Optimisation of an integrated energy system consisting of a power grid and carbon neutral heat grid

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Challenge the future

Optimisation of an integrated energy system consisting of a power grid and carbon neutral heat grid

by

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Executive summary

Introduction

The global commitment to reducing greenhouse gas emissions, underlined by the Paris agreement, has led to significant challenges in the management of energy infrastructure. Due to the transition to sustainable energy sources large scale electrification is increasing the pressure on the existing power grid. In this thesis, the need for energy system integration is addressed through the combined optimisation of a power grid and a carbon-neutral heat grid. The most cost-effective solution to satisfy the energy demands within the Drechtsteden region will be investigated.

Research questions

The primary research question of this thesis is: *How can the optimisation of an integrated energy system, consisting of a power grid and a carbon-neutral heat grid, satisfy the demand for heat at minimal cost?*

The research is further subdivided to address this overarching question into four sub-questions:

- Can different energy grids operate independently to meet energy demands, or is their coordination necessary?
- What role can waste heat play as a heat source in a heat grid?
- How does reinforcing the power grid compare to expanding the heat grid in terms of cost-effectiveness for meeting the 2030 heat demand?
- How does variation in the technology cost influence the decisions in overall investments?

Methodology

The research was done using a python model build using the Python for Power System Analysis (PyPSA) library. It is an open-source tool designed for simulating and optimising a power grid with the possibility to integrate extra energy carriers with their corresponding components. A case study based on the Drechtsteden region is used to apply the model. The existing power grid and heat grid are incorporated into the model to simulate three scenarios.

- **Scenario 1: Power grid expansion** - In this scenario, only the existing power grid infrastructure will be reinforced and no additional P2H sources or heat grid expansion takes place.
- **Scenario 2: Heat grid expansion** - here, the power grid infrastructure remains unchanged and only P2H sources and heat grid expansion is allowed.
- **Scenario 3: No restrictions** - The model optimizes solely based on cost-effectiveness without any restrictions, so both the power and heat grid are allowed to expand as well as building new P2h sources.

In addition to these 3 scenarios, a sensitivity analysis is performed to asses how variations in capital expenditure (CAPEX) cost impacts the optimisation results.

Results

The proposed framework for the model was applied to the Drechtsteden region to analyse the three defined scenarios as well as the sensitivity analysis. The analysis results are as follows:

study findings reveal the cost implications and operational outcomes. Scenario 1 identifies the cost associated with reinforcing the power grid infrastructure to meet the increase in heat demand in the Drechtsteden region while maintaining without expanding the current heat grid. Scenario 2 uses the current power grid to satisfy as much of the additional heat demand as possible and expands the heat grid with extra P2H sources for the remaining heat demand. The total cost of scenario 2 is twice that of scenario 1.

In scenario 3, where no restrictions on the model are enforced, a pure power grid expansion is chosen. Since the heat grid expansion adds significant costs, it is not used.

The sensitivity analysis further highlights the difference in cost of power grid expansion in comparison to the heat grid expansion. Variations in the CAPEX cost of the main components used in the model can cause the model for a small heat grid expansion but the main solution to satisfy the heat demand remains reinforcing the power grid.

Conclusion and recommendations

From the results can be concluded that the most cost-effective solution to satisfy future heat demand is to electrify heat demand and reinforce the power grid infrastructure, assuming no significant geopolitical events and material shortages. If the cost for adding new users to the heat grid decreases (such as in densely populated areas or through government subsidies) then part of the heat demand can be fulfilled by the heat grid. This does assumes that an already existing heat grid with heat sources is present.

Future research should include the resources needed for expansion such as time and manpower. These are often the bottleneck in energy infrastructure projects. Through their inclusion a better distribution of resources can take place. Additionally, a optimisation of the model but for the year 2050 instead of 2030 can be performed. By using the optimisations of both years, a better priority of reinforcing current and building new infrastructure can be made. Looking that far ahead will introduce more uncertainties which should be taken into account. Finally, an inclusion of the available physical space for building extra capacity or new components would be useful. Space in cities is often limited and/or expensive and could limit or stop expansion. This could mean that the more expansive solution might be the only possible solution.

Overall, this thesis provides insights into the optimisation of an integrated energy system consisting of a power grid and heat grid to satisfy increasing energy demands in a sustainable way.

Acknowledgements

This thesis marks the end of my master in Electrical Power Engineering. It is the culmination of everything I have learned in my years as a student at the TU Delft. It has not only deepened by passion for sustainability but also given me a better understanding of the challenges we face with the energy transition.

I would like to thank Milos Cvetkovic, for supervising my thesis, giving his honest feedback and providing valuable insights. He was my supervisor for my very first project as a bachelor student here in Delft, so it seems only fitting that he would be the same for my last project. I am also extremely grateful to Christian Doh Dinga, who helped ensure with his incredible knowledge about the subject and the programming that I would have a working model. The weekly meetings always brought me many new insights which were crucial to forming the thesis into what it has become.

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List of Abbreviations

AC Alternating Current

CAPEX Capital Expenditure

CHP Combined Heat and Power

COP Coefficient of Performance

DC Direct Current

DSO Distribution System Operator

HTL High-Pressure Transmission Line

HV High Voltage

LV Low Voltage

MES Multi-Energy System

MIP Mixed Integer Programming

MV Medium Voltage

OPEX Operational Expenditure

P2H Power-to-Heat

PyPSA Python for Power System Analysis

RES Renewable Energy Sources

RTL Regional Transmission Line

TSO Transmission System Operator

V2G Vehicle-to-Grid

WACC Weighted Average Cost of Capital

Contents

1. Introduction

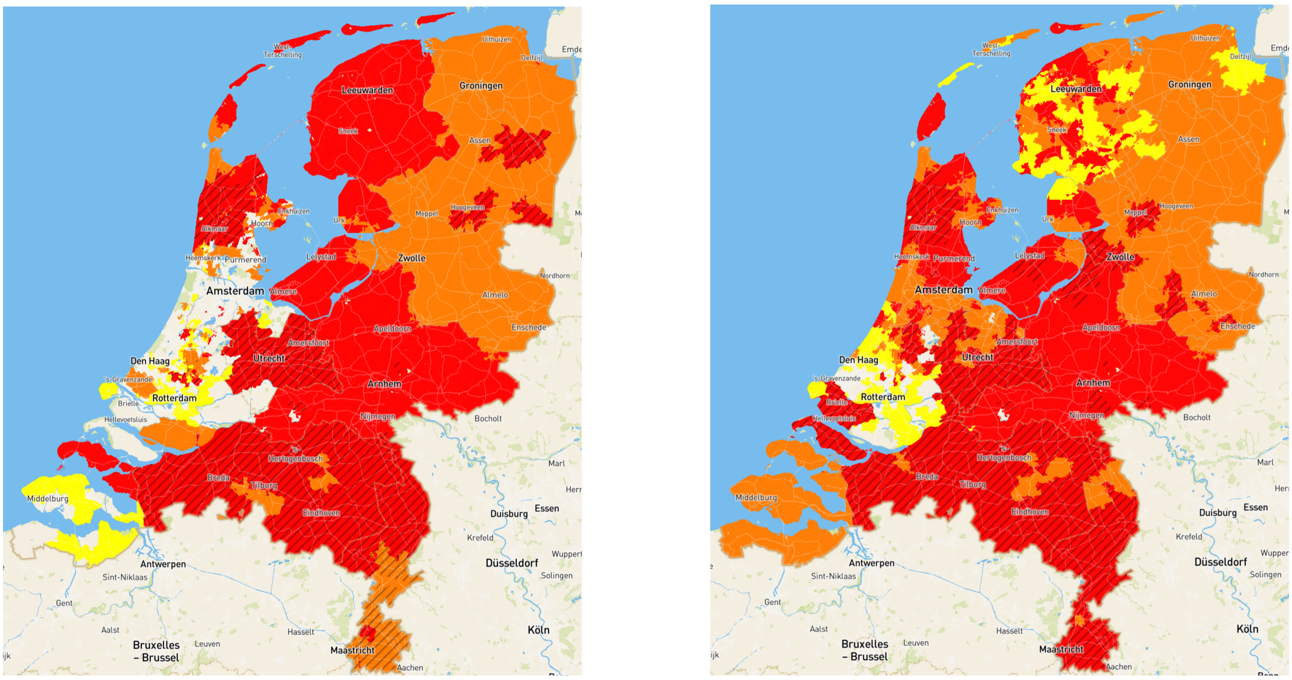
1.1 General Introduction

Since the industrial revolution, the role that machines play in maintaining the current quality of life has steadily been increasing. This was all made possible thanks to fossil fuels, that are still an essential and irreplaceable corner stone of the modern world. But the consequences of the large scale use of fossil fuels can be felt now more than ever. Especially the increasing temperature of the Earth is cause for great concern. To control the increase in temperature, the Paris agreement was made. At the UN climate change conference in Paris (France), 196 Parties accepted this treaty on climate change [1]. The main goal of the treaty is to keep the increase in average global temperature below 2°C. For the EU, this treaty resulted in creating a long-term strategy for the year 2050 with the aim of becoming the world's first climate-neutral continent [2]. Each Member state then had to submit their own national long-term strategy. In the Netherlands this document is called "Long term strategy on climate mitigation" [3].

The main focus for reaching the climate goals is on reducing or changing the current energy usage. The use of fossil fuels in almost every industry and most modes of transportation must strongly diminish, preferably to zero. Energy must increasingly come from more sustainable alternatives or even better, from fully renewable energy sources. The biggest energy carrier of renewable sources is electricity. Thus, a massive electrification of most industries is taking place requiring a huge increase in transport of electrical energy, often over large distances. This long distance transport, such as in between countries or from a power plant to a specific region, is done by a Transmission System Operator (TSO). After transportation to the region, it is then distributed to the end user by the Distribution System Operator (DSO).

The electrification is happening all around and the consequences are indisputable, sometimes even for individual households. Currently, the capacity of most parts of the power grid is already running into its limits and causing congestion, shown very clearly in Figure 1.1. The amount of congestion will keep on increasing if no further action is taken because the electrical power demand will not stop rising. This is why the DSOs came up with a document to lay out a road map with multiple scenarios to continue providing the needed energy to the users and achieve the 2050 sustainability goals.

Blindly building electrical power stations where more capacity is needed, is not an efficient and practical way to invest in the energy infrastructure. Permits, planning procedures and shortage of manpower can quickly add up to a project spanning of multiple years. Prioritisation of the projects has to be properly managed and road maps are a helpful means to assist with this prioritisation.



(a) Supply congestion (b) Demand congestion

Figure 1.1: Congestion maps of the Netherlands as of may 2024. Capacity legend: Red: Full, Orange: temporarily full, Yellow: limited, transparent: available. Shaded areas are where congestion management is being applied to try and mitigate the congestion [4]

Due to the large variability and seasonality of the Renewable Energy Sources (RES), interdependence of the different energy carriers has become very important. If a large surplus of electricity is generated, this surplus is stored for later use when there is a shortage of energy, ideally without any loss. Such integral energy systems are called Multi-Energy Systems (MES). The main idea is that, by using different energy carriers, the demand of energy can be met directly, from storage or through the conversion of one energy form into another. An example is electricity from offshore wind farms. This energy can be converted into hydrogen. Hydrogen can then be used to create electricity, or burned instead of methane, for industrial usage. Electricity can also be converted into heat, either to warm up houses and offices or to create steam which is also needed in a lot of industries such as chemical plants or smelt furnaces. MES are complicated due to the many variables but they are indispensable for creating the energy system of the future since electricity only, as an energy carrier, is simply not enough if the 2050 sustainability goals are to be met. This thesis aims to contribute to modelling and optimising such an integrated energy system.

1.2 Objective

The objective of this thesis is to develop a cost based optimization model of a power grid and a heat grid by investigating the differences between domestic heat pumps and power-to-heat sources in a heat grid. This objective leads to following research question:

1.2.1 Research question

How can optimisation of an integrated energy system, consisting of a power grid and carbon neutral heat grid, satisfy the demand for heat at minimal cost?

To answer this research question, following sub-questions were formulated:

- Can different energy grids work independently to meet the energy demand or will coordination be necessary?
- What role can waste heat play as a heat source in a heat grid?
- How does power grid reinforcement compare to heat grid expansion in cost to fulfill the heat demand in 2030?
- How does variation in technology cost influence the decisions in overall investments?

1.3 Outline

The structure of the thesis is as follows. Chapter 2 the concept of different energy systems working together is introduced. Chapter 3 compares the options that can be used to model expansions of energy systems. Chapter 4 explains how the software chosen for the model works. The case study to which the model is applied is shown in Chapter 5. The results of the model are shown and explained in Chapter 6. In Chapter 7, the sub-questions are answered. To end, a conclusion of the thesis is presented together with recommendations for future work in Chapter 8.

2. Integral Infrastructure

This chapter explains the concept of integral infrastructure. Section 2.1 explains the definition of integral infrastructure. In section 2.2, an overview of the story lines associated with integral infrastructure is given. Section 2.3 describes the power grid structure and Section 2.4 the gas grid structure. Section 2.5 lays out the two possible solutions to satisfy the heat demand. Finally, in Section 2.6 the different types of storage are listed.

2.1 Integral infrastructure in the Netherlands

Integral infrastructure is used to describe a network in which the different components of said infrastructure are interconnected. In the case of an energy system, this translates to networks of multiple interconnected energy carriers, with the ability to move energy between these carriers. The main advantage of such an integrated energy system is the flexibility of energy supply. This flexibility translates to better efficiency since it can select the least expensive energy to meet the demand. The flexibility also increases reliability of the energy system because the network has options to meet the demand. An energy system with an integral infrastructure is often called a Multi-Energy System (MES).

A MES is a very broad term that denotes a system containing multiple energy carriers such as fossil fuels, hydrogen, electricity and heat at the same time. The individual carriers can interact with each other to increase the performance and efficiency and decrease the emissions of the system as a whole. This is also vital for decarbonising the current energy grids. In the Netherlands, the DSOs and TSOs have formed an organization called "Netbeheer Nederland" that further promotes cooperation between the service operators and represents their interests towards government, market players and other stakeholders [5]. With the sustainability goals of 2050 presenting quite a challenge, Netbeheer Nederland called for an integral vision on the Dutch energy infrastructure in 2019. This call sparked the discussion on creating a document about exploring necessary developments needed in the years 2030 to 2050 to meet the goals. The first version of that document, called "Het Energiesysteem van de Toekomst", contains possible scenarios and road maps towards the energy system of the future. This document will be revisited frequently to better reflect the most recent developments. The second version is called Integrale Infrastructuurverkenning 2030-2050 [6] which translates into "Integral infrastructure exploration 2030-2050". This second version is used as a reference for information and data in this thesis.

2.2 Story lines

The document focuses on four possible scenarios for 2050. Each scenario represents a clearly defined and specific system model that corresponds to a possible solution for creating a climate neutral energy grid. The choices made in each scenario differ from each other . They reflect the impact of social reform on the transition of the energy system and how they are interwoven. The 4 scenarios can be summarised as follows:

1. National leadership: On a national scale, the consistency and technologies used for the energy mix are strongly influenced by the Government who makes the choices. This encompasses the used sources as well as the amount of generated energy. To this end, the government makes compulsory policies and regulations and financially supports projects of national importance. The government also promotes the development of new industries and encourages electrification

of existing industries. For energy generation, large-scale national projects, such as wind on sea and flexible nuclear reactors, are used. Hydrogen plays a vital role in balancing the power grid, in the industry where high temperatures are needed and as a raw material.

2. European integration: European countries align their energy policies making use of each other's resources and reduce their dependencies on non-European countries. There is a solid growth of solar and wind energy combined with strong deployment of nuclear power. Countries around the North Sea exploit opportunities for wind energy in cooperation. Industry becomes more sustainable thanks to electrification and the deployment of European biomass and hydrogen as fuel. Carbon Capture and Storage (CCS) is applied on a large scale, including power generation, negative emissions and the production of blue hydrogen. Cities and buildings are made more sustainable per neighbourhood with a strong focus on development of heat grids.

3. Decentralized initiatives: Private business cases of climate neutral techniques are supported. There is a high degree of autonomy. Solar and wind energy on land will experience a large growth. There is limited steering on the transition for energy intensive industry. Therefore, part of that industry will disappear from the Netherlands. Heat will be supplied by a mix of geothermal, heat pumps, Combined Heat and Power (CHP) plants, green hydrogen and green gas.

4. International trade: The Netherlands aims to develop its own economy through full commitment to international global energy and resource chains. The international energy and resource market is fully used. The lowest cost and international free trade plays an important role. Hydrogen and other climate neutral energy carriers are imported from countries where they can be produced relatively cheaply. The Netherlands also becomes a transit country for hydrogen. In the built environment, there is less use of green gas but a lot of hybrid heating through hydrogen. Production of green hydrogen will take place thanks to offshore wind but due to the high energy imports, less production is needed.

From these four scenarios the two most relevant statements are that electrification will happen on a large scale and that heat can be provided from (hybrid) domestic heat pumps or from heat grids using CHP plants, geothermal energy and power-to-heat sources. The most recent version is from 2023 and differs from the plan the most recent government of that same year [7]. This government plan states that heat will only be provided by smaller domestic heat pumps. Since there is a difference in what the government and what the DSOs and TSOs think is best, more research seems needed to make funded choices.

2.3 Power grid infrastructure and operation

The power grid is the backbone of the electricity system. It is responsible for transmitting and distributing the generated and consumed electrical power. The power grid consists of multiple layers, where each layer uses a different voltage. These layers can be divided into three groups: High Voltage (HV), Medium Voltage (MV) and Low Voltage (LV). In the Netherlands, above 66 kV is manged by a single TSO called Tennet. Below 110 kV is managed by seven different DSOs. The voltage values can differ between DSOs. In this thesis, the values used to differentiate between voltage levels are those that Stedin uses and are shown in Table 2.1.

HV	Above 23 kV
MV	In between 10 kV and 23 V
LV	Below 400 V

Table 2.1: Voltage levels as used by Stedin to divide the power grid into groups

These different voltage levels are needed to match the generated voltages with the voltages used by the users while maximising the efficiency. They reduce the cost of transportation of the overall power grid.

The explanation is as follows: the electricity produced at a power plant can not be directly delivered to a household. The voltage and current are much higher than what a household or industry could handle. So a transformation has to take place. This transformation happens at electrical substations placed throughout the country, where transformers transfer the electricity from one voltage level to the other. The second element, the efficiency of the transport, is strongly linked to the different voltages used for transportation. At high voltage levels, the electrical losses are lower with the trade-off that the costs of the components are more expensive. That is why high voltage levels are used over longer distances. A schematic representation of the transportation of electricity is shown in Figure 2.1.

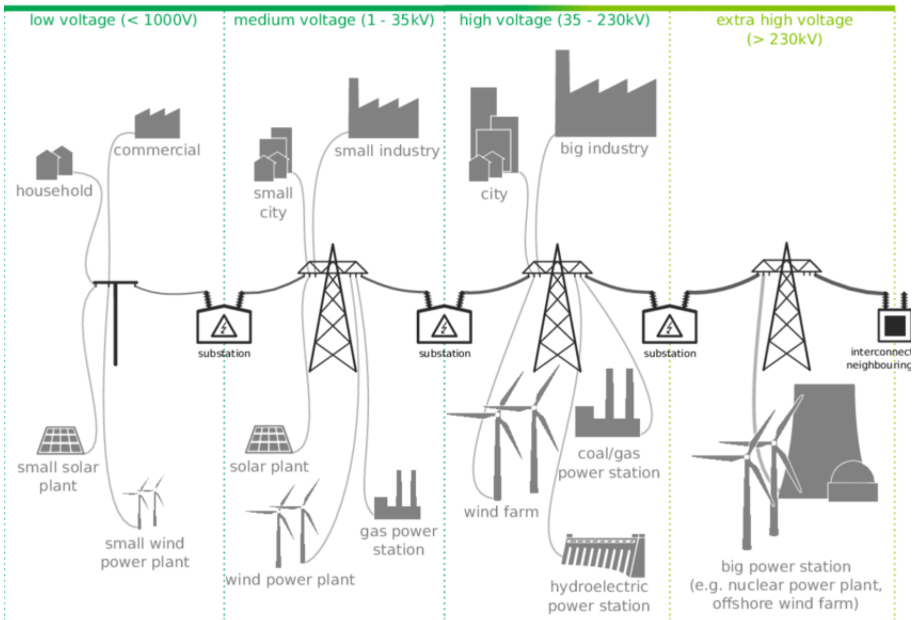


Figure 2.1: Electricity distribution over multiple voltage levels [8]

With the increase in Renewable Energy Sources (RES) of the last decade and the large scale electrification, the current limits of the power grid in the Netherlands are already being encountered in too many places. Furthermore, the current grid stability in the Netherlands largely depends on fossil fuel power plants [9]. If they have to be replaced by RES or removed entirely, the grid stability will diminish while electricity will still have to come from elsewhere.

2.4 Gas grid infrastructure and operation

As mentioned, fossil fuel power plants still play a key role in supplying electricity in the Netherlands. The largest part, 60%, comes from fossil fuels of which natural gas has the largest share at 70% [10]. A gas field in the province of Groningen, the largest in Europe, was found in 1959 and caused the start of the national development of the gas infrastructure. This 'cheap' gas created a big lock-in which is why gas still represents 44% of all energy use and why 90% of the households still use it for heating. [11]. With the 2050 climate goals, the CO2 emissions need to be reduced significantly. This translates directly into a large reduction of natural gas usage. On the cost side, natural gas has become much more expensive in recent years due to geopolitical events. Despite the increased profits from gas export, the government decided to shut down the gas field in Groningen in October 2023 due to the increased frequency and severity of earthquakes related to the extraction of gas. Since then all natural gas has to be imported.

The transmission of gas in the Netherlands is done by the TSO Gasunie and the distribution is done by multiple DSOs of which Stedin is one. In the same way that the electrical power grid uses multiple voltage levels, the gas grid uses multiple pressure levels. The gas network is divided into two subnetworks: the main transmission network that uses big pipelines and high pressure (HTL) and the distribution network that uses smaller pipelines and medium pressure (RTL). The different layers of the gas network and who manages them are shown in Table 2.2.

TSO	HTL	below 67 bar
	RTL	between 67 and 16 bar
DSO	RTL	below 16 bar

Table 2.2: Gas infrastructure pressure levels [12]

The transition towards using less gas has already started, but natural gas will keep on being used in the foreseeable future although at a much lower level. The existing infrastructure will, however, undergo changes. The most important innovation is the re-purposing of the gas network to use it for hydrogen transmission and distribution. This has garnered a lot of attention the last few years. Extensive research and experiments have been done to determine that the re-purposing of the existing natural gas grid is safe and desirable [13].

2.4.1 Hydrogen

Hydrogen is a gas that can be produced in three different ways that were given the name of a colour based on their carbon footprint. The most common form is grey hydrogen obtained through Steam Methane Reforming (SMR) where natural gas and steam are combined at high temperature and pressure. This reaction produces hydrogen gas and CO2. The next form is blue hydrogen, which is the same process as for grey hydrogen except that CCS is used to contain part of the green house gasses. Lastly, green hydrogen is the preferred way from a sustainability point of view. To obtain green hydrogen, electrolysers use electricity from RES to split water into hydrogen and oxygen through an electrochemical reaction. In any case, the advantage of hydrogen is that as a gas it can be easily stored and transported. At the same time, the increased production from RES will also increase the fluctuations in produced electricity. To alleviate this problem, the surplus of electricity may be used to produce hydrogen. This requires storage of hydrogen which will be explained further in Section 2.6.

2.5 Heat

Heat is a basic necessity that provides the whole society with warmth and hot water. In the Netherlands, heat generated by natural gas is done with a central heating boiler that can reach temperatures of up to 80°C. This temperature is very important to achieve enough heat production in old, badly insulated houses to make it livable in the winter. For modern homes with better insulation, much lower temperatures will do. Alternatively, users may benefit from centralised production called district heating.

2.5.1 District heating and cooling systems

District heating centralizes heat production and distributes the produced heated water through a network of pipes to the consumers. This production can be done by using natural gas, either directly or as a byproduct using a CHP plant, coal or biomass. But it can also be done with RES such as geothermal energy, large scale heat pumps, large industrial boilers called E-boilers, waste heat and hydrogen. Especially waste heat is promising since it can make existing systems more efficient. Waste heat can be collected from waste incineration plants, data centers, nuclear power plants and green hydrogen production[14]. In the Netherlands however, district heating is still primarily run by fossil fuels [15]. The first heat grid, came to be in the late 1800s. This was very rudimentary and a lot of innovations have been made since. Each large change in technology called in a new generation of district heating. The current generation is the fourth. It is focused on reducing emissions and integrating RES as much as possible. The heat grid in this thesis is also fourth generation.

There is, however, already a fifth generation of district heating. In fact, it is a district heating and cooling network. The heat is distributed at ambient temperatures and converted into either warmer heat or cooling by heat pumps located at the place of consumption. The water needed for this conversion has to be stored somewhere such as an old unused coal mine in Heerlen in the Netherlands [16]. With global warming, the added benefit of not only having access to heat but also to cooling without the need for extra equipment could be very valuable.

2.5.2 Decentralised heating solutions

The traditional way of heating is using an energy source obtained through a DSO and converting that into heat at the location of consumption. This can be done with natural gas but also with electricity. With climate goals in mind, more and more private and industrial consumers are shifting from natural gas to either fully or partially electric heating solutions such as hybrid or electric heat pumps. The end result of this electrification is an increase in demand on the power grid, which is why in the Netherlands not everybody is allowed to install a heat pump anymore. There are even cases were an already installed heat pump had to be turned off due to congestion. The upside here is that most consumers who buy a heat pump also buy or already have solar panels which means that the costs of running the heat pump considerably go down.

2.6 Energy storage

An important reason why fossil fuels were and still are so practical is because they are very easy to store and transport. With RES, that becomes an issue since electricity can be stored but it requires more effort, resources and space. Consequently, using RES is often, if not always, more expensive than fossil fuels. Nevertheless, energy storage will play an essential role in balancing the energy flows since the demand and supply of RES do not match. Following subsections will elaborate on the different ways of energy storage.

2.6.1 Electricity

Electricity is usually stored in batteries, nowadays mostly made from Li-Ion being the most cost effective in €/ kWh [17]. It is used in most electric devices today from small electronic devices to cars and boats. But projects to connect large battery fields to the power grid have only recently become more common with the prices of Li-ion batteries dropping enough for cost-effective business cases. With the impact of the weather on RES being uncontrollable, batteries are one solution to store the energy that would otherwise have gone to waste. An interesting idea with more congestion in the power grid is to use electric cars as a buffer when plugged in to the grid. By "smart charging" the car only charges when electricity prices are low or when the energy is produced by the owner's solar panels. Of course this reduces the load on the grid in peak demand hours. In return, for instance when there is more demand from the grid then supply, the car may 'sell' the electricity back to the grid. This is called Vehicle-to-Grid (V2G) [18].

2.6.2 Hydrogen

Hydrogen can be stored as a gas in high pressure containers for smaller applications but research is also being done to see if hydrogen can be stored in empty gas fields and depleted wells [19]. Large dependency on RES will result in a large mismatch between supply and demand of energy. Batteries always deteriorate with time and temperature differences and are therefore not very good for long term storage. Hydrogen is. By producing enough hydrogen in the summer from all the excess electricity from solar panels and/or wind, a part of the winter energy needs can be met. Specific industries, for example those that need natural gas to achieve high temperatures, will also become (more) dependent on hydrogen if they need to reduce their emissions to stay in business. Thus, production and storage of hydrogen will play an important role in reaching the 2050 climate goals.

2.6.3 Heat

Less common than batteries and hydrogen, the last type of storage is the storage of heat. The production of hydrogen is one way of using the surplus of electricity but this surplus could also be used to generate and store heat for use in district heating. In Denmark this type of storage is already in use [20]. A similar storage has been built in the Netherlands as a demo for research and testing [21]. The heat grid used in [16] is also built around the idea of heat storage but at a lower temperature. The two main challenges of heat storage in comparison to hydrogen are the high losses in temperature and the fact that it is mostly a one-directional process. If electricity is transformed into heat, it is not very easy or efficient to transform that heat back into electricity. The only way to achieve this is with a so-called 'Carnot' battery system but their efficiency is rather low (40-70%) for widespread and long-term use [22]]. This system, however, may well serve as a short term heat storage buffer for weekly use [23]].

3. Modelling of Integrated Energy Systems

This chapter discusses the modelling of integrated energy systems. In Section 3.1 the need for planning of expansion is underlined. Section 3.2 lists the possible tools that can be used to model the expansion. Section 3.3 describes the uncertainties introduced when using a model. Finally, Section 3.4 shows the software requirements and which software tool is chosen.

3.1 Expansion planning

The energy system of the future has to deal with seasonality and with energy supply and demand mismatches. As a consequence, a much more careful planning is needed since the energy supply is not readily available as before with fossil fuels power plants. As explained in Chapter 2, integrated energy systems are a good solution to maintain reliability and efficiency of multiple energy grids. The modelling of integrated energy systems, however, requires a lot of data. When DSO Stedin makes an expansion plan for 2030 or 2050, this plan contains assumptions from their own data. For a complete plan Stedin should incorporate the data and expansions plans from the TSO and from large consumers like the chemical industry to ensure the continued distribution of energy without encountering congestion. This is another reason why the document [6] exists. DSOs like Stedin cannot await the moment when an electricity substation is at its capacity and then start commissioning a newer larger one. The necessary growth of the energy grid calls for clear investment priorities due to a shortage of manpower and long procedures for financing and permits. The establishment of expansion plans renders clear communications between the DSOs and with large consumers vital for a good functioning energy grid.

3.2 Choosing the software tool

The modelling of an integrated energy system is done in specific software that can simulate the flow of multiple energy sources in the same model. In this thesis, the two energy sources that have to be modelled are electricity and heat. The energy system model can then take three different types of approaches: Top-down, bottom-up and hybrid. A top-down model begins with an entire system which is split up into smaller parts. In a bottom-up model, multiple sub-systems are modelled which are then grouped together to form entire systems. The hybrid model combines a top-down and bottom-up model. The methodology used for these models has to provide the option for an optimisation. Not all tools can handle every type of energy. Some also allow to add in new energies but most have a predetermined list that contains a combination of electricity, fossil fuels, heat, cooling and hydrogen. The time horizon and temporal resolution allowed by the tool also have to be taken into account. Lastly, the modelling tool has to use the Python programming language and has to be open source to follow the university guideline to use and promote free software. The tools that fit these criteria are shown in Table 3.1. The Acronyms used in the table are: Assessment Criteria: EE = energy efficiency, Em = emissions, Fi. = financial, S = social. Mathematical Approach: DP = dynamic programming, LP = linear programming, MIP = mixed integer programming. Sectoral Coverage: El. = electricity, F = fossil resources, H = heat, Hyd. = hydrogen. Technical Coverage: Conv. = conventional generation, Ren. = renewable generation, Stor. = storage (electricity and heat). Uncertainties: D: Deterministic; P: Probabilistic.

Tool	Calliope	Ficus	Oemof	Temoa	Urbs	PyPSA
Methodology	Optimization	Optimization	Optimization	Optimization	Optimization	Optimization
Assesment criteria	Fi	Fi	Fi, EE, Em	Fi	Fi, Em	Fi, EE, Em
Mathematical Approach	LP	LP, MIP	LP, MIP	LP	LP	LP
Temporal Resolution	User-defined	15 min	User-defined	Years	User-defined	User-defined
Time Horizon	User-defined	1 year	User-defined	User-defined	User-defined	User-defined
Sectoral coverage	El, H, Hyd, F	Any	El, H, Hyd, F	Any	Any	El, H, Hyd, F
Technical coverage	Ren, Conv, Stor	Ren, Conv, Stor	Ren, Conv, Stor	Ren, Conv, Stor	Ren, Conv, Stor	Ren, Conv, Stor
Uncertainties	D/P	D	D	D/P	D	D

Table 3.1: Software tools that satisfy the requirements[24], [25]

3.3 Uncertainties

When planning ahead for the year 2030 and 2050, the data needed for the calculations are still non-existent and thus have to be created based on assumptions. A DSO can use the measured data of the past year, together with the expected growth of markets and known plans of government and consumers to make a dataset based on estimates. These estimates introduce uncertainties into the dataset. Furthermore, RES are weather dependent. Their yield may vary greatly depending on the wind and sun hours. Prices can also vary immensely, often due to their correlation with large scale geopolitical events. The energy need of large users may also change significantly. Industries can grow faster, slower or even move away entirely. All of which will have varying degrees of impact on the data and the planning based on it. If uncertainties are handled with a deterministic approach, it is up to the user to do a sensitivity analysis to evaluate the influence of varying parameters. A probabilistic approach takes the uncertainties of the variables into account during the optimisation and presents these in the results. This gives the advantage of having a more complete output but also being more difficult to interpret. This thesis uses the deterministic approach.

3.4 Model requirements and selection

With the objective of answering the research question in mind, a list of requirements was made which are:

- Use the Python programming language
- Perform optimisation based on cost
- Use time steps of one hour
- Simulate over one year
- Allow electricity and heat as energy sources
- Integrate multiple energy sources in the same system

All six selected software tools could be used based on these criteria. The decision will be then be made based on documentation available. The tool with the the most extensive documentation is PyPSA [26]. It has extensive documentation as well as detailed examples on its own website [27]. More examples with detailed explanation are also found on the Data Science for Energy System Modelling of the Technical University of Berlin [28].

PyPSA met all software requirements, has the most extensive documentation and lacks negative aspects that could prevent the use of this software. PyPSA has therefore been chosen for this thesis.

4. Modelling and optimisation framework

This chapter describes how PyPSA works. In Section 4.1 an overview is given. Section 4.2 explains how a model in PyPSA is solved. Section 4.3 introduces the financial parameters used. Section 4.4 describes what an objective function is and how it is used. Finally, in Section 4.5 the evaluation of robustness of the model is presented.

4.1 PyPSA overview

Python for Power System Analysis (PyPSA), is, as the name implies, an open-source tool for power system analysis that can simulate and optimise modern power and energy systems [27]. Power system tools in general model the interactions between the electrical grid and the consumers and generators which use the grid. PyPSA was developed to bridge the gap between power system and general energy system modelling tools [26]. RES and sector coupling were key functionalities from the start around which the tool was build.

Network	Container for all other network components
Bus	Fundamental nodes to which al other components attach
Carrier	Energy carrier (e.g. wind, solar, gas, etc.)
Load	A consumer of energy
Generator	Generator whose feed-in can be flexible subject to minimum loading or minimum down and up times, or variable according to a given item series of power availability
Storage Unit	A device which can shift energy from one time to another, subject to efficiency losses
Store	A more fundamental storage object with no restrictions on charging or discharging power
Shunt Impedance	An impedance in shunt to a bus
Line	A branch which connects two buses of the same voltage
Transformer	A branch which connects two buses of different voltages
Link	A branch with a controllable power flow between two buses

Table 4.1: PyPSA components [26]

The components available for use in PyPSA are shown in Table 4.1. The store, bus and link are fundamental components which are used as building blocks for more complicated components such as generators, storage units, CHPs, etc. The carrier describes the energy carriers used in the network. For electricity networks, AC and DC are available values. A carrier can also be given any arbitrary value such as wind, heat, natural gas or hydrogen. Extra attributes can also be given to carriers such as a level of CO2 emissions.

Buses are the nodes to which all other components attach. At each bus, energy conservation is enforced. The energy flow in and energy flow out should be equal to the energy demand and energy generation. This is shown visually in Figure 4.1. Stores are components, only for storing energy, to shift power from one time to another where losses from energy leakage can be taken into account. Links are components that control the directed flow between two buses for any chosen energy carrier with a defined efficiency. The efficiency can be static or time-varying.

Power balance at the bus is determined by loads, generators, stores, storage units and shunt impedances attached to it. Loads represent power demand; Generators represent power supply; Storage units are a store and 2 links combined that can charge and discharge energy; Lastly, shunt impedances have a power consumption that depends on the voltage.

Lines and transformers are passive components. Lines represent transmission and distribution lines. Transformers convert AC power from one voltage level to another. The power that flows through the lines and through the transformers is not directly controllable but determined by their impedances and the imbalances at the buses.

The model will consist of a power grid and a heat grid connected to each other with the necessary components to appropriately represent a part of the electricity network and of the district heating network. The two energy carriers used will be "AC" for the electrical part and "Heat" for the heat part.

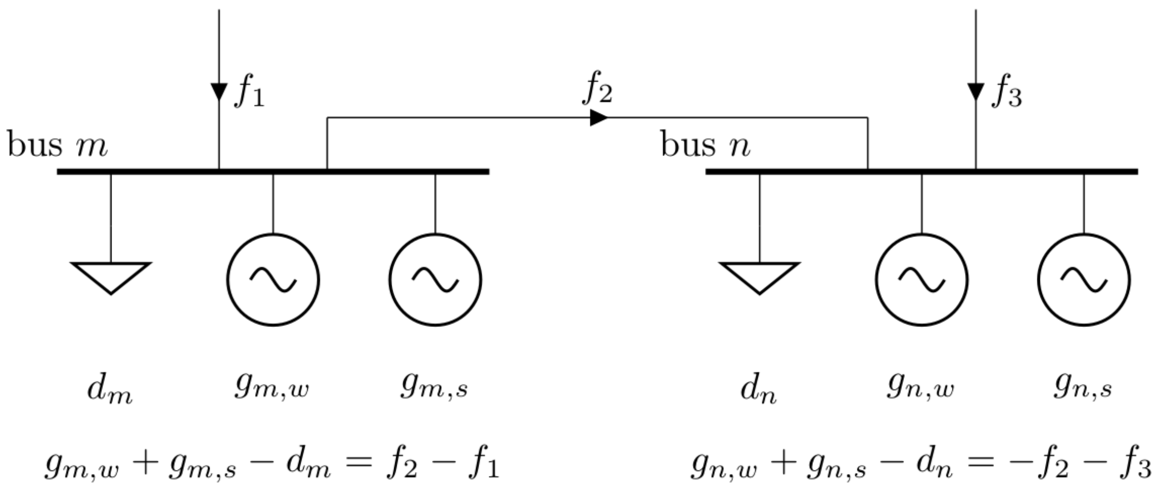


Figure 4.1: Schematic representation of the conservation of energy between two busses [27]. The power flow in and out of a bus is depicted by *f*. The triangle is used for the demand *d* and the circle with a sine wave inside is used for the generators *d*.

On the electrical side, the components used will be: Buses, lines, transformers, generators and loads. On the heat side, the components used will be: Buses, links, stores and loads. Links will be used to convert electricity into heat, which is called Power-to-Heat (P2H).

The data of each component are stored in a DataFrame, which is part of the Pandas Python package [29]. The input data can be static data consisting of a single value or in some cases time-varying, such as the efficiency of a link but also the power demand of a load or the power generation of a generator.

4.2 Running the model

PyPSA can run the model in two different ways. The first option is to calculate the power flow, which can be linear and non-linear. The second is to optimize the system cost of the infrastructure used for generation, storage and transmission.

4.2.1 Power flow calculation

For a power flow calculation, the power of all connected components is used to calculate the resulting voltages in the network together with the power flow in the passive branches (lines and transformers). An example of this is the calculation of the non-linear AC power flow, for which Equation 4.1 is used. Here S_i is the apparent power injected at each bus i, I_i^* is the conjugate of the complex current and $V_i = |V_i|e^{j\theta_i}$ is the complex voltage. Y_{ij} is the bus admittance matrix, based on the branch impedances and on any shunt admittances attached to the buses. The unknown variables in the non-linear Equation 4.1 can be found using the Newton-Raphson algorithm to solve the system [27].

$$S_i = P_i + jQ_i = V_i I_i^* = V_i \left(\sum_j Y_{ij} V_j \right)^* \tag{4.1}$$

4.2.2 Power system optimisation

The energy system can also be solved as a linear problem using linear power flow equations if the goal is to optimise operation and investment. This is done by minimizing total system cost which consists of cost of generation, storage, transmission and technical and physical constraints. All variables used for the optimisation are placed in the objective function. To reduce run time and to increase the relevance of the results, constraints can be applied to the decision variables.

The power balance at each bus i has to be guaranteed for each time t. Equation 4.2 represents this power balance that enforces energy conservation.

$$\sum_s g_{i,s,t} + \sum_s h_{i,s,t} - \sum_s f_{i,s,t} - \sum_l K_{il} f_{l,t} = \sum_s d_{i,s,t} \tag{4.2}$$

In this equation $g_{i,s,t}$ is the dispatch of generator s , $h_{i,s,t}$ is the dispatch of a store and/or storage unit s, $f_{i,s,t}$ is the link flow (if positive it withdraws and if negative it generates energy) of a link s, $d_{i,s,t}$ is the exogenous load at each node and K_{il} is the incidence matrix containing information on whether a branch l exists and starts or ends at a bus i.

4.3 Financial parameters

The decision on whether an investment is sound or not has to be based on the expected costs of keeping the grid (power or heat) running. These expenses can be divided into two categories: Capital Expenditure (CAPEX) and Operating Expenses (OPEX). CAPEX are large one-off expenditures to buy new equipment and OPEX are day-to-day costs for keeping the equipment running. Additionally the lifetime and Weighted Average Cost of Capital (WACC) of the components have to be known. They are needed to calculate the annuity which is used to determine the annualised cost. These annualised costs are a better comparison since components can have different lifetimes which could create biased results. Equation 4.3 shows the formulas used to calculate annuity and annualised cost.

$$\begin{aligned} a(r,n) &= \frac{r}{1-(1+r)^{-n}} \\ annualised\,cost &= CAPEX \cdot a(r,n) \end{aligned} \tag{4.3}$$

In PyPSA, CAPEX is called capital cost and OPEX is called marginal cost. It was built in such a way that these costs are calculated per component based on the amount of MW. So capital cost and marginal cost are given as parameters with a value in €/MW. In practice, when a substation is reinforced this is not done per MW but in larger predetermined steps. If an extra 5 MW is needed at a substation, the reinforcement will add a fixed amount that can be 20 or 30 MW. Another shortcoming of PyPSA is that transformers do not have the option to add OPEX (marginal cost). The model will not take this into account with the decision making. Instead, it will be calculated afterwards so as to add them in the total cost. See also Chapter 6.

4.4 Objective function

To optimise the model, a function has to be established that contains the decision variables whose values can vary to either minimize or maximize the function. This function is called the objective function, shown in Equation 4.4.

$$\min_{\substack{F_\ell, G_{i,r}, H_{i,s}, E_{i,s} \\ f_{\ell,t}, g_{i,r,t}, h_{i,s,t}}} \left[\sum_\ell c_\ell \cdot F_\ell + \sum_{i,r} c_{i,r} \cdot G_{i,r}\right] + \sum_{i,s} c_{i,s} \cdot H_{i,s} + \sum_{i,s} \hat{c}_{i,s} \cdot E_{i,s}$$
$$+ \sum_{i,r,t} \big(w_t \cdot o_{i,r} \cdot g_{i,r,t}\big) + \sum_{i,r,t} w_t \cdot o_{i,s} \cdot [h_{i,s,t}]^+ \tag{4.4}$$

In this equation, capital letters are used for the capacities of the components, small letter c for annuitised fixed costs per capacity, o for variable costs associated with dispatch of energy and w_t is an extra weight that can be given to each period for simple stochastic optimisation. This w_t will remain unused and equal to one. F_ℓ stands for the flow capacities of each branch ℓ with cost c_ℓ; $G_{i,r}$ stands for the generator capacities at each bus i for component r with cost $c_{i,r}$; $H_{i,s}$ stands for the storage unit capacities at each bus i for component s with cost $c_{i,s}$; $E_{i,s}$ stands for the store at each bus i for component s with cost$\hat{c}_{i,s}$; $g_{i,r,t}$ stands for the dispatch of component r at bus i at time t; $[h_{i,s,t}]^+$ stands for the positive dispatch of component s at bus i at time t.

On the objective function, the following constraints are applied:

$$\tilde{g}_{n,r,t} \cdot G_{n,r} \leq g_{n,r,t} \leq \bar{g}_{n,r,t} \cdot G_{n,r} \quad \forall n, r, t \tag{4.5}$$
$$\tilde{h}_{n,s,t} \cdot H_{n,s} \leq h_{n,s,t} \leq \bar{h}_{n,s,t} \cdot H_{n,s} \quad \forall n, s, t \tag{4.6}$$
$$\tilde{e}_{n,s,t} \cdot E_{n,s} \leq e_{n,s,t} \leq \bar{e}_{n,s,t} \cdot E_{n,s} \quad \forall n, s, t \tag{4.7}$$
$$\sum_r g_{n,r,t} + \sum_s h_{n,s,t} + \sum_\ell \alpha_{\ell,n,t} \cdot f_{\ell,t} = d_{n,t} \leftrightarrow w_t \cdot \lambda_{n,t} \quad \forall n, t \tag{4.8}$$
$$\left|f_{\ell,t}\right| \leq F_\ell \quad \forall \ell, t \tag{4.9}$$
$$\tilde{f}_{\ell,t} \cdot F_\ell \leq f_{\ell,t} \leq \bar{f}_{\ell,t} \cdot F_\ell \quad \forall \ell, t \tag{4.10}$$

4.5 Parametric uncertainties and sensitivity analysis

The obtained results from the optimisation are sensitive to the parameters used to define the system. These parameters introduce a level of uncertainty in the model, that can significantly influence the decision-making and final outcomes of the optimisation. To better understand how sensitive the model is to specific variations, a sensitivity analysis will be performed.

The parameters that will have the most impact on the decision-making process of the model are:

- CAPEX: The optimisation determines the most cost-effective solution to satisfy the energy demands in the system. If the price of a certain the components is varied, then the model might implement different sources that are cheaper in comparison.
- Energy demand profiles: The profiles used are obtained as is from Stedin and HVC. These profiles are however estimations of what the energy demand could be like in 2030. These profiles are subject to many uncertainties and if they change, then the needed capacity might also change.

In this Thesis, only the CAPEX will be used for the sensitivity analysis. Using the energy demand profiles for the sensitivity analysis could offer valuable insights and could be implemented through stochastic optimisation.

To perform a sensitivity analysis in PyPSA using CAPEX, a deterministic approach is used for the optimisation. The method to apply a sensitivity analysis involves modifying one decision variable at a time while all others remain constant. The list of decision variables used will be presented in Chapter 5.

5. Case study: Applying the model

In this chapter the case study of the Drechtsteden region is introduced. Section 5.1 shows how the power grid and heat grid have been replicated in the model. Section 5.2 gives the specifics of the implementation of the power grid and heat grid. Section 5.3 provides the information on what data was used in the model. Section 5.4 explains how the sensitivity analysis will be performed. Finally, the limitations are listed in Section 5.5.

5.1 The Drechtsteden region

The area selected to use as a case study had to be within the Stedin region of operation and had to contain a heat grid. The Drechtsteden region fits this bill and had been used before [14], [30] as a case study so there would probably be enough knowledge to develop an optimisation model. The Drechtsteden region was therefore selected for the case study and application of the model. Figure 5.1, shows a map of the Drechtsteden region.

Figure 5.1: Map of the region of Drechtsteden [31]

5.1.1 Power grid

The electricity in Drechtsteden is obtained from TenneT (the TSO) at a single HV substation. Distribution of electricity in the region is done by three 150/50 kV substations. The next voltage level goes down at MV. There are a total of 13 substations that transform the voltage from 50kV to 13 kV. The names and specific connections of the MV substations to HV substations will not be mentioned in this thesis for data security reasons. Instead, the names will be replaced with letters and numbers. An HV substation will get a capital letter (A, B, C) and an MV substation will get a capital letter and a number (B1, B2, etc.). The schematic diagram of the power grid as used in the model (with the names replaced) is shown in Figure 5.2. The following components will be used in the model to represent the grid: Bus, Generator, Load, Transformer and Line.

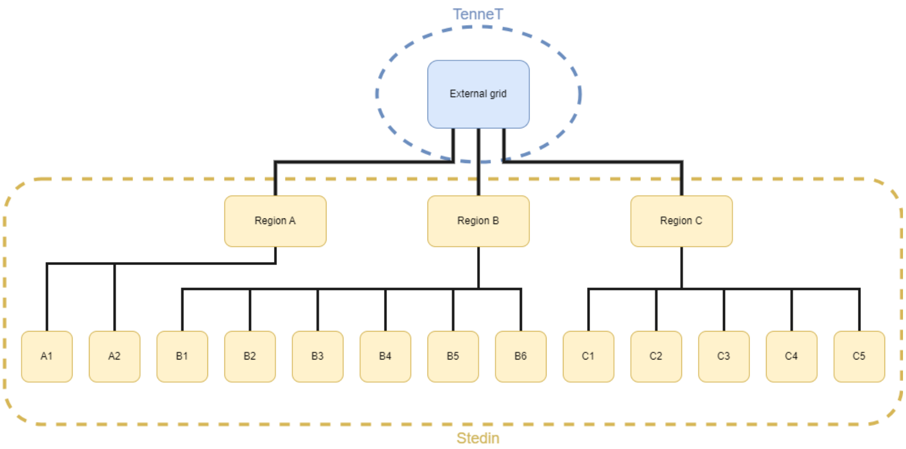


Figure 5.2: Schematic diagram of the power grid in Drechtsteden as used in the model

5.1.2 Heat grid

The local DSO that manages the heat grid is the public company called HVC. HVC is a waste management company that branched out into the energy sector and now also provides different types of energy to their customers. Their main forms of energy are RES, green gas production and heat generation and distribution. They operate in over 50 municipalities in the Netherlands but the heat grid used for the model is that of the city of Dordrecht. A map of that heat grid is shown in Figure 5.3.

Currently, the heat demand of the heat grid can be fully provided by the waste heat from the waste incineration plant. As a back-up, to ensure that the heat demand can also be met in case of maintenance or technical issues, an industrial E-boiler has been built and this boiler is operational. However, HVC wants to expand this heat grid (a map of their possible expansions is shown in the Appendix Figure A.1). If this expansion is to happen, HVC also needs to build extra heat sources to provide enough heat to the extra consumers. A schematic diagram of the heat grid with current heat sources, possible heat sources and their connections to the power grid is shown in Figure 5.4. The direction of the energy flow is shown since the conversion of electricity to heat is one-directional. The new sources, that will use electricity to generate heat, are denoted by P2H. At substation A and substation B one P2H source can be built. The following components will be used to represent the heat grid: Bus, Store, Link, Load.

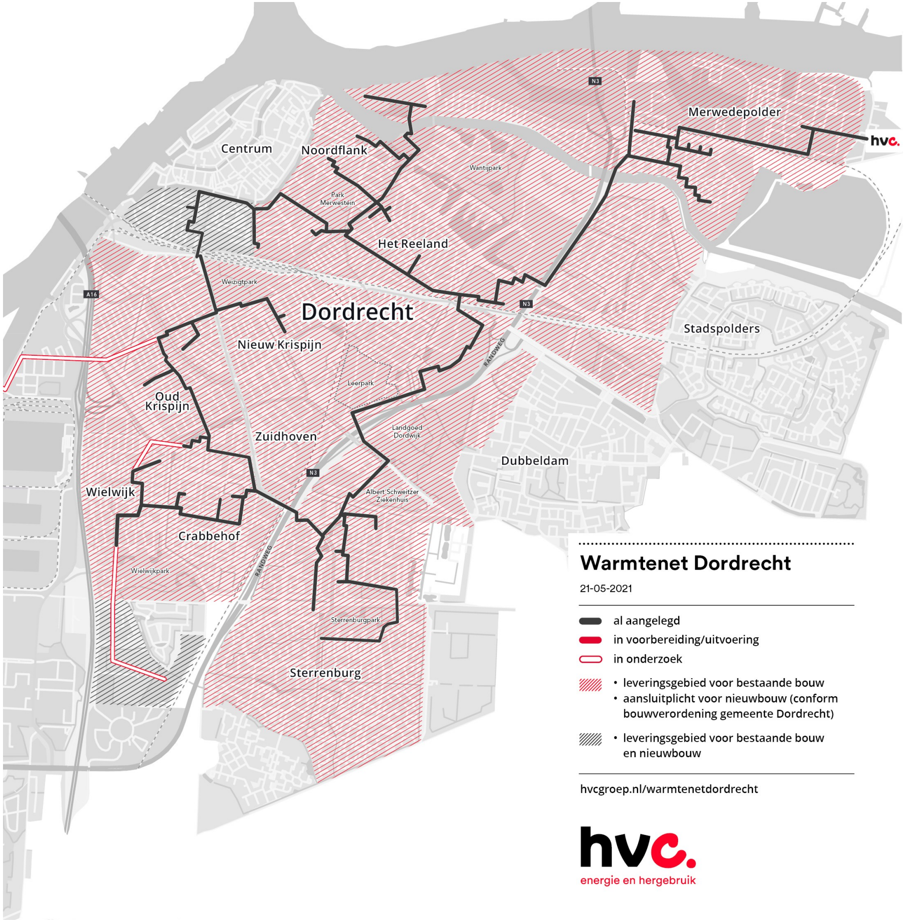


Figure 5.3: Map of the heat grid of Dordrecht [32]

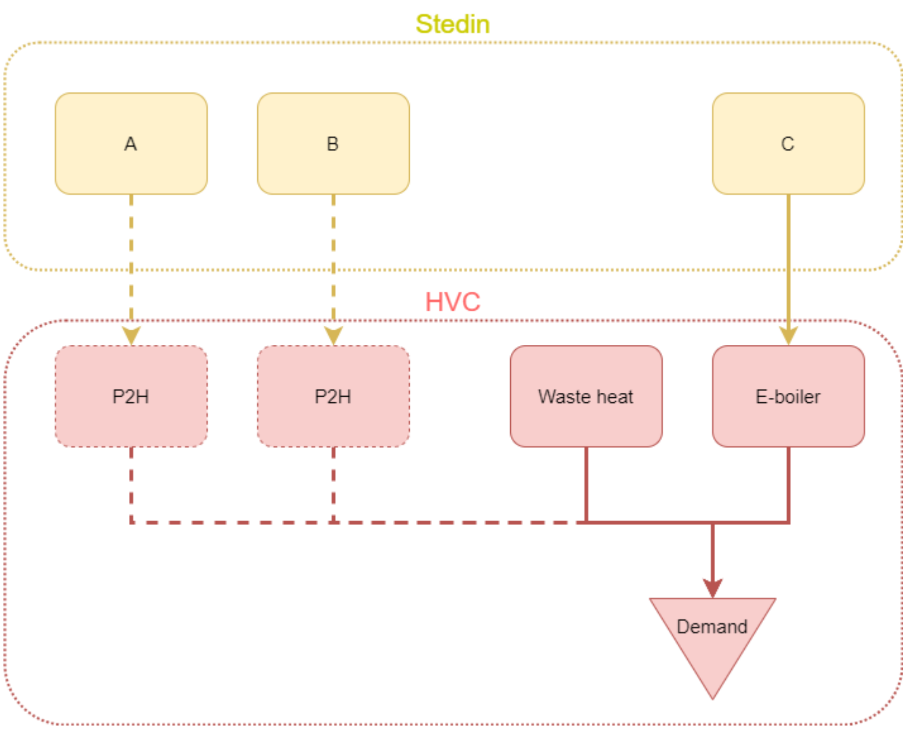


Figure 5.4: Schematic of the heat grid with heat sources and their connection to the power grid. Solid:existing, dotted:possibility

5.2 Model description

The model consists of a power grid and a heat grid connected to each other via P2H components. The mere modelling provides insight into where enough capacity is available to connect a P2H source. However, that would be without incorporating important information on how the heat demand of consumers is satisfied. Stedin has information on the expected amount of domestic heat pumps installed in 2030. If the demand on the power grid increases from the added load of both the heat pumps and the new P2H sources, then the heat demand would be satisfied twice. That is why the heat load will be separated from the 2030 power demand profile of each substation and will be converted into a 2030 heat demand profile in the model. Each heat demand at every substation will then be connected to the heat grid. If the model decides to build more P2H sources, extra heat energy becomes available. In the case where a substation has to be reinforced to meet the original heat demand, the heat grid can then provide that extra energy and the substation reinforcement can be prevented. The schematic representation of region A consisting of substation A, A1 and A2 together with the heat grid connections is shown in Figure 5.5.

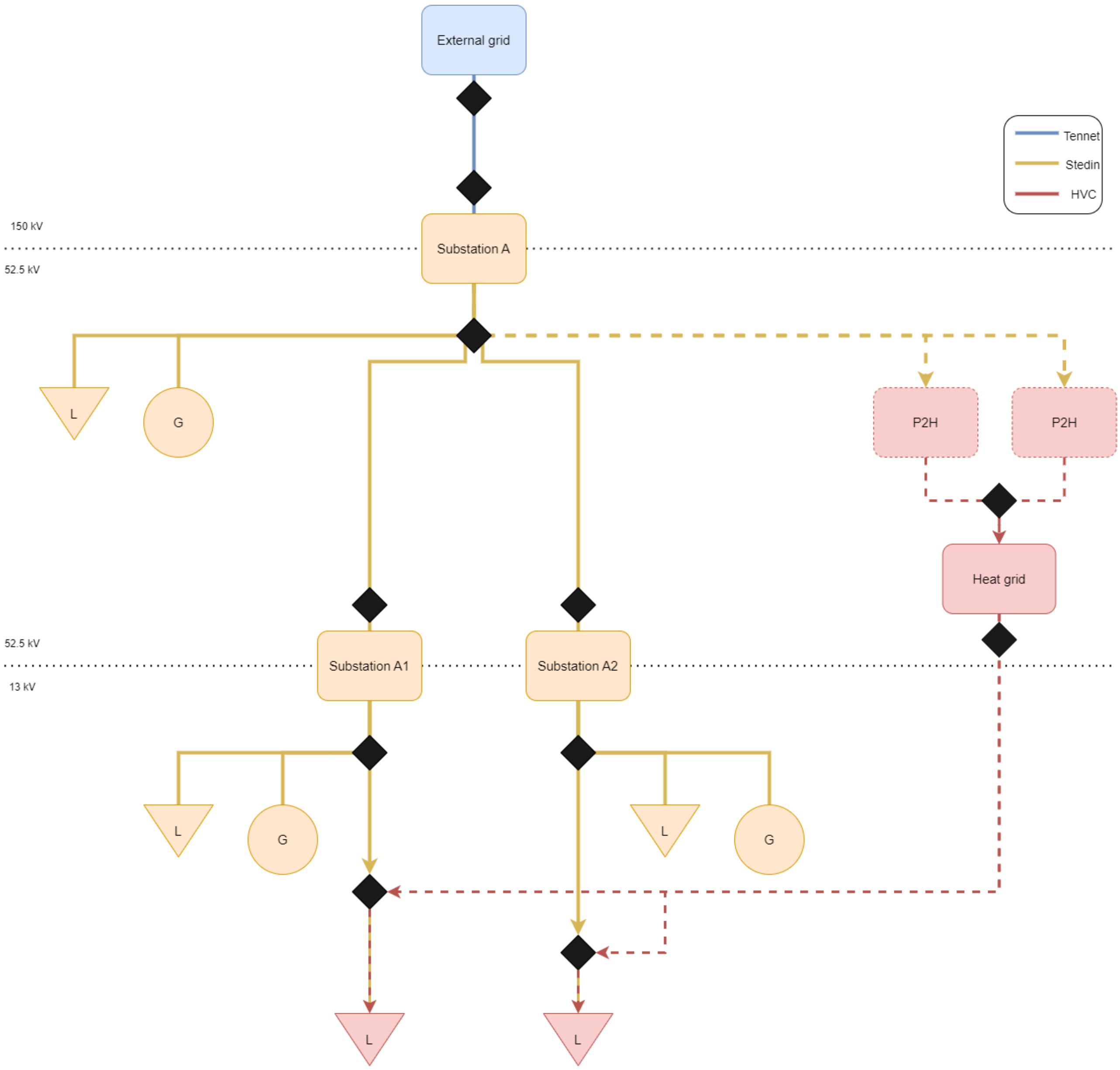


Figure 5.5: Schematic representation of substation A, A1 and A2 with the heat grid connections in the model. Solid line: existing connection, dotted line: expansion possibility

Buses are shown with black diamonds. Connections between buses are made with *Lines* and are shown as solid in Figure 5.5. Lines are given a capacity (1000MVA) that does not limit the system in any way and have no costs attached to them. Conversion from power to heat is done with a *Link*. When the distribution of energy happens with a loss and efficiency has to be applied, a *Link* is also used.

5.3 Model input data

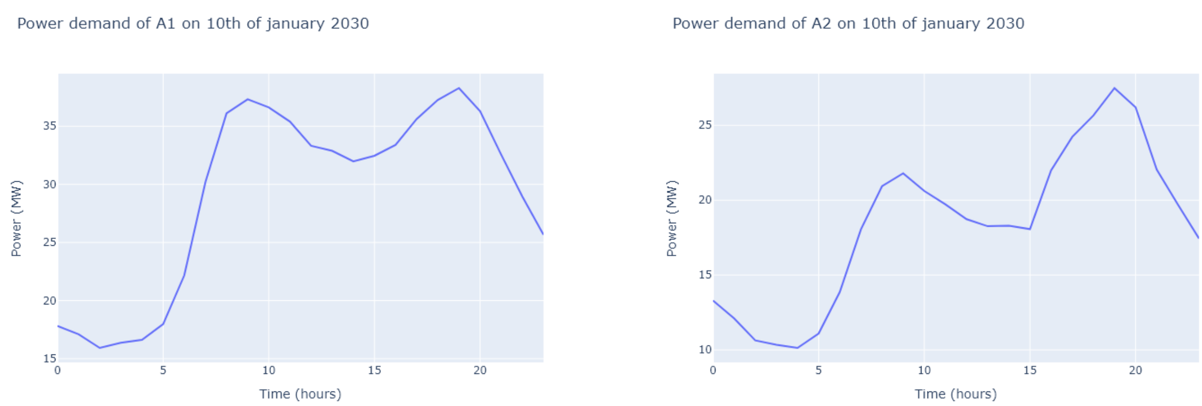
First the energy profiles used to simulate the model for the year 2030 are discussed, and then the parameters used in the model. They are split up into two groups. The first group contains all technical information (Energy profiles, nominal power, capacity, etc.). The second group contains all financial information (CAPEX, OPEX).

5.3.1 Energy profiles

The energy profiles for the power grid were obtained from Stedin and for the heat grid from HVC. These profiles are for the year 2030 and have a temporal resolution of 1 hour.

Profile of a winter day

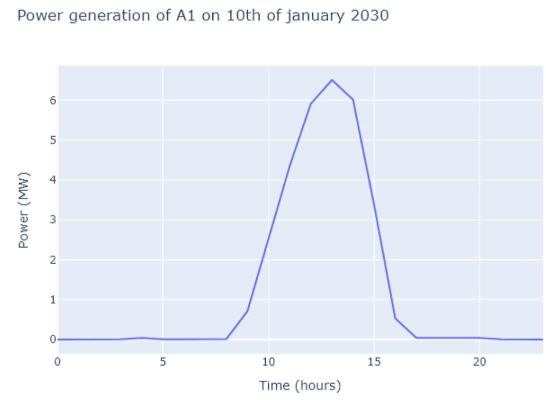
A winter day with high load was chosen as an example of the profiles. The power demand at substations A1 and A2 is shown in Figure 5.6, the power generation is in Figure 5.7, the heat demand in Figure 5.8 and the heat demand of the heat grid is shown in Figure 5.9. The corresponding exact values are shown in Appendix A.2.



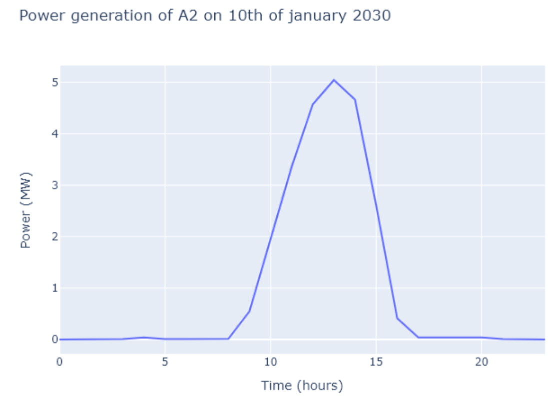
(a) Power demand A1

(b) Power demand A2

Figure 5.6: Power demand of substation A1 and A2 on the 10th of January 2030

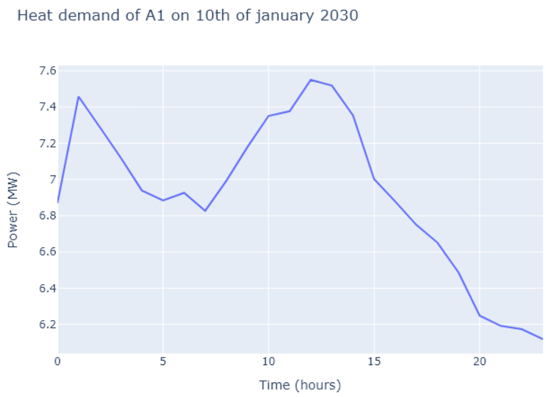


(a) Power generation A1

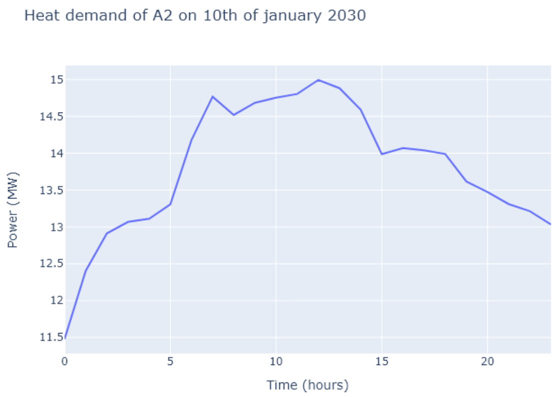


(b) Power generation A2

Figure 5.7: Power generation of substation A1 and A2 on the 10th of January 2030



(a) Heat demand A1



(b) Heat demand A2

Figure 5.8: Heat demand of substation A1 and A2 on the 10th of January 2030

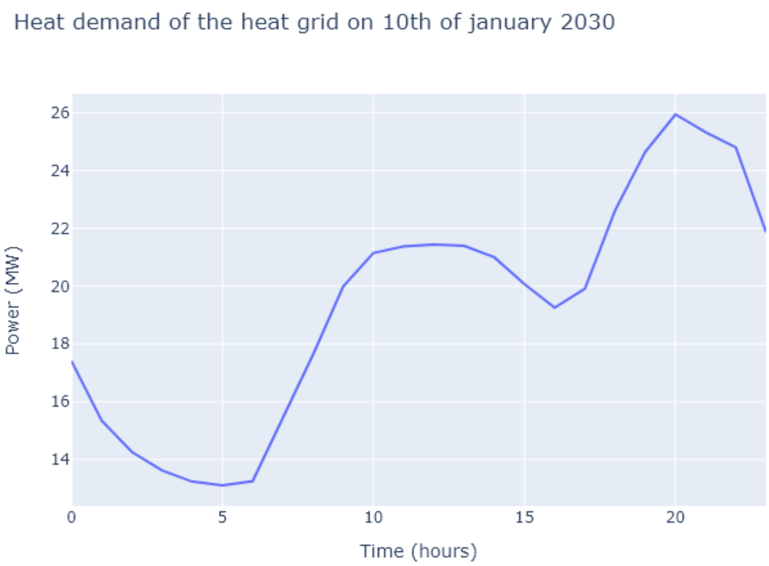


Figure 5.9: Heat demand of the heat grid on the 10th of January 2030

Profile of the whole year 2030

To show a profile of power demand for the whole year, the 50 kV substation B was chosen. In Figure 5.10, the profile is shown. In the colder months, the demand is higher and in warmer months the demand is lower or even negative. When the demand is negative, more energy is being generated from renewable energy sources than is being consumed. A common method of showing the profile over a year to better visualize the peak demand and generation is a load duration curve. The load duration curve for substation B is shown in Figure 5.11.

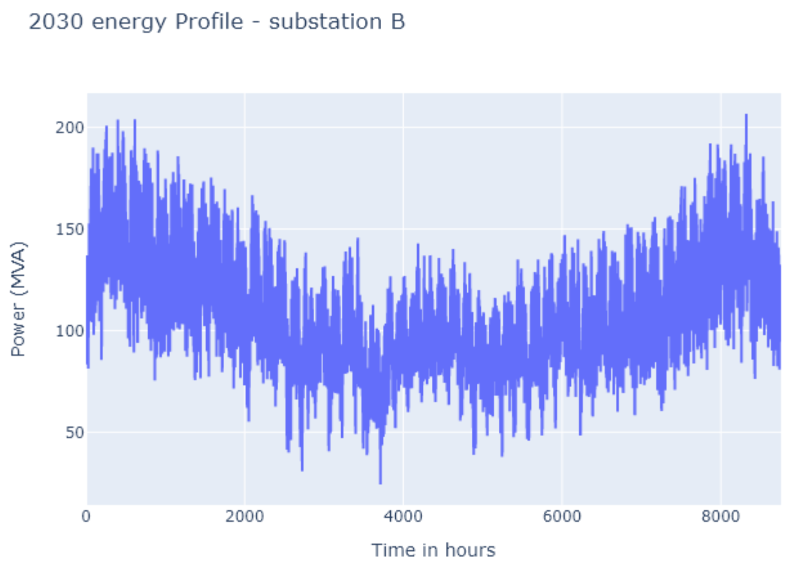


Figure 5.10: Power demand of substation B in 2030

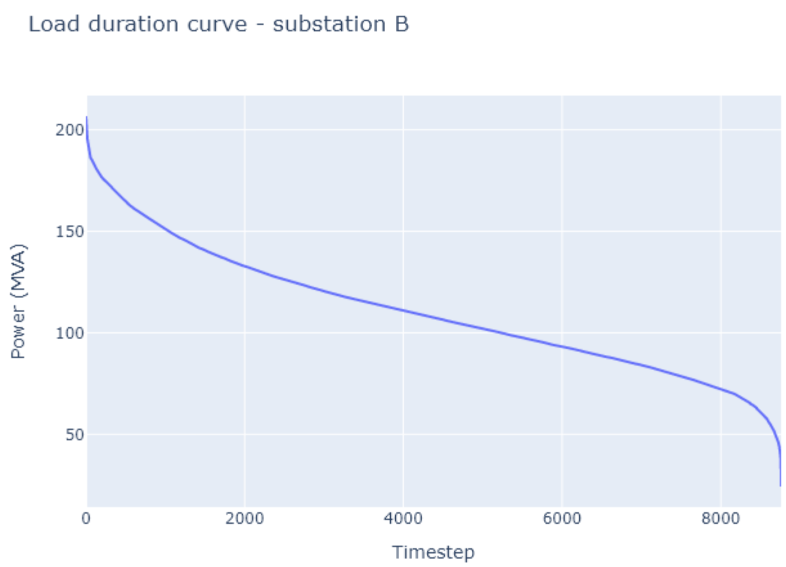


Figure 5.11: Electrical load duration curve of substation B in 2030

From Figure 5.11, the maximum demand for the year 2030 can be easily seen. It also shows for how many hours per year the demand is above a certain power value. This can be used to implement limitations on a substations to reduce the costs of reinforcement. Such a limitation would directly translate to demand congestion if it were to be applied in the real world. Electricity supplied to consumers would then be less than desired the available capacity will then be divided accordingly.

5.3.2 Technical parameters

The specifications of the substations are shown in Table 5.1 and those of the heat grid in Table 5.2. A list of each PyPSA component with their counterpart in the grid and/or function is described as follows:

- Bus: The node to which each component has to be connected
- Generator: Supplies the energy generated by RES at each bus to the power grid
- Load: Simulates the energy demand at each bus
- Transformer: Represents each substation
- Line: Creates a connection between busses
- Link: Transfers energy between buses with the possibility to change energy carriers and add efficiency
- Store: Energy storage, in combination with a link represents a constant availability of an energy

Name	Component	Capacity [MVA]	Voltage high [kV]	Voltage low [kV]
A	Transformer	200	150	52.5
A1	Transformer	40	52.5	13
A2	Transformer	25	52.5	13
B	Transformer	225	150	52.5
B1	Transformer	26	52.5	13
B2	Transformer	32	52.5	13
B3	Transformer	58	52.5	13
B4	Transformer	32	52.5	13
B5	Transformer	40	52.5	13
B6	Transformer	40	52.5	13
C	Transformer	150	150	52.5
C1	Transformer	40	52.5	13
C2	Transformer	40	52.5	13
C3	Transformer	40	52.5	13
C4	Transformer	40	52.5	13
C5	Transformer	30	52.5	13

Table 5.1: Transformer parameters

Name	Component	Nominal power[MW]	Efficiency
Waste heat	Store + Link	40	1
Heat grid pipes	Link	40	0.75

Table 5.2: Heat grid parameters of existing infrastructure

Three different types of P2H components can be placed at each 50 kV substation bus, in any possible combination allowed by the capacity. The hree types are: E-boiler, industrial heat pump and a geothermal energy plant. The E-boiler has an efficiency, more commonly referred to as Coefficient of Performance (COP), of one. The heat pump has a COP of more than one, which means that the energy produced is more than the energy used. The energy produced is obtained through an exchange of heat with a source. This can be the ground for geothermal applications or the air. In this thesis, industrial heat pump denotes an air-sourced industrial heat pump and geothermal energy is used when referring to a heat pump that collects heat from the ground. The temperature outside has an influence on the efficiency of the industrial heat pump. To calculate the efficiency at every hour for the year 2030 Equation 5.1 [28] is used with the temperature data from [33]. The obtained series of efficiencies can then be passed to the heat pump, which is a *Link* in PyPSA. The efficiency of a *Link* can be more than one value (a series in python for example). This allows for a efficiency that changes at every hour of the year using temperature. Since temperature has a large impact on industrial heat pump performance, this allows for a more accurate efficiency representation throughout the year. Geothermal energy retrieves heat from the ground which is already at a much higher temperature ranging from 50°C to 150 °C. The temperature depends on the location of the well and how deep it is drilled. Since the retrieved heat can be used directly or needs only a slight boost in temperature, the COP is much higher at 20 [34].

$$COP(\Delta T) = 6.81 - 0.121\Delta T + 0.00063\Delta T^2 \tag{5.1}$$

Using Figure 5.5, all components with their technical parameters can be added to the model in PyPSA. Some components will be added with a nominal power of zero since they are non-existent, but they can be built ('extended' in PyPSA) if they are deemed necessary to satisfy the energy demands. Each 50kV substation will have an E-boiler and heat pump connected, making six P2H components in total. A connection between the heat grid and the heat demand at each 13kV substation will also be established with the *Link* component. Since these connections will be connected to the heat grid, the same loss as for the heat grid of 25% has to be introduced. The heat demand at each 13kV substation comes from the small domestic heat pumps installed (from houses and offices for example). This heat demand will also use Equation 5.1 to convert the power grid load to the amount of heat consumed.

Name	Component	Efficiency
E-boiler	Link	1
Heat pump	Link	Variable
Geothermal energy	Link	20
Heat grid expansion to power grid	Link	0.75

Table 5.3: Non-existing components that can be built by the model to satisfy the energy needs

5.3.3 Financial parameters

The financial parameters were converted to values in €/MVA or €/MW to work in PyPSA. These values were obtained from Stedin and HVC as well as from the site of the Energy Transition Model [34]. The specifications used for the costs are shown in Table 5.4.

Name	Component	CAPEX [€]	OPEX [€]
HV substation	Transformer	300.000 [$/MVA$]	6.000* [$/MVA$]
MV substation	Transformer	250.000 [$/MVA$]	5.000* [$/MVA$]
Industrial heat pump	Link	500.000 [$/MW$]	10.000 [$/MW$]
Industrial E-boiler	Link	59.700 [$/MW$]	1.200 [$/MW$]
Geothermal energy	Link	1.325.000 [$/MW$]	26.500 [$/MW$]
Heat grid pipes	Link	200.000 [$/MW$]	4000 [$/MW$]

Table 5.4: Financial parameters of the model. *:not included in model decision making

5.4 Sensitivity analysis

The decisions the model makes can be influenced by the user. The standard is that each component can have a fixed amount of capacity that may not be exceeded. This can be changed to allow the component to extend its own capacity. The costs for extending the capacity are obtained from the *Capital cost* parameter in $€/MVA$ or $€/MW$. The possibility to turn the expansion of specific components on and off will be used to emulate the following 3 scenarios:

- Scenario 1: Only the power grid is allowed to expand, the heat grid can not build any new P2H sources
- Scenario 2: Only the heat grid is allowed to expand, the power grid can not extend the capacity of any transformer
- Scenario 3: Both the power and heat grid are allowed to expand, the model will decide on its own what is the most cost-effective way to satisfy the demands

To evaluate which variables have the most influence on the decision making, a sensitivity analysis has been performed using scenario 3. The variables used and their variability is shown in Table 5.5.

Name	HV transfomer	MV transformer	Industrial heat pump	Industrial E-boiler	Heat grid pipes
Variability [*percentage*]	-40, -20, -10, 0, +10, +20, +40				

Table 5.5: Components to which variability of the capital cost parameter is applied

5.5 Limitations

It is, however, important to mention that the results are based on the assumption that the capacity of components can be done in small incremental steps instead of in larger blocks as is the case in practice. If a substation only needs 2 or 3 MW extra capacity, PyPSA will only calculate the cost of that required extra capacity instead of the 40 MW which is a more realistic number for a new transformer. The same holds true for the P2H components in the heat grid. For the construction of new heat grid connections, the total cost can also be less than assumed in the model if the connections are very close together and if less pipes have to be laid under the ground. These circumstances could therefore make the heat grid a better option in neighbourhoods with large flats.

Further limitations that were not taken into account are the hours and manpower needed to reinforce the substations, to build the P2H components and for new pipes of the heat grid. In reality, the time needed from start to finish could vary greatly, which means that if an energy demand has to be satisfied within a specific time frame there might only be one possible, perhaps less cost-effective, solution.

Lastly, the required space for building new capacity of the substations, for new P2H components or for new heat grid infrastructure, was not used in the decision making. If a substation has to be reinforced and there is no available space to construct an extra or bigger substation, then the only option for consumers who want to move away from natural gas is to be connected to the heat grid. Especially in big cities where free space is scarce or non-existent this solution could become quite common.

6. Results

This chapter describes the results from the use of the model that has been applied to the Drechtsteden region. As explained in Chapter 4 three different scenarios have been chosen to meet the expected power demand in this region in 2030. Section 6.1 shows the results of scenario 1. The results of scenario 2 are described in Section 6.2. Finally, The results of and sensitivity analysis performed on scenario 3 are given in Section 6.3.

In each scenario, the model has to build/expand the necessary components to meet the demand of the system. The system demand is given by the energy profiles of Stedin and HVC. The capacity added will vary per scenario, but the demand will remain constant throughout. The heat demand is the part of the load that can be taken over by the heat grid to reduce the total capacity needed at a substation. The heat demand at each substation stems from electrical load caused by domestic heat pumps in the energy profiles of the 13kV substations. As described in Section 5.3.2, the variable COP is used to convert the electricity demand to heat demand. The maximum demand of heat at each substation is shown in Figure 6.1 and the exact values are shown in Appendix A.2.

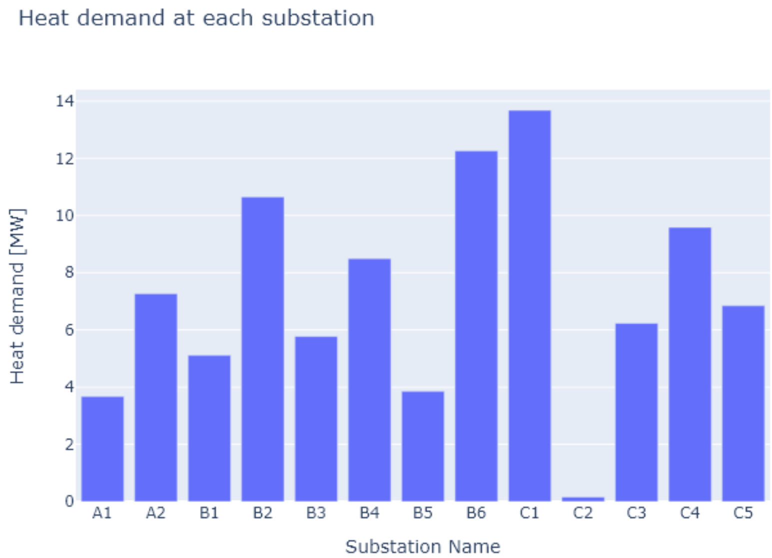


Figure 6.1: Maximum heat demand at each substation in 2030

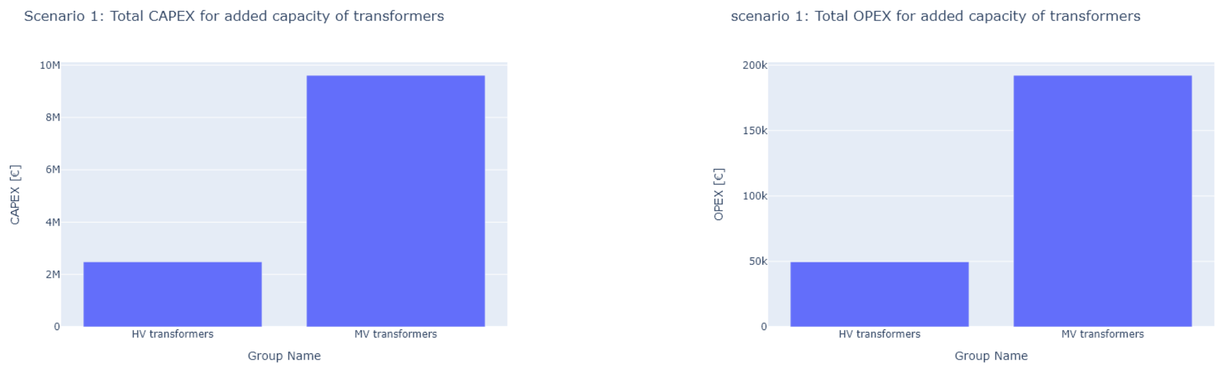
6.1 Scenario 1: Power grid expansion

In the first scenario, the size of the heat grid will stay the same and only the *Transformers* are allowed to increase their capacity. No P2H sources are built and the heat grid is not allowed to extend by building extra pipes to help meet the heat demand at the substations.

In Table 6.1, the extra capacity built and the associated CAPEX and OPEX cost is shown. A comparison of the CAPEX and OPEX of the HV and MV transformer is shown in Figure 6.2. In Figure 6.3, all the substations are shown with the amount of capacity that has been added. This is what will be added on top of the the already existing capacity as stated in 5.1. The added capacity, new capacity, CAPEX and OPEX split up per substation is shown in Appendix A.1.

Name	Capacity [MVA]	CAPEX [€]	OPEX [€/year]
HV Transformer	8.22	2.479.589	49.592
MV Transformer	38.24	9.607.319	192.146

Table 6.1: Scenario 1: Summed cost of the transformer per type



(a) CAPEX of added power capacity

(b) OPEX of substations

Figure 6.2: Scenario 1: Costs of adding capacity to and operation of substations

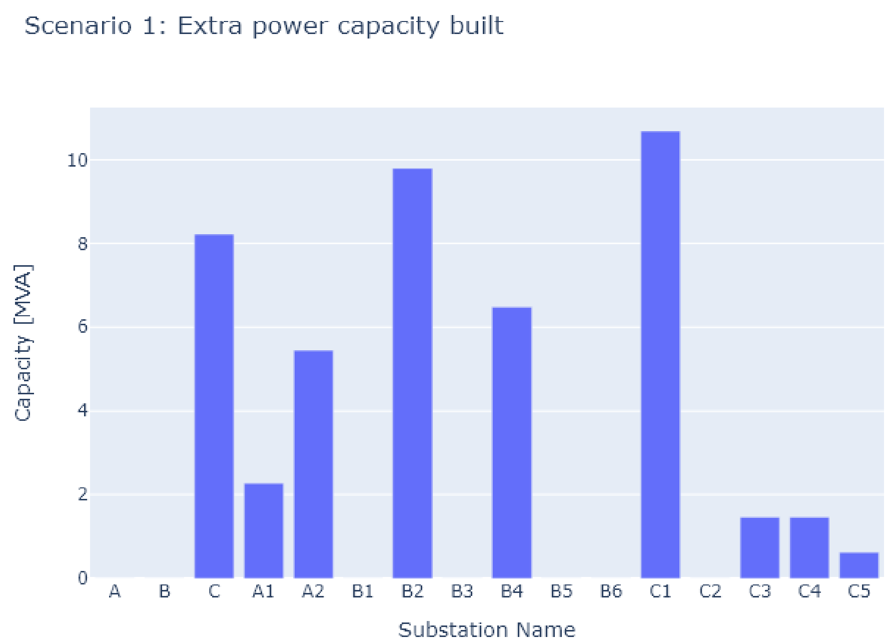


Figure 6.3: Scenario 1: Power capacity added to substations

The extra capacity needed that stands out the most is that of substation C. It is the only 150kV substation that needs to be reinforced. This outcome was not unexpected because this substation had the lowest capacity with only 150 MVA in comparison to 200 MVA and 225 MVA. Looking at the 13kV substations, C1 needed most added capacity with B2 being a close second. These results are important because they can be used to create a priority order of which substations have to be reinforced first to avoid or diminish congestion.

The total energy needs are met, both the electrical demand and the heat demand of the domestic heat pumps. This shows that a heat grid is not needed based on the used energy profiles of 2030.

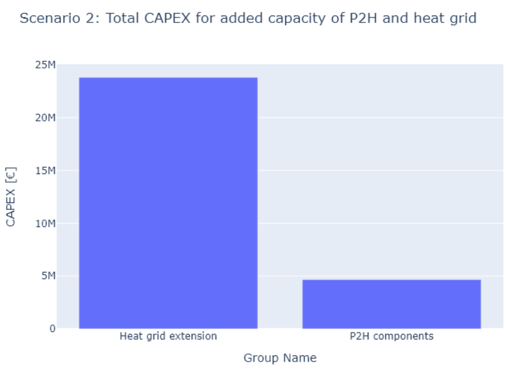
6.2 Scenario 2: Heat grid expansion

In the second scenario, no extra capacity can be added to the *Transformers* and only the heat grid can expand. In Figure 6.5, the P2H components and expansion of the heat grid to satisfy the heat demand at each of the 13kV substations, are shown. The costs made to build and run these components is shown in Figure 6.4. The full numbers split up per component are shown in Appendix A.3.

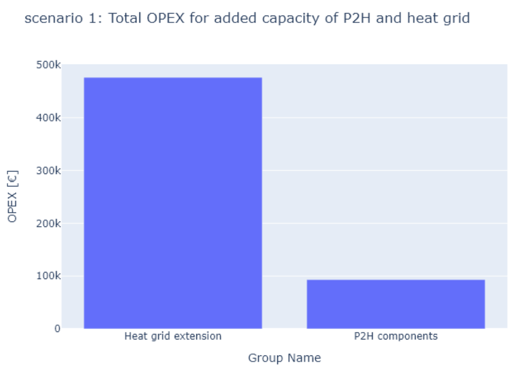
If the heat demand is too high and/or the capacity at a substation is too low, an extension of the heat grid is built. Figure 6.5 shows that some substations have enough capacity to meet the heat demand from Figure 6.1. These results can be used to determine from which substations (neighbourhoods) the highest demand for heat will come and where it would be most cost-effective to start building new connections for the heat grid.

Name	Capacity [MW]	CAPEX [€]	OPEX [€/year]
P2H	78	4.659.311	93.190
Heat grid extension	119	23.818.520	476.370

Table 6.2: Scenario 2: Summed cost of the P2H components and heat grid extension



(a) CAPEX of added heat capacity



(b) OPEX of heat grid components

Figure 6.4: Scenario 2: Costs of adding capacity to the heat grid

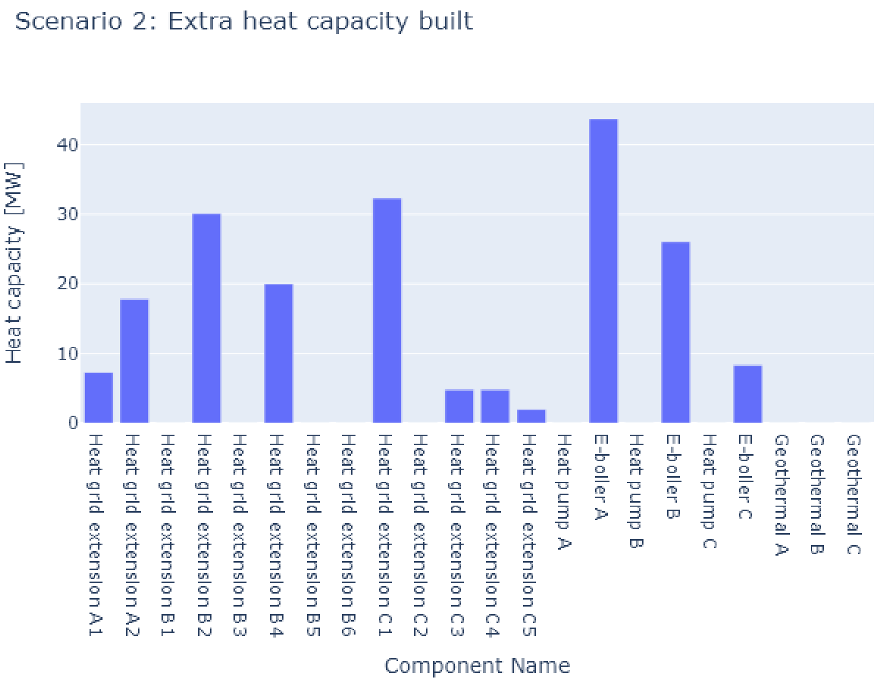


Figure 6.5: Scenario 2: Capacity added to the heat grid

From Figure 6.5 can be seen that the industrial heat pump and geothermal energy are never chosen as a P2H source. This means that both an air-source industrial heat pump and a ground-water source industrial heat-pump are not cost-effective solutions to provide heat for a heat grid. The total capacity of the E-boilers that needs to be built to satisfy all the heat demand is 78 MW, as shown in Table 6.2. Due to the losses introduced by the pipes of the heat grid more power is needed in comparison to when the heat would be directly generated at the place of consumption.

With no infrastructure currently existing for the heat grid to provide heat to the new consumers, a lot of costs would have to be made to build these new connections. The total costs for this heat grid expansion would come down to 30 million € which is almost twice the costs of the power grid only scenario of 16 million € .

The fact that the model managed to perform a successful run means that for scenario 2 the total energy needs are also met. So both the electrical demand and the heat demand of the domestic heat pumps were satisfied. Consequently, the expansion of the power grid is not necessary based on the used energy profiles of 2030.

The P2H sources are not always used since the peak demand for heat is only for limited amount of hours per year. In Figure 6.6, it can be seen that waste heat is primarily used. In figure, 6.7, only the 600 highest heat production values for the heat grid are shown. The amount of hours in 2030 for which the full available capacity of the heat sources is needed is around 50 hours.

Even though the power grid could not expand, the domestic heat pumps were still able to use the remaining capacity of the substations to its fullest. In Figure 6.8 and 6.9, the generation of heat from the domestic heatpumps has been added to the load duration curve. It can be seen that the heatpumps still satisfy the largest amount of the demand for heat.

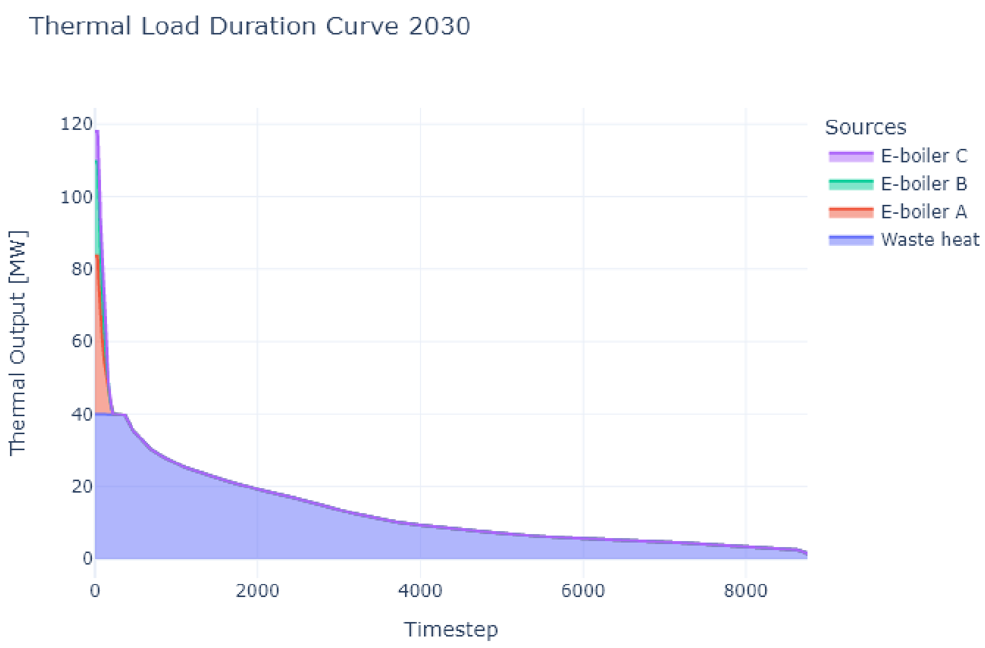


Figure 6.6: Scenario 2: Load duration curve for the full year 2030

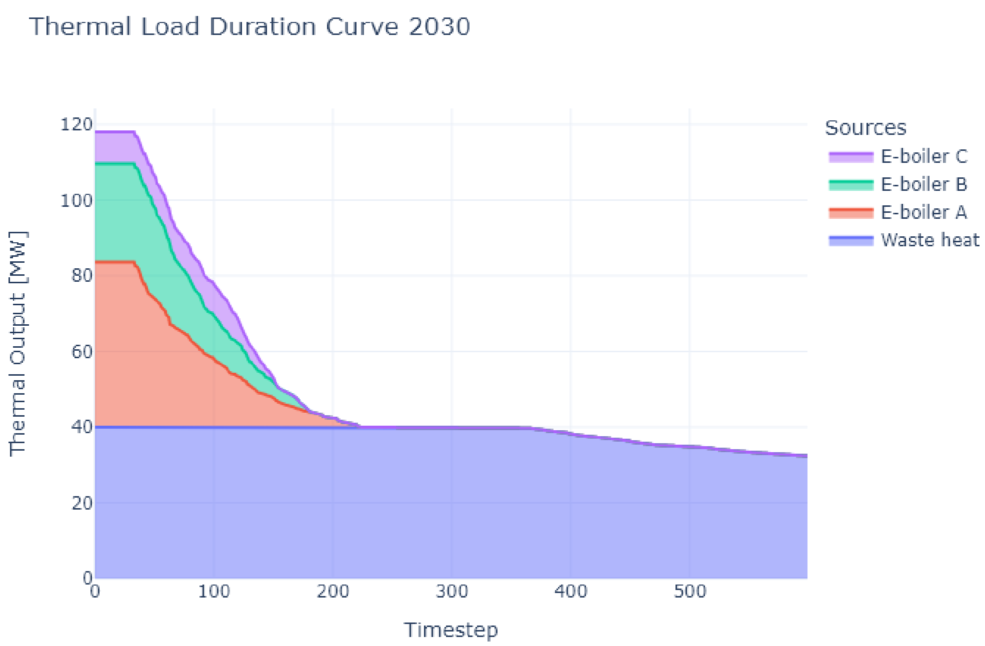


Figure 6.7: Scenario 2: Load duration curve for the 600 highest heat production hours of 2030

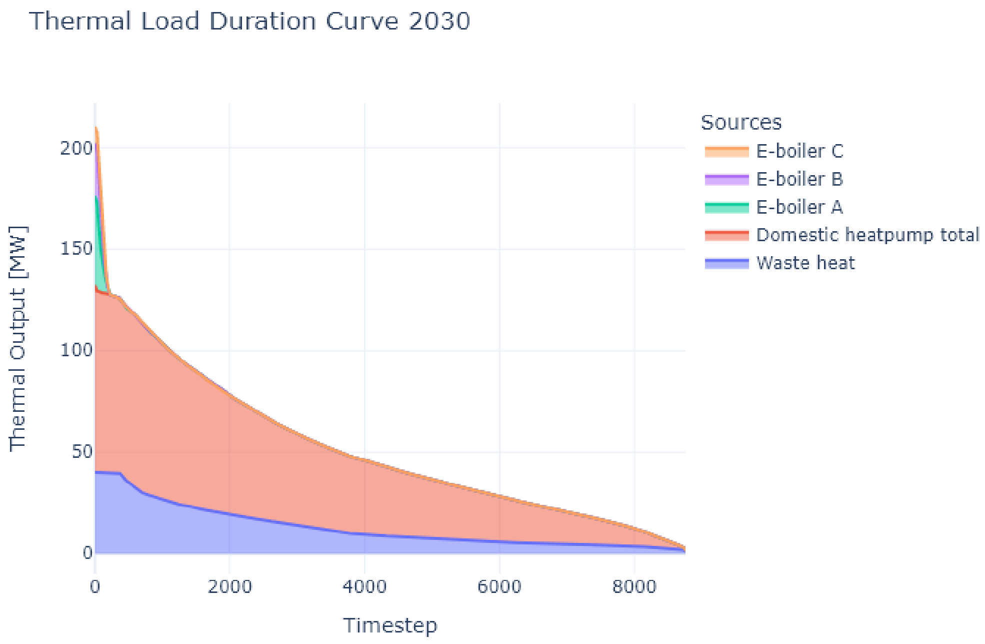


Figure 6.8: Scenario 2: Load duration curve for the full year 2030 with domestic heatpumps

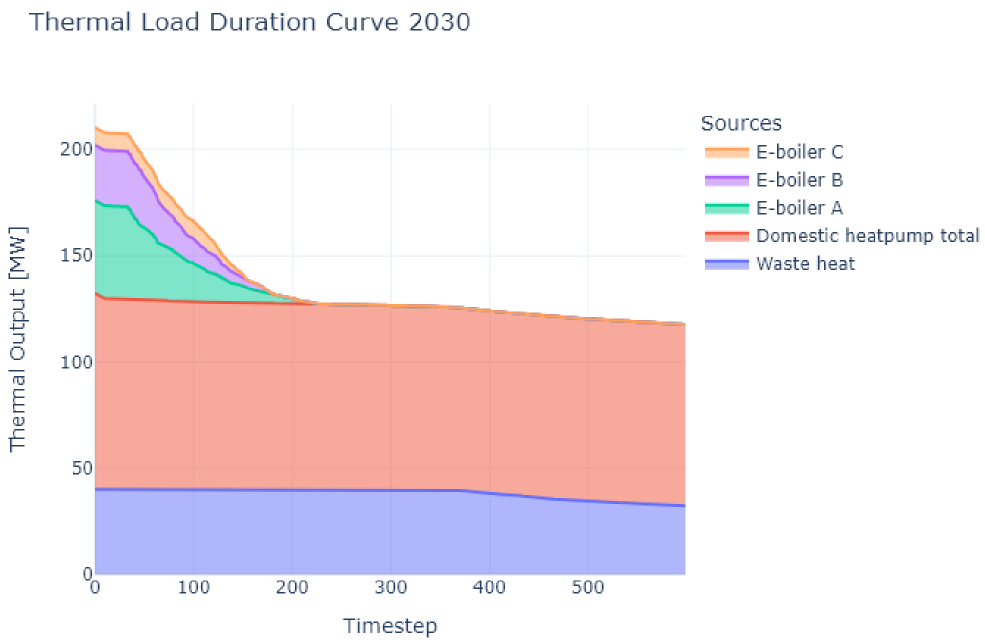


Figure 6.9: Scenario 2: Load duration curve for the 600 highest heat production hours of 2030 with domestic heatpumps

6.3 Scenario 3: No restrictions

Scenario 3 is divided into two parts. The first part shows the result of the model with no interference and change to any variables of the components. The second part describes the sensitivity analysis performed on scenario 3.

6.3.1 Standard conditions

In the third scenario, no heat grid or transformer capacity limitations are enforced and the model can truly optimise.

Running the model showed that the optimisation was successful. The added capacity, CAPEX and OPEX cost are shown in Table 6.3. Consequently, the total cost in scenario 1, see Table 6.1, equals the cost from scenario 3 as shown in Table 6.3. The capacity added by the model per substation for the power grid is shown in Figure 6.10 and per component for the heat grid in Figure 6.11.

Name	Capacity [MVA]	CAPEX [€/year]	OPEX [€]
HV Transformer	8.22	2.479.589	49.592
MV Transformer	38.24	9.607.319	192.146
P2H	0	0	0
Heat grid extension	0	0	0

Table 6.3: Scenario 3: Summed cost of the transformer per type

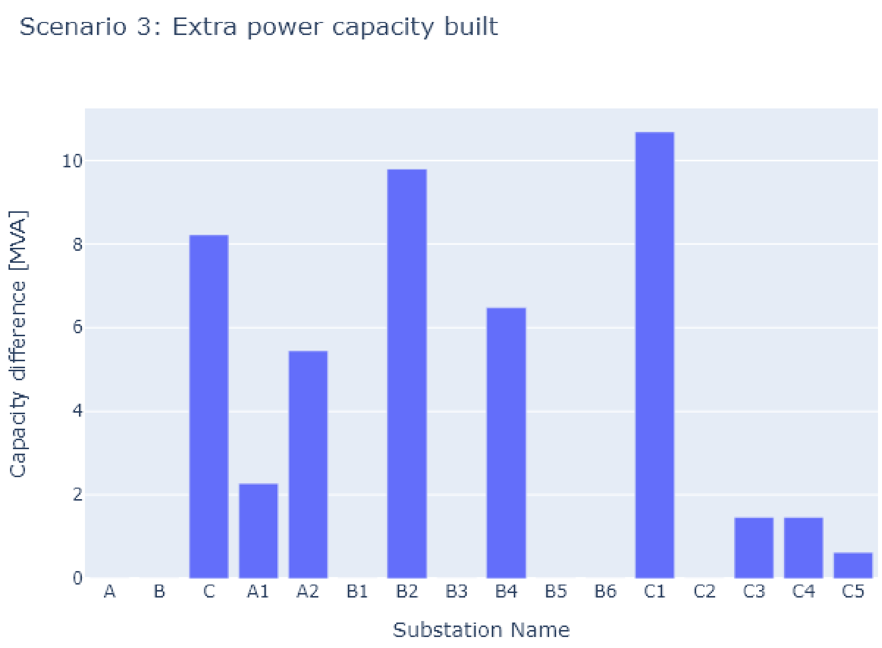


Figure 6.10: Scenario 3: Capacity added to the power grid

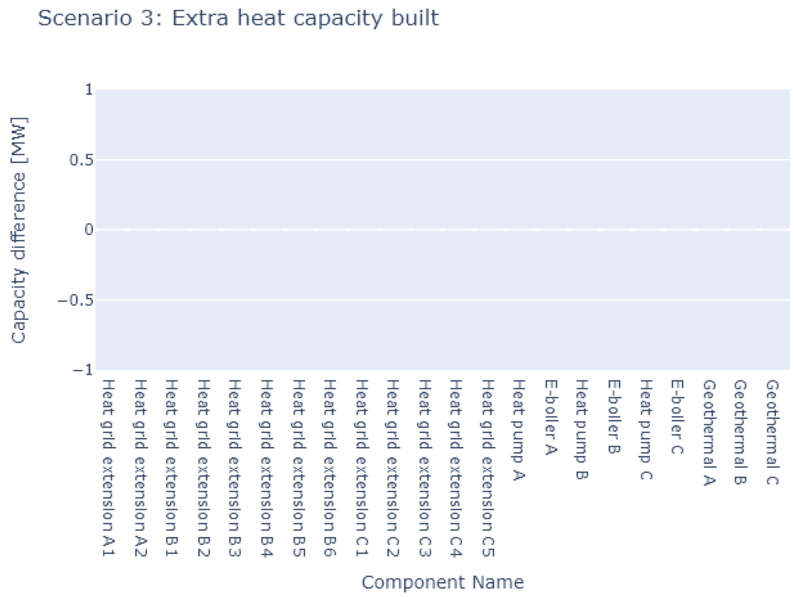


Figure 6.11: Scenario 3: No capacity added to the heat grid

Thus it becomes clear that, based on the parameters given to the model, an optimisation to minimize the system cost does not lead to expansion of the heat grid.

So the same observations as for scenario 1 apply here. Figure 6.10 shows how the model results can be used to prioritise the planning of the reinforcement of the substations. According to the model the heat grid does not need expansion so there is no need to invest into extra P2H sources or to build new connections to the heat grid.

6.3.2 Sensitivity analysis

The financial parameters listed in Table 5.5 were used to perform a sensitivity analysis on the optimisation model in scenario 3. Changing these variables gives a better insight in which costs have most influence on the end result. These increases and decreases of the price emulate events that could happen in practice. An increase in price may happen when raw materials become more expensive, as a consequence of inflation or due to geopolitical events that negatively affect the energy market prices. A decrease in price could happen thanks to subsidies from the government. This might be the case when the government decides to enforce new rules and regulations to decrease the use of fossil fuels or to increase the amount of consumers connected to a heat grid.

The parameters were changed accordint to Table 5.5 and reapplied in the model. The outcome was as follows:

- Varying the CAPEX of the E-boiler caused no changes in the end result.
- Varying the CAPEX of the industrial heat pump caused no changes in the end result.
- Increase in the CAPEX of the transformers resulted in less power grid reinforcement. No change happened when the price decreased.
- Decrease in the CAPEX of the heat grid extension resulted in the heat grid being extended. No change happened when the price increased.

In Figure 6.12, the change in extra capacity built caused by the varying of the CAPEX of the transformers is shown.
In Figure 6.13, the change in extra capacity built caused by the varying of the CAPEX of the extension of the heat grid is shown.

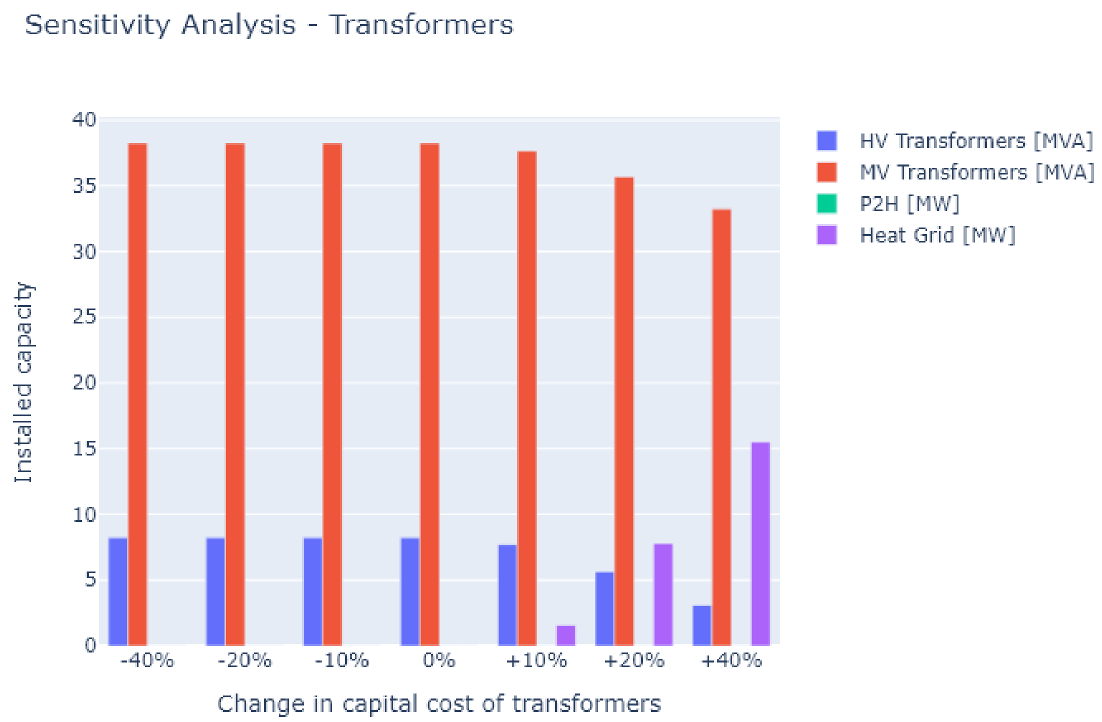


Figure 6.12: Scenario 3: Sensitivity of the model to changes in CAPEX of substations

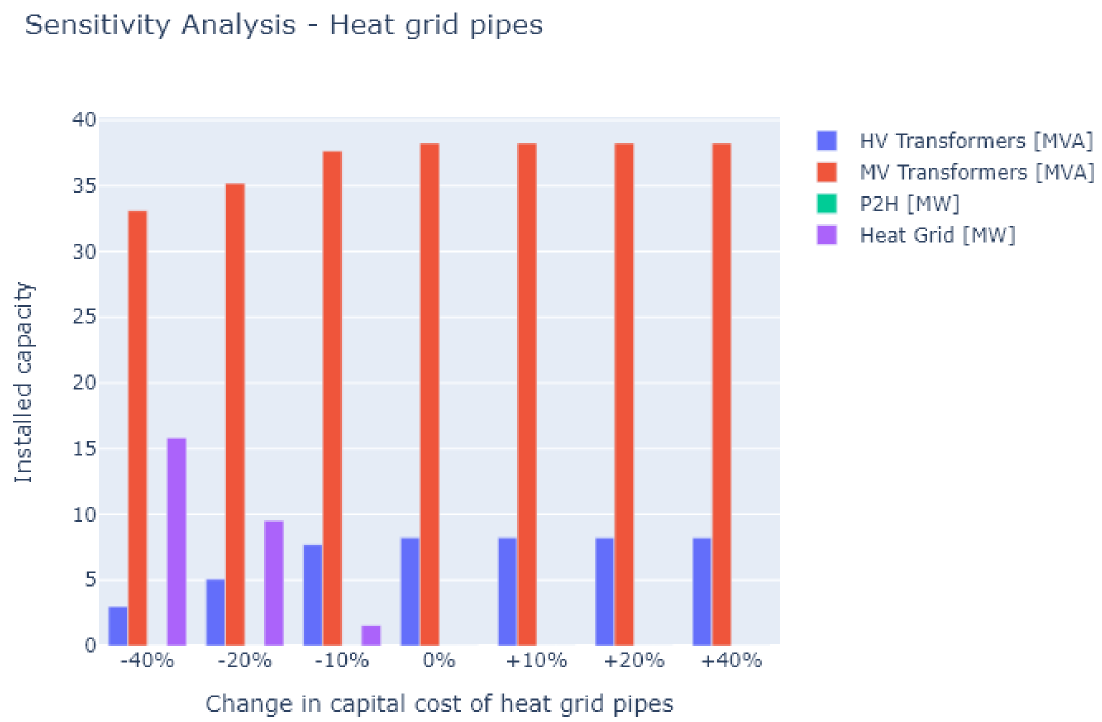


Figure 6.13: Scenario 3: Sensitivity of the model to changes in CAPEX of heat grid expansion

7. Discussion

In the following chapter, the results of the model obtained in Chapter 6 are discussed. Section 7.1 answers the four sub-questions of this thesis and in Section 7.2 a suitable location for a back-up heat source is determined.

7.1 Answers to the research questions

7.1.1 Sub-question 1

Can different energy grids work independently to meet the energy demand or will coordination be necessary?

The study finds that the different energy grids, namely the power grid and the heat grid, will most probably not operate independently to meet future energy demands effectively. If the heat grid does not have to be carbon-neutral, then natural gas can be used as is most often the case currently. This would increase the amount of greenhouse gasses produced and work against reaching the required sustainability goals. A special case were the power grid and heat grid could operate separately, is if instead of natural gas, hydrogen would be used to fuel CHP and gas boilers. Hydrogen does not produce greenhouse gasses when combusted and is a viable alternative that would not impact the power grid. In the near future (2030), the production and export/import of hydrogen will not be ready to meet the demand needed to provide the heat grids with enough energy. It is also possible, in theory, to only use electricity to satisfy the heat demand. But the practical implementation of expanding the existing power grid infrastructure is not realisable. As such, interaction between different energy carriers is necessary when looking at solutions for 2030.

7.1.2 Sub-question 2

What role can waste heat play as a heat source in a heat grid?

Waste heat can play a vital role in supplying heat to a heat grid if it uses existing infrastructure and industry. Building new sources for waste heat is also a possibility, such as electrolysers, however that would still impact the power grid. If the source is already established and connected to the power grid, the added impact would be zero or negligible in comparison to a P2H source. It would even further improve the process from which the heat is retrieved since more energy is being used.

The usefulness of the waste heat source does vary per source. For example, the waste heat from a data-center can be used, but since the temperature is quite low a lot of energy (electricity) is still needed to use it in most current heat grids. In comparison, the waste heat from a waste incineration plant is much higher and can be used directly.

7.1.3 Sub-question 3

How does power grid reinforcement compare to heat grid expansion in cost to fulfill the heat demand in 2030?

The results indicate that using the heat grid in combination with P2H sources can provide enough heat to satisfy the heat demand. This method does first use up as much capacity of the current power grid as possible before building new P2H sources and extending the heat grid pipe network. Even though it might be possible, it is however not cost-effective. When comparing scenario 2 (only heat grid expansion) to scenario 1 (only power grid expansion) the total CAPEX cost was significantly higher for scenario 2 being more than twice as much. Despite this, if there is existing heat grid infrastructure and readily available sources such as waste heat it can be more cost-effective to first use the heat grid to its fullest with the current heat sources.

7.1.4 Sub-question 4

How does variation in the technology cost influence the decisions in overall investments?

The technology costs that had the most impact were determined using the sensitivity analysis. Since the model optimised the system based on cost, the CAPEX cost of the components to be build or reinforced in the model were used as the parameters to vary. The variation was done from -40% to +40%, with the exact values shown in 5.5.

Varying the CAPEX of the P2H-sources in the specified range had no effect on the models decision making. This means that based on CAPEX and OPEX, the E-boiler is the most cost-effective solution to generate heat from electricity.

Varying the CAPEX of the transformers did change the results of the optimisation. If the price of the transformers increased, then the heat grid would be expanded. The more the cost went up, the more the heat grid expanded and the less the transformers were reinforced. If the price of the transformers decreased, nothing happened.

Varying the CAPEX of the pipes used in the heat grid network also led to different results. If the price of the pipes for the heat grid increased, nothing happened. But when the price decreased, the model started to expand the heat grid. Just the same as for the transformer costs, the more the price decreased the more the heat grid was expanded.

7.2 HVC back-up boiler

HVC manages the heat grid and has to ensure that their customers are provided with the heat for which they have connection. Their heat grid was fully dependent on the waste heat from the waste incineration plant, but have since added an E-boiler of 25MW as a back-up heat source in case that the heat from the waste incineration plant can not be provided or maintenance has to be done. However, with the expected growth of new connections to the heat grid in case of failure of the waste heat source a single E-boiler will not be enough to guarantee that 100% of the heat demand can be met. The solution would be to add another E-boiler of 25WM. With the knowledge obtained from performing the optimisation, an analysis of the power grid can be done in the Drechtsteden region to see if one of the three 50 kV substations (A, B and C) have capacity left over in scenario 3 (which is the same as scenario 1, as mentioned in Section 5.3) to place an extra back-up E-boiler at that substation.

To see what the maximum power demand at substations A, B and C is, the load duration curve will be used. In Figures 7.1, 7.2 and 7.3, the 1000 highest values of the load duration curves is shown. These have been cropped to only show 1000 to better see the maximum power demand value.

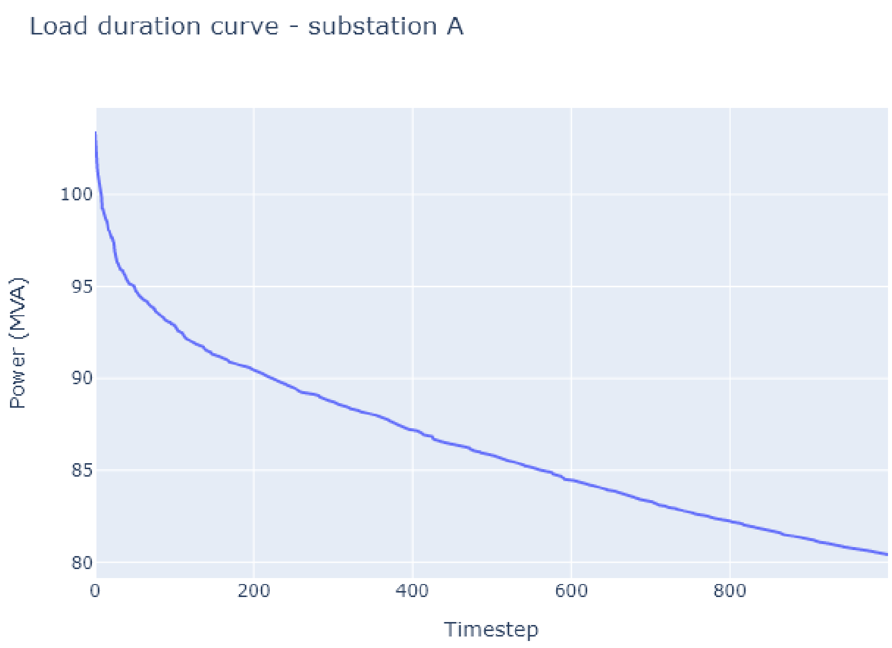


Figure 7.1: Load duration curve of the power demand of substation A

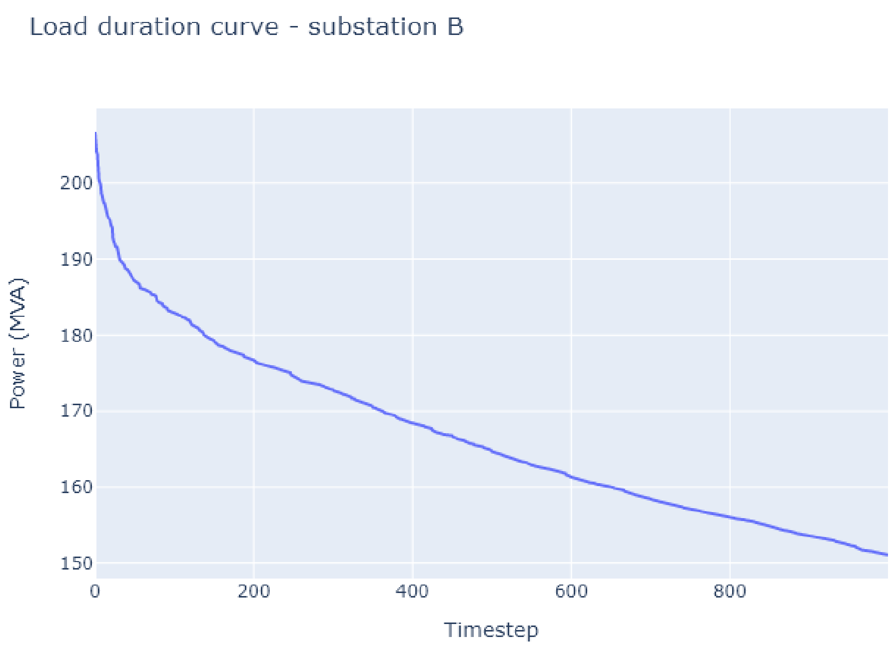


Figure 7.2: Load duration curve of the power demand of substation B

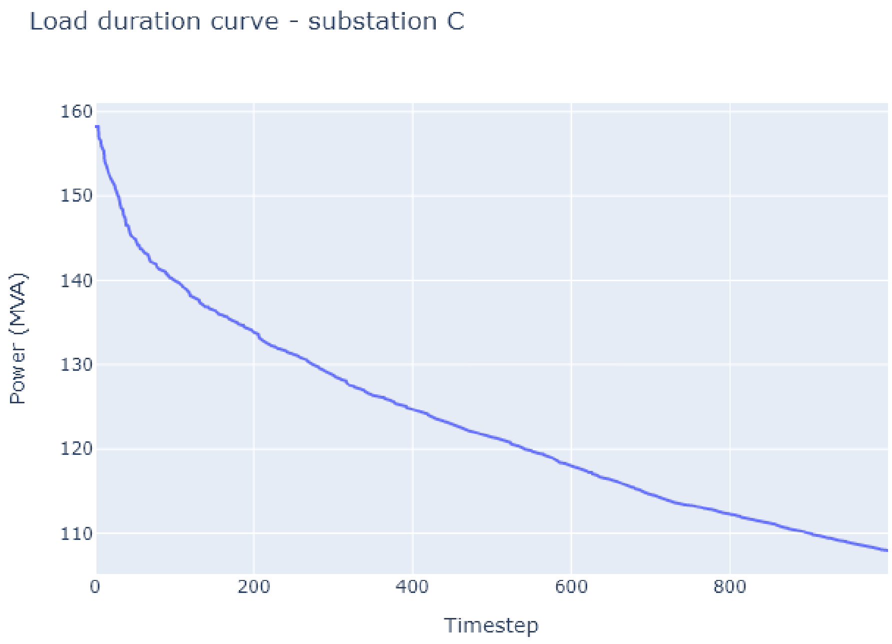


Figure 7.3: Load duration curve of the power demand of substation C

Substation	A	B	C
Capacity	200	225	150
Max power demand	104	208	159

Table 7.1: Current capacity and maximum power demand in 2030 of the 50kV substations A, B and C

The capacities of the substations given in Table 5.1 and the maximum power demand as seen in Figures 7.1, 7.2 and 7.3 are put side by side and shown in Table 7.1. Substation A has more than enough capacity left to add a 25MW E-boiler that will only be used as a back-up heat source. Substation C is already past its capacity, and with substation B having less than 25MW left there is also no alternative.

In conclusion, if a back-up heat source in the form of a 25MW E-boiler has to be added to the heat grid to guarantee the supply of heat to the customers of HVC then it has to be built at and connected to substation A.

8. Conclusions and recommendations

This thesis researched a cost optimisation of a power grid and a heat grid working together as an integrated energy system to answer the following question:

How can optimisation of an integrated energy system, consisting of a power grid and carbon neutral heat grid, satisfy the demand for heat at minimal cost

To answer this question, an optimisation model was made. The model had to contain two types of energy, electricity and heat. The principle of integral infrastructure was used to create an integrated energy system of a power grid and heat grid.

The Python tool PyPSA was chosen to create an accurate representation of the Dutch power grid and heat grid. The components that make up both grids and the corresponding technical and financial parameters were obtained from Stedin and HVC. The electrical demand and generation at each electrical substation and heat demand in the heat grid was used as input data to establish the model. The year 2030 was used for the demands in the model.

The objective function of the model is to minimize the total system cost and the model only provides output if all energy demands in the system are satisfied. The electricity demand at each substation from the power grid is split up in electrical load and load associated with heat such as heat pumps. The heat demand from the heat grid consists of only the users of the heat grid.

The model setup was as follows: to satisfy the energy demand in the year 2030, extra capacity can be added to the components of the model. The substations in the power grid can increase their capacity. The heat grid can build Power-to-Heat (P2H) sources to increase heat generation. The heat grid can also build extra connections to each of the substations to take over a part of the heat demand to decrease electrical load on a specific substation. Three different scenarios were used in a case study to validate the model and give recommendations on future courses of actions and investments. In the first scenario only the power grid was allowed to expand capacity. In the second scenario only the heat grid could expand capacity. In the third scenario there was no interference with the decision making of the model but a sensitivity analysis was carried out by varying the capital cost (capital expenditure) of the used components in the model.

The three scenarios were applied on a case study concerning the Drechtsteden region were Stedin is the District System Operator (DSO) in charge of electricity and gas and HVC is the DSO in charge of the heat grid.

In the first scenario, the final result showed that the minimum capital cost needed to satisfy the power demand is 5.6 million € for the high voltage substations (150/52.5 kV) and 9.2 million € for the medium voltage substations (52.5/13 kV). Resulting in a total capital cost of nearly 15 million €.

In the second scenario, it turned out that the minimum capital cost needed to satisfy the heat demand is 4.4 million € for the P2H sources and 26 million € for the pipes needed to connect the new consumers to the heat grid. This resulted in a total capital cost of just over 30 million €.

In the third scenario, the model showed that only the change in capital cost of the reinforcement of the substations and changes in the cost of pipes to connect new consumers had an effect on the decision making of the model:

- In the case of no changes to the variables the model would only choose to add capacity to the power grid.

- If the capital cost of transformers is increased, the heat grid starts to take over parts of the heat demand at the substations. For a decrease in capital cost, no changes were observed.
- If the capital cost of the heat grid connection to new consumers is decreased, the heat grid starts to take over parts of the heat demand at substations. For an increase in capital cost, no changes were observed

If prices remain constant, no shortages of materials for components occur and no specific subsidies are given, the most cost effective solution is to only reinforce the power grid. Future heat demand will be satisfied entirely through the direct conversion of electricity into heat in a decentralized way at the location of consumption. The 25% loss in the heat grid pipes together with the high cost of laying down pipes to new consumers reduces the viability of using district heating as a cost-effective means to meet the heat demand.

The main outcome of this thesis is therefore that the most cost effective way to satisfy the electric and heat demand in the Drechtsteden region in the year 2030, based on the parameters and values as used by PyPSA, is to use the power grid. If the prices of transformers for substations needed to reinforce the power grid become higher or the cost of building extra connections to the heat grid decreases, then part of the heat demand can be fulfilled by the heat grid. However, this only holds true if an already existing heat grid is near the location of the heat demand to be taken over.

8.1 Recommendations

Stedin and HVC already have plans for the foreseeable future where demand will increase and also know how much time it will take to build or reinforce the components necessary to fulfill the increase in demand. Integrating these plans into the model could provide a more accurate result. Secondly, this thesis compared the cost of the power together with a heat grid to satisfy the heat demand in 2030. A next step could be to look at the year 2050. This will however introduce more uncertainties.Thirdly, storage in all kinds (electricity, hydrogen or heat) will become an indispensable element for dealing with overproduction of electricity at low demand moments. It would be interesting to see how storage would impact the model results. Finally, it would be interesting to expand the model to investigate the influence of the available physical space for building the added capacity or new components.

A. Appendix

A.1 Case study

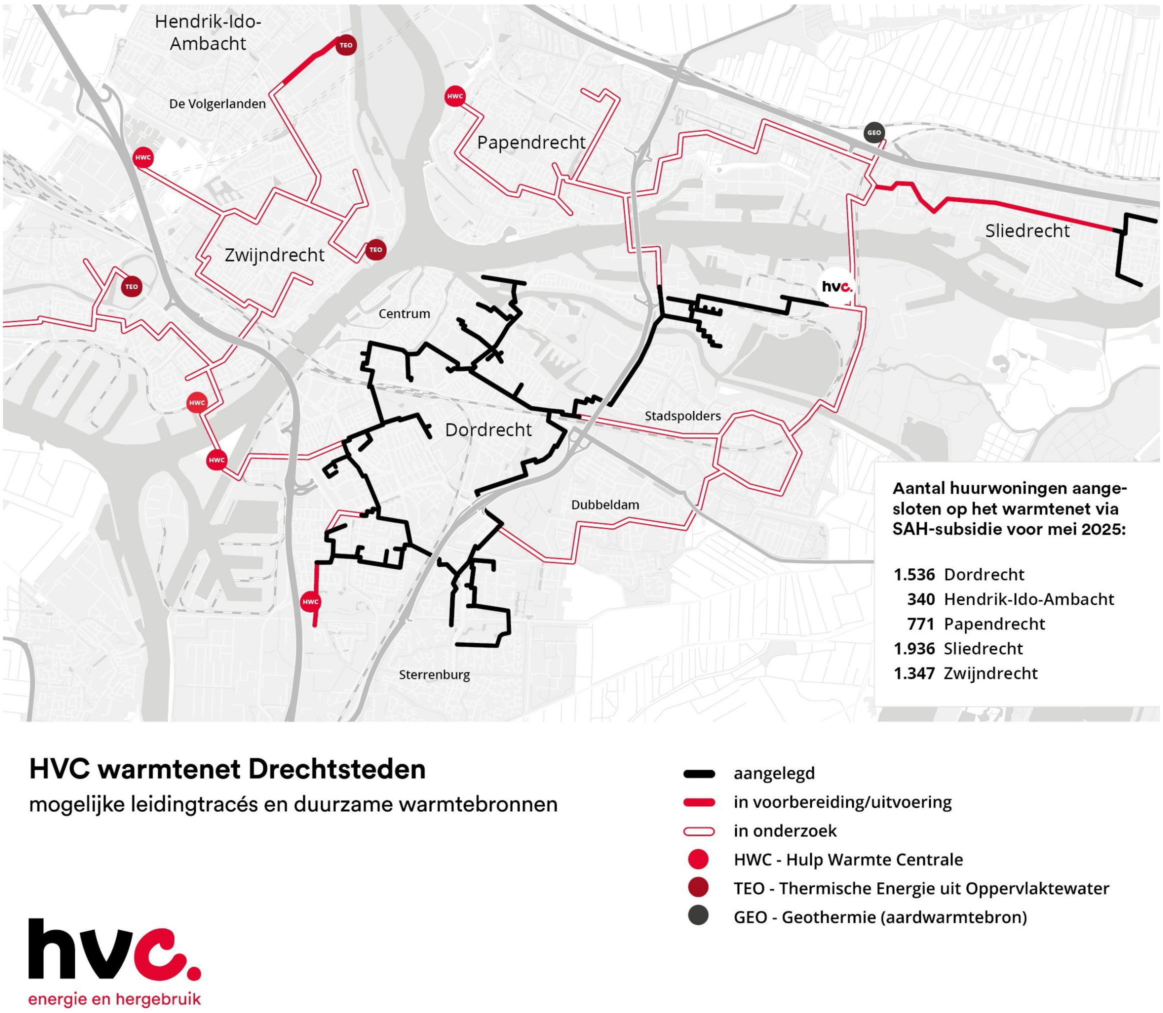


Figure A.1: Plans for expansion for the heat grid of HVC

A.2 Results

Name	Added capacity	New capacity	CAPEX	OPEX
A	0	200	0	0
A1	2.28	42.28	572..414	11.448
A2	5.44	30.44	1.368.048	27.361
B	0	0	0	0
B1	0	0	0	0
B2	9.80	41.8	2.461.884	49.238
B3	0	0	0	0
B4	6.48	38.48	1.628.540	32.571
B5	0	0	0	0
B6	0	0	0	0
C	18.47	168.47	5.568.033	111.361
C1	10.68	50.68	2.684.508	53.690
C2	0	40	0	0
C3	0	40	0	0
C4	1.46	41.46	367.520	7.350
C5	0.62	30.62	156.885	3.138

Table A.1: Scenario 1: Added power capacity and the new final capacity per substation

Name	Heat demand $[MW]$
A1	3.67
A2	7.26
B1	5.11
B2	10.65
B3	5.78
B4	8.50
B5	3.85
B6	12.26
C1	13.68
C2	0.16
C3	6.24
C4	9.59
C5	6.85

Table A.2: Maximum heat demand per substation

Name	Capacity	CAPEX	OPEX
E-boiler A	0.00	0	0
Heat pump A	48.25	2.880.531	57.611
E-boiler B	0.00	0	0
Heat pump B	25.37	1.514.608	30.292
E-boiler C	0.00	0	0
Heat pump C	0.00	0	0
Heat grid expansion A1	7.27	1.454.219	29.084
Heat grid expansion A2	17.86	3.571.285	71.426
Heat grid expansion B1	0.00	0	0
Heat grid expansion B2	30.05	6.010.889	120.218
Heat grid expansion B3	0.00	0	0
Heat grid expansion B4	20.03	4.005.993	80.120
Heat grid expansion B5	0.00	0	0
Heat grid expansion B6	0.00	0	0
Heat grid expansion C1	32.30	6.460.718	129.214
Heat grid expansion C2	0.00	0	0
Heat grid expansion C3	16.31	3.262.844	65.257
Heat grid expansion C4	6.13	1.225.898	24.518
Heat grid expansion C5	1.98	396.597	7.932

Table A.3: Scenario 2: Added heat capacity and the CAPEX and OPEX per component

Name	Added capacity [MVA]	New capacity [MVA]	CAPEX [€]	OPEX [€]
A	0	200	0	0
A1	2.28	42.28	572..414	11.448
A2	5.44	30.44	1.368.048	27.361
B	0	0	0	0
B1	0	0	0	0
B2	9.80	41.8	2.461.884	49.238
B3	0	0	0	0
B4	6.48	38.48	1.628.540	32.571
B5	0	0	0	0
B6	0	0	0	0
C	18.47	168.47	5.568.033	111.361
C1	10.68	50.68	2.684.508	53.690
C2	0	40	0	0
C3	0	40	0	0
C4	1.46	41.46	367.520	7.350
C5	0.62	30.62	156.885	3.138
P2H	0 [MW]	0 [MW]	0	0
Heat grid extension	0 [MW]	0 [MW]	0	0

Table A.4: Scenario 3: Added power capacity per substation and total heat capacity

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