Operational study on a future heating system of Amsterdam without natural gas

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Abstract

Amsterdam is set to eliminate natural gas as a resource for heating its buildings, as it aims to be independent from fossil fuels in the heating system by 2050. This study aims to provide the missing technical knowledge of transitioning the heating system and investigates the operation of a renewable heating system for Amsterdam in 2050 by three different scenarios: 1) reference scenario 2) renewable heating scenario without thermal storage and 3) renewable heating scenario with thermal storage. This study also takes the broader perspective into account considering socio-technical transformations of systems, by the Multi-Level Perspective. From that perspective, it is important to consider the mechanisms surrounding socio-technical changes. Technically, it has been found that with an expansion of the district heating network, replacements of the CHP-plants with biomass as a recourse, a larger share of excess heat and the addition of electric heat pumps, an electric boiler, a biogas-fired boiler, solar thermal energy and thermal storage, the heat sector is able to fully operate without natural gas.

Keywords: energy engineering, energy planning, district heating, heating systems, combined heat and power, renewables, transitional studies

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Preface

This thesis is the final product of the master Sustainable Cities from the University of Aalborg in Copenhagen. It concludes a two-year study program that focuses on sustainability in all different aspects of urban planning, such as transportation, food and the energy sector. Energy can also be considered a cross-sector within urban planning, as it is rooted in many of those sectors. With that, energy may be seen as a highly influential aspect in becoming more sustainable as a city. It therefore has my particular interest to investigate a heating system that runs on renewables. A study on an energy system of a city associates well with my master outlines, as the university has a renowned expertise in energy planning.

Besides its relevance in sustainability, I started this thesis and this master degree with a passion for spatial planning and urban design, and planning an energy system is a combination of both fields. I proudly present to you a study on a renewable heating system for Amsterdam.

1. Introduction

With the international signing of the 2015 Paris Agreements to halt climate change, nations across the globe agree to recognize that "sustainable lifestyles and sustainable patterns of consumption and production (…) play an important role in addressing climate change" (United Nations, 2015, p. 4) With that, the energy sector is expected to (continue to) change. In the long run, the sector is ambitioned to shift from a fossil fuel dominance to a sector fully operating on renewables. As of today, renewable energy is still in a development stage. Often, it seems costly and/or complex. Though this may be correct in the short term, studies show that transitioning to a renewable energy mix is feasible in the long term. "In terms of costs, based on 2020 price assumptions a 100% renewable energy scenario will be approximately 20% more expensive than a business as-us-usual scenario, but under 2050 price assumptions they will be the same price." (Connolly & Vad Mathiesen, 2014, p. 8). In transforming an energy system towards being fully renewable, a key change to the system is the widespread implementation of district heating. Commonly, houses are heated with individual gas-fired boilers or radiators. These use natural gas to heat water or generate steam, which then heats the home by transportation through pipes or tubes. Natural gas boiler or radiators are widely implemented in the individual heating of houses in the Netherlands. Studies show that a more efficient way of heating houses is to centralize the production of heating (Connolly & Vad Mathiesen, 2014). This allows the sharing of the production capacity, which reduces the thermal capacity necessary to meet the heat demand and in turn uses less fuel. The heating produced in such a common boiler or plant is then delivered to those in demand of heat. The heat is transported through a large network of pipes usually in the form of hot water. This concept of more centralized heat production is called district heating. Besides the centralization of production, district heating also allows the utilization of waste heat from power plants and industries. Heat from these sources is captured and used to heat water, which in turn is transported through the district heating network. In doing so, it lowers the amount of fuel needed to supply heating. A third advantage of district heating is that it allows solar thermal and geothermal energy to be included in the widespread supply of heat. Energy from these renewable sources is used to heat water too, which is also transported through the district heating network.

1.1. The case of Amsterdam

The heat supply in the Netherlands is mainly provided by natural gas. It accounts for around 80% of the Dutch heating market (Persson & Werner, 2015). Most of that natural gas is retrieved domestically, which has led to national environmental concern, especially in the northeastern part of the Netherlands, where empty gas fields subtract and cause a sinking surface. As a result, (anthropogenic) earthquakes cause severe damage and danger to locals (NAM, 2015). Pressured by citizen organizations and local governments, the national government has since 2016prioritized to be fully independent from natural gas by 2050 in all the nation's households (Ministry of Economic Affairs and Climate Policy, 2016). As the capital of the Netherlands, Amsterdam, is home to about 825.000 inhabitants and is one of the most densely populated areas of the country. With that, the demand for heat is relatively concentrated (appendix Figure 9). And as explained earlier, short distances in urban areas suit well to supply heat in general (Connoly, et al., 2013). Amsterdam already has one of the country's largest district heating networks. Nevertheless, it only supplies heat to about a quarter of the city's buildings (Municipality of Amsterdam, 2016). Though new buildings are instantly connected to the district heating network, most existing buildings are heated with individual gas-fired boilers. Currently, in line with national numbers, around 80 to 90% of the city's heat demand is covered by burning natural gas. Natural gas is also used to generate electricity in the city's power plants. In aspiring to eliminate natural gas as an energy source, the city has published a strategy for an Amsterdam without natural gas by 2040. It wishes to expand the district heating network as much as possible, aiming to go from 72.000 in 2015 connected buildings (the latest published measure) to 102.000 by 2020 and 325.000 by 2040. The strategy emphasizes the importance of a powerful cooperation between inhabitants, housing corporations, energy suppliers, net operators and the municipality. Pipes are owned by municipalities or net operators; networks are connected to houses owned by housing corporations; the heat provided comes from energy suppliers and inhabitants are the ones using it. Stakeholders in district heating heavily depend on each other. In steering the process of creating a renewable heating system, the municipality mainly plays a facilitating role in engaging all stakeholders. As the municipal strategy also summarizes, the technical knowledge of how to build a renewable heating system is lacking. This study aims to provide such technical know-how, by modelling a renewable heating system for Amsterdam.

A major transition of an energy system is complex and can take decades. This study builds on the transitional theory of systems, which is called the Multi-Level Perspective. It explains how certain systems, the heating system in particular, are changed over time. A good example of such a process is the case of Sweden. There, the heating system transitioned successfully from being oil-based to renewables. Heating systems have successfully been transformed from fossils to renewables in the recent past. As will be elaborated on in the transitional theory, researchers have examined this transition in Sweden (Ericsson & Di Lucia, 2014). Such a heating system can first be destructed (de-aligned) and then reformed (re-aligned). In a timeframe of 1960-2011, the Swedish district heating production transitioned from being completely dependent on oil to being dominated by biomass and other renewable energy sources. After the oil crisis triggered the fall of the existing oil-based heating system by lowering the significance of oil in the system, biomass emerged in the 1990s as a steered process governed by actors and supported by external events. In other words, a series of processes have stimulated the development of biomass in Sweden. This case will be illustrated with the Multi-Level Perspective and related to this study of Amsterdam's heating system. Supported by the Multi-Level Perspective, this will be further elaborated upon in the transition theory chapter. Relating Amsterdam's heating system with its current dominance in natural gas and ambition to operate on renewables and excess heat, the possible transition of its heating system can be illustrated from a transitional perspective.

1.2. Research question

This study compares Amsterdam’s current heating system with a renewable heating system that uses no fossil fuels. It aims to illustrate how a renewable energy system can be operated, while providing the same amount of heat as in the current heating system. The reference scenario is the current heating system and is compared to two different renewable scenarios. One renewable scenario includes thermal storage and the other excludes thermal storage. As will be described in the methodology, thermal storage brings along complexity, which is why the renewable scenario are of two different kinds. Additionally, it is important to consider the transition of a heating system from a broader perspective, such as the Sweden case. This study relates to the Multi-Level Perspective, which will be explored in the theoretical background chapter and will be discussed in the discussion chapter. The research question and its corresponding sub-questions are as follows.

While meeting the city’s heat demand, how can Amsterdam’s heating system fully operate on renewable energy by 2050?

- How does the current heating system operate?
- How does a renewable heating system without thermal storage operate?
- How does a renewable heating system with thermal storage operate?
- How does the current heating system compare to the renewable scenarios?
- How can the heating system change over time from a Multi-Level Perspective?

1.3. Scope

This study focusses on the heat sector of Amsterdam. The heat sector is part of the city’s energy system. This study attempts to focus on the heat sector only, despite including electricity for CHP plant, electric heat pump and electric boiler operation. This study chooses that particular focus on heat, because doing a full energy system study requires the inclusion of the electricity market, which could lose the geographical focus on the city. This is because the electricity market tends to be widespread, cross-country or international. For example, off shore wind parks generate electricity that is used in Amsterdam, but is not geographically part of the city. Furthermore, import and export of electricity influences the geographical complexities. An energy system study on a city would then be more suitable to a larger geographical scale. The heat market, however, tends to be more of a local market as district heating is mostly applicable to areas with high population densities, partly due to the fact that network losses increase significantly when distances for transportation increase. Thus, focusing on the heat market avoids geographical complexity of energy sources for electricity. This allows an energy study on a city scale. However, electricity cannot be fully disregarded as cogeneration generates heat and power. For that power, the electricity spot market is included in this study. This will be further explained in the methodology.

2. Theoretical background

2.1. Multi-Level Perspective

To analyze the transition from natural gas to renewable energy sources in the Dutch capital's heating system, this study employs an analytical approach based on the Multi-Level Perspective (Geels, 2002). The Multi-Level Perspective theory provides an explanation to transitions in sustainability. Geels describes that a transition can be explained by the (changing) dominance of certain technological practices in society, such as the dominance of fossil fuels in energy production. His theory conceptualizes dynamic patterns in socio-technical transitions, and is meant to describe such transitions. It involves changes in technology and society, and focusses on the relation between them. A new technology, such as nuclear power by the time, may technically have the ability to completely change the energy system in a short amount of time, but it is the connection to society that decides if it can create an energy transition. This is because, as he claims, technology is deeply embedded in society by its user practices, regulation, industrial networks, infrastructure and its symbolic meaning. It is the perspective to that technology that defines its dominance. Because, according to Geels, technology itself has no power. It only fulfills societal functions in associations with human interaction, societal structures and organizations. Because of that human perspective on technology, core actors lie at the center of the theory. In this study, those actors are inhabitants, housing corporations, energy suppliers, net operators and the municipality. Though this study does not attempt a stakeholder analysis, it is important to consider the presence of different stakeholders, because, as mentioned briefly in the introduction, these stakeholders are depending on each other. Furthermore, the Multi-Level Perspective builds on three main concepts or developments that can change a certain system: landscape developments, socio-technical regimes and technological niches. The following elaborates on these three terms.

To explain the Multi-Level Perspective in more detail, Geels wrote another article (Geels, 2011). A certain socio-technical system can change over time. The system in this study is the heating system of Amsterdam. Geels describes that a system relates to tangible and measurable artefacts, such as consumption patterns, infrastructure and market shares. The heating system can be displayed by its energy mix and leaves infrastructural traces by the ways in which heating is done. Figure 1 displays the elements of a system as such in abstract form, as created by Geels. He explains that systems change by developments on landscape, regime and niche level. A landscape is defined as an external structure or wider context and in this study the landscape represents the energy system in general. A landscape is often a wider context than the system itself, as developments in the energy landscape can influence the heating system. For instance, policies to increase the share of renewables in the energy mix involve the source of heating. Regimes are, unlike a system, relating to intangible artefacts and underlying deep structures, such as engineering beliefs, standardized ways of doing things and social norms. A regime is described as "the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artefacts and persons, ways of defining problems; all of them embedded in institutions and infrastructures" (Geels, 2002, p. 1259). The dominant sociotechnical regime in this study is based on natural gas. A niche is a small-scale development of innovation that has the potential to change the regime and the system. Niches are at the base of change. The success of a niche to influence or change a regime is determined by its own strength and its relation to the existing regime and landscape. The alignment of developments, which are defined by (successful) processes within the niche and reinforced by changes at regime level and at the level of the sociotechnical landscape, determine if a regime shift will occur (Kemp, et al., 2001). In other words, innovation with renewable heating is not necessarily a guarantee for a successful energy transition. The success rate of innovation depends on many different factors. These factors can be found in a regime, as can be seen Figure 1. Infrastructure, markets, policy, knowledge and others are strongly related to the success of an innovation. Landscape developments can also influence the success rate of a niche. In a stable circumstance of a system, the regime faces no pressure from upcoming niches or landscape developments, or from the previously mentioned factors within the regime.

This study considers the natural gas-based heating system as the socio-technical regime, as it currently is the dominant way to provide heating in the Netherlands and in Amsterdam. A certain socio-technical dominance has evolved over a significant amount of time, which in turn makes it difficult to alter. This process is called path dependency. As Schot et. al. explain, a socio-technical change is "a path dependent cumulative process in which the existing body of knowledge, techniques and tools determine which further steps can be taken in the future" (Schot, et al., 2001, p. 271). Path dependency plays an important role in the shaping of a regime, as these bodies of knowledge, techniques and tools have helped shape the dominance of a certain regime. Despite their path dependency, systems are able to change over time. The following elaborates on how systems can first be destructed (de-aligned) and then reformed (re-aligned).

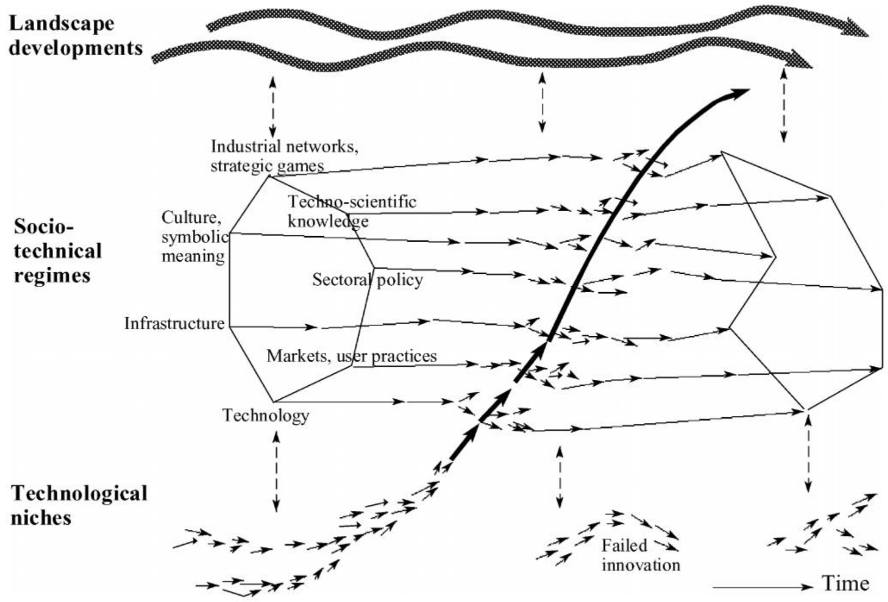

Figure 1. Geels' multi-level perspective on technological transitions (Geels, 2002).

2.1.1. System de-alignment

The transition of the Swedish heating system involved a series of steps, as explained by Ericsson and Lorenzo (2014) changes in the regimes developed gradually. The oil-based regime in Sweden was strongly affected by the oil-crisis in the 1970s, as it collapsed rapidly. The de-alignment of the regime accordingly involved a three-step process. Firstly, during the oil crisis, the crisis pressured the established oil-based regime enough to create socio-technical momentum. It created changes in public opinion and policy discourse, which pressured district heating utilities and gave way to research alternatives for oil. Secondly, actors in the regime responded to their performance problems by aiming to reduce their reliance on oil. Thirdly, commitment to the established oil-based regime of core actors weakened further and district heating utilities started significantly replacing oil in their production. In short, social and institutional factors influenced the rapid fall of the oil-based regime. Though as of today there is no natural gas crisis to the extent in which there was an oil-crisis in Sweden in the 70s, public opinion and policy discourse in Amsterdam is changing. The municipality is clearly aiming to reduce its reliance on natural gas, envisioned in its municipal strategies. The current regime is under pressure and is not supposed to have a future in the upcoming decades. However, the natural gas regime in Amsterdam has not collapsed (yet) as it is still the main source of heating. Assuming it will collapse someday, considering the vision to eliminate natural gas, the system will also re-align. This restructuring of the heating system took a few steps in the case of Sweden.

2.1.2. System re-alignment

Re-alignment of a system does not necessarily start after de-alignment. Moreover, the final phase of de-alignment can go hand in hand with the first phase of re-alignment. The first stage of re-alignment involves a continuously changing perception of the current dominant source of heating and a continuous increase of funding research programs. In the first stage of re-alignment in Sweden, the perception of biomass changed as a potentially important source of energy. Governments began funding research programs, the Swedish bioenergy association arose, a number of municipalities invested in a biomass-fired CHP plant and the government introduced a carbon tax. These internal dynamics in the emerging biomass niche initiated a shift towards biomass fuel in the district heating sector. Secondly, internal dynamics in the district heating sector enforced that shift even more. The fossil fuel supplies proved to be replaceable, which decreased the significance of relying on fossil fuels. Thirdly, landscape dynamics supported the rise of biomass-based district heating. The oil crisis illustrated the need for a more secure energy market and climate policies pressured the carbon-neutrality of the energy source. Lastly, interaction with the forest industry provided the district heating industry with a matching energy source by supplying large amounts of wood fuels. (Ericsson & Di Lucia, 2014)

Comparing the re-alignment of the Sweden case to Amsterdam, biomass can also play a large role in the heating market of Amsterdam. This study investigates CHP plant operation on biomass instead of natural gas. The main difference however, is that the Netherlands does not have a forest industry the size of Sweden, which will make it harder to provide the heating industry with a similar share of biomass. Nevertheless, natural gas has to be proved to be replaceable as this was a crucial step in the Sweden case with fossil fuels in general. This study does so in attempt to decrease the significance of relying on that fossil fuel.

3. Methodology

3.1. Research design

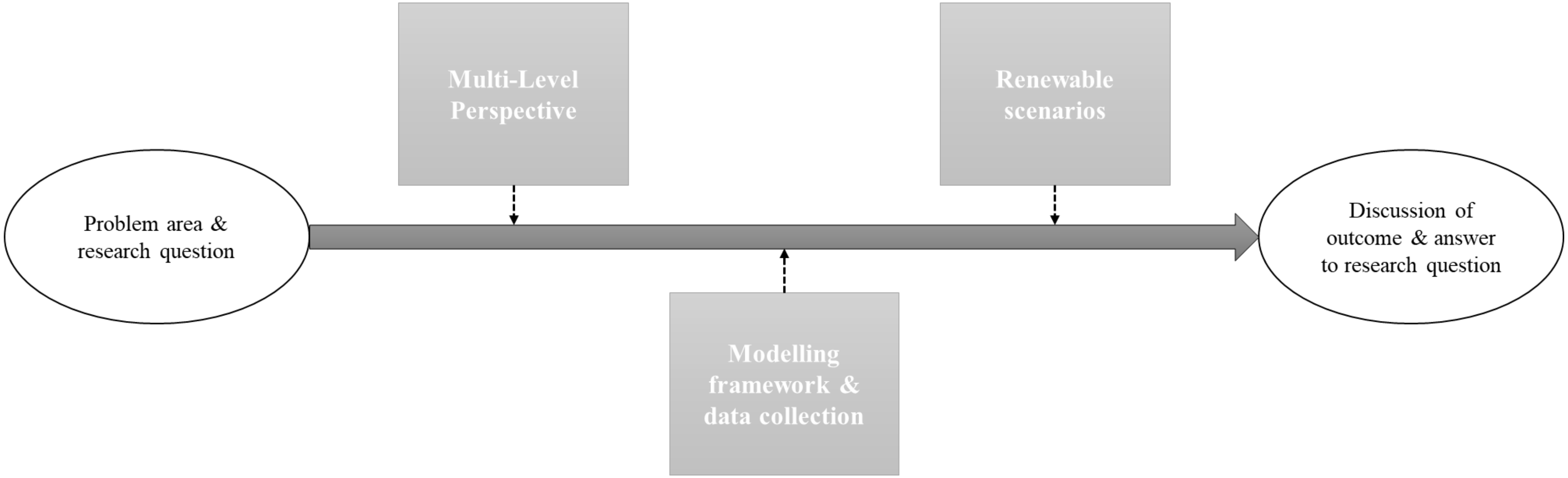

Figure 2. Research design.

3.2. Modelling framework

Currently, two combined heat and power (CHP) plants are at the center of district heating in Amsterdam. Different simulation tools can be used to model such a heating system. Commonly at Aalborg University, energyPRO and energyPLAN are used to model with energy systems. EnergyPRO is an advanced computer tool for the design, simulation and annual operation of CPH-plants. Generally, energyPRO is used to calculate the optimal operation of a power plant, to model cogeneration and to make detailed investment analyses. It also includes the simulation of plants in combination with the electricity market (EMD International A/S, 2016). EnergyPLAN on the other hand analyzes different policy scenarios, such as different shares of renewable energy, and is more of a strategy analysis tool (Aalborg University, 2018). EnergyPRO has been used to model cogeneration in Denmark for many years (Lund & Andersen, 2005). It has rooted in other European countries as well, such as Lithuania (Lund, et al., 2005). However, as of the period this study is written, energyPRO has not been used in any Dutch energy system.

Though both simulation tools can analyze hour-to-hour dynamics of a system operation, energyPRO has the capability to visualize the different heat demands and heat production with their corresponding energy mix through different times of the day, week, month and year. This gives transparency into the energy mix of a renewable heating system. Modelling a local renewable heating system with energyPRO enables more precise analyses than energyPLAN can offer. Therefore, energyPRO is a better matching tool for this study than energyPLAN. Also, energyPLAN has its focus on the operation of national energy systems. Its scope is therefore too large, as this study aims to focus on a city scale. For this too, energyPRO is an appropriate fit.

3.2.1. Model input

3.2.1.1. Units

EnergyPRO models with different units. It has the ability to model energy sources, converters, demands, storages and losses. The *energy sources* in this case are natural gas, excess heat from industries and renewables. The *energy converters* are the gas engines in the CHP-plants, the electrical boiler and the electrical heat pump. The *energy demands* are the heat demands for Amsterdam. The *energy storages* are the thermal storages that store heat from the energy converters or sources. The *energy losses* represent the loss of heat caused by the district heating network's transmission and distribution. The setup of the units builds upon an existing model in energyPRO 'Cogeneration plant on a spot market', which is an example that illustrates two CHPs participating on a spot market (appendix Figure 13). This preset includes two gas-fired CHP-plants, a gas-fired boiler, a thermal storage, a heat demand and an electricity spot market. The electricity spot market will be explained later. This study adapts the setup of the mentioned units to the case of Amsterdam and adds renewable energy. This will be further elaborated on in the data collection.

3.2.1.2. Production priorities

In the operation strategy of energyPRO, there is the opportunity to operate with different priorities of heat production. This regards to the energy units used in the model, which are the CHP-plants, the waste-to-heat plant, the electric heat pump, the electrical boiler, excess heat and solar thermal energy. In this energy unit setup, the unit can be operated with low priority, high priority or calculated priority. With a low priority, the model will depend on this particular unit as little as possible. With a high priority, the model will depend on this particular unit as much as possible. With a calculated priority, the dependency on this particular unit can vary as it related to external conditions. These external conditions, such as electricity prices, are preset in energyPRO. The energy unit setup with its corresponding production priorities for this study is found in appendix Table 10. Here, using renewable energy has high priority.

3.2.2. Model output

3.2.2.1. Operational reports

EnergyPRO produces several operational reports. This study incorporates reports for the graphic production and annual energy conversion to visualize the different heat demands and heat production with their corresponding energy mix through different times of the day, week, month and year. This study will also display the graphical layout to illustrate the design of the model. EnergyPRO can also produce reports for the load duration curve for the heat demand, for environmental effects and for financial analyses.

3.3. Data collection

3.3.1 CHP-plants

Currently, the two CHP-plants in Amsterdam have a respective capacity of 266 MW electricity and 180 MW heat (CHP plant 'Diemen Centrale 33', built in 1995) and 435 MW electricity and 260 MW heat (CHP plant 'Diemen Centrale 34', built in 2011). These outputs are given by its energy operator Nuon (Nuon, 2018). Frankly, these are relatively low power-to-heat ratio's. Normally, modern CHP-plants operate with a power-to-heat ratio of 1 MW electricity to 3 MW heat (Gambini & Vellini, 2013). It seems unsure why Amsterdam's CHP-plants operate to such a low ratio, but an answer may be found within the technical calibration of the power plants. Perhaps, the plants are mostly designed to generate electricity. Coinciding with that power generation, excess heat is generated to a lower extend than in modern cogeneration. Because CHP-plants have a lifetime of around 25 to 30 years (Dornburg & Faaij, 2001), this study assumes that the existing plants are replaced by 2050. Therefore, this study models with two CHP-plants with a capacity of 200 MW electricity and 600 MW heat each. The capacity of these plants has been calculated in retrospect, meaning that they are adapted to match the heat demand in combination with the other energy units in the renewable scenarios. Eventually, the power capacities are lower in these scenarios than in the reference scenarios. The modelled 2050 CHP-plants produce less electricity compared to the current CHP-plants, but it is assumed that by 2050 more wind and solar power are generating electricity in the local power mix. Increasing the wind and solar power capacity is envisioned in Amsterdam's strategy. The municipality has goals for 2020, in which it wishes to increase their wind capacity from 67 to 85 MW and their solar capacity from 9 MW to 160 MW compared to 2017 (Municipality of Amsterdam, 2017). The modelled CHP-plants operate to a modern power-to-heat ratio and a modern general efficiency of 90%, regardless of their power-to-heat ratio (Gambini & Vellini, 2013).

3.3.2. Heat demand

The exact heat demand for Amsterdam is unknown. According to national statistics of the Dutch energy mix, the national heat demand is 416,9 PJ or 115,8 TWh (=115,8 million MWh) (Rijksdienst voor Ondernemend Nederland, 2016). With Amsterdam housing about 825.000 inhabitants, the city is home to about 5% of the total of 17 million national inhabitants. Assuming an average demand for heat in the city compared to that of the entire nation, an estimation of the city's heat demand can then be made based on the proportion of people living in Amsterdam. The estimated annual heat demand for Amsterdam is then 20,8 PJ or 5,8 TWh (=5,8 million MWh), which is 5% of the national heat demand.

The heat demand is adapted to differing heat demands throughout the day, month and year. It builds upon the heat demand of the existing model 'Cogeneration plant on a spot market'. Adapted heat demands accounts for different demands in different climates and different times of the day. At different times of the day, households demand heat for warming the house. Cooking is assumed to be electrical or by induction, as natural gas is to be eliminated from the heating system.

Additional to the previously calculated heat demand is the loss of heat in the district heating network. Building on average network losses in Europe, this study assumes network losses of 17% (David, et al., 2017). This equals about 990.000 MWh per year and has to be added to the total annual heat demand.

The price for the sale of heat is based on the existing model 'Cogeneration plant on a spot market', which is €37,5 per MWh.

3.3.3. Excess heat

On Heat Roadmap Europe, all industrial excess heat activities are highlighted in Europe. In Amsterdam, six industrial sites produce excess heat during their particular production processes (see appendix Table 6). Based on a rough estimation by the makers of Heat Roadmap Europe, the city of Amsterdam has a potential excess heat of 77,6 PJ (Aalborg University, 2016). The industrial area outside the city limits (read: the areas IJmuiden and Velsen, appendix Figure 9) accounts for about three quarters of that heat. Because of its great potential and its near location to the city, the activities there are included in Amsterdam's excess heat potential. However, 77,6 PJ is a rough estimation. As this could deliver 21,6 million MWh of heat, it would easily meet the city's heat demand of about 5,8 million MWh. This seems unlikely, because e.g. excess heat can vary greatly in terms of heat quality (as will be further explained in the discussion). Besides, some heat will reportedly be used to supply heat locally (Omgevingsdienst IJmond, 2018). Therefore, this study assumes a realization of 10% of Amsterdam's excess heat potential. This results in around 2 million MWh and a theoretical heat capacity of 600 MW.

3.3.4. Electric boiler

In a study on a renewable energy system in Northern-Denmark, an electrical boiler is used to produce heat from electricity (Lund, et al., 2012). It provides heat for the municipality of Frederikshavn, which has a population of about 60.000. The boiler has a capacity of 10 MW. Since Amsterdam is about ten times the size, this study uses an electric boiler with a capacity of 100 MW, assuming this is technically possible. Electric boilers produce heat from electricity, preferably when electricity prices are low. Electric boilers generally have an efficiency of 95 to 100%, meaning the 100 MW electricity it uses is converted into 95 to 100 MW heat (Blarke, 2011). This study assumes a 100% efficiency.

3.3.5. Electric heat pump

Like electric boilers, electric heat pumps generate heat from electricity. Though the electric boilers also have a high efficiency, the efficiency of a heat pump is even greater. Generally, electrical heat pumps have a COP (coefficient of performance; ratio between heat production and electricity usage) of 3,0. Because of that high efficiency, this study incorporates electric heat pumps to produce as much heat as possible and electric boilers to produce heat when electricity prices are low. Electric heat pumps use electricity to warm up water and generate heat. They have averages capacities of 1-20 MW. Main sources of water for electrical heat pumps are sewage water, industrial waste water and nearby sea, lake or river water. Accordingly, by 2050, electrical heat pumps are expected to supply 25-30% of heat in district heating systems in Europe. (David, et al., 2017) This study builds on several heat pumps, totaling a capacity of 150 MW for heat production, while using 50 MW electricity.

3.3.6. Electricity spot market

Considering the scope of this study, electricity production is included because it is cogenerated with heat and because some energy units consume electricity. A cogeneration plant produces electricity and the electric heat pump and electric boiler need electricity to produce heat. This study then includes electricity for the power supply of electrical heat pump and boiler and for delivering a surplus that has been produced by CHP-plants to the power spot market. An electricity spot market creates that type of efficiency to the power industry. A spot market is an electricity market system that has the (hourly) prices and quantities of power fixed one day ahead, as a daily electricity demand has to be met with the same or a greater supply. Electricity is expected to be provided instantly by the user, but cannot be produced as fast. It has to be pre-delivered to the net. Though complex, an electricity spot market solves the issue of an insufficient power supply in advance. In the Netherlands, the APX (Amsterdam Power Exchange) Group operates the electricity spot market. The APX Group is ruled by the EPEX (European Power Exchange) SPOT, as electricity pricing is regulated by European law. EnergyPRO’s most recent version has the ability to include EPEX 2017, which contains the European electricity sport market pricing for 2017. It should be noted that it is uncertain if the current way of using electricity in a spot market will still be the main way of handling electricity by 2050. New forms of a competitive electricity market are on the rise: capacity markets. The current spot markets “do not provide adequate incentives to stimulate the proper quantity or mix of generating capacity consistent with mandatory reliability criteria” (Joskow, 2006, p. 58). In other words, spot markets are not reliable enough at peak levels of electricity consumption and are inadequately priced when the power capacity is fully utilized (Joskow, 2008). At peak times, the electricity market struggles to generate enough power to the limits of their capacity.

Batteries that store electricity to use when demands are peaking are relatively costly (Fabra & Creti, 2007). A so-called installed capacity market could provide a solution. A possible reform of the electricity market may affect the operation of Amsterdam's future heating system by the pricing of electricity, because many energy units are related to electricity.

3.3.7. Solar thermal energy

Solar thermal energy generates heat by using solar collectors to heat water. The water flows through small pipes in the solar collectors. The world's largest solar thermal station has a capacity of 150 MW and is located in Seville, Spain. By 2013, most solar thermal stations are located in warm climates with a relative abundance of sunlight, such as Spain and the southern United States (Tian & Zhao, 2013). In the Netherlands, sunlight is less present. Nevertheless, solar collecting systems are present in the Netherlands. Yet they only have a relatively small market share (Verhees, et al., 2012). This study also includes solar thermal energy. It regards a relatively small solar thermal station of 10 MW. It is connected to thermal energy storage, which increases its performance by the ability to store energy while it's not demanded and extracts it when it is in demand. Despite the solar thermal's relatively small capacity, there is still the necessity to model accordingly to the times of the day when the sun shines. EnergyPRO allows non availability periods, in which solar thermal energy is not available between 8pm and 7am on a daily basis. This time frame is based on an estimation over a yearly average of sun light.

3.3.8. Thermal storage

Energy systems often use thermal stores to reach cost-efficient solutions. Two of the main reasons are heat load situations during summertime and fluctuating electricity tariffs in general (EMD International A/S, 2016). When electricity prices on the spot market are substantially lower than usual, heat can be produced at that very moment and then stored for later use. Accordingly, the municipality of Amsterdam has unexploited potential for thermal storage of 1400-1550 GJ annually per hectare (Nationale Energie Atlas, 2016). This equals to about 389-431 MWh per hectare. Though the municipality has around 100 places marked where there is a potential for thermal storage, such as at hospitals, hotels and docks, the total potential for thermal storage is to be estimated (Municipality of Amsterdam, 2018). Considering Amsterdam covers about 22.000 ha, the potential for thermal storage for the whole municipality would be around 8,5-9,5 million MWh. However, this seems rather high. It assumes storage for every ha of Amsterdam. This is physically impossible. Besides, there are only about 100 places available for thermal storage, as listed by the municipality. It is unlikely that there will be 100 different places for storage, because that is a rather large amount for a city. Though ten different places are more likely, this study models thermal storage as if it is in one place. This is to keep the model simple. In reality, it is more efficient to store that heat on the same place as where the heat is generated. But this would force energyPRO to model many different smaller thermal storages and that would negatively impact the overview of the model. The capacity of thermal storage has been estimated in retrospect, meaning that the size has been adapted to what seemed appropriate in the heat demand and supply of the system.

With this method, it was found that 150.000 MWh is a decent size for thermal storage. Therefore, this study models with one thermal storage of 150.000 MWh annually. This study also assumes that it is possible for all energy sources and units to store its thermal energy, because all generated heat can potentially be stored.

The inclusion of thermal storage is expected to make the graphic production more complex to understand than with the exclusion of thermal storage. The production of heat with in the inclusion of heat is then not solely related to the heat demand, but also to electricity prices.

3.3.9. Other units

A few other energy units are also modelled in this study. First, a waste-to-heat plant. Operating since 1993, AEB is a waste-to-heat plant with a thermal capacity of 64 MW (AEB Amsterdam, 2018). This is modelled in both renewable heating scenarios. Second, biomass as an energy resource. Biomass has a heat value of 17 MJ per kg. The price for biomass varies per sort of biomass. Biomass is made of wood pellets, gardening residue and wood chips and is priced up to around €0,20 per kilogram in the Netherlands (Ministry of Economic Affairs, 2018). In this study, biomass is modelled with the price of €0,20 per kilogram. Third, to potentially add flexible energy into the energy mix, the renewable heating scenarios are modelled with a biogas boiler. The boiler has a capacity of 250 MW and an efficiency of 90%. The efficiency builds on average efficiencies of boilers (Che, et al., 2004). The capacity is theoretical and serves as the last option for generation heat. Lastly, related to the biogas boiler is biogas itself as an energy resource. It is modelled with a heat value of 11 kWh (equals 36 MJ) per m^3, assuming technology in 2050 can provide that relatively high heat value (Tippayawong & Thanompongchart, 2010; Xu, et al., 2015).

	Reference	RE without storage	RE with storage
CHP 1 (Diemen Centrale 33)	266 MW_e & 180 MW_{th} 90% efficient Natural gas	200 MW_e & 600 MW_{th} 90% efficient Biomass	200 MW_e & 600 MW_{th} 90% efficient Biomass
CHP 2 (Diemen Centrale 34)	435 MW_e & 260 MW_{th} 90% efficient Natural gas	200 MW_e & 600 MW_{th} 90% efficient Biomass	200 MW_e & 600 MW_{th} 90% efficient Biomass
Boiler	1500 MW 90% efficient Natural gas	250 MW 90% efficient Biogas	250 MW 90% efficient Biogas
Waste-to-heat	64 MW	64 MW	64 MW
Electric Boiler	-	100 MW 100% efficient	100 MW 100% efficient
Electric Heat Pump	-	150 MW COP 3,0 Heated from 25℃ to 80℃	150 MW COP 3,0 Heated from 25℃ to 80℃
Excess heat	-	150 MW	150 MW
Solar Thermal Energy	-	10 MW Not available between 20.00h and 07.00h daily	10 MW Not available between 20.00h and 07.00h daily
Thermal Storage	-	-	150.000 MWh
Other	125 MW Non-natural gas, renewables, other	-	-

Table 1. Summarized technical specifications of the simulation model. RE = Renewable Energy.

4. Analysis

This chapter shows the energy mixes of the reference scenario and of the two renewable heat scenarios. The year modelled is 2017. Every scenario is first illustrated by their energy mix over the year. A full year graph gives insight into a differing energy mix for different season of the year. Then, to exemplify a period of relatively high heat demands, where production needs to peak and the energy mix is most complex, every scenario is followed by a figure that illustrates the energy production and heat demand corresponding with the month of January. January is, as can be seen in the figures of the energy mix with its corresponding heat demand over the year, a month of relatively one of the highest heat demands in the year. Thirdly, every scenario has its energy mix displayed in numbers in the tables for their annual energy conversion. All scenarios match the heat demand.

4.1. Reference scenario

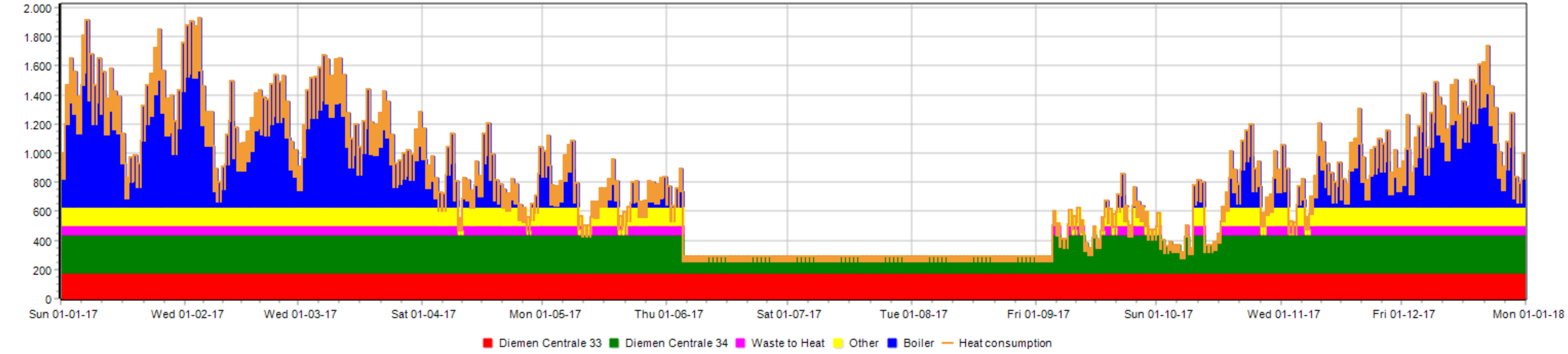

Figure 3. Simulation of the annual heat production of the reference scenario. Source: energyPRO.

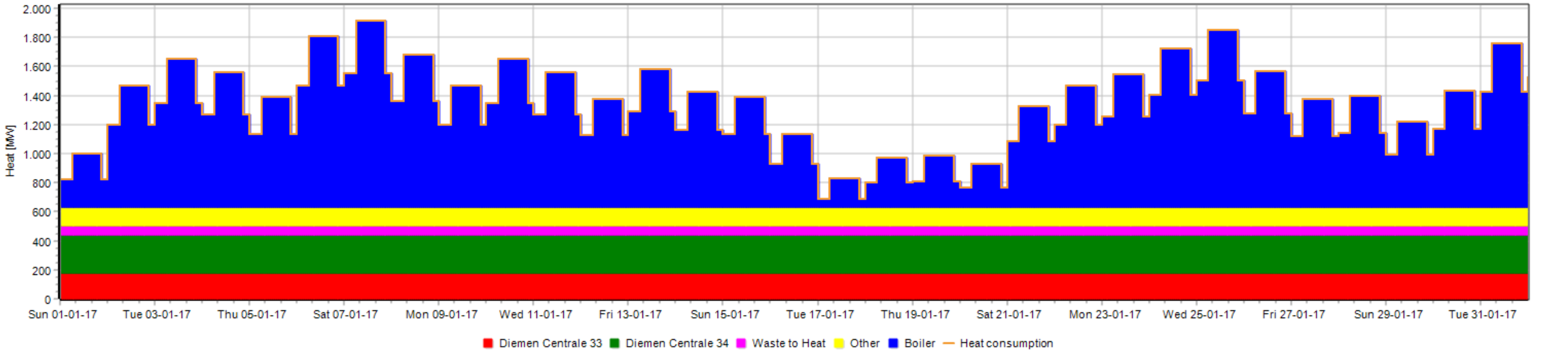

Figure 4. Simulation of the annual heat production in January of the reference scenario. Source: energyPRO.

Main remarks reference scenario

In the simulation of Amsterdam's current heating system where natural gas dominates the energy mix, the following can be observed:

- The operation of the current heating system may differ slightly from the simulation model. What's more important to align with reality is the energy mix for the annual energy conversion. Natural gas is used to generate heat in both CHP-plants and the boiler. The share of natural gas in the total heat production then amounts to 84,1%, as can be summed up in table 2. As mentioned in the introduction, the municipality reported a natural gas share of 80% to 90%.
- Figure 3 shows relatively high heat demands in the winter, declining demands towards the summer, low demands in the summer and increasing demands towards the winter. In a period of high heat demands, the simulation model can be considered most accurate. The natural gas-fired boiler generates heat in times of relatively high heat demands, as the boiler is used as a supplementing energy unit to the base load the CHP-plants provide. This is illustrated with more detail in Figure 4. The boiler operates 60,2% of the year.
- In the summer time, one CHP-plant operates continuously and one operates on partial load. In reality, CHP-plant operation may differ over the year, as waste-to-heat and the category of other energy sources are not likely to be shut off over the summer. Then again, the main focus should of the reference scenario should be on the annual energy conversion, so that the natural gas-based system can be compared to renewable scenarios.
- The total amount of natural gas used in this scenario is 1.150.050.184,9 m^3, as can be found in the appendix Table 7.

Heat demands:

Total sale of heat	5.828.068,9 MWh	
Network loss	990.000,2 MWh	
Total	6.818.069,1 MWh	
Max heat demand	1.932,2 MW	

Heat productions:

Diemen Centrale 33	1.576.800,0 MWh/year	23,1%
Diemen Centrale 34	1.889.097,8 MWh/year	27,7%
Other	707.175,6 MWh/year	10,4%
Boiler	2.269.251,7 MWh/year	33,3%
Waste to Heat	375.744,0 MWh/year	5,5%
Total	6.818.069,1 MWh/year	100,0%

Electricity produced by energy units:

Spot market:

	All periods [MWh/year]	Of annual production
Diemen Centrale 33	2.330.160,0	42,4%
Diemen Centrale 34	3.160.605,9	57,6%
Total	5.490.765,9	100,0%
Of annual production	100,0%	

Peak electric production:

Diemen Centrale 33	266.000,0 kW-elec.
Diemen Centrale 34	435.000,0 kW-elec.

Hours of operation:

Spot market:

	Total [h/Year]	Of annual hours
Diemen Centrale 33	8.760,0	100,0%
Diemen Centrale 34	8.760,0	100,0%
Out of total in period	8.760,0	

Production unit(s) Not connected to electricity market:

	Total [h/Year]	Of annual hours
Other	6.111,0	69,8%
Boiler	5.271,0	60,2%
Waste to Heat	5.871,0	67,0%
Out of total in period	8.760,0	

Turn ons:

Diemen Centrale 33	0
Diemen Centrale 34	0
Other	16
Boiler	41
Waste to Heat	32

Table 2. Annual energy conversion of the reference scenario. Source: energyPRO.

4.2. Renewable scenario, without thermal storage

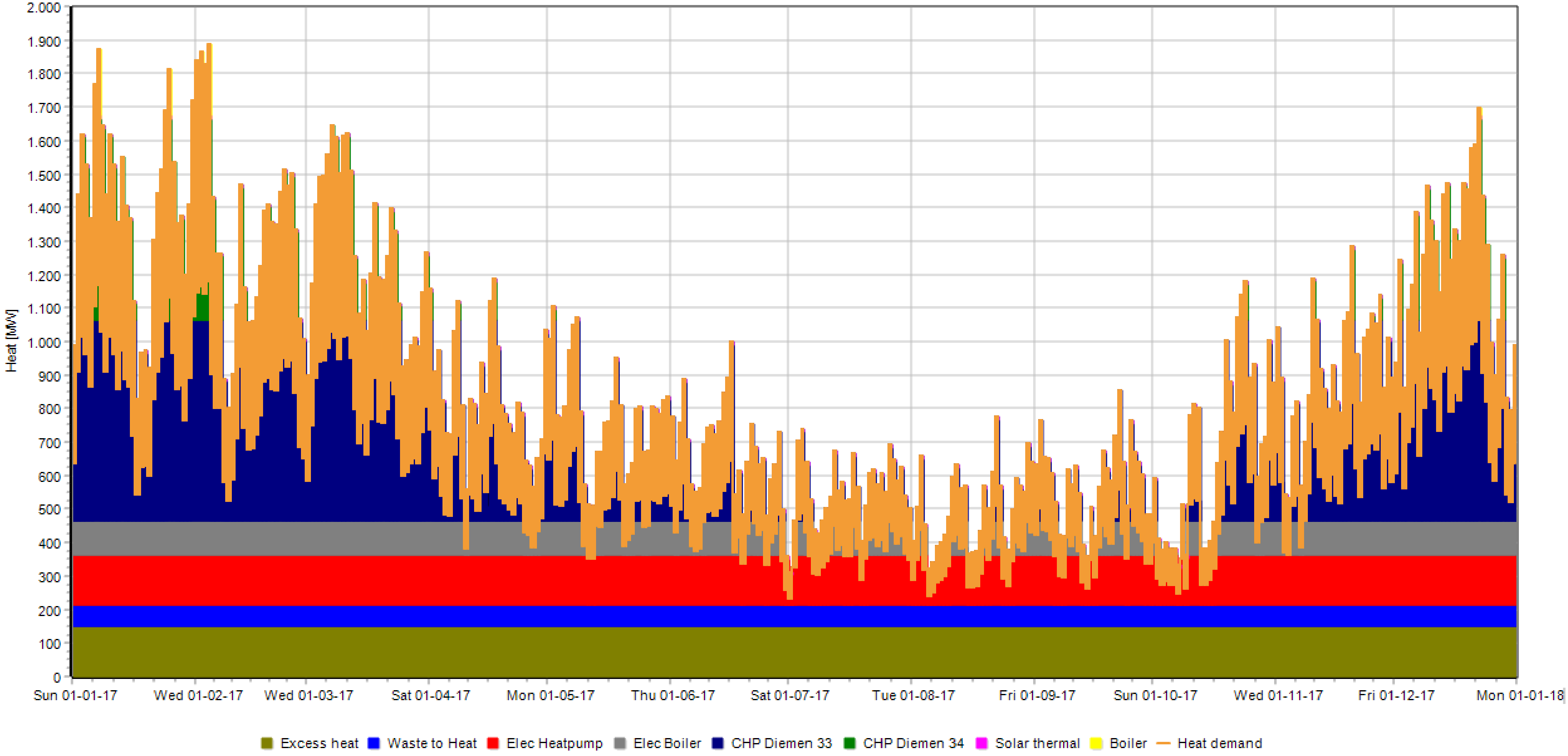

Figure 5. Simulation of the annual heat production of the renewable scenario without thermal storage. Source: energyPRO.

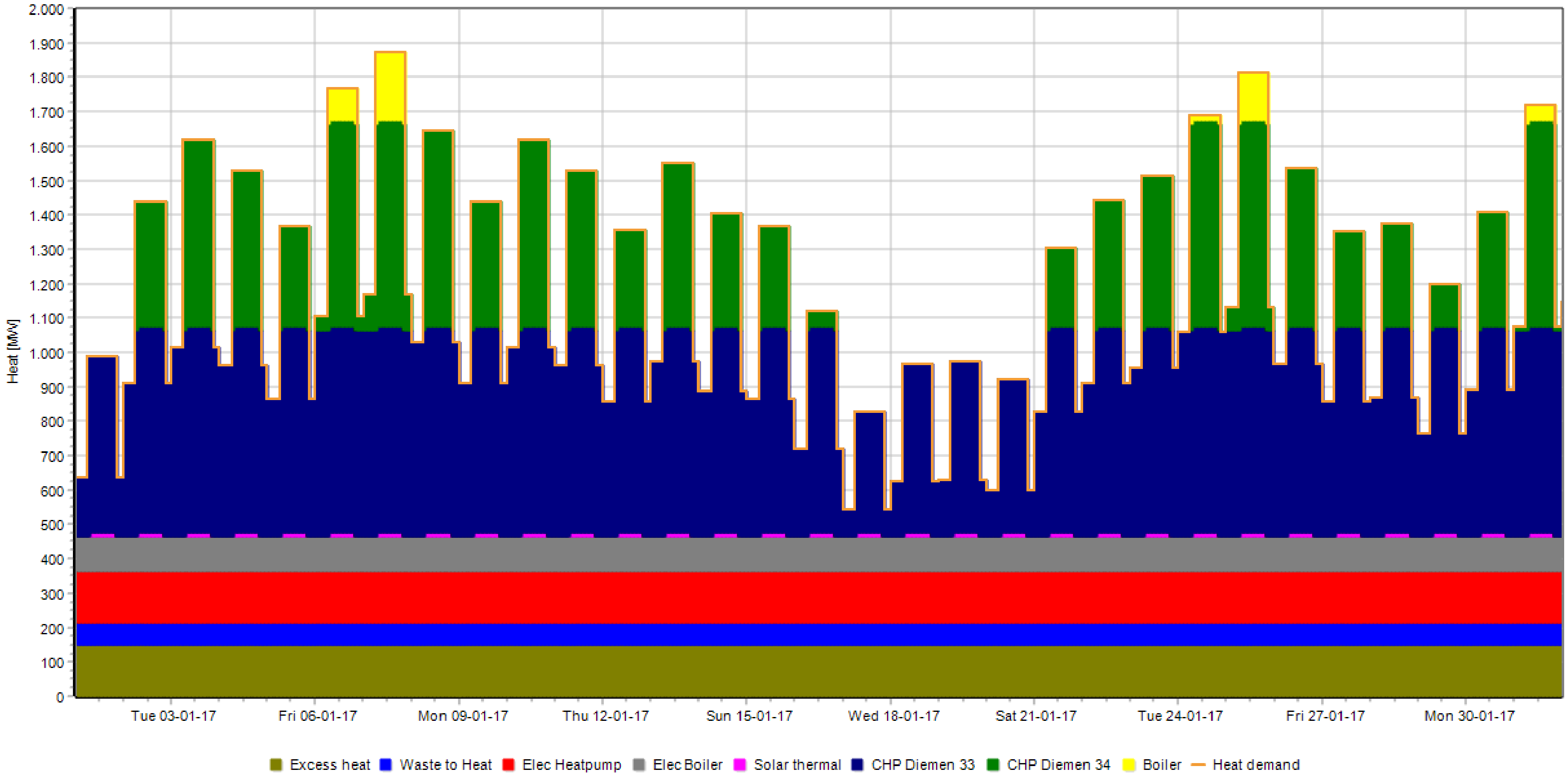

Figure 6. Simulation of the heat production in January of the renewable scenario without thermal storage. Source: energyPRO.

Main remarks renewable scenario, without thermal storage

In a scenario where renewables without thermal storage rule the energy mix of Amsterdam's heating system, the following can be observed:

- No natural gas is used.
- Excess heat and waste-to-heat provide a base load for heating over the year.
- The electric boiler generates heat at times when heat demands are high, such as throughout the winter. The electric boiler supplements the heat pump and operates 92,5% of the year.
- The biogas-fired boiler is used to supplement heat during peak demands, as the yellow part of the bars marks clearly in Figure 6.
- The electric heat pump operates 100% of the year, but operates on partial loads during the summer when heat demands are relatively low.
- CHP-plants operate on full loads and partial loads at different times of different heat demands, as can be seen in Figure 5.

Heat demands:

Total sale of heat	5.824.851,5 MWh	
Network loss	990.000,2 MWh	
Total	6.814.851,7 MWh	
Max heat demand	1.888,2 MW	

Heat productions:

CHP Diemen33	2.361.466,6 MWh/year	34,7%
CHP Diemen34	482.015,7 MWh/year	7,1%
waste to heat	560.640,0 MWh/year	8,2%
Elec Heatpump	1.281.067,7 MWh/year	18,8%
Solar thermal	47.450,0 MWh/year	0,7%
Excess heat	1.314.000,0 MWh/year	19,3%
Elec Boiler	749.492,7 MWh/year	11,0%
Boiler	18.719,0 MWh/year	0,3%
Total	6.814.851,7 MWh/year	100,0%

Electricity produced by energy units:
Spotmarket:

	All periods [MWh/year]	Of annual production
CHP Diemen33	787.155,5	83,0%
CHP Diemen34	160.671,9	17,0%
Total	947.827,4	100,0%
Of annual production	100,0%	

Electricity consumed by energy units:
Spotmarket:

	Of annual [MWh/year]
Elec Heatpump	427.022,6
Elec Boiler	749.492,7
Total	1.176.515,3

Peak electric production:

CHP Diemen33	200.000,0 kW-elec.
CHP Diemen34	200.000,0 kW-elec.

Hours of operation:
Spotmarket:

	Total [h/Year]	Of annual hours
CHP Diemen33	7.000,0	79,9%
CHP Diemen34	1.657,0	18,9%
Elec Heatpump	8.760,0	100,0%
Elec Boiler	8.103,0	92,5%
Out of total in period	8.760,0	

Table 3. Annual energy conversion. Source: energyPRO.

4.3. Renewable scenario, with thermal storage

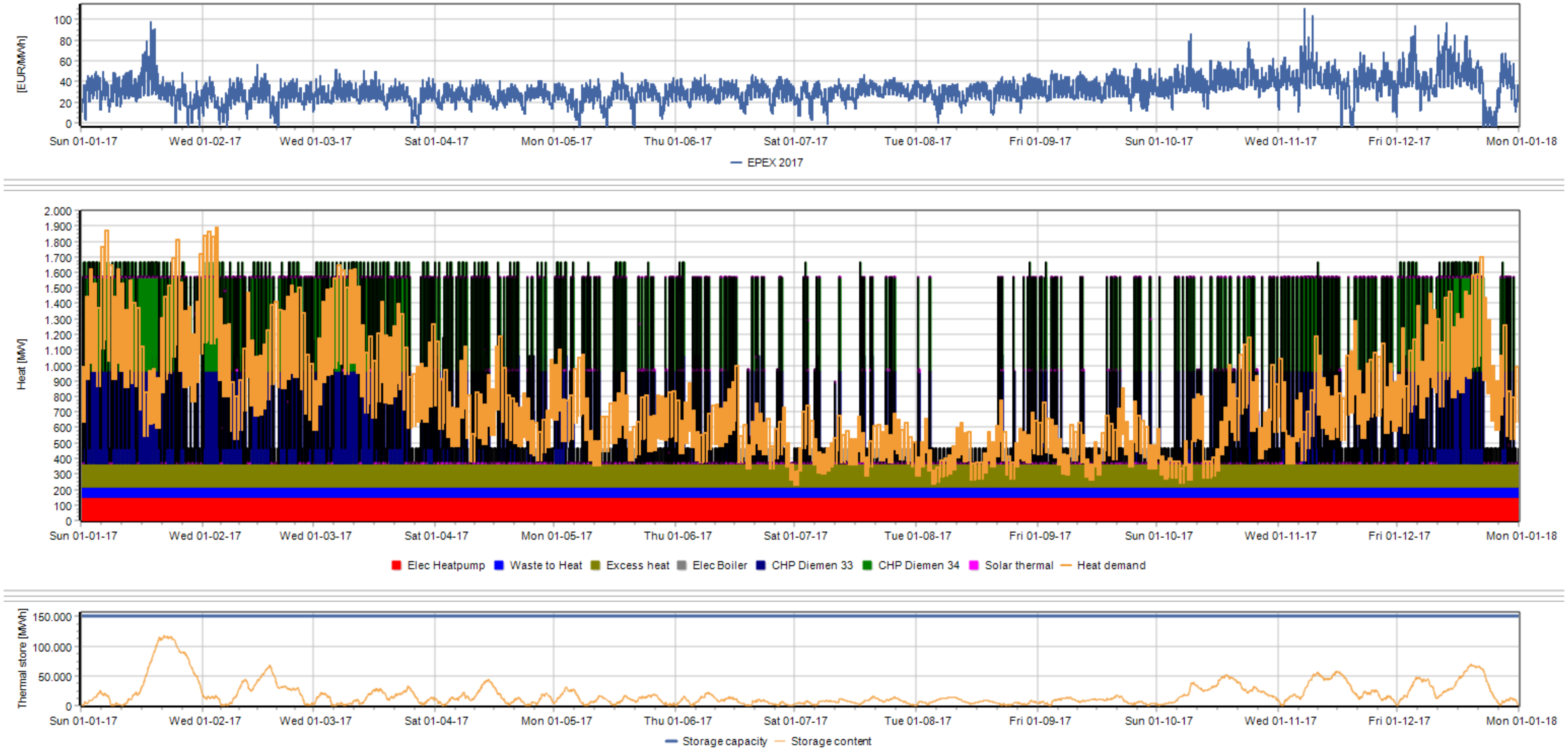

Figure 7. Simulation of the annual heat production of the renewable scenario with thermal storage, including corresponding electricity prices and thermal storage content. Source: energyPRO.

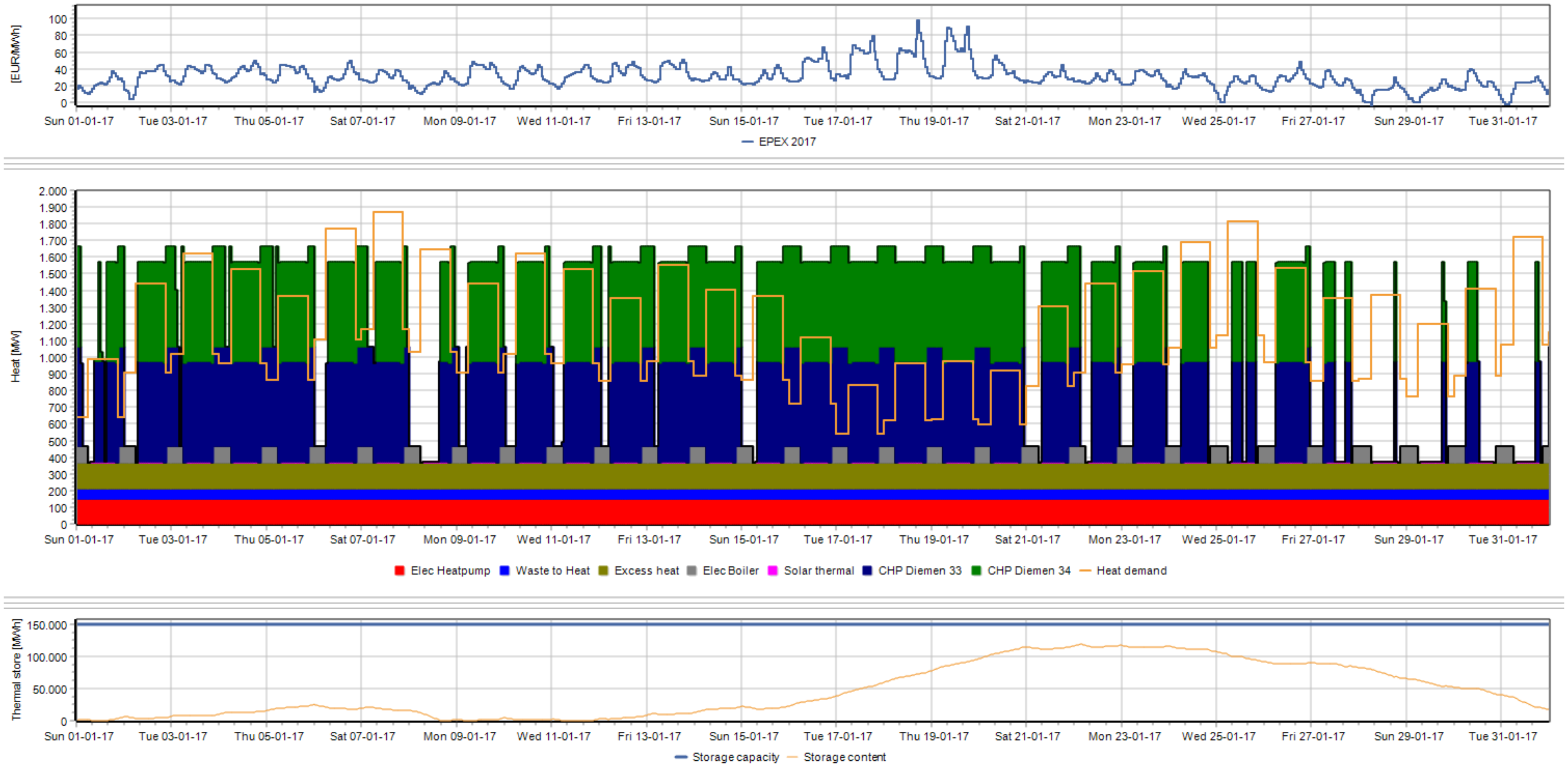

Figure 8. Simulation of the heat production in January of the renewable scenario with thermal storage, including corresponding electricity prices and thermal storage content. Source: energyPRO.

Main remarks renewable scenario, with thermal storage

- No natural gas is used.
- There is an alignment of heat production from the electric boiler to electricity prices. The boiler operates only when electricity prices are low, which is usually during the night when heat demands are low. This is clearly visible in Figure 8.
- It seems in Figure 7 and 8 as if heat demands are not met. This is only a graphic illusion. At times where heat production seems to exceed the demand, heat is stored in the thermal storage. At times where the heat demand seems to exceed the production, heat is extracted from the thermal storage. The relation is very visible in Figure 8. Thermal storage enables the generation of heat to be less related to the heat demand. It provides flexibility to the system.
- The electric heat pump, waste-to-heat and excess heat operate or generate heat continuously throughout the year.
- The electric boiler supplements the heat pump and operates 37,3% of the year.

Heat demands:

Total sale of heat	5.824.851,5	MWh
Network loss	990.000,2	MWh
Total	6.814.851,7	MWh
Max heat demand	1.888,2	MW

Heat productions:

CHP Diemen 33	1.751.869,5 MWh/year	25,7%
CHP Diemen 34	1.499.892,2 MWh/year	22,0%
waste to heat	560.640,0 MWh/year	8,2%
ElecHeatpump	1.314.000,0 MWh/year	19,3%
Solarthermal	47.450,0 MWh/year	0,7%
Excess heat	1.314.000,0 MWh/year	19,3%
ElecBoiler	327.000,0 MWh/year	4,8%
Boiler	0,0 MWh/year	0,0%
Total	6.814.851,7 MWh/year	100,0%

Electricity produced by energy units:

Spot market:

	All periods [MWh/year]	Of annual production
CHP Diemen 33	583.956,5	53,9%
CHP Diemen 34	499.964,1	46,1%
Total	1.083.920,6	100,0%
Of annual production	100,0%	

Electricity consumed by energy units:

Spot market:

	Of annual [MWh/year]
ElecHeatpump	438.000,0
ElecBoiler	327.000,0
Total	765.000,0

Peak electric production:

CHP Diemen 33	200.000,0 kW-elec.
CHP Diemen 34	200.000,0 kW-elec.

Hours of operation:

Spot market:

	Total [h/Year]	Of annual hours
CHP Diemen 33	2.934,0	33,5%
CHP Diemen 34	2.516,0	28,7%
ElecHeatpump	8.760,0	100,0%
ElecBoiler	3.270,0	37,3%
Out of total in period	8.760,0	

Table 4. Annual energy conversion. Source: energyPRO.

4.4. Comparison of scenarios

In the two renewable scenarios compared to the reference scenario, the heating system can match Amsterdam's heat demand without the use of natural gas. Both scenarios include the use of an electric heat pump, an electric boiler, solar thermal energy and biomass as a resource for CHP-plants. Both scenarios build on the assumption of an increased realization of excess heat and the replacement of CHP-plants with two of modern standards. Both scenarios enable excess heat and the electric heat pump as the base load operation. Both scenarios have an equal or similar heat production share in the energy mix of waste-to-heat, electric heat pump, solar thermal energy and excess heat generation. Main differences are as follows.

Biogas-fired boiler operation. In a scenario without thermal storage, biogas from a boiler supplements heat production at times of high heat demands. In a scenario with thermal storage, the production on biogas by a boiler is not necessary.

CHP-plant operation. In the reference scenario both CHP-plants operate fully all year around. In both renewable scenarios, CHP-plants operate less as they are supported by more energy units. However, in a scenario without thermal storage the percentage of hours of plant operation in a year are respectively 79,9% and 18,9% each. In a scenario with thermal storage those percentages are respectively 33,5% and 28,7%. The CHP-plants operate differently in both renewable heating scenarios. Relating to the average price of the sale of electricity in Table 5, the inclusion of thermal storage has allowed the CHP-plants to operate when electricity can be sold for a relatively high price. The cogenerated heat can be stored or used. A high price for the sale of electricity has a positive influence on the revenues of the operational income (Table 5 and Table 7, 8 and 9 in the appendix).

Biomass usage. Though a scenario with thermal storage is supposed to provide more efficiency to the system, this scenario uses more biomass than it does in a scenario without thermal storage (Table 5). This seems contradicting and could use further research.

Electric boiler operation. With thermal storage, the electric boiler can generate heat at times when electricity prices are low, that can be stored and used for times when demands are high. Thermal storage can provide more flexibility to the system. As can be seen in Table 5, the electric heat pump and the electric boiler consume more electricity in a renewable scenario without thermal storage than in a scenario with thermal storage. As can be seen in Table 3 and 4 and Table 11 in the appendix, the electric heat pump consumes slightly less electricity in a scenario without thermal storage. Moreover, the electric boiler consumes around twice as much electricity in the scenario without thermal storage than in the scenario with thermal storage. This is because the operation of the electric boiler is coupled with electricity prices. As can be seen in Figure 8, the electric boiler produces heat when electricity prices are low. The coupling of electricity prices with heat production from the electric boiler provides more efficiency to the heating system.

	Reference scenario	RE scenario without thermal storage	RE scenario with thermal storage
Heat produced by CHP-plants	3,47 TWh	2.84 TWh	3,25 TWh
Biomass used in CHP-plants	-	891.180.807,3 kg	1.019.140.368,0 kg
Electricity consumed by electric heat pump and electric boiler	-	1,18 TWh	0,77 TWh
Biogas used in boiler	-	1,8 million m^3	-
Average price of electricity sale	€30,63	€33,55	€40,03

Table 5. Comparison of additional features of the scenarios, annually. Source: energyPRO.

5. Discussion

5.1 The transition of the heating system from a broader perspective

Public opinion and governmental policies are committed to transition the heating system from natural gas based to renewables. The vision of the municipalities to eliminate natural gas as an energy source creates socio-technical momentum. Also, commitment to the established natural gas-based regime of core actors seems to be starting to weaken, as the CHP-plants owner Nuon announced during the time of this study to invest in biomass as an energy resource (Amsterdam Fossielvrij, 2018). Nuon will invest in a new biomass-fired boiler with a thermal capacity of 150 MW on the same site as the two current CHP-plants. This momentum could indicate a development of a biomass niche and the rise of a biomass-based regime. With that, the current heating system of Amsterdam seems to be destructing or de-aligning. However, various research institutions and organizations have signed a petition to stop the building of that biomass-fired boiler. Those signing the petition claim that there is not enough biomass available locally. Research indicates that Amsterdam is in close proximity of 2,04 PJ bio-waste annually (Aalborg University, 2018). This study indicates that there is a need for around 9 hundred-thousand to 1 million tons of biomass annually in both scenarios, which amounts to around 15 to 17 PJ. Nuon aims to get their biomass from forest industries abroad, because of that apparent lack of local biomass available to supply the biomass-fired boiler. The petition claims that this will lead to significant pollutant emissions and losses to biodiversity abroad. Another critical note to the simulated renewable scenarios is that both scenarios produce significantly less electricity than in the reference scenario. Though the municipal strategy pushes for larger wind and solar capacity, it is questionable whether or not this will compensate for the lower amount of electricity production in the renewable scenarios. Compensated electricity may have to be produced elsewhere. Moreover, the introduction of the electric boiler and the electric heat pump to supply heat increase the electricity demand. From an electricity production perspective as well, the locality of the city's energy system may lose focus as the specifications of a city's energy system can have consequences on wider geographical systems. Therefore, there seems to be a need for a more holistic approach in order for a new energy system to arise in Amsterdam. One approach could be strategic energy planning (Sperling, et al., 2011; Bale., et al., 2012). Here, local municipal plans are more aligned with (inter)national policies, implications and processes. Strategic energy planning enables continuous, institutionally frame worked, sector-specific planning, in which (inter)national and local energy planning are strongly related. In line with strategic energy planning, one of the goals of the municipality is to play a more prominent role in facilitating the energy transition of the heating system. As it states in the strategy, it aims to make agreements with housing corporations to make more energy efficient buildings. It also states that it aims to make arrangements with different energy sectors to more actively strive for energy savings. Other statements regarding renewable energy policies are to investigate in new legislation that stimulates the energy transition (Municipality of Amsterdam, 2017). Simulative legislation can assist in niche developments, as in a protected space. Protected spaces are limited domains in which innovations can grow relatively freely. Creating such a protected space can be done by developing research and development centers for renewable heating studies (Schot, et al., 2001). Research shows that in the process of strategic energy planning, modelling frameworks can assist in the decision-making of planning (Gironès, et al., 2015). The modelling framework in this research may therefore provide valuable information for the future heating system of Amsterdam. Despite that, it remains important to understand the wider context of the transition of the heating system. The technical transition may be feasible, but the socio-technical transition may be challenging. Amsterdam's heating system has to destruct and reform. Here, different actors within the system have different relations to each other and to the system. The actors in this are inhabitants, housing corporations, energy suppliers, net operators and the municipality. Citizens demand heat from the system, regardless of their source. Municipalities aim to achieve their climate goals, as they aim to cooperate with housing corporations. Energy suppliers would need thorough changes in their business as the supply of heat in the renewable scenarios undergoes an extensive transformation. Municipalities can stimulate makings such changes by supporting finances through subsidies. In short, the transition of the heating system is more than the technical ability to transform, it also includes socio-technical change.

5.2. Limitations

A critique on the Multi-Level Perspective is that "the different levels are not ontological descriptions of reality, but analytical and heuristic concepts to understand the complex dynamics of socio-technical change" (Geels, 2002, p. 1259). In other words, the theory is not a reflection of reality, but is merely a tool to understand that reality. For this reason, a statement towards what level Amsterdam's current heating system is at in the theory must be received with care.

A main limitation of this study and of the energyPRO simulation models is that it focuses on the operation of certain heating systems. Investment costs in the renewable scenarios are not included. Despite positive revenues in all scenarios (as can be seen in the appendix Table 7, 8 and 9) the exclusion of investment costs might underestimate the feasibility of the operation on renewables. Another limitation is that it does not make a distinction between low quality and high quality heat. Demands for heat can differ per high and low temperatures, which relates to the heat quality.

5.3 Further research

This study relies to some extent on thermal energy storage. The ability to store enables the annual heat demand to be met, whereas the exclusion of thermal storage would not meet that demand. This study has modelled with a theoretical storage capacity of 150.000 MWh. This is a rather large capacity for a single storage. More likely, many different thermal storages with relatively smaller capacities would be installed to store that amount collectively. This study does not go into great detail about how such a decentralized thermal storage system would work. Further research would be required to fully analyze the operation of thermal energy storage in a renewable heating system for Amsterdam. With the displayed interaction of the city's thermal energy storage and its heat production, this study provides pivotal information for further research.

Another lead for further research is the inclusion of district cooling. District cooling has the potential to increase the overall efficiency of the energy system, as it can interlink with heating to operate as a smart energy system. A smart energy system involves the optimum interaction of energy sources, distribution and consumption and is expected to developed in a few years. (Lund, et al., 2016)

6. Conclusion

This study has researched the technical transition of Amsterdam's heating system from natural gas based to renewables. The municipality aims for the elimination of natural gas as an energy source by 2050, but lacks technical knowledge of the operation of a renewable heating system. This study has simulated the current heating system and two possible renewable future heating systems, of which one operates without thermal storage and one with. The heating system is in both simulated renewable scenarios able to match the heat demand without the use of natural gas The simulated model of the current heating system operates with two natural gas-fired CHP-plants, a natural gas-fired boiler, a waste-to-heat plant and a small share of other energy units. A renewable scenario without thermal storage can operate with two biomass-fired CHP-plants, excess heat, the same waste-to-heat plant, solar thermal energy, an electric boiler, an electric heat pump and a biogas-fired boiler. A biogas-fired boiler can supplement heat at times of high heat demands. A renewable scenario with thermal storage can operate with the same energy setup, except it includes thermal energy storage and can exclude the biogas-fired boiler. Thermal energy storage provides more efficiency to the heating system, as it is able to couple electricity prices with heat production from the electric boiler and with CHP- plant operation.

Although this study has shown that the transition is technically possible, it is important to understand the wider context of this transition. Innovation with renewable heating is not necessarily a guarantee for a successful energy transition. Path dependency of a heating system depending heavily on natural gas suggests why the transition may be difficult over time, as the establishment of the natural gas based regime may make it difficult to create changes in the heating system. A successful development and alignment of niche developments in renewables can stimulate the rise of a renewables based socio-technical regime.

Furthermore, the implementation of a renewable heating system can bring along complications. The sustainability of biomass as an energy resource can be questionable, actors depending on each other make the socio-technical transition more challenging and the compensation of the lower electricity production by the CHP-plants may have consequences on wider geographical systems.

7. Reflection

Retrieving data

It has been challenging to retrieve data for the simulation of the heating systems. Unfortunately, a lot of power capacities and demands vary from source to source or were unable to find at all. This study makes estimations to generate this crucial data. In a future energy system study, it may give more precise outcomes to cooperate with a municipality or agency that owns such data.

EnergyPRO

Considering the timeframe of this study, figuring out how to use energyPRO has taken up a large amount of time. It has been difficult to become familiar with the technicalities of the software. EnergyPLAN could have made more sense to use over energyPRO, because energyPRO requires more practice than energyPLAN. EnergyPRO can be seen as more of an engineering tool than energyPLAN, as it is more of a planning tool. EnergyPRO has the ability to thoroughly analyze and optimize operations in different demands throughout the year. EnergyPLAN on the other hand analyzes different policy scenarios, such as different shares of renewable energy. EnergyPRO was and is a better fit for the scope and focus of this study.

Supervision

Due to unfortunate private events of my initial supervisor Lars Grundahl, I was forced to switch supervisors during the study. I want to thank Lars for his contributions to help me get this thesis started and wish him all the best. I am also thankful for Rasmus Søgaard Lund, who stepped in as the replacing supervisor of this thesis. I especially want to thank him for his contributions on assisting me with energyPRO.

Learning goals

The motivation for doing this particular study was to gain a better understanding of energy systems on a city scale. I have always been intrigued by city mechanisms and during my master studies I have been introduced to renewable energy systems. I personally feel like a city’s energy system is an overlooked and underestimated topic under urban planning students. More popular study topics under students, at least in my program, are transportation, infrastructure and general policies. Also, my initial interest in urban planning was sparked by architectural designs of buildings, districts, public spaces and much more. The underlying crucial element for such things is the provision of energy. In such an area, not only the tangible and visible characteristics matter to make designs to what they are. More hidden is the energy system that lies underneath it all. This study has definitely given me a better understanding of energy systems. I have a better feeling for power and heat capacities and I have a better understanding of the interactions of different energy units. Using energyPRO certainly provided a helpful guidance to gaining that knowledge. I am also able to investigate an energy transition from a broader perspective, as it has become clear that changing energy systems is more than a technical feasibility study.

Larger scope

By the end of this study, it seems that a more holistic approach is necessary to stimulate the transition of the heating system. The relation of heat production with electricity and the possibility to include district cooling for a higher efficiency of the overall system suggest that in future heating studies the scope should be larger than solely on heating. However, such a study is likely to be a longer and more extensive study than this one has been as the enlargement of the scope can bring along more complexities on e.g. the interaction of different energy systems and the localities of energy sources.

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Appendix

Table of content

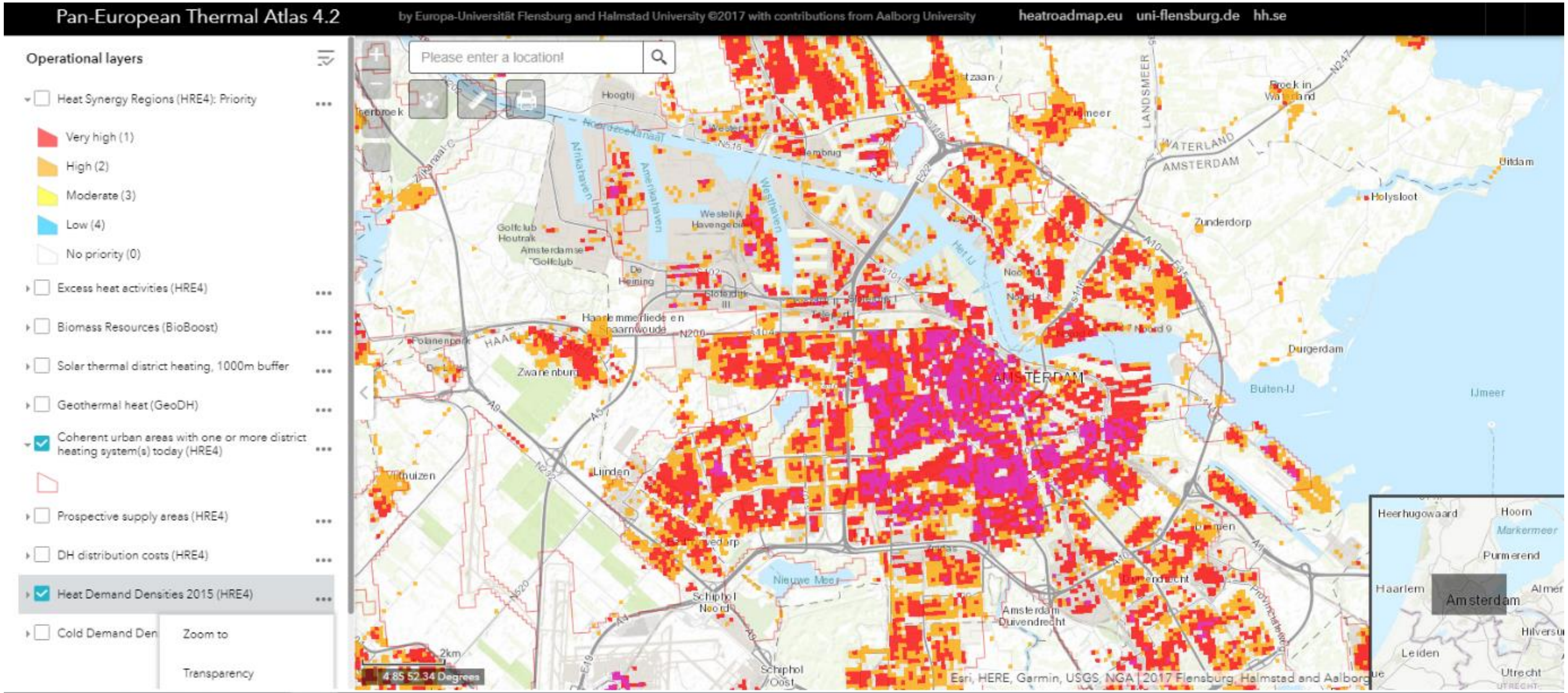
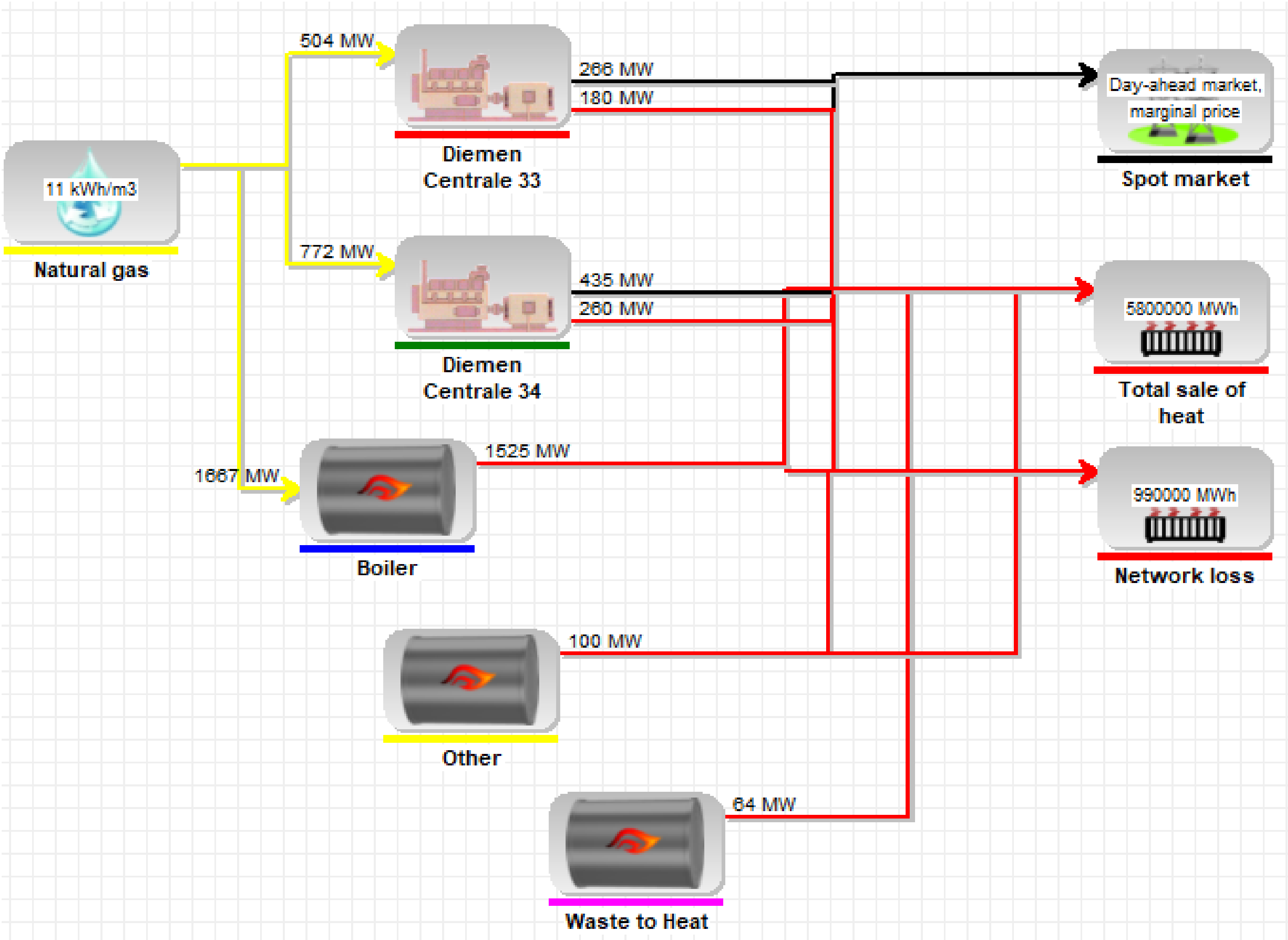


Figure 9. Heat demand density. Source: Heat Roadmap Europe.

Figure 10. Graphical layout of the reference scenario. Red lines represent heat, black lines represent electricity and the yellow line represents gas. Source: energyPRO.



Graphical layout note

Due to limited refined graphic design options in energyPRO, a few things should be noted about the following two graphical layouts for the renewable scenarios:

- Realistically, not all collected or produced heat goes through the thermal storage prior to be delived to the heat demand. Only modellistically, that heat is firstly connected to thermal storage to allow heat to be stored in general before supplied.
- The black lines representing electricity may seem to interconnect more than it actually is. Electricity is produced by the CHP-plants and is delivered to the electric heat pump, the electric boiler or the spot market. The spot market can also supply electricity to the electric heat pump or the electric boiler.
- All heat is supplied to match the total heat demand, which is the total sale of heat and the network losses.
- Green lines represent biomass, red lines represent heat, black lines represent electricity and the yellow line represents gas.

Figure 11. Graphical layout of the simulation model for a renewable scenario without thermal storage. Source: energyPRO.

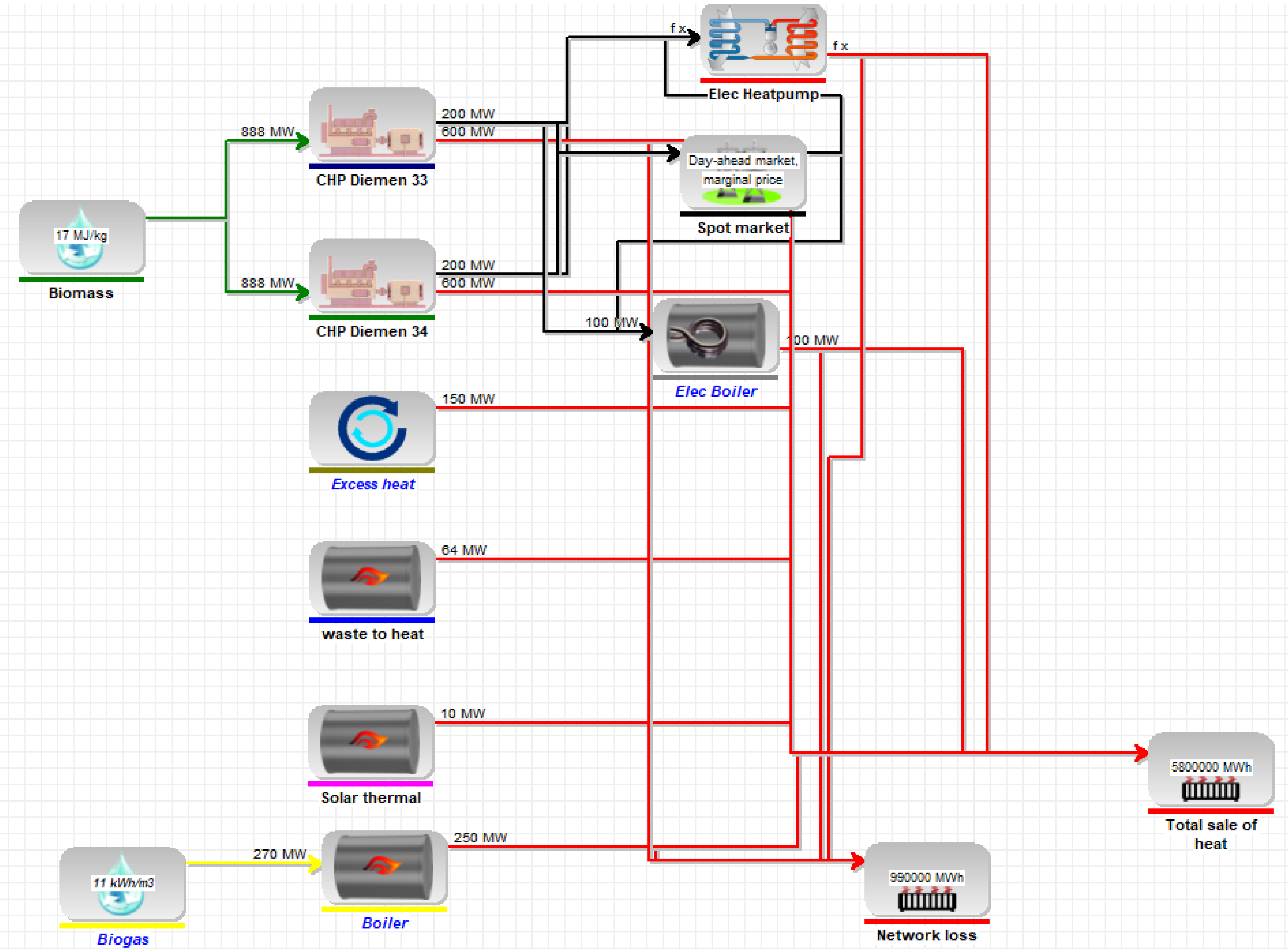


Figure 12. Graphical layout of the simulation model for a renewable scenario with thermal storage. The biogas boiler is modelled but not used. Source: energyPRO.

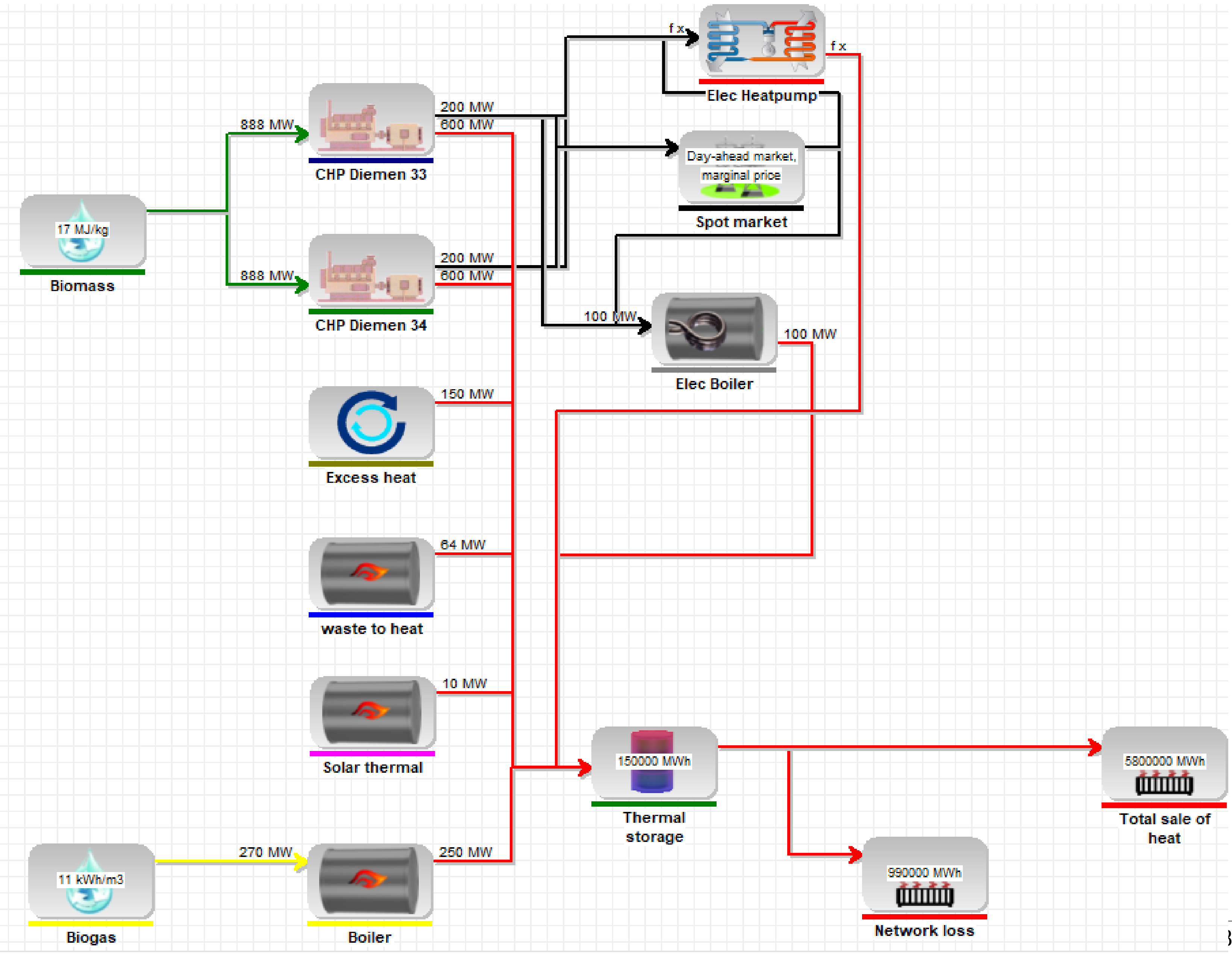


Figure 13. Graphical layout of 'Cogeneration plant on a spot market'. Source: energyPRO.

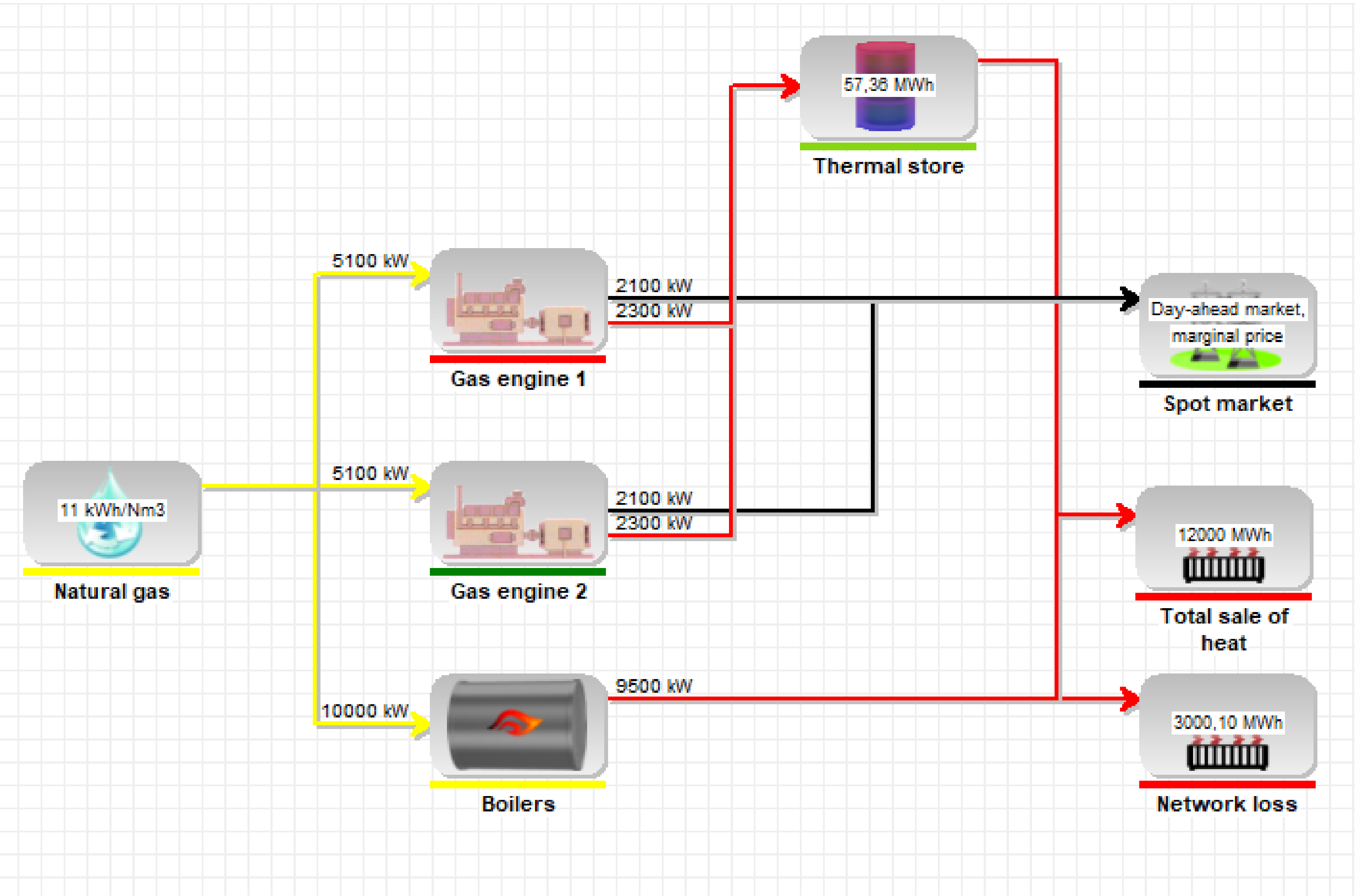


Table 6. Excess heat activities in the Amsterdam. Data source:
Aalborg University, Pan-European Thermal Atlas 4.2.

		(annual) PJ	(annual) MWh	(annual) million MWh	
Steel factory	Tata Steel Velsen-Noord	18,0	5.005.555,6	5,0	
Electricity power plant	Nuon IJmond 1	14,2	3.952.777,8	4,0	
Electricity power plant	Nuon Velsen	26,7	7.422.222,2	7,4	
Paper factory	Crown van Gelder N.V.	0,7	180.555,6	0,2	
Electricity power plant	Nuon Hemweg	17,8	4.941.666,7	4,9	
Sugar refinery	Tate & Lyle Netherlands BV	0,2	52.777,8	0,1	
					capacity (MW)
Total		77,6	21.555.555,6	21,6	5987,7

Revenues								
Sale of heat								
Total sale of heat	:	5.828.068,9 MWh	at	37,5	=	218.552.584		
Sale of heat Total							**218.552.584**	
Sale of electricity								
Sale of electricity	:	5.490.765,9 MWh	at	30,629*	=	168.178.729		
Sale of electricity Total							**168.178.729**	
Total Revenues								**386.731.313**
Operating Expenditures								
Fuel costs								
Natural gas	:	1.150.050.184,9 m3	at	0,3	=	345.015.069		
Fuel costs Total							**345.015.069**	
Operation&Maint.								
Engine 1	:	2.330.160,0 MWh	at	6,0	=	13.980.960		
Engine 2	:	3.160.605,9 MWh	at	6,0	=	18.963.635		
Boilers	:	573.802,4 MWh	at	1,2	=	688.563		
Operation&Maint. Total							**33.633.158**	
Total Operating Expenditures								**378.648.227**
Operation Income								**8.083.085**

* Average price

Table 7. Operation income in the reference scenario. All amounts in euro. From 01-01-2017 00:00 to 31-12-2017 23:59. Operating expenditures index prices of natural gas, the engines and the boiler are based on the existing model ‘Cogeneration plant on a spot market’. Source: energyPRO.

Revenues							
Sale of heat							
Total sale of heat	:	5.824.851,5MWh	at	37,5	=	218.431.930	
Sale of heat Total						**218.431.930**	
Sale of electricity							
Sale of electricity	:	265.349,3MWh	at	33,548*	=	8.902.013	
Sale of electricity Total						**8.902.013**	
Total Revenues							**227.333.943**
Operating Expenditures							
Fuel costs							
Biomass	:	891.180.807,3kg	at	0,2	=	178.236.164	
Biogas	:	1.837.863,5m3	at	2,0	=	3.675.727	
Fuel costs Total						**181.911.891**	
Operation&Maint.							
Engine 1	:	787.155,5MWh	at	6,0	=	4.722.933	
Engine 2	:	160.671,9MWh	at	6,0	=	964.031	
Boiler	:	1.837.863,5m3	at	6,0	=	11.027.181	
Operation&Maint. Total						**16.714.146**	
Total Operating Expenditures							**198.626.037**
Operation Income							**28.707.906**

* Average price

Table 8. Operation income renewable scenario without thermal storage. All amounts in euro. From 01-01-2017 00:00 to 31-12-2017 23:59. Operating expenditures index prices of biomass, biogas and the engines are based on the existing model ‘Cogeneration plant on a spot market’. Source: energyPRO.

Revenues								
Sale of heat								
Total sale of heat	:	5.824.851,5 MWh	at	37,5	=	218.431.930		
Sale of heat Total							**218.431.930**	
Sale of electricity								
Sale of electricity	:	883.586,3 MWh	at	40,025*	=	35.365.695		
Sale of electricity Total							**35.365.695**	
Total Revenues								**253.797.625**
Operating Expenditures								
Fuel costs								
Biomass	:	1.019.140.368,7 kg	at	0,2	=	203.828.077		
Biogas	:	0,0 m3	at	0,0	=	0		
Fuel costs Total							**203.828.077**	
Operation&Maint.								
Engine 1	:	583.956,5 MWh	at	6,0	=	3.503.739		
Engine 2	:	499.964,1 MWh	at	6,0	=	2.999.784		
Operation&Maint. Total							**6.503.523**	
Total Operating Expenditures								**210.331.600**
Operation Income								**43.466.025**

* Average price

Table 9. Operation income renewable scenario with thermal storage. All amounts in euro. From 01-01-2017 00:00 to 31-12-2017 23:59. Operating expenditures index prices of biomass, biogas, the engines and the boiler are based on the existing model ‘Cogeneration plant on a spot market’. Source: energyPRO.

Energy unit	Selected priority in operation strategy
CHP Diemen 33	Calculated
CHP Diemen 34	Calculated
waste to heat	High
Elec Heatpump	Calculated
Solar thermal	High
Excess heat	High
Elec Boiler	Calculated
Boiler	Calculated

Table 10. Energy unit setup with selected production priorities. * Source: energyPRO.

*Here, the priority is on renewable energy and excess heat. Notice that excess heat has a calculated priority. Modelled with a high priority, energyPRO overvalues excess as an energy source and this results in an unlikely share of more than 50% in the annual energy conversion.

		Reference	No Storage
Heat demand	[MWh]	6.814.851,7	6.814.851,7
Electricity produced by energy units	[MWh]	1.083.920,6	947.827,4
Electricity consumed by energy units	[MWh]	765.000,0	1.176.515,3
Exported electricity	[MWh]	883.586,3	265.349,3
Peak	[MW]	350,000	250,000
Imported electricity	[MWh]	564.665,7	494.037,1
Peak	[MW]	150,000	149,619
Energy unit: CHP Diemen 33			
Fuel consum.	[kg]	549.056.497,0	740.111.419,0
Fuel consum.	[MWh]	2.592.766,8	3.494.970,6
Heat prod.	[MWh]	1.751.869,5	2.361.466,6
Elec. prod.	[MWh]	583.956,5	787.155,5
Operating hours	[hours]	2.934,0	7.000,0
Full load operating hours	[hours]	2.919,8	3.935,8
Turn ons	[Turn ons]	342,0	123,0
Energy unit: CHP Diemen 34			
Fuel consum.	[kg]	470.083.871,7	151.069.388,3
Fuel consum.	[MWh]	2.219.840,5	713.383,2
Heat prod.	[MWh]	1.499.892,2	482.015,7
Elec. prod.	[MWh]	499.964,1	160.671,9
Operating hours	[hours]	2.516,0	1.657,0
Full load operating hours	[hours]	2.499,8	803,4
Turn ons	[Turn ons]	330,0	110,0
Energy unit: waste to heat			
Heat prod.	[MWh]	560.640,0	560.640,0
Operating hours	[hours]	8.760,0	8.760,0
Full load operating hours	[hours]	8.760,0	8.760,0
Turn ons	[Turn ons]	0,0	0,0
Energy unit: Elec Heatpump			
Heat prod.	[MWh]	1.314.000,0	1.281.067,7
Elec. consum.	[MWh]	438.000,0	427.022,6
Operating hours	[hours]	8.760,0	8.760,0
Full load operating hours	[hours]	8.760,0	8.540,5
Turn ons	[Turn ons]	0,0	0,0
Energy unit: Solar thermal			
Heat prod.	[MWh]	47.450,0	47.450,0
Operating hours	[hours]	4.745,0	4.745,0
Full load operating hours	[hours]	4.745,0	4.745,0
Turn ons	[Turn ons]	365,0	365,0

Table 11. Compared annual energy conversion with thermal storage ('reference') and without storage. Source: energyPRO.