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STUDENT REPORT

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A feasibility study on the alternatives for renewable energy based heating systems in urbanised areas

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Synopsis:

This project examines the feasibility of alternative heating scenarios which are based on renewable energy sources. The research is set up based on two case studies, one in Esbjerg and the other one in Groningen. In both case study areas, the analysis consists of centralised unit energy system scenarios and diversified energy system scenarios. The feasibility revolves around the concept of efficient primary energy consumption with a minimisation of biomass and simultaneously the socioeconomic should be as low as possible. These aspects were analysed in order to answer the following research question:

Using the cities Esbjerg and Groningen as case studies, how does the feasibility of renewable energy based heating system alternatives compare?

The results show that the diversified energy systems are in both case the studies to most efficient with the primary energy supply whilst also having the lowest lifetime and annual costs. In addition, the research shows that Esbjerg has the ability to supply its heating demand via local energy sources, whereas Groningen requires additional biomass resources from outside its local region.

Preface

All the prices in this report are defined by the € (euro) currency. The exchange rate with the Danish Kroner (DKK) is 1 € equals 7,45 DKK.

References in this report are according the Harvard method which has the form of [Surname, year] within the text. If more than one reference, these will be separated by a semicolon. All the references are collected within bibliography at the end of the report. The references refer to the bibliography where books, articles, and technical reports are referred by author, title, publisher, year, and URL when available. Websites are referred by the author, title, year, URL, and the date on which the page was visited last. All the Figures and tables are numbered according to the particular chapter they occur in.

The format used for the separators of numbers is commas (,) for decimal separation and periods (.) for separating groups of thousands.

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Nomenclature

Abbreviation	**Explanation**
CHP	Combines Heat and Power
COP	Coefficient of Performance
CRF	Capital Recovery Factor
DK	Denmark
EU	European Union
NL	The Netherlands
NPV	Net Present Value
O&M	Operations and Management
PV	Present Value

Table 1: An overview of the abbreviations and their explenations

Unit	**Explanation**
K	Kelvin
$^{\circ}C$	Celcius
k	kilo 10^3
M	Mega 10^6
G	Giga 10^9
P	Peta 10^{12}
J	Joule
W	Watt
W_{th}	Thermal capacity in Watt
W_{el}	Electricity capacity in Watt
Wh	Watt hour
s	second
h	hour
m^2	1 squared meter
m^3	1 cubic meter
g	1 gram
tonne	1.000 kg
DKK	Danish Kroner
€	Euro

Table 2: An overview of the units applied in this study

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Introduction 1

The impacts of climate change by the consumption of fossil fuels are noticeable all around the world [IPCC, 2014]. For this reason, the European Union has set actions to mitigate the climate change effects caused by society. [Bertoldi *et al.*, 2018] describes the '20-20-20' target by 2020 that the EU has set out, this encompasses the reduction of greenhouse gasses with 20% compared to 1990 levels, to have a 20% share of renewable energy consumption and a 20% increase in energy efficiency within the primary energy consumption. As the EU is closing in on the year 2020, it seems that the targets are close to being met with some countries performing better than expected and other countries having more troubles achieving their goals [Eurostat, 2017]. In order to continue this trend to mitigate climate change, the 2030 targets are as followed; A 40% decrease in greenhouse gas emissions, at least a 27% share of renewable energy consumption and 30% energy savings compared to business as usual.
About 40% of the total energy consumption in Europe is caused by the built environment. Within the northern European countries, up to 80% of energy demand in the residential sector is comprised of the demand for heating including hot water [Bornemann et al.]. In addition, heating in the residential sector accounts for up to 30% of the overall CO2 emissions in the EU [von Manteuffel et al., 2016]. The prominent reason for these emissions is that the heating and cooling sector is primarily produced by fossil fuels [EC, 2016a]. The residential sector and its energy consumption seem to be essential for the development towards lower emissions and more energy efficiency. A big part of the built environment is located in cities due to the urbanisation of the recent decades. According to [UN, 2014], already more than 73% of Europeans are living in urbanised areas and this share is expected to grow over the years. In addition, the energy consumption per capita is found to be higher in urbanised areas compared to non-urbanised regions. All these shares show that the energy consumption in cities, especially due to heating is very influential to the goals set up by the EU. Fortunately, the EU recognises that there are opportunities within the residential sector and cities to support the road towards the targets [EC, 2016a]. It is expected that changes in the production of heating can result in effective mitigation results.

It is now clear that cities could play an important role in the energy challenges that the EU and its inhabitants face. The current state of heating supply in cities in Europe varies significantly, where in some places the heating is supplied via district heating and in other places individual heating plays a major role. Besides the heating infrastructure, different types of technology can be found in heating systems such as individual boilers or heat pumps, combined heat and power (CHP) plants which subsequently run on different fuels, e.g. natural gas, coal, municipal waste or biomass [Persson and Werner, 2015]. Nonetheless, the heating systems in place are relatively simple where either one large centralised unit supplies heating via district heating or the heating is supplied on site and the fuel is transported to the individual users.

Technically speaking, it would be possible to supply heating to all buildings via the use of district heating networks yet from an economic perspective this is not always the optimal choice [Amer-Allam et al.]. The concept of district heating is primarily based on the specific heat density, i.e. the amount of heat demand per unit of space. The specific heat demand is often the highest in densely populated areas such as cities. The current share of district heating is only 13% of the total heating demand of Europe [Connolly *et al.*, 2014], which is relatively low compared to the level of urbanisation of Europe. The potential of district heating with regards to the total heat demand in (ex-)member states has been analysed by [Connolly *et al.*, 2016]. Some of the results include a district heating potential of 40% in Croatia, 60 % for Italy and 70% for the United Kingdom (70%). Although the colder central and northern region of Europe have a more intense energy consumption in buildings it does not exclude other areas to implement district heating [Bellos and Tzivanidis, 2017].

There are several reasons why district heating is thought to be beneficial for the development of the heating systems. First, it can utilise a wider variety of energy sources. The possible alternatives to produce heating within individual heating systems based on non-fossil sources are more limited. Additional sources that are applicable for district heating and not specifically for individual heating purposes are waste or excess heating, geothermal heating or heat pumps that extract energy from other (natural) heat sources. Since one of the goals of the EU is to improve energy efficiency, the use of otherwise wasted energy would help significantly. Excess heating can come from different processes, e.g. it can come from industrial processes where high temperatures are needed or the heat produced during the generation of electricity in the form of CHP can also be considered as wasted heat. Another benefit of district heating is the possibility of having more flexibility in the system due to having more options to alter the fuel/energy source [Magnussen, 2012].

Whether the choice is made to implement a district heating system or use individual heating sources, it is necessary to find solutions that help to decarbonise the heating system. Before any possible solutions are analysed and before the research question is introduced, some aspects of the energy system need to be clarified and understood. To start, the influence of the differences between socioeconomic costs and business economic costs are presented. Followed by the necessary understanding needed on the finite biomass resources as an energy source for heating purposes.

1.1 Socioeconomic vs. business economic

The use of renewable energy sources such as wind, solar and bioenergy are all mainly policy driven. Due to the relatively cheap price of fossil fuel energy the alternatives are often required to be promoted by targets and incentives [EC, 2017]. By making non-fossil fuel alternatives more attractive from a business economic perspective, the implementation of said alternative could increase. Throughout Europe the implementation of wind turbines has been heavily promoted with the use of tenders, which gives the organisation that owns the wind turbines more security for a shorter return on investment. Like wind power incentives, biomass can have the same concept where for every production of a unit power a subsidy can be given. However, in contrast to wind power, biomass has a finite accessibility in contrast to wind. For example, Denmark has a subsidy on the production of electricity from biomass which makes it more profitable to produce electricity from biomass. According to [Lund, 2015], the use of large scale CHP plants that operate within a system where biomass is subsidised a mismatch is created between the socioeconomic and business economic perspective. In other words, the subsidy for CHP plants has the effect that from a business economic perspective the operation is profitable whereas from a socioeconomic perspective, it would have a negative influence on the overall costs. Moreover, it would result in excessive use of biomass resources to an unsustainable level of consumption simply because the operation is profitable. Within a smart energy system, there is a need for smart use of resources which can be obstructed by subsidies. Therefore, reviewing an energy system from a socioeconomic perspective can result in energy systems that are more beneficial for society.

1.2 Biomass restriction

As it is mentioned, the production of energy with biomass as a source can be policy driven through subsidies. This is one of the options to implement decarbonisation in an energy system and is an option that Denmark has embraced in their energy system policies. Denmark has been transforming several of their coal fired power plants to run on biomass. There are several examples of coal fired power plants that have been successfully transformed to run on biomass resources such as wood pellets, e.g. in 2016 the Studstrupværk in Århus had a completed transition from a coal fired power plant to become the largest biomass fired power plant in the world with 360 MW electricity and 515 MJ/s heating for the district heating grid [Wittrup, 2016]. Due to the conversions from coal to biomass, biomass has now become the largest share or renewable energy in Denmark and will most likely grow with more planned conversions [DEA, 2017a].

Denmark is an example of a country that has embraced the use of biomass to reach their renewable energy goals. Although the use of biomass is regarded as a viable solution since it is a renewable energy source, the sustainability factor is questionable [DEA, a]; biodiversity losses from large scale biomass production, the competition with food supply, possible carbon storage imbalances, etc. [Letcher and Scott, 2012]. Another troublesome aspect to the consumption of biomass within heating systems is that it reduces the availability of biomass in other sectors such as the industry. To conclude, due to the limited amount of biomass available and the limited potential of it, the consumption of biomass should be minimised [Mathiesen et al.].

1.3 Problem formulation

The transition towards fossil fuel free heating systems seems to be affected by a wide variety of aspects such as heat density, fuel price uncertainty and sustainability factors. Moreover, the heating systems found in urbanised areas in Europe are significantly different from each other. For example, Denmark has a district heating share of 53% of the total heat demand in 2015 and 63% of the heat demand within the residential heating sector [Mathiesen *et al.*, 2015; of Green, 2015]. This share is achieved as result of the implementation a long time ago, dating back to the 1920's, and Denmark continued implementing it. On the other hand, the Netherlands with a higher heat density compared to Denmark has only a share of around 4% of the heat demand covered by district heating[Menkveld *et al.*, 2015]. The Netherlands is based on individual heating on natural gas as 83% of the heating demand is covered by natural gas [Persson and Werner, 2015].

Decarbonising the heating system can be achieved via various pathways. These pathways to decarbonise the heating system are analysed with the help of two cities that represent as case studies. These two cities have a completely different type of energy system in place, however, both are reviewing their options to decarbonise the heating system. One city is Esbjerg, in Denmark and the other city is Groningen in the Netherlands. Esbjerg, which has a district heating system, is looking for alternatives to a coal fired CHP plant. Whereas Groningen is needs to make the transition away from the use of natural gas in individual gas boilers.

The analyses on finding alternatives of providing heating are depending on the concept to minimise the use of biomass in the system. Moreover, from a socioeconomic perspective the costs should be kept at a minimum too. With the following research question the analyses of various non-fossil fuel based heating systems is conducted;

Using the cities Esbjerg and Groningen as case studies, how does the feasibility of renewable energy based heating system alternatives compare?

This research question aims to find the characteristics of different kinds of pathways including district heating or individual heating, and different kind of renewable energy sources. The feasibility is based around finding low cost alternatives which have an optimal primary energy supply.

1.4 Delimitation

In order to help steer the research in an adequate direction, some limitations have been set up. These limitations are relevant subjects of the thesis yet they their exclusion is premeditated. First, the technologies that are included in the analyses are based on known technologies that are presently available. In other words, any technologies that are currently in their development phase are not included. The change towards decarbonisation of the heating system is a pressing issue where there is little time to depend on future developments, i.e. both case study areas are in presently looking for alternatives. Moreover, basing the analyses on known technologies has the advantage that specific information, such as costs and efficiencies, is generally more tested and it can be more accessible.

The second limitation is that throughout the complete analyses, the heat demand, the fuel types and characteristics, remain the same. A basis year is taken to determine the heat demand, the amount of buildings, the electricity and other fuels prices. The purpose of this research is to compare various scenarios with regards to system dynamics and the costs of the heating systems.

Thirdly, the primary focus of the energy system is based around making socioeconomic analyses. Therefore, specific regulations, taxes and subsidies are not included in the research. Nonetheless, there are some business economic aspects included in the research in order for the scenarios to be closer to reality and to show the influence of certain policy driven concepts.

1.5 Project structure

The following section is set up to show the different chapters that will follow in this project and what their respective purpose is for answering the research question.

Chapter 2: Theoretical Framework and Methodology

- The scientific framework is set up for the entire research and the applied methods are explained. The process of the research done in this project is according to the theories that are mentioned in this chapter. The methodology includes all the necessary tools that are utilised throughout the process of answering the research question.

Chapter 3: Case Study Areas

- The scenario analyses in this project are based on two case study areas. The necessary background information of both case study areas are given in this chapter. Moreover, this chapter allows for an examination on the similarities and the differences of the characteristics of both areas.

Chapter 4: Thermal Energy Production Units

- The possible heating systems can be based on various thermal energy producing units. This chapter gives a rather complete overview of the different production units, with their general operation strategy and their characteristics. The efficiencies and costs of all the units are presented.

Chapter 5: Quantification of the Local Energy Sources

- The research question aims to find feasible heating systems where the primary energy supply is meant to be as efficient as possible. This includes to increase the amount of potential energy that would currently go to waste. These energy sources are quantified according a variety of sources.

Chapter 6: Decarbonised Heating System Alternatives

- The previous chapters are all leading up to the modelling and analysis of the potential heating systems. In this chapter, various scenarios are introduced and analysed with the purpose of finding the most feasible heating system. Comparisons are made for both case study areas between centralised unit energy systems, diversified energy systems and individual heating systems. In addition, the two case study areas are compared to each other. All the scenarios are compared according to their system dynamics, their primary energy supply, the lifetime costs and the annualised costs.

Chapter 7: Discussion and Future Research

- In the discussion of the project the aspects that are not included in the research but which could be influential on the results are discussed. Moreover, the possible future research options are determined which would create a deeper understanding of the research topic of decarbonised heating systems.

Chapter 8: Conclusion

- The last chapter is set up to provide the answer to the research question according to results found from the analyses.

Theoretical Framework and Methodology

2

This chapter includes the theoretical framework in which research question roams and the methodology applied throughout the research. The theoretical framework allows for a deeper understanding of the subject and simultaneously provides a scientific framework. This entire chapter is focused on the application of the transition process from a fossil fuel based heating system towards a sustainable and fossil fuel free based heating system in the urban environment.

Choice awareness theory

The transition towards a fossil free heating system includes the change towards other technologies than those currently in place. From a societal perspective the choice awareness theory can assist in the knowledge and discourse of the transition. The choice awareness theory revolves around radical technological changes and its interaction with society and other stakeholders.

Before the application of choice awareness is explained, the concept of radical technological change needs to be known. According to [Lund, 2014], technology can be defined by the following five constitutes: Technique, Knowledge, Organisation, Product and Profit. A radical change of technology can only be successful when more than one of these five constitutes is changed. An example for a radical technological change is the transition towards a fossil free energy system. This would inevitably mean a transition with regards to the technique used. In addition, the organisation aspect is altered since the production of energy is met with the arrival of more decentralised forms of energy production such as wind and (private) solar and simultaneously an increase in the synergies between energy sectors is taking place. Due to this change in organisation, the profits are likely to be distributed differently. Lastly, new knowledge and expertise is needed for the future energy systems since it is inherently different to the previous energy system. Radical technological changes, such as the transition towards a renewable energy system, are often found in an environment that includes a large number of different stakeholders, with different levels of power.

In the case of the renewable energy transition, the current organisations that are invested in non-renewable technologies can feel threatened, especially if these organisations are not aiming to change alongside with the transition. One result of threats posed to these organisations, who often have a significant amount of power due their size, is to eliminate choice for the public. Via specific discourse, influence can be asserted to eliminate certain alternatives or even creating the perception of "no choice" and by doing this saving their existing position. Choice awareness theory can be, in turn, be a response to the idea of eliminating alternatives. The theory strives to improve and increase the choices for alternatives. One of the measures that Lund [Lund, 2014] mentions in order to create awareness on the alternatives is to make feasibility studies. [Hvelplund et al., 2004] states that the purpose of feasibility studies is to give answer to question on what alternative is most feasible for solving a specific problem. Since the choice awareness revolves around the concept of providing alternatives, it is necessary to analyse alternatives. A specific distinction needs to be made between types of feasibility studies, i.e. the difference between a socioeconomic or a business/private economic evaluation. Herein is the socioeconomic perspective focused on the question if a project is feasible for the society as a whole whereas the business economic perspective solely looks at whether the operation is profitable for the organisation. Feasibility studies allow to give insight in the potential of innovative political and public regulation measures. Based upon the results of a socioeconomic feasibility studies, specific regulation measures can be applied that can stimulate a path towards the most feasible solution.

Strategic Energy Planning

Municipalities have gained an important role in the concept of the future energy system which is becoming increasingly determined by local energy sources. The local energy planning authorities should support the path towards the national energy goals which are in turn in line with the European goals. The planning of municipalities should also be aimed at refining the national goals and applying concrete actions. It should be the role of the municipalities to examine the local resources and energy potentials and how these can be integrated. To assist the municipalities with the road towards sustainable energy systems, the tool of strategic energy planning can be applied. Strategic energy planning involves the use of long term planning, scenario analysis, internal and external coordination of the planning process and the use of local ownership and involvement should be promoted. [Lund et al., 2013] gives the following definition for strategic energy planning;

> *The process where municipalities are planning for the development of energy supply and demand within electricity, heating, mobility and other relevant sectors, based on long term scenario analyses, in coordination with the relevant municipal departments and external actors including the local communities, to reach long term societal goals in the most feasible way.* [Lund et al., 2013]

Strategic energy planning in this research is applied through finding the most feasible route towards decarbonising the heating system.

One of the measures highlighted in strategic energy planning is the application of scenario planning. [Bandhold and Lindgren, 2003] states that scenario planning is often used to creating plausible futures via generating, analysing and implementing strategies. Instead of making the attempt to predict the future, scenario planning is meant to open an insight into the future. It allows to tell various stories that could represent several occurrences that can happen in the future. A main benefit of the use of scenario planning is the idea that it can challenge current thinking by showing a wider range of paradigms [Chermack et al., 2001]. There are different kinds of scenario analyses and each of them have their own unique purpose. According to [Börjeson et al., 2006], who made a user's guide for scenarios and how to make clear distinctions in the type of scenarios and when to use what type of scenario, there are three main paths that scenarios can take. First of all, scenarios can be predictive which focuses on that current trends are continued, and what the result in the future of these trends would be. Secondly, explorative scenarios are scenarios where external actors or policies are changed to a current system. These types of scenarios are focused on what influence outside entities can have on the current system. Lastly, the normative scenarios are meant to show possible pathways to achieve the same goal that is currently the goal of a system but with an alteration to the system. A difference is found between two normative scenarios, where one focuses on preserving the current system to a certain extent and the other scenarios focus on transforming the current system whilst both maintaining the same goal. This last type of scenario would be most applicable to this research since the goal remains the same, i.e. supplying the heat demand, but through different pathways, i.e. renewable energy based pathways.

Worldview
There are similarities found in the choice awareness theory and the method of strategic energy planning. These similarities are shown in the use of showing alternatives. And more importantly, attempting to provide the best alternative for society. Feasibility studies aim to understand the whole possible field of alternatives and scenario planning is a tool that can assist in this aim. It is therefore that due to these two methods, which are thought to have synergies with each other, the worldview in this study is based on finding the best alternative for society. This exceeds the view on solely finding the most feasible solution for the local community, i.e. that the feasible solutions for the local community does not take away the opportunity for others to achieve similar results. It is important to note that a socioeconomic view on reality does not have to be a true reflection of reality. The results of a socioeconomic feasibility study are meant to show what the alternatives for reality can be.

Case study method
The use of case studies within the field of research of the renewable energy transition is not new and it has been applied in a variety of researches. However, the use of case studies has also been criticised and thus the appropriateness of the methodology should be known. A case study is, according to [Yin, 1994], an empirical method to investigate a contemporary phenomenon within a real-life context. In other words, a case study can be used to analyse data within a specific context [Zainal, 2007]. For a long time, the use of case studies was regarded as not useful and even not as a scientific method. [Flyvbjerg, 2006] states there were 5 misconceptions on the application of the case study methodology. One of these misconceptions is that one cannot generalise from a case study, as it is based upon a specific context. However, generalisation can be applied to a certain extent given that the preconditions of the case are known. Nonetheless, the author states that commonly the generalisation based on a single case is overvalued where the practise to provide examples is undervalued. To provide examples of the possibilities of alternative heating structures, the use of case studies is applied within this research.

Modelling tools
The energy system analysis and the application of scenario planning both combine to demand the use of energy modelling tools. Modelling tools can help with examination of the socioeconomic parameters such as economic and environmental aspects, as well as the technical viability of an energy system. This study requires a modelling tool that is known to work well with local and regional planning of heating systems and where the economic feasibility can be determined. Moreover, the tool should be able to represent reality to the extent that the results can be utilised as an example and where the modelling can be done for a multi-year period. With the help of [Connolly et al., 2010], who made a comprehensive comparison of 37 energy system modelling tools in collaboration with the tool developers, the modelling tool EnergyPRO by EMD came forward to be suitable for this project. EnergyPRO is known to be used to analyse regional or city scenarios with regards to the heating system [Østergaard; Kiss, 2015; Amer-Allam et al.].
EnergyPRO is an input/output model meaning that given the same inputs, the same output is generated regardless of the amount of times that the program is ran. According to a deterministic

approach it is possible to input user defined parameters into the system, e.g. time series, fuels, energy conversion units, taxes, investment, operation and management costs, etc. EnergyPRO can use time series from a specific year and alter these time series in order to model multiple years. For example, the electricity prices of a specific year can be implemented, and EnergyPRO will use this time series of one year to generate time series for multiple years. EnergyPRO also has the tool to access local weather data such as temperatures and solar radiation.
One of the major qualities of EnergyPRO is the prioritisation model embedded in the software tool. An illustration of the prioritisation model is found in the matrix of Figure 2.1. On the x-axis the electricity prices are found and on the y-axis the price for the production of heating is displayed. Electricity producing units have a decreasing line whereas the units that consume have an increasing line. The production units that do not consume or generate electricity have a horizontal priority line.

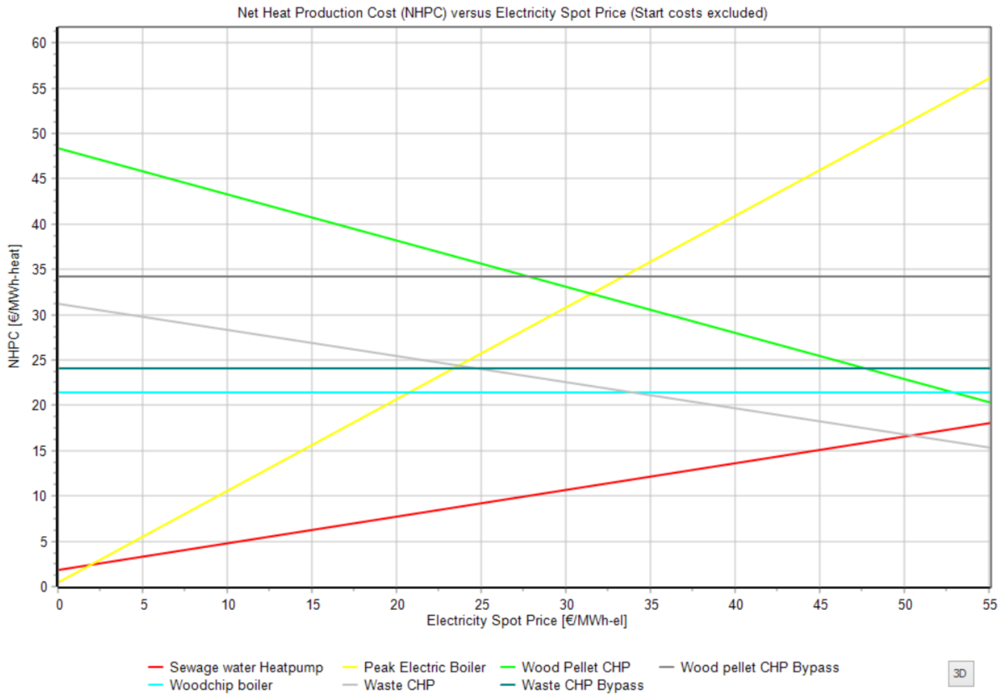

Figure 2.1: An example of the operation strategy method applied in EnergyPRO.

Whereas other modelling tools often follow a chronological time step, EnergyPRO applies a non-chronological analysis according to the prioritisation [Østergaard and Andersen, 2016]. With the help of priority matrix, the prioritisation is determined for all related electricity prices and the fuel and operating costs. In this matrix the lower number of prioritisation equals to the highest priority. According to the time steps, e.g. hours or minutes, the demand is being supplied throughout the entire period. The production units with the highest priority will be operated first, followed by the production unit with the second highest priority. This process is continued until the demand is met in the complete period whilst taking restrictions such as fuel stock, storage and transmission congestion into account. The prioritisation model is one of the reasons that EnergyPRO is suitable for this project as the strategy of operation is based on the minimising the costs.

Net present value

The present value plays an important role in this project as it allows to include the lifetimes of the various technologies implemented. A net present value is the aggregation of all the present values of the operational costs, revenues and investments made within the chosen life of the project. In other words, the present value shows the future cash flows in the value of the present. An important aspect of the net present value is the discount rate, as this indicates at what rate the value of money decreases. The lower the discount rate, the less changes happen to the value of money. If the discount rate is positive, then the future cash flow of certain amount of money is always lower than the same amount of cash flow at present times. The equation of the NPV is given in Eq. 2.2. [Berk and DeMarzo, 2014]

$$NPV = PV_{revenue} - PV_{costs} - Investments\ costs \tag{2.1}$$

$$PV = \sum_{n=1}^{N} \frac{C}{(1+r)^n} \tag{2.2}$$

Where,
$PV = present\ value$
$C = payment$
$n = year$
$N = N - period$
$r = discount\ rate$

Capital recovery factor
Whereas the NPV allows to determine the present value of future investments, the present value does not show what the annualised costs of a project are over its lifetime. To be able to give an amount for the annual costs of a system over its lifetime the so-called capital recovery factor (CRF) can be applied. The CRF takes the lifetime and the discount rate of a project in consideration and together with the CRF and the present value of the investments, the annualised costs can be determined. The equation used to determine the annualised costs and the CRF are shown in Equation 2.3 and 2.4.

$$C_{annual} = CRF * C_{PV} \tag{2.3}$$

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{2.4}$$

Where,
$C_{annual}\ [Euro] = Annual\ cost$
$C_{PV}\ [Euro] = Present\ Value$
$i\ = Discount\ rate$
$N\ [years] = Project\ lifetime$

A combination of the present value of investments and operating costs and revenues, and the CRF allows for determining the annual costs of a project where investments with different lifetimes are implemented at various moments throughout the project's lifetime.

Case Study Areas 3

With regards to heating systems there are significant differences found within countries and their cities. Heating systems are characterised by a variety of factors such as fuel type, the distribution system, the specific heating demand, and heat demand density. The latter two are primarily depending on the geographical location and the built environment and its occupants.

In the following, the characteristics of the two case study areas will be highlighted. Their overall similarities and differences are shown consisting of the location, climate, size and heating demand. Moreover, the current energy system is determined.

3.1 Groningen

Groningen is located in the northern region of The Netherlands within the eponymous province. The total land area for the city of Groningen is around 78 km^2 whereas the land area of the province is about 2.690 km^2. Groningen has a little over 200.000 inhabitants which takes up a large share of the total inhabitants of the province as there are about 580.000 inhabitants living in the province. The population density, based on the inhabitants and land area size above, is $2.572/km^2$. The city of Groningen has one of the youngest demographics of the country, with about a quarter of the population being a student. The amount of buildings is considered around 101.000.

The heating system currently in place in Groningen is heavily relying on the use of natural gas in individual boilers. Similarly, to the rest of The Netherlands, about 95% of the heating demand is covered by natural gas. Thanks to the discovery of natural gas reserves within the country and in the North Sea, the country did a complete overhaul of the Dutch national heating and cooking industry in the 1960's. Groningen has the ambition to become carbon neutral by 2035 and the municipality has set up a platform where the progress is illustrated and data regarding the energy system is given [Groningen]. Thanks to this platform called the 'energiemoniter Groningen' several key numbers can be found. The total energy demand in Groningen in 2016 was 15.160 TJ, hereof 30% was consumed by households, 47% by businesses and institutions, and the rest for transportation.

A focus is put solely on two of the three domains, i.e. households, and the businesses and institutions. With regards to the households the energy consumption is divided in three aspects; 80 percent Gas, 17 percent electricity and a small share of almost 2 percent renewable heating. From that consumption of gas, it assumed that 25% of gas used is for domestic hot water, 72% for space heating and the remaining 3% for cooking [Milieucentraal]. In addition, individual boilers applied in this study have an efficiency of 95% for space heating and 62% for domestic hot water [van Melle et al., 2015]. As mentioned before, the heating from gas represents only 95% of the total heat supplied therefore the resulting heating demand from gas consumption refers to only 95% of the household heating demand. With this information, the total heating demand for all households can be determined and this is displayed in Table 3.1.

The other domain within the built environment that has an influence on the heating demand are the businesses and institutions that are located in Groningen. According to the energiemonitor, the businesses and institutions account for 7.191 TJ of energy demand which is almost half (47,53%) of the total energy consumption in Groningen. This consumption entails 5 sectors; Industrial companies (39%), Governmental institutions (5%), Educational institutions (9%), Health care institutions (16%) and the remaining companies (31%). Of this energy demand, only a specific share is dedicated to the consumption of heating. To make an adequate analysis of the heating demand of the built environment, the share of energy demand from the industry is excluded as it assumed that space heating and domestic hot water play a minor role in the overall energy consumption of the industry. The remaining sectors are considered to be bundled as the service industry, where it is found that the national average of energy demand is for 58% space heating and less than 1% for domestic hot water [ECN, 2018]. In this case, the heating demand is not depending on boiler efficiencies.

The climate of Groningen is considered to be a sea climate, which shows in the relatively modest maximum and minimum temperatures of the city. According to online data from EnergyPRO, the temperatures are taken from the year 2016. Groningen has an average temperature of 10,0 $°C$, a minimum of -5,16 $°C$ and a maximum of -3,04. An overview of all the characteristics of the city are given in Table 3.1.

3.2 Esbjerg

Esbjerg is located in the southern region of Denmark, within the county of Southern Jutland. Esbjerg including the suburbs and the town Varde is around 50 km^2 and the entire county is almost 4.000 km^2. The combined inhabitants of the city of Esbjerg, suburbs and Varde is almost 94.000. The inhabitants of the county are a little above 205.000. the amount of buildings in the Esbjerg area is a little over 30.000.

The reason that it is not only Esbjerg that is being considered is due to the current heating system. The aforementioned areas are all connected through a district heating grid. This heating grid provides 99% of the inhabitants of heating. The heating is provided via two centralised units at the moment, a waste incineration plant and a condensing coal power plant. The waste plant was put into operation in 2003 and is owned by a cooperative of 13 municipalities, all around Esbjerg. The coal fired power plant is expected to have the end of its technical lifetime by 2023.

According to Din Forsyning, the company that operates the district heating grid in the area, the total heating demand, in 2017, was 981.636 MWh or 3.534 TJ. The total heating demand includes the losses resulting from the district heating piping system, which are 20%, or 707 TJ. Currently the share of domestic hot water is between the 20 and 30 of total heat demand in buildings [Menkveld, 2009; Yang et al., 2016]. The share of domestic hot water is set on 25%, similarly to Groningen. In contrast to Groningen, there is no share of cooking involved in the calculations, therefore the remaining 75% is in this case completely associated with the space heating demand. 25% of the domestic hot water translates to 707 TJ and 75% of space heating is equal to 2.120 TJ.

Esbjerg, located near the North Sea has a sea climate where the average temperature is 9,94 $°C$. The minimum temperature is -3,04 $°C$ and a maximum temperature of 27,45 $°C$. All the aforementioned characteristics of the city of Esbjerg are bundled in Table 3.1.

Parameters	**Unit**	**Groningen**	**Esbjerg**
Size	km^2	84	50
Inhabitants		200.733	93.922
Total buildings		101.427	30.507
Space heating	[TJ]	5.181	2.120
Domestic hot water	[TJ]	648	707
Total heating demand	[TJ]	5.829	2.827
Elevation	[m]	7	11
Average Temperature	$[^\circ C]$	10	9,94
Lowest Temperature	$[^\circ C]$	-5,16	-3,04
Highest Temperature	$[^\circ C]$	31,425	27,45

Table 3.1: Overview of local characteristics of Groningen and Esbjerg.

Thermal Energy Production Units

4

In the following chapter an overview is given of the applied energy producing and storing technologies within the research. For each of the technologies a short description is given with regards to their operation and fuel usage. Moreover, technology specific characteristics are given such as the efficiencies, investment costs and operation and maintenance (O&M) costs. Before the technologies are explained, an overview of the fuels used in this study are given and shown in Table 4.1.

Fuel characteristics	Price [€/tonne]	Ref.	Heating Value [GJ/tonne]	Ref.
Waste	59,87	A	11,5	A
Wood pellets	152,7 (DK) / 155 (NL)	B/C	17,4	D
Wood chips	58,79	B	9,4	D
Straw	79,2	E	14,4	D
Synthetic gas	0,286[1]	F	13[2]	G
Natural gas	0,15[3]	H	37,8[4]	I

Table 4.1: Overview of the values and references of fuel prices and heating values.

A: Din Forsyning
B: [DEA, b]
C: [ECN, 2017b]
D: EnergyPRO
E: [EA, 2013]
F: [Ridjan et al., 2014]
G: [Lupa et al., 2013]
H: [ECN, 2017a]
I: [IEA, 2012]

4.1 Combined heat and power

The generation of heating can be achieved by technologies that are either heat-only or combined heat and power. In this section a focus is put on the technologies that can generate both heating and electricity. Co-generation units are known to be one of the most energy efficient ways to

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[1] €/m^3

[2] MJ/m^3

[3] €/m^3

[4] MJ/m^3

produce electricity and heating [of Green, 2015]. The implementation of CHP plants in Denmark increased heavily due to the oil crisis in the 1980's. As a result, the Danish energy system can be considered to have the most extensive co-generation of heating and electricity in Europe [CODE and Europe, 2014]. Like other thermal energy producing technologies, a wide variety of fuels can be applied. Each of the fuels represent different characteristics for the plant and these will be described hereafter.

CHP plants utilise turbines and generators to produce power, these turbines can be subsequently being driven by either steam or gas. With regards to steam turbines, only two of the three different types of operating strategies are considered within this study. The three operation modes are condensing, extraction/back pressure and bypass. The condensing operation is focused on producing electricity. As a result, the pressure and temperature of the steam after the power production is too low to be utilised for heating and thus the heat is wasted via condensation. The coal fired power plant in Esbjerg is a plant that can operate in condensing mode and it therefore has a relatively high efficiency for producing electricity. The second operation possibility is the extraction mode where the steam can be extracted from the steam turbine before going all the way through the turbine. The thermal energy can then be utilised for heating purposes in district heating systems. Lastly, in some cases it is possible to bypass the turbine as a whole and solely generate heating via the bypass mode. Besides steam turbines, also gas turbines are applied in this study, however, these do not have a condensing mode. [Friis-Jensen, 2010]

4.1.1 Waste

The use of waste as a fuel for CHP started in the beginning of the 1900's and the first co-generation plant in Denmark used waste as a source [of Green, 2015]. The heating value of waste is strongly depending on the materials the waste is composed of. Factors that can influence the heating value of waste are the amount paper and cardboard, plastics, wet materials, organic material, etc. A basic assumption that can be made is that materials containing relatively large amounts of carbon and hydrogen, and relatively little amounts of water are contributing positively to the heating value [Skatteministiriet, 2009; Christensen, 2010]. Examples of these materials are plastics, food and wood wastes, or textiles. With regards to these materials the idea of recycling plays an important role in the whole process since an increased amount of recycling can have a influence on the fractions of each waste type. With plastics and textiles largely being removed from the waste composition due to recycling, will result in a lower heating value of waste and therefore the output of the waste incineration plant.

The European Union has set up a directive for all the member states that emphasises several steps before waste disposal should be applied [EC, 2016b]. It states that waste should, above all, be prevented and if this is not the case it should either re-used, recycled or recovered. If all of these steps are not possible or available, only then the waste should be disposed of, which could be in the form of landfills or waste incineration. Within this study it should therefore be known that the available waste in the future could decrease. Besides to the amount of waste, the fractions of different types of wastes are most likely to change which can reduce the heating value of waste and it can influence the price of waste. In Table 4.2 the characteristics of the plant can be reviewed.

Waste incineration CHP	**Unit**	Extracting mode	Bypass mode
Thermal efficiency	[%]	76	97
Electricity efficiency	[%]	21	0
Investment costs	[M€/MW]	2,36	2,36
LTE costs	[M€/MW]	0,24	0,24
Fixed O%M costs	[€/MW/year]	93.400	93.400
Variable O%M cost	[€/MWh_{th}]	7,63	5,98
Lifetime	[years]	25	25

Table 4.2: Overview of the characteristics of the waste CHP plant [DEA, 2013]

4.1.2 Wood pellets

A CHP which runs on wood pellets is a relatively often used method in Denmark. Several large scale power plants have already been installed and some are under construction [Lauritsen, 2014]. The use of wood pellets has also been applied in smaller scale district heating systems. A differentiation is made between two types of wood pellet driven CHP plants; Coal fired power plants that are being transformed to run on wood pellets or newly built wood pellet CHP's. Since the coal fired power plants are condensing power plants, the efficiencies for the generation of heating are relatively low. In this study, where the focus is on finding alternatives for heating energy systems, the condensing wood pellet CHP is excluded. Solely the wood pellet CHP which is designed for co-generation are considered. In order to show the operation strategies, Table 4.3 shows the efficiencies of the 3 different operation modes.

Coal-to-Wood pellet CHP	**Unit**	Condensing mode	Extracting mode	Bypass mode
Thermal efficiency	[%]	0	58,6	63.7
Electricity efficiency	[%]	44	31,6	0

Table 4.3: Overview of the efficiencies of a condensing wood pellet CHP plant [DEA, 2013]

A newly built wood pellet CHP has significantly different values with regards to the efficiencies. The main reason for this is the that this plant is focused more on the production of heating whereas the coal-to-biomass CHP is seen as a centralised power plant that focuses on the production of electricity at first. An overview of the characteristics of the newly built wood pellet CHP are given in Table 4.4

Wood pellet CHP	**Unit**	Extracting mode	Bypass mode
Thermal efficiency	[%]	64	97
Electricity efficiency	[%]	33	0
Investment costs	[M€/MW]	0,75	0,75
Fixed O%M costs	[€/MW/year]	20.900	20.900
Variable O%M cost	[€/MWh_{th}]	0,80	0,53
Lifetime	[years]	25	25

Table 4.4: Overview of the characteristics of the new wood pellet CHP plant (extracting) [DEA, 2013]

4.1.3 Combined-cycle gas turbines

As mentioned before, besides steam turbines there are also gas turbines that operate with help of heated gasses. Gas turbines are known for having the advantage over the steam turbines with regards to the regulation ability. Gas turbines can be started and stopped within minutes and are therefore useful to supply peak load, i.e. to supply electricity and/or heating at a short time's notice. The combined-cycle indicates that in addition to a gas turbine, a steam turbine is added to energy system. This way the heat output from the gas turbine can drive the generation of steam which subsequently can be used to drive a steam turbine. A typical fuel for the combined-cycle gas turbine is natural gas, however, it is also possible to use biogas or synthetic gasses. Synthetic gasses are the gasses that can be produced from wood chips or straw and consists primarily of hydrogen and carbon monoxide. The characteristics of the combined-cycle gas turbine are found in Table 4.5.

Combined-cycle gas turbine CHP	**Unit**	Extracting mode	Bypass mode
Thermal efficiency	[%]	51	75
Electricity efficiency	[%]	58	0
Investment costs	[M€/MW]	1,3	1,3
Fixed O%M costs	[€/MW/year]	29.300	29.300
Variable O%M cost	[€/MWh_{th}]	10,48	7,59
Lifetime	[years]	25	25

Table 4.5: Overview of the characteristics of the combined-cycle gas turbine CHP plant [DEA, 2013]

4.2 Heat only boilers

In addition to combined heat and power plants, heating systems can be comprised of units that are designed to only produce heating. These units are often less expensive compared to CHP plants however the capacities are often lower. Before the district heating sized boilers are mentioned, the smaller sized individual gas boilers are explained.

4.2.1 Individual natural gas boilers

Although individual boilers are primarily driven by natural gas, a fossil fuel, the technology is explained since it is necessary to determine the current energy system in Groningen. Residential size or individual gas boilers are an often-used method to provide space heating and how water demands. In countries where there are relatively inexpensive sources of natural gas such as the United Kingdom and The Netherlands it can serve as the preferred option for heating. Currently, about 95% of the Dutch residential heating demand is covered by individual natural gas boilers [ECN, 2017a]. In Table 4.6 the specifications are found for only two capacities, the smaller capacity for houses and the larger capacity for apartment buildings.

Individual gas boiler	**Unit**	10 kW	400 kW
Domestic hot water efficiency	[%]	62	62
Space heating efficiency	[%]	95	95
Investment costs[5]	[€]	3.000	23.400
Fixed O%M costs	[€/year]	209	683
Lifetime	[years]	20	25

Table 4.6: Overview of the characteristics of individual natural gas boilers [DEA, 2017c]

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[5] In the year 2030

4.2.2 Straw and wood chips boilers

The application of boilers is relatively simple compared to CHP units since there are less components involved such as the turbine and generator. This research has makes use of both straw boilers and wood chip boilers. The capacities of these types of boilers often do not exceed the 10 MW thermal capacity. The characteristics of both type of boilers are found in Table 4.7

Straw and wood chip boiler	**Unit**	Straw	Wood chip
Thermal efficiency	[%]	102,1	114,9
Investment costs	[€/MW]	0,89	0,79
Fixed O%M costs	[€/MW/year]	52.403	37.055
Variable O%M cost	[€/MWh_{th}]	2,14	2,26
Lifetime	[years]	25	25

Table 4.7: Overview of the characteristics of both the straw and the wood chip boiler [DEA, 2013]

4.2.3 Electric boilers

The use of electricity to generate heating can be both on residential scale and larger scales such as district heating systems. In this study only the large scale electric boilers are considered. These boilers are often designed as peak load units, similar to the combined-cycle gas turbines. As a peak load unit they can regulate their production within minutes. In addition, the simple design of the electric boilers allows for little to no maintenance. Capacities of electric boilers are found to be between 10 to 50 MW. The specifications of the electric boiler are found in Table 4.8.

Electric boiler	**Unit**	
Thermal efficiency	[%]	99
Investment costs	[€/MW]	0,07
Fixed O%M costs	[€/MW/year]	1.050
Variable O%M cost	[€/MWh_{th}]	0,5
Lifetime	[years]	20

Table 4.8: Overview of the characteristics of electric boilers [DEA, 2013]

4.3 Compression heat pumps

Compression heat pumps work according to a compression cycle in which sensible heat from a source can be isolated and increased with a relatively small share of electricity. The resulting higher amount of thermal energy can subsequently be transferred to another heat carrier such as water. It is basic thermodynamics where a change in the pressure due to the compression results in a temperature increase. Within the compression and following expansion cycle an energy carrier needs to be used which are generally refrigerants. Refrigerants are have favourable characteristics with regards to boiling points and heat absorption.

A heat pump is different from the previously mentioned heat only units as it needs a heat source to extract thermal energy from. Heat pumps are usually characterised by the definition of the Coefficient of Performance (COP). The COP shows the amount of power needed to provide a certain amount of thermal energy. The COP on a variety of aspects but most importantly the heat source, the refrigerants and the heat sink or the heating demand, i.e. the temperature that needs to be delivered [Lindström, 1985]. A lot of different type of heat sources can be applied, with a wide variety of temperatures. Some examples of heat sources can be industrial waste heating, waste heat from supermarkets, sewage water, sea water, ground water, rivers, lakes and ambient air [Lund and Persson, 2016]. The heat sources considered in this study are industrial waste heat, sewage water, sea water, ground water and surface water, i.e. rivers and lakes.

4.3.1 Large scale

Heat pumps are considered to be a vital part of the future district heating systems. The Heat Roadmap Europe project estimates the use of heat pumps in district heating systems on ≈25-30% of the total heat demand of Europe [David et al., 2017]. In Sweden, already over a 1000 MW of capacity has been installed [Averfalka et al., 2017]. Their favourable energy conversion efficiency and the fact that they use electricity as a main source of energy allow for an improvement integration of variable renewable electricity sources. In addition, heat pumps have the ability to utilise heat sources that are otherwise being wasted. Typical capacities of large scale heat pumps range from 100 kW to 35 MW. An overview of the characteristics of large scale heat pumps is shown in 4.9.

large scale heat pumps	**Unit**	
COP	[%]	3-4,5
Investment costs	[€/MW]	0,66
Fixed O%M costs	[€/MW/year]	2.000
Variable O%M cost	[€/MWh_{th}]	1,8
Lifetime	[years]	25

Table 4.9: Overview of the characteristics of large scale heat pumps [DEA, 2013]

4.3.2 Residential

The use of heat pumps in residential settings is technically similar to that of the heat pumps applied in large scale operations. However, the advantages of utilising waste heat and other available heat sources are often lost since residential heat pumps are restricted to a specific location, that where the heat is required. The two often used heat sources are either ground sources or ambient air. Ground source heat pumps utilise the characteristics of the ground where outside temperatures have little to no influence on the temperature of the ground. This allows to store heating from the summer to extract it in the winter, and the other way around to cool the ground during the winter to utilise this during the summer. A prerequisite of ground source heat pumps is that space or ground is needed. Unfortunately, the ground as a heating source has a limit to the amount of heat that can be extracted from the source [Rees, 2016]. The use of ambient air as a heat source does not require the need of a specific land area. In this study, only the application of air source heat pumps is considered as the urbanised city characteristic restrict the wide use for ground source heat pumps. Whereas the ground source heat pump is less influenced by the outside temperature, the ambient air is strongly influenced by it. As a result, the COP of air source heat pumps are often lower, especially during colder periods where both the amount of available heating is lower and the overall heat demand is higher. Since the heat sink plays a role in the COP of the heat pump and therefore the performance, it is often required that for an adequate performance of the heat pump, the heating demand is as low as possible. This can be achieved via isolation and renovation of buildings. The capacities that are applied in this study are either the 10 kW capacity or the 400 kW capacity. These capacities are similar to the individual gas boiler mentioned in Table 4.6. The specifications are shown in Table 4.10.

residential air source heat pumps	**Unit**	10 kW	400 kW
COP	[%]	2,6	2,6
Investment costs	[€/MW]	9.400	141.000
Future investment costs	[€/MW]	8.500	127.000
Lifetime	[years]	18	20

Table 4.10: Overview of the characteristics of residential air-to-water heat pumps [DEA, 2017c]

4.4 Geothermal

Geothermal energy is based on the energy that is found below the surface of earth. The temperatures are increasing with every kilometre of the depth. The use of geothermal energy can be technically applied in many places however it is predominantly depending on how accessible the energy is. For example, in Iceland, the majority of the heating and power production is relying on geothermal energy sources. The geographical location of Iceland allows for this extraction since the geothermal sources are found very close to the earth's surface. In general, the feasibility of the use of geothermal sources is depending on the physical properties of the earth and the depth of the thermal energy source. The exploration and the drilling costs are the main drivers for the overall costs.

It is possible to provide thermal energy for district heating systems or it is possible to provide power production with the help of steam turbines. In order to provide power, substantial temperatures are required. An often used method of extracting the energy from the earth is through a doublet. The lifetime of a doublet is not expected to exceed the 30 years from an economic perspective [Smit, 2010]. In Table 4.11 an overview is given for the specifications of geothermal heating generation.

Geothermal doublet	**Unit**	Geothermal Doublet
Thermal efficiency	[%]	100
Investment costs	[M€/MW]	1,875
O%M costs (% of investment costs)	[%]	0,2
Lifetime	[years]	30

Table 4.11: Overview of the characteristics of using geothermal sources for heating purposes [CE Delft, 2016]

4.5 Thermal storage

The use of thermal storage is essential in heating systems where the thermal energy production units are operated based on external incentives, i.e. the use of heat pumps during low electricity prices or the use of CHP units when the electricity prices give an incentive to operate in co-generation mode. Two types of thermal storages are considered with different characteristics with regards to temperature and the costs. The first thermal storage that is considered is the hot water storage tank. Temperatures for the hot water storage tank can reach up 98 $^{\circ}C$ and the sizes can be in the multiples of 10.000 m^3. The other option that is considered is the pit storage, where instead of a tank principle the water is stored in a gravel pit. As a result, the sizes can be higher than that of tank storages. Capacities range from over the 50.000 m^3 to 200.000 m^3 and the temperatures can technically be around the 95 $^{\circ}C$ but in practice is more common to not exceed the 80 $^{\circ}C$. In Table 4.12, an overview is given of the costs and lifetimes.

Thermal storages	**Unit**	Hot water tank	Pit
Thermal efficiency	[%]	95	95
Investment costs	[€/m^3]	160	35
O%M costs (% of investment costs)	[%]	-	0,7
Lifetime	[years]	25	25

Table 4.12: Overview of the characteristics of both thermal storages [DEA, 2016]

Quantification of the Local Energy Sources

5

This section entails the various local energy sources that can assist in the improvements regarding energy efficiency and greenhouse gas reductions. For each of the type of energy sources the potential capacity is determined for both Groningen and the Netherlands. The potential is predominantly determined on local aspect of the energy sources, i.e. whether the city can be self-sufficient without taking away capacity for other locations.

5.1 Waste

Within the Netherlands moste of the waste is being incinerated, a few of the district heating systems in The Netherlands are driven by the use of a large waste incineration plant [Rijkswaterstaat and the Environment, 2015]. However, in Groningen the waste treatment and disposal of waste is based on separation, and recycling. The remaining amount of waste ends up either at a landfill or it us used to produce biogas [Attero]. The municipality of Groningen has released some insight on their strategy on reducing waste in the future. Their recently waste road map towards a waste-less city shows that Groningen is focusing on the recycling of waste to a large extent [Attero, 2015]. The document states that by 2025 they want to have reduced their rest waste to the maximum amount through recycling. Nonetheless, the amount of waste is determined to be 41.667 ton per year which is based on data from 2014.

In contrast to Groningen, Esbjerg already has waste incineration taking place in their heating system. The waste that is being consumed is derived from the municipal waste produced by Ebsjerg and 12 surrounding municipalities. Annually the waste incineration plant incinerates about 215.000 ton of waste [Din Forsyning].

5.2 Geothermal

Two types of geothermal energy are being considered in this study, i.e. shallow geothermal energy for low temperatures and possible storage, and deep geothermal energy in the form of aquifer doublets.

Extensive research for fossil fuels, especially natural gas, has resulted in significant amounts of knowledge of the Dutch soil. The potential of the geothermal resources is based on an online tool made by the governmental institution RVO (Rijksdienst voor Ondernemen) called the 'WarmteAtlas' [RVO, Visited on: 1/5/18]. The WarmteAtlas includes a wide variety of maps, analyses and sources focused on subject such as heat density, CO2 emissions, the built environment, sustainable energy sources, etc. The WarmteAtlas has been created by the government with the purpose of providing information for new heat projects to advance the sustainable transition. It allows for everyone of society, municipalities, businesses and citizens, to get an insight in the possibilities of the sustainable transition. With the help of the atlas, synergies between spatial planning and energy on provincial and municipal level can be stimulated.

The WarmteAtlas shows specific geothermal potential of at least 5 MW_{th} available in and around the city of Groningen. In addition, several other studies have shown that there is significant potential for geothermal heating [Kramers et al., 2012; Swart, 2012]. The prominent source of geothermal heating is the Rotliegend sandstone layer between the 2.750 and 3.200 meter. In total, the recoverable heat of the Rotliegend sandstone is 11,897 PJ, however only a small part of the sandstone is located below the city of Groningen [Kramers et al., 2012]. Figure 5.1 shows an illustration on how close the potential is found near the city. A pre-study of the sandstone layer shows that the potential of one doublet with a capacity of 16,7 MW at 177 $m^3/hour$ is possible [Swart, 2012]. A project currently in progress shows the use of this geothermal energy to supply heating to 10.000 homes via a district heating system. The total investment costs for both the doublet and the distribution system are 51 million euro and 2.55 million euro operational expenditures [Pintoa and da Graçab, 2018].

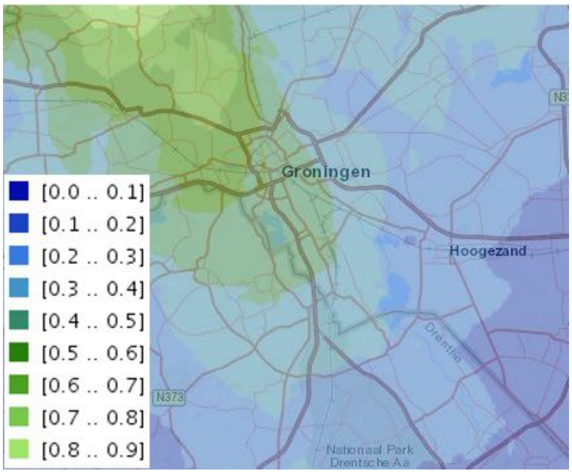

Figure 5.1: An overview of the technical potential of geothermal energy for dwellings where the legend is based on $PJ\ per\ km^2$ [TNO].

Just like as in the Netherlands there are aquifers present in Denmark. According to [Mathiesen et al., 2013], there are currently three operating geothermal plants in Denmark, all spread out over the country and with different depths. With regards to Esbjerg's location, there are no potential reservoirs found that can serve as geothermal sources for district heating due to the wells being too shallow.

5.3 Biomass

The bioenergy potential in Groningen based on the WarmteAtlas mentioned in Section 5.2. The total biogas potential of Groningen is based upon the municipality of Groningen and the surrounding municipalities. 11 municipalities are assessed and the total size of these municipalities combined is almost 1.100 km^2. The biogas potential consists of liquid manure, organic waste and rest streams of agricultural production. The biomass waste consists of excess forestry streams and pruning waste. The amount of biogas that can technically be produced is 827 GJ per year. The total amount woody biomass per year is found to be 26 GJ per year.

The WarmtaAtlas is not applicable to determine the bioenergy potential for Esbjerg. To understand what the potential of bioenergy is in Esbjerg, the heat atlas created by the Heat Roadmap Europe project is used [Stratego]. The freely available heat atlas is a pan-European project that provides assistance in energy planning on a national and international scale. The atlas aims to stimulate the development towards district heating and cooling solutions by displaying possible synergies found in energy demand and supply. The heat atlas shows possible biomass resources based on the provinces of Denmark. The total annual amount of biomass resources in the province is 10.440 GJ of which 710 GJ of forest residues, 9.290 GJ of straw and 440 GJ bio wastes. However, Southern Jutland has an area of about 8.800 km^2 ($\approx 20\%$ of total area size of Denmark), which is significantly larger than the areas considered with the case of Groningen. Therefore, the total number of biomass resources shall be decreased by a factor 9 in order to take the amount of citizens in Esbjerg and Denmark and the population density into account. The resulting biomass resources available annually for Esbjerg is 1.160 GJ.

5.4 Low temperature industrial waste heat

The use of excess heating is an often-used source for district heating in Denmark and the Netherlands. Especially CHP and waste-to-energy production is an often-used method. These types of excess heating are utilised without the use of heat pumps since the temperature level is sufficient for the required supply temperature. The use of excess heating from other industrial sources in combination with a compression heat pump is on the other hand a lesser used form of thermal energy [Lund and Persson, 2016]. The temperature levels of excess industrial heat for heat pumps is considered to not exceed the 100 $°C$. One type of low temperature heat sources are supermarkets due to their excessive need for cooling in the building. Another example are companies with servers that need to be cooled.

According to [RVO, Visited on: 1/5/18], the potential low temperature heat sources are shown in the Figure 5.2. The shown values are estimates and not actual measured data.

Table 5.1 shows an overview of all the point sources with an estimate capacity of at least 5 TJ per year. These values are all based on the idea that this amount of energy can be produced in the temperature range of 30 $°C$ to 45 $°C$ in condensation form. The total amount of excess heating of this level is 185,9 TJ and the temperature level is set on 30 $°C$. One additional source of excess heating is found with a total of 250 TJ [Stratego]. The temperature level of this heat source is considered to be 40 $°C$ [Noorden, 2013]. All the sources are considered to be available all year round.

Location	$[TJ/Year]$
Supermarkt H.J. v.d. Heide BV	7,9
Albert Heijn BV	7,9
Ciboga Supermarkt BV	18,4
Midsol Travel BV	11,8
Stationsfoodstore BV	7,9
Traffic4U BV	59,1
Willems Supermarkten BV	7,9
Vevida BV	27,6
VNU Vacature Media BV	27,6
Koninklijke Coöperatie Cosun UA	9,8
Total	185,9

Table 5.1: Potential excess heating sources above an estimated 5 TJ/year.

Esbjerg does not have the same literary source available about the low temperature industrial excess heating potential. According to [Lund and Persson, 2016], there are 178 locations in Denmark with low temperature industrial excess heat, which is excluding supermarkets. However, it is unknown where the locations are of these excess heating sources, therefore Esbjerg is considered to have no low temperature industrial excess heating. Nonetheless, there are 3

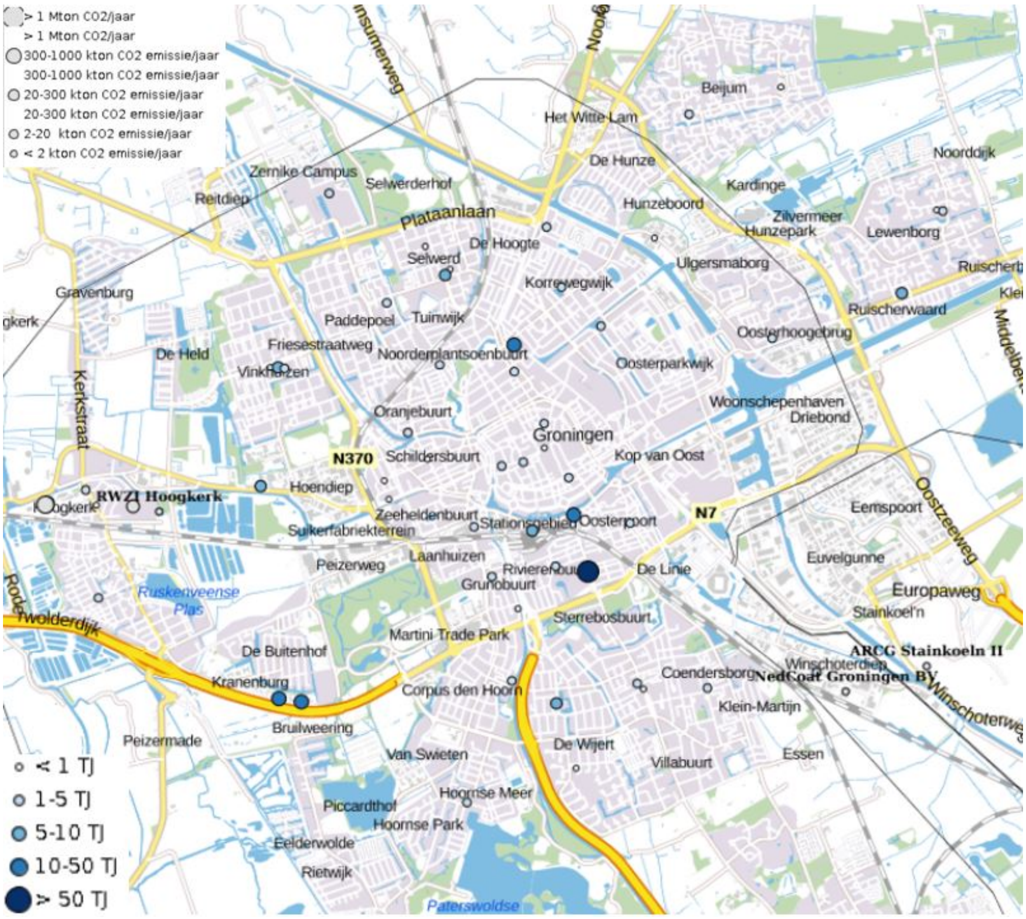

Figure 5.2: An overview of the point sources in Groningen, the blue circles represent the low temperature assumptions between 30 °C and 45 °C. The Grey circles represent the large industries. [RVO, Visited on: 1/5/18]

supermarkets found in Esbjerg with a yearly excess heating potential of at least 1,31 TJ [Svenning et al., 2014]. Unfortunately, these supermarkets are not included due to uncertainty whether they exceed the annual 5 TJ.

5.5 Sewage water

The water usage of residential buildings consists of about 60% of heated water which leads to the idea that sewer systems represent as the largest source of heat leaking in the residential sector [Schmid, 2008; Cipolla and Maglionico, 2014]. There are several key factors that make the use of sewage waste water a useful heat source for heat pumps. First of all, the favourable temperatures of waste water, which during winter times generally does not come below 10 °C and during summer times it does not exceed 30 °C [Zhou, 2004]. These temperatures are especially compared to other heat sources such as groundwater, geothermal heat or outdoor air relatively high during the heating season [Schmid, 2008]. Secondly, the stability of the heat source, since it is not expected that the heat source would disappear from urban areas [David et al., 2017]. Lastly, the heat source is predominantly found near urban areas where the energy can be utilised in a district heating system. The potential of sewage water as a heat source is considerable and this would significantly improve the energy conservation and environmental protection [Chao et al., 2012]. It comes as no

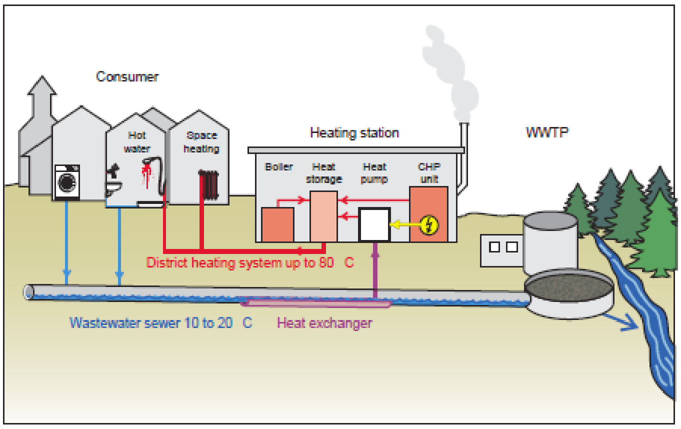

Figure 5.3: A schematic overview of one the possible pathways in which sewage water can be used as a heat source for heat pumps [Schmid, 2008].

surprise that the use of sewage water in combination with heat pumps is a widely used concept and therefore a proven technology. Worldwide there are more than 500 heat pump systems operating with sewage water as a heat source. For example, from all the heat pump capacity in Sweden, which is over a 1.000 MW, more than half of this is supplied by this heat source [Averfalka et al., 2017]. Figure 5.3 shows an often-used pathway through which waste water can be utilised.

The total heating potential of the sewage water in Groningen is determined based on the total flow of sewage water and the specific parameters of the water. According to [Neugebauer et al., 2015], formula 5.1 enables the determination of the waste water thermal extraction output.

$$P_{ww} = V_{ww} * c * \delta T \tag{5.1}$$

Where,
$P_{ww}\ [kW] = Thermal\ extraction\ output$
$V_{ww}\ [m^3/h] = Volume\ flow\ rate$
$c\ [kWh/(m^3 * K)] = Specific\ thermal\ capacity\ of\ waste\ water$
$\delta T\ [K] = Temperature\ difference$

The waste water treatment facility near Groningen that receives all the waste water mentions that the average flow of water from the city is 1.800 $m^3/hour$ during dry weather [Noorderzijlvest]. The specific thermal capacity of waste water is 1,66 $kWh/(m^3 * K)$. The temperature difference is set on a decrease of 5 $^\circ K$. This results in a theoretical thermal energy potential of 10,44 MW.

Whereas waste water treatment in Groningen happens at one central location, the process in Esbjerg is significantly more decentralised. Within Esbjerg there are two different waste treatment plants and Varde has its own plant too. The following total amounts of waste water are found in each of the plants:

- Renseanlæg Vest: 10.271.404 tonnes/year (2014) [Kommune, 2015]
- Renseanlæg Øst: 4.887.198 tonnes/year (2014) [Kommune, 2015]
- Varde Renseanlæg: 9.518 m^3/day (2013) [Orbicon, 2016]

The total amount of waste water includes the amount of rainwater that has ended in the sewage. The amount of rainwater is approximately 40% [Kommune, 2015]. According to this information, and formula 5.1, the theoretical amount of thermal extraction output can be determined. Renseanlæg Vest and Øst has the potential of 4,08 and 1,94 MW, respectively. Varde Renseanlæg has the potential of 1,38 MW. The total amount thermal extraction capacity available in the Esbjerg area is 7,4 MW.

5.6 Seawater

The use of seawater as a heat source has been applied for several decades and although it is often used in the Nordic countries, there are also heat pumps present in China, the United States, Canada and Japan [Shu et al., 2015]. Seawater has the benefit of being technically without any limits regarding its capacity [Lund and Persson, 2016]. In Stockholm, there are 6 heat pumps in place that each have a thermal capacity output of 30 MW and the average temperature is around 3 $^{\circ}C$ [Friotherm]. Seawater has the advantage over other water sources that the minimum temperature of the water leaving the heat pump can be below 2 $^{\circ}C$. Seawater heat pump systems are considered to have relatively low investment costs, primarily compared to ground source heat pumps [Idsø and Årethun, 2017]. However, there are some additional costs to the resistance to saltiness [Grassi, 2017]. The potential of thermal energy from seawater is based on the average temperature of the seawater.
As for Groningen, the geographical location prohibits the use of seawater as a heat source. Esbjerg however, is located directly next to the sea where the capacity of seawater is considered to be unlimited with an average temperature of 3 $^{\circ}C$ and a temperature drop of 2 $^{\circ}C$ is feasible.

5.7 Ground water

Similar to the use of geothermal energy from deep depths underground, the concept of using ground water as a heat source is based on the temperature differences found underground compared with the ambient temperatures. In addition, similarly to geothermal heat sources, there are higher risks involved due to the uncertainty of water resource availability [Lund and Persson, 2016]. To determine the potential in both Groningen and Esbjerg the real life case of a ground water source heat pump in Gammel Rye, Denmark is chosen as an example. This heat pump has a thermal output of 2 MW with a COP of 3,5. It is assumed that such a capacity of ground water heat pump is possible for every km^2 within the cities limits. This assumption is restricted by the viability on the ground water resources available in both cities.
For Groningen, the so-called 'WKO-tool' is used, this tool is developed to shows all possible shallow geothermal open and closed ground water systems [Rijksoverheid]. The tool shows that there several open and closed systems available within the city of Groningen. Therefore, with a city surface of 84 km^2, a total potential thermal capacity of 168 MW is deemed possible.

Similar to the Netherlands, also in Denmark there is a presence of ground water resources throughout the country. According to [GEUS, 2016], there are ground water sources available in Esbjerg. The total area size of Esbjerg is around 50 km^2 resulting in a potential thermal of 100 MW.

5.8 Surface water

The use of surface water from rivers and lakes is an often-used heat source for heat pumps. For example, the heat pump located in Drammen, Norway where water is located in a fjord at a temperature of 8 $°C$ [EHPA]. The COP of this system is 3,05 and a temperature drop from 8 $°C$ to 4 $°C$. Another example is found in Paris, France where 8 heat pumps have a combined capacity of 50 MW with the surrounding river as heat source [Grassi, 2017]. One of the issues with rivers or lakes is the limitation of the minimum temperature of the water. A temperature drop that results in temperature of leaving the heat pump of less than 2 $°C$ is not considered to be feasible. Therefore, during certain times of the years when the water is near freezing or freezing the heat pump can not operate. To determine the thermal potential of the waterways and lakes in either Esbjerg or Groningen, the following assumptions are made. An average speed of water flow of 5 m^3/s [Lund and Persson, 2016]. An average depth of 2 meters for both waterways and lakes. A drop of 2 $°C$ for lakes over a year time and a drop of 5 $°C$ for the waterways. With the help of formula 5.1, the total capacity of the waterways can be calculated. Whereas the total capacity for lakes is based on the volume of water available in the lake.

In Groningen, there is one waterway and one lake with a sufficient size considered. The waterway in Groningen is assumed to have flow velocity of 5 m^3/s or 18.000 m^3/h. The total potential thermal extraction output is 104.400 kW or 104,4 MW. The lake has a surface of 2,7 km^2 which results in a total volume of 5.400 m^3. The total thermal capacity of the lake is 12.528 kWh or 12.5 MWh which on a total heating demand of over 1.600 GWh is insignificant and therefore not included in the scenario planning.

Esbjerg on the other hand does not have any lakes or waterways of sufficient size to be acting as heat sources for heat pumps.

6

Decarbonised Heating System alternatives

In this chapter the results from the analyses of different energy system scenarios are presented. According to two case studies in Esbjerg and Groningen, the implementation of either an energy system that is based on one or two centralised heating units is analysed. Or on the other hand, the analysis consists of scenarios that are based on a diversified energy system where as many local resources as possible are included. The results are first shown for Esbjerg, then followed by the results of Groningen. Lastly, a comparison is done between the two case studies.

6.1 Heating System Alternatives in Esbjerg

The results from the EnergyPRO analyses for Esbjerg are shown in this chapter. First of all, the energy production per technology is given in order to show the system dynamics, this is followed by the fuel consumption that is needed to supply the heating demand. Secondly, the life time costs are displayed which entails the present value of the gross operational costs, revenues and investments. Lastly, the annualised costs are given, these costs are the yearly costs that are made based on the operational costs, revenues calculated with the capital recovery factor of 0,0627 and the annualised costs of the investment with their respective CRF. The lifetime of the project is 22 years and all the economic results are based on present values with a discount rate of 3%. The time series used for the spot market prices is the DK West spot market in €/MWh. The EnergyPRO parameters such as unit size, efficiencies and costs, are found in the Appendix A.

6.1.1 Esbjerg centralised unit

The first energy system that is analysed is the centralised unit energy system in Esbjerg. Table 6.1 shows the 4 different scenarios that are analysed. This waste incineration plant is due to regulations designed to operate as the first priority, before any other thermal energy producing unit may provide heating.

Esbjerg	Scenario description
Scenario A1	A centralised straw boiler with waste incineration prioritised
Scenario A2	A centralised wood pellet CHP heating system **without** subsidy for electricity produced from biomass resources and with waste incineration
Scenario A3	A centralised wood pellet CHP heating system **with** the current subsidy of 7,5 øre (0.01009 €) per kWh electricity produced from biomass resources and with waste incineration prioritised
Scenario A4	A centralised wood pellet CHP heating system **with** the current subsidy of 15 øre (0.02018 €) per kWh electricity produced from biomass resources and **with** waste incineration prioritised

Table 6.1: Overview of the centralised unit scenarios applied in Esbjerg

The system dynamics of the centralised unit system scenarios are found in Figure 6.1.

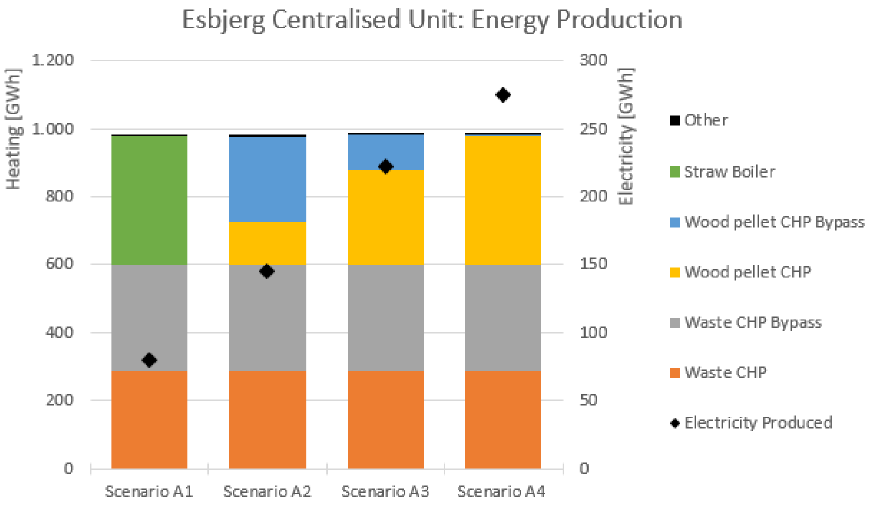

Figure 6.1: The energy production of the various technologies in the centralised unit systems in Esbjerg

- The share of heating demand that is covered by the waste CHP extraction mode and the waste CHP bypass mode is almost divided in half for both modes. And the waste CHP unit delivers more a little over half of the total heating demand.
- Within all 4 scenarios, the heating production of the waste CHP and waste CHP bypass mode combined are equal. This is the result of their prioritised operation regardless of any outside changes made to the energy systems.
- Scenario A2, Scenario A3 and scenario A4 show different shares of heat production between the wood pellet CHP and the wood pellet CHP bypass mode. The share of wood pellet CHP in extraction mode increases alongside with the increase in of subsidies for the electricity produced.
- Scenario A1 shows the electricity production of a system where there are not electricity producing units besides the waste CHP.
- Scenario A2, Scenario A3 and scenario A4 show that with the increase of the subsidy, the amount of electricity produced by increases due to the increase of the extraction mode.

The primary energy supply of the centralised unit system scenarios are found in Figure 6.2.

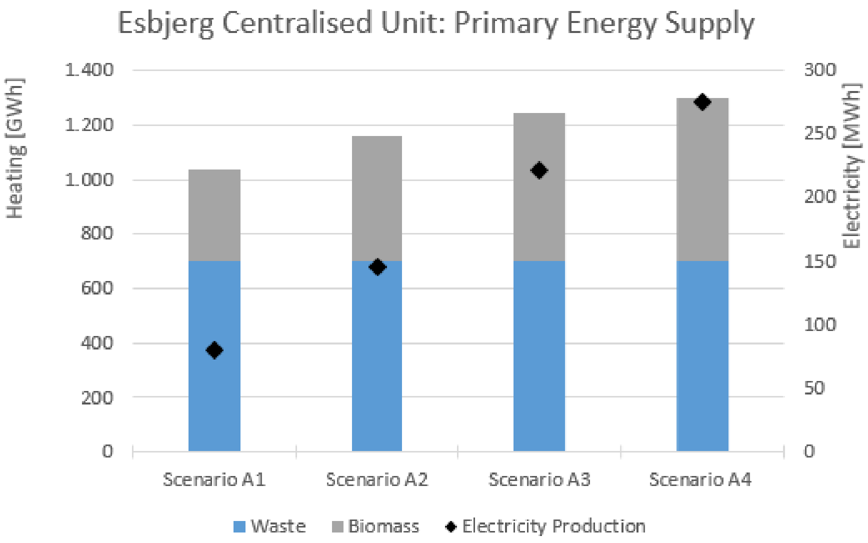

Figure 6.2: The primary energy supply required for the production of heating in the centralised unit systems in Esbjerg

- The primary energy supply of scenario A1 is lowest compared to the rest of the scenarios which is due to a lesser amount of biomass consumption.
- The biomass consumption for the other 3 scenarios, scenario A2, scenario A3 and scenario A4, increases per scenario.
- With the increasing PES in scenario A2 through A4, the electricity production increases in a similarly fashion per scenario.

The lifetime costs of the centralised unit system scenarios are found in Figure 6.3.

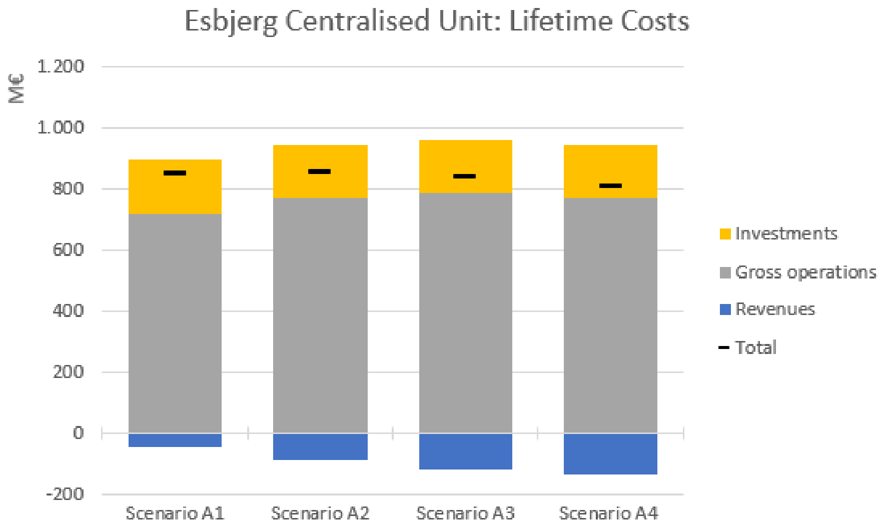

Figure 6.3: The lifetime costs of the various scenarios with regards to the heating aspect of the centralised unit systems in Esbjerg

- The lifetime costs of the 4 scenarios are very similar, where scenario A4 has the lowest cost by only a small margin.
- In all scenarios it shows that the operation costs make up for largest share of the system.
- The revenues coming from the sale of electricity are increasing going from from scenario A1 to scenario A4

The annualised costs of the centralised unit system scenarios are found in 6.4.

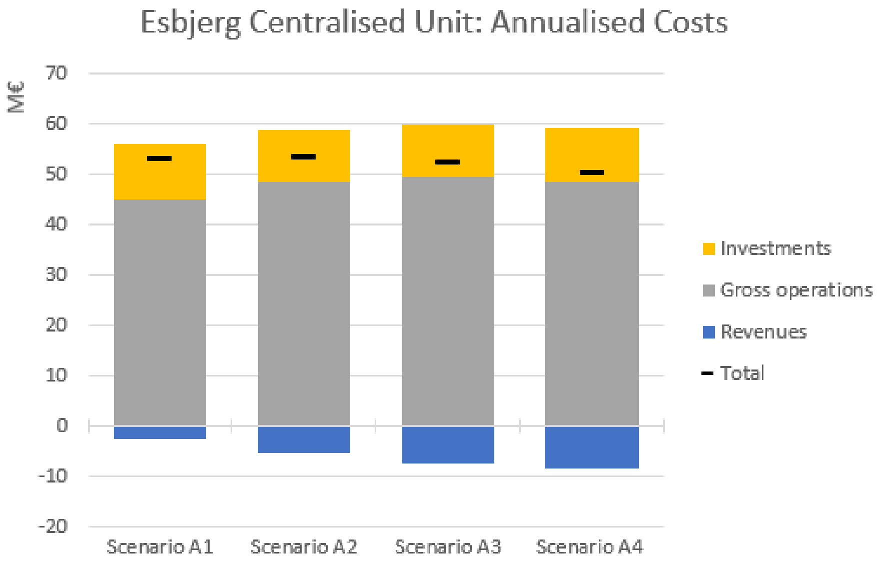

Figure 6.4: The annualised costs of various scenarios in the centralised unit systems in Esbjerg

- The annualised costs of all 4 scenarios are similar. Although scenario A4 has overall the lowest annual cost.
- In all scenarios the investment costs are only small share of the total costs.

6.1.2 Esbjerg diversified system

Within the energy planning of the diversified system, there are 3 different scenarios analysed. These scenarios are shown in Table 6.2.

Esbjerg	**Scenario description**
Scenario B1	A diversified heating system **with** waste prioritised and a relatively large straw boiler is implemented
Scenario B2	A diversified heating system based on local resources only and **with** waste prioritisation
Scenario B3	A diversified heating system based on local resources and **without** waste prioritisation

Table 6.2: Overview of the diversified scenarios applied in Esbjerg

The system dynamics of the diversified energy systems are shown in Figure 6.5.

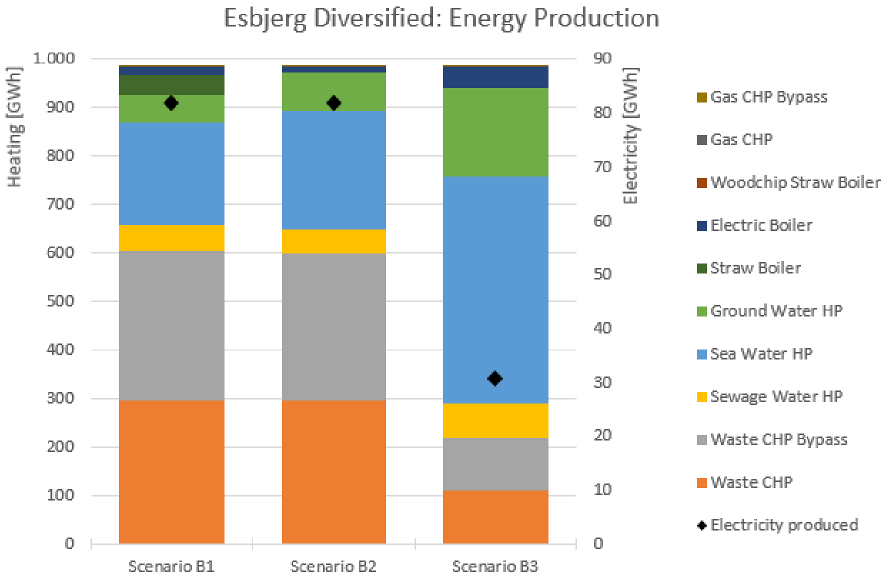

Figure 6.5: The energy production of the various technologies in the diversified energy systems in Esbjerg

- The system dynamics for scenario B1 and scenario B2 are relatively similar. It shows that straw boiler in scenario B1 takes shares of the production of sea water and ground water heat pumps.
- The waste prioritisation in scenario B1 and scenario B2 has significant influence on the utilisation of the heat pumps as seen in the difference with scenario B3. Without a waste incineration prioritisation, the waste CHP and waste CHP bypass operate significantly less and the heat pumps generate a majority of the heating demand.
- The electricity production is reduced significantly in scenario B3 compared to scenario B1 and scenario B2.

The primary energy supply of the diversified energy systems are shown in Figure 6.6.

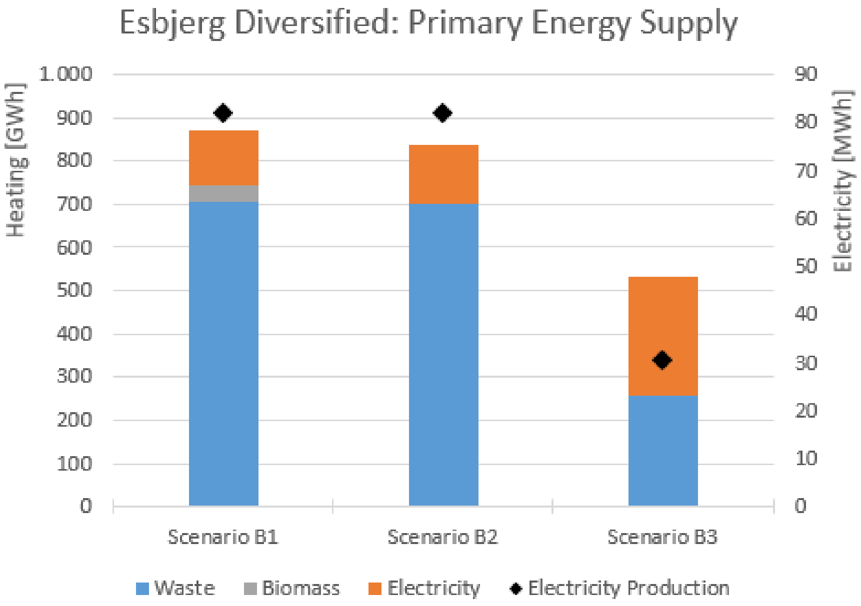

Figure 6.6: The primary energy supply required for the production of heating in the diversified energy systems in Esbjerg

- The primary energy supply in scenario B3 is the lowest compared to all three scenarios, although the electricity consumption is higher.
- The primary energy supply of scenario B1 and scenario B2 is similar, where only a small difference is found in the biomass and electricity consumption.

The lifetime costs of the diversified energy systems are shown in Figure 6.7.

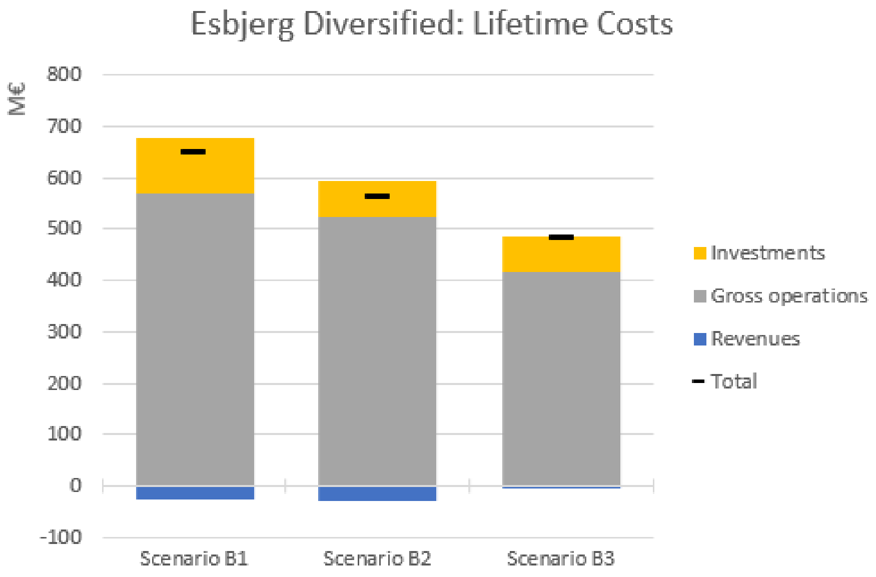

Figure 6.7: The lifetime costs of the various scenarios in the diversified energy systems in Esbjerg

- The lifetime costs of scenario B3 are lowest due to the lower gross operations.

- For all three scenarios, the lifetime costs is primarily determined by the gross operations and not the investment costs.

The annualised costs of the diversified energy systems are shown in Figure 6.8.

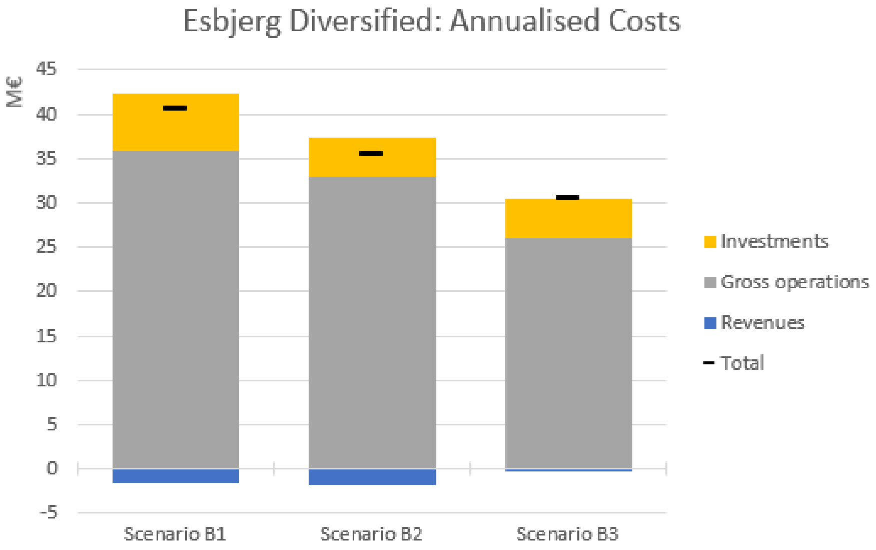

Figure 6.8: The annualised costs of the various scenarios in the diversified energy systems in Esbjerg

- The annualised costs of the scenario B3 are the lowest.
- Similar to the lifetime costs, the annualised costs for all three scenarios are primarily determined by the gross operations and whereas the investment costs make up for only a small share of the total costs.

6.1.3 Esbjerg combined scenarios

In this section some of the analysed scenarios are compared to show how the feasibility of the scenarios compare.

The primary energy supply for all of the scenarios combined are shown in Figure 6.9.

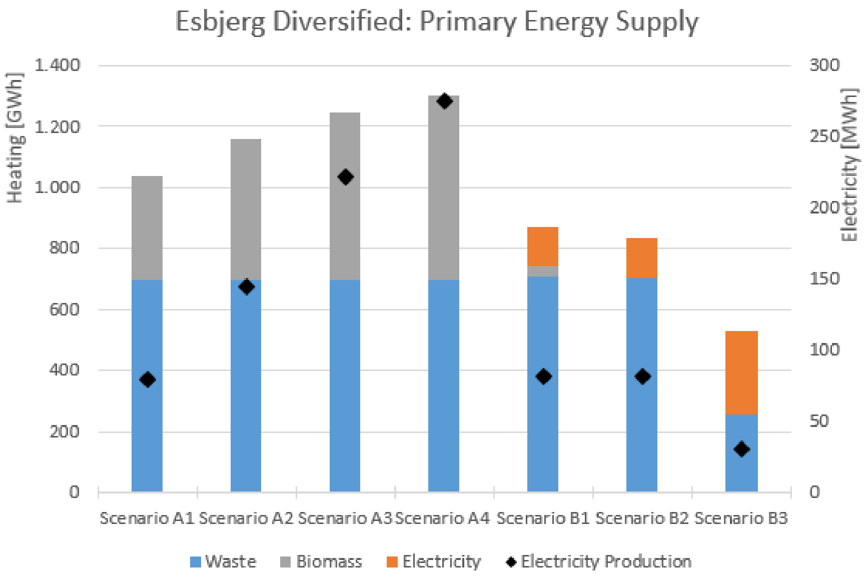

Figure 6.9: The primary energy supply required for the production of heating for all scenarios is Esbjerg

- The primary energy supply is the lowest in scenario B3, and the highest for scenario A4.
- The biomass consumption is overall the highest for scenario A4.
- The electricity production from scenario A1, scenario B1 and scenario B2 are similar whereas the PES is lower for both scenario B1 and scenario B2.

The lifetime costs for all of the scenarios combined are shown in Figure 6.10.

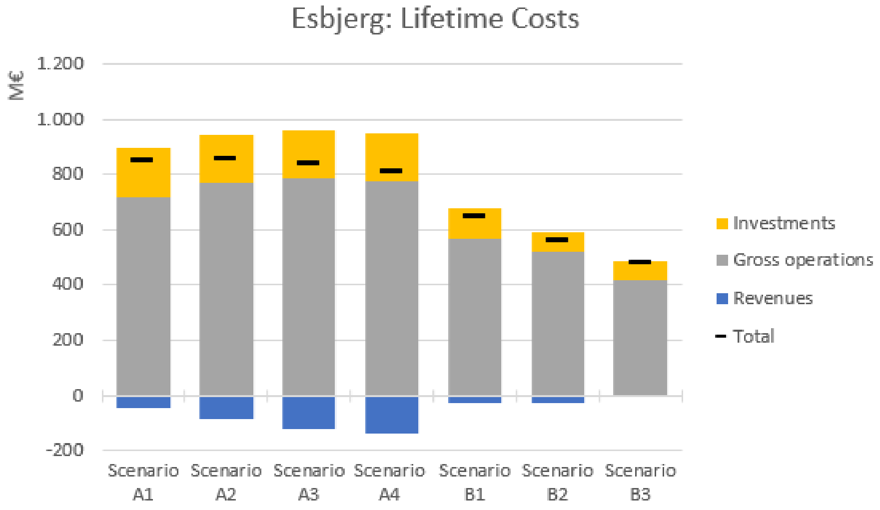

Figure 6.10: The lifetime costs of the various scenarios in Esbjerg

- The lifetime costs are the lowest in scenario B3 out of all scenarios. In addition, the lifetime costs for all scenarios of the diversified energy systems are lower compared to the centralised unit system scenarios.
- The investment costs for scenario A1 to A4 are all higher than the investment costs for the scenarios of B1 to B3.
- The revenues of the centralised unit system scenarios are all higher than the diversified energy system scenarios.
- The largest share of the lifetime costs for all scenarios is due to the gross operation costs.

The annualised costs for all of the scenarios combined are shown in Figure 6.11.

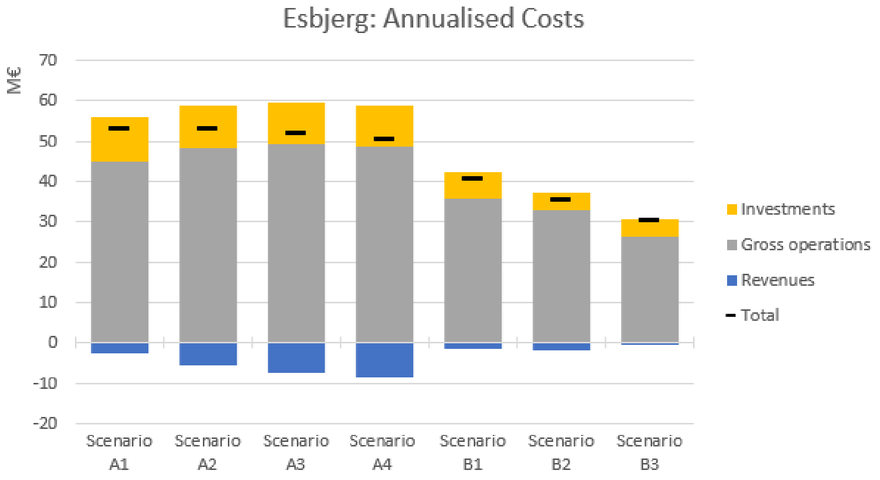

Figure 6.11: The annualised costs of all the scenarios in Esbjerg

- Similar to the lifetime costs, scenario B3 has overall the lowest costs.
- The annualised costs for the diversified energy system scenarios are all individually lower than the centralised unit system scenarios.

- The results show that the costs of are primarily depending on the gross operations for all scenarios.
- Scenario A2, scenario A3 and scenario A4, show the influence of the subsidies on the total costs. It shows that the revenues increase due to electricity sales. In other words, the subsidies applied in this study have the adequate size to increase electricity production but the subsidy is not translated into a profit.

6.2 Heating System Alternatives in Groningen

This chapter is set up equally to the Chapter 6.1 however, additional calculations are made outside of EnergyPRO. The time series used for the spot market prices is the EPEX spot market in €/MWh. The EnergyPRO parameters such as unit size, efficiencies and costs, are found in the Appendix A. At first, the current energy system in Groningen is assessed on the idea that there will be a continued use of individual natural gas boilers. This scenario is followed by the centralised unit energy system scenario and then the diversified energy system scenarios. Lastly, a scenario is implemented where all individual boilers are replaced by individual heat pumps. The inputs into EnergyPRO are shown in Appendix A.

6.2.1 Groningen currently

This section is meant to show the analysis of the current energy system of Groningen that relies heavily on individual natural gas boilers. This is the first scenario which is coined scenario C1. The PES, lifetime costs and annualised costs are determined for this scenario.

The primary energy supply of the current energy system of Groningen.
The gas consumption of the current heating system is based on the following parameters shown in Table 6.3.

Gas consumption costs	**Unit**	
Natural gas price	[€/m^3]	0,15[1]
Gas consumption	[million m^3]	166,9
Gas consumption	[GWh]	1.753
Total costs	[M€/year]	25

Table 6.3: Overview of the costs related to gas consumption directly related to the heat production

The lifetime and annual costs of the current energy system in Groningen.
The life time costs of the current energy system of Groningen is based on the following factors:

- The costs for gas consumption
- O&M costs individual gas boilers
- The potential investment costs for new boilers
- O&M costs gas grid
- The distribution costs for the gas grid

The costs for the gas consumption on an annual basis are given in Table 6.3.
The O&M costs of the individual gas boilers are based on the amount of boilers in the system. This is based on the amount of buildings present in the city. As seen in Chapter 4 and Table 4.6, two capacities of boilers are considered; either 10 kW for houses or 400 kW for apartments. Per apartment building it is assumed to have 40 dwellings aggregated per building. It is found that there are about 55.000 houses and 900 apartment buildings.
The potential investment costs are also based on the same amount of buildings. Since it is unknown when the technical life times of the current gas boilers are ending, an assumption is made to solely

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[1] The gas price is based on the year 2016 [ECN, 2017a]

have a one time investment cost to replace all boilers, all in 2030.
The total O&M costs and investment costs for the individual boilers are given in Table 6.4.

Boiler related costs	**Unit**	**Houses**	**Apartments**
Amount of units		55.133	900
Investment	[€/unit]	3.000	23.400
Fixed O&M	[€/unit/year]	209	683
Total Investment	[M€]	165,4	21
Total O&M	[M€/year]	11,5	0,6

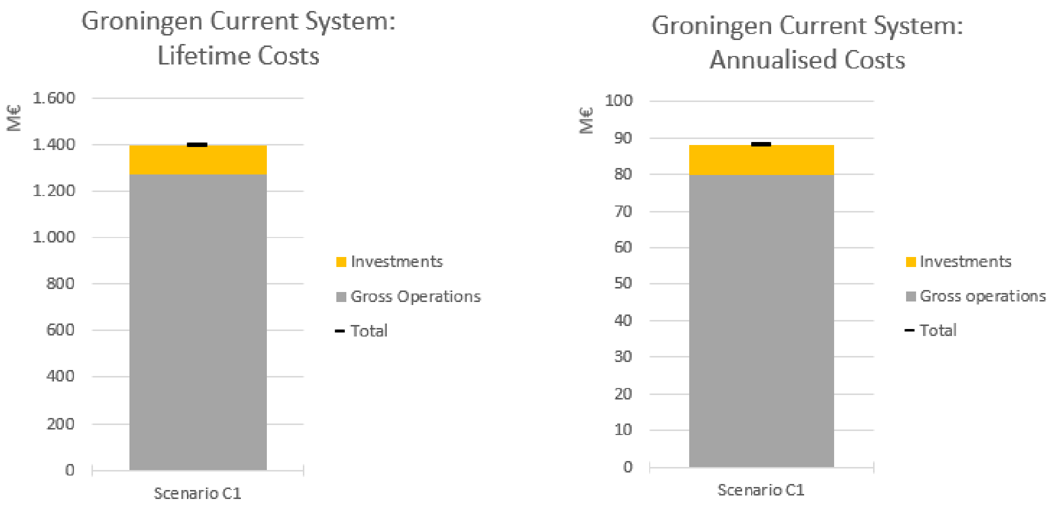
Table 6.4: Overview of the costs related to the individual gas boilers

The gas grid costs are determined based on parameters shown in Table 6.5. Only the gas that is related to the generation of heating is considered within the total amount of energy distributed.

Gas grid costs	**Unit**	
Fixed O&M	[€/MW/year]	20
Peak Capacity	[MW]	700
Distribution costs	[€/MWh/year]	10
Energy distributed	[GWh/year]	1.753
Total Costs	[M€/year]	17,5

Table 6.5: Overview of the costs related to distribution costs of the gas transport for individual gas boilers

To conclude the lifetime and annualised costs, an overview of the results are given in Figure 6.12.



(a) The lifetime costs of the current energy system in Groningen

(b) The annualised costs of the current energy system in Groningen

Figure 6.12: the lifetime and annualised costs for the current energy system in Groningen

- For both the lifetime and the annualised costs, it shows that the operational costs are the dominant costs.

6.2.2 Groningen centralised unit

The second set of scenarios that are analysed are the centralised unit system scenarios. In the case of Groningen there are no technologies currently available that are providing heating. In addition, there is no district heating grid currently present so the investment costs are included. The different scenarios that have been analysed are the scenarios shown in Table 6.6.

Groningen	**Scenario description**
Scenario D1	A centralised heating system based on a wood chip boiler
Scenario D2	A centralised wood pellet CHP heating system **without** a subsidy for electricity produced from biomass resources
Scenario D3	A centralised wood pellet CHP heating system **with** a subsidy of 0.005 € per kWh electricity produced from biomass resources
Scenario D4	A centralised wood pellet CHP heating system **with** a subsidy of 0.01 € per kWh electricity produced from biomass resources
Scenario D5	A centralised wood pellet CHP heating system **with** a subsidy of 0.02 € per kWh electricity produced from biomass resources

Table 6.6: Overview of the centralised unit energy system scenarios applied in Groningen

The system dynamics for the centralised heating system scenarios are shown in Figure 6.13.

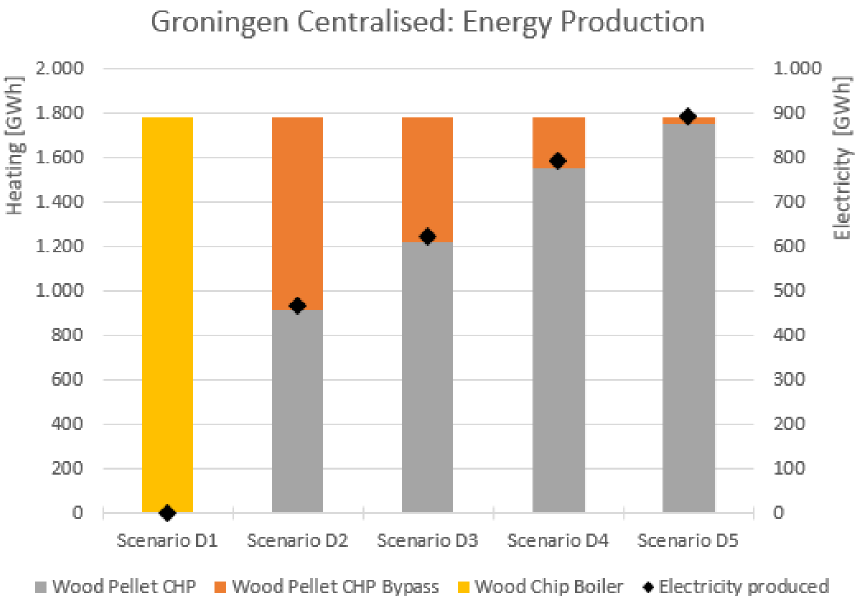


Figure 6.13: The energy production of the various technologies in the centralised unit systems in Groningen

- Scenario D2, shows that without any subsidies on the production of electricity from biomass resources the CHP extraction mode and the CHP bypass mode generate equal amounts of heating.
- With the increase of the subsidy from going from scenario D2 to scenario D5, it shows that the share of the wood pellet CHP is increasing in contrast to the share to wood pellet CHP bypass.
- Accordingly to the increase of the subsidy, the electricity generation increases as well in scenario D3 to scenario D5.

The primary energy supply of the centralised unit system scenarios is shown in Figure 6.14.

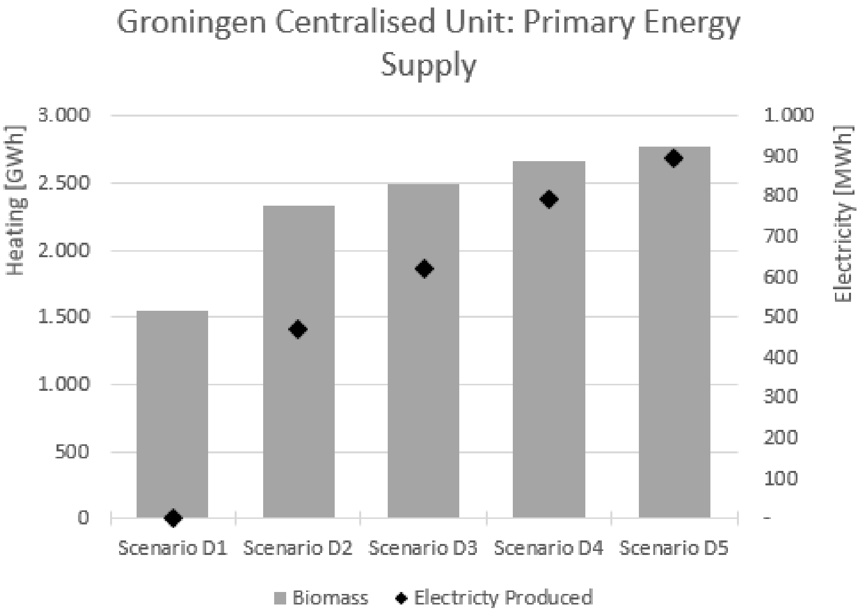


Figure 6.14: The primary energy supply required for the production of heating in the centralised unit systems in Groningen

- The PES for scenario D1 is the lowest of all scenarios.
- For all scenarios, the PES is solely consisting of biomass.
- Scenario D2 through to scenario D5 show an increased use of biomass but simultaneously an increase of electricity production is seen.

The lifetime costs of the centralised unit system scenarios are shown in Figure 6.15.

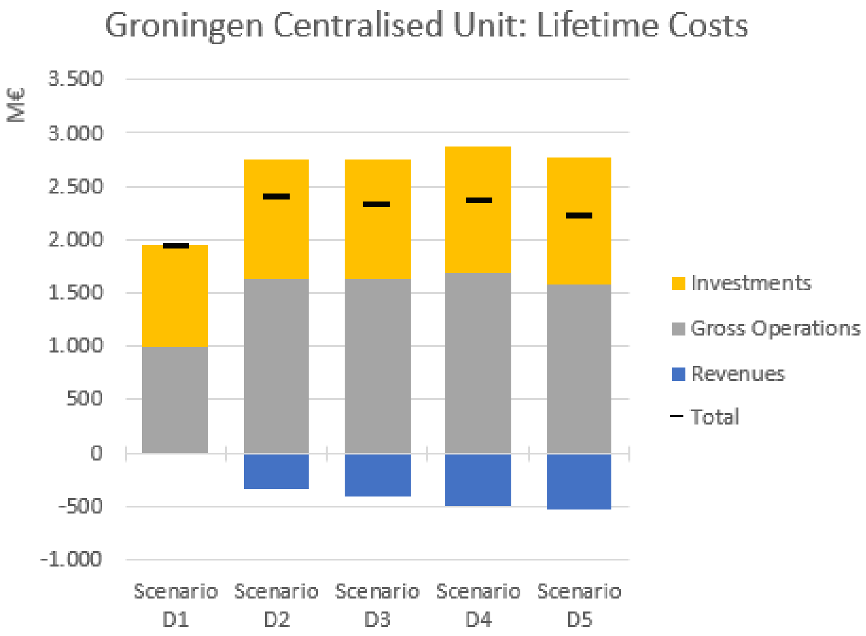


Figure 6.15: The lifetime costs of the various scenarios in the centralised unit systems in Groningen

- Scenario D1 has the lowest lifetime costs out of all scenarios.
- Scenario D2 through to D5 show similar lifetime costs. Where scenario D4 is slightly more expensive than the scenario D3 and scenario D5 since the investment costs are increased.
- The costs in scenario D1 are divided almost equally in investment costs and gross operational costs. With regards to scenario D1 to scenario D5, the share of operational costs is larger than the investment costs. However, the due to the revenues, the net operational costs are only a little over half the total investment costs.

The annualised costs of the centralised unit system scenarios are shown in Figure 6.16.

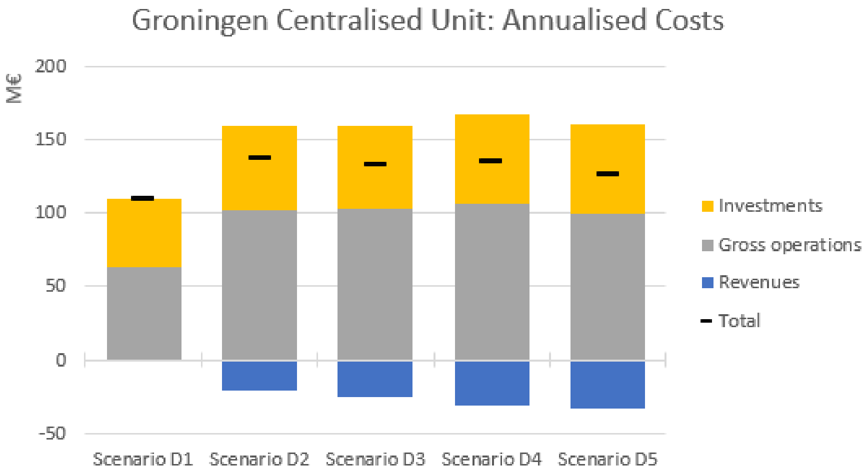


Figure 6.16: The annualised costs of the various scenarios in the centralised unit systems in Groningen

- Scenario D1 has the lowest annual costs.
- The annual costs for scenario D2 till scenario D5 are relatively similar to each other with only small changes amongs them.
- In scenario D1, the gross operations take a slightly larger share of the total annual costs.
- The gross operational costs in scenario D2 to D5 make up for the majority of the total costs. The revenues in these scenarios result in a significantly lower net operational costs and therefore the share of investments is almost equally divided with the net operational costs.

6.2.3 Groningen diversified system

The diversified energy system scenarios for Groningen are summarised in Table 6.7. Whereas for Esbjerg it was possible to design the energy system that is based solely on local resources, it was not possible for Groningen. Therefore, on top of local resources, the implementation of either a wood chip boiler or a wood pellet CHP unit is applied.

Groningen	**Scenario description**
Scenario E1	A diversified heating system with a wood chip boiler
Scenario E2	A diversified heating system with a wood pellet CHP **without** a subsidy for electricity produced from biomass resources
Scenario E3	A diversified heating system with a wood pellet CHP **with** a subsidy of 0.005 € per kWh electricity produced from biomass resources
Scenario E4	A diversified heating system with a wood pellet CHP **with** a subsidy of 0.01 € per kWh electricity produced from biomass resources
Scenario E5	A diversified heating system with a wood pellet CHP **with** a subsidy of 0.02 € per kWh electricity produced from biomass resources

Table 6.7: Overview of the diversified energy system scenarios applied in Groningen

The system dynamics of the diversified energy system scenarios are shown Figure 6.17.

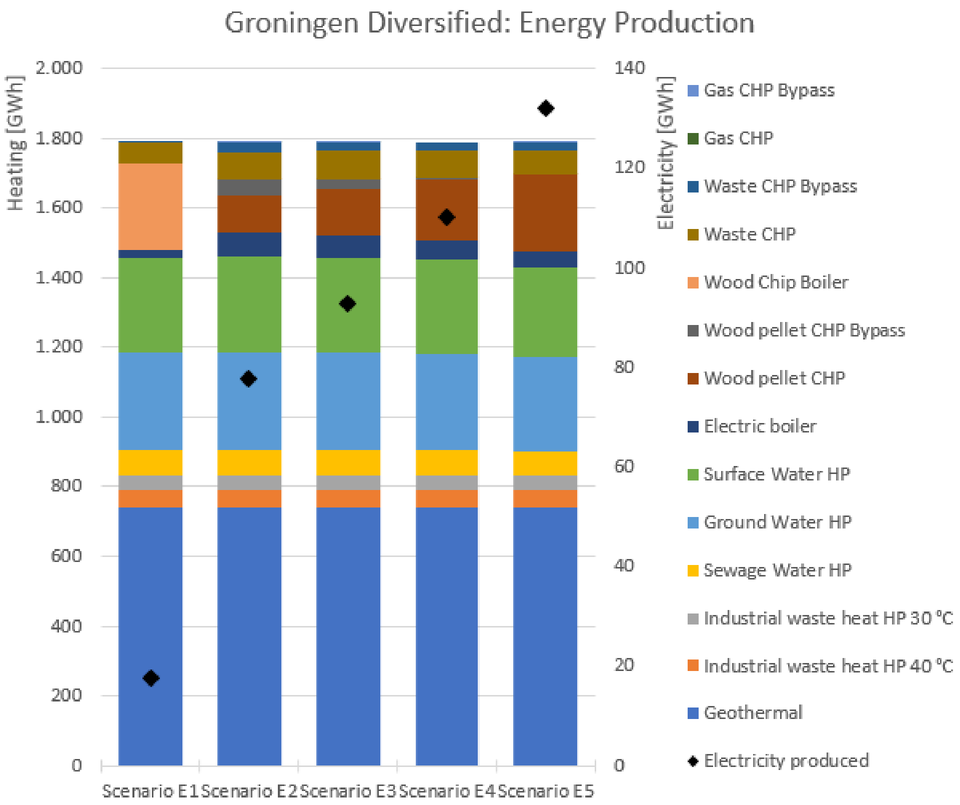


Figure 6.17: The energy production of the various technologies in the diversified energy systems in Groningen

- In all scenarios the geothermal energy source and the heat pumps remain very similar compared to each other.

A close up of the system dynamics between each of the scenarios for the diversified energy system scenarios is shown in Figure 6.18.

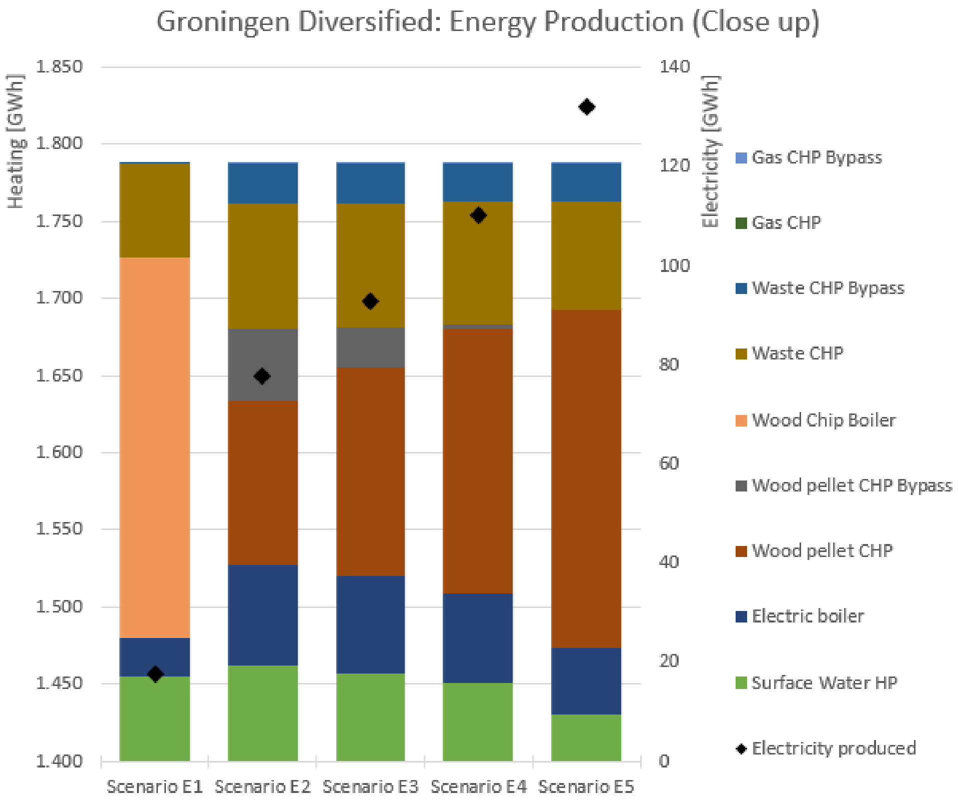


Figure 6.18: A close up of the energy production of the various technologies in the diversified energy systems in Groningen

- The wood chip boiler in scenario E1 takes up a majority of the remaining heating supply. The electric boiler and waste CHP unit both generate less heating than they do in scenario E2 through scenario E5.
- In scenario E2, the wood pellet CHP in extraction mode generates more heating than the bypass mode. With the increase of subsidies, this share only increases until the point where the wood pellet CHP bypass mode barely operates anymore.
- The overall heat production from the wood pellet CHP is increasing alongside with the increase of the subsidy.
- The electric boiler has an smaller share of energy production when the subsidy is increased.
- The electricity production increases significantly between scenario E1 and scenario E2. Between scenario E2 through scenario E5, the subsidy on electricity production causes an increase in electricity production.

The primary energy supply of the diversified energy system scenarios are shown Figure 6.19.

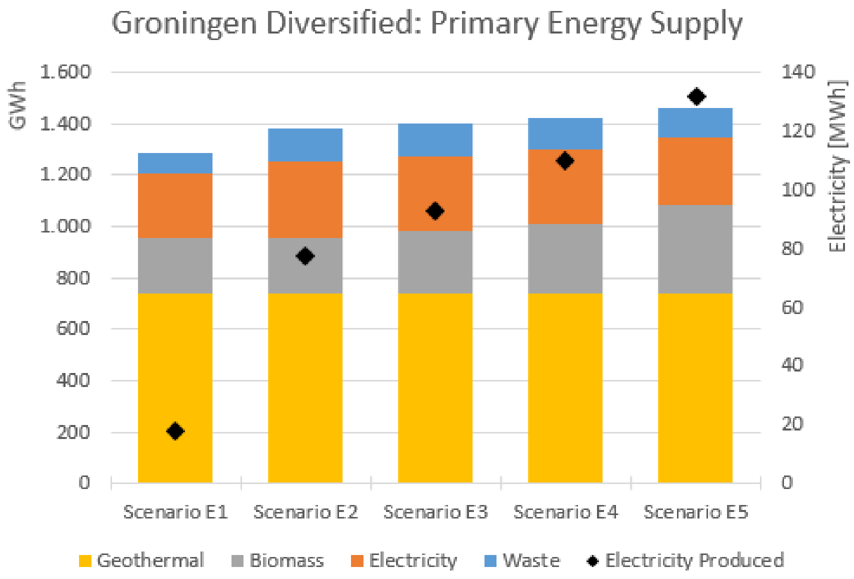


Figure 6.19: The primary energy supply required for the production of heating in the diversified energy systems in Groningen

- The PES for scenario E1 is the lowest, however not by a large margin.
- The biomass consumption between scenario E1 and E2 is very similar even though that scenario E1 has a large scale boiler and scenario E2 has a wood pellet CHP.
- The main cause for the increasing PES of scenario E2 through E5 is the increase in biomass consumption. However, the electricity production increases alongside with it.

The lifetime costs of the diversified energy system scenarios are shown Figure 6.20.

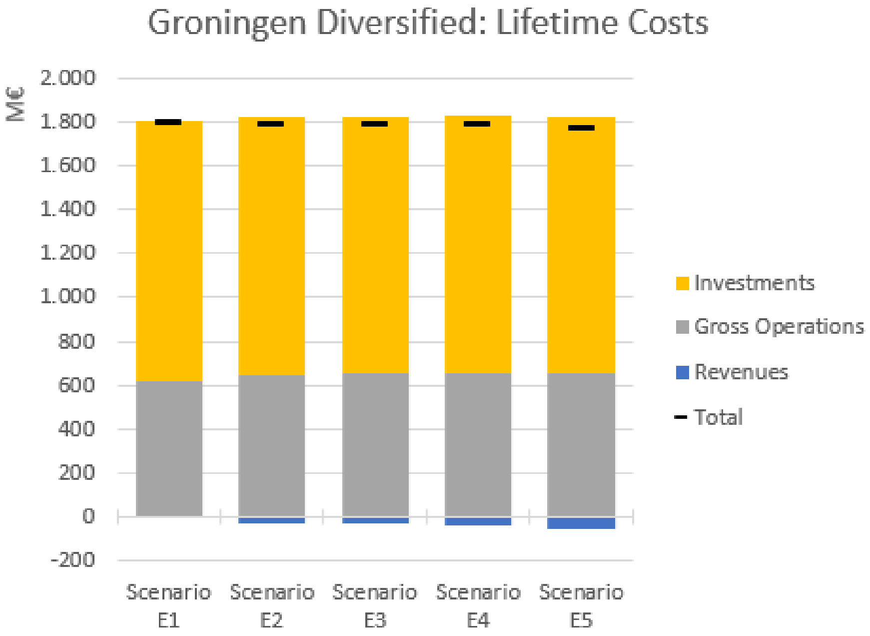


Figure 6.20: The lifetime costs of the various scenarios in the diversified energy systems in Groningen

- The lifetime costs of all the scenarios are practically the same across all scenarios.
- The majority of the lifetime costs are a result of the investments as the gross operations make up for a small share compared to the investments.

The annualised costs of the diversified energy system scenarios are shown Figure 6.21.

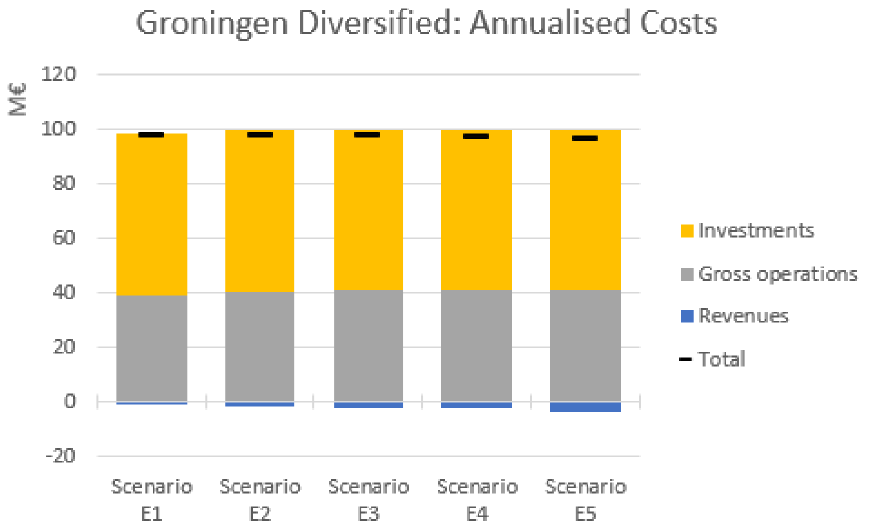


Figure 6.21: The annualised costs for the various scenarios in the diversified energy systems in Groningen

- The annualised costs have almost the same result regardless of the scenario.

- All the scenarios show that the investments take up the largest share of the total annualised costs.

6.2.4 Groningen individual

The last scenario, scenario F1, is the alternative to keep the idea of individual heating and thus omitting the use of district heating. However, in order to implement the idea of decarbonising the system, the individual heating is supplied via heat pumps. Due to the restrictions of land area, the only considered type of heat pump is the Air-to-Water heat pump. Similarly to scenario C1, the individual natural gas boilers, the amount of heat pumps is determined by the type of buildings. According to [DEA, 2017c], the heat pumps that are used for houses are typically smaller than for apartments due to the amount of dwellings per building. The same amount of units are used in this scenario as in scenario C1. Therefore, the amount of units are about 55.000 houses and 900 apartment buildings. The heat pump capacity related to the houses is said to be 10 kW and apartment buildings will have a 400 kW heat pump capacity.

The primary energy supply of the individual heat pump scenario.
The electricity consumption needed for the production of heating is based on the heating demand and the COP of the heat pump. The COP, at 2,6, is relatively low however, this is based on the yearly operation which includes the colder periods where a heat pump struggles more to be efficient. Table 6.8 shows the results of the PES.

Electricity consumption	**Unit**	
Heating demand	[GWh]	1.619
COP heat pumps		2,6
Total electricity demand	[MWh]	622.756
Average electricity price	[€/MWh]	28,98
Total costs	[M€/year]	18,05

Table 6.8: Overview of the primary energy supply for the individual heat pump scenario in Groningen and the related costs

The lifetime and annualised costs of the individual heat pump scenario.
The following aspects are included into defining the lifetime and annualised costs of scenario F1;

- The costs for electricity consumption
- O&M costs individual heat pumps
- The (future) investment costs for heat pumps
- O&M costs of the electricity grid
- The distribution costs for the electricity grid

The costs for electricity consumption are found in Table 6.8.
The investment and O&M costs related to both of the heat pumps are shown in table 6.9.

Heat pump costs	**Unit**	**10 kW**	**400 kW**
Amount of units		55.133	900
Investment	[€/unit]	9.400	141.000
Fixed O&M	[€/unit/year]	278	1.650
Total Investment	[M€]	518,3	126,9
Total O&M	[M€/year]	15,3	1,5

Table 6.9: Overview of the costs related to the air-to-water heat pumps in Groningen [DEA, 2017c]

An additional investment is needed for both of the types of heat pumps since the technical lifetimes are shorter than that of the project. The investment costs have decreased by that time to 8.500 € for the 10 kW heat pump and 127.000 € for the 400 kW heat pump. The present value of these investments is 329 M€.
The costs for the investment in the electricity grid are analysed since [van Melle et al., 2015] states that the use of individual heat pumps would results in a strong increase in the use of the electricity net, a growth by a factor 2 or 3, even provided that heat demand savings are applied. [Lund, 2017] mentions that incremental changes to the electricity grid are relatively cost effective whereas a doubling or more of the grid results in costs similar to the capital value. In other words, in the case of an individual heat pump scenario in Groningen there is a need for an investments to the electricity grid similar to the capital value of a new grid. The capital value of the grid consists of the service lines and single lines. The service lines are the connection between the buildings and the single line which can be also referred to as the main distribution line. Two capacities of service lines are considered, a 0-20 kW line and a 100+ kW line. The smaller service line are designated for the 10 kW capacity heat pumps and the 100+ kW service is designated for the 400 kW heat pumps. Table 6.10 shows the costs for the investment costs related to the distribution grid.

Electricity grid investment costs	**Unit**	**0-20 kW**	**100+ kW**
Amount of units		55.133	900
Investment	[€/unit]	2.149	12.131
Total Investment	[M€]	118,5	10,9

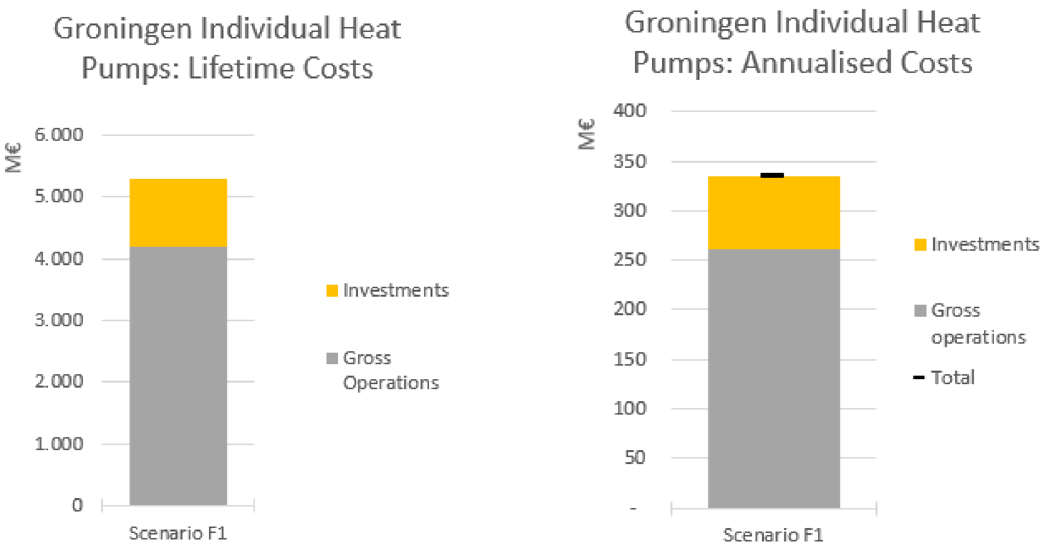
Table 6.10: Overview of the costs related to the investment of the electricity grid [DEA, 2017b]

Lastly, the distribution costs related to the electricity consumption that is required for the heat pumps are determined. These distribution costs are based on the type of built environment, in this case the built environment has a city characteristic.

Electricity distribution grid costs	**Unit**	
Distribution costs	[€/MWh/year]	365
Total electricity demand	[MWh]	622.756
Total costs	[M€/year]	227,3

Table 6.11: Overview of the costs related to distribution costs of the electricity demand for individual heat pumps

The operational expenses of the electricity grid are significant due to the combination of the low COP of the air-to-water heat pump chosen in this study and the relatively high heating demand.



(a) The lifetime costs of the individual heat pump energy system in Groningen

(b) The annualised costs of the individual heat pump energy system in Groningen

Figure 6.22: The lifetime and annualised costs for the individual heat pump energy system scenario in Groningen

- The gross operational costs are main cause of the total costs whereas the investment costs only take a small share.

6.2.5 Groningen overall results

The primary energy supply of all the scenarios are shown in Figure 6.23.

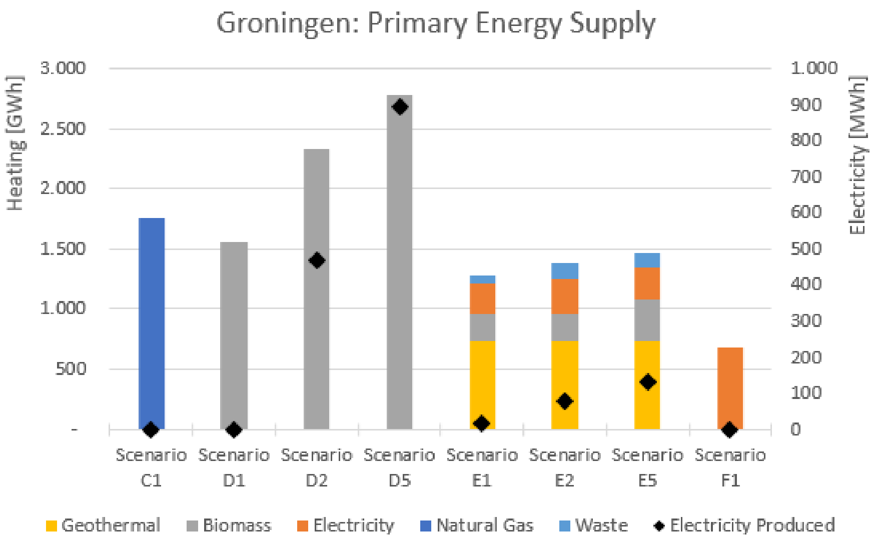


Figure 6.23: The primary energy supply required for the production of heating of all the scenarios in Groningen

- The PEs is the lowest in scenario F1 due to the relatively high efficiency of heat pumps. Scenario F1 is followed by all three of the diversified energy system scenarios.

- Scenario C1 shows that current situation has a worse PES than majority of the other scenarios except for the scenario D2 and scenario D5.
- The biomass consumption is significantly larger in scenario D1, scenario D2 and scenario D5.
- Scenario D2 and scenario D5 show that the wood pellet CHP units result in significantly higher electricity production.

The lifetime costs of all the scenarios are shown in Figure 6.24.

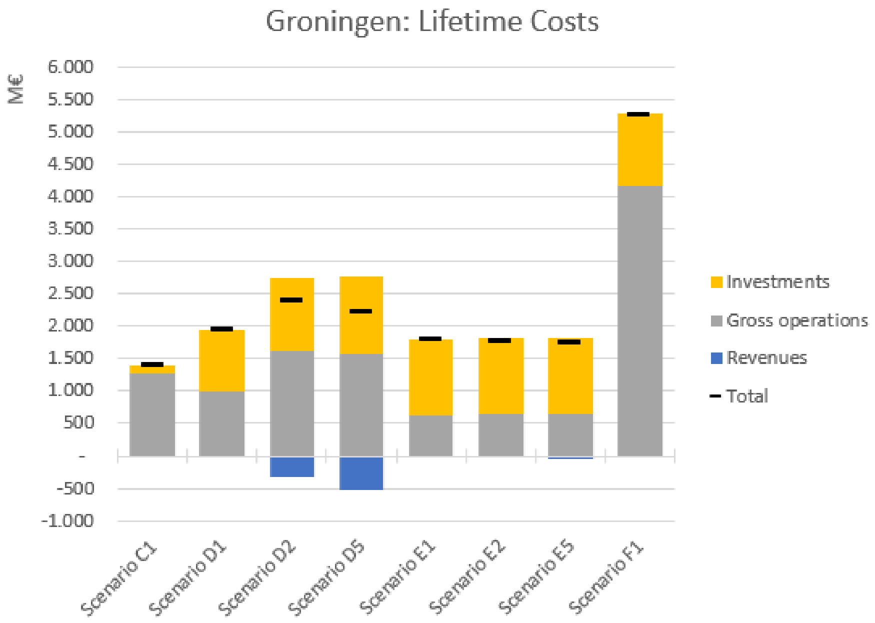


Figure 6.24: The lifetime costs of the various scenarios

- The lifetime costs are the lowest for the scenario C1 followed by the diversified energy systems scenarios E1, E2 and E5.
- The lifetime costs of scenario F1 are by far the highest.
- The costs of scenario E1, scenario E2 and scenario E5 are primarily defined by their investments whereas the investment costs play a smaller role in the scenario D1, scenario D2 and scenario D5.
- The individual scenarios, scenario C1 and scenario F1, have exceptionally high shares of gross operations in their total costs.

The annualised costs of all the scenarios are shown in Figure 6.25

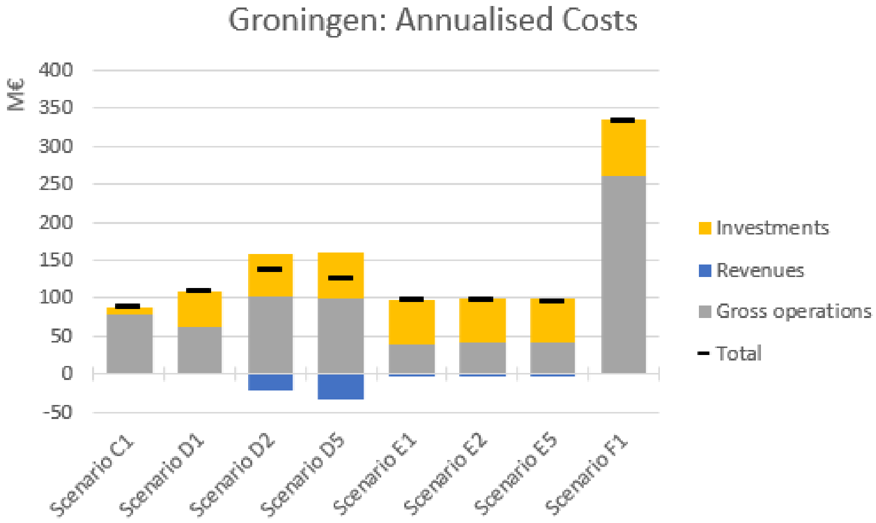


Figure 6.25: The annualised costs for all the scenarios in Groningen

- The annualised costs for scenario C1 is the lowest.
- The annualised costs for scenario D1, scenario E1, scenario E2 and scenario E5 are almost similar and are not far from scenario C1.
- Scenario F1 is not competing with the other scenarios since the following highest costs is less than half the annual costs.

6.3 Esbjerg compared to Groningen

The results of the analyses made on the scenarios in both cities show similiraties and differences. The analyses were set up in order to have the ability to compare them to a certain extent.

To start, it is found that the idea of supplying the entire energy system via renewable and local energy sources is only possible for Esbjerg. Even with the use of geothermal energy and waste heat from industrial processes in Groningen, it is not possible to supply the current heating demand with these resources. It can therefore be concluded that the challenge for Groningen to implement a feasible heating system is greater than for Esbjerg.
When comparing the centralised energy systems with the diversified energy systems it is found that the in both of the case studies the diversified energy system scenarios have the lowest primary energy supply. The centralised unit systems with biomass boilers comes in both scenarios close to the diversified energy system. However, the biomass consumption of the centralised biomass boiler is excessive and considered to not be feasible. In addition, the biomass consumption in the diversified energy system scenarios in Groningen is significantly higher than that of the diversified energy system scenarios of Esbjerg. If the individual heat pump scenario of Groningen is included, then this has the lowest primary energy supply compared to the other scenarios in Groningen.
The lifetime costs and the annualised costs give similar results. The diversified energy system scenarios have the overall lowest costs compared to all other scenarios for the respective case study. It is noticeable that the costs difference between the diversified energy system scenarios and the centralised unit system scenario is smaller in the case of Groningen. In other words,

Esbjerg shows that a diversified energy system would be significantly more feasible whereas this is not the case for Groningen.

One thing that is remarkable is the fact that in the diversified energy system scenarios in Esbjerg are primarily determined by the gross operation costs and less by their investment costs. On the other hand, the lifetime and annualised costs of the diversified energy system scenarios in Groningen are for more than half determined by the investment costs and only for a small part on the gross operational costs. The difference can be partly explained by the large share of the waste incineration plant in Esbjerg that has relatively low investment costs and higher operation costs. On the other, Groningen has the geothermal energy production where the investment costs are significantly higher than the operational costs.

Discussion and Future Research 7

In this chapter a discussion is set up based on the results of this research and it includes a discussion on the possible additions to the research that could influence the results and conclusions. Where possible, advice is given on future research opportunities that could assist or built on this research.

Heat savings
In this project any changes in the heating demand are excluded from the scope of the research as it would assist in the comparison of the various scenarios. However, energy efficiency goals set by the European Union show the necessity for energy conservation in the built environment. From a socioeconomic perspective, energy conservation should be applied with an 'as-soon-as-possible´ principle as it is more cost effective if the renovations are implemented today [Harrestrup and Svendsen, 2014]. Energy conservation can include the use heat savings in the built environment, both in already existing and the future building stock. There is a theoretical optimum to what extend heat savings should be implemented instead of making changes to the supply of energy. The determination of this theoretical socioeconomic optimum is relatively difficult and some studies have shown their view on it, e.g. [Mathiesen et al., 2016; Harrestrup and Svendsen, 2014; Hansen et al., 2016]. Nonetheless, there is no discussion that energy savings should be applied to a certain extent.

Looking at the two case studies in Esbjerg and Groningen it seems that the current building stock allows for energy conservation. An often-used argument with regards to energy savings is the idea that the specific heating demand will decrease due to the building regulations for new buildings. However, by the year 2040, only a small part of the buildings in Denmark and The Netherlands, would be built between the time of a couple of years ago and the year 2040. [Mathiesen et al., 2016] states that the rate of newly built buildings is around 1-1.5% in Denmark, and this rate is predominantly based on a growth of the housing stock, not on the replacement of older building stock. With relation to The Netherlands, [van Melle et al., 2015] mentions that 75% of the buildings in which the Dutch society will live has already been built. As a result, renovations and refurbishments are important to attain the energy efficiency goals. It is necessary to underline that from a socioeconomic perspective, heat savings are only viable to being implemented when building are already up for renovation or refurbishment, which is after 20 to 50 years [Mathiesen et al., 2016]. The implementation of heat saving is therefore depending on the date when the building was originated. To substantiate this, [Hansen et al., 2016] states that the costs of heat savings are closely related to the specific heat demand of buildings since energy savings will have more impact energy when the specific heat demand is higher.
Subsequently, the built year often has an influence on the buildings' specific heat demand since older buildings generally have a higher heat demand [Harrestrup and Svendsen, 2014]. Building

regulations are found the have an influence on the specific heat demand. More stringent building regulations were implemented in the Netherlands in 1995 whereas in Denmark the regulations significantly changed around 1977 [RVO; Harrestrup and Svendsen, 2014].

The building regulations, the dates from when the buildings were built, the principle of implementing heat savings as soon as possible all have an influence on the specific heat demand development. Together with the project's lifetime of 22 years until the year 2040 it is expected and more socioeconomically to have heat savings in the built environment. To what extent the heat savings should be applied and how much these savings are can be analysed in future research.

Sensitivity Analysis

According to [Bornemann et al.], municipalities struggle with the uncertainty about the future energy demand and the energy landscape with regards to regulations, fuel accessibility and fuel prices. In order to provide possible future scenarios, it is advised to apply sensitivity analyses that review the influence on the changes in the fuel prices. The results show that there each of the scenarios has different shares of investments compared to the operational costs. This could be an indication to how well each of the energy systems is resilient towards changes in certain aspects of the costs. In other words, scenarios where the majority of the costs are as a result of operational costs which includes the fuels, it can be possible that a change in the costs of fuels can have a significant impact. In addition, with the use of EnergyPRO and the prioritisation model that is built in the tool, a change in the fuel costs can result in a change in the of the prioritisation of various technologies. Therefore, a change in the fuel costs could not only result in a change of fuel costs but also in the system dynamics and the primary energy supply. In addition, the prices on the investment costs and operation and maintenance costs could also be up for examination. Most of the data is derived from sources from the Danish energy agency and their technology catalogues. These prices are based on previous experiences of implementations of the technologies. Therefore, the prices represent reality to a large extent however, there are also technologies implemented in this study which have a significantly larger capacity than the capacities mentioned in the technology catalogue. Primarily the large-scale boilers in scenario A1 and scenario D1 are questionable. The capacities are 200 MW and 550 MW for scenario A1 and scenario D1, respectively. The technology catalogue only has data that is based on 6 MW feed in boilers which due their scale has relatively high investment costs and O&M costs. Table 7.1 shows the comparison between a wood chip boiler and a wood pellet CHP which are the two types of units compared in the centralised unit energy system scenarios in Groningen.

Boiler and CHP costs	**Unit**	Wood pellet CHP small	Wood pellet CHP large	Wood chip boiler
Investment costs	[M€/MW]	0,93	0,75	0,79
Fixed O%M costs	[€/MW/year]	41,700	20.900	37.055
Variable O%M cost	[€/MWh_{th}]	0,63	0,80	2,26
Fuel costs	[€/GJ]	8,91	8,91	6,25

Table 7.1: A comparison between the costs of small and large-scale wood pellet CHP's and a wood chip boiler

The costs in Table 7.1 show that economy of scale of wood pellet CHP's fixed O&M result in almost halving the costs. Since the technology catalogue does not present any large-scale biomass boilers, the prices that are applied in the scenarios for the large scale boilers can be too high. A change in the costs for large-scale biomass boilers would be realistic and it could have an impact on the results where large scale boilers are applied.

Resilience
Following the sensitivity analyses, the resilience of the various scenarios is important. In this case a differentiation takes place between the centralised unit systems and the diversified energy systems for both case studies and in addition to Groningen also the individual heat pump scenario. All the scenarios and their energy systems are depending to different extents on external influences such fuel prices, electricity prices and fuel availability. The influence of changes in these aspect on the system dynamics and the costs can be analysed in a sensitivity analysis. In addition, it should be mentioned that influence of changing these aspects is based on the resilience of the energy system. Both the centralised unit systems and the individual heat pump scenario are relying on either one or two different fuel sources which makes them less resilient to changes in possible changes of the availability and prices. Whereas a diversified energy system is most likely to be less influenced by the same changes to these prices and the availability as it makes up for a smaller share of the total system. This can also be reviewed in the lifetime and annualised costs of the diversified energy systems of Groningen where the majority of the costs are determined by the investment costs and not the operational costs.
In addition, with the idea of the possibility of heat savings and the changes in the external prices and availability of resources, a systems' resilience can be shown on how effective it can change its operation to adjust to external influences. In order to be able to quantify this, it is possible to review the return of investment of different technologies since a shorter return on investment allows for changes that can be made. An example for this is that it is often thought that boilers have a relatively short return of investment compared to CHP units. Therefore, basing an energy system more on boilers instead of CHP units can improve the resilience of the system.

Flexibility
Flexibility of a system can be correlated to the resilience of an energy system which has been mentioned before. However, flexibility in this case is the strategy on how investments are made into the system. Investments made to the energy system on the scale of municipalities requires rather large investments. In the case of Esbjerg, the investments in the system are primarily related to the replacement of the coal fired power plant. This would require a one-time investment at the moment that the coal fired power plant is omitted from the energy system. There is not much room to phase the investments over a longer period regardless the type of energy system. Both the centralised unit system and the diversified energy system are both required to be at full capacity within a short period after the closing of the coal fired power plant.
On the contrary, the scenarios assessed in Groningen have significant changes in the flexibility of the system. First, the district heating system is not in place yet and therefore it is not necessary to implement the thermal production units at the full capacity need to supply the entire heating demand. In Groningen it is possible to phase out the current energy system and to implement a decarbonised more gradually. With regards to the centralised unit energy system, the gradual implementation is considered to be less of an option due to the large centralised units. The diversified energy system is considered to have more flexibility with regards to the implementation. The smaller sized energy production units can be implemented in different phases in collaboration of the gradual increase of the district heating grid. The combination of heating units should still be realistically able to cover the heating demand, e.g. the implementation of one heat pump is not

considered feasible as they are designed to cover base loads. Phasing in the diversified will start out to be less resilient and gradually become more resilient with the addition of a larger variety of energy sources. The last option, the individual heat pump scenario would be most effective with the phasing of the heat pumps as a replacement for the individual boilers. However, the replacement of the electricity grid is considered to be a lot less flexible.

Overall, the flexibility of the investments is different for all the scenarios, where Esbjerg has almost no flexibility and within Groningen the flexibility is depending on the different type of energy system. In future research, the implementation strategy of any of the systems can be determined which would inherently also determine the investment strategy.

Case studies

In Chapter 2, it is mentioned that the results of case studies are not results that can be copied into other locations. The case studies are merely meant to show as an example of the possibilities and the feasibility of the studies. With that in mind, the initial idea of this thesis was based on analysing the decarbonisation of the heating market in urbanised areas of Europe. Within the research there are only two cases chosen to analyse the heating system. The choice of the heating systems was primarily decided on the current heating system that is in place. As mentioned in Chapter 3, the two cities are geographically not situated far from each other and they have similar climates. In addition, the economic situation is relatively similar in both countries. To show a better image of the feasibility of decarbonised heating systems in urbanised areas, it is necessary that scenario analyses are done in other cities. For example, cities with more extreme weather temperatures and also cities where the local energy sources are different.

Conclusion 8

In this thesis the feasibility of various heating system scenarios is examined according to normative scenario planning. These scenarios are meant to show alternative routes towards the decarbonisation of the current heating systems. In order to analyse the influence of the different scenarios, they were applied in two separate but similar case studies based in the cities of Esbjerg and Groningen.
According to the following research question the aim of the research is defined:

> *Using the cities Esbjerg and Groningen as case studies, how does the feasibility of renewable energy based heating system alternatives compare?*

The feasibility of the alternatives is focused on the socioeconomic perspective where both a requirement for low costs for society is included and where energy supply is done in the most efficient way, i.e. efficient use primary energy sources with a minimisation of biomass resources. The scenarios are predominantly divided in two segments, where one of the options is to supply the heating via large centralised units. This is similar to many places in Europe now where district heating is applied however, it should be done based on renewable energy. The other option is to apply a diversified energy system, one where the utilisation of local resources is prioritised. The results from the analyses show that the diversified energy systems are in both case studies the most feasible solution. Both in terms of primary energy supply and in total costs. This conclusion can be substantiated with following summary of findings:

- Esbjerg
  - The primary energy supply is the lowest for diversified energy systems. Especially when waste incineration is operated to have the lowest costs. However, even when waste incineration is prioritised in the system, the energy consumption that is needed to cover the heating demand is the lowest in the diversified energy systems. The implementation of heat pumps results into efficient use of resources.
  - With a socioeconomic perspective it is essential that the consumption of biomass, which is a finite renewable resource, should be limited in the energy system. This enhances the favourable results of the diversified energy systems since they consume significantly less biomass resources.
  - With regards to the costs of the different scenarios it is found that the costs, both the lifetime and the annual costs are the lowest for the diversified energy systems.
- Groningen
  - The primary energy supply for Groningen is the lowest for the individual heat pump scenario. This scenario is followed up by all the diversified energy system and also closely by the centralised unit energy systems.

  - The biomass consumption is in all the district heating energy systems relatively high, and they consume more than is locally available. The centralised unit energy systems consume drastically more biomass than the diversified energy systems.
  - The lifetime and annualised costs results show that the diversified energy systems are all lower in total costs however, the margin is very little with the centralised biomass boiler. The centralised energy systems follow the other scenarios in costs relatively closely. The individual heat pump energy system is more than three times more expensive than the diversified energy systems.

The results show that a diversified energy based on local energy sources is possible for Esbjerg, whereas this is not the case for Groningen. It can be stated that a city as such as Groningen has a bigger challenge with regards to decarbonising the energy system. A conclusion that can be drawn out of this is that if an urbanised area is capable of being supplied by local energy sources, that it is advised to do so since other urbanised areas which cannot achieve this need exterior help with regards to energy sources.

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EnergyPRO Parameters

A

In this appendix and overview is given of all the parameters that were applied in the EnergyPRO analyses.

A.1 Esbjerg scenario A1

Scenario A1	[Unit]	Waste CHP	Waste CHP Bypass	Straw Boiler
Size	$[MW_{input}]$	94,7	94,7	200
Thermal efficiency	[%]	76	97	102,1
Electric efficiency	[%]	21	-	-
Investment costs	[M€]	-	-	181,738
Lifetime extension	[M€]	22,728	22,728	-
Fixed O%M	[M€/year]	5,7767	5,7767	1 0,48
Variable O%M	$[€/MW_{th}]$	7,6315	5,9793	2,1441
Minimal operation	[hours]	4	4	0
Allowed to store	[Y/N]	Yes	Yes	No
Partial Production	[Y/N]	No	Yes	Yes

Table A.1: Overview of the parameters applied in the centralised energy system scenario planning in Esbjerg

A.2 Esbjerg scenario A2/A3/A4

Scenario A2/A3/A4	[Unit]	Waste CHP	Waste CHP Bypass	Wood pellet CHP	Wood pellet CHP Bypass
Size	$[MW_{input}]$	94,7	94,7	200	200
Thermal efficiency	[%]	76	97	64	97
Electric efficiency	[%]	21	-	33	-
Investment costs	[M€]	-	-	150	150
Lifetime extension	[M€]	22,728	22,728	-	-
Fixed O%M	[M€/year]	5,7767	5,7767	4,18	4,18
Variable O%M	$[€/MW_{th}]$	7,6315	5,9793	0,7981	0,5285
Minimal operation	[hours]	4	4	4	4
Allowed to store	[Y/N]	Yes	Yes	Yes	No
Partial Production	[Y/N]	No	Yes	Yes	Yes

Table A.2: Overview of the parameters applied in the centralised energy system scenario planning in Esbjerg

Additional investment and costs are related to the investment of a thermal storage tank of 40.000 m^3 at the price of 6,4 M€. The district heating O%M costs are 5.369.127 € per year.

A.3 Esbjerg scenario B1/B2/B3

Scenario B1/B2/B3	[Unit]	Waste CHP	Waste CHP Bypass	Sewage Water HP	Sea Water HP	Ground Water HP
Size	$[MW_{input}]$	94,7	94,7	2,846	200	
Thermal efficiency	[%]	76	97	360	300	300
Electric efficiency	[%]	21	-	-	-	-
Investment costs	[M€]	-	-	6,76	29.7	7,92
Lifetime extension	[M€]	22,728	22,728	-	-	-
Fixed O%M	[M€/year]	5,7767	5,7767	0,02049	0,09	0,0325
Variable O%M	[€/MW_{th}]	7,6315	5,9793	1,8	1,8	1,8
Minimal operation	[hours]	4	4	4	4	4
Allowed to store	[Y/N]	Yes	Yes	Yes	Yes	Yes
Partial Production	[Y/N]	No	Yes	Yes	Yes	Yes

Table A.3: Overview of the parameters applied in the diversified energy system scenario planning in Esbjerg

Scenario B1/B2/B3	[Unit]	Electric Boiler	Wood Chip Straw Boiler	Gas CHP	Gas CHP Bypass	Straw Boiler
Size	$[MW_{input}]$	15	1	2	2	42
Thermal efficiency	[%]	99	1,1	42,5	0,75	102,1
Electric efficiency	[%]	-	-	51	-	-
Investment costs	[M€]	1,05	0,825	2,6	2,6	38,16
Lifetime extension	[M€]	0,9	22,728	-	-	-
Fixed O%M	[M€/year]	0,01605	0,04	0,0586	0,0586	2,2008
Variable O%M	[€/MW_{th}]	0,5	1,5	10,476	7,586	2,1441
Minimal operation	[hours]	0	0	4	0	0
Allowed to store	[Y/N]	No	Yes	Yes	Yes	Yes
Partial Production	[Y/N]	Yes	Yes	Yes	Yes	Yes

Table A.4: Overview of the parameters applied in the diversified energy system scenario planning in Esbjerg

Additional investments are needed for the thermal storage, which is 2,8 M€ for a 80.000 m^3 and with O&M costs 19.600 € per year. The district heating O&M costs are 5.369.127 € per year.

A.4 Groningen scenario D1

Scenario A1	[Unit]	Wood Chip Boiler
Size	$[MW_{input}]$	550
Thermal efficiency	[%]	114,9
Investment costs	[M€]	434,5
Lifetime extension	[M€]	-
Fixed O%M	[M€/year]	20,38
Variable O%M	[€/MW_{th}]	2,26
Minimal operation	[hours]	4
Allowed to store	[Y/N]	Yes
Partial Production	[Y/N]	Yes

Table A.5: Overview of the parameters applied in the centralised energy system scenario planning in Groningen

Additional investments are for the 120.000 m^3 thermal pit storage with an investment cost 4,2 M€ and O&M costs of 29.400 €. The investment costs for the district heating grid are said to

509.337.928 € with 5,093 M€ O&M costs.

A.5 Groningen scenario D2/D3

Scenario A1	[Unit]	Wood Pellet CHP	Wood Pellet CHP Bypass
Size	$[MW_{input}]$	800	800
Thermal efficiency	[%]	64	97
Electric efficiency	[%]	33	-
Investment costs	[M€]	600	600
Lifetime extension	[M€]	-	-
Fixed O%M	[M€/year]	16,72	16,72
Variable O%M	[€/MW_{th}]	0,798	0,528
Minimal operation	[hours]	4	4
Allowed to store	[Y/N]	Yes	No
Partial Production	[Y/N]	Yes	Yes

Table A.6: Overview of the parameters applied in the centralised energy system scenario planning in Groningen

A.6 Groningen scenario D4/D5

Scenario A1	[Unit]	Wood Pellet CHP	Wood Pellet CHP Bypass
Size	$[MW_{input}]$	900	900
Thermal efficiency	[%]	64	97
Electric efficiency	[%]	33	-
Investment costs	[M€]	675	675
Lifetime extension	[M€]	-	-
Fixed O%M	[M€/year]	18,81	18,81
Variable O%M	[€/MW_{th}]	0,798	0,528
Minimal operation	[hours]	4	4
Allowed to store	[Y/N]	Yes	No
Partial Production	[Y/N]	Yes	Yes

Table A.7: Overview of the parameters applied in the centralised energy system scenario planning in Groningen

Additional investments are for the 120.000 m^3 thermal pit storage with an investment cost 4,2 M€ and O&M costs of 29.400 €. The investment costs for the district heating grid are said to 509.337.928 € with 5,093 M€ O&M costs.

A.7 Groningen scenario E1

First Table A.8 and Table A.9 will show the parameters that are applicable in all of the diversified energy systems, scenario E1-E5. Table will show the specifics for scenario E1 and Table will show the specifics of the rest of the scenarios.

Scenario E1/E2/E3/E4/E5	[Unit]	Waste CHP	Waste CHP Bypass	Sewage Water HP	Surface Water HP	Ground Water HP
Size	$[MW_{input}]$	60	60	4,02	20	20
Thermal efficiency	[%]	78,5	101,1	360	300	300
Electric efficiency	[%]	23	-	-	-	-
Investment costs	[M€]	141,6	141,6	9,54	39,6	48,31
Lifetime extension	[M€]	-	-	-	-	-
Fixed O%M	[M€/year]	5,604	5,604	0,0289	0,12	0,12
Variable O%M	$[€/MW_{th}]$	7,389	5,545	1,8	1,8	1,8
Minimal operation	[hours]	4	4	4	4	4
Allowed to store	[Y/N]	Yes	Yes	Yes	Yes	Yes
Partial Production	[Y/N]	Yes	Yes	Yes	Yes	Yes

Table A.8: Overview of the parameters applied in the diversified energy system scenario planning in Esbjerg

Scenario E1/E2/E3/E4/E5	[Unit]	Geothermal	Industrial Waste Heat 30 $°C$	Industrial Waste Heat 40 $°C$	Electric Boiler	Gas CHP	Gas CHP Bypass
Size	$[MW_{input}]$	100,2	2	2,26	30	4	4
Thermal efficiency	[%]	100	400	450	99	0,48	0,75
Electric efficiency	[%]	-	-	-	-	0,42	-
Investment costs	[M€]	187,875	5,288	6,727	2,1	5,2	5,2
Lifetime extension	[M€]	-	-	-	-	-	-
Fixed O%M	[M€/year]	3,757	0,01602	0,02038	0,0315	0,1172	0,1172
Variable O%M	$[€/MW_{th}]$	0	1,8	1,8	0,5	10,48	5,87
Minimal operation	[hours]	24	4	4	0	0	0
Allowed to store	[Y/N]	Yes	Yes	Yes	No	Yes	No
Partial Production	[Y/N]	Yes	Yes	Yes	Yes	Yes	Yes

Table A.9: Overview of the parameters applied in the diversified energy system scenario planning in Esbjerg

Scenario E1	[Unit]	Wood Chip Boiler
Size	$[MW_{input}]$	280
Thermal efficiency	[%]	114,9
Investment costs	[M€]	221,2
Lifetime extension	[M€]	-
Fixed O%M	[M€/year]	10,375
Variable O%M	$[€/MW_{th}]$	2,26
Minimal operation	[hours]	4
Allowed to store	[Y/N]	Yes
Partial Production	[Y/N]	Yes

Table A.10: Overview of the wood chip boiler that is added to the energy system parameters mentioned in Table A.8 and Table A.9

Scenario E2/E3/E4/E5	[Unit]	Wood Pellet CHP	Wood Pellet CHP Bypass
Size	$[MW_{input}]$	280	280
Thermal efficiency	[%]	64	95
Electric efficiency	[%]	33	-
Investment costs	[M€]	210	210
Lifetime extension	[M€]	-	-
Fixed O%M	[M€/year]	5,852	5,852
Variable O%M	$[€/MW_{th}]$	0,798	0,536
Minimal operation	[hours]	4	4
Allowed to store	[Y/N]	Yes	No
Partial Production	[Y/N]	Yes	Yes

Table A.11: Overview of wood pellet CHP unit that is added to the energy system parameters mentioned in Table A.8 and Table A.9

In addition to the diversified energy system in Groningen there are investment costs for the 160.000 m^3 pit storage of 5,6 M€ and O&M costs of 40.360 €. The investment costs for the district heating grid are said to 509.337.928 € with 5,093 M€ O&M costs.