCost = C^{inv} + C^{om} + C^{vom} + C^{fuel} \tag{3.1}$$

Investment cost, C^{inv}, is calculated as the sum of investment costs for co-generation facilities, power plants which generate only electricity, large-scale boilers, heat pumps, solar PV facilities, onshore wind turbines, offshore wind turbines, and pipeline installations:

$$C^{inv} = \sum_{f \in F} C_f^{inv} + C_{pipe}^{inv} \tag{3.2}$$

These investment cost values for individual facility types, C_f^{inv} are calculated as the future value of investment costs which are spent to install additional capacities over the years in each municipality:

$$C_f^{inv} = \sum_{y \in Y} \sum_{m \in M} A_{y,m,f} * inv_{y,f} * r_y \forall f \in F \tag{3.3}$$

Lastly, the pipeline installations yield investment cost, C_{pipe}^{inv}, which adds up to the energy generation facilities' investment costs. It is calculated as the sum of the future values of investment costs for pipeline installations between municipalities. This investment cost is also based on the distance between municipalities.

$$C_{pipe}^{inv} = \sum_{y \in Y} \sum_{m_1 \in M} \sum_{m_2 \in M: m_2 \neq m_1} A_{y,m_1,m_2}^{pipe} * inv_{y,pipe} * d_{m_1,m_2} * r_y \tag{3.4}$$

Annual O&M cost, C^{om}, is calculated in the model as an annual payment which is made with respect to the installed capacity of a facility. Total annual O&M cost is basically the sum of annual O&M costs for co-generation facilities, power plants which generate only electricity, large-scale boilers, heat pumps, solar PV facilities, onshore wind turbines, offshore wind turbines. O&M costs for the pipeline installations are neglected in this study. Therefore, the total annual O&M cost can be calculated as the sum of future values of annuities of these facilities in each municipality over the years:

$$C^{om} = \sum_{f \in F} \sum_{y \in Y} \sum_{m \in M} C_{y,m,f} * fom_{y,f} * r_y^{dec} \tag{3.5}$$

Variable O&M cost, C^{vom}, is the amount of money which is spent on energy generation facilities' operating and maintenance needs if and only if these facilities are actively used. This is the fundamental difference between annual O&M and variable O&M costs in this model. The latter is spent without taking the generation processes into account, while the former exists if a facility is used and electricity or heat is produced. In line with this description, the variable O&M cost of a facility increases proportionally to the generated electricity and heat by using this facility. Total variable O&M cost is calculated as the future value of the total cost of usage over the years. To calculate the cost of usage, amount of generated primary output, electricity or heat, is multiplied by the unit cost of variable O&M cost.

$$C^{vom} = \sum_{f \in F} \sum_{y \in Y} \sum_{d \in D} \sum_{h \in H} \sum_{m \in M} G_{y,d,h,m,f}^{po} * vom_{y,f} * r_y^{dec} \tag{3.6}$$

Fuel cost, C^{fuel}, is the cost related to the amount of coal, gas or biomass used in fuel-based facilities. Total fuel cost is the sum of the cost of fuel used in co-generation facilities, power plants which generate only electricity, and large-scale boilers. The rest of the technologies' fuel cost is basically 0. Fuel cost of facilities, C^{fuel} is calculated by multiplying the amount of fuel used with the unit cost of the related fuel type and summing these values for each facility:

$$C^{fuel} = \sum_{f \in F} \sum_{y \in Y} \sum_{d \in D} \sum_{h \in H} \sum_{m \in M} AF_{y,d,h,m,f} * fc_f * r_y^{dec} \tag{3.7}$$

3.3.3. Constraints

The optimization process looks for the optimal objective function values within the solution space which is identified by the constraints. In this section, the mathematical formulation of the constraints together with their practical meanings and role in the model are explained in detail.

Initialization constraints

The first set of constraints are related to the initialization of generation capacities. Since the model adopts a greenfield approach, capacity of each generation facility is set to zero at the beginning. Therefore, any additional installation for a facility in the first year means that it is constructed from scratch. The initialization constraints are used for co-generation facilities, power plants which generate only electricity, large-scale boilers, heat pumps, solar PV facilities, onshore wind turbines, offshore wind turbines, and pipeline installations. Capacity of each facility installation in each municipality starts from the sum of its initialized value which is set to zero, and the value of capacity increase which is chosen by the model in the same year. These relations are represented by using the following equations:

$$C_{y,m,f} = ic_{m,f} + A_{y,m,f} \quad \forall y \in \{Y : y = 2020\}, \ \forall m \in M, \ \forall f \in F \tag{3.8}$$

$$C^{pipe}_{y,m_1,m_2} = ic^{pipe}_{m_1,m_2} + A^{pipe}_{y,m_1,m_2} \quad \forall y \in \{Y : y = 2020\}, \ \forall m_1 \in M, \ \forall m_2 \in M : m_2 \neq m_1 \tag{3.9}$$

New capacity installation constraints

With the described initialization constraints in the previous part, it is dictated to the model that available generation capacities in the first model year, which is 2020, are equal to the amount of added capacity in this year. By doing so, it is ensured that the model does not choose random starting values for its capacity variables. However, what happens after the starting point should also be described to the model by using another set of constraints.

Available capacity of a generation unit or a pipeline installation in a year should be equal to the sum of the installed capacity in that particular year and the previous year's available capacity. Following equations are used to represent this relation in the model:

$$C_{y,m,f} = C_{y-1,m,f} + A_{y,m,f} \quad \forall \{y : y \in Y, y \neq 2020\}, \ \forall m \in M, \ \forall f \in F \tag{3.10}$$

$$C^{pipe}_{y,m_1,m_2} = C^{pipe}_{y-1,m_1,m_2} + A^{pipe}_{y,m_1,m_2} \quad \forall \{y : y \in Y, y \neq 2020\}, \ \forall m_1 \in M, \ \forall m_2 \in M : m_2 \neq m_1 \tag{3.11}$$

To ensure that the pipeline network is symmetrically constructed, following constraint is also added to the model:

$$C^{pipe}_{y,m_1,m_2} = C^{pipe}_{y,m_2,m_1} \quad \forall y \in Y, \ \forall m_1 \in M, \ \forall m_2 \in M : m_2 \neq m_1 \tag{3.12}$$

Electricity generation constraints

Electricity generation process is modeled in a way that the amount of generated electricity in an hour is equal to the sum of electricity produced by co-generation facilities, only electricity facilities, and renewable power plants such as solar PV systems and wind farms in that particular hour.

Amount of electricity produced by co-generation facilities and electricity generation facilities in an hour is calculated by using the amount of fuel consumed by these facilities in that particular hour, the calorific value of the fuel type and the electricity generation efficiency of these facilities. Calculated values indicate the generated electricity in the whole country in an hour:

$$G^{e}_{y,d,h,f} = \sum_{m \in M} AF_{y,d,h,m,f} * fcv_f * e_f \quad \forall y \in Y, \ \forall d \in D, \ \forall h \in H \ \ \forall f \in FE \tag{3.13}$$

On the other hand, the amount of electricity produced by solar PV systems or wind turbines in an hour is calculated by multiplying the installed capacity of these facilities with the output of the related renewable source. It should be noted that this calculation does not include a decision variable which has an hourly resolution. Instead, it uses the capacity value of a facility together with an output parameter which has an hourly resolution.

Such a calculation is possible since the renewable sources are assumed that they are being utilized whenever they are available. It is considered that this would not be an unrealistic assumption since there is no fuel cost for such facilities. When these facilities are installed, they are able to generate electricity without incurring fuel costs and emissions. Related constraints are formed as follows:

$$G^e_{y,d,h,f} = \sum_{m \in M} C_{y,m,f} * o_{y,d,h,m,f} \quad \forall y \in Y,\ \forall d \in D,\ \forall h \in H\ \ \forall f \in RE \tag{3.14}$$

Total amount of electricity generated in an hour can be calculated by summing the amount of electricity produced by each of these identified facilities.

$$GT^e_{y,d,h} = \sum_{f \in FE} G^e_{y,d,h,f} + \sum_{f \in RE} G^e_{y,d,h,f} \quad \forall y \in Y,\ \forall d \in D,\ \forall h \in H \tag{3.15}$$

Heat generation constraints

Heat generation is modeled quite similar to the electricity generation processes whose generation constraints are explained in the previous section. The amount of generated heat in an hour in a municipality is equal to the sum of the amount of heat generated in this hour by the facilities which are placed within that particular municipality and amount of industrial waste heat in each municipality. Heat generation processes are conducted by using co-generation facilities, heat-only boiler facilities, and heat pumps.

Amount of heat generated by the co-generation facilities and heat-only boiler facilities in an hour is calculated by multiplying the amount of consumed fuel in the chosen hour with the calorific value of the related fuel type and thermal efficiency of related facilities. Calculated values indicate the generated heat for each municipality.

$$G^t_{y,d,h,m,f} = AF_{y,d,h,m,f} * fcv_f * t_f \quad \forall y \in Y,\ \forall d \in D,\ \forall h \in H,\ \forall m \in M\ \ \forall f \in FT \tag{3.16}$$

Heat generation of the heat pumps is included to the system in a slightly different way. Since these facilities do not consume any fuel but electricity, the amount of heat they generate is in proportion to the amount of electricity they use. Still, the fuel variable is used to represent the heat pump's processes. However, it should be noted that when the facility is a heat pump, the fuel it uses is not an actual fuel but electric energy.

$$G^t_{y,d,h,m,f} = AF_{y,d,h,m,f} * t^f \quad \forall y \in Y,\ \forall d \in D,\ \forall h \in H,\ \forall m \in M\ \ \forall f \in HP \tag{3.17}$$

As a result of the equations above, heat generation is described in the model for each facility type. However, sum of these values together with the industrial waste heat capacity of each municipality should be calculated to reach the total amount of generated heat in an hour in each municipality.

$$GT^t_{y,d,h,m} = \sum_{f \in FT} G^t_{y,d,h,m,f} + \sum_{f \in HP} G^t_{y,d,h,m,f} + wh_m \quad \forall y \in Y,\ \forall d \in D,\ \forall h \in H, \forall m \in M \tag{3.18}$$

Electricity demand constraints

The electricity generation constraints are presented in the previous sections. After having those constraints, how electricity is generated is described to the model. However, the link between this supply and externally defined demand is missing.

The model should be able to satisfy the electricity demand by using the amount of electricity it chooses to generate. This should be the case for all the hours included in this model.

$$GT^{e}_{y,d,h} = ed_{y,d,h} + SE_{y,d,h} + \sum_{m \in M} \sum_{f \in HP} AF_{y,d,h,m,f} \quad \forall y \in Y,\ \forall d \in D,\ \forall h \in H \tag{3.19}$$

The constraint above states that the amount of generated electricity in a chosen hour of a day in a year should be equal to the sum of electricity demand of that particular hour $ed_{y,d,h}$, amount of spilled electricity in that hour $SE_{y,d,h}$, and amount of electricity demand created in that hour by the heat pumps of all the municipalities included in the model, $AF_{y,d,h,m,f}$ while f is in the set of HP.

Heat demand constraints

Similar to the electricity demand, heat demand of a municipality in an hour should be satisfied by using the system's heat generation facilities. However, there are a few changes to the formulation of the related constraint due to the allowed heat transfer among the municipalities.

It should be described to the model that sum of the amount of generated heat in an hour in a municipality, $GT^{t}_{y,d,h,m}$, and the amount of heat transferred from other municipalities to this particular municipality, TH_{y,d,h,m_2,m_1}, should be equal to the sum of heat demand of this municipality in this particular hour, $hd_{y,d,h,m}$, the amount of spilled heat energy in this municipality, $SH_{y,d,h,m}$, and the amount of heat energy transferred from this municipality to the other municipalities, TH_{y,d,h,m_1,m_2}.

While forming the equation related to these relations, it should be noted that the amount of transferred heat is affected by heat loss, hl. Also, the heat demand of a municipality is calculated with respect to the share of district heating network in that municipality, $dh_{y,m}$. By taking all these points into account, the related constraint can be structured as follows:

$$\begin{gathered} GT^{t}_{y,d,h,m_1} + \sum_{m_2 \in M} TH_{y,d,h,m_2,m_1} * hl = hd_{y,d,h,m_1} * dh_{y,m_1} + SH_{y,d,h,m_1} + \sum_{m_2 \in M} TH_{y,d,h,m_1,m_2} \\ \forall y \in Y,\ \forall d \in D,\ \forall h \in H\ \ \forall m_1 \in M \end{gathered} \tag{3.20}$$

Generation capacity constraints

Capacity installation constraints, electricity and heat generation constraints and balance constraints for heat and electricity demand are described in the previous sections. By doing so, the model is dictated to satisfy electricity and heat demand by utilizing the facilities, and also it is capable of installing new generation capacities. This brings the final missing link among these functions to the table, which is the link between generation capacity and generation processes. This section explains the related constraints which make the model use the facilities with available generation capacities.

How to generate electricity or heat to fulfill the demand in a particular time is described to the model, but it is not restricted by using the capacity of the facilities, yet. The model should choose its decision variables in such a way that the amount of generated electricity or heat by using a facility cannot exceed the generation capacity of that particular facility. The same situation applies to the pipeline network, too. The amount of heat energy transferred from one municipality to the other cannot exceed the transmission capacity of that particular pipeline branch. These relations are formed by using the following inequalities:

$$C_{y,m,f} \geq AF_{y,d,h,m,f} * fcv_f * e_f \quad \forall y \in Y,\ \forall d \in D,\ \forall h \in H,\ \forall m \in M,\ \forall f \in FE \tag{3.21}$$

$$C_{y,m,f} \geq AF_{y,d,h,m,f} * fcv_f * t_f \quad \forall y \in Y,\ \forall d \in D,\ \forall h \in H,\ \forall m \in M,\ \forall f \in HOF \tag{3.22}$$

$$C_{y,m,f} \geq AF_{y,d,h,m,f} * t_f \quad \forall y \in Y,\ \forall d \in D,\ \forall h \in H,\ \forall m \in M,\ \forall f \in HP \tag{3.23}$$

$$C^{pipe}_{y,m_1,m_2} \geq TH_{y,d,h,m_2,m_1} \quad \forall y \in Y,\ \forall d \in D,\ \forall h \in H,\ \forall m_1 \in M,\ \forall m_2 \in M : m_2 \neq m_1 \tag{3.24}$$

There is no capacity constraint identified for solar PV systems and wind turbine installations. This is because the model does not include an operational decision for these facilities. Instead, as it is stated before in the previous sections, these facilities are utilized whenever they are available. After this assumption, described electricity generation constraints also restraint these facilities to produce electricity within their capacity limits.

As another point, co-generation facilities do not have a capacity constraint related to their heat generation processes. It is assumed that electricity is the primary output of co-generation facilities and capacity constraints are set to limit the electricity generation of them. Heat generation is assumed to be the secondary output which basically has its value after the model decides on the amount of electricity produced by a co-generation facility.

It should be noted that this way of forming constraints does not hinder the model to generate heat by using co-generation facilities when there is no electricity demand to be fulfilled. It just leads to a situation where the generated electricity is spilled if it is not possible to use it for a reason, and heat is supplied to its demand point.

Emission constraints

In order to represent the CO_2 reduction policies imposed by European Union and also the Dutch government, last set of constraints which are related to the amount of CO_2 emissions are identified in the model. Targets are imposed on the model by using the following constraints:

$$E_y \leq emission^{ref} * target_y \forall y \in Y \tag{3.25}$$

Yearly emission values are calculated as the sum of total emission values of fossil-fuel based facilities in the model. These values are based on the amount of fuel used by those facilities within a particular year and the unit emission values of these fuel types. The related calculations are formed in the following way:

$$E_y = \sum_{d \in D} \sum_{f \in FFB} \sum_{m \in M} \sum_{h \in H} AF_{y,d,h,m,f} * fev_f \forall y \in Y \tag{3.26}$$

3.4. Input data

In the previous sections, the designed optimization model is described and the mathematical formulations are presented. As described before, there are many parameters in the model which represent certain quantities in the real system. These parameters are external data points which are used in the model.

In order to prevent ”garbage in garbage out” concept of modelling, data collection is conducted with the utmost care. Among many, the recent studies and data sets are chosen to be able to represent more realistic values in the model. Also, due to the unavailability of certain data sets, several data processing techniques are implemented within this study. In this section, the data collection steps are explained together with the data processing techniques which are used to increase the quality of the collected data.

3.4.1. Electricity demand data

Hourly electricity demand data of the Netherlands is collected from ”Open Power System Data” which is a free and publicly accessible platform (Open Power System Data, 2019). The collected data is hourly resolution, and no missing values is found when it is checked. Collected data covers the years between 2006 and 2017.

Before making any decision about the data set at hand, other available data sets are also evaluated. ENTSO-E (2019c) provides with estimated hourly electricity demand for 2020, 2025, 2030, and 2040. When the scenarios which are used to generate these data sets are examined, it is realized that all the scenarios include a certain growth for the heat pump installations over the years (ENTSO-E, 2018). It is considered that if these data sets are used in this study, it means that the electricity demand due to the heat pump installations is counted twice because the created model also installs heat pumps to fulfill the heat demand. Therefore, it has been decided that continuing with the collected data is a better option for this research.

Since this study focuses on the years between 2020 and 2050, using past data to represent future values can be quite problematic if the values show a changing trend over the years. When the data is evaluated in that respect, it is seen that the electricity demand values have a slight increase between 2006 to 2017. The values for 12 years and drawn trend line can be seen in Figure 3.5. Since this study aims to find out how the design of integrated electricity and heat networks look like in the future, and 2050 is the targeted year, even a slightly increasing behaviour can critically determine the future conditions. In order to forecast the future values, a Python library, fbprophet, is used (Taylor & Letham, 2017). In Figure 3.6, the outcome of this forecasting process is presented. After the forecasting process the data set gets ready to be used in the model.

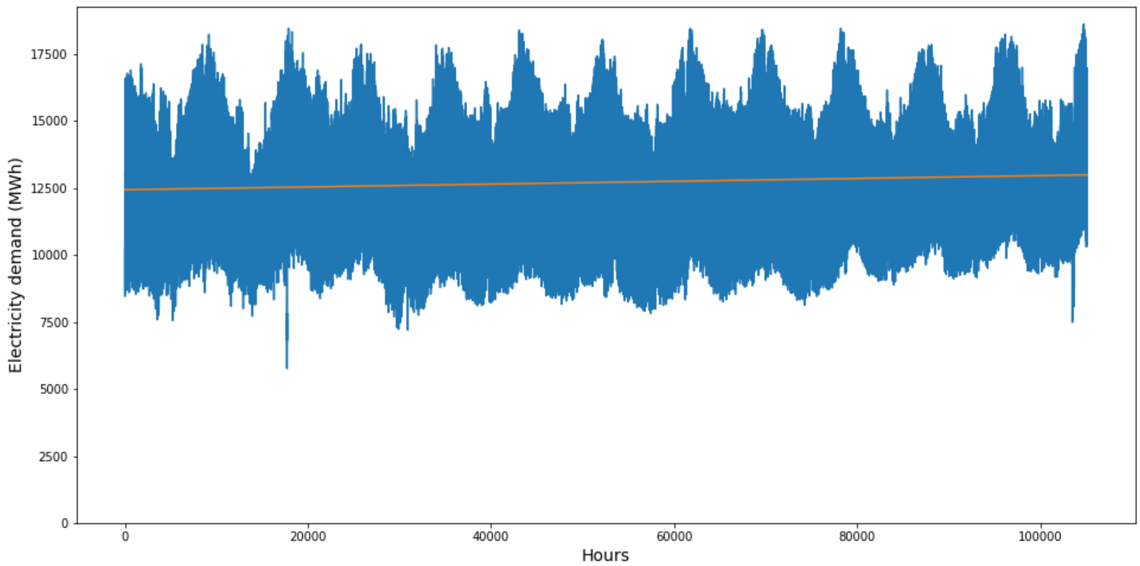


Figure 3.5: Collected electricity demand data for 2006-2017 together with its trend line

3.4.2. Heat demand data

For the heat demand, as described in the problem domain section, it is considered that the scope of the study should cover the heat demand of households, greenhouses, and office environments. However, during the data collection process, hourly heat demand of municipalities could not be found directly. Therefore, heat demand values are artificially generated.

First of all, it is assumed that the natural gas consumption of the households, offices, or greenhouses can be an indicator for the heat demand of these buildings. Then, data for

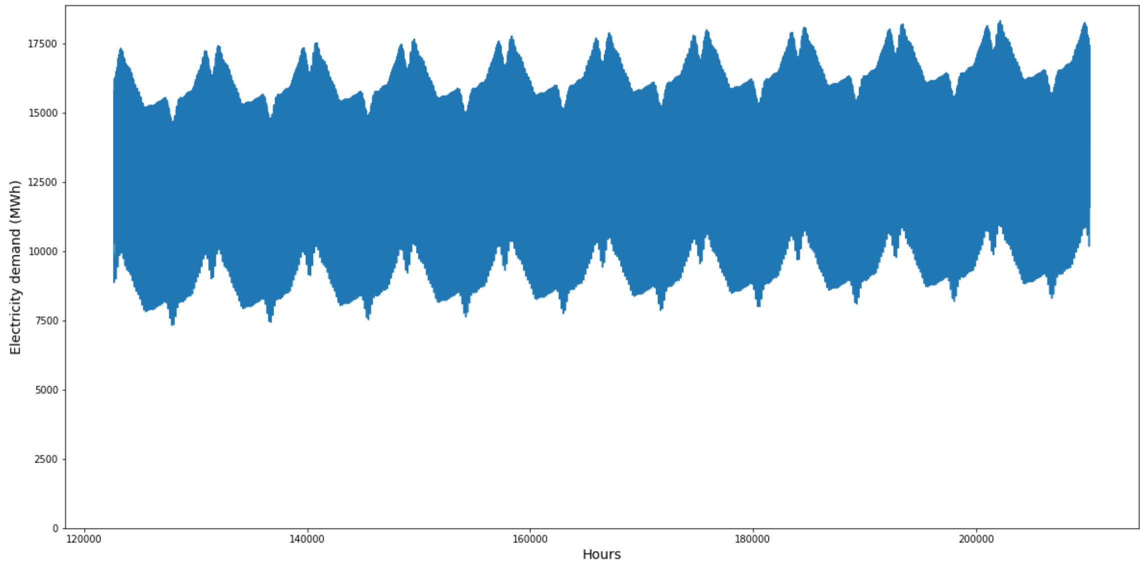


Figure 3.6: Forecasted electricity demand data sample for 2020-2030

average gas consumption of non-residential buildings, greenhouses and households in each municipality is collected from WarmteAtlas (Rijksdienst voor Ondernemend Nederland, n.d.). However, this average values are yearly average values of municipalities. Since this study requires hourly values, further processing is needed.

In order to convert the gas consumption values to heat demand, different conversion rates are used for different building types. For households, it is assumed that 96.69% of the natural gas consumption is used for space heating and hot water supply (Menkveld, 2009). For the office environments and greenhouses, this value is assumed to be 100%. After converting the yearly average gas consumption values to yearly average heat demand values, a Python library called ”demandlib” is utilized to generate hourly heat demand profiles for these buildings (Hilpert et al., 2018). This library requires yearly heat demand of a building, the type of the building, and hourly outdoor temperature values to generate hourly heat demand profiles.

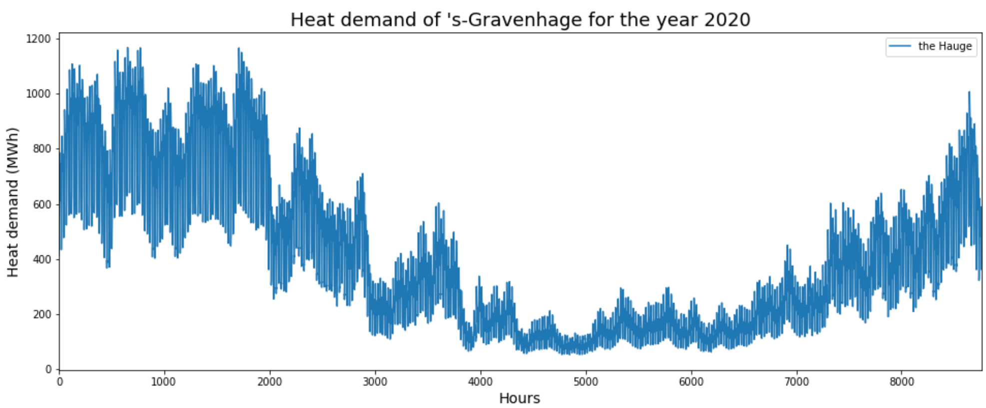


Figure 3.7: Heat demand of ’s-Gravenhage for the year 2020

Hourly outdoor temperature values for each municipality is collected from ”Renewables.ninja” (Pfenninger & Staffell, 2016; Staffell & Pfenninger, 2016). As a publicly available power systems simulation tool, it provides the raw data by request. Hourly outdoor data is one of the data sets that can be gathered by using this source. Then it is merged with the average yearly heat demand values of the municipalities. For households, ”multi-family household type (MFH)” is chosen as a fixed type of building, for the office environment ”total load profile of business environment (GHD)” is chosen, and finally for the greenhouses ”horticulture (GGB)” is chosen as the building types. The abbreviations are based on a framework which is used by ”demandlib” (BDEW, VKU, GEODE, 2011).

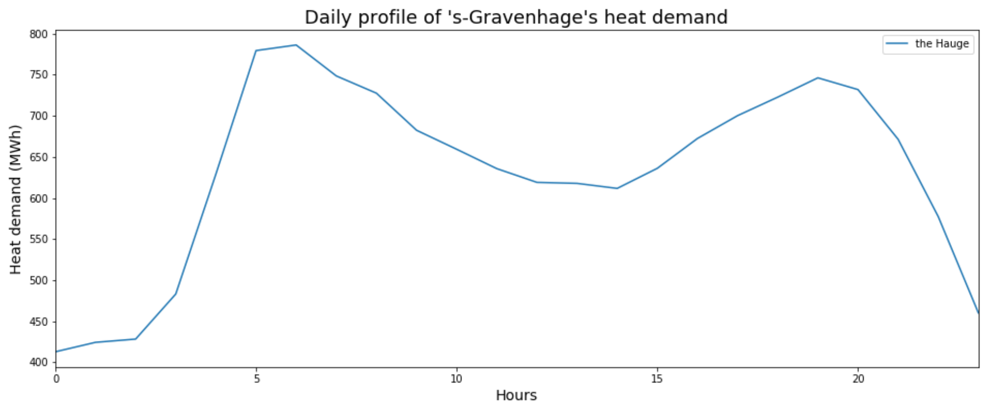


Figure 3.8: Daily profile of ’s-Gravenhage’s heat demand

When the heat demand profiles are generated by using demandlib, all three types of profiles are aggregated to reach the municipality’s total heat demand per hour. This data is generated for 10 years. When the regression line of this generated data set is checked, the line does not show any increasing or decreasing behaviour. Therefore, instead of continuing with a forecasting process, the heat demand values are just replicated 3 times to have a data set for 30 years which represents from 2020 to 2050. Figure 3.7 represents ’s-Gravenhage’s heat demand profile in 2020. Also, daily heat demand profile of the same municipality which shows a sample day’s heat demand is presented in Figure 3.8.

After the processing of heat demand data, one more step is considered before the data set gets ready for its use. The collected heat demand is the total municipal heat demand of the households, office environment and greenhouses. However, in reality, a certain share of these buildings are connected to a district heating network, while the rest individually operates with respect to their heat demands. Since this model focuses on the district heating networks, the value of district heating share in each municipality is collected from WarmteAtlas (Rijksdienst voor Ondernemend Nederland, n.d.).

3.4.3. Solar energy output

Output values of a solar PV system with 1 kW capacity data is collected from ”Renewables.ninja” (Pfenninger & Staffell, 2016; Staffell & Pfenninger, 2016). It is of hourly resolution and collected for each of the municipalities in the Netherlands. The collected data covers 10 years, starts from the beginning of 2006 and goes until the end of 2015. There is no missing value found in the data set. When the data is checked by using linear regression methods, it does not imply any increasing or decreasing behaviour over the years. Therefore, instead of forecasting future values, the existing data set is replicated three times to acquire a data set which can be used for 30 years.

At this point, instead of using the hourly solar output data for each municipality in the model, it is considered that using the average value of these 355 municipalities is a better representation of the real system. As described in the domain of the study, currently the solar energy in the Netherlands is distributed around the country quite homogeneously. When the municipal data values are provided to the model, it selects certain municipalities to install solar facilities. However, in reality, due to the subsidies provided by the government, many

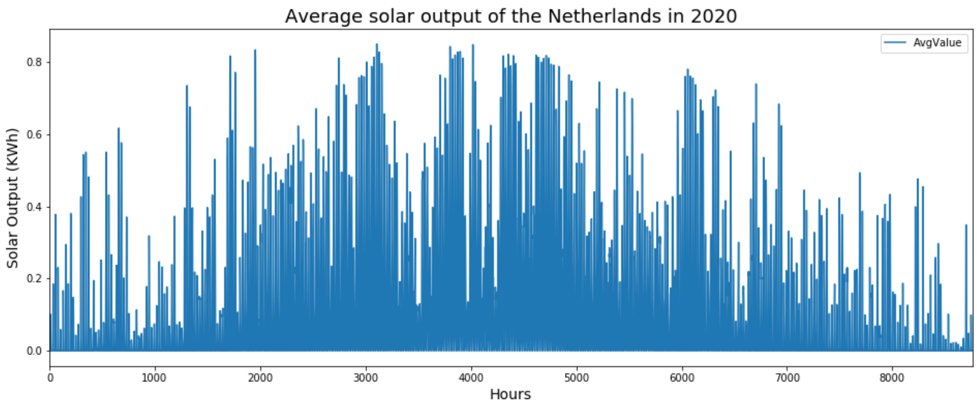


Figure 3.9: Average solar output of the Netherlands in 2020

households and offices around the Netherlands have solar PV installations. Therefore, hourly average values of solar output are calculated for the model use. The resulting data set's yearly values can be seen in Figure 3.9, while Figure 3.10 presents an hourly profile of solar output.

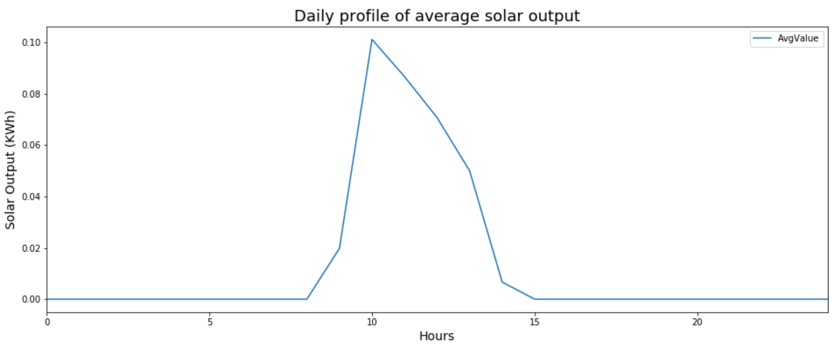


Figure 3.10: Daily profile of average solar output

3.4.4. Onshore wind speed

In order to calculate the electricity production of the wind turbines, hourly wind speed values of municipalities are needed. "Royal Netherlands Meteorological Institute (KNMI)" (n.d.) provides hourly wind speed values which are collected from 50 weather stations in the country. Collected data covers 10 years which starts from the beginning of 2006 and goes until the end of 2015.

When the data sets from different weather stations are examined, some missing values are detected that in several data sets. Figure 3.11 represents one example set for the missing values and another example for a complete set. Both images show data for 10 years.

In order to fix these missing values, a python library called "datawig" is utilized (Biessmann, Salinas, Schelter, Schmidt, & Lange, 2018). It is an imputation model which uses a neural network architecture called "Long Short-Term Memory (LSTM)". The complete data sets of hourly wind speed values are used to train the neural network, and then the trained neural network is used to repair the sets with missing values. By doing so, the daily and yearly patterns of wind speed values are represented in the artificially filled parts of the data sets.

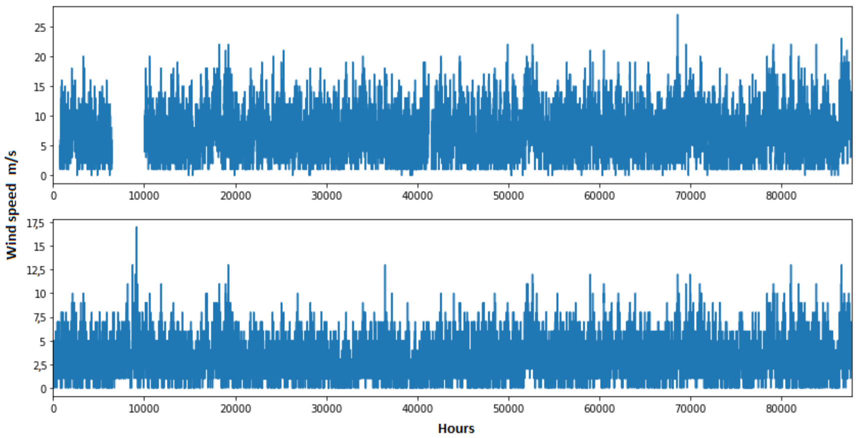


Figure 3.11: Example data sets for onshore wind speed values

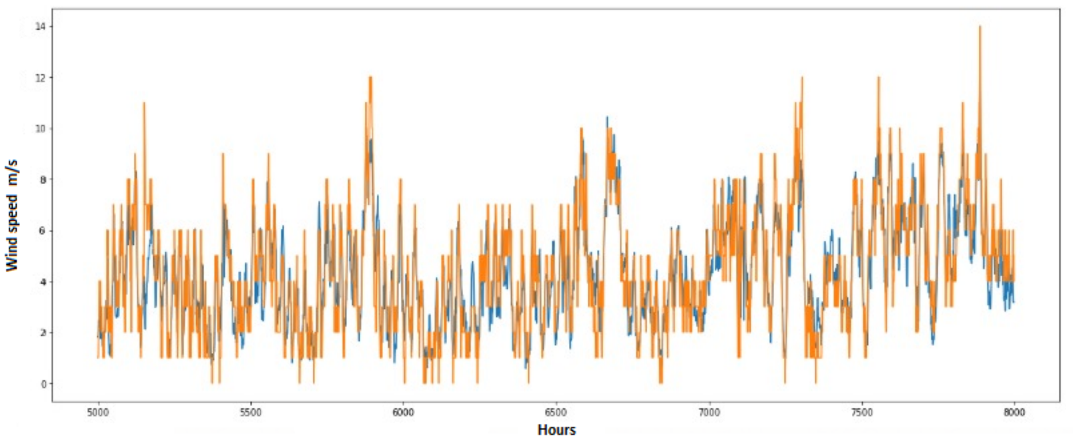


Figure 3.12: Control run for the neural network architecture with real (orange) and artificial (blue) data together

In Figure 3.12, a control run of the neural network is presented. For this control run, a randomly selected part from a randomly selected complete set is deleted deliberately. Then, the neural network is trained by using other complete sets, and the deleted part is refilled by using the trained neural network. As seen in the Figure 3.12, the estimated values follow the original values quite close. The same imputing technique is used for the parts which are missing in the original data.

When the missing values are handled, the data set is checked whether it shows incremental behaviour over the years, or not. It is recognized that there is not a distinctive trend for the data. Therefore the data at hand which covers 10 years is replicated 3 times and it is used for 30 years.

A similar approach to the solar output data processing, which is explained in the previous section, is adopted for the wind speed processing. After handling the problematic values of the data set and making it ready, the data at hand is compared to the dynamics of the real system.

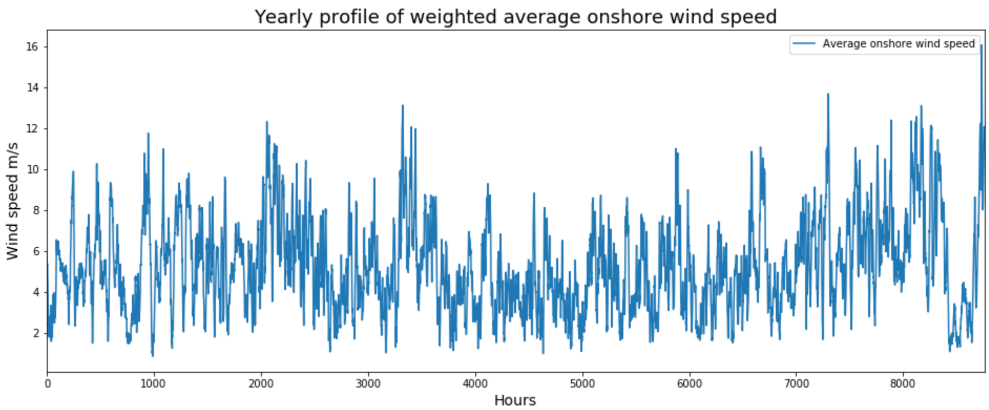


Figure 3.13: Yearly profile of weighted average onshore wind speed

As described in the previous chapter 2, wind power is concentrated in several provinces and it does not have a homogeneous distribution over the country. 7 provinces have 95.81% of the wind turbine installations in the Netherlands. On the other hand, the distribution of wind projects in these provinces is quite homogeneous. To be able to represent this homogeneous distribution in the 7 provinces, the collected data is filtered respectively.

These 7 provinces are selected to represent the places which are capable of producing electricity by utilizing wind power in the Netherlands. The existing wind speed data set is filtered with respect to its source weather stations. The distribution of the weather stations is presented in Figure A.1 in Appendix E.

By only including the data points which come from the weather stations in the selected provinces, a weighted average of the wind speed values is calculated and weights are identified by using the share of each province. Higher share of installed wind capacity means higher weight for the average wind speed. In Figure 3.13, yearly profile of calculated average wind speed is shown.

After the calculation of average wind speed over the years, it needs to be converted to the format which is meaningful for the model use. It means, it should indicate the electricity output instead of wind speed. For this purpose, first, the average capacity of the wind turbine installations in selected provinces for the last 2 years is found as 3 MW. Then, as one of the wind turbine models which has a close capacity value to the average, Senvion's 3.4M104 3400kW is chosen as a representative wind turbine for the onshore installations. Since the wind speed data which is collected from the weather stations represent the wind speed values for the ground level, the wind speed value of the hub height for the chosen wind turbine needs to be calculated. Wind speed at these heights is estimated by using ”Hellman exponential law” whose formulation is provided in equation below (Bañuelos-Ruedas, Camacho, & Rios-Marcuello, 2011).

$$v/v_0 = (H/H_0)^{\alpha} \tag{3.27}$$

v represents the speed to find, while v_0 is the ground level wind speed. Similarly, H represents the target height whose wind speed is estimated, and H_0 ground height. Lastly, α is assumed to be 1/7 for the onshore facilities (Bañuelos-Ruedas et al., 2011). By using this formulation, the low height wind speed values are converted to the wind speed at the hub height of chosen wind turbine model.

After correcting the wind speed with respect to hub height of wind turbines, by the help of power curve of the chosen wind turbine model, the wind speed values are converted into power output. In Appendix E, Figure A.2 shows the used power curve for the onshore installations. Since the capacity of a wind turbine is 3.4MW, the generated electricity is found respectively. By dividing the values to the maximum capacity, electricity output of a wind turbine installations with 1 kW capacity is calculated for the model use. Yearly profile of the onshore output values is presented in Figure 3.14.

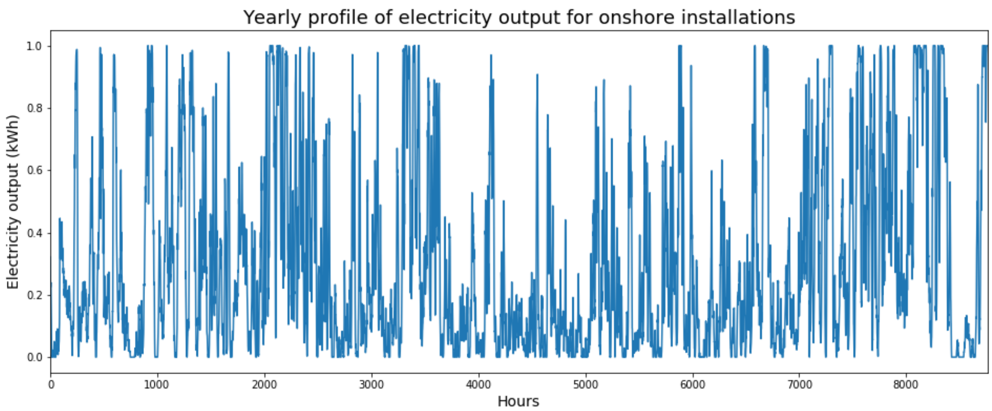


Figure 3.14: Yearly profile of electricity output for onshore installations

3.4.5. Offshore wind speed

Wind speed data for offshore projects is also collected from ”Renewables.ninja” Pfenninger and Staffell (2016); Staffell and Pfenninger (2016). Similar to the solar output data and outdoor temperature data, wind speed data values are of hourly resolution, and can be collected for any point in the Netherlands, including actual offshore points. For the sake of this model's scope, it is considered that selecting a point which is placed in the middle of existing wind offshore facilities of the Netherlands can be a valid representative point for the future offshore projects. Collected data is available from the beginning of 2006 until the end of 2015, so it covers 10 years.

Neither the collected data has a missing value, nor it shows an increasing or decreasing behaviour over the years. Therefore, it is concluded that collected offshore wind speed values are ready to be used in the model right after it is replicated three times to cover 30 years. In Figure 3.15 the yearly patterns of the collected data values for offshore wind speed can be seen.

Similar to the data processing steps for the onshore installations, the data values should be converted to electricity output. For this purpose, the average capacity of the offshore wind

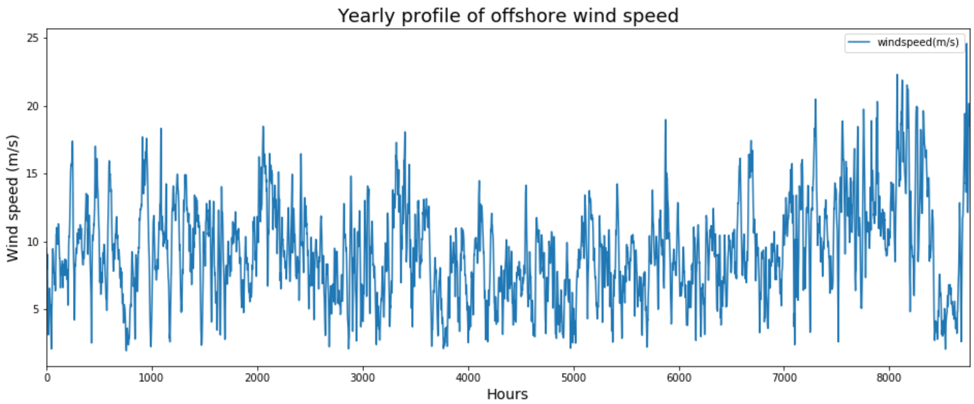


Figure 3.15: Yearly profile of offshore wind speed values

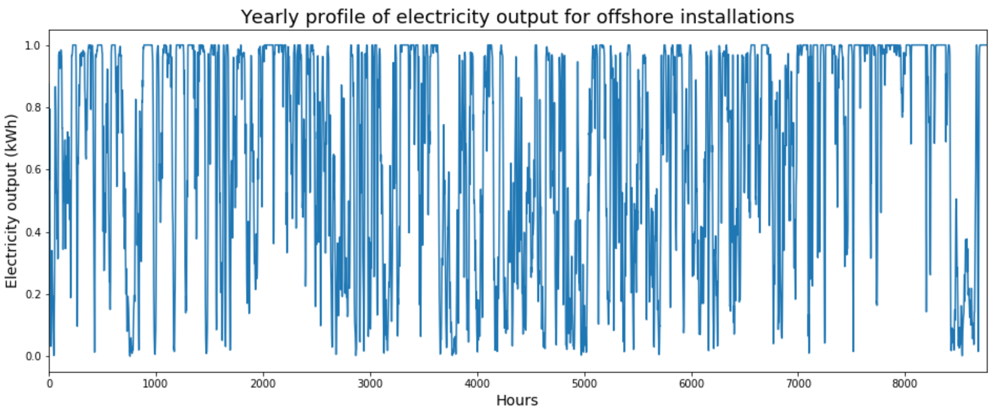


Figure 3.16: Yearly profile of electricity output for offshore installations

turbines is calculated for the facilities which have been installed in the last 2 years and also the offshore projects which are currently under construction. The value is calculated as 5.3MW. As one of the wind turbines which provide with publicly accessible power curve data and also whose capacity value is close to the average, Senvion's 6.3M152 6300kW is chosen to represent offshore facilities. Power curve of the chosen offshore wind turbine model can be seen in Figure A.3 in Appendix E.

Since the data collected from Renewables.ninja is already adjusted to the required hub height, no further processing is necessary. The wind speed data is converted into electricity output data and it becomes ready for the model use. Figure 3.16 shows the yearly profile for the electricity output of offshore installations with 1 kW capacity.

3.4.6. Techno-economic variables

Until this point, all the presented input data is related to the time series which are used in the model. This section is used to explain the techno-economic parameters. These techno-economic parameters are the data points which describe the functioning of generation facilities, or they are needed to represent the real system in the model in a clearer way.

All the collected data here is about the facilities and the fuel types that they use. Electricity generation efficiency, and thermal efficiency of the facilities are included as the technical parameters. On the other hand, nominal investment cost of the facilities per unit capacity, fixed O&M cost per unit capacity, and finally the variable O&M cost per unit amount of energy generated by a facility are included as the economic parameters related to the facilities.

To be able to prevent the use of biased data, multiple sources are utilized while collecting the techno-economic parameters. Average values of the collected data points are provided to the model as input data. Values of these parameters which are included in the model can be seen in Table A.1 in Appendix A. It should be noted that certain parts of this data values are collected but not included in the actual modelling phase because of the implemented reduction techniques to decrease the computational heaviness.

Bertsch et al. (2012) provide the parameters of coal based co-generation facilities; natural gas based co-generation facilities; biomass based co-generation facilities; coal, natural, and biomass gas based power plants; solar PV systems; and finally onshore and offshore wind turbine projects. Similarly, in their study Fürsch et al. (2013) share parameters for the same set of facilities. Brouwer et al. (2015) provide the techno-economic parameters of natural gas based co-generation facilities, coal power plants, natural gas power plants, solar PV systems, onshore wind turbines and offshore wind turbines. Report prepared by Pöyry Energy (2009) presents techno-economic parameters for natural gas and biomass based co-generation facilities, district scale natural gas and biomass boilers, and district scale heat pumps. Hirth (2013) provides the parameters for coal and natural gas based power plants, solar PV systems, and onshore and offshore wind turbine installations. VGB PowerTech (2012) publishes the investment and operating cost values for coal, natural gas and biomass based power plants, solar PV installations, onshore and offshore wind turbine installations. In its levelized cost of energy consultancy reports, Lazard (2018) shares values for coal and natural gas based power plants, solar PV systems, onshore and offshore wind turbine installations. In its 2010 report for energy technologies, IEA (2010) provides with data values for coal, natural gas, and biomass based power plants, solar PV installations, onshore and offshore wind turbine projects, with a more recent report from 2017, IEA (2017) updates the data for biomass based electricity facilities. In its report which is a collection of technology data for energy plants, Energinet (2012) provides with techno-economic parameters for all the included facilities in this model but coal and natural gas based co-generation facilities. Finally, energy supply technologies data reports which are provided by IEA-ETSAP are used while collecting data about the generation facilities (IEA-ETSAP, 2010a, 2010b, 2010c, 2010d, 2013a, 2013c).

Parameters for heat transmission network are determined by utilizing expert opinion. 53.44

€ per MW per meter is chosen as the investment cost of pipeline branches. Heat loss during transmission is included in the model as 3.5% per pipeline installation (Wang, Duanmu, Li, & Lahdelma, 2017). To differentiate between expenditure in different decades, an interest rate is identified and applied to the each cost element in the model. It is assumed that the yearly interest rate is fixed over the decades and equal to 4.5% for energy projects (*Rapport Werkgroep Discontovoet 2015*, n.d.).

As one of the heat sources included in the model, industrial waste heat data is collected from Vesta-MAIS model (R. & van den Wijngaart R., 2017). Included values of industrial waste heat are calculated as the sum of heat energy which comes from industrial facilities, and heat energy comes from refineries. The values are identified for each municipality, and the generation of waste heat is assumed to be stable over the years. Figure 3.17 shows the included industrial waste heat values in each municipality which has a positive value of industrial waste heat.

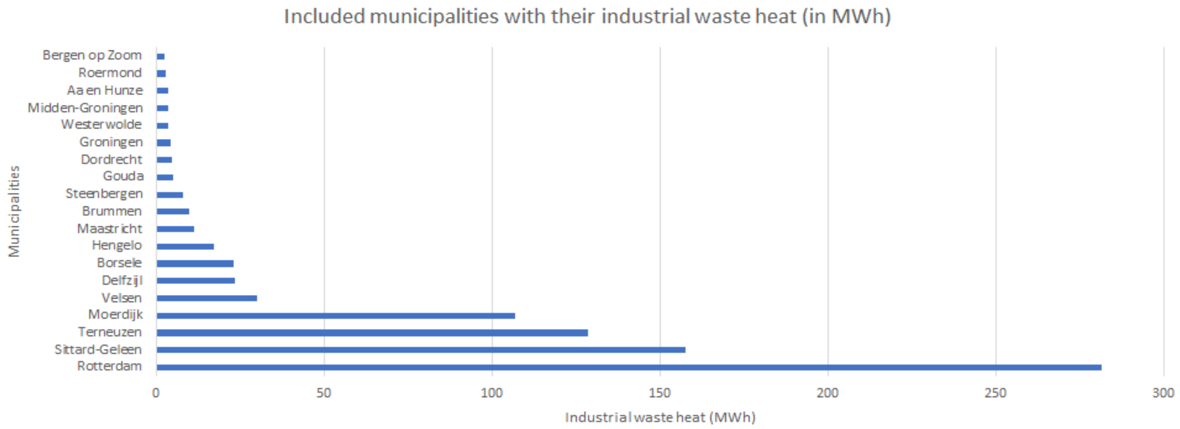


Figure 3.17: Amount of industrial waste heat in municipalities (in MWh)

Besides the techno-economic parameters of generation facilities and heat distribution network, input data for fuel types which are included in the model is also collected via several reports and studies. Natural gas' price value is found in the yearly report of TenneT (2018), and the average value of 2018 is assumed to be the natural gas price value for this study. For the calorific value of the natural gas, it is considered that the use of Groningen gas is more suitable since the study aims the Netherlands' systems. It is collected from GasTerra's yearly report (2012), while for the CO_2 emission values of the natural gas RVO's report is used (2002). As a result, the unit price of the natural gas is determined as 0.196 €$/m^3$; the calorific value of natural gas is determined as 8.792 kwh$/m^3$; and finally the CO_2 emission values of natural gas is stated as 1.776 kg$/m^3$.

For the parameters related to coal, the same TenneT report (2018) provides with the price values, while the calorific value and CO_2 emission values are collected from RVO's report (2002). When the collected values are converted to the units which are used in the model, unit price of coal is set as 0.089 €/kg, the calorific value of coal is determined as 7.972 kWh/kg, and CO_2 emission values of coal is stated as 2.698 kg_{CO_2}/kg_{coal}.

As the third and last fuel type which is included in this study, input data for biomass is collected via several reports. It should be noted that the biomass fuel used in this model is ”wood pellets”. All the provided data values are collected specifically for wood pellet biomass fuel. The price value of the wood pellets is found as 0.113 €/kg (Goh & Junginger, 2015). Data for calorific value, and CO_2 emission values of biomass are collected from the same RVO report (2002), and calorific value is set as 4.194 kWh/kg, while the emission value is set to 0 kg_{CO_2}/m^3_{gas}.

3.5. Solutions to computational constraints

The model which is described in the previous sections have been tested by using the input data which also is explained in the previous sections. The model run was not able to reach an optimal result within an acceptable time period. Therefore, it is recognized that certain speed-up technologies are needed to be able to provide solutions by using this model. This chapter is used to describe the utilized methods to reduce the computational heaviness of the model. After applying methods introduced in the following paragraphs, the number of decision variables has come down to 416268, which initially was 33119370000.

3.5.1. Limiting the spatial and temporal resolution

When it is seen that radical reductions are needed in the required computational power to be able to conduct analysis by using the model, some changes in the model settings are made. These changes are mainly the adjustments of temporal and spatial resolution which is used in the model.

Assuming the electricity system as a copper-plate already reduces the required power significantly, and the electricity system already operates in the country level. However, for the heating system, the model's spatial resolution is at the municipal level. As it is stated before, the model has 355 municipalities as its nodes, and it tries to come up with the minimum cost design of primary heating network and set of electricity and heat generation facilities. Each node is a candidate for an installation of a co-generation facility, a large-scale boiler, or a heat pump.

When the existing structure of the model is considered, it is realized that some of the computational power is unnecessarily used for a certain set of computations. Heat demand of the municipalities is determined based on the district heating share of each municipality, and there are municipalities with 0% district heating share. Installing a facility which generates heat energy in these municipalities with 0 heat demand is not suitable for the model.

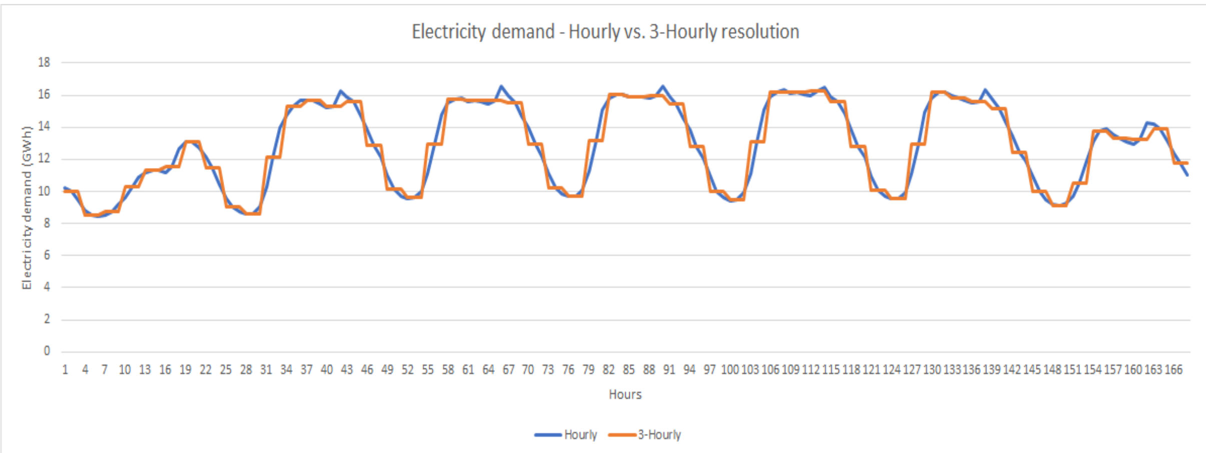


Figure 3.18: Electricity demand - Hourly vs. 3-Hourly resolution

Even under cases which the neighbours of these municipalities are of certain amount of heat demand, it does not make any sense for the model to install a new generation facility and install required pipelines to carry heat from this facility to the neighbours with positive demand. This is because the model does not have the sense of economies of scale. It cannot differentiate between situations where installing higher capacities yield cheaper production due to the economies of scale. This incapability of the model opens the way to reduce the computational requirements a little further, since by recognizing this it becomes possible to remove the municipalities without any district heating infrastructure. By excluding the municipalities with no district heating network, the model disburdens some of its weight.

By taking a step further, it is assumed that the heat energy can be transferred between municipalities if and only if these municipalities are neighbours.

For the temporal resolution, a more straightforward application is performed. The model was in hourly resolution. In order to reduce the required computational power, it is converted into a model with 3-hourly resolution. The changes are presented in Figure 3.18 which shows the differences in hourly and 3-hourly electricity demand. Similarly, Figure 3.19 indicates the changes in heat demand. Besides the changing hourly resolution for operational decisions, it is assumed that the strategical decisions are made during decision windows which exist once in each decade.

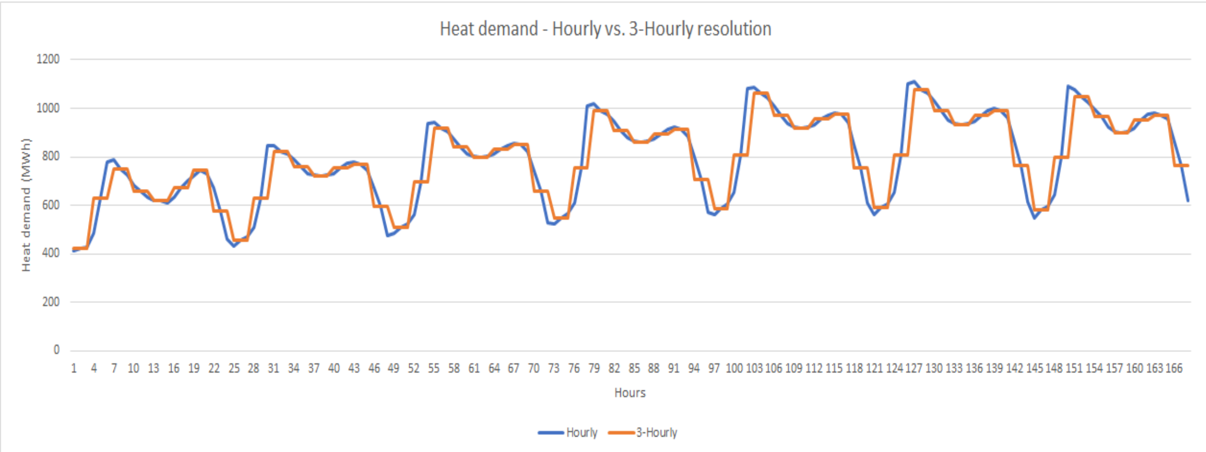


Figure 3.19: Heat demand - Hourly vs. 3-Hourly resolution

In order to reduce the error due to this conversion, each time series data included in the model is checked for 5 different options. Selecting the average value of three consecutive hours, the first hour, the second hour, the third hour, and selecting the maximum of three as the representative value of these consecutive hours are compared to each other. It is found that selecting the second hour to represent its three hourly block yields the least error for all of the time-series, and it also mostly conserves the peak values.

3.5.2. Use of representative days

Besides the changes in spatial and temporal resolution of the model, further reductions in computational requirements are sought to be able to achieve a model which can produce results in acceptable time limits. It is stated that the use of a chosen set of data points to represent a whole year's operations can reduce the computational requirements without harming the quality of the model's outputs drastically (Poncelet, Höschle, Delarue, Virag, & D'haeseleer, 2017). Also in the same study, use of a hybrid technique which is conducted by randomly selecting the representative days and optimizing the weight of the chosen days by the help of an LP model is suggested (Poncelet et al., 2017). This method is used to come up with a set of representative days together with their frequencies, which yields the least time-series distance for given data sets.

Based on the study of Poncelet et al. (2017), the hybrid method is implemented to find the days which represent the period of 10-years the best for the provided time-series data. These time-series data sets are namely hourly solar output, hourly offshore wind speed, hourly onshore wind speed, hourly electricity demand and hourly heat demand. The aim of this practice is basically to identify certain days in 10 years which show the distinctive characteristics, so that they can be used to represent the whole period. It is expected that with such an application, significant amounts of computational power can be saved.

Since the number of representative days which gives the best performance with respect to

Table 3.1: Selected representative days and their frequencies in 10 years

Years	Representative Days	Frequencies
5^{th}	27 January	411
7^{th}	19 February	557.5555
1^{st}	30 May	79.70549
4^{th}	10 June	607.3673
10^{th}	27 June	918.7522
4^{th}	14 October	298.4528
4^{th}	16 November	584.0925
1^{st}	3 December	160.5743
9^{th}	31 December	32.5

related amount of error is not known in advance, the process starts by selecting two representative days, and selection is repeated while increasing the number of representative days by one in each iteration. This repetition stops when the time series distance converges to a certain value, and the further reductions which can be achieved by increasing the number of representative days become insignificant.

Selection of the representative days is done randomly, and the selected representative days are fed to the LP model to calculate the optimal frequencies of these days. Frequency is basically the rate of occurrence of a single day within 10 years. LP model is used for 15000 randomly selected samples. The results are shown in Figure 3.20.

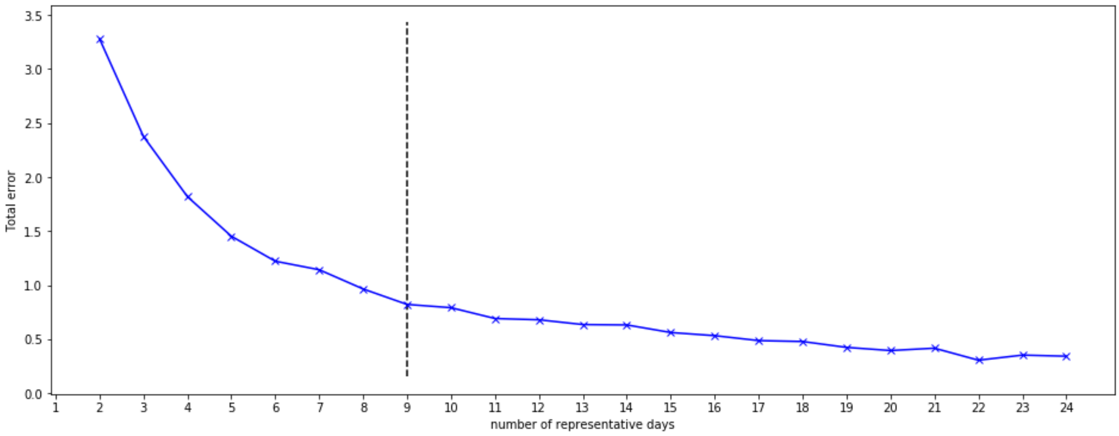


Figure 3.20: Decreasing error values with respect to the increasing number of representative days

When the elbow method is used to identify the most suitable number of representative days, it suggests that 9 days perform sufficiently. These days are identified as the 149^{th}, 336^{th}, 1255^{th}, 1381^{st}, 1414^{th}, 1486^{th}, 2239^{th}, 3284^{th}, and 3462^{th} days of the period of 10 years. Table 3.1 presents these representative days and their related frequencies.

After the implementation of representative days, the heaviness of time series data used in the model significantly decreases, and the model starts using 9 days to represent a decade. As described in the previous sections, 30 years data is generated by replicating the original data sets because they do not show any changing behaviour. One exception is the electricity demand data. However, when it is checked, it is recognized that the forecasting method generates similar patterns for future electricity demand. Therefore, identifying the set of representative days for the years between 2020 and 2030, and then using the same set of representative days for other decades in the model is considered as an appropriate approach. In Figure 3.21 the electricity demand profiles during these representative days are presented. Similar to that, in Figure 3.22, heat demand profiles of the municipalities are shown. Figure

3.23 shows the output of onshore and offshore wind installations, while Figure 3.24 presents the output of solar PV installations.

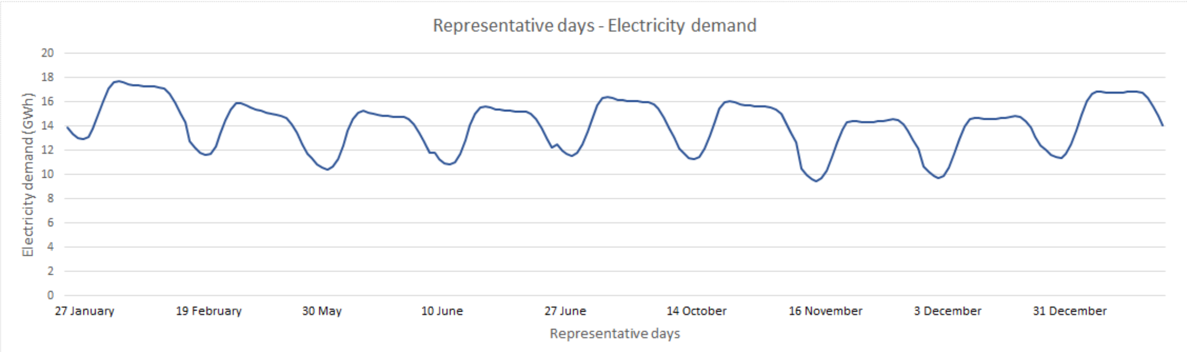


Figure 3.21: Daily electricity demand profiles for representative days

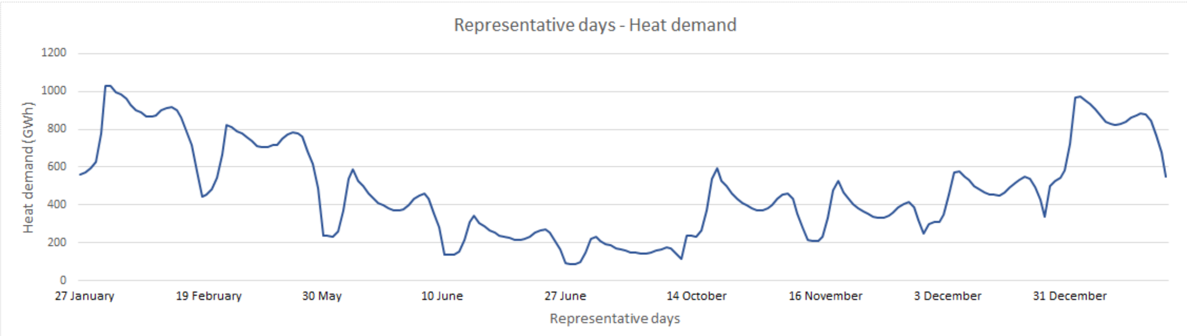


Figure 3.22: Daily heat demand profiles of the Hauge for representative days

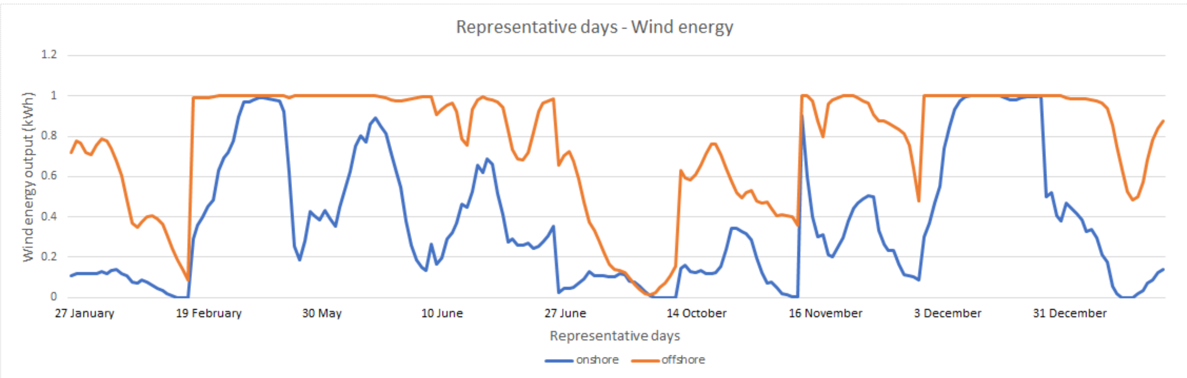


Figure 3.23: Daily profiles of onshore and offshore electricity output for representative days

3.5.3. Removing the integrality constraints

As described in the previous sections, using 3-hourly data values instead of hourly data, reducing the number of decision variables by removing unnecessary nodes from the system, and using representative days technique are the methods used to decrease the computational heaviness of the created model. All of these techniques aim a reduction in the number of decision variables, so that the model can reach the optimal solution more quickly.

However, reducing the number of decision variables is not the only option to decrease the required computational power. If the model has binary or integer variables, implementing

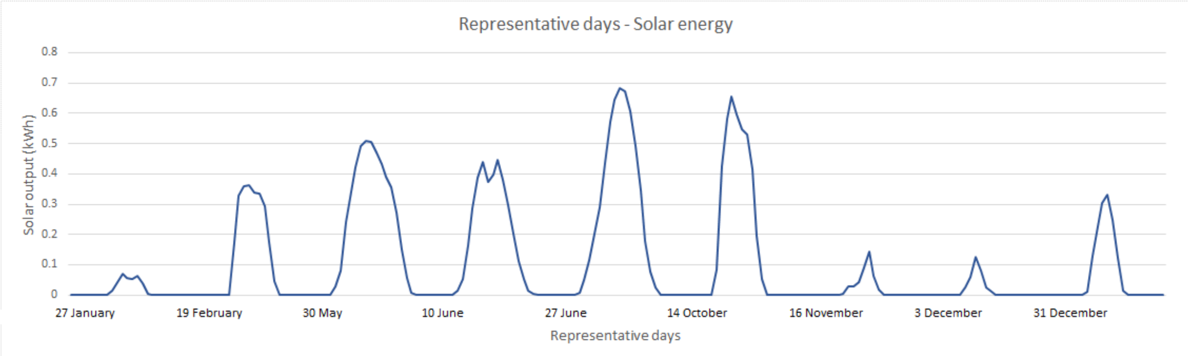


Figure 3.24: Daily profiles of solar PV electricity output for representative days

”relaxations” might be an option. It is basically removing the integrality constraints, and letting the model choose float values for the quantities which are described as integers before. By applying such conversions, the Mixed-Integer Linear Programming (MILP) model is converted to a Linear Programming (LP) model, which reaches the optimal solution in a much faster way when it is compared to the previous model settings.

First version of the created model for this study had the integer variables for the number of wind turbines installed in a municipality. When it is realized that the model faces with a barrier related to required computational power, relaxation is considered as an option to be implemented.

Although such relaxation methods help to model reach a solution in a shorter amount of time, the meaning behind such an application should be considered carefully. Assuming that the wind turbine installation can have a floating number values basically means that it is possible for the model to install, for example, ”a half wind turbine” when it yields a better result. It should be noted that such relaxations drag the model away from the real system, but it is a necessary step to take to be able to use the model for further analysis.

4

Model testing

The model is described in the previous chapter, Chapter 3, in its entirety. Included dynamics of the model, utilized data sets, and applied speed-up methods are shared. At this point, there is a model at hand, but it is not known, yet, whether this model is created correctly, or it fits the purpose. Also, it is not known what the base case results of this model are, and how these results are affected with respect to the changing variable values. Therefore, before proceeding with the experiments, it is necessary to check the above mentioned points.

First subsection in this chapter is used to explain the tests which are conducted by using the model to check whether its working correctly, or not. Subsection 4.2 presents the base case scenario of the model, which constitutes the backbone of future experiments and comparisons. Subsection 4.3 provides with the validation process which checks whether the model fits the research purposes with an acceptable degree. Lastly, subsection 4.4 is used to analyze the sensitivity of the model for changing variable values.

4.1. Verification

After formulating the mathematical model, translating it into code, and feeding the collected input data, the first results are gathered. However, at this point the question arises: is the model translated correctly? This section is used to conduct a verification analysis which checks whether the model is coded according to its formulation.

Verification checks whether the model works in accordance with the modellers expectations. For that purpose, a set of cases which has expected outcomes are prepared by changing certain parameters in the model, and it is checked whether the model is able to produce the expected outcome, or not. Below, the checks which are used for verification purposes are shared. It is concluded that the model operates as expected and it passes all the tests provided below.

- If the investment, annual O&M or variable O&M cost of a facility significantly decreases, its share in the generation mix increases. (This check is applied to each facility type.)
- A significant decrease in the cost of a particular fuel type leads to increase in capacity of facilities which use the related fuel. (This check is applied to each fuel type.)
- Increasing efficiency of facilities leads to lower total fuel cost. (This check is applied to each facility type.)
- As the number of municipalities with positive district heating share increases, total heat generation increases.
- As the share of wind energy increases, the spilled electricity increases.

- Increasing pipeline installation costs leads to lower number of connected municipalities.
- When only wind or solar energy sources are included, the model installs tremendously high amounts of capacity due to the hours with low energy output.
- Less emission reduction targets for the future years yields decreasing total system costs.
- More emission reduction targets leads to higher installation capacities of carbon-free sources.

Besides the cases, the input data is compared to the output. The electricity demand and heat demand data fed into the model are compared to the generated amount of electricity and generated amount of heat energy in the model. For the electricity system, when the heat pumps are deactivated, it is expected that the model generates exactly the same amount due to the copper-plate assumption. It should be noted that this expectation is for the time periods with low renewable energy output, so the model needs to use other sources to fulfill the demand. On the other hand, the model should generate more heat energy than the given demand data, without utilizing the industrial waste heat, if it builds pipelines. This is because the pipelines has a heat loss factor. Excluding industrial waste heat is necessary because it is used as a stable source of heat energy in the model regardless the heat demand. When these are checked, it is concluded that the model gives the expected outcomes. The electricity generated is the same as electricity demand without the effect of heat pumps, and the generated heat is slightly higher than the demand itself due to the heat losses.

4.2. Reference scenario

Before conducting any experiments with the model, this section is used to explain the reference case which is designed to represent the dynamics of the real system as much as possible. The reasoning behind this scenario's design and also its findings are shared in this section. Then, based on the findings shared here, the what-if scenarios are used for the experiments which are designed to shed some light on the identified research questions.

4.2.1. Climate targets

First of all, the main starting point of the reference scenario is related to the ”Climate Act” which is discussed in the Dutch parliament in June 2018 (*Climate policy*, n.d.). It is stated that the Dutch government aims to reduce the greenhouse gas emissions by 49% by 2030 compared to its emission levels in 1990. Similarly, the target reduction value climbs up to 95% by 2050.

It is considered that the model should operate under similar emission targets to be able to reflect on the applicability of these policies. Also it becomes possible to analyze the future systems more realistically when such governmental targets are included in the design of the base scenario.

4.2.2. District heating targets

The second point which affects the design of this base case scenario is related to the district heating share in the municipalities. As stated before, the current district heating share in the Netherlands is around 5.5%. It is stated that total district heating share in the Netherlands can increase up to 56% (Paardekooper et al., 2018). This value, 56%, is determined as the starting point of the district heating calculations of this study.

When the data is collected for district heating share of each municipality from CBS 2019d, it is recognized that the municipality of Leeuwarden has the least share of district heating with 3%, among the municipalities with positive district heating share. Then, heat density of municipalities is calculated by dividing the total heat demand of a municipality by its surface area. As the municipality with the minimum district heating share, Leeuwarden's heat density is calculated as 4069.53 MWh/km^2.

By assuming that the heat density of Leeuwarden is the least acceptable heat density to construct a district heating network, the municipalities are filtered. As a result, 173 municipalities are identified as the candidate municipalities for future district heating installations. Besides these municipalities, 9 more municipalities are included since they have industrial waste heat potential but their heat density is below the identified threshold. As a result, 182 municipalities are included in the analysis for base scenario. The rest is assumed that they will not be connected to district heating networks due to their low heat density values.

It is considered that the heat density can be used as a measure of prospected district heating share of municipalities in the future. For example, the most dense municipality gets 90% of its heat demand from a thermal grid, while the least dense municipality gets only 25% of its heat demand from a network. To identify such values, the municipalities are ranked with respect to their heat densities. However, it is realized that the gap is too high between the most and the least dense municipalities, and a linear distribution over the municipalities cannot reach 56% total share at the end. To decrease the gap without losing the original ranking, square-root of the heat density values are used to rank the municipalities and to distribute the future district heating shares respectively. Included municipalities in the reference scenario, together with the mapping of heat density values of all municipalities are presented in Figure 4.1. On these maps, as the color gets lighter, heat density values reach higher points.

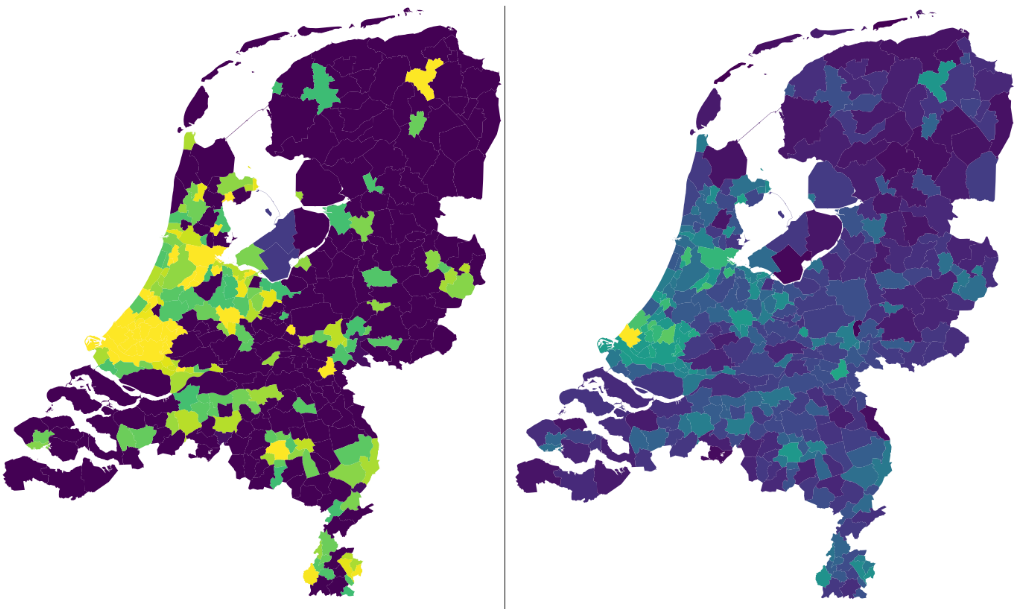


Figure 4.1: Included municipalities in reference scenario with their 2050 thermal grid targets (left), Heat density of municipalities (right) (Lighter color means higher values)

Two more assumptions are made related to district heating networks. First, the maximum share which can be reached by a municipality is set as 90%. The 10% gap is representing the households, offices or greenhouses which are not in easily reachable places, therefore they are excluded from the network. Second, it is assumed that district heating networks are expanded with a steady pace in each municipality, and this pace is calculated based on the target district heating share of a related municipality for the year of 2050. For example, if a municipality has 0% district share in 2020 and its target is 90% for 2050, then in 2030 the municipality reaches 30%, in 2040 it reaches 60%, and in 2050 it reaches its target value, whereas if a municipality has an existing district heating share which is 10% and its target is 70%, then it reaches 30% in 2030, 50% in 2040 and it reaches its 70% share in 2050.

Assumed development of district heating networks is presented in Figure 4.2.

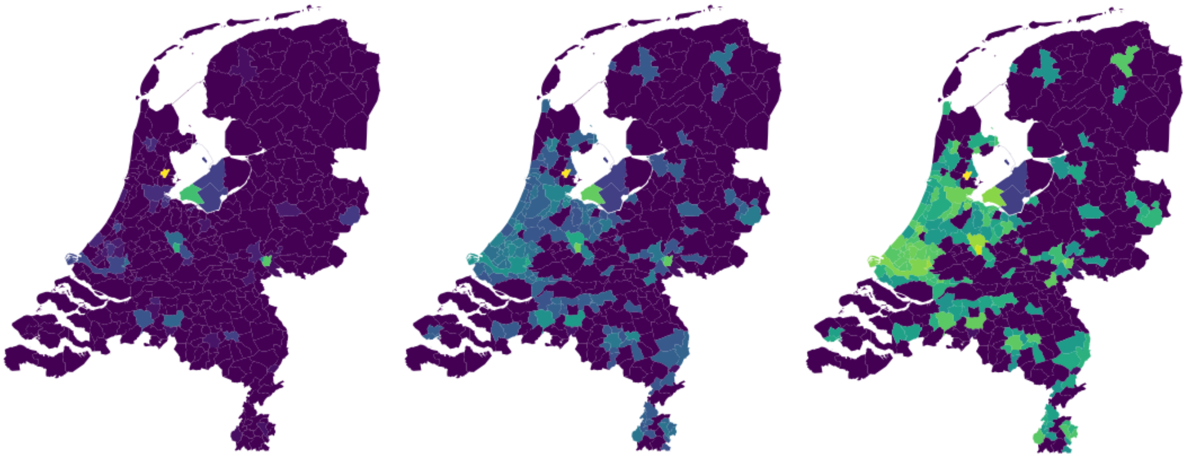


Figure 4.2: Expansion of the thermal grids over the years (2020, on the left; 2030, in the middle; 2040, on the right) (Lighter color means higher values)

4.2.3. Results of the reference scenario

After the model is prepared and the reference scenario is created, the model is run with the described reference scenario. As described in the previous section, the district heating networks start from 5.5% and hits 56% in 2050, and emission targets are set in line with the governmental targets in the reference scenario. This section is used to present the gathered findings by using this scenario.

The optimal system cost of designing an integrated electricity and heating system in the Netherlands by using a greenfield approach is calculated as 540.66 billion €. As two major parts of this total value, investment decisions are responsible for 39.51% of this total value, whereas the share of fuel costs is calculated as 37.90%. 17.91% of this total value is for annual O&M costs, and the rest is due to the variable O&M costs. Each facility type's contribution to the total cost can be seen in Figure 4.3 which shows the yearly values of investment cost, annual O&M cost, variable O&M cost, and fuel cost in a detailed way.

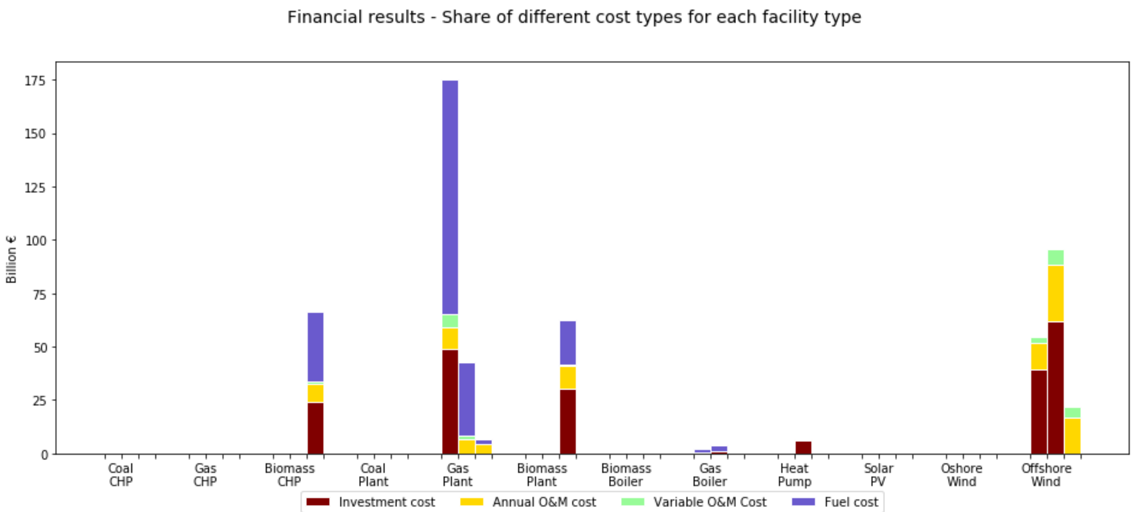


Figure 4.3: Cost values for each facility type (first bar:2020, second bar: 2030, third bar: 2040)

It can be seen that the biggest individual cost value is the fuel cost of natural gas-based electricity generators in the years between 2020 and 2030, while the investment costs, in general, are of the highest share among the other cost factors. As the carbon emission targets increase over the years from 49% to 95%, the use of natural gas is significantly restricted. As a result, for the years between 2040 to 2050, there is just a small share of natural gas.

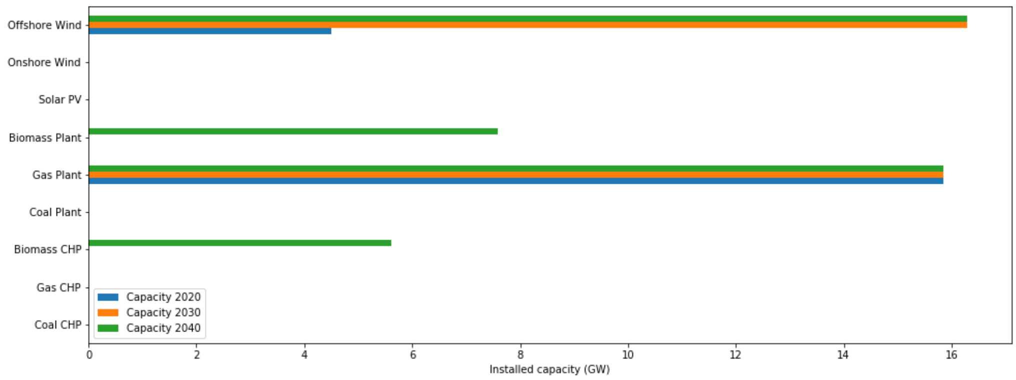


Figure 4.4: Electricity sector - existing capacity in each decade

When the electricity generation share is checked, it can be concluded that the dominating generation type is changing in each decade. It is seen that in the first decade the model invests in natural gas-based electricity generation facilities, which are the CCGT plants in the model. While there are not strict carbon emission reduction targets, natural gas dominates the electricity sector. As the secondary source of electric energy, offshore wind turbine installations are seen in the results. On the other hand, the second decade indicates huge investments for offshore wind turbines, while gas plants' total capacity stays the same. With the imposed carbon emission targets, the model shifts its investments to offshore wind facilities. Lastly, for the years between 2040 to 2050, it is seen that biomass co-generation facilities and biomass electricity generation facilities are getting investments. When the carbon emission reduction targets hit 95%, the model invests in new baseload technologies which it can use to compensate intermittent nature of wind capacities. The results can be seen in Figure 4.4.

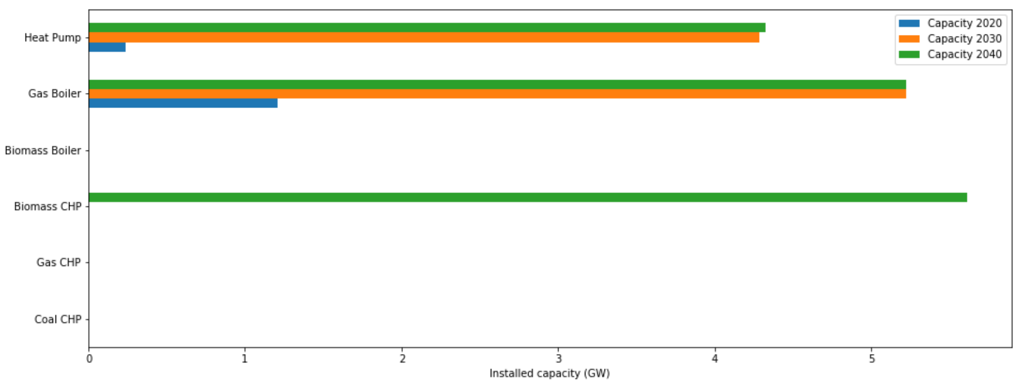


Figure 4.5: Heating sector - existing capacity in each decade

Similar changes can also be observed in the heating sector. The first decade's capacity investments are made for the gas boilers and heat pumps. Since in each decade, the district heating share increases with a steady pace, at the end of 2029, the amount of heat demand which needs to be fulfilled increases significantly. As a result of this, the model invests again. However, unlike the capacity investments for the electricity sector, the natural gas-based heat generation gets higher capacity investments. Also, it is visible that the heat pump installations increase significantly. There are two main reasons behind such a jump.

First, the model invests offshore wind facilities in the second decade, and as a result the amount of electricity generated by renewable sources increases. This increase can show itself as the use of heat pumps in the heating sector as a way to utilize spilled electricity. Secondly, the carbon emission reduction target is imposed in 2030 as 49%, and this requires certain reductions in the heating sector, too. Heat pumps are able to generate heat energy with zero carbon-emission if the electricity is generated by one of the renewable sources.

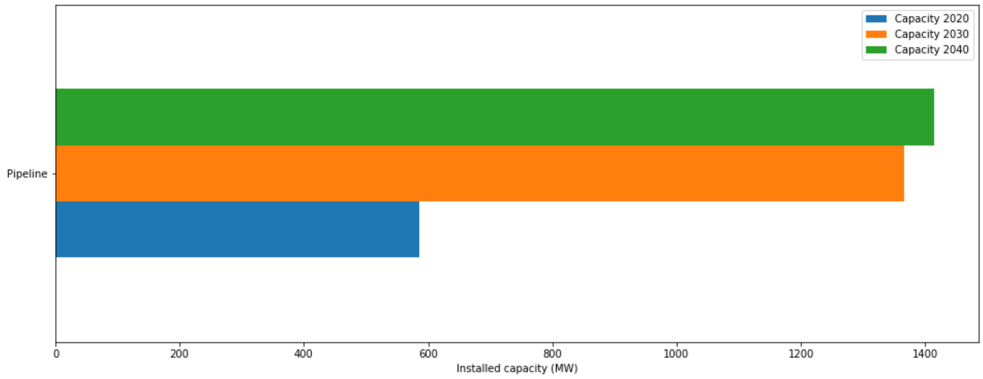


Figure 4.6: Pipelines - existing capacity in each decade

The investments for biomass co-generation facilities peaks in the years between 2040 to 2050. It is concluded that when the model needs generation facilities which can generate electricity with the absence of wind energy, this also affects the heat sector due to the installed heat pump capacities. Shifting biomass co-generation facilities solves both of the sector's problem simultaneously. The overall situation can be seen in Figure 4.5.

Besides the capacity investments in electricity and heating sectors, the model also invests in pipelines. Although the overall capacities are of a smaller scale when they are compared to the electricity sector, the model builds around 585 MW capacity pipeline network in 2020. This value rises to 1365 MW in 2030, and 1415 MW in 2040. The change in the total pipeline capacity can be seen in Figure 4.6

It is also critical to check how these generation capacities are used. When the electricity generation mix is checked, it is concluded that for the first decade the electricity generation is significantly dominated by natural gas combustion. This happens as a result of the high investments for gas power plants during the first investment window in 2020. Electricity from offshore wind turbines also constitutes an important part of the generation mix during the first 10 years. Figure 4.7 presents the electricity generation mix in the first decade. Since the representative days are used in the model, the graph shows each day's 3 hourly generation profile.

Heat generation mix between 2020 and 2030 is dominated by three sources, which are the gas boilers, heat pumps and industrial waste heat. Especially during the first decade, the assumed district heating share of municipalities is still low, and as a result of this, the thermal grid's heat demand is quite low when it is compared to other decades. However, the industrial waste heat is stable over the years. As it can be seen in Figure 4.8 which shows the heat generation mix between 2020 and 2030, as a steady heat source, industrial waste heat is utilized to a certain extent.

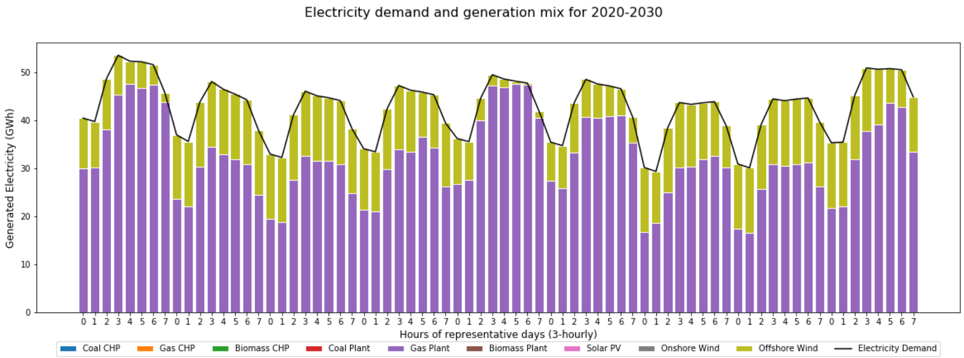


Figure 4.7: Electricity generation mix for 2020 and 2030

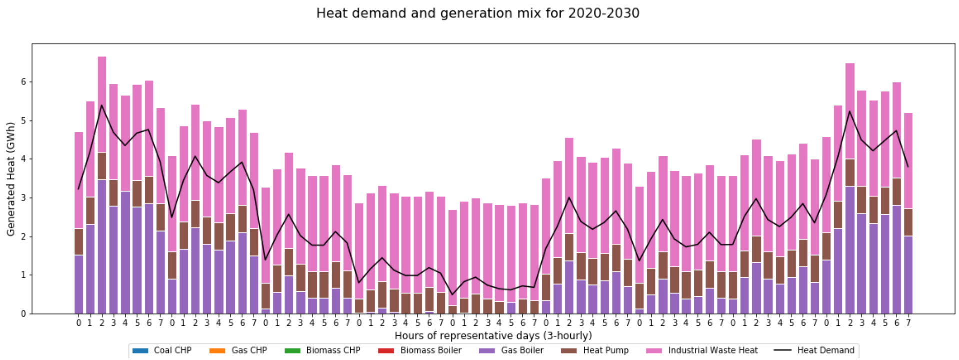


Figure 4.8: Heat generation mix for 2020 and 2030

The visual can be considered a little bit counter-intuitive because it looks like the model spills some heat energy from industry, and generates heat by using gas boilers and heat pumps at the same time. However, it is understandable because the industrial waste heat is not available in every municipality. Municipalities with industrial waste heat utilize this option quite well, while the other municipalities need other heat sources.

As one of these "other heat sources", the model uses heat pumps when the electricity sector's installed capacity has some available units to generate electricity for the heating sector. This behaviour becomes specifically visible during summer which has a limited amount of wind power. Heat demand is satisfied via heat pumps if the electricity system has some slack capacity, but if this is not the case, then gas boilers are actively used. During the winter periods, the use of gas boilers overpasses the use of heat pumps. These dynamics can also be seen in Figure 4.8.

As stated before, 5^{th} representative day's 6^{th} hour on the graph shows the change in preferences when the electricity system does not have enough capacity to serve both of the sectors. As a result, heat demand is fulfilled by using gas boilers. With the decreasing demand in the next block, the burden on the electricity sector decreases and the model can use heat pumps to fulfill the heat demand.

The generation mixes for electricity and heat sectors in the second decade undergoes several changes. With the imposed emission reduction target in 2030, wind power takes over the domination in the electricity generation mix. This change shows itself in the heat generation mix as an increase in the use of heat pumps. As it can be seen from Figure 4.9, only a couple of representative days highly utilize natural gas-based facilities and these days represent either quite cold winter days which have high heat demand or summer days with limited wind power output. Figure 4.10 shows the generation mix for the heating sector in the second decade. The high heat demand can be observed for the days which have high gas plant utilization in the electricity sector. Also it can be noted that with the increasing heat demands due to increasing district heating shares, the industrial waste heat is utilized more.

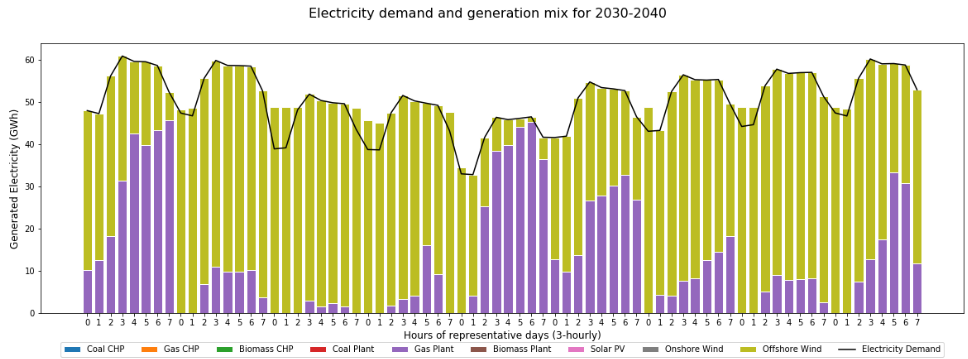


Figure 4.9: Electricity generation mix for 2030 and 2040

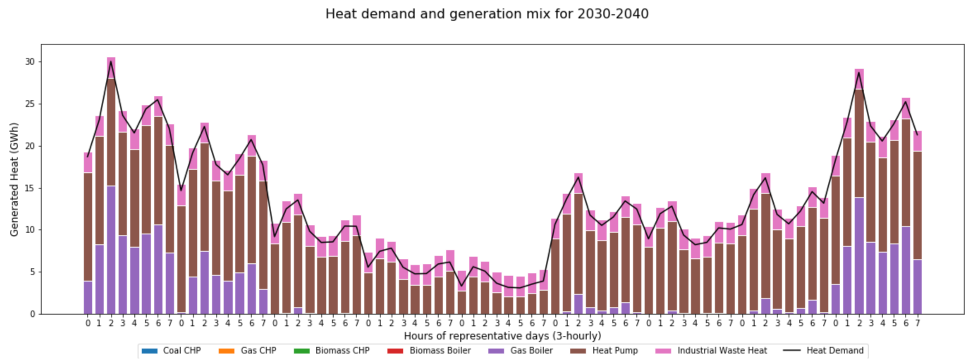


Figure 4.10: Heat generation mix for 2030 and 2040

The last decade, 2040 to 2050, shows drastic changes in the electricity and heat demand mixes. As it can be seen from Figure 4.11 and Figure 4.12, the investment made for biomass co-generation facilities and biomass plants are visible in the generation mixes, too. Since the carbon emission reduction target hits 95%, the system looks for carbon-free energy sources which serve for both sectors. It should be noted that especially during the summer period, installed biomass co-generation facilities spill serious amounts of heat energy, but when the electricity mix is checked, it is seen that the biomass co-generation facilities are used to compensate the absence of intermittent wind power.

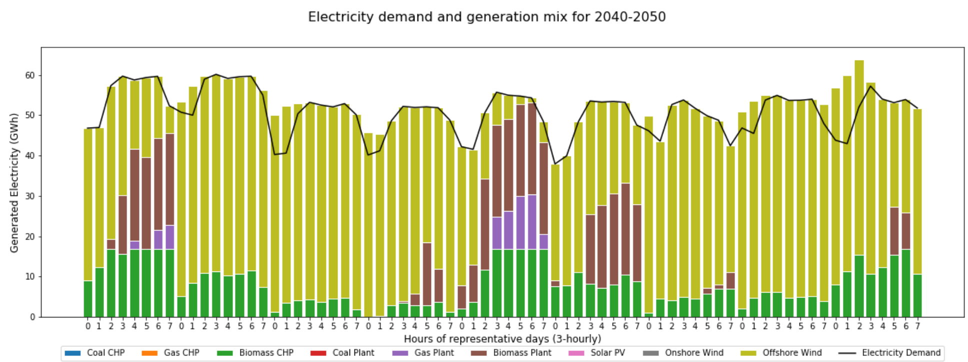


Figure 4.11: Electricity generation mix for 2040 and 2050

It is concluded that the 5% emission margin is used for electricity generation, and most of it happens during times with limited wind power. Besides biomass co-generation, biomass plants are used to generated electricity and heat pumps, again, are used to generate heat. It should be considered carefully that the third decade has also the highest heat demand due to the increasing district heating share. It looks like the utilization of heat pumps is significantly decreased. However, when the values are checked it can be seen that the capacity is still being used during cold days. There is a decrease in the use of heat pumps, especially during warm periods.

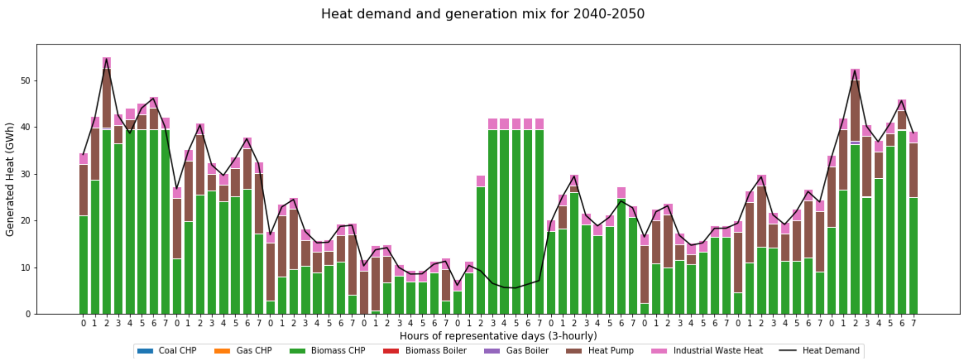


Figure 4.12: Heat generation mix for 2040 and 2050

All these generation mixes, installed capacities, and share of costs give certain insights, but they do not provide with the spatial distribution of generation facilities. In Figure 4.13, the capacity increases for gas boilers in each investment period is presented, while Figure 4.14 shows the same for heat pump installations. Figure 4.15 indicates the spatial distribution of biomass capacity increases during investment windows, namely 2020, 2030 and 2040. It can be concluded that the high heat density and high heat demand show themselves in the distribution of generation facilities.

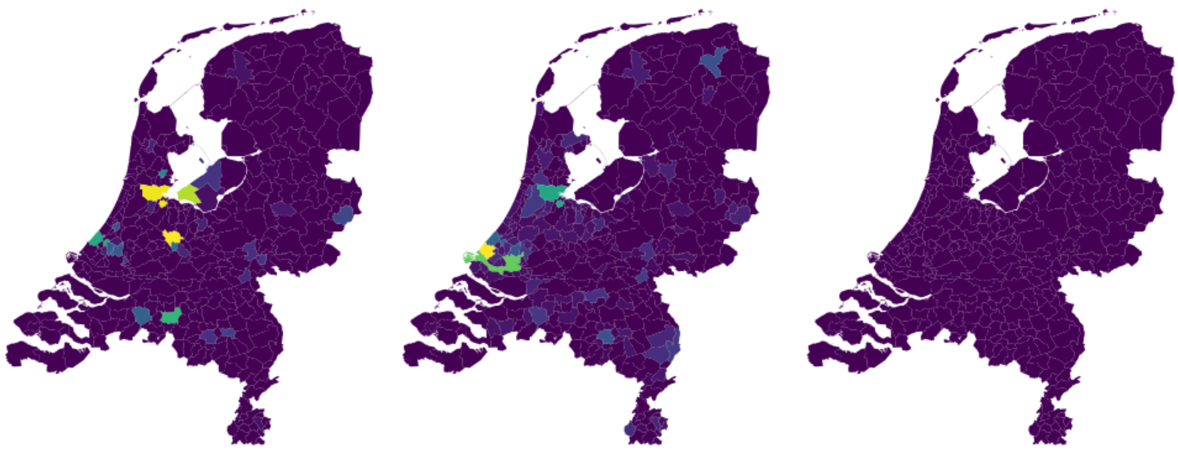


Figure 4.13: Additional capacity installments of gas boilers in each municipality (left, 2020; middle, 2030; right, 2040) (Lighter color means higher values)

Both gas boiler and heat pump installations are majorly clustered in the provinces of Zuid-Holland and Noord-Holland for the years between 2020 and 2040. However, it should be noted that especially for the first decade, the heat generation capacity investments are made to the municipalities which are not able to use industrial waste heat. Especially around Rotterdam, Sittard-Geleen, Terneuzen and Moerdijk, the generation capacity investments are quite limited. This is because the heat demand is fulfilled by using pipeline infrastructure which transfers the industrial waste heat from these cities to other cities.

As it is described in the previous paragraphs of this section, with the influence of significantly increasing greenhouse gas emission target, during the last investment window in 2040, major investments are made for biomass co-generation facilities. Existing capacities for gas boilers and heat pumps in the municipalities are dominated by the amount of investments made for the biomass CHP's. With the increasing heat demand, the use of industrial waste heat starts to fall short, and as a result of this, the biomass CHP investments become visible for the municipalities with high industrial waste heat, too.

Figure 4.14: Additional capacity installments of heat pumps in each municipality (left, 2020; middle, 2030; right, 2040) (Lighter color means higher values)

The distribution of heat generation capacities over the municipalities bring another subject to the table which is the distribution of pipeline networks. As shown in Figure 4.16, most of the pipeline installations are constructed in the first and second decade with the purpose of utilizing industrial waste heat as much as possible since it is assumed as a fixed and free heat source. The pipeline capacities are represented as the thickness of the lines on the map, while the colors represent different year's investments. Two or three colored lines indicate the expansion of pipeline installations over the years.

Figure 4.15: Additional capacity installments of biomass CHP's in each municipality (left, 2020; middle, 2030; right, 2040) (Lighter color means higher values)

The high heat demand and heat density, available industrial waste heat, together with the slightly clustered generation facilities in the Zuid-Holland province lead to a pipeline network which connects almost every municipality in the region to a thermal grid. Specifically, Rotterdam requires further attention since it serves as a hub for heat energy transmission. In 2020; Westland, Pijnacker-Nootdorp, Midden-Delfland, Lansingerland, Capelle aan den IJssel and Barendrecht are all connected to Rotterdam with pipeline installations. Among these, connection to Westland has the biggest capacity with 30 MW while the pipeline connection to Barendrecht has only 1.1 MW capacity. In 2030; Westvoorne, Vlaardingen, Schiedam, Nissewaard, Maassluis, Brielle, and Albrandswaard joins the thermal grid. As a significant increase, capacity of pipeline branch between Rotterdam and Westland increases to 47 MW in this decade. In the last decade, no significant increase is observed in the thermal grid, the biomass CHP investments are made in a decentralized manner. On the other hand, other municipalities which are again in Zuid-Holland and Noord-Holland provinces, present small capacity installations between 2-3 municipalities in the third decade.

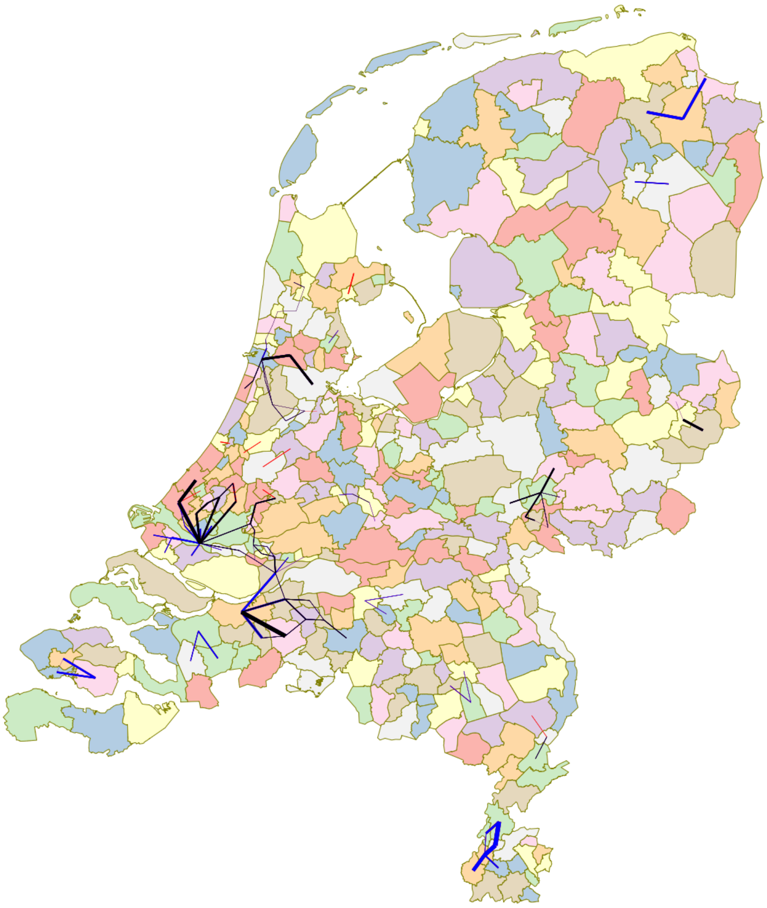


Figure 4.16: Expansion of pipeline networks over the years (black, 2020; blue, 2030; red, 2040)

4.3. Validation

In the first section of this chapter, the verification tests are shared. They basically provide insights that the optimization model is correctly translated into computer languages. However, this does not guarantee that the model correctly represents reality and it fits for the purposes of this research. This section is used to present the validation process which compares model results to real energy systems in the Netherlands. However, since the model adopts a green-field approach, the findings for certain aspects may diverge from the reality. To compensate this deficiency, the results are also compared to similar studies from literature.

The results of the model run based on the reference scenario are shared in the previous section in detail. As stated before, natural gas-based power plants and offshore wind turbine installations dominate the electricity generation system in 2020. The model results indicate that the gas power plants have 15.85 GW capacity which represents 77.9% of the total generation capacities, while the offshore wind turbine installations have 4.5 GW capacity which

Table 4.1: Comparison of generation mixes

Type	Real share	Model's share
Natural gas	51%	78%
Hard coal	15%	0%
Nuclear	2%	0%
Waste	2%	0%
Biomass	2%	0%
Solar PV	13%	0%
Wind energy	15%	22%
Hydro power	0%	0%

is the remaining 22.1% of the installed capacities.

There are differences between these capacity values and the actual installed capacity of generation facilities in the Netherlands. Installed capacity per production type data by ENTSO-E (2019a) is compared to the reference scenario results in Table 4.1. It can be concluded that the real system has more variety in its inventory for electricity generation. Natural gas based electricity generation has the highest share, while hard coal based plants follow as second. In the model results, the share of hard coal is represented as 0% because coal based electricity generation is excluded due to the ”Coal Phase-out” policies in the Netherlands. Therefore, it is relatively understandable for the model to have a gap which is related to coal-based electricity generation.

One of the significant differences is related to wind energy. The real share of wind energy is lower, and also most of it comes from onshore wind installations. On the other hand, the model's wind energy comes from offshore installations, and it has 22% of the total generation capacity in 2020. The model does not have any limitation with respect to the maximum capacity which can be built in a place. This leads the model to select less number of different generation types as it only selects the most efficient ones without restrain itself with any maximum capacity limit. As a result, it selects offshore installations which are more expensive but in the end capable of generating cheaper electricity because of higher wind speed values in the offshore points.

The missing solar energy generation in the model grabs attention since the Netherlands has a solar production capacity around 4 GW and this is not represented in the model. In reality, solar PV installations are distributed homogeneously around the country because solar installations are subsidized by the government. The model does not have such a scheme represented in its dynamics and as a result, the default settings for solar generation does not compensate its cost in the model.

It should be noted that the total generation capacity of the model is less than the actual system's. This is mainly because the artificial system does not have any redundant capacity. Real systems built such excessive capacities to increase the flexibility and security of the system, but in the model these notions are excluded. As a result, the model installs the amount of generation capacity which is barely enough to fulfill the demand.

Other than these differences, there are also similarities between the real system and the model's findings. Both systems have natural gas-based electricity generation as the most dominant generation type. The actual capacity of natural gas-based electricity generation is found as 15.57 GW in ENTSO-E's data (2019a), while the model installs 15.85 GW natural gas-based electricity generation capacity. Similar values are also achieved when the wind energy installations are considered as a whole. The real system has 4.6 GW of generation capacity for wind turbines, and this value is found to be 4.5 GW for the model.

When the results of reference scenario are compared to the findings of other studies, a resemblance based on installed electricity generation capacities can be detected. Sharma and Balachandra (2019) indicate the necessity of fuel-based electricity generation to maintain a more reliable energy system and to reduce the burden on the budgets. In line with these findings, the model results indicate that the electricity generation systems remain to have a certain share of fuel-based generation. Although a transition towards renewable sources take place in the future, the results suggest the use of natural gas for the first two decades, and biomass for the last decade. These findings are also supported by Zappa and van den Broek (2018) whose study indicates the advantage of dispatchable energy generation plants in future systems.

Besides the electricity system, when the represented heating system is compared to its reality, it is realized that several aspects are in line with each other. Due to the limited data availability for district heating technologies, a comparison based on installed capacities cannot be done. However, when the findings are evaluated, it can be concluded that the model provides insights related to current policy discussions about the heating sector.

"Heat Roundabout" in the province of Zuid-Holland is one of the policy discussions which is about connecting the municipalities to each other with a thermal grid and achieving reductions in energy use. This project foresees a provincial thermal grid, which utilizes the heat from Rotterdam Port, for the future of Zuid-Holland. In line with this, the findings of the reference scenario indicate an installed thermal grid in the province of Zuid-Holland where Rotterdam serves as a hub for heat transmission.

When the installed capacities for heat generation are evaluated, it is seen that the model results represent the reality to a certain degree. It is reported that the 69% of heat energy supplied to district heating networks is generated by the power plants, while the rest comes from the small-scale co-generation facilities, heat pumps, waste incinerators, waste heat from industrial processes, and biomass facilities in 2013 (Niessink & Rösler, 2015). Similarly, the model supplies the majority of the generated heat to the networks by utilizing large-scale natural gas boilers, and the rest is produced via heat pumps distributed among the municipalities with district heating, or industrial waste heat which is available in several municipalities.

For the future decades, the findings of the reference scenario are compared to the other studies' results. Romanchenko, Odenberger, Göransson, and Johnsson (2017) indicate that the future of co-generation facilities is more focused on electricity generation, while heat is the secondary output of their processes. The results of reference scenario suggest the use of biomass co-generation facilities for the third decade. When the generation mix of electricity and heating systems are evaluated, it can be seen that the installed capacity of biomass CHPs is mainly used for electricity, then heat energy as the secondary output is distributed to the thermal grid. Kang, Lu and Li (2017) suggest the use of heat pumps together with co-generation facilities. Such a co-existence is also visible in the third decade of the model results for the reference scenario.

4.4. Identification of critical model inputs

As stated before, computer models are useful to acquire insights which are not possible to get due to the physical or financial limitations. Using a model to examine a functionality or an existing dynamic in the real world is more meaningful if the extent of assumptions made and their influence on the model's outcomes are known. By conducting analysis to measure the sensitivity of a designed model for the changes in its input parameters, further confidence can be built for the model outcomes because knowing what is significant helps the analysis to focus on the points which matter the most.

There are various methods to conduct "sensitivity analysis" and many studies compare these methods to each other and discuss the pros and cons of them. Hamby (1994) states that "One-at-a-time" sensitivity measurement is the simplest approach can be adopted for such an analysis. It is a local sensitivity analysis method which varies one parameter at a time and keeps the rest constant. As a result, the change in the outcome with respect to a change in single parameter's value is measured. However, this approach ignores the interactions between parameters. Saltelli and Annoni (2010) discusses the inability of ”One-at-a-time” approach to grasp the insights about uncertainties when the models are not linear or additive. They suggest the use of ”global” sensitivity analysis approaches because these approaches are more informative and robust (Saltelli & Annoni, 2010). As the adopted modelling approach is ”Linear Programming”, the model dynamics do not include any non-linear behaviour. Therefore, it becomes meaningful for this study to use ”One-at-a-time” approach to conduct sensitivity analysis.

With the reference scenario setting, it takes 5-7 hours for the designed model to reach its optimal solution. Therefore, some precautions are taken prior to analyze the sensitivities. The model size is shrunk by only including a part of the country. Results of the reference scenario shows that the province of Zuid-Holland has the majority of the installed pipelines and heat generation capacity. Therefore, the spatial settings of the model is adjusted to cover only the municipalities in Zuid-Holland as a representative case which requires less computational power.

By using ”One-at-a-time” approach, sensitivity analysis is conducted for investment cost of each facility type, investment cost of pipelines, annual O&M cost of each facility type, variable O&M cost of each facility type, price of biomass fuel, price of natural gas, yearly interest rate used for the projects, and heat loss rate assumed for the pipeline installations. Also, the analysis is conducted in a way that the results focus on the installed generation capacities which is different than the actual model outcome. The model outcome is minimized value of total system cost, but it is considered that this value means nothing without providing information about the installed capacities. On the other hand, if a changing parameter value leads to a change in the installed capacities without changing the objective function value significantly, it still carries importance for this study’s targets.

The analysis checks 30% decrease, 15% decrease, 15% increase, and 30% increase in a parameter’s value with respect to the default value of that particular parameter. Results indicate that variable O&M costs are not significant when they are compared to the investment cost and annual O&M cost of facilities. Also annual O&M cost of solar PV installations, onshore installations, heat pumps, gas plants, gas CHPs, gas boilers, biomass plants, and biomass boilers are found to be insignificant for the model outcomes. Besides these, it is observed that the model results are not affected by the evaluated changes in investment cost of gas plants, gas boilers, gas CHPs, and biomass boilers. Finally, the heat loss rate is found to be insignificant for the current model settings.

Investment cost of pipelines and annual O&M cost of biomass CHPs have a limited influence on the installed capacities. It is observed that the investment cost of pipelines directly influences the installed thermal grid capacity, but it does not affect the generation capacities drastically. While, the O&M cost of biomass CHPs and plants are of limited effect on the installed capacities and pipeline installations. Also, annual O&M cost of offshore installations is capable of changing installed capacities when the change hits 30% increase.

It is found that both gas and biomass fuel prices are quite critical for the achieved set of generation capacities. Also, the annual interest rate seems highly critical for the expansion of the capacities in the system. The changing installed capacities are shown in Figure 4.17, Figure 4.18 and Figure 4.19 respectively. Also, the investment cost of onshore and offshore wind turbines, solar PV installations, biomass CHPs, biomass plants, and heat pumps significantly influence the installed capacities in the system. The resulting graphs are shown in Appendix D, from Figure A.1 to Figure A.22.

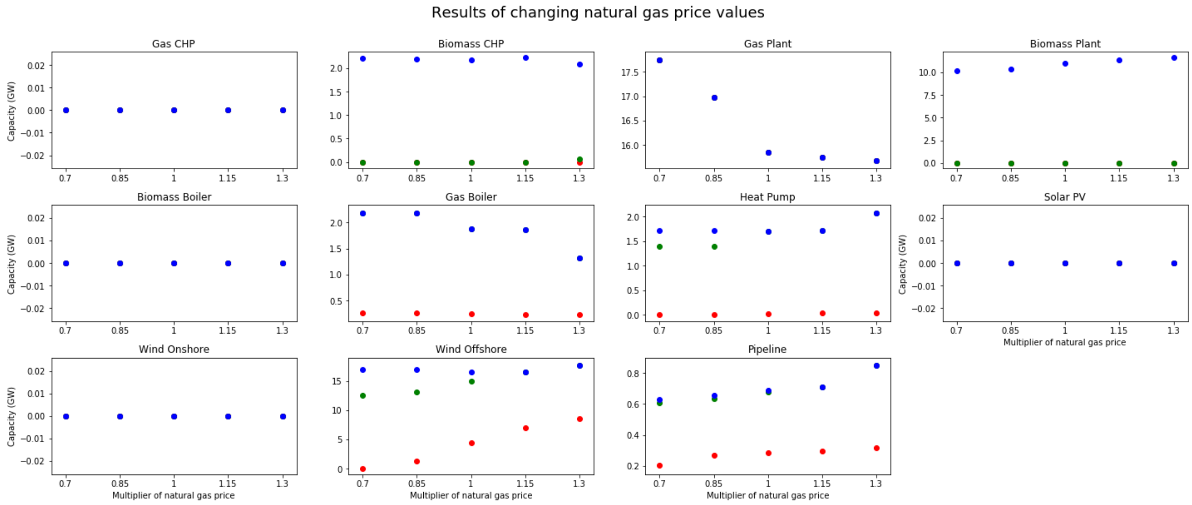


Figure 4.17: Sensitivity analysis for natural gas prices (red, 2020; green, 2030; blue, 2040)

Figure 4.18: Sensitivity analysis for biomass prices (red, 2020; green, 2030; blue, 2040)

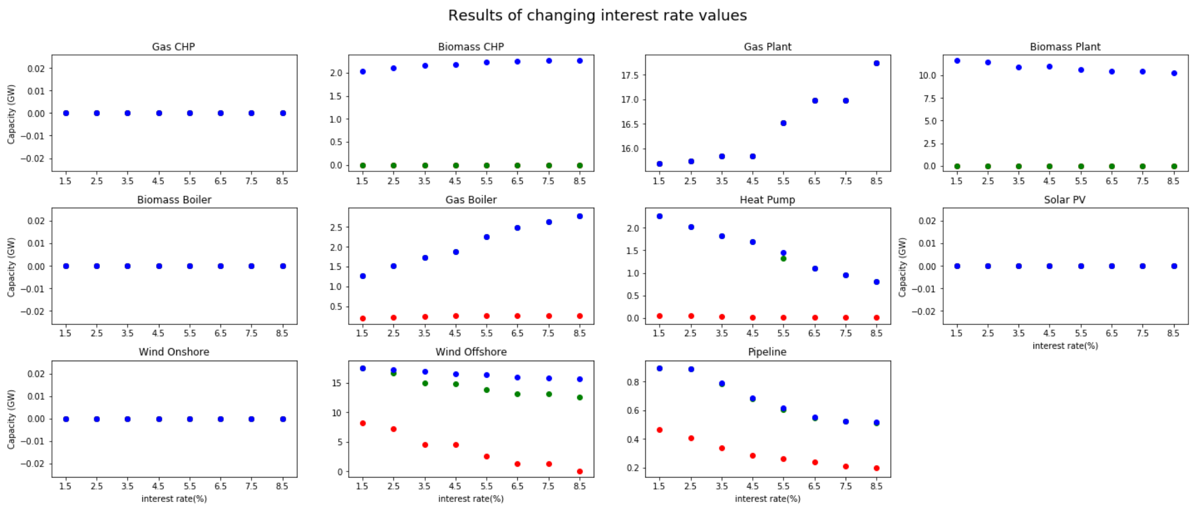


Figure 4.19: Sensitivity analysis for annual interest rate (red, 2020; green, 2030; blue, 2040)

5

Experimentation

This optimization model is created to be able to evaluate the effect of energy conversion technologies on the energy transition towards renewable sources, the effect of renewable integration on the district heating systems, the role of co-generation facilities in the future energy systems, and the factors which leads to new installations for the heat transmission networks.

Although the reference scenario results indicate certain insights about the system represented, further experimentation is needed to be able to shed some light on these research points in a better way. A set of experiments which are designed with respect to these particular targets should be conducted by using the model at hand. In this chapter, the designed experiments are presented, and the reasoning behind the experiments is shared.

5.1. Experiment design

As stated before in the previous chapter, there are identified emission reduction targets by the Dutch government for 2030 and 2050 and this study's reference case is designed based on those. However, it is also insightful to check certain what-if scenarios related to these targets. With that purpose, two scenarios are designed which puts 60% and 40% emission reduction targets for 2030. These scenarios basically imply the urgent action which is taken by the Dutch government against emission measures. The overall steps towards a sustainable future can be more ambitious than intended due to unexpected developments, 60% reduction scenario represents this, whereas 40% reduction scenario represents a more stagnant system which misses the targets.

Besides the emission targets, several scenarios are designed to check the effect of reducing the price of technologies. These reductions can occur due to new technological developments, or they can occur basically due to subsidies. The latter is more interesting for this research's identified targets. As stated before, it is aimed to identify the role of energy conversion technologies in the energy transition as one of the research targets, and these technologies are represented in the model by using heat pumps.

As presented in the previous chapter, the conducted sensitivity analysis shows that the investment cost of heat pumps significantly affects the installed capacities in the system. Therefore, it is expected that by subsidizing the heat pump installations, optimal system configuration can be altered. In order to explore this point more, a set of scenarios in which the investment cost of heat pumps gradually decreases are designed to check how the system changes with respect to changing heat pump measures.

Lastly, another set of scenarios are designed to investigate the changing system configurations with respect to changing pipeline investment costs. As introduced in the first chapter, the research aims to identify the minimum cost solutions for electricity and heating systems' generation capacities and thermal grid installations. One of the identified sub-questions was related to the identification of dominant factors leading to the new pipeline installations. Sensitivity analysis results show that when the investment cost of pipelines changes, the installed pipeline capacity also changes in the model. Different scenarios are identified to explore the effect of changing prices on thermal grid further.

Following sections describe each set of scenarios in detail, and presents the related results.

5.2. 40% emission reduction target

When the model is run with the changes in emission reduction targets for 2030, the optimal solution is reached when the total system cost hits 540.02 billion €. Since the model has a greenfield approach, the numbers do not indicate exact values for the energy systems of the Netherlands. However, a comparison of this value to the reference case indicates certain insights. When 49% reduction is aimed, the optimal result is found as 540.66 billion €. The difference between the two values is just around 0.1% of the total cost. This indicates that the target for 2050 restricts the system in a way that 2030 targets are just a step towards 2050. In Appendix A, Figure A.1 presents the distribution of investment costs, annual O&M costs, variable O&M costs and fuel costs in the first, second and third decade.

The comparison between the results of 40% reduction scenario and reference scenario results indicate a similar behavior for the electricity system's installed capacities. The first decade is dominated by the natural gas-based electricity generation, while the second decade witnesses a jump in the capacity installations of offshore wind turbines, and lastly third decade is dominated by the extensive use of biomass plants and biomass CHP's. However, with a less strict emission target, the system installs fewer wind turbines and more gas plants. Similar approaches are adopted for the heating system, too. The first decade's heat demand is fulfilled by using gas boilers primarily and heat pumps support this heat supply. In the second decade, the difference between emission targets shows itself as an increased gap between heat pumps and gas boilers. In the reference scenario, years between 2030 and 2040 indicate the almost equal amount of installations for heat pump and gas boilers, while 40% reduction scenario has distinctively fewer heat pumps installed in the second decade. Both of the scenarios indicate the use of biomass CHP's for the third decade. In Appendix A, Figure A.2 and Figure A.3 presents the installed capacities over the years for electricity and heating system respectively.

Besides the installed generation capacities, there are several differences between the experiment scenario and the reference scenario with respect to the pipeline investments. Decreasing reduction target yields less installed pipeline capacity in the system for the second and third decades. The pipeline network is used to carry renewable heat energy when the heat supplier is heat pumps. When the reduction target is less, the burden on the system to generate green electricity and heat is also lighter. As a result, such decreases in the renewable source capacities, heat pumps and pipeline installations is observed. In Appendix A, Figure A.4 shows the capacity changes over the years when the emission target is set to 40% for 2030.

In the generation mix of electricity and heat energy, especially for the first two decades do not indicate a significant change other than the expected increase in gas plant and gas boilers use. Since for the 40% reduction scenario, the installed capacity of heat pumps is less than the reference case, share of biomass CHPs shows a slight increase in the third decade's heat generation mix. The electricity generation mix of the years can be seen in Figure A.5, Figure A.7, and Figure A.9 while heat generation mix of the years are shown in Figure A.6, Figure A.8, and Figure A.10 which are presented in Appendix A.

One distinctive difference between 40% and 49% reduction targets for 2030 shows itself in the third decade. When the model has a less strict target for 2030, the heat pump instal-

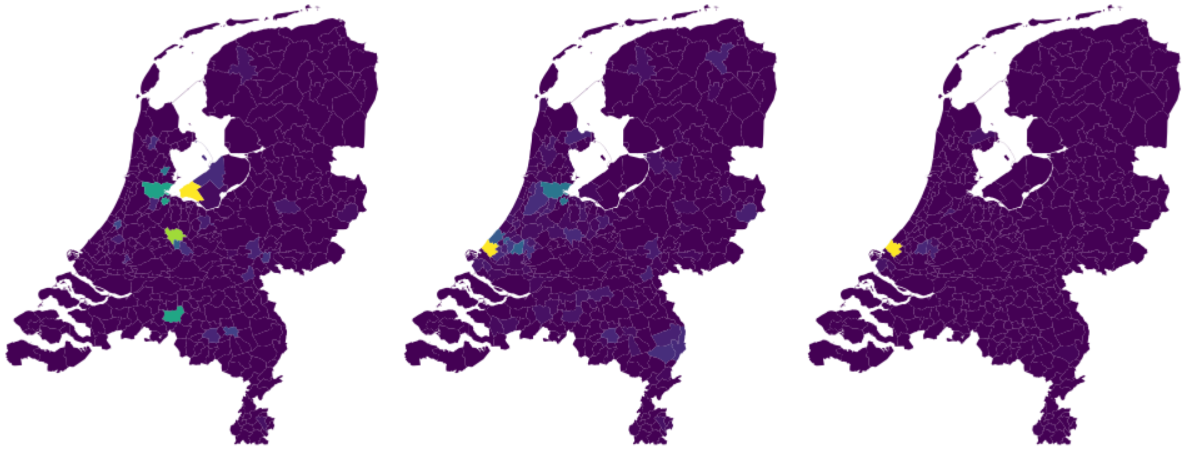


Figure 5.1: Scenario40% - Additional capacity installments of heat pumps in each municipality (left, 2020; middle, 2030; right, 2040) (Lighter color means higher values)

lations are made before the third decade, and they are used until the end of the modelling term. However, experiments with 40% reduction target shows that some of the heat pump investments are pushed to the third decade. This situation is presented in Figure A.12. Other than the heat pumps, there is no significant divergence between two scenarios with respect to the installation of gas boilers and biomass co-generation facilities. The related maps are shown in Figure A.11 and Figure A.13 which are presented in Appendix A.

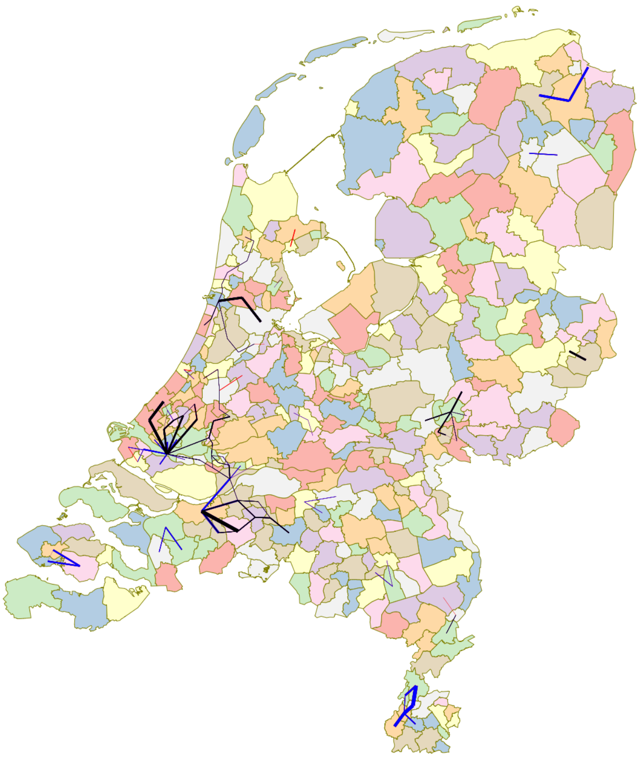


Figure 5.2: Scenario40% - Expansion of pipeline networks over the years (black, 2020; blue, 2030; red, 2040)

Lastly, it is realized that although the overall structure of the pipeline network stays the same, it is observed that certain branches are removed from the map, and some new branches are included. However, these changes occur for the small capacity pipeline installations. The real difference is observed not for the network structure, but for the network capacity. Decreased emission targets make the model install less pipeline capacity when it is compared to the reference scenario results. Besides the capacity, the main features remain the same. Still, the municipalities with industrial waste heat constitutes the backbone of thermal grids. It is observed that Rotterdam, Sittard-Geleen, Terneuzen and Moerdijk keep serving as thermal energy hubs. Figure 5.2 presents the network structure and its expansion over the years.

5.3. 60% emission reduction target

This scenario represents a more ambitious approach for the emission targets, specifically, the system aims to reduce its emissions by 60% in 2030. The optimal solution yields the total system cost as 543.60 billion €. The distribution of this amount among the various cost quantities is presented in Figure A.14 in Appendix A. As stated before, the number can be misleading due to the adopted greenfield approach, but what matters is the development of cost with respect to changing scenarios. In the previous section, it is stated that when the target reduction is set to 40%, the difference between optimal values is around 0.1% of the total cost for the reference scenario and 40% scenario.

The difference between optimal total system cost values reaches to 2.94 billion € when the emission reduction target of 2030 is set to 60%. Although the margin between the emission targets is the same for these scenarios, the cost increases exponentially. In a way, this result indicates the difficulties of reaching higher reduction targets due to non-linear relation between emission targets and total cost values.

Differences between 60% reduction scenario and reference scenario are quite in line with the differences between 40% reduction scenario and reference scenario. As the system sets a more ambitious target for 2030, the installed capacity of wind power increases for the second decade. This increase in the wind power capacity also shows itself in the years between 2040 to 2050 as the less required capacity for biomass facilities. 60% scenario results indicate slightly fewer biomass installations due to the extensive use of wind power. The installed capacities of the electricity sector are presented in Figure A.15 which is placed in Appendix A. More wind capacity due to higher emission targets also affects the heating sector. More heat pump installations are observed while the total capacity of gas boilers is decreased. Also, 60% reduction scenario indicates slightly more capacity for pipeline installations. In Appendix A, Figure A.16 and Figure A.17 present these differences related to heat generation capacities and pipeline installations.

For the generation mix of electricity and heat, 60% reduction scenario has the effects of the extensive wind offshore investments in the second decade. Starting from the second decade, the number of days whose electricity demand is fulfilled by utilizing only wind energy increases in this scenario. Also, as stated before, increased wind energy capacity decreases the share of biomass facilities in the generation mix of electricity. A similar result is found for the heating sector in which the number of days whose heat demand is satisfied by utilizing only heat pumps is increased. The decreased biomass capacity due to the extensive use of wind turbines shows itself in the heating sector as an increase in the use of heat pumps during the third decade. Related graphs are presented in Figure A.18, Figure A.20, and Figure A.22 for the electricity generation mix, while heat generation mix of the years are shown in Figure A.19, Figure A.21, and Figure A.23 which are presented in Appendix A.

It should be noted that the first decade indicates natural gas-based electricity and heating sectors, and a leap occurs in the second decade due to the investments made for the offshore technologies. In order to comply with the emission target, the model needs to decrease its emissions by 60%. It basically invests in natural gas more during the first decade, so that the amount of decrease in the emissions can get higher when the investment to offshore facilities are made. This is basically a quick loophole that helps the model to comply with the new 2030 emission target. It is important to take into account while evaluating the results of this scenario.

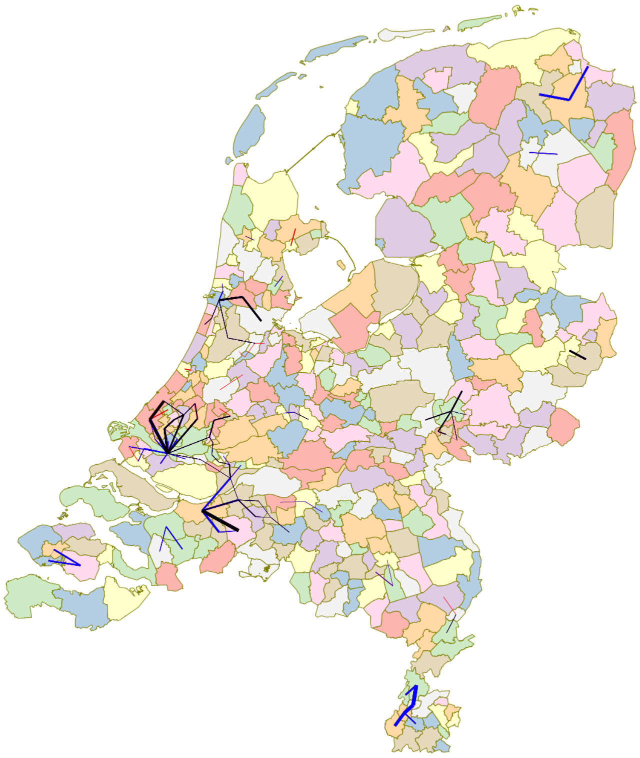


Figure 5.3: Scenario60% - Expansion of pipeline networks over the years (black, 2020; blue, 2030; red, 2040)

Despite the changing capacities of biomass co-generation facilities, heat pumps and gas boilers; their distribution among the municipalities stays the same. In appendix A, distribution of gas boilers are presented in Figure A.24, heat pumps are shown in Figure A.25 and lastly biomass co-generation facilities are presented in Figure A.26.

The thermal grid does not change significantly with the changing emission reduction target for 2030. Several pipeline branches are removed and new branches are added to the system, but they are all small capacity branches. The real change is observed in the installed transmission capacity of the pipelines. As the emission reduction target gets stricter, the total installed pipeline capacity increases. Figure A.27 presents the expansion of thermal grid when the reduction target is set to 60% for 2030.

5.4. Exploring heat pumps

In order to understand the effect of power-to-heat conversion technologies on the represented system, a set of experiments are designed. In the reference scenario, 40% reduction scenario and 60% reduction scenario, Zuid-Holland province shows similar patterns in the results. It is the province which shows the densest connections in the network, and also it has the municipality with the highest heat demand in its borders. Due to these reasons, Zuid-Holland is chosen as a case province, and it is used for the further analysis of heat pump installations.

In the designed set of scenarios, a default scenario is run with the original cost parameters. Two scenarios are included in which the investment cost of heat pumps are decreased by 10% and 20%. Lastly, one scenario run is added as a what-if analysis which examines 20% increase in the costs of heat pump technologies. Selected investment cost values are seen in Table 5.1, in which "Default-Scenario" represents the reference case, and the rest is 120%, 90% and 80% of the default investment cost values respectively.

Default-Scenario shows great coherence to the reference scenario of this study. One signif-

Table 5.1: Different cost scenarios for heat pump installations

	Default-Scenario	Scenario-120%	Scenario-90%	Scenario-80%
Investment cost - 2020 (€/MW)	652666.67	783200	587400	522133.33
Investment cost - 2030 (€/MW)	634333.33	761200	570900	507466.67
Investment cost - 2040 (€/MW)	634333.33	761200	570900	507466.67

icant difference is due to the fact that the reference scenario's scope is the country, while here Default-Scenario's scope is the province of Zuid-Holland. Therefore, the total heat generation is smaller when it is compared to the reference scenario values. As shown in Figure 5.4, the installed generation capacities for the electricity system are dominated by gas plant investments during the first decade. This is followed by offshore wind turbines and biomass co-generation facilities in the following decades.

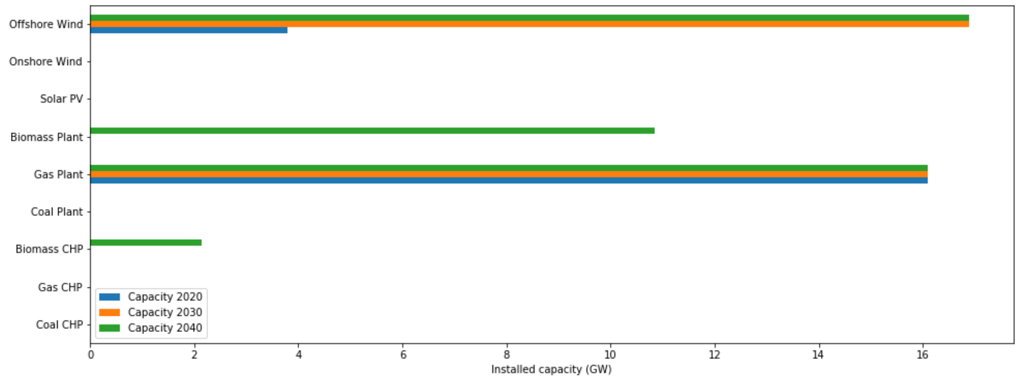


Figure 5.4: Default-Scenario - electricity sector - existing capacity in each decade

The situation is also as expected for the installed capacities in the heating sector, which are shown in Figure 5.5. Most of the investments are made for the gas boilers in the first decade, whereas these investments shift to heat pumps in the years between 2030 and 2040. Last decade shows a jump in the capacity of biomass co-generation facilities. As stated before, this default scenario is quite in line with the reference scenario because it uses the same parameters but focuses on a smaller part of the Netherlands.

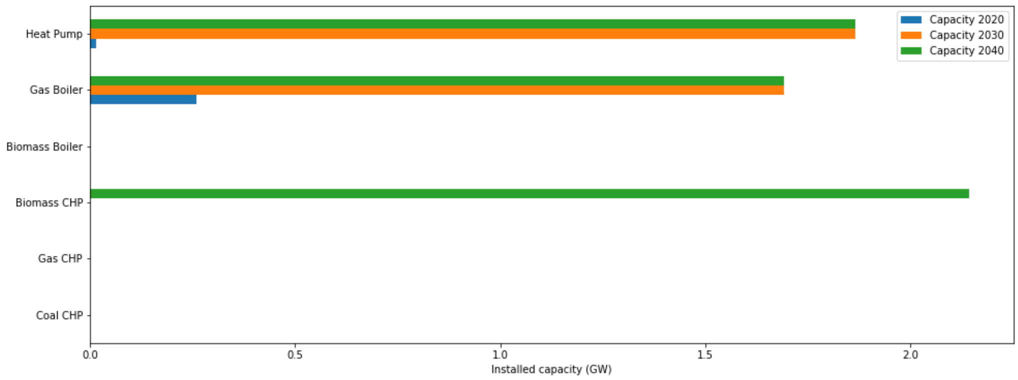


Figure 5.5: Default-Scenario - heating sector - existing capacity in each decade

As the scenario which has the cheapest heat pump investment cost, Scenario-80% indicates certain dynamics behind the heat pump investment decisions. As shown in Figure 5.6, despite the 20% cost reduction, capacity investments in the first decade are still made for gas boilers. On the other hand, the jump for the heat pumps makes them reach a higher capacity value than gas boilers in the years between 2030 and 2040. Similar patterns are visible for Scenario-90% whose capacity installations are shown in Figure A.24, in Appendix B.

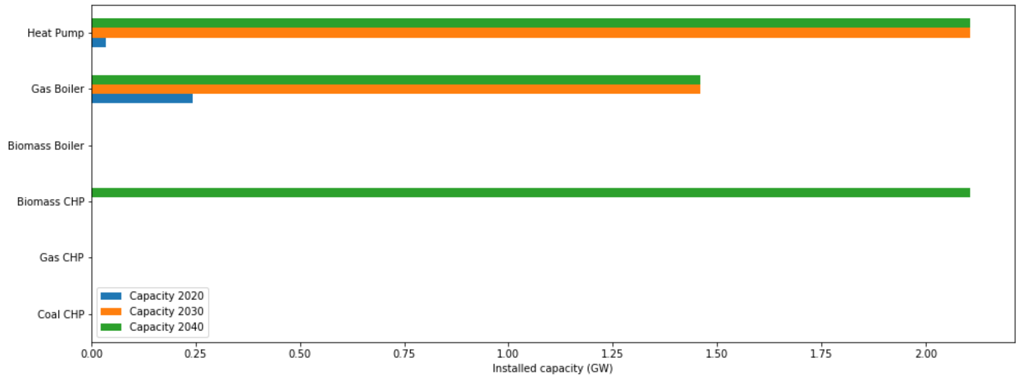


Figure 5.6: Scenario-90% - heating sector - existing capacity in each decade

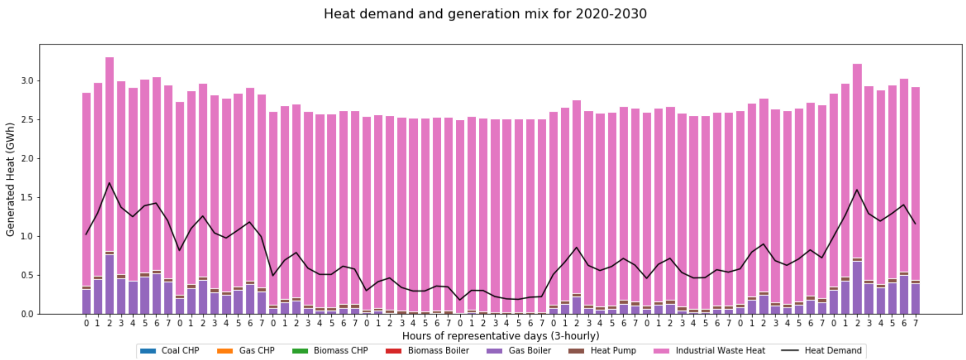


Figure 5.7: Default-Scenario - Generation mix of heat energy in 2020-2030

The influence of these different capacity investments is quite visible on the generation mix of heat energy. As shown in Figure 5.7 and 5.8, when the first decade heat generation mix of Default-Scenario and Scenario-80% are compared to each other, they are quite similar since the differences become prominent starting from the second decade. This is because the carbon emission reduction target is imposed in 2030 which is the starting year of the second decade, and also it is the first year which district heating networks are expanded in the system. As a result, the heat demand also increases, and the model seeks for solutions which can both fulfill the heat demand and comply with the emission targets. As the investment cost of heat pumps decrease, it becomes more likely that the model chooses them as the solution that it seeks. This is also visible in the heat energy generation mix of the second decade of Default-Scenario and Scenario-80% which are shown in Figure 5.9 and Figure 5.10 respectively.

The increasing use of heat pumps also brings some changes in the heating network structure. It is observed that as the investment cost of heat pumps decreases, the more heat pump installations take place in the system. Increasing heat pump installations yield lower capacities for pipeline installations, but, the number of pipeline installations increases. The model starts installing more pipeline branches with smaller capacity values.

The pipeline capacity decreases because the model installs heat pumps in higher number of

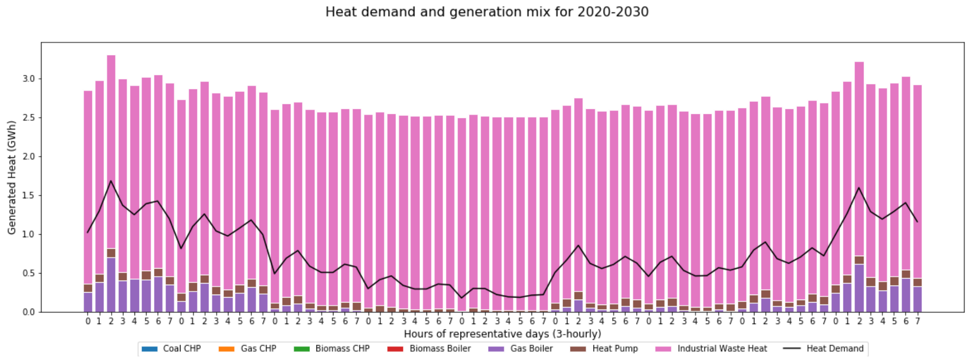


Figure 5.8: Scenario-80% - Generation mix of heat energy in 2020-2030

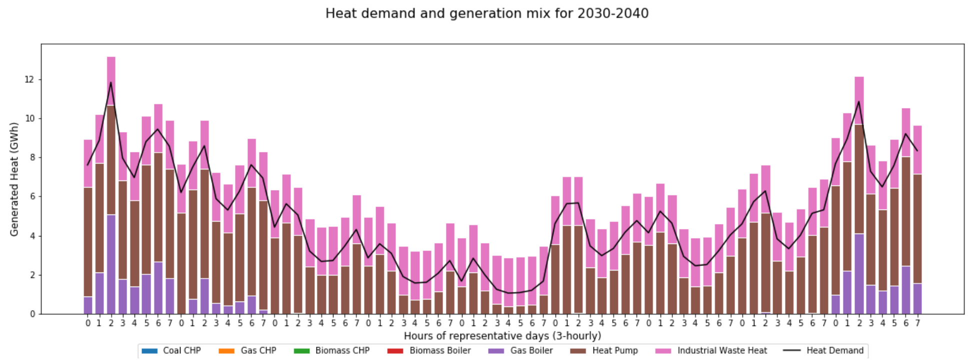


Figure 5.9: Default-Scenario - Generation mix of heat energy in 2030-2040

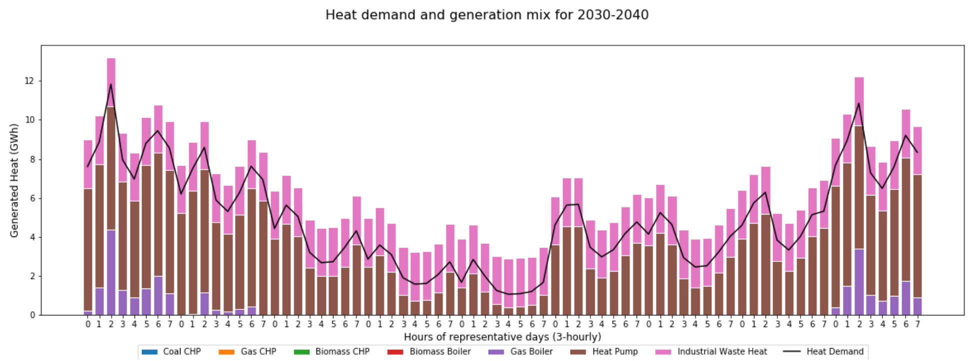


Figure 5.10: Scenario-80% - Generation mix of heat energy in 2030-2040

municipalities. Then, these municipalities start generating heat energy when the electricity system is available, and this decreases their dependence on the other municipalities.

On the other hand, the increasing number of pipeline installations can be explained with a different point of view. This behaviour is observed more clearly when the industrial waste heat is excluded from the system.

When there is abundance of renewable energy, the heat pumps can use the excess electricity to generate heat. When a municipality's heat demand is fulfilled by a heat pump, if the capacity of the heat pump is not fully used, the remaining capacity can be allocated to generate heat energy for another municipality which is connected to the municipality with heat pump installation. Transmitting heat from one municipality to another can help to reduce the peak demands, and therefore, the required generation capacities can be decreased. When the industrial heat demand is available, the peak smoothing is handled by utilizing this heat energy. However, there are municipalities which do not have a neighbour with available industrial heat, so the explained functionality can serve in those municipalities. It should be noted that the industrial waste heat puts this dynamic into the shades because it has the utilization priority due to its cost-free use. Figure 5.11, 5.12 provides with the comparison of installed pipeline capacities in Default-Scenario and Scenario-80%.

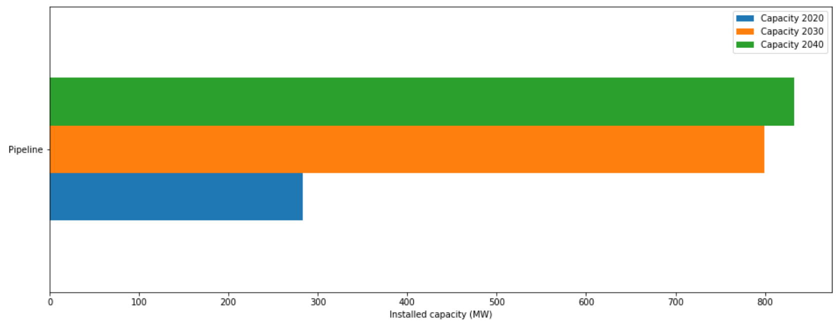


Figure 5.11: Default-Scenario - installed capacity of pipelines

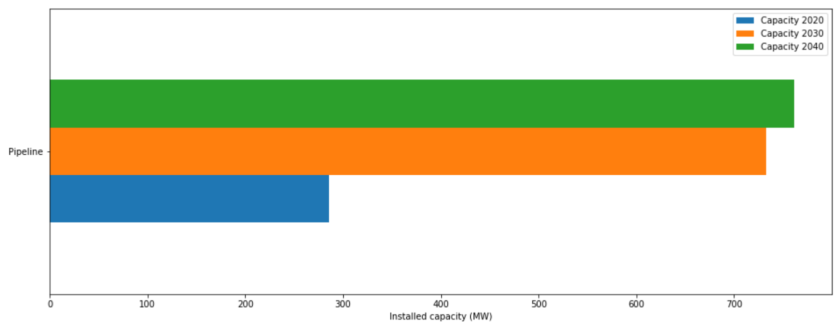


Figure 5.12: Scenario-80% - installed capacity of pipelines

It is observed that the changing capacity values of heat pumps do not directly affect the thermal grid structure. Several pipeline installations with small capacity values are removed and new installations become available, but all of these occur in low scales. The major connections between municipalities stays still. Related mapping of thermal grids can be seen in Figure 5.13. The remaining generation mix figures related to these scenarios, financial results, and also the spatial distribution of generation facilities are presented in Appendix B, from Figure A.1 to Figure A.43.

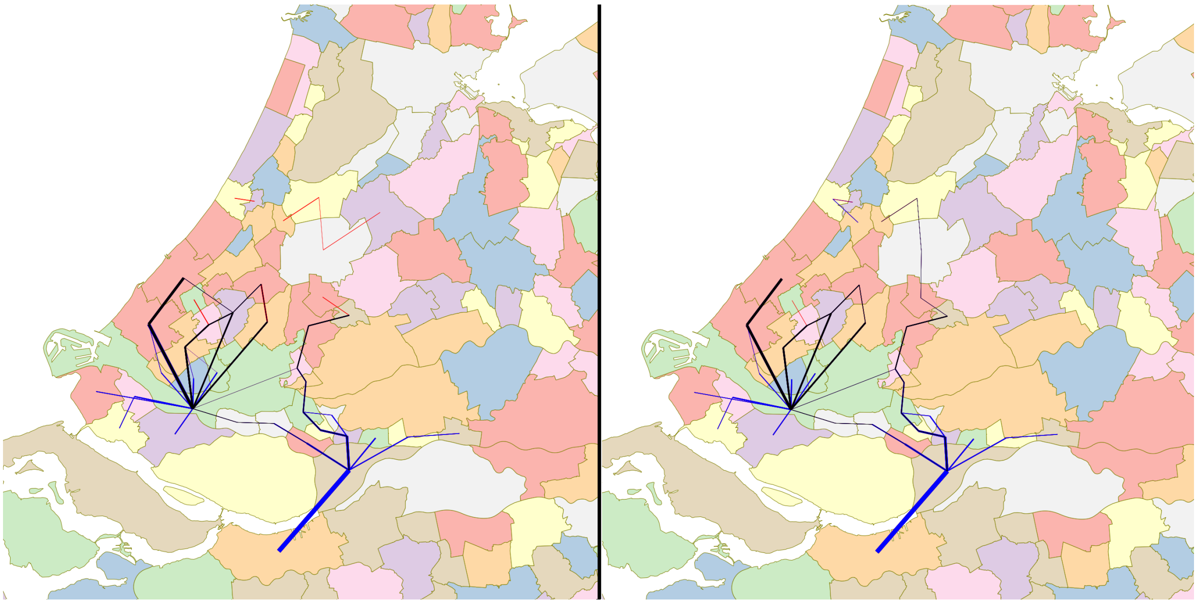


Figure 5.13: Default-Scenario (left), and Scenario-80% (right) - Expansion of thermal grid over the years (black, 2020; blue, 2030; red, 2040)

Table 5.2: Different cost scenarios for pipeline installations

	Investment cost (€/m per MW)
Scenario150%	80.16
Scenario125%	66.8
Default-Scenario	53.44
Scenario75%	40.08
Scenario50%	26.72

5.5. Exploring price effect on thermal grid expansion

Until this point, all the experiments conducted indicate certain changes in the thermal grid's structure. These changes are related to increasing district heating share over the years in the reference scenario, changing the share of renewable integration in the designed scenarios, and increasing the share of heat pumps.

On the other hand, the sensitivity analysis indicates that the installed pipeline capacity changes with respect to the changing investment cost of pipeline installations. However, it is still not known whether the changing capacity values also alter the thermal grid's structure, or not. Also, as it is presented in Figure A.11, changing pipeline investment cost slightly affects the installed heat pump capacities in the system.

In order to explore the effects of changing pipeline costs on the thermal grid and heat generation mix, a set of scenarios is designed with changing values for pipeline installations. The summary of these scenarios can be found in Table 5.2. Similar to the experiments for heat pumps installations, Zuid-Holland is used as a sample province. Default investment cost of a pipeline installation with 1 MW capacity for 1 meter is fed to the reference scenario as 53.44 € per m per MW. The scenarios are designed in such a way that this cost value is 50% higher, 25% higher, 25% lower, and 50% lower.

The resulting thermal grid expansion schemes are presented in Figure 5.14, 5.15, and 5.16. It is observed that the decision behind constructing a pipeline between municipalities is quite dependent on the price of pipeline installations. With the decreasing pipeline investment costs, the thermal grid expands over the province of Zuid-Holland, and more municipalities become connected to each other.

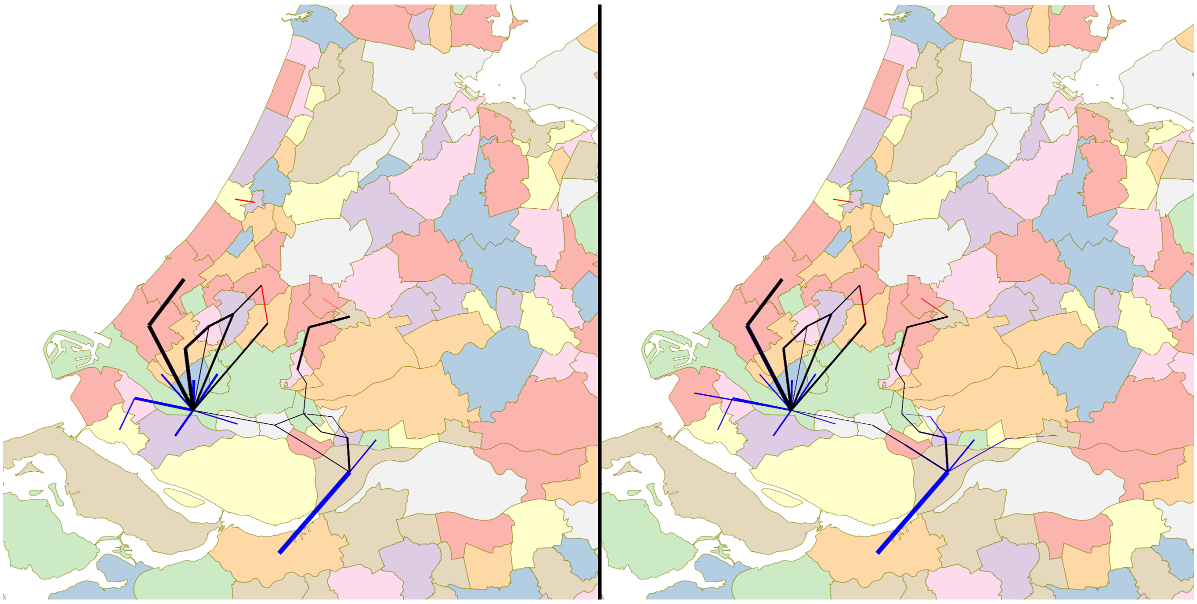


Figure 5.14: Scenario150% (left), Scenario125% (right) - Expansion of thermal grid over the years (black, 2020; blue, 2030; red, 2040)

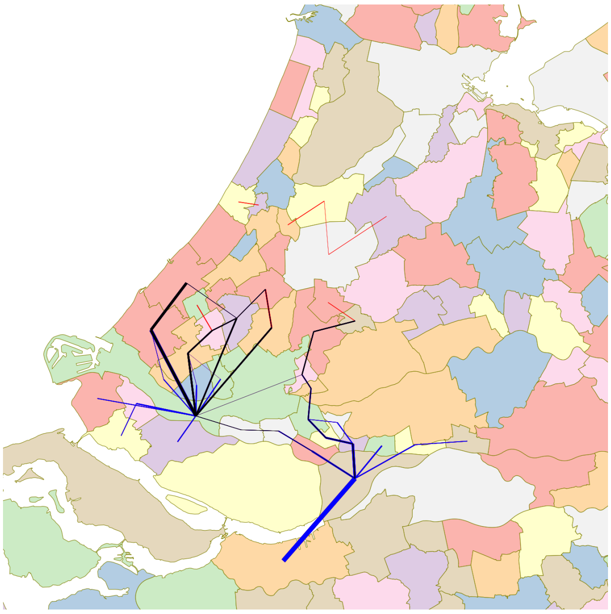


Figure 5.15: Default-Scenario - Expansion of thermal grid over the years (black, 2020; blue, 2030; red, 2040)

Changing pipeline structures also affect the generation mix of heat energy in the system. Figure 5.17 presents the generation mix of Scenario150% in the first decade, while Figure 5.18 shows the same values for Scenario50%. It is observed that with the increasing pipeline installations, the utilization of the industrial waste heat increases. The increased utilization of industrial waste heat decreases the share of other sources in the generation mix of heat energy. Figure A.44, A.46, A.45 and A.47 present the second and third decade heat generation mix of Scenario150% and Scenario50%.

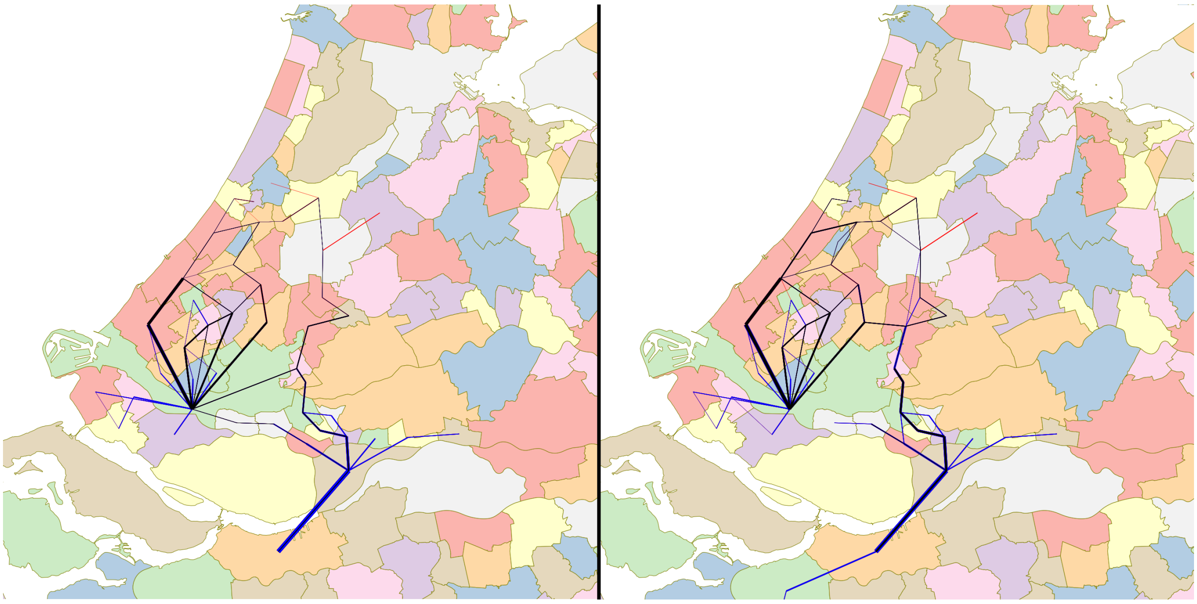


Figure 5.16: Scenario75% (left), Scenario50% (right) - Expansion of thermal grid over the years (black, 2020; blue, 2030; red, 2040)

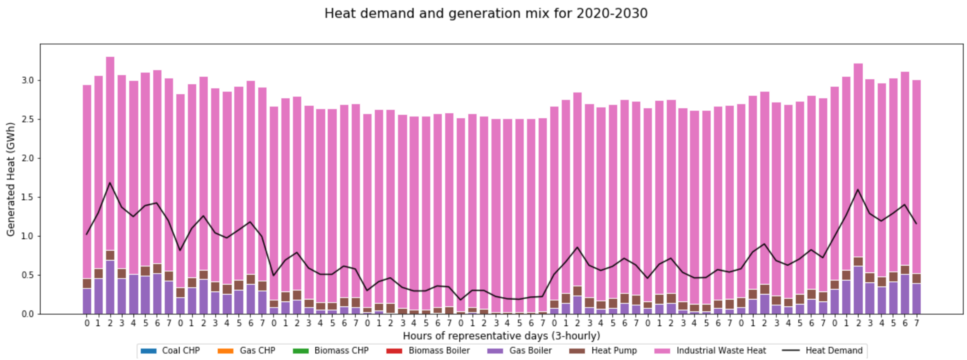


Figure 5.17: Scenario150% - Generation mix of heat energy in 2020-2030

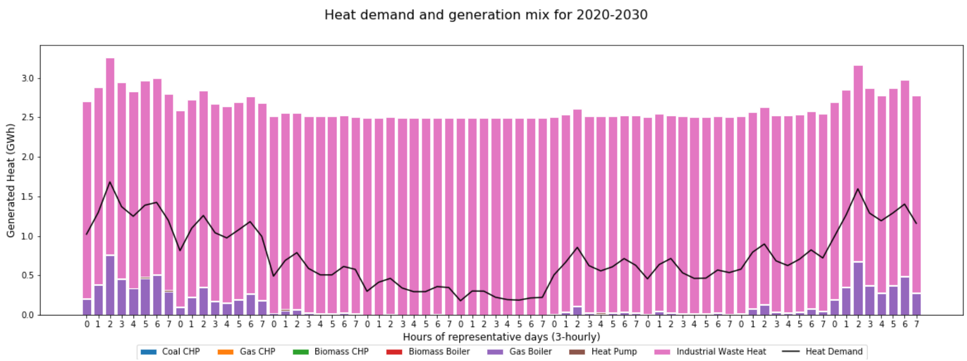


Figure 5.18: Scenario50% - Generation mix of heat energy in 2020-2030

6 Discussion

This chapter is used to discuss the findings of the conducted analysis in describing the real-world system. In the first subsection, the results from the mathematical model are discussed. The comparisons are made and the reasons behind the outcomes at hand are discussed. Lastly, the strengths and shortcomings of this study and its implications for the heat and power sectors are discussed.

6.1. Interpretation of the results

Before diving into the findings, it is important to recall the starting point of this research. As stated before, the concerns related to greenhouse gas emissions lead energy systems to have a transition towards renewable sources. This transition, however, means that there is a drastic change in the current functioning of electricity and heating sectors. The combustion of fuels is the fundamental process which is capable of generating heat and electricity simultaneously. The transition towards renewable sources means that this relationship is going to be eradicating as the integration of renewable sources such as wind energy increases for the electricity generation. This, then, leads to radical changes in the heating systems and creates ambiguities for the future electricity and heating systems. Therefore, in the first chapter of this report, it is aimed to explore the future capacity distributions of electricity and heating systems while also taking the expansion of the thermal grids and power-to-heat conversion technologies into account.

As shared in the previous chapters, it is observed that the electricity sector is dominated by the use of natural gas-based power plants and offshore installations in the near future, between 2020 and 2030. The heating sector utilizes natural gas boilers and heat pumps for the same period to supply heat to the district heating networks. Between the years of 2030 and 2040, a leap for offshore installations happens in the electricity system, while the heat energy is still fulfilled by the same set of facilities but with higher capacities.

These behaviours are basically related to two issues which happen in 2030. First, the carbon emission target of 2030 abandons being a target and becomes reality. This forces the energy system to come up with a new set of generation facilities which are carbon-free, and the decision is made for offshore wind facilities. Such a decision occurs because of the modelled wind turbines have a high capacity factor for offshore installations. As one of the shortcomings of this study, the new capacity installations are not restricted by a maximum value. This leads to the selection of the best option and utilization of it without any limitation. Therefore, the variety in the final set of generation facilities is found to be lower than reality.

The second issue related to the drastic change in 2030 is based on the increasing district heating shares. It is considered that this is one of the most vulnerable points of this study. Due to the computational limitations, it is assumed that municipalities in the Netherlands construct a district heating network within the municipal borders with a steady pace over the years. This pace is assumed to be linear, and the municipalities which can have a certain share of district heating are chosen based on their yearly heat demands and heat densities. The final share of district heating in the Netherlands is determined by external studies (Paardekooper et al., 2018). As a result, this study starts looking at the reality from a single window, which is pre-determined before the actual model use. It should be noted that this was a necessary but limiting decision. As a result of this decision, heat demand increases due to increasing district heating shares in the Netherlands in 2030, and this shows itself as the changes in heat generation mix in 2030.

The heat generation mix in 2030 indicates a shift from gas boiler dominating sector to heat pump dominating sector. The reason behind such a decision is understood in a better way when the generation mix of heating and electricity sectors are considered together. In the same period, due to the restricted emission values, the electricity system shifts towards renewables and starts utilizing offshore installations. The shift into wind energy triggers the use of heat pumps, and carbon-free heat energy is produced. This point connects this discussion to the first subquestion of this study already, which is about the effect of power-to-heat conversion technologies on efforts to reach emission targets.

Bloess, Schill and Zerrahn (2018) discuss that power-to-heat technologies are helpful to reduce emissions because they serve as a flexibility option which makes the system have a better integration of renewable sources. It is argued that the power-to-heat installations decrease the required capacity to fulfill peak heat demand values, they perform better with district heating networks, and they reduce the need for storage facilities because they are also useful to balance the fluctuating renewable energy out (Bloess et al., 2018). In another study, Bloess (2019) states that the power-to-heat technologies have lower costs than storage facilities as a flexibility option. Then it can be motivated that when the storage applications are not economically viable or when the geographical conditions are not feasible to construct a large-scale power storage, the use of power-to-heat technologies can provide the electricity and heating systems with solutions.

Shortly, in line with the literature, it is concluded that the power-to-heat conversion technologies are found to be quite useful for the sake of energy transition towards renewable sources because they help the system to utilize renewable energy sources in a better way. The answer with a little more detail requires the subject to be evaluated from several aspects.

It is realized that the relation between emission targets and power-to-heat conversion technologies is two-sided. It is not a direct relation in which the use of power-to-heat technologies helps the energy systems reducing their emissions. These technologies can provide green heat energy if and only if the electricity they consume is generated by renewable sources. Therefore, the utilization of power-to-heat technologies is conditional when it comes to its relationship with emission targets. The energy system needs to provide green electricity, then these technologies can amplify the reduction by using it to generate heat energy. On the other hand, it can be considered that the use of power-to-heat conversion technologies also amplifies the integration of renewable sources since the system has a tool which better utilizes the generated electricity via renewable sources.

This behaviour is visible specifically for two points in the findings of this study. When the experiment results of 60% reduction target scenario are checked, it is seen that for the years between 2030 and 2040, the model indicates serious amounts of investment for the offshore installations. This is because a huge reduction target is imposed and the system needs to utilize carbon-free sources to decrease its emission values. As a result of this jump in the capacity of renewable sources, heat pump capacity also reaches its peak in the system because by using heat pumps it gets possible to make use of the spillage electricity. On the other hand, when the experiments related to heat pump costs are checked, it is seen that the use of heat pumps stimulates a higher capacity for the wind offshore installations. As the technology gets cheaper, the installed capacity increases, and as the installed capacity increases, the model compensates this additional capacity by building new offshore installations.

Therefore, it can be stated that heat pumps are helpful to reach emission targets when there are investments made for the electricity generation systems based on renewable sources. One positively affects another, increases the system efficiency, and together they help the energy systems to reduce their emission levels. These findings are also in line with van Vuuren et al. (2017), mentioning that the electric heating and heat networks will become critical in the future systems to comply with the identified emission targets.

This also sheds some light on the second target of this research which is about the exploration of the effect of renewable integration on the district heating systems. The experiment results for the changing 2030 emission targets indicate that increasing renewable integration due to emission-based restrictions leads the system to invest more in the heat pumps and pipeline installations. The more integrated wind energy yields more capacity investments for heat pumps, and as a result of this, it is observed that the share of gas boilers decreases over time.

Although the heat generation and transmission capacities change with respect to changing emission targets, the overall thermal grid structure and also the spatial distribution of the generation facilities stay the same as shown in the experiment results. This happens because the model's limited scope allows it to have only two motivations for pipeline installations, and the dominant one is related to a fixed parameter, which is the industrial waste heat. The first motivation to install pipeline branches is to have a better utilization of industrial waste heat because it is assumed to be free and steady over the years.

The second motivation is about peak demand reduction. A municipality installs a certain amount of heat pump capacity to generate heat for its own use. Then, during the low heat demand periods, if wind energy is abundant, the heat pump installation in this municipality can be used to generate surplus heat. This surplus heat, then, can be transferred to another municipality. By doing so, the second municipality's peak demand can be reduced. As a result, the required amount of capacity installation to satisfy peak demand in the second municipality decreases. The model constructs pipelines to be able to acquire this benefit. The experimentation results indicate that this ”peak demand reduction” occurs when there is absence of industrial waste heat because municipalities with available industrial heat overshadows the ”peak demand reduction” dynamics.

When the years between 2040 and 2050 are examined, the dominance of biomass technologies grabs the attention. 2040 is the period in which 95% emission reduction policies are imposed. As a result of this, the energy systems abandon the use of natural gas to a great extent. Both reference and experiment scenarios indicate that the 5% margin for carbon emission is used to satisfy the electricity demand during the days with low wind energy output. Since the use of natural gas is highly restricted, the emptied base-load generation is filled by investing in the biomass facilities. Both biomass-based electricity generation facilities and biomass co-generation facilities reach high capacity values between the years 2040 and 2050. These findings are also supported by the literature sources which indicate that the use of renewable sources require a certain share of dispatchable sources to perform in a better way (Sharma & Balachandra, 2019; Zappa & van den Broek, 2018).

This point then brings the subject to the third research target which is the exploration of future conditions of co-generation facilities. The findings indicate that the biomass co-generation systems exist in the future power sector as a base-load alternative. Due to the relatively higher cost values, the installation of biomass facilities is delayed until it becomes an obligation because of the emission reduction targets. The situation is visible in all the experiment findings, and when the electricity generation mixes are checked, it can be seen that the capacity of the biomass co-generation facilities is utilized to its maximum during the days with low wind energy output. This implies that the co-generation facilities in the system generates electricity as their first product, and heat becomes the secondary product of these facilities. This finding shows resemblance with the findings of Romanchenko et al. (2017) which state the future role of CHP facilities will be more electricity focused.

Kang et al. (2017) suggest that co-generation and power-to-heat technologies perform better when they co-exist in a system. Whereas, Wang et al. (2015) indicate the future systems will utilize renewable sources together with co-generation facilities and thermal grids, while the thermal storage facilities will be widely used to balance out the fluctuating nature of renewables. The third decade findings of this study are in line with the literature to a certain extent, while it diverges from those when the storage applications are considered. The study at hand does not include storage facilities as a flexibility option, but the heat pumps are included and they provide with a certain flexibility. When the functionality of these technologies is considered instead of the specific types, both the literature and this study imply that the future performance of co-generation facilities and renewable sources is based on flexibility measures.

At this point, these findings require another connection to another shortcoming of this study. The adopted approach to model the emission levels, and included a set of technologies in the model in a way obliges it to install biomass for the third decade. This sort-of obligation yields high capacities for biomass installations, which is contrary to the expectations because the biomass subsidies have been seized since 2011 in the Netherlands (CODE2, 2019). Such a divergence occurs because when the emission reduction targets hit 95%, there are only 2 options for the system to choose in order not to increase emission values.

The first option is installing biomass capacities and utilizing it as the new base-load generation system. The second option is installing a set of onshore wind, offshore wind and solar PV facilities together with increased heat pump installations to satisfy the electricity and heat demand. The second option utilizes the compatibility between solar and wind sources and by letting the system have huge amounts of spillage, it fulfils the demand. Because the model does not include storage technologies, the second option loses its profitability due to the low capacity factors and high investment costs. It can be argued that with a system including storage technologies, the structure of the system between 2040 and 2050 can be different than the current findings. Storage applications are excluded from the system since their functioning requires a model approach which is capable of differentiating between periods chronologically, whereas, the current model structure is based on representative days due to the computational limitations.

Besides the generation capacities, it is important to touch upon the reasoning behind pipeline constructions. The experiments related to changing prices of pipeline installations indicate that there is a significant correlation between pipeline installations and investment cost of pipeline network which is an expected result. However, the cost of installation is one of the reasons to construct a pipeline branch. It is observed that majority of the pipeline network installations exist to utilize the industrial waste heat which is available in several municipalities. Whereas, some small capacity installations are used to reduce the peak heat demand of municipalities as described in the previous paragraphs. The significant influence of industrial waste heat leads the thermal grid to have clusters around the country, which regards the municipalities with available industrial heat as hubs in this system.

6.2. Implications for the power and heat sectors

Prior to describing the implications for power and heat sectors, touching upon the shortcomings and heroic assumptions of this study is necessary. By doing so the results of the study can be evaluated in a more practical perspective and the trade-offs can be discussed to enlighten the missing links between this research and the real systems.

First of all, this research has adopted a greenfield approach which ignores the existing power and heat facilities together with thermal grid structures. Basically, with this research, ”What would happen if an integrated electricity and heat system were designed for the Netherlands from scratch?” is explored. There are good things about adopting such an approach, as well as the problematic aspects. To begin with the perks, adopting such an approach helps the decision makers to have out-of-box ideas because the results are purified from the effects of any locked-in situation. It can be argued that today’s energy systems are the heritage of last centuries' understandings, and also this is the reason why today we are facing with the need of an energy transition. By excluding every past step and using a refreshed system, different insights can be gathered than the insights from a study including existing facilities.

On the other hand, these insights from studies which include existing facilities are quite valuable because they basically keep an ear close to the ground. For example, the real power system has higher installed capacity values, with lower capacity factors for its facilities in the Netherlands. There are redundancies in the real system, and they are regarded as inefficiencies with this research's perspective. However, these redundancies provide with security, flexibility, and resilience when the system undergoes some extreme cases. With the greenfield optimization study at hand, the use of redundancies in real life cannot be represented and this means all the insights are left untouched.

Besides assuming that the Netherlands' power and heat system is going to be constructed from scratch, which is already a huge statement to make, another elephant in the room is related to the assumption of copper-plate power system. It is assumed that the power system has no transmission losses, and no transmission capacities. Such a measure is taken to reduce the computational requirements of this study, but it is important to discuss the points that are ignored by assuming these.

First of all, by this assumption, the TSO and DSOs in the Netherlands are left out of the scope of this research. Therefore, the study falls short to encapsulate the interactions of these actors with the power and heat systems. As a result, certain dynamics which could be highly insightful are excluded. One example is related to the "no transmission capacity" side of this assumption which suggests the electricity is transmitted without taking the amount into account. However, even a recent example of solar power discussions indicate the opposite. The increasing capacity of solar PV installations puts the electricity networks in a difficult position, which leads to delays, and more critically, connection problems ("More solar power in the Netherlands but networks may be unable to cope", September 21, 2018). Copper-plate assumption simply ignores such constraints.

Secondly, the exclusion of TSO and DSOs and optimization of the total system cost ignores the fact that different actors are of changing interests and collision of these interests may lead to multiple objectives within the system. Installing a new pipeline branch requires a certain amount of capital by the party who will be responsible for the construction, and this party looks for a compensation for the expenditures. While, the end-user has nothing to do with these considerations and they just care about the unit price they will face when the hot water from network reach to their radiators.

As one of the biggest assumptions made in this research, the use of a static district heating share for the municipalities requires further considerations. As stated before, it is assumed that the total share of buildings connected to a district heating network reaches 56% in 2050, and starting from 2020, the expansion of district heating networks in the municipalities adopts a steady pace. All the findings of this research should be evaluated by taking this into account, since changing values of this district heating share would mean changing heat demand, changing number of included municipalities in the analysis, and therefore changing thermal grid structure together with installed capacities. Such an application in reality would mean a quite intense construction works in most of the municipalities in the Netherlands to place district heating installations, and this would require a huge budget together with social concerns related to disrupted neighbourhoods.

Lastly, the assumption of no exports and imports requires some explanation. It is assumed that the Netherlands' has isolated electricity and heating systems. It is not allowed to buy or sell any electric or heat energy to the neighbour countries. In reality, of course, the situation is exactly the opposite. In 2018, the amount of imported electricity was 24%, exported electricity was 17% of the amount of generated electricity in the Netherlands (CBS, 2019c). By assuming an isolated system, the possibility to import cheap electricity from abroad for the peak hours and reducing the required capacity is ignored. Also, the effects of such a flexibility option remains untouched for this research.

All these assumptions then make the applicability of the research outcomes in the real life questionable. The findings indicate the installation of pipeline branches between certain municipalities, changing generation mixes, and varying dominant generation types over the decades for both electricity and heating sectors. However, it is quite critical to recognize that the final value of a variable of the model is a completely different thing than the real value of represented quantity (Thompson & Smith, 2019).

The model results imply sharp jumps from one energy source to another in between the decades. It should be interpreted in a way that these jumps represent more smooth transitions over the years. Otherwise it would mean the construction of thousands of MW capacity overnight, which is completely infeasible. As another, the results indicate numerous pipeline connections with small capacities. They are represented quite thin on the maps showing thermal grid expansions, which means they are of at max 1-2 MW of capacity. The real life applicability is arguable, but installing such small capacities would mean digging the ground and placing a pipeline with the diameter of 6-10 cm (IEA-ETSAP, 2013b). Then this would imply that when the ground is dug, the real life applications have the tendency to install higher capacities to compensate the construction costs. Similarly, the expansion maps indicate that the ground is being dug multiple times over the years because the pipeline capacities are expanded. However, this would create a huge mess and social unrest by the citizens, besides the higher construction costs it brings. Therefore, it might be more meaningful when the pipeline installations are constructed during the early years by considering their prospected future capacities.

Also, as stated before, the energy systems have many actors with varying interests and most of the times these interests diverge to different directions. The research results imply that all these long-term strategical decisions are made in a snap, but in reality these would require months of preparations, discussions and lobbying activities. Therefore, it is of the utmost importance that the results of this research should not be interpreted as exact results. The whole purpose is to provide decision makers with a slight steer, so that a better-informed decisions can be made.

This decision support can also be linked to the existing policies. Specifically, two existing policies in the Netherlands present great coherence with this research's targets and findings. First one is the ”SDE++” policy advice, which is the continuation of the existing renewable energy subsidy scheme, ”SDE+” (PBL, n.d.). The government considers expanding the current scheme to cover CO_2 reducing options besides the renewable energy generation, and the year for this scheme is identified as 2020. The current directions of policy advice cover large-scale heat pumps, and use of industrial waste heat. As stated in the previous sections, this research results also suggest similar applications. However, it is also observed that the represented system puts a lot of emphasis on the dispatchable units, while the ”SDE++” discussions focus on electrification of heat, industrial waste heat and hydrogene production. Considering about subsidizing large scale biomass co-generation facilities for the future decades might be an addition to the existing discussions.

Lastly, in all the experiments conducted, it is observed that the municipalities with available industrial waste heat serve as heat hubs which supply heat energy to the neighbour municipalities. For the province of Zuid Holland, the results suggest the municipality of Rotterdam to be the hub. This structure in Zuid-Holland has a quite valid equivalent in reality, which is the ”Heat Roundabout”. It is targeted that the heat energy from Port of Rotterdam is supplied to multiple cities with a thermal grid, and so the overall fuel use can be reduced. Besides the industrial waste heat, when the results of reference scenario are checked, the model suggests the installation of dispatchable units in Rotterdam and Westland municipalities. During the first two decades, this units are in the form of natural gas plants, while in the last decade they evolve to CHP facilities. The model's industrial waste heat comes from industrial facilities and refineries only. In the light of this, it can be concluded that the real system can compensate the dispatchable unit need by utilizing the existing power plants in the Port of Rotterdam.

7 Conclusion

In this final chapter, first, the connection between the findings of this study and the identified research questions in chapter 1 is formed. Then, recommendations for policy-makers are presented based on the model results. Finally, possible future research lines which can be explored are shared.

7.1. Conclusions

This study is conducted to be able to answer how the integrated electricity and heat systems look like in the Netherlands under the effect of future emission targets and transition towards green technologies. The research question is identified in the first chapter as:

How should the electricity and heat generation facilities be installed and heating transmission networks be expanded to achieve an energy system which yields minimum system costs under the effect of emission reduction targets?

It is concluded that the electricity sector maintains a fossil-fuel dominated generation scheme in between 2020 and 2030, while wind energy is utilized with a relatively small share. As the emission targets are imposed, the generation mix undergoes drastic shifts towards renewables. The years between 2030 and 2040 witness a jump in the installed wind power capacity, and for the last decade the investments shift to the biomass facilities.

Similarities are observed in the heat generation sector. Besides the steady use of industrial waste heat, for the years between 2020 and 2030, a major part of the generated heat energy comes from natural gas boilers, and a small share is fulfilled by power-to-heat technologies. As the emission reductions are imposed, this generation mix shifts to a major use of power-to-heat technologies in between 2030 and 2040, and biomass co-generation facilities in the years between 2040 and 2050. It is observed that the major pipeline installations between municipalities take place mostly in the province of Zuid-Holland, while several thermal clusters around the country are suggested.

To what extent do the energy conversion technologies help to reach the emission targets?

It is found that the power-to-heat technologies are helpful to reach emission targets when there are investments made for the electricity generation systems based on renewable sources. One positively affects another, increases the system efficiency, and together they help the energy systems to reach their emission targets.

Experiments with gradually decreasing heat pump prices indicate that more heat pumps lead to more wind energy utilization, and this means the system can reach fewer emission values. This decreasing prices can be considered as a subsidy scheme which is provided by the government. In a way, the analysis shows promising results for the use of power-to-heat technologies for the pursuit of fewer carbon emissions.

What is the effect of renewable integration on district heating systems?

From the experiments, it is observed that imposing more restricting climate targets leads the system to invest more in the power-to-heat conversion technologies and thermal grid capacities. As the policies target further reductions in the emissions, the investments made for the renewable sources show incremental behaviour. As a result of the increased capacity of renewable sources, the investments for power-to-heat conversion technologies become more preferable to generate clean heat energy. Therefore, stricter climate targets make the shift from natural gas boilers to heat pumps sharper.

What is the role of co-generation facilities in the future energy systems?

It is concluded that the biomass co-generation systems exist in the future power sector as a dispatchable generation alternative. Due to the relatively higher cost values, the installation of biomass facilities is delayed until it becomes an obligation because of the emission reduction targets.

What are the dominant factors leading to the installation of new pipelines between cities?

First and the most dominant reason is observed as to utilize the industrial heat demand which is available in several municipalities. The thermal grids are clustered around these municipalities and the changes in the other quantities mostly affect the installed capacity but not the structure of the grid.

Secondly, it is found that the new pipeline installations occur with the motivation of decreasing peak demand of municipalities by utilizing heat pumps while the wind energy is abundant. By pursuing such motivation, fewer capacity installations are needed in the overall system, and the electricity and heat demands can be fulfilled while yielding less total cost.

Conducted analysis with the changing pipeline installation prices indicates that the investment cost is a significant determinant of construction decision. Similar to the power-to-heat technologies case mentioned earlier in this chapter, the decreasing costs of pipeline investments can be considered as a governmental subsidy scheme. It is concluded that a thermal grid with more municipalities connected is possible as the cost of pipeline investments decreases, and a more connected thermal grid can utilize the green heat in a better way, which results in a positive effect on the emission reduction efforts.

7.2. Policy recommendations

The one of the main findings of this analysis is related to the use of industrial waste heat. Current policy discussions for ”Heat Roundabout” to utilize the heat from Port of Rotterdam can be expanded to other municipalities with available industrial facilities. From the analysis; Sittard-Geleen, Moerdijk, Velsen, and Brummen are the municipalities which come to the forefront for such applications.

With the increasing renewable integration, a subsidy scheme which covers electrification of heat can be implemented. The analysis indicates the positive effects of these technologies on the emission reduction targets, besides their utilization as a flexibility option.

It is observed that the power system always needs a certain share of dispatchable generation unit. By considering the ongoing ”Coal Phase-out” until 2030, the future compensation of the missing generation capacities can be directed towards biomass based installations. With a subsidy scheme for such generation types, the burden on the power system can be decreased while shifting towards green technologies. Also, due to the high investment and operational costs, the shift to biomass facilities is delayed until the very last moment which it becomes an obligation due to the increasing emission reduction targets. A subsidy scheme can also be considered to incentivize the biomass use and achieve the shift earlier.

Lastly, as the starting point of all the findings and suggestions based on those findings in this analysis, the decision-makers should take critical actions for the inner-city district heating network installations. Higher share of district heating especially brings higher utilization of industrial waste heat. As a result, the fuel consumption of the country can be decreased drastically. By directing towards a more centralized heat generation scheme, the tractability of the heat sector can be increased and this can positively affect the pursuit of lower emissions. That's why, a subsidy or tax reduction can be considered as an option to incentivize the district heating installations.

7.3. Future works

There are many assumptions made, during the research process, for this model to reach a conclusion. Some of these assumptions turn out to be negligible while some are proven that they are the shortcomings of this study. These points can be seen as vulnerabilities of this research, but also they are the opening windows to future research. This section is used to elaborate on these points.

As one of the biggest assumptions made in this research, the use of a static district heating share for the municipalities is one of the promising points for future research. The future share of district heating networks in each municipality is quite uncertain. Expansion of these inner-city networks as a decision in this study's model gets too exhaustive for the computational requirements, but with another approach, it might be achievable to explore the shares within the cities.

The study is conducted by adopting a greenfield approach due to the limited data related to local heat generation technologies. When such a data set is available, it can be highly insightful to conduct a similar study by adopting brownfield approach, so that a better comparison between model results and real-life outcomes can be made and this can help to achieve clearer findings in the end.

The model uses a detailed network structure for heat energy transmission networks between the cities, but a similar approach is not used for the electricity transmission network. Instead, it is assumed to function as a copper-plate which brings zero transmission losses and no transmission capacities. By including transmission network, and allowing the country to import and export with the neighbour countries, the model scope can be expanded and new insights can be gained related to energy systems functionality in the future.

Finally, storage applications are excluded in this study because of the computational limits. The representative days are being used in the model and it makes the model lose the sense of time for short term operations. A set of representative days and the number of days in 10 years which are represented by this set of representative days are known, but the order of the "represented" days is not known. However, use of storage requires specific information about the chronological order of days, so that the stored energy can be carried from one day to the other. Since the model is not capable of providing with this order, it is not possible to include storage applications in such a system representation. However, as a future step, the structure of the model can be adjusted, and storage installations can be added to the system to have a better representation of the real electricity and heating systems.

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Appendix A

A.1. Results of 40% reduction scenario

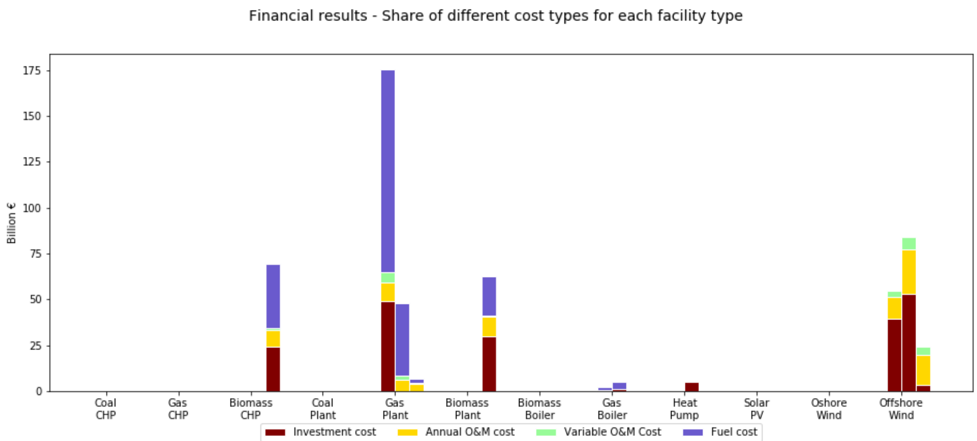

Figure A.1: Scenario40% - Cost values for each facility type

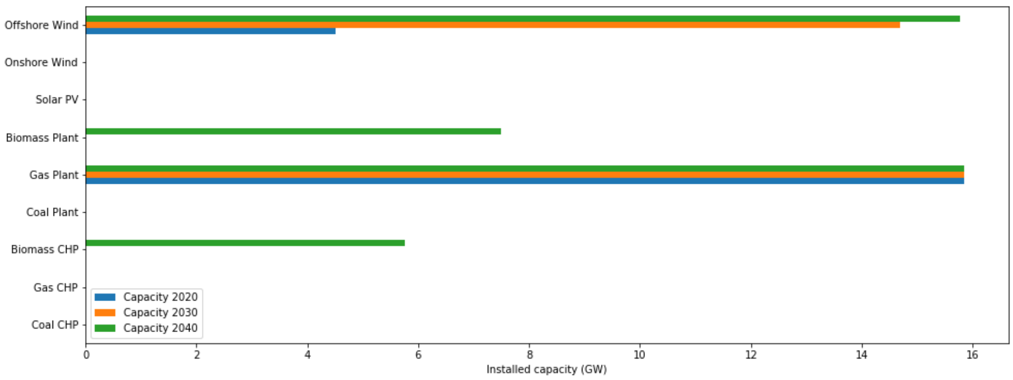

Figure A.2: Scenario40% - Electricity sector - existing capacity in each decade

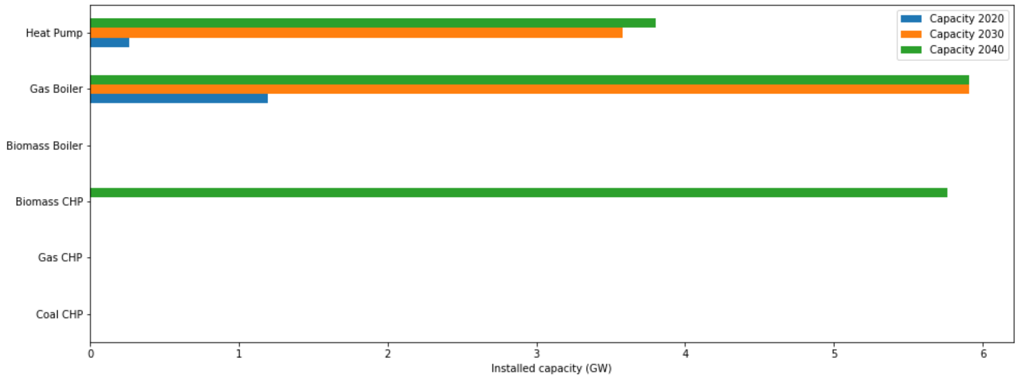

Figure A.3: Scenario40% - Heating sector - existing capacity in each decade

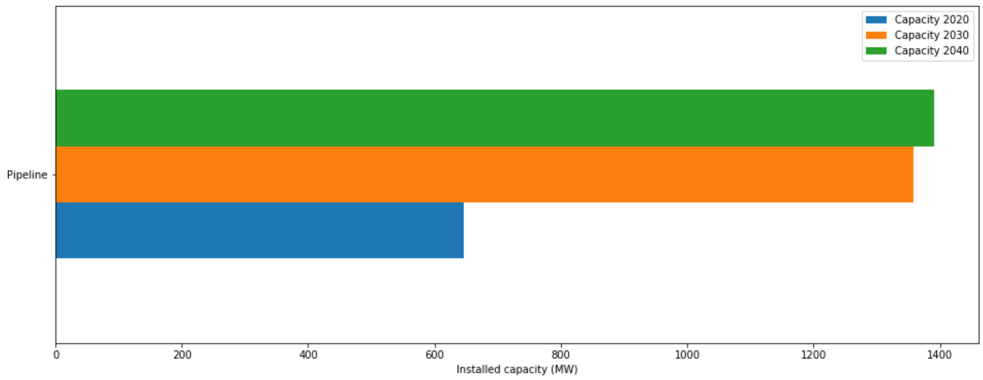

Figure A.4: Scenario40% - Pipelines - existing capacity in each decade

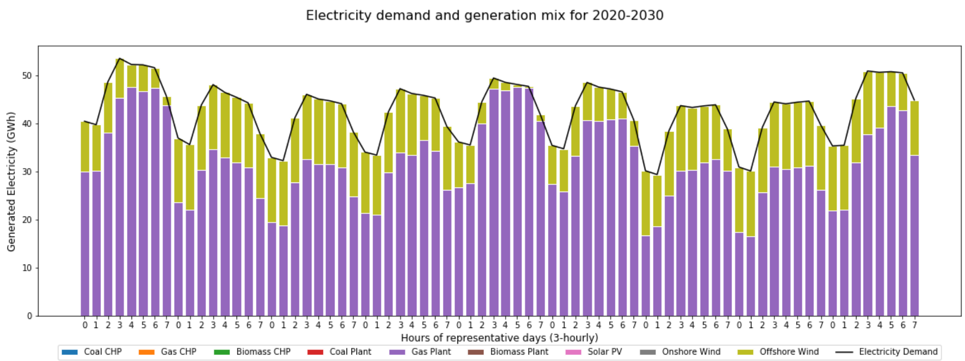

Figure A.5: Scenario40% - Electricity generation mix for 2020 and 2030

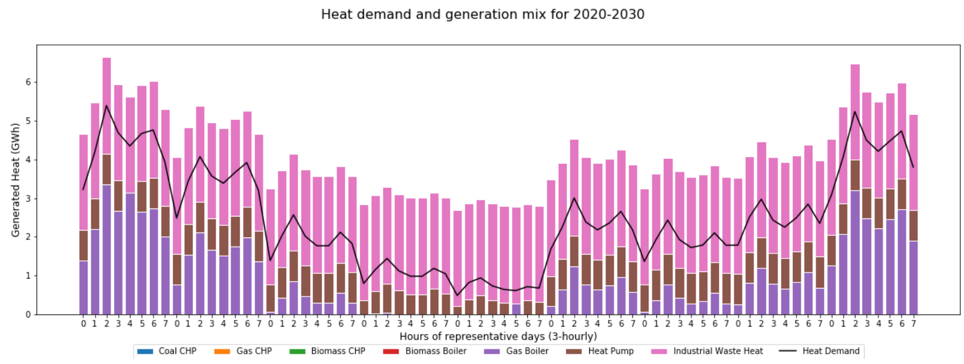

Figure A.6: Scenario40% - Heat generation mix for 2020 and 2030

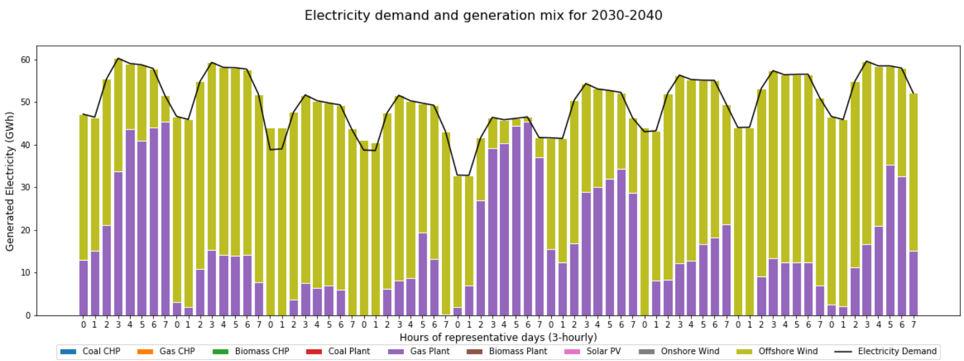

Figure A.7: Scenario40% - Electricity generation mix for 2030 and 2040

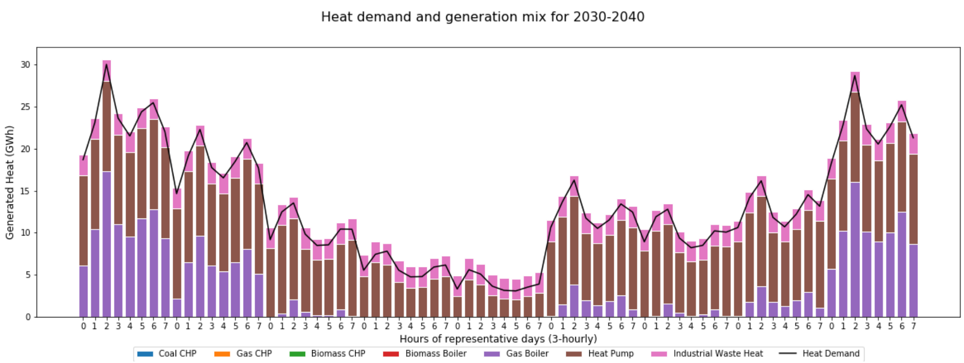

Figure A.8: Scenario40% - Heat generation mix for 2030 and 2040

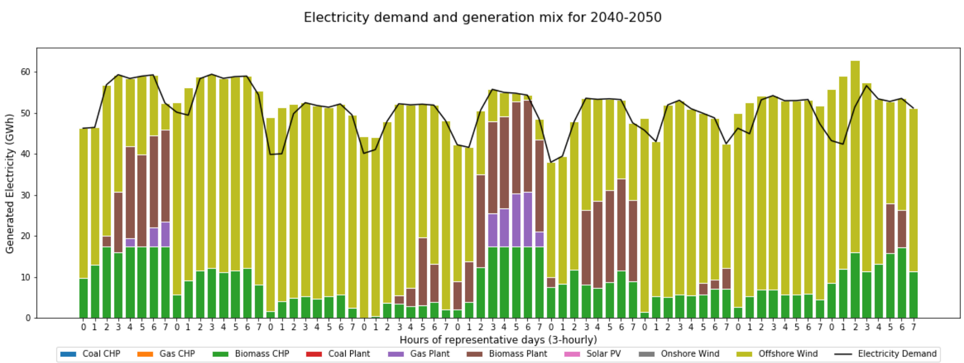

Figure A.9: Scenario40% - Electricity generation mix for 2040 and 2050

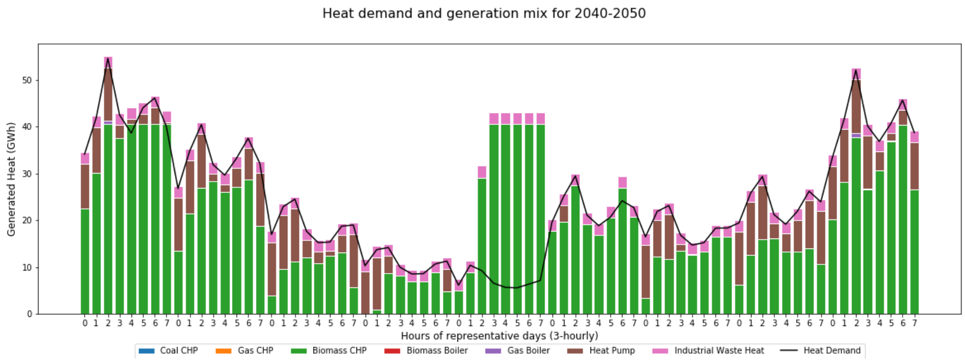

Figure A.10: Scenario40% - Heat generation mix for 2040 and 2050

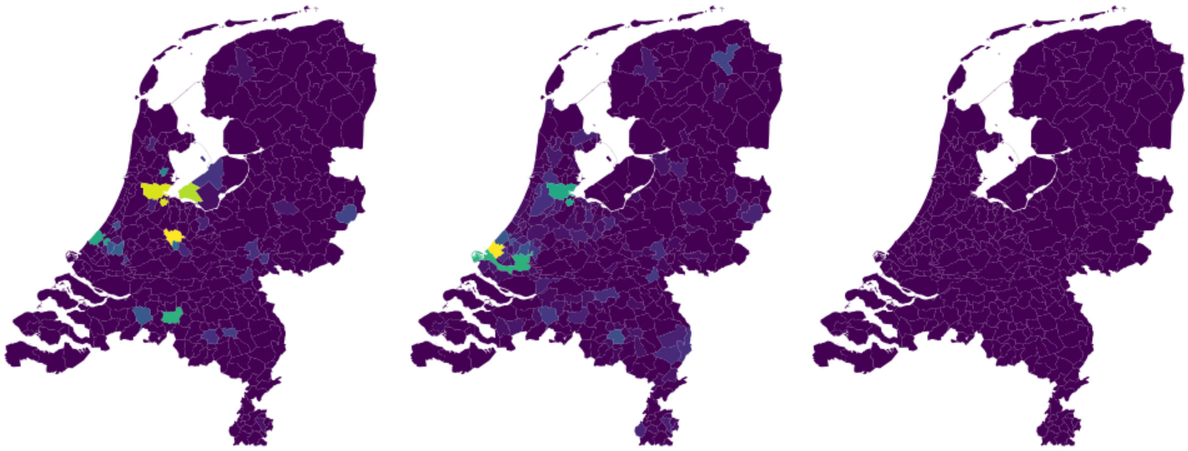

Figure A.11: Scenario40% - Additional capacity installments of gas boilers in each municipality (left, 2020; middle, 2030; right, 2040)

Figure A.12: Scenario40% - Additional capacity installments of heat pumps in each municipality (left, 2020; middle, 2030; right, 2040)

Figure A.13: Scenario40% - Additional capacity installments of biomass CHP's in each municipality (left, 2020; middle, 2030; right, 2040)

A.2. Results of 60% reduction scenario

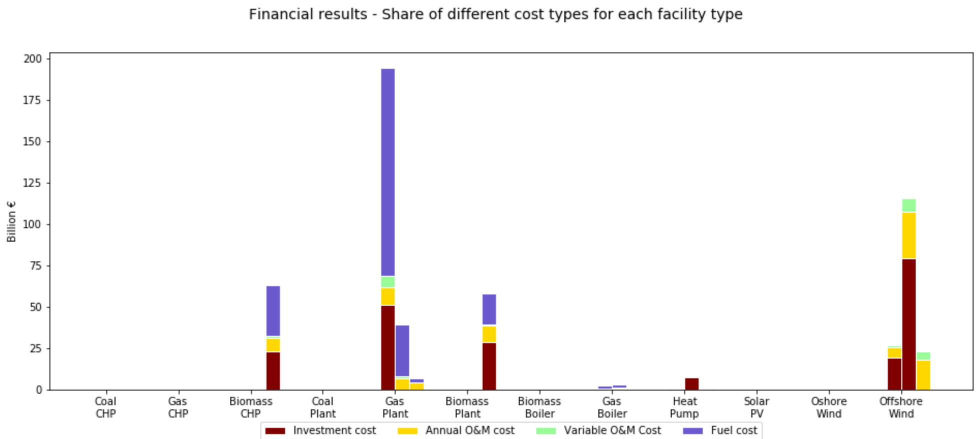

Figure A.14: Scenario60% - Cost values for each facility type

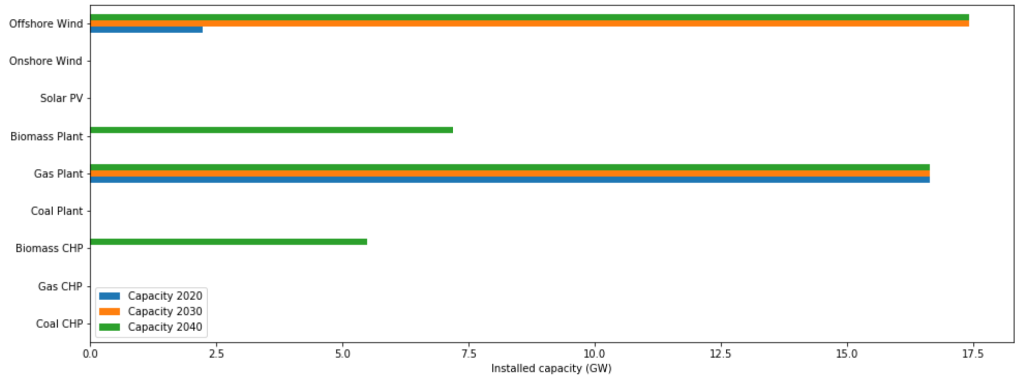

Figure A.15: Scenario60% - Electricity sector - existing capacity in each decade

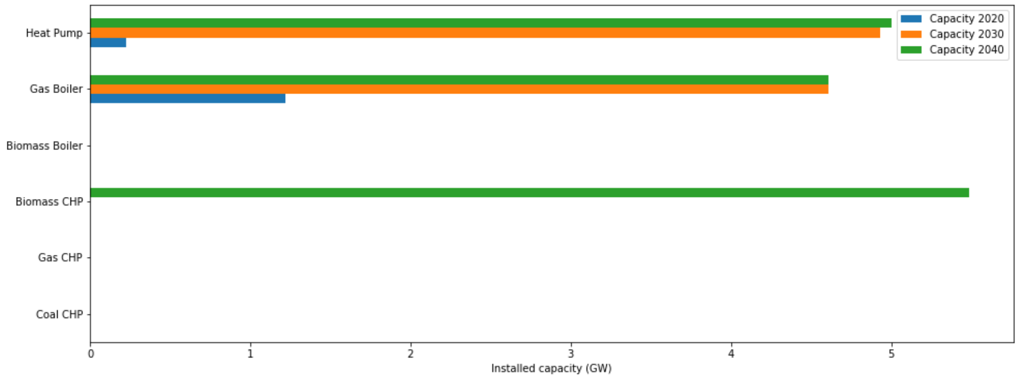

Figure A.16: Scenario60% - Heating sector - existing capacity in each decade

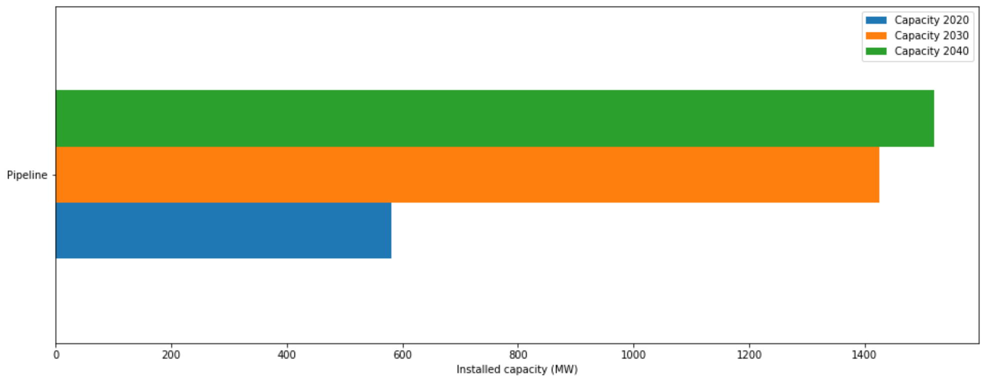

Figure A.17: Scenario60% - Pipelines - existing capacity in each decade

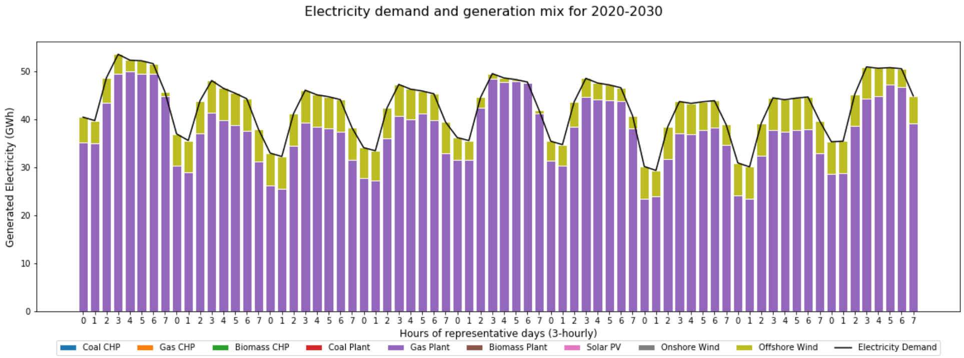

Figure A.18: Scenario60% - Electricity generation mix for 2020 and 2030

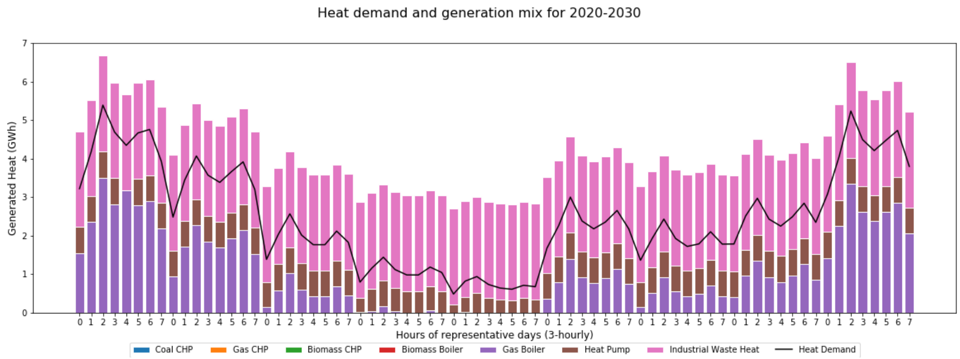

Figure A.19: Scenario60% - Heat generation mix for 2020 and 2030

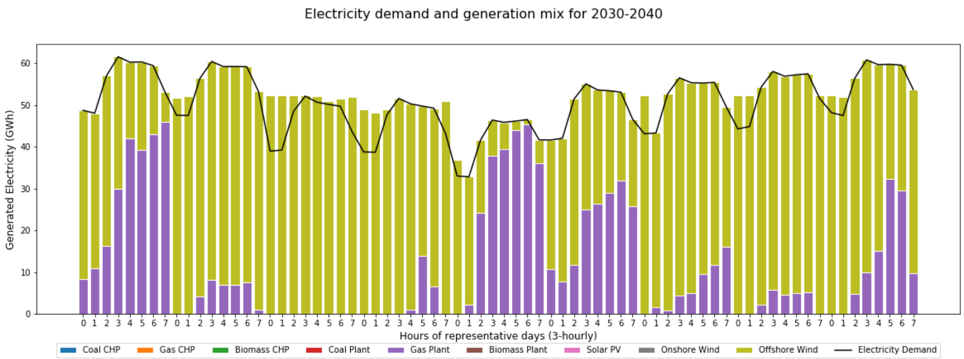

Figure A.20: Scenario60% - Electricity generation mix for 2030 and 2040

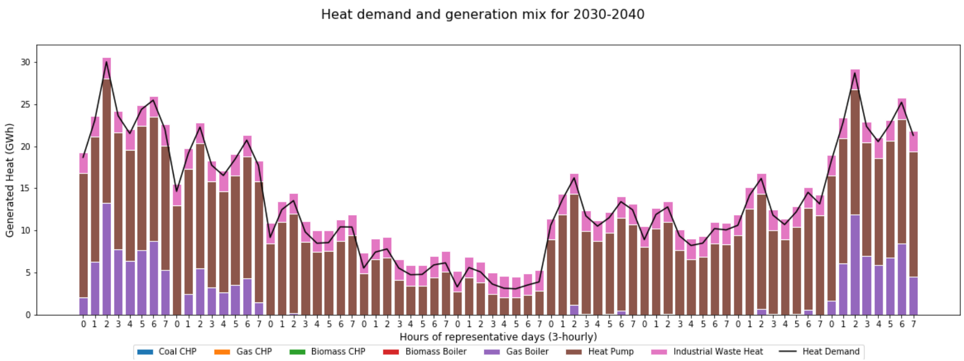

Figure A.21: Scenario60% - Heat generation mix for 2030 and 2040

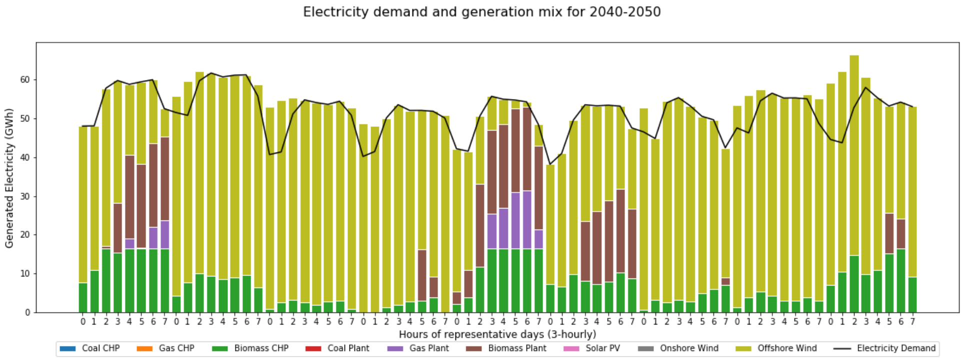

Figure A.22: Scenario60% - Electricity generation mix for 2040 and 2050

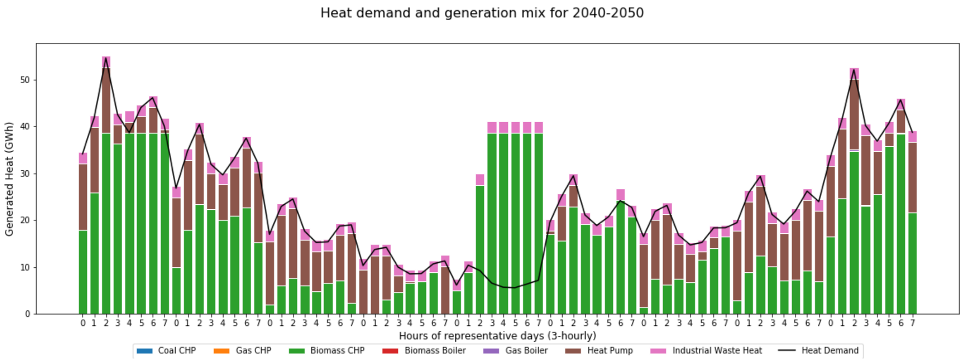

Figure A.23: Scenario60% - Heat generation mix for 2040 and 2050

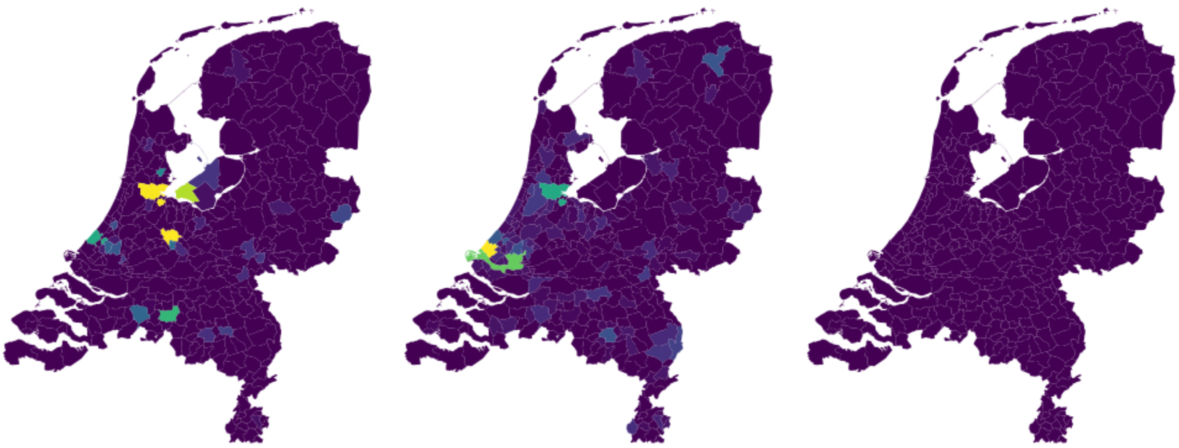

Figure A.24: Scenario60% - Additional capacity installments of gas boilers in each municipality (left, 2020; middle, 2030; right, 2040)

Figure A.25: Scenario60% - Additional capacity installments of heat pumps in each municipality (left, 2020; middle, 2030; right, 2040)

Figure A.26: Scenario60% - Additional capacity installments of biomass CHP's in each municipality (left, 2020; middle, 2030; right, 2040)

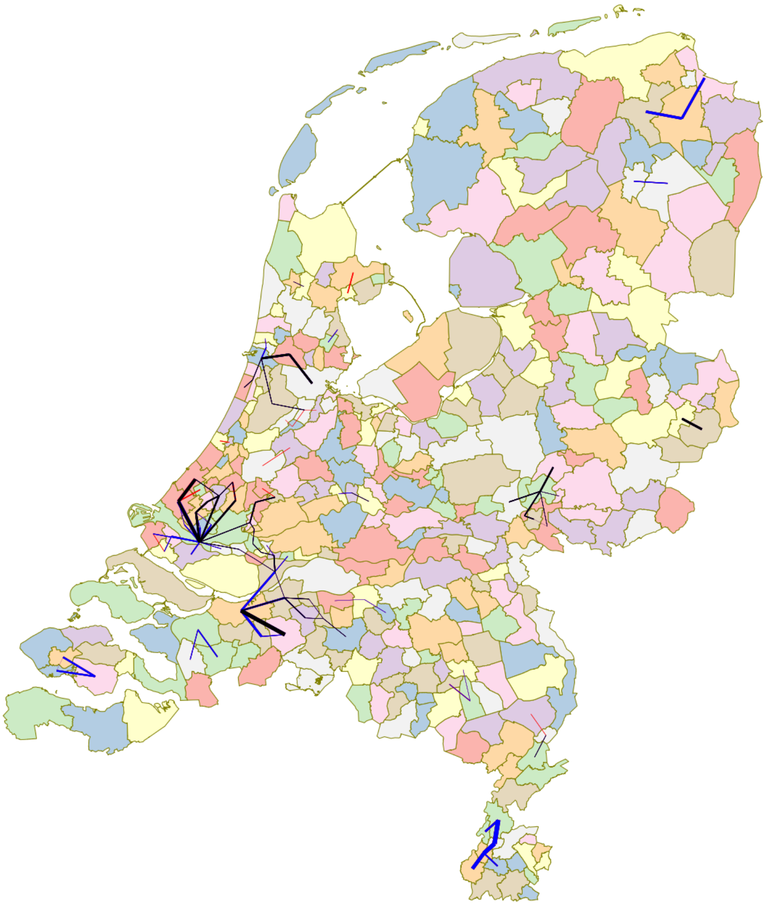

Figure A.27: Scenario60% - Expansion of pipeline networks over the years (black, 2020; red, 2030; blue, 2040)

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Appendix B

A.1. Default-Scenario - heat pump analysis - remaining figures

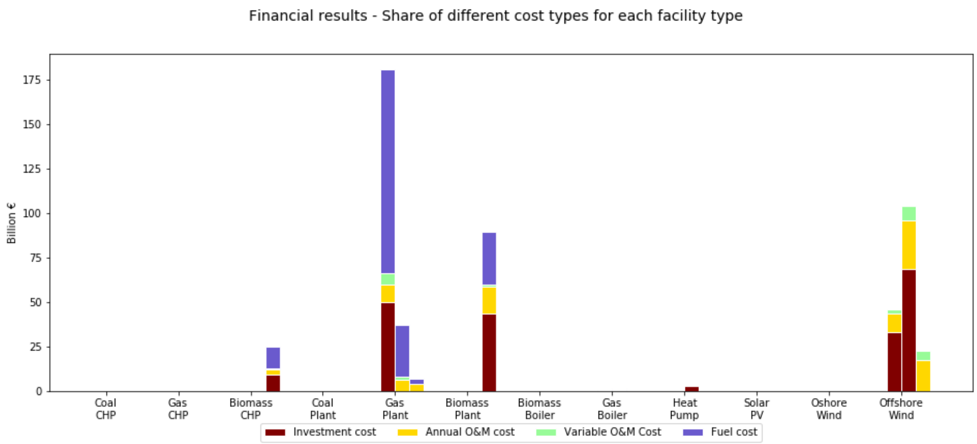

Figure A.1: Default-Scenario - cost values for each facility type

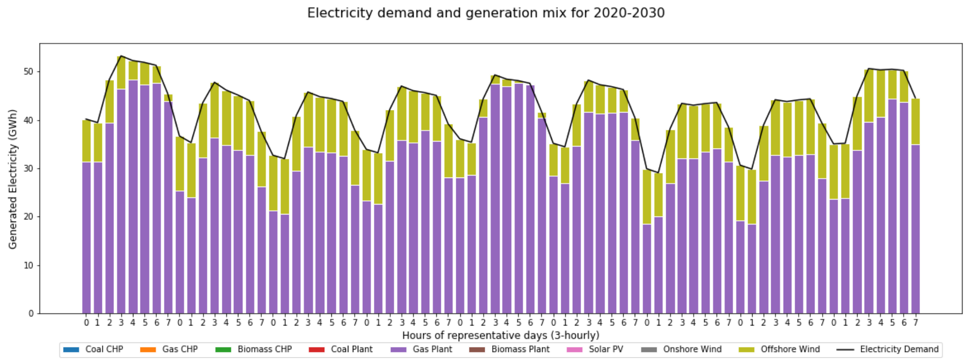

Figure A.2: Default-Scenario - electricity generation mix for 2020 and 2030

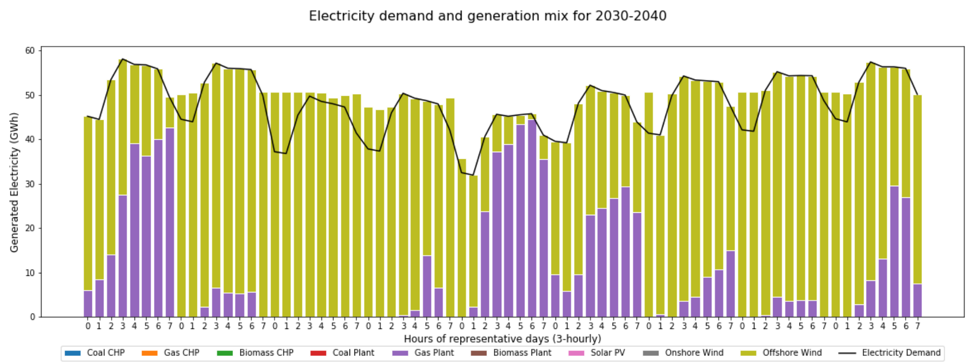

Figure A.3: Default-Scenario - electricity generation mix for 2030 and 2040

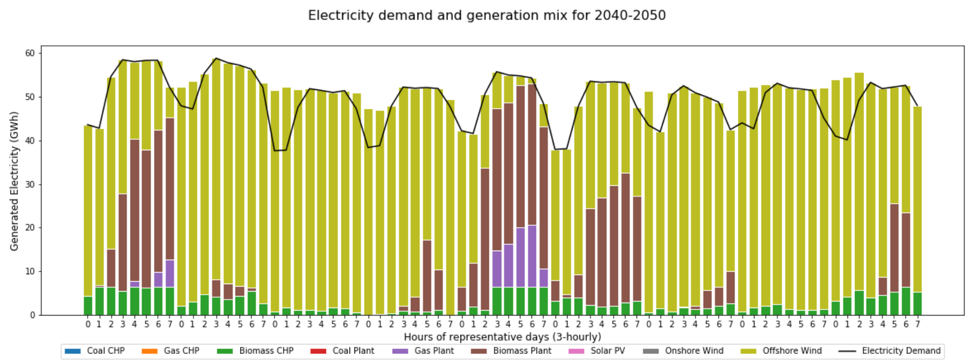

Figure A.4: Default-Scenario - electricity generation mix for 2040 and 2050

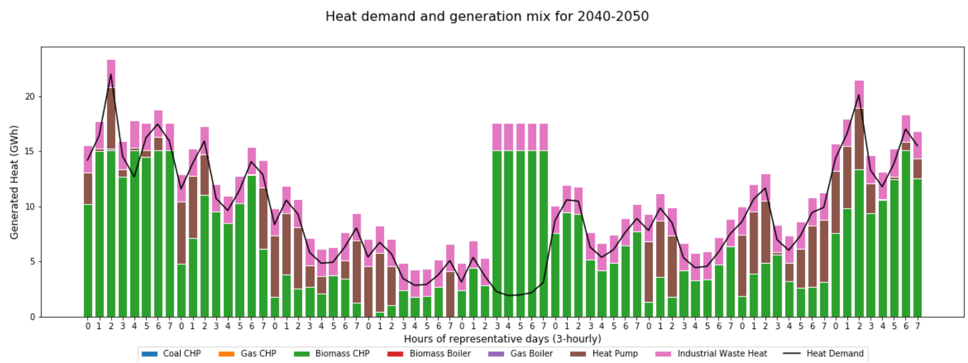

Figure A.5: Default-Scenario - heat generation mix for 2040 and 2050

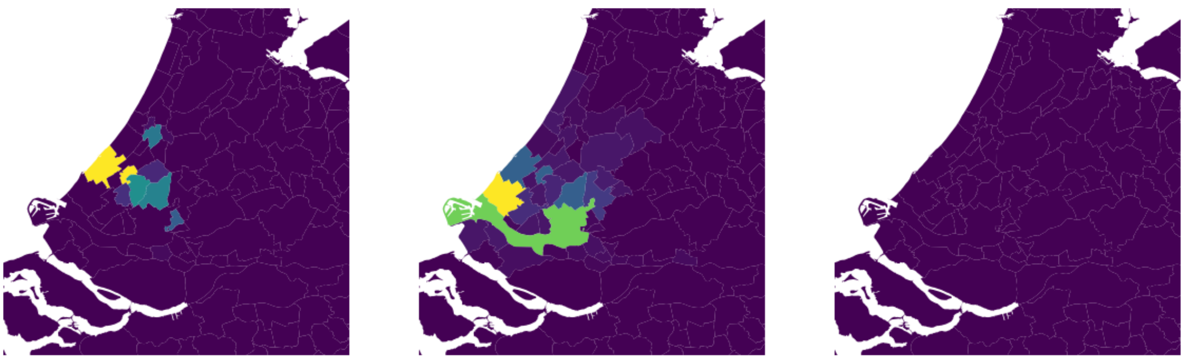

Figure A.6: Default-Scenario - additional capacity installments of gas boilers in each municipality (left, 2020; middle, 2030; right, 2040)

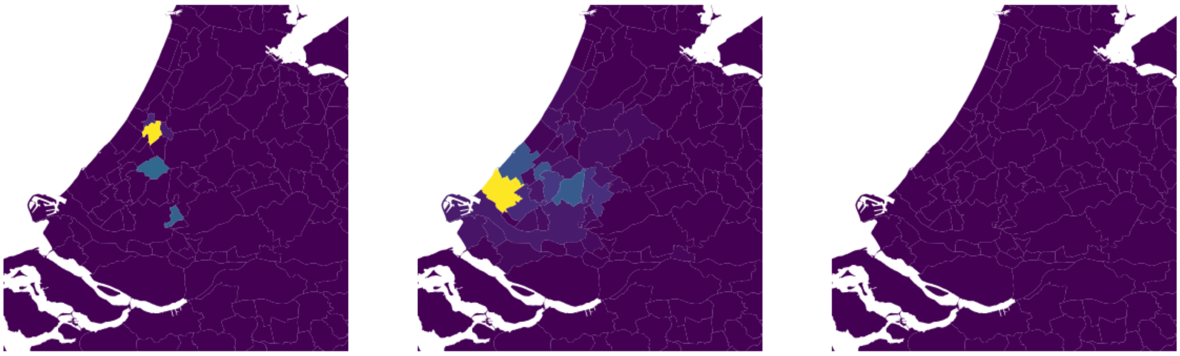

Figure A.7: Default-Scenario - additional capacity installments of heat pumps in each municipality (left, 2020; middle, 2030; right, 2040)

Figure A.8: Default-Scenario - additional capacity installments of biomass CHP's in each municipality (left, 2020; middle, 2030; right, 2040)

A.2. Scenario-120% - heat pump analysis

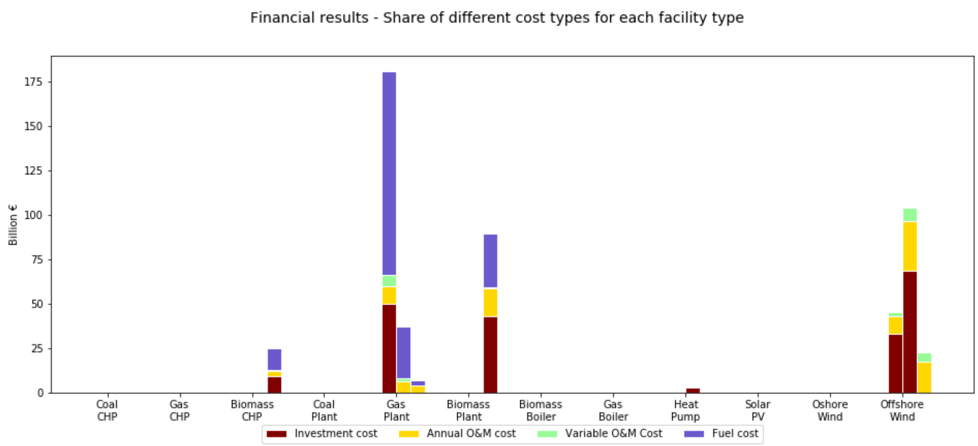

Figure A.9: Scenario-120% - cost values for each facility type

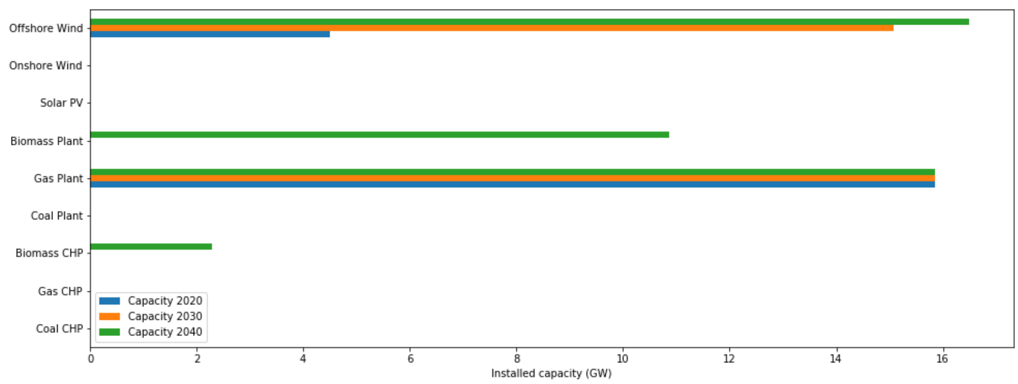

Figure A.10: Scenario-120% - electricity sector - capacity installations in each investment window

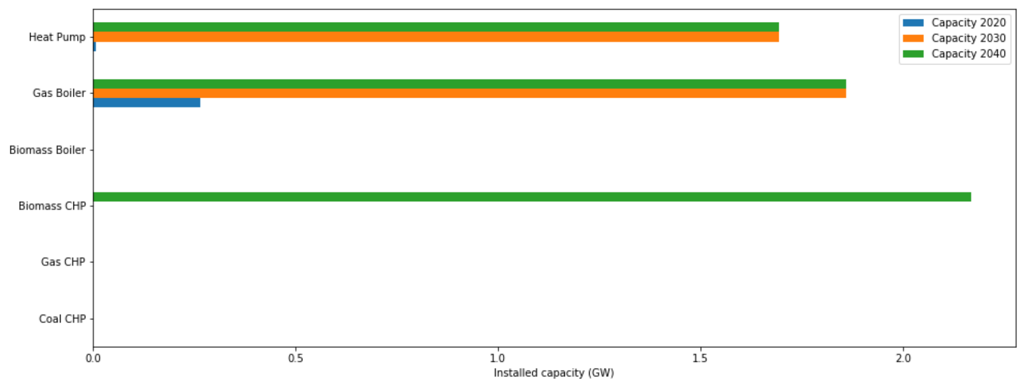

Figure A.11: Scenario-120% - heating sector - capacity installations in each investment window

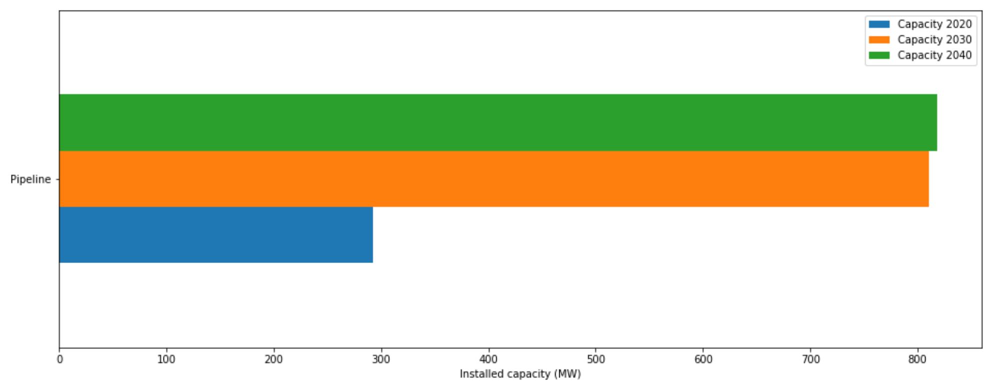

Figure A.12: Scenario-120% - pipelines - capacity installations in each investment window

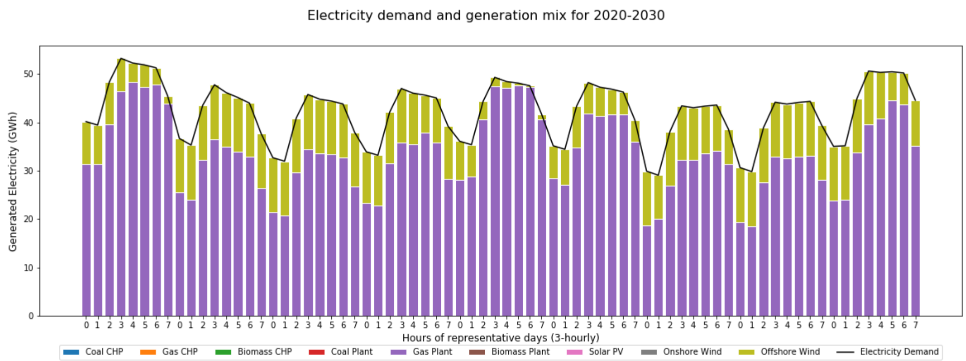

Figure A.13: Scenario-120% - electricity generation mix for 2020 and 2030

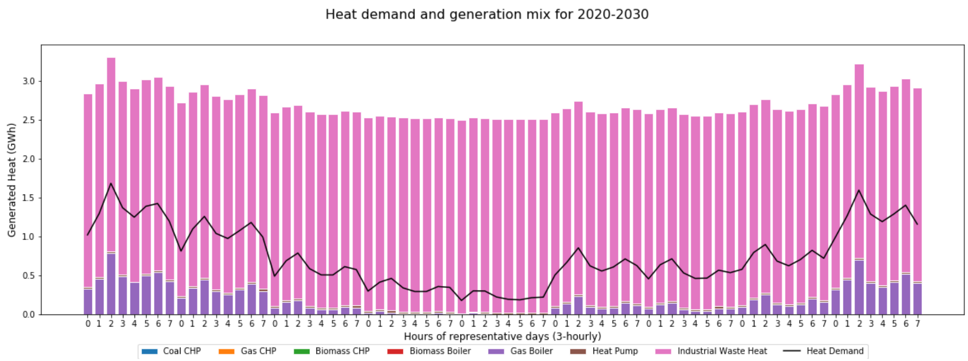

Figure A.14: Scenario-120% - heat generation mix for 2020 and 2030

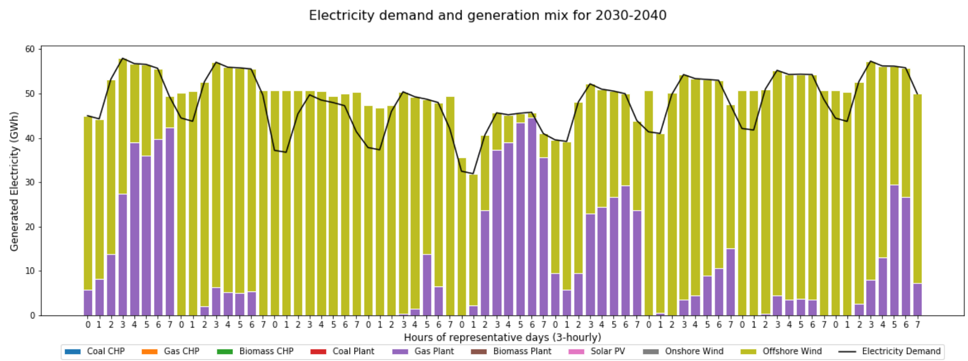

Figure A.15: Scenario-120% - electricity generation mix for 2030 and 2040

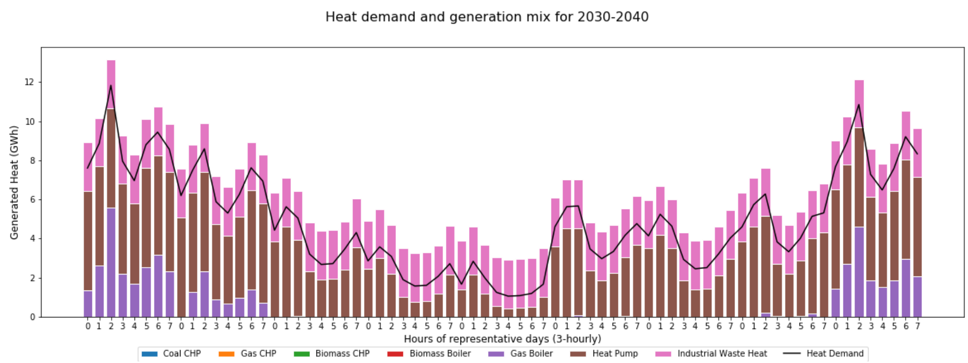

Figure A.16: Scenario-120% - heat generation mix for 2030 and 2040

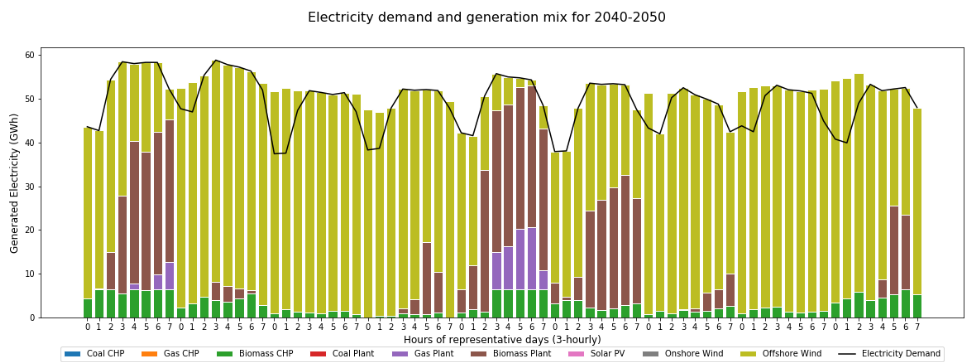

Figure A.17: Scenario-120% - electricity generation mix for 2040 and 2050

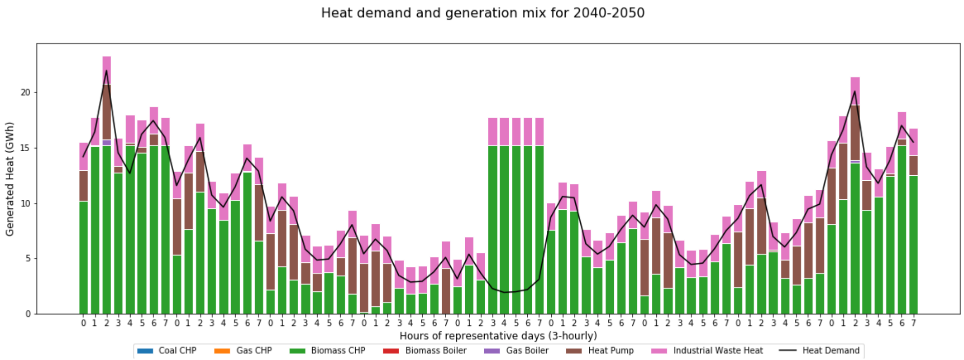

Figure A.18: Scenario-120% - heat generation mix for 2040 and 2050

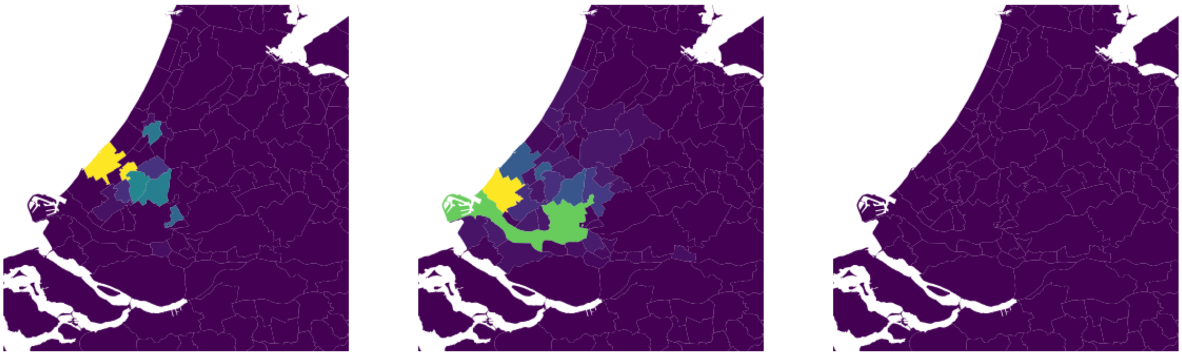

Figure A.19: Scenario-120% - additional capacity installments of gas boilers in each municipality (left, 2020; middle, 2030; right, 2040)

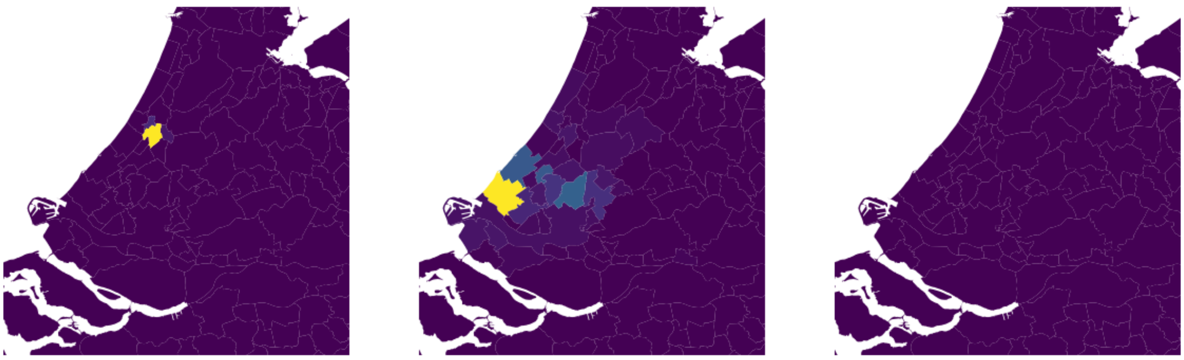

Figure A.20: Scenario-120% - additional capacity installments of heat pumps in each municipality (left, 2020; middle, 2030; right, 2040)

Figure A.21: Scenario-120% - additional capacity installments of biomass CHP's in each municipality (left, 2020; middle, 2030; right, 2040)

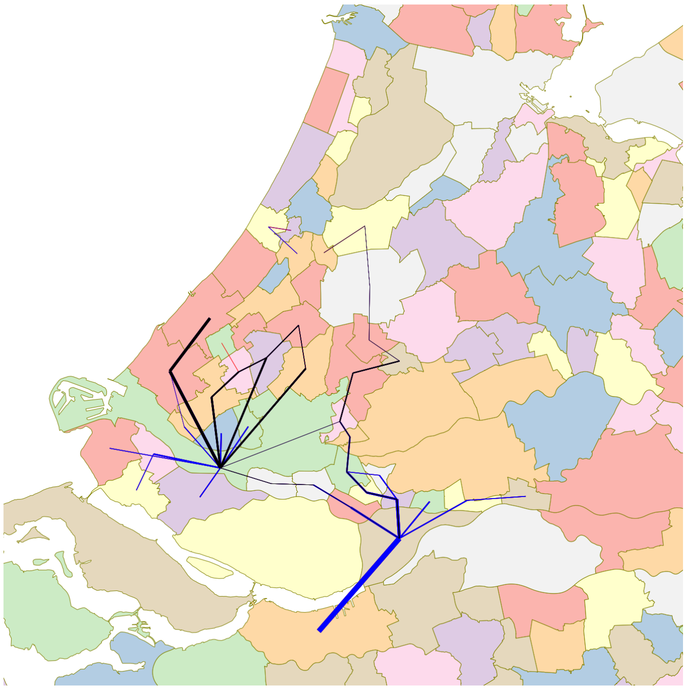

Figure A.22: Scenario-120% - expansion of pipeline networks over the years (black, 2020; blue, 2030; red, 2040)

A.3. Scenario-90% - heat pump analysis

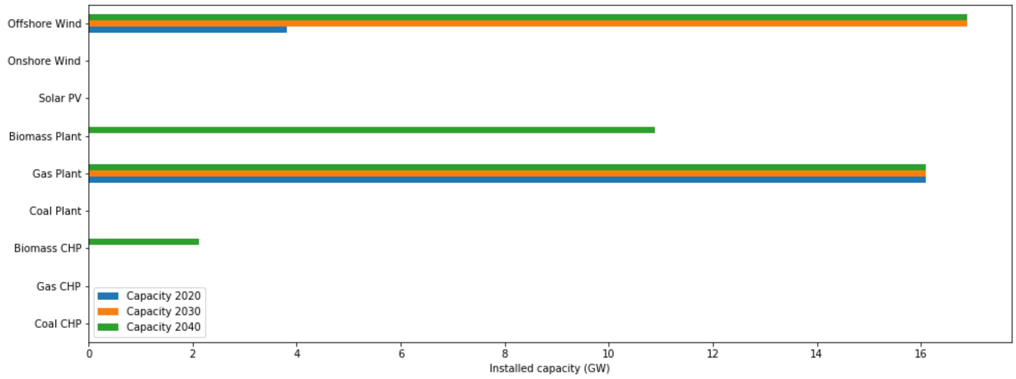

Figure A.23: Scenario-90% - electricity sector - capacity installations in each investment window

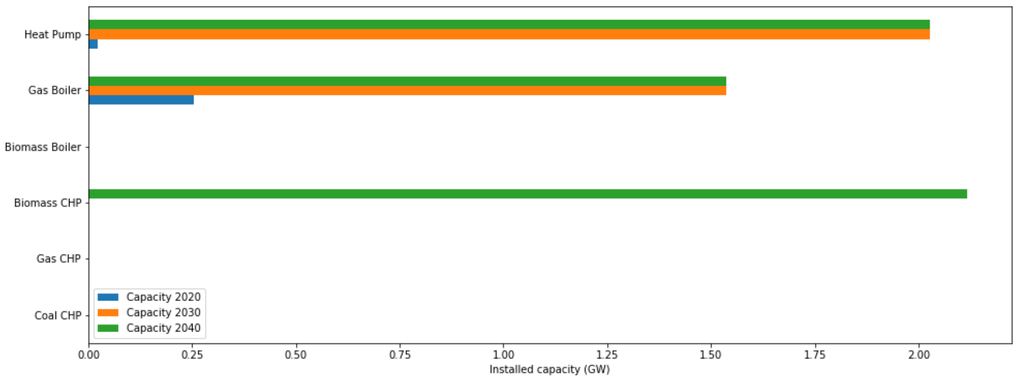

Figure A.24: Scenario-90% - heating sector - capacity installations in each investment window

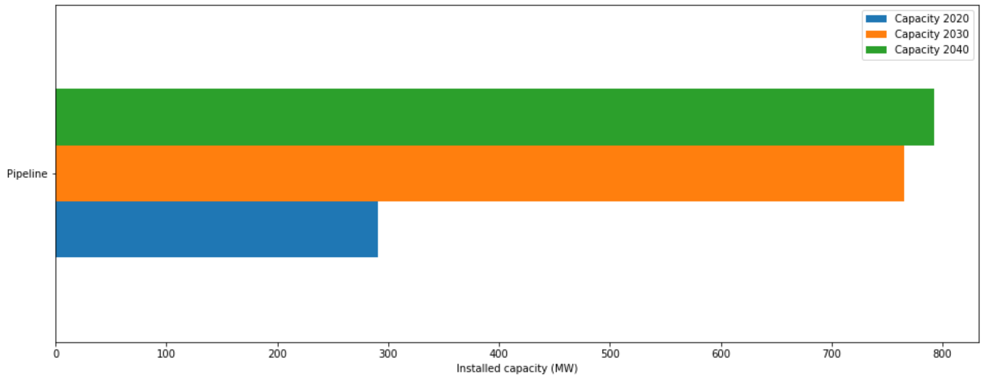

Figure A.25: Scenario-90% - pipelines - capacity installations in each investment window

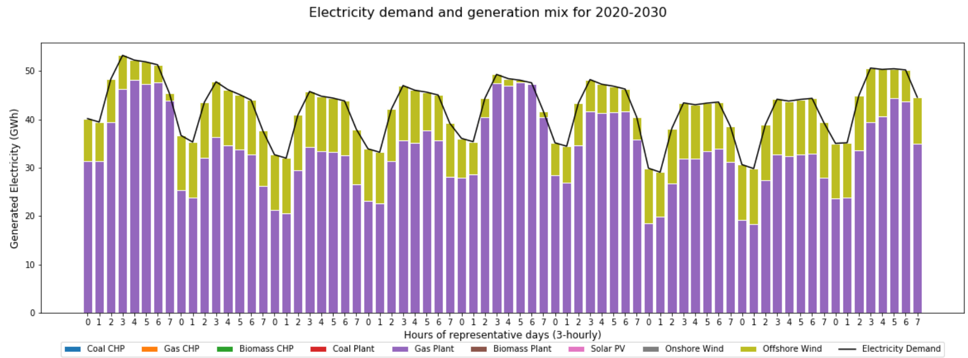

Figure A.26: Scenario-90% - electricity generation mix for 2020 and 2030

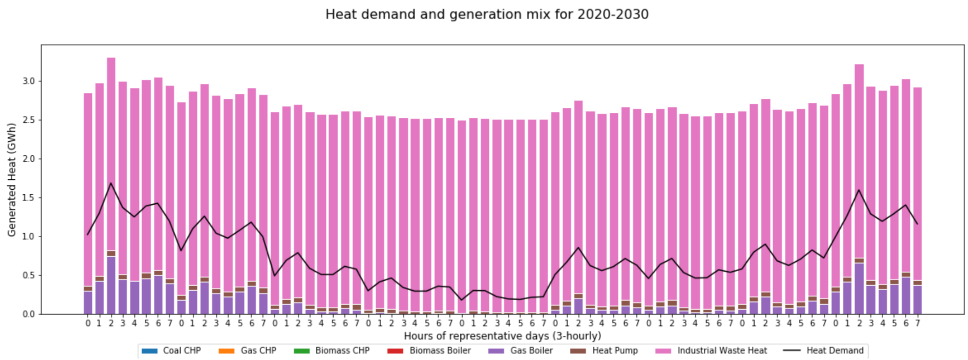

Figure A.27: Scenario-90% - heat generation mix for 2020 and 2030

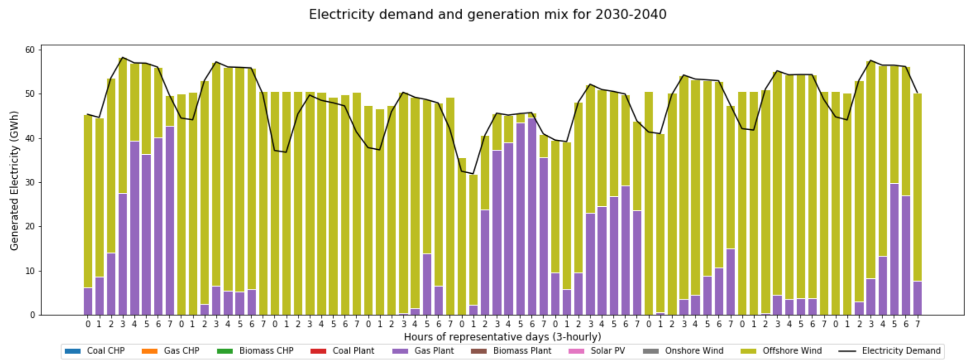

Figure A.28: Scenario-90% - electricity generation mix for 2030 and 2040

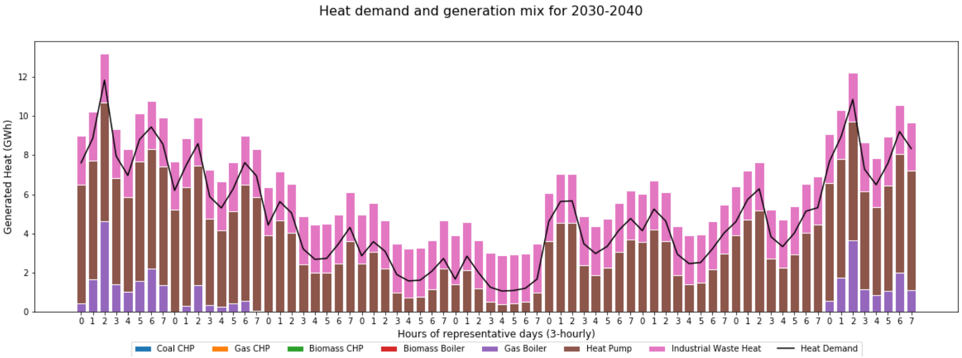

Figure A.29: Scenario-90% - heat generation mix for 2030 and 2040

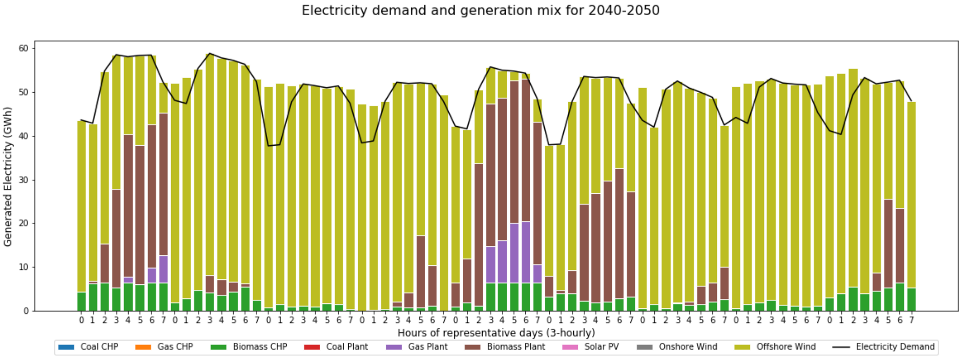

Figure A.30: Scenario-90% - electricity generation mix for 2040 and 2050

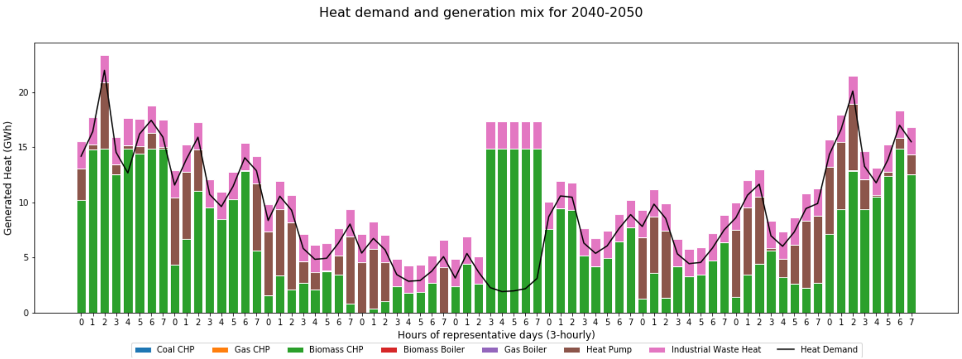

Figure A.31: Scenario-90% - heat generation mix for 2040 and 2050

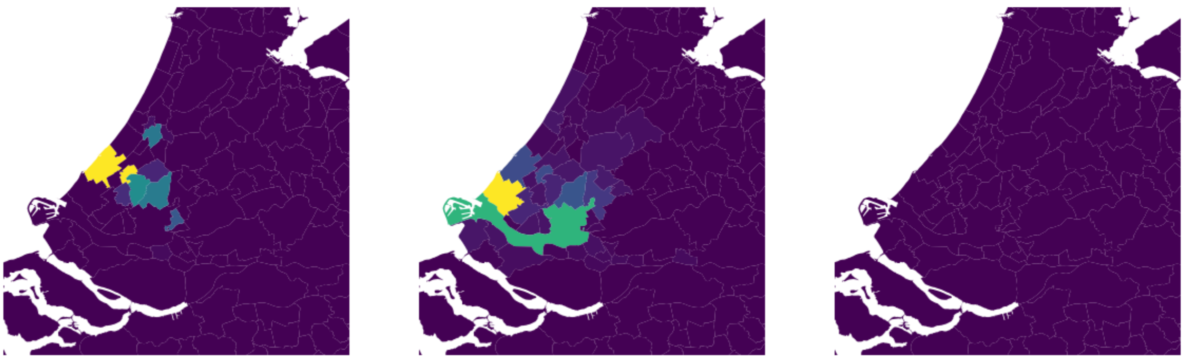

Figure A.32: Scenario-90% - additional capacity installments of gas boilers in each municipality (left, 2020; middle, 2030; right, 2040)

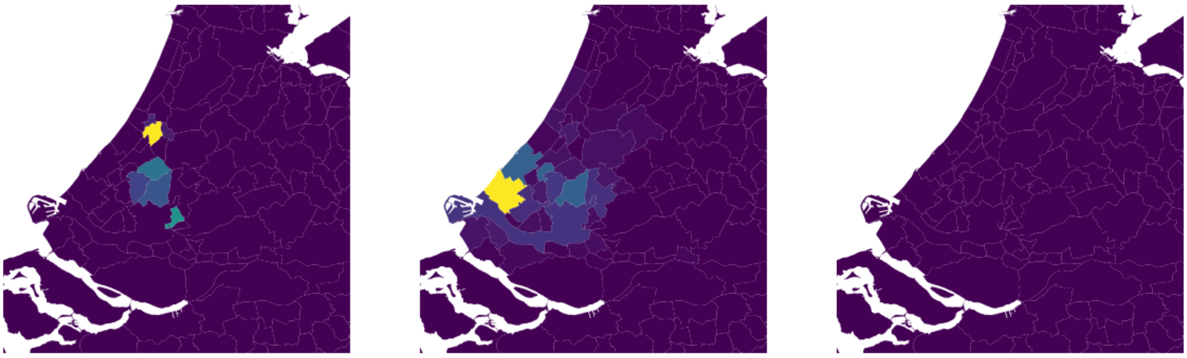

Figure A.33: Scenario-90% - additional capacity installments of heat pumps in each municipality (left, 2020; middle, 2030; right, 2040)

Figure A.34: Scenario-90% - additional capacity installments of biomass CHP's in each municipality (left, 2020; middle, 2030; right, 2040)

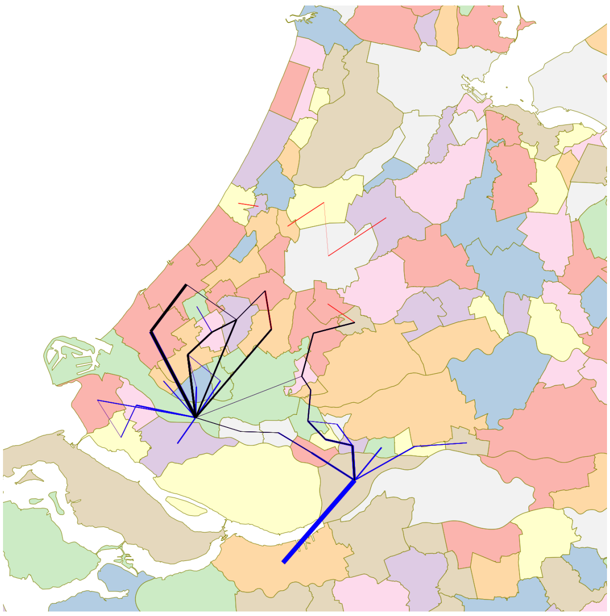

Figure A.35: Scenario-90% - expansion of pipeline networks over the years (black, 2020; blue, 2030; red, 2040)

A.4. Scenario-80% - heat pump analysis - remaining figures

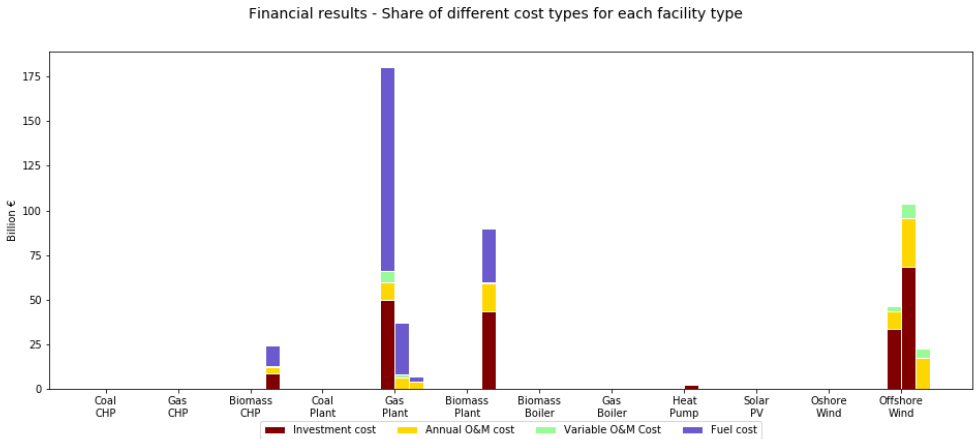

Figure A.36: Scenario-80% - cost values for each facility type

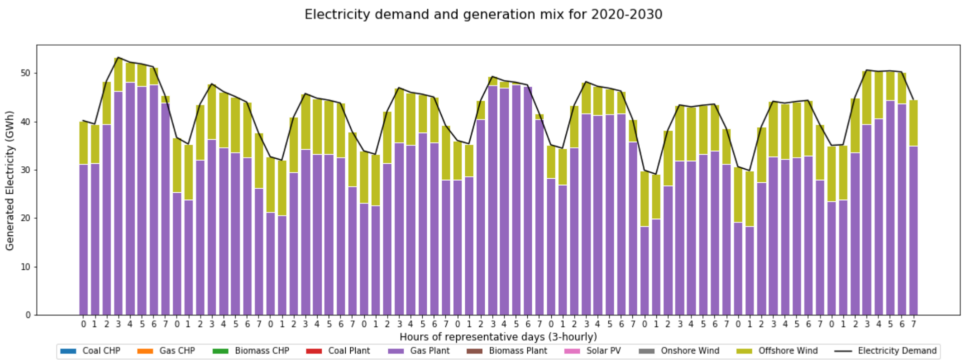

Figure A.37: Scenario-80% - electricity generation mix for 2020 and 2030

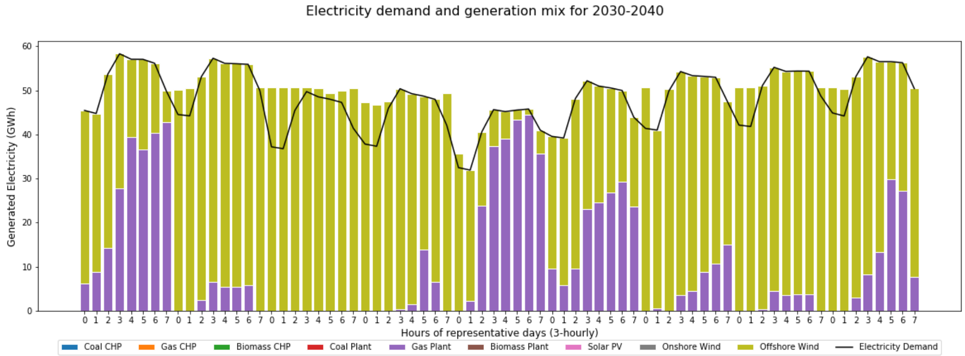

Figure A.38: Scenario-80% - electricity generation mix for 2030 and 2040

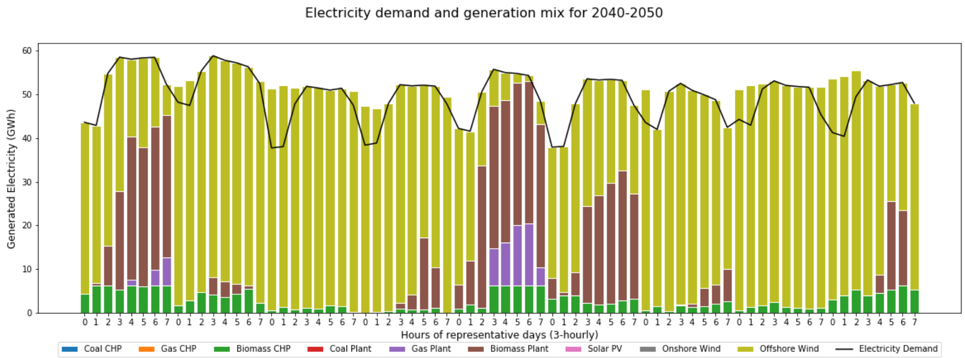

Figure A.39: Scenario-80% - electricity generation mix for 2040 and 2050

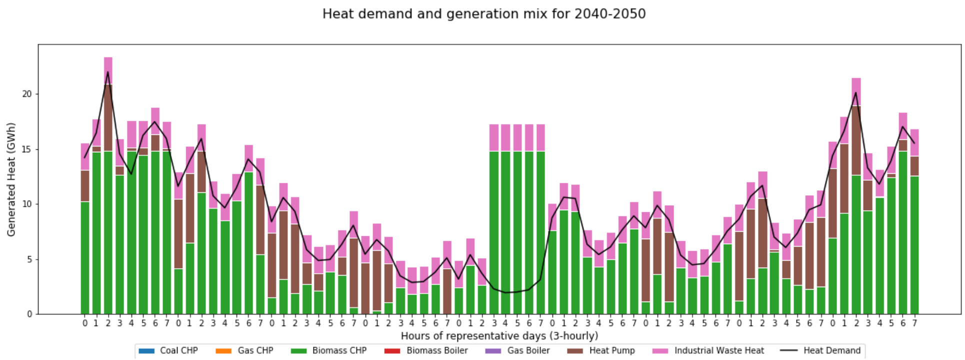

Figure A.40: Scenario-80% - heat generation mix for 2040 and 2050

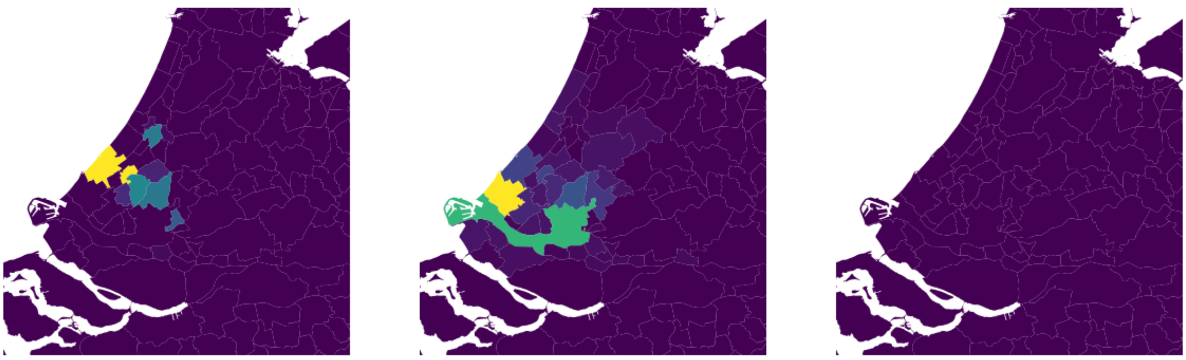

Figure A.41: Scenario-80% - additional capacity installments of gas boilers in each municipality (left, 2020; middle, 2030; right, 2040)

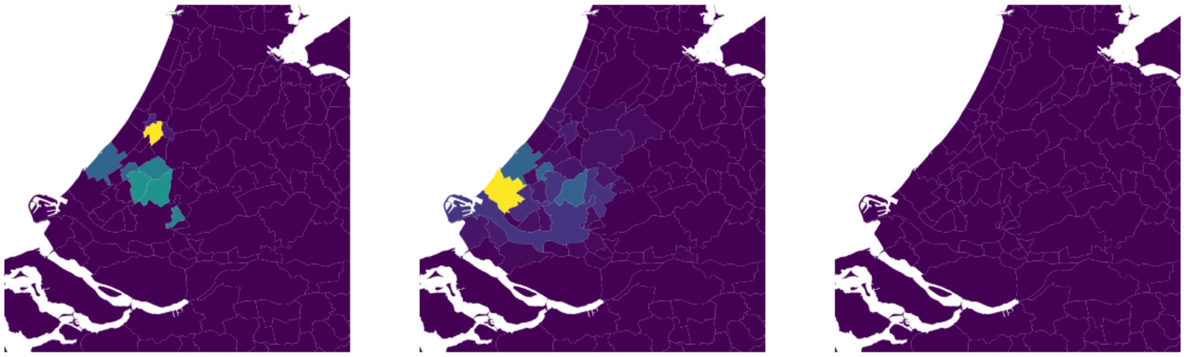

Figure A.42: Scenario-80% - additional capacity installments of heat pumps in each municipality (left, 2020; middle, 2030; right, 2040)

Figure A.43: Scenario-80% - additional capacity installments of biomass CHP's in each municipality (left, 2020; middle, 2030; right, 2040)

A.5. Pipeline investment cost scenarios - generation mix of heat energy

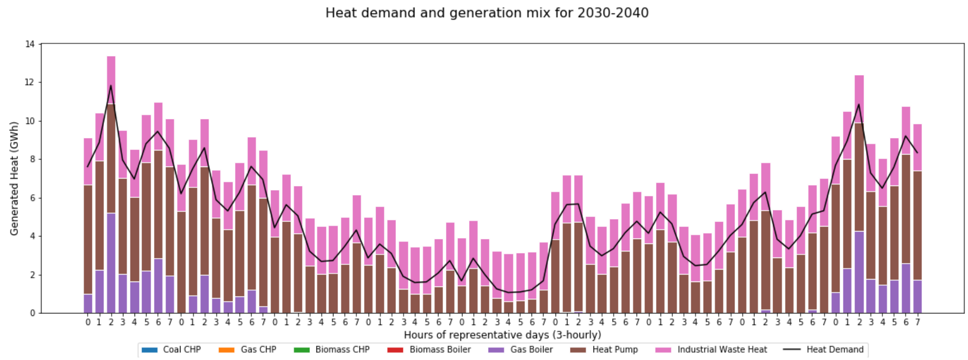

Figure A.44: Scenario150% - Generation mix of heat energy in 2030-2040

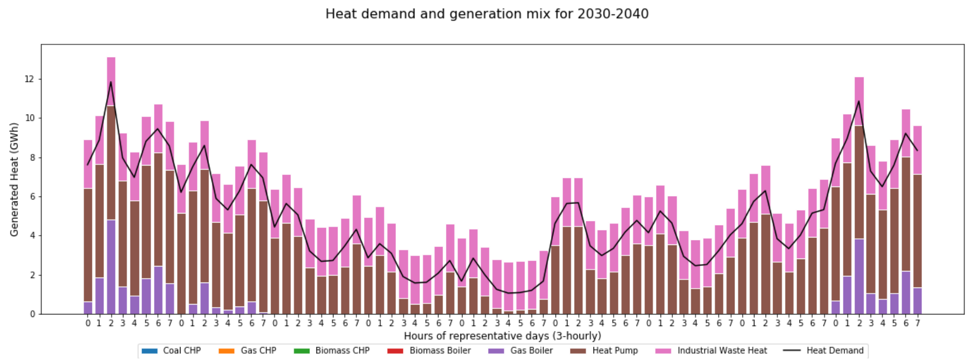

Figure A.45: Scenario50% - Generation mix of heat energy in 2030-2040

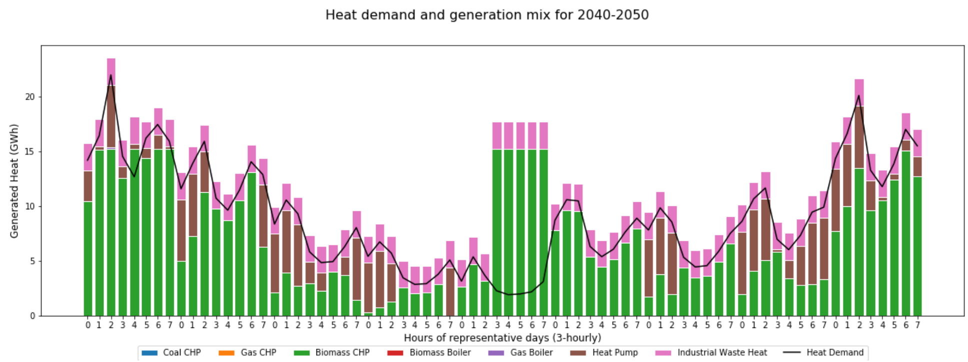

Figure A.46: Scenario150% - Generation mix of heat energy in 2040-2050

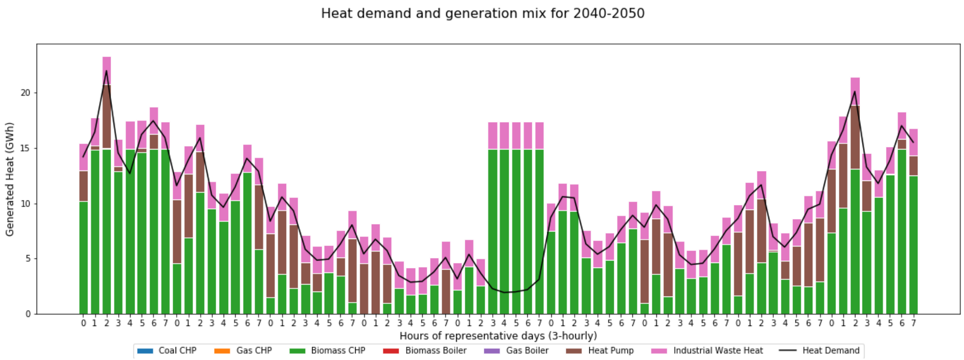

Figure A.47: Scenario50% - Generation mix of heat energy in 2040-2050

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Appendix C

Table A.1: Collected techno-economic parameters

Year	ValueType	Coal CHP	Gas CHP	Biomass CHP	Coal Plant	Gas Plant	Biomass Plant	Biomass Boiler	Gas Boiler	Heat Pump	Solar PV	Onshore	Offshore
2020	Electric Efficiency (%)	0.243	0.411	0.252	0.462	0.587	0.367	0.000	0.000	0.000	1.000	1.000	1.000
2020	Thermal Efficiency (%)	0.610	0.357	0.603	0.000	0.000	0.000	1.010	0.930	2.550	0.000	0.000	0.000
2020	Technical lifetime (years)	43.333	27.500	31.000	38.571	26.429	31.000	18.333	28.333	20.000	26.429	23.333	23.333
2020	Construction time (years)	2.333	2.000	3.417	4.583	2.000	3.250	0.750	0.750	0.750	0.750	1.250	2.250
2020	Nominal investment (€ / MW)	2494490.000	1022570.000	2757774.000	1596426.961	827088.889	2621000.000	632552.333	85933.333	652666.667	1839616.667	1271492.500	2345118.750
2020	Fixed O&M (€ / MW / year)	55100.000	38720.000	117350.000	35770.500	20425.000	111001.818	16538.500	3413.333	6356.667	22427.756	33722.662	85351.390
2020	Variable O&M (€ / MWh)	0.000	5.820	3.900	2.005	2.220	2.200	5.400	0.000	0.000	8.500	3.250	4.250
2030	Electric Efficiency (%)	0.250	0.415	0.256	0.471	0.592	0.380	0.000	0.000	0.000	1.000	1.000	1.000
2030	Thermal Efficiency (%)	0.590	0.353	0.597	0.000	0.000	0.000	1.010	0.930	2.583	0.000	0.000	0.000
2030	Technical lifetime (years)	43.333	27.500	31.000	38.571	26.429	31.000	18.333	28.333	20.000	26.429	24.167	24.167
2030	Construction time (years)	2.333	2.000	3.417	4.583	2.000	3.250	0.750	0.750	0.750	0.750	1.250	2.250
2030	Nominal investment (€ / MW)	2230433.333	1002264.000	2734340.000	1571517.598	816271.111	2569166.667	632552.333	85933.333	634333.333	1603616.667	1237167.500	2168493.750
2030	Fixed O&M (€ / MW / year)	55100.000	38720.000	117350.000	35770.500	20425.000	111001.818	16538.500	3413.333	6356.667	21520.256	33199.805	81817.104
2030	Variable O&M (€ / MWh)	0.000	5.784	3.900	2.005	2.220	2.200	5.400	0.000	0.000	4.750	3.000	4.000
2040	Electric Efficiency (%)	0.250	0.416	0.256	0.473	0.593	0.380	0.000	0.000	0.000	1.000	1.000	1.000
2040	Thermal Efficiency (%)	0.590	0.353	0.597	0.000	0.000	0.000	1.010	0.930	2.583	0.000	0.000	0.000
2040	Technical lifetime (years)	43.333	27.500	31.000	38.571	26.429	31.000	18.333	28.333	20.000	26.429	24.167	24.167
2040	Construction time (years)	2.333	2.000	3.417	4.583	2.000	3.250	0.750	0.750	0.750	0.750	1.250	2.250
2040	Nominal investment (€ / MW)	2119766.667	996984.000	2733140.000	1564850.931	814715.556	2568166.667	632552.333	85933.333	634333.333	1516283.333	1219842.500	2056243.750
2040	Fixed O&M (€ / MW / year)	55100.000	38720.000	117350.000	35770.500	20425.000	111001.818	16538.500	3413.333	6356.667	21362.756	33148.377	80125.676
2040	Variable O&M (€ / MWh)	0.000	5.748	3.900	2.005	2.220	2.200	5.400	0.000	0.000	4.750	3.000	4.000
2050	Electric Efficiency (%)	0.250	0.417	0.256	0.487	0.601	0.383	0.000	0.000	0.000	1.000	1.000	1.000
2050	Thermal Efficiency (%)	0.590	0.353	0.597	0.000	0.000	0.000	1.010	0.930	2.650	0.000	0.000	0.000
2050	Technical lifetime (years)	43.333	27.500	31.000	38.571	26.429	31.000	18.333	28.333	20.000	26.429	25.000	25.000
2050	Construction time (years)	2.333	2.000	3.417	4.583	2.000	3.250	0.750	0.750	0.750	0.750	1.250	2.250
2050	Nominal investment (€ / MW)	2051433.333	991704.000	2731540.000	1496573.154	795786.667	2467121.667	632552.333	85933.333	617666.667	1094243.333	1159506.250	1834481.250
2050	Fixed O&M (€ / MW / year)	55100.000	38720.000	117350.000	34634.136	19970.456	107183.636	16538.500	3413.333	6356.667	17000.710	31538.507	74797.883
2050	Variable O&M (€ / MWh)	0.000	5.712	3.900	2.005	2.220	2.200	5.400	0.000	0.000	3.250	3.000	3.750

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Appendix D

A.1. Sensitivity analysis results for changing investment costs

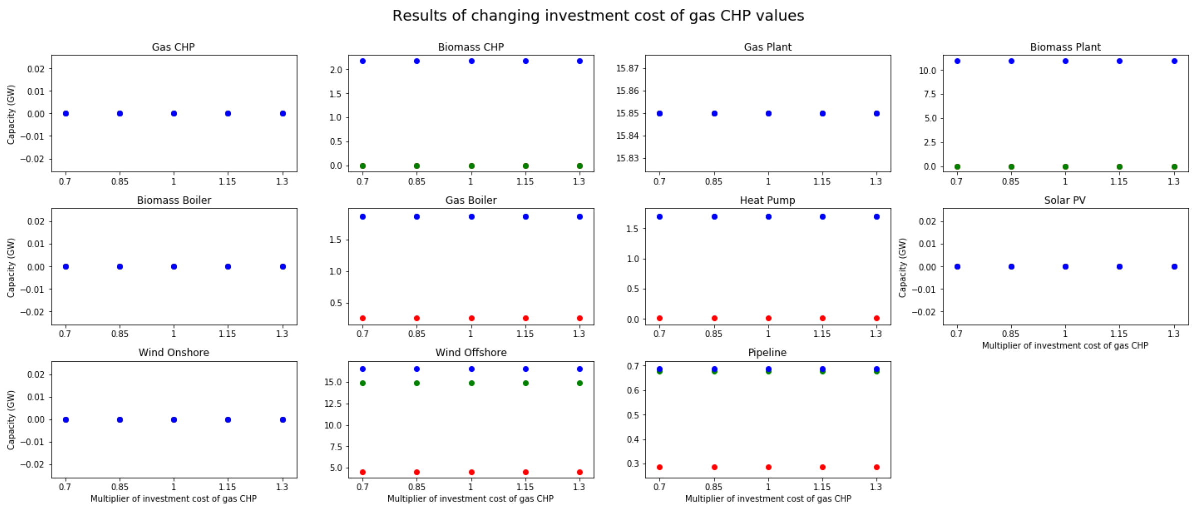

Figure A.1: Sensitivity analysis for investment cost of gas CHPs (red, 2020; green, 2030; blue, 2040)

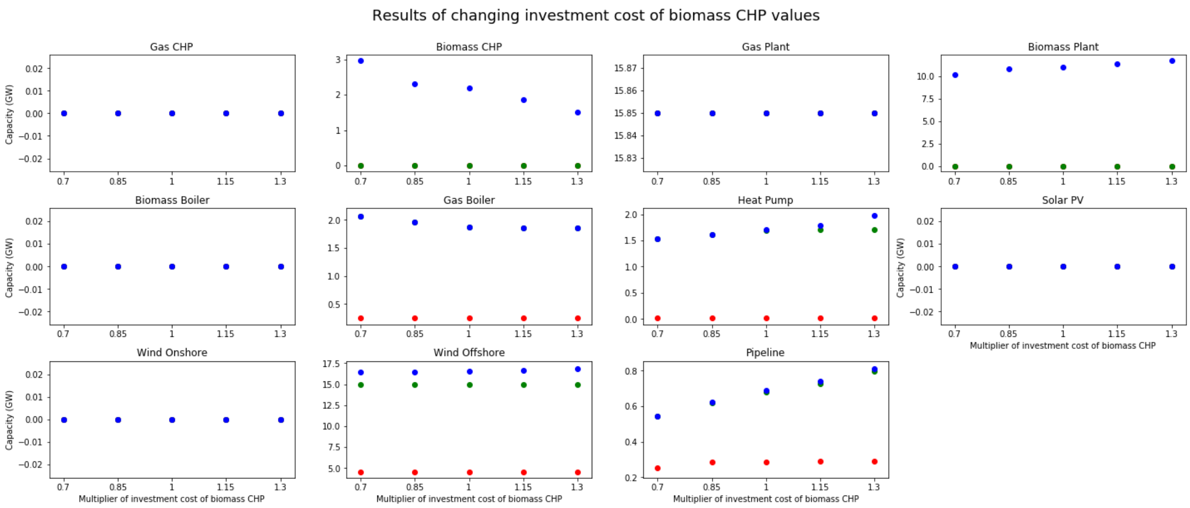

Figure A.2: Sensitivity analysis for investment cost of biomass CHPs (red, 2020; green, 2030; blue, 2040)

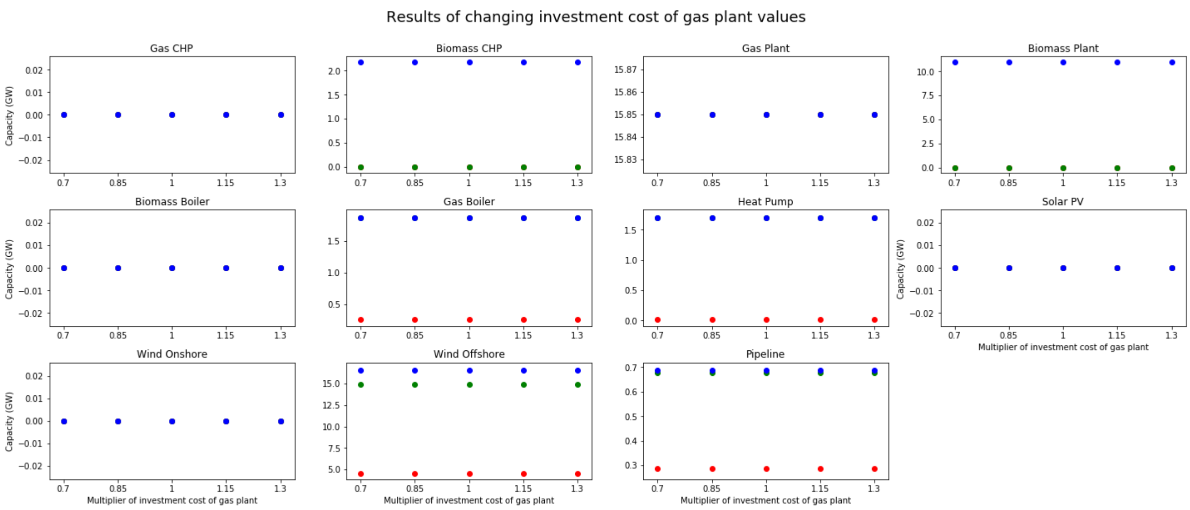

Figure A.3: Sensitivity analysis for investment cost of gas plants (red, 2020; green, 2030; blue, 2040)

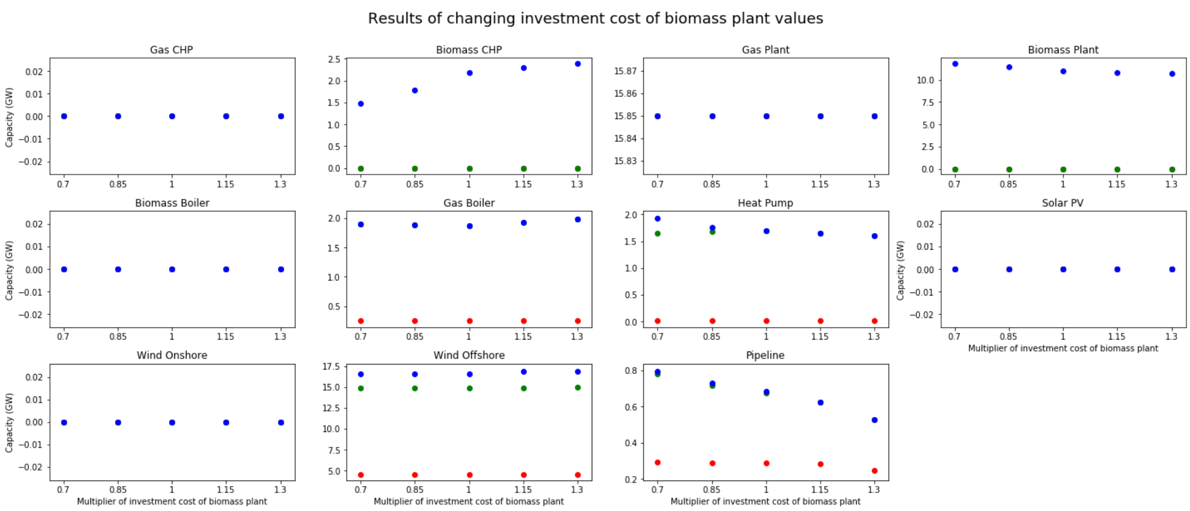

Figure A.4: Sensitivity analysis for investment cost of biomass plants (red, 2020; green, 2030; blue, 2040)

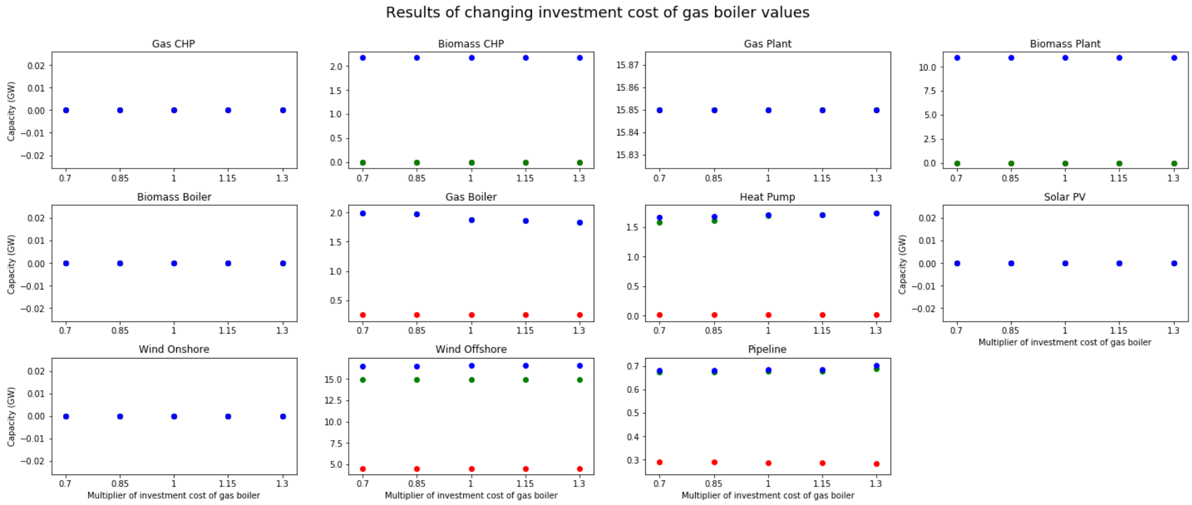

Figure A.5: Sensitivity analysis for investment cost of gas boilers (red, 2020; green, 2030; blue, 2040)

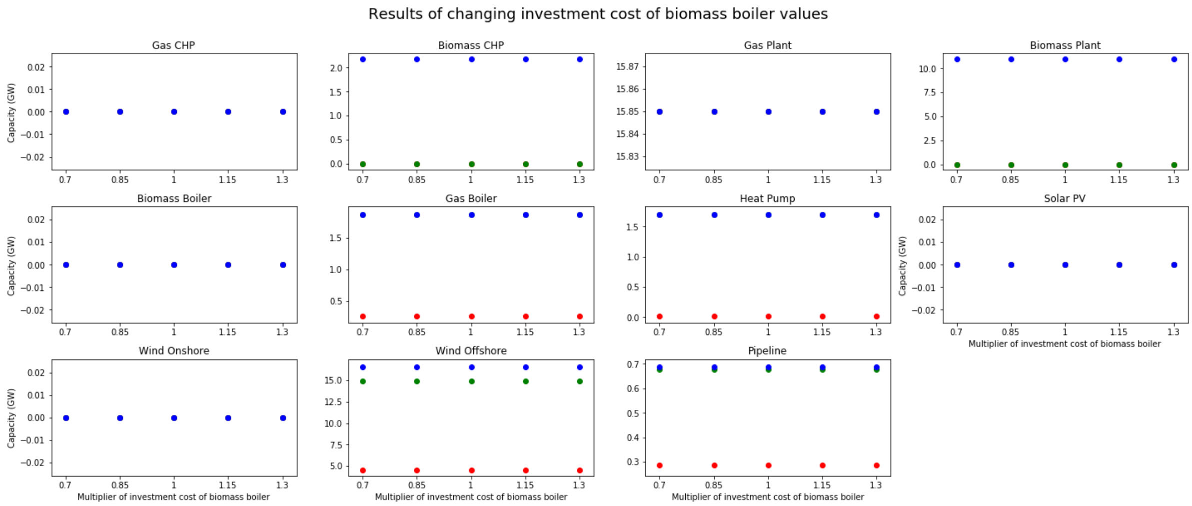

Figure A.6: Sensitivity analysis for investment cost of biomass boilers (red, 2020; green, 2030; blue, 2040)

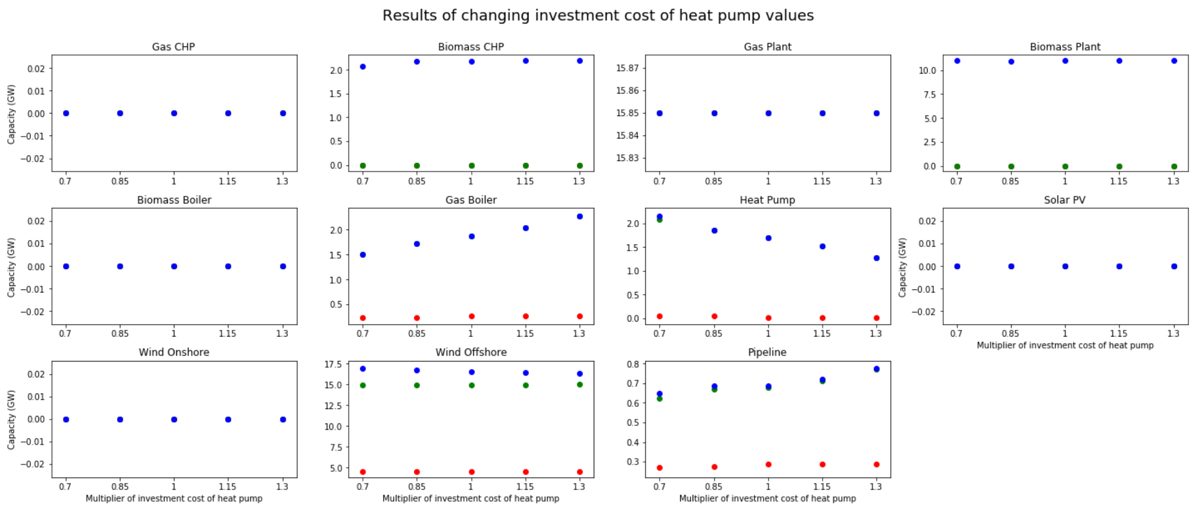

Figure A.7: Sensitivity analysis for investment cost of heat pumps (red, 2020; green, 2030; blue, 2040)

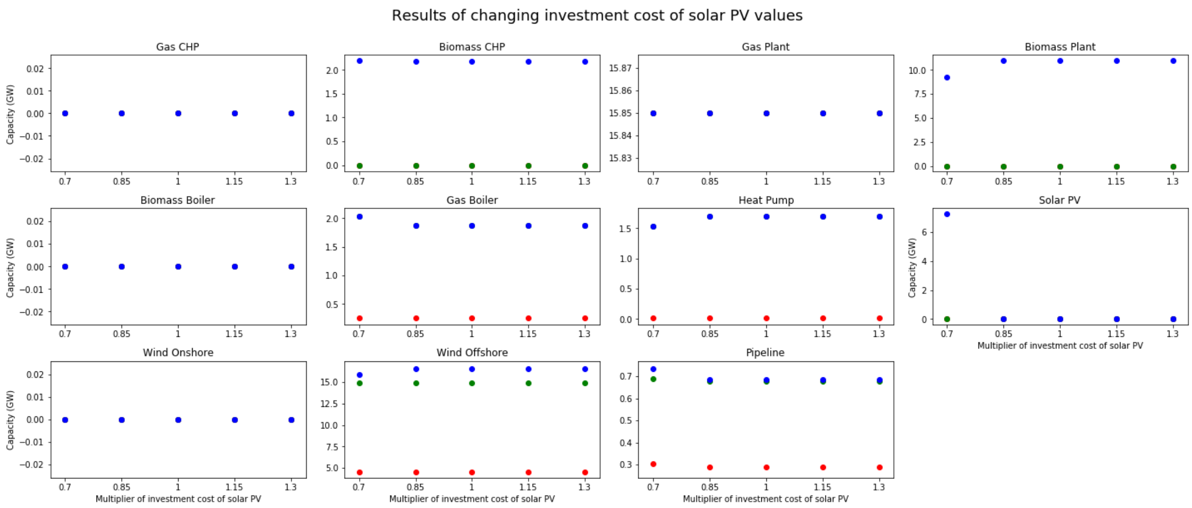

Figure A.8: Sensitivity analysis for investment cost of solar PV installations (red, 2020; green, 2030; blue, 2040)

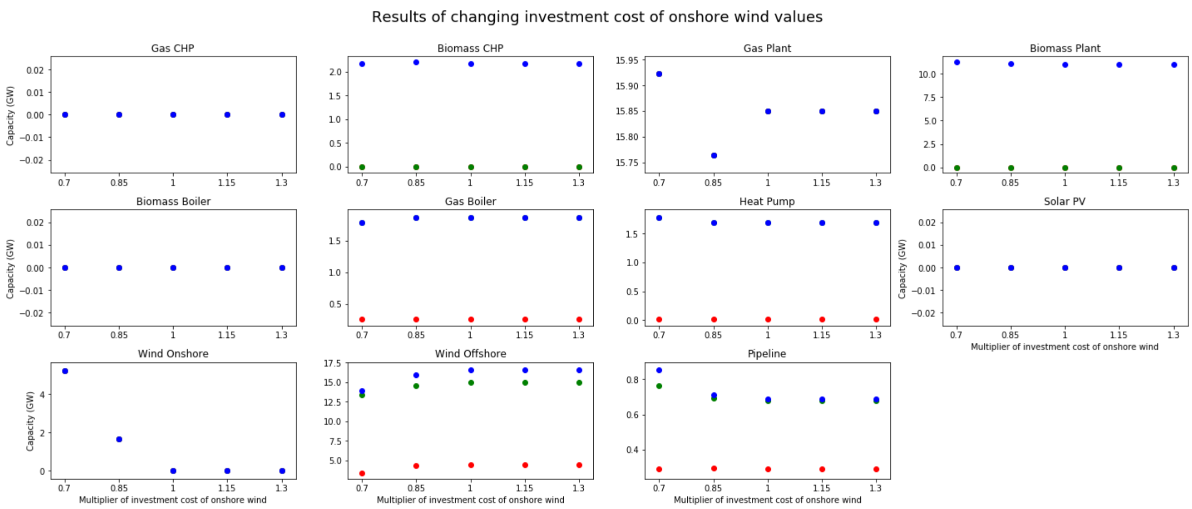

Figure A.9: Sensitivity analysis for investment cost of onshore installations (red, 2020; green, 2030; blue, 2040)

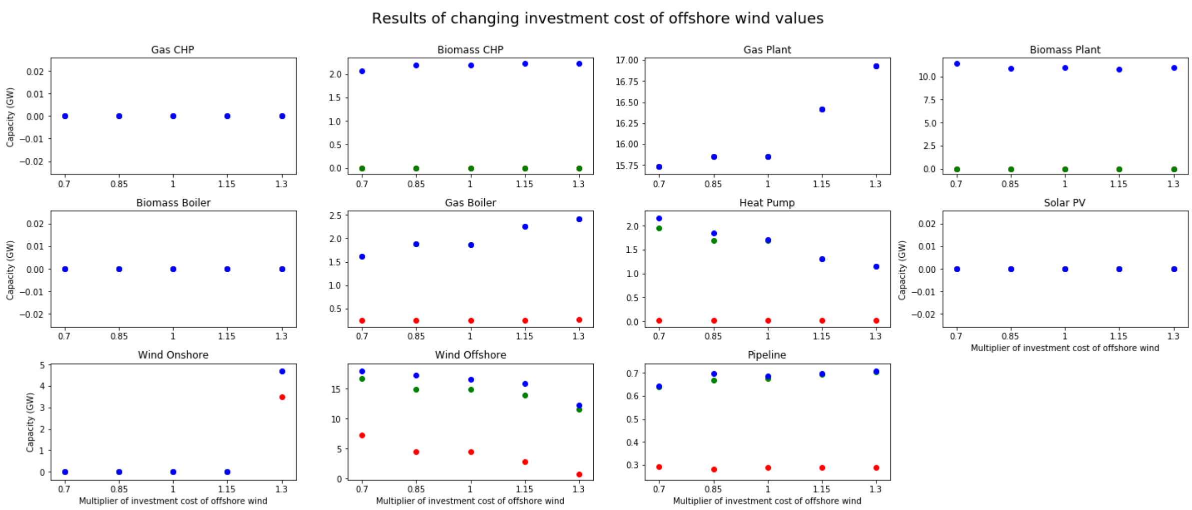

Figure A.10: Sensitivity analysis for investment cost of offshore installations (red, 2020; green, 2030; blue, 2040)

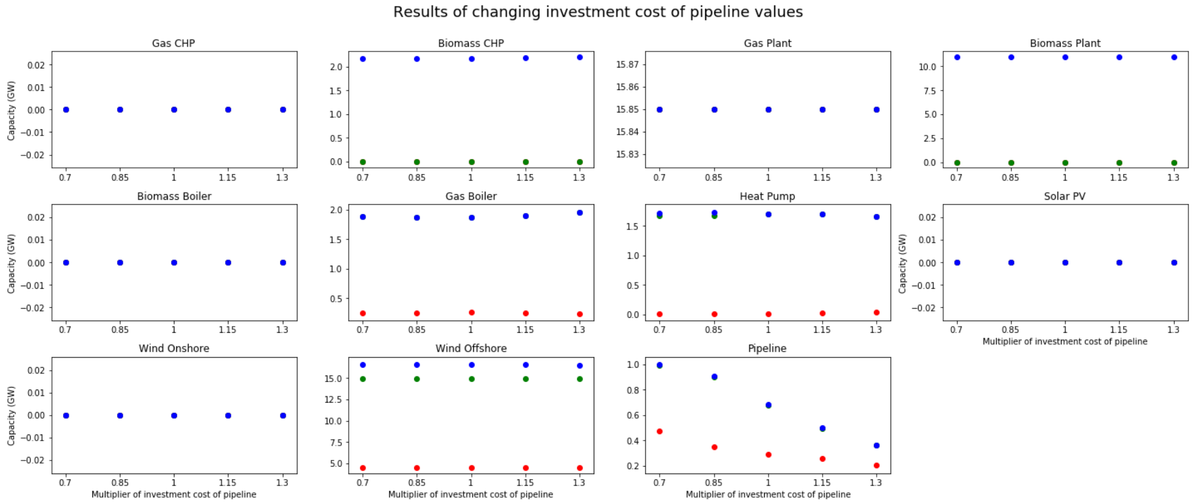

Figure A.11: Sensitivity analysis for investment cost of pipeline installations (red, 2020; green, 2030; blue, 2040)

A.2. Sensitivity analysis results for changing annual O&M costs

Figure A.12: Sensitivity analysis for annual O&M cost of gas CHPs (red, 2020; green, 2030; blue, 2040)

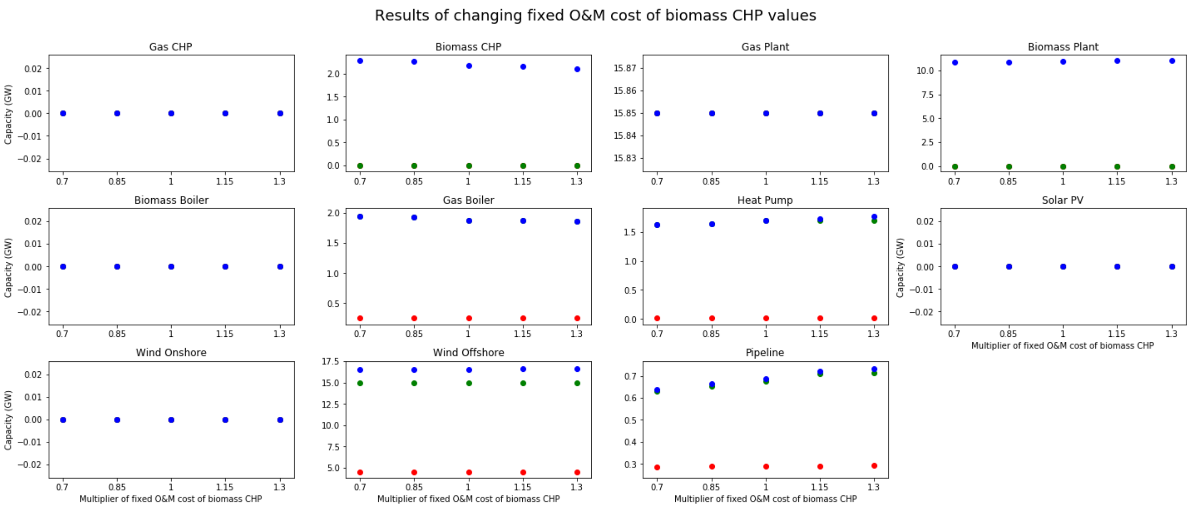

Figure A.13: Sensitivity analysis for annual O&M cost of biomass CHPs (red, 2020; green, 2030; blue, 2040)

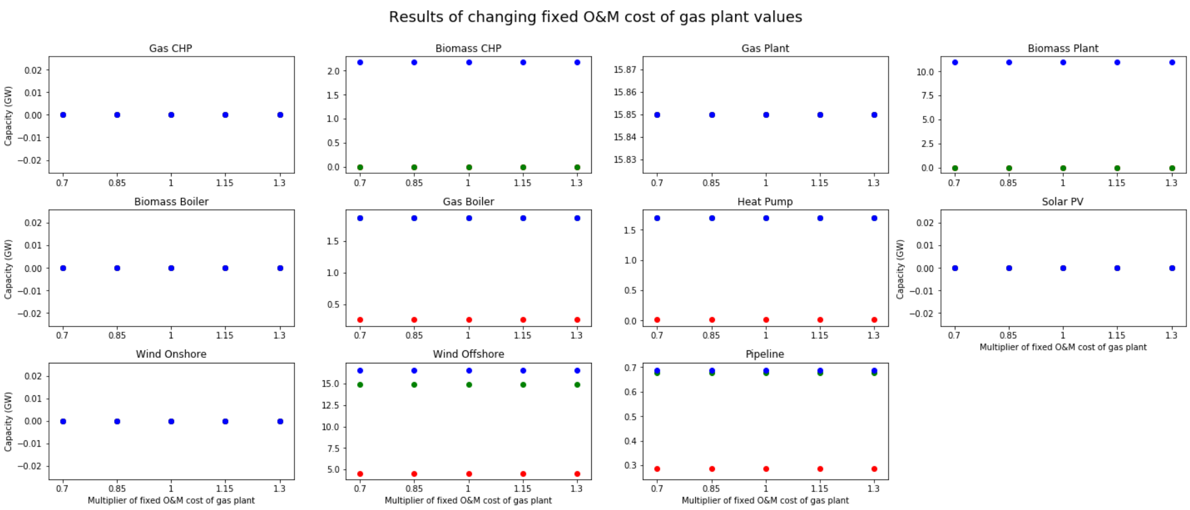

Figure A.14: Sensitivity analysis for annual O&M cost of gas plants (red, 2020; green, 2030; blue, 2040)

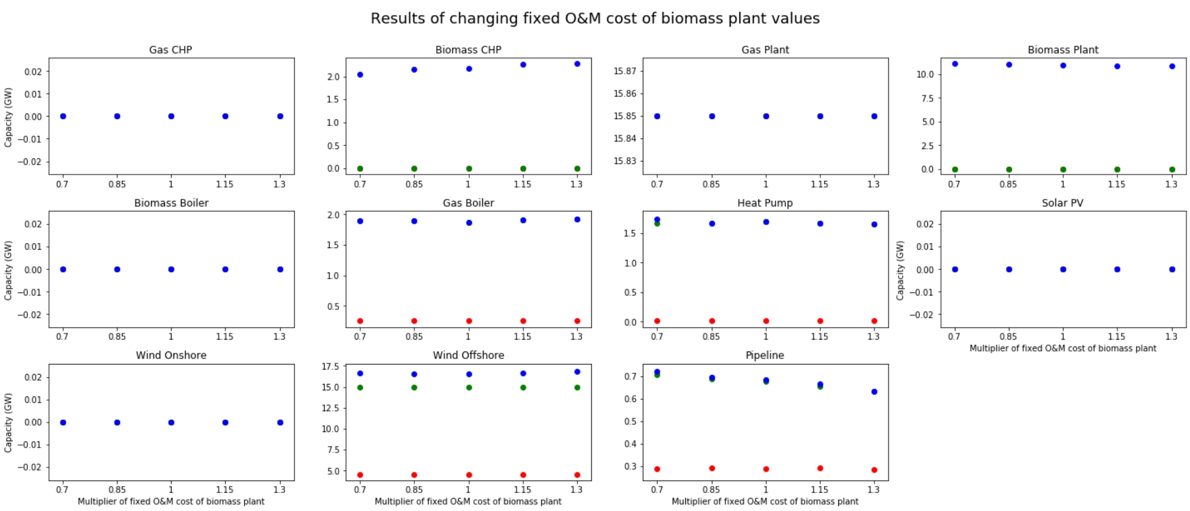

Figure A.15: Sensitivity analysis for annual O&M cost of biomass plants (red, 2020; green, 2030; blue, 2040)

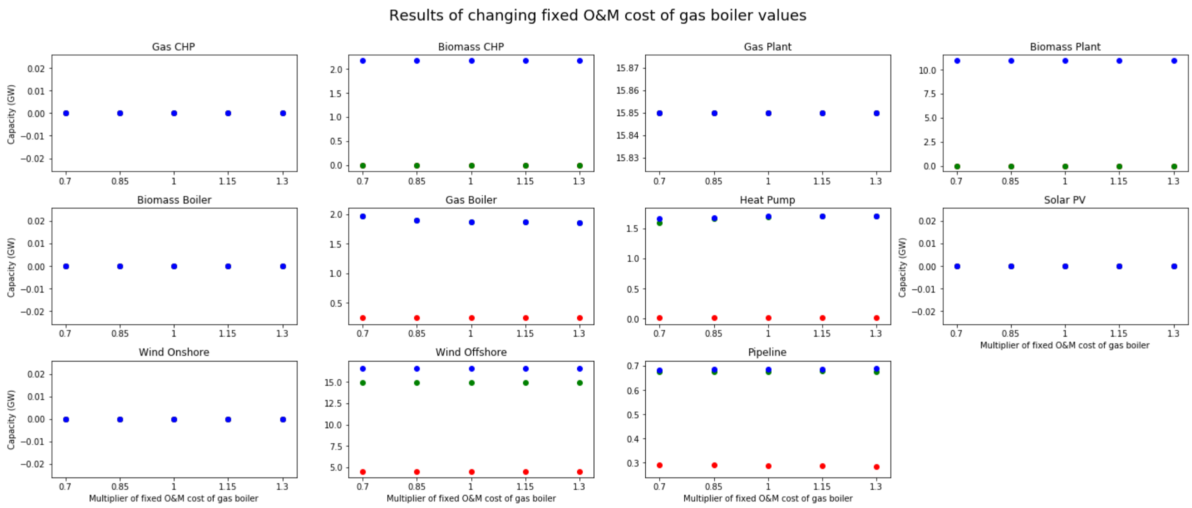

Figure A.16: Sensitivity analysis for annual O&M cost of gas boilers (red, 2020; green, 2030; blue, 2040)

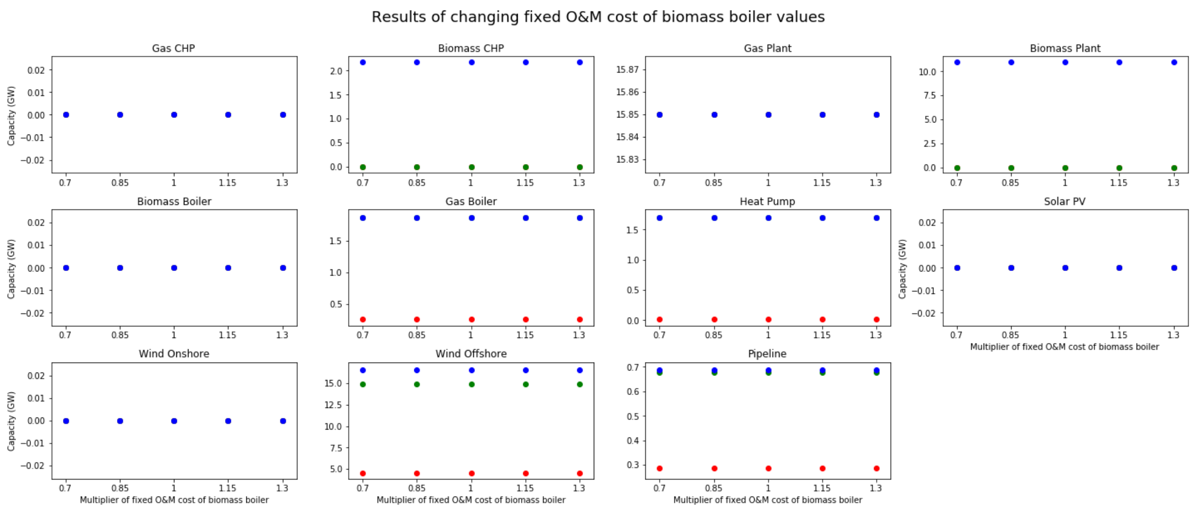

Figure A.17: Sensitivity analysis for annual O&M cost of biomass boilers (red, 2020; green, 2030; blue, 2040)

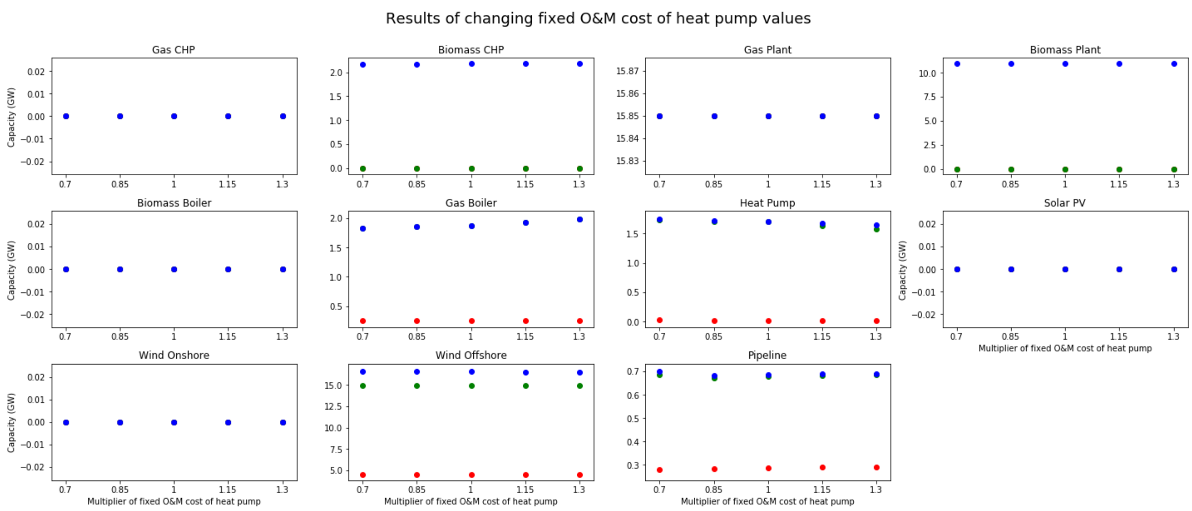

Figure A.18: Sensitivity analysis for annual O&M cost of heat pumps (red, 2020; green, 2030; blue, 2040)

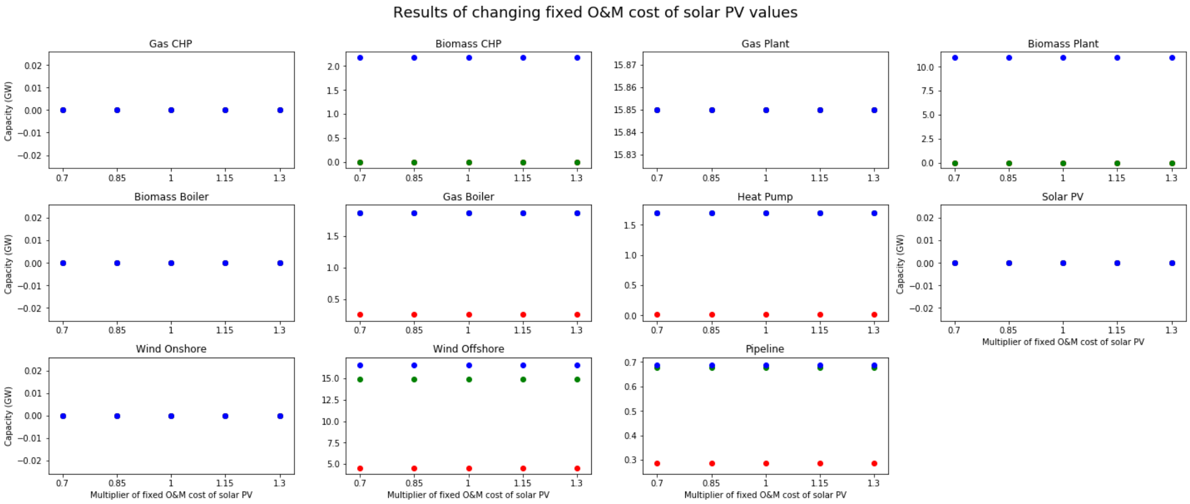

Figure A.19: Sensitivity analysis for annual O&M cost of solar PV installations (red, 2020; green, 2030; blue, 2040)

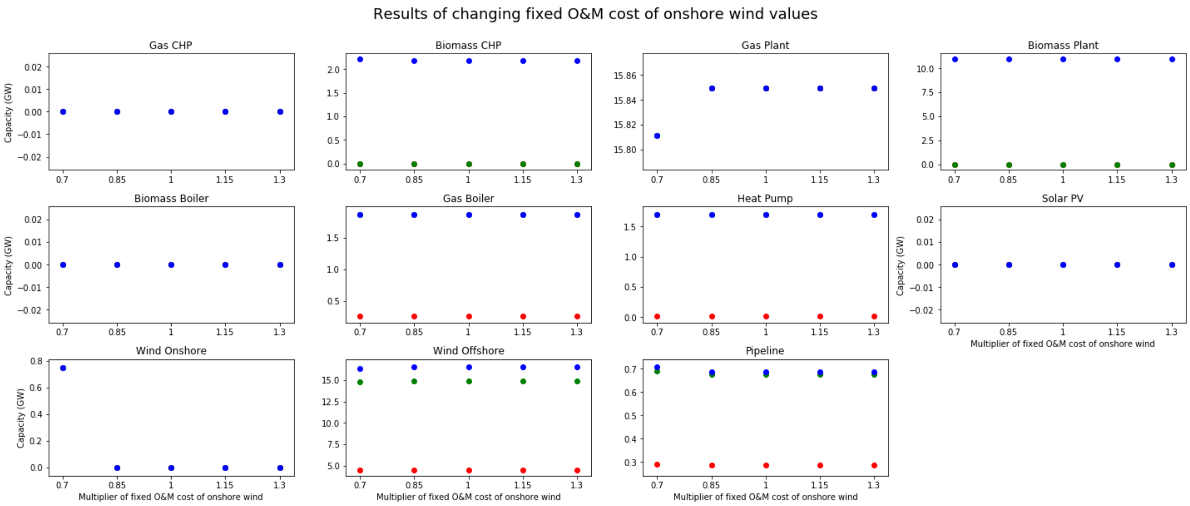

Figure A.20: Sensitivity analysis for annual O&M cost of onshore installations (red, 2020; green, 2030; blue, 2040)

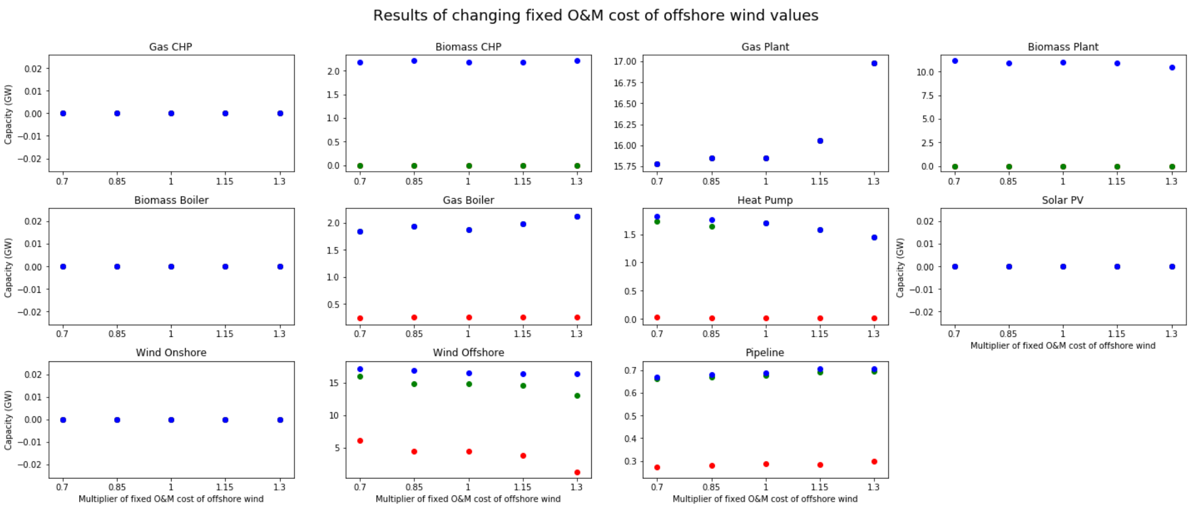

Figure A.21: Sensitivity analysis for annual O&M cost of offshore installations (red, 2020; green, 2030; blue, 2040)

A.3. Sensitivity analysis results for changing heat loss values

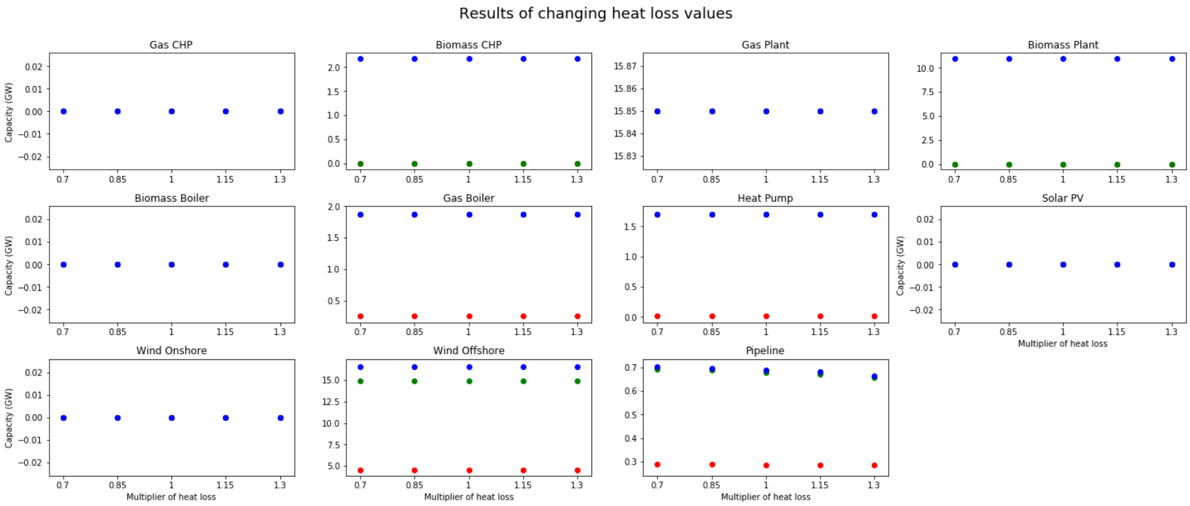

Figure A.22: Sensitivity analysis for heat loss values (red, 2020; green, 2030; blue, 2040)

A

Appendix E

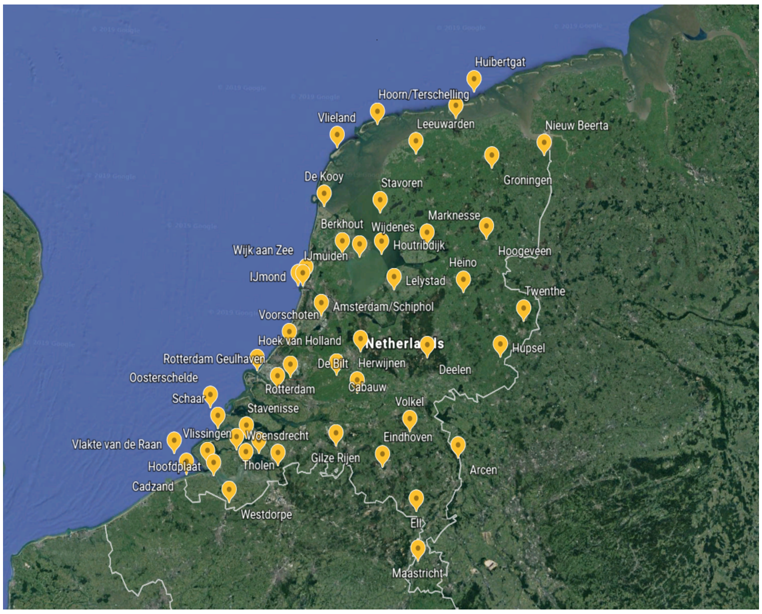

Figure A.1: Weather stations in the Netherlands which provide with publicly accessible data

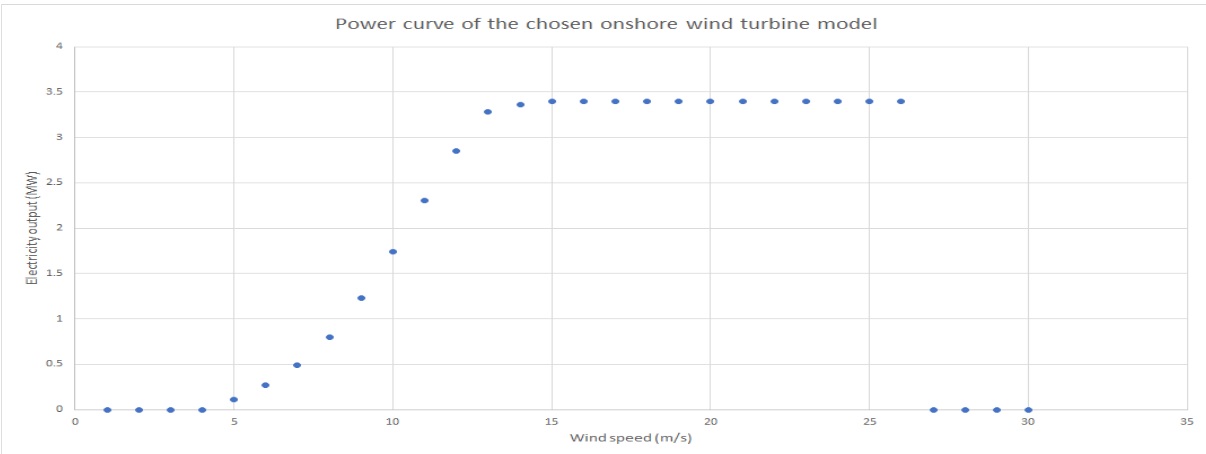

Figure A.2: Power curve of the chosen onshore wind turbine model

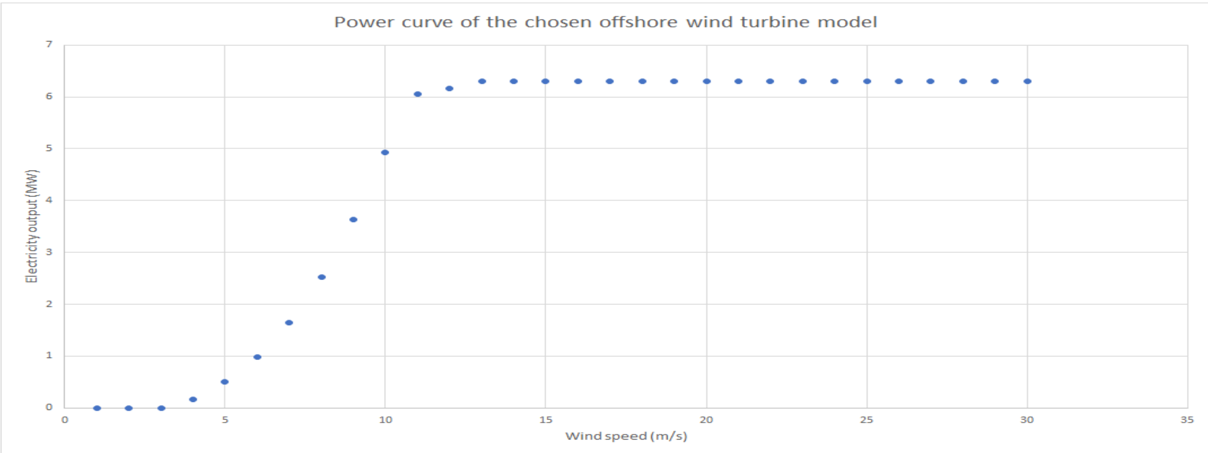

Figure A.3: Power curve of the chosen offshore wind turbine model