A Study on the Business Economic Feasibility of a Cross-Sector District Heating System with a Behind-the-Meter Approach in Mørkøv


Figure 0.1: Front picture [1]

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Title: A Study on the Business Economic Feasibility of a Cross-Sector District Heating System with a Behind-the-Meter Approach in Mørkøv

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Writers confirm, that no plagiarism has occurred during the writing of this report.

Abstract

The objective of this study is to examine how it can become business economical feasible for Mørkøv district heating and Holbæk municipality to achieve local and national goals by integrating a cross-sector energy system with a behind-the-meter approach in 2030. To guide the choices of research for the analysis, the framework for a feasibility study has been applied to evaluated the economic business results of established cross-sector energy systems. To establish the energy system, Scenario Theory has been applied as the overall approach in understanding for future studies. The scenarios established and the specific actions of the smart energy systems performed in the simulation are inspired by the concept of smart energy systems.

Data were collected following the mathematical modeling method that applied the data spreadsheet software Excel as a tool to perform the simulated scenarios and to produce the required output.

The results reported here confirm that it is possible Mørkøv district heating to achieve the national and local goals of Holbæk municipality by integrating the cross-sector approach and producing heat through an electric-fueled district heating system. This is certain after the establishment of the second scenario that delivered a competitive business scenario for the current energy system for Mørkøv district heating.

Preface

This project was carried out by Simon W. Sølyst as a master thesis project on the master program Sustainable Energy Planning & Management at Aalborg University. The research of this study is related to the transition from fossil fuels to renewable energy by applying cross-sector integration as an appropriate tool for that transition.

The author thanks the great supervision from Iva Ridjan Skov on the project and Jesper Graa Andreasen from NIRAS for providing data and contributing with relevant discussion on the project.

Reading guide

This report is divided into chapters, subsections, and sub-sections. All parts are numbered chronologically to get an overview of how the sections are connected, as seen in the table of contents.

The table and figures are numbered first as the chapter in which they appear and second as it numerically orders appears in the chapter.

The reference structure applied in this report is numbered by the Vancouver standard and can be seen at the end of the report under 'References'.

The appendix of this report can be seen last in the report, also numbered.

Nomenclature

Abbreviation

CO_2	Carbon dioxide
CHP	Combined heat & power production
DSO	Distribution System Operator
GW	Gigawatt
LCOE	Levelised Cost of Energy
MW	Megawatt
MWh	Megawatt hour
NIMBY	Not in my backyard
NPV	Net Present Value
O&M	Operation and maintenance
PV	Photo-voltaics
TSO	Transmission System Operator
TWh	Terawatt hour

Contents

1 Problem analysis

1.1 International and national climate goals

In 2015, the first legally binding global climate change agreement was adopted. An agreement that is better known as the Paris Agreement. The main goal of the Paris agreements is to avoid dangerous climate change by limiting the increase in global warming to 1.5 ° C [2].

To achieve the goals of the legally binding Paris Agreement, the EU has set out several energy packages. Recently, the European Green Deal has become the most ambitious package. From the European Green Deal, some specific goals have been written into the European Climate Law. These specific goals require Europe's economy and society to reduce net greenhouse gas emissions by at least 55% in 2030 compared to 1990 levels, and to become climate neutral in 2050 [3].

Since the Paris Agreement is legally binding, the goals must become law on a national level and the Danish parliament agreed on an even more ambitious climate law in 2019. A climate law that established the target goals of reducing greenhouse gas emissions by 70% in 2030 and achieving climate neutrality in 2050 [4].

1.2 Greenhouse gas emissions in Denmark

In 1990, Denmark emitted in total 83.0 million tons of greenhouse gases, excluding CO_2 from biomass and international transport. This number has minimally decreased and in 2019 Denmark emitted 82.9 million tons of greenhouse gases in total, excluding CO_2 from biomass and international transport [5]. That is, a reduction of 0.12% from 1990 to 2019, which means that Denmark still needs to reduce 58.8 million tons of green house gases to achieve Denmark's own climate goal of a reduction of about 70% in 2030. To locate where carbon reduction can be achieved, it is relevant to get an overview of the carbon emitting industry, which can be seen in Figure 1.1

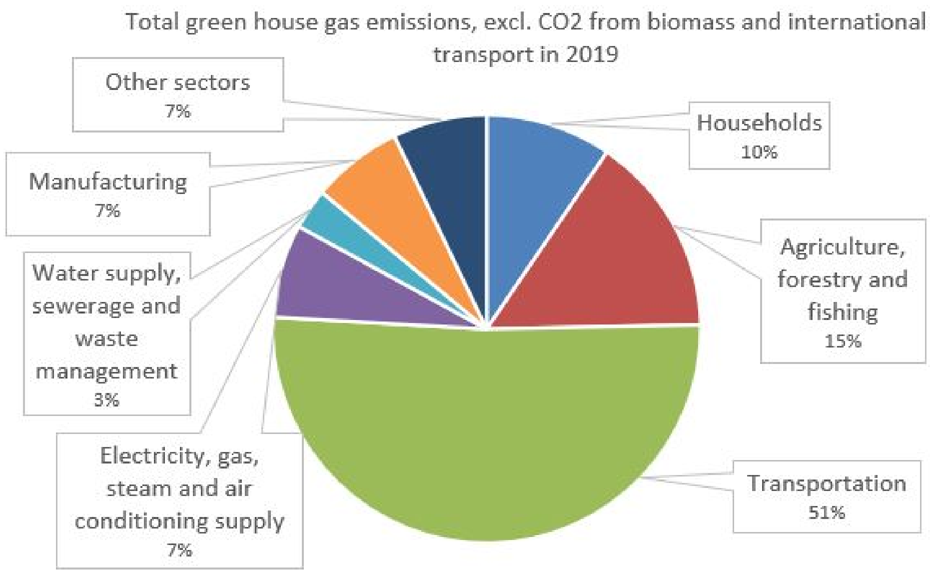

Figure 1.1: Pie-chart over total green house gas emissions, excl. CO_2 from biomass and international transport in 2019 [5].

Figure 1.1 shows the six main sectors with the highest percentage of greenhouse gas emissions in 2019 and their exact percentage of CO_2 pollution. In addition, 'Other sectors' is shown, which includes fourteen other smaller sectors. Figure 1.1 shows that the sector with the highest emission is 'Transportation' and the fourth highest emitter of green house gases is 'Electricity, gas, steam, and air conditioning supply' with a total of 5,9 million tons of CO_2 in 2019. 5.9 million tons of CO_2 contribute to 7% of total CO_2 emissions, which also appears to be a relevant carbon emitting sector to achieve the climate goals. 'Electricity, gas, steam, and air conditioning supply' is divided into three parts which can be seen in table 1.1

Table 1.1: Table of carbon emissions of Danish 'electric, gas, steam, and air conditioning supply' in 2019 [5].

Parts of energy supply	**Million tons CO_2**	**% of energy supply**
Production and distribution of electricity	4.84	83%
Steam and hot water supply	0.68	12%
Manufacture and distribution of gas	0.33	6%

In Table 1.1 it is clear that some of the fuels applied in the production of electricity and district heating are fossil fuels. Section 1.3 will look at the fuels applied in district heating plants and in electricity production to obtain an overview of the fuels that should be displaced from both a carbon neutral point of view and a security of supply point of view.

1.3 Historical development and current electricity and district heating sectors

From a historical point of view, two main issues for the Danish energy sector have been the security of supply and the transition from fossil fuels to renewable energy, both of which will be elaborated on in this section.

1.3.1 Fuels applied in the danish electricity and district heating production

Since 1994, the different fuels applied to the production of electricity and district heating have changed a lot. The most significant changes have been the transition from fossil fuels to transition fuels and then to renewable fuels [6]. Figure 1.2 shows the historical development of the three most dominant fuels used for the production of district heating and electricity in Denmark.

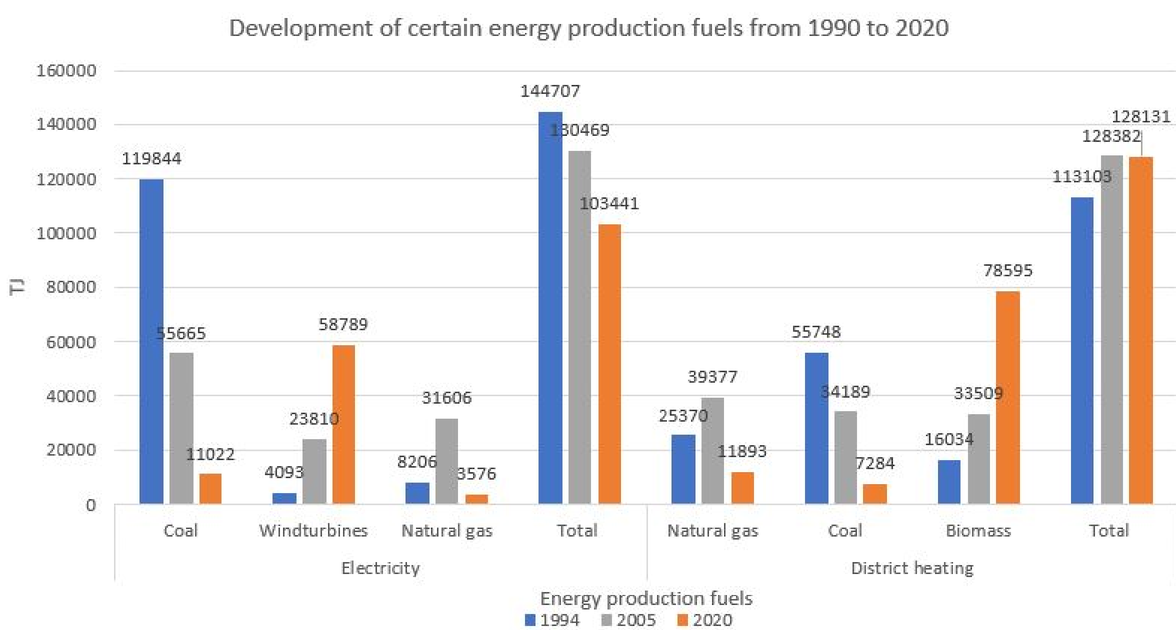

Figure 1.2: Development of certain energy production fuels [6].

Figure 1.2 shows that coal was the fuel most widely applied in 1994, but has changed now and carbon neutral fuels are being applied, such as wind energy and biomass. This shows that development has been good for renewable energy sources, but there is still some development to be done.

1.3.2 Self-sufficiency in the Danish energy sector

Since Denmark began to have a major consumption of energy, it has never been self-sufficient in all fuels applied. Denmark has been dependent on supply from other countries and has always had an import of energy. In 1972, Denmark was in the first energy crisis due to the lack of imported oil; then Denmark imported coal, as seen in Figure 1.2, and today Denmark is in a problematic situation due to its dependence on Russian natural gas. 50 years after the first energy crisis, the Danish energy system has not made the transition and has not become independent and self-sufficient, although there is technology to become self-sufficient [7]. To protect the future energy system from unexpected events and become reliable, the national grid must be independent of the national energy source and avoid import of the energy source. Figure 1.3 shows that the Danish energy sector has moved in the opposite direction.

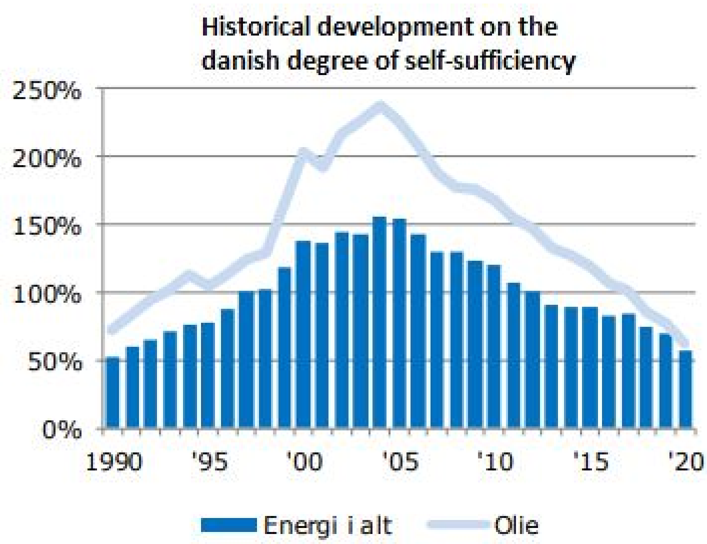

Figure 1.3: Historical development of Danish degree of self-sufficiency

Figure 1.3 shows that the Danish energy sector was at the highest level of self-sufficiency in 2004 with 155% and since then has decreased to 57% in 2020. The change in the degree of self-sufficiency is mainly due to oil, which is shown in Figure 1.3, but other fuels, such as natural gas and biomass for district heating, can have an impact on the degree of self-sufficiency. In relation to district heating production, systems still depend on the import of biomass. In 2016, 43% of Denmark's biomass was imported as a share of solid biomass consumption from primary baltic countries, which is problematic for national energy security, as most of it is not produced at the national level [8]. To become self-sufficient in energy resources, an obvious solution could be increasing the production of wind energy.

1.4 The development of wind energy in Denmark

In 2020, wind energy produced 83,845 TJ and is by far the renewable energy source that produces the most energy in Denmark [6]. Wind turbines are the most developed renewable technology with the best environmental conditions in Denmark, which is the reason for the huge capacity. The expansion and accumulated capacities can be seen in Figure 1.4

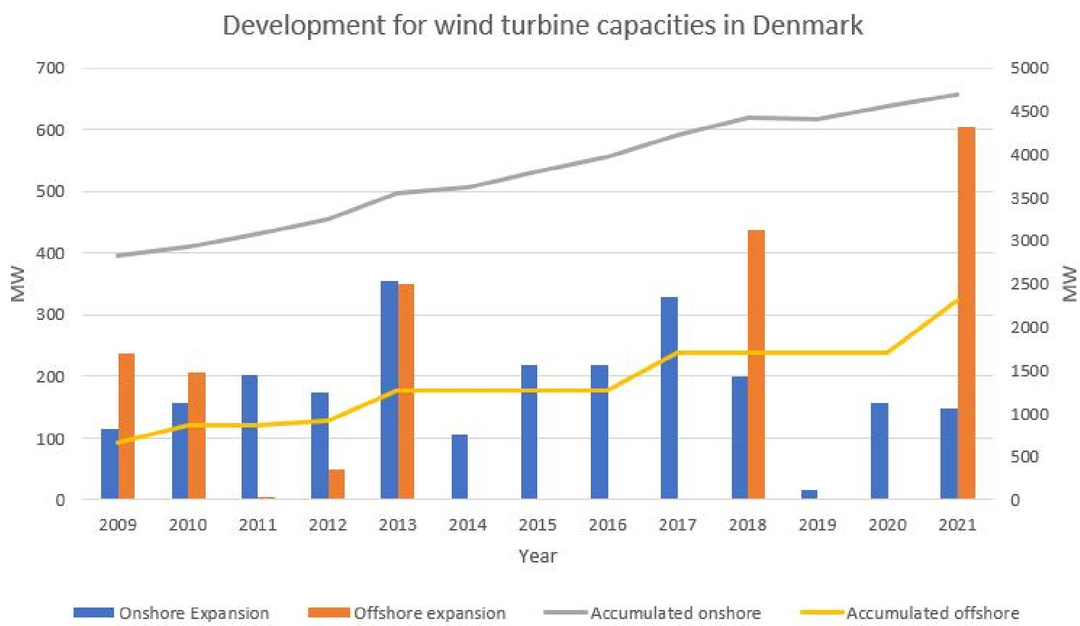

Figure 1.4: Yearly development for wind turbines capacities in Denmark [9].

Figure 1.4 shows that the accumulated wind energy for the onshore and offshore wind has increased, but with different expansion patterns. The average expansion of onshore wind turbines has since 2009 been 185 MW per year, which means that 2019, 2020, and 2021 have all been below average. A development that does not please Søren Klinge, who is the electricity market manager in the wind industry's organization, Wind Denmark. He comments on the development: *Our message has in many contexts been that it is necessary to expand with something in the direction of 700 MW onshore wind turbine equivalents each year until 2030 in order to achieve the goals that have been set up in climate policy* [10]. A clear statement by Søren Klinge that the current expansion of onshore wind energy is not even close to the capacities that are needed to achieve the national climate goals of Section 1.1.

1.5 Barriers for the onshore wind turbine expansion

Onshore wind turbines are one of the cheapest sources of electricity production, but paradoxically, the development of onshore wind turbines does not agree with the projected future demand for electricity [10]. There are many barriers to missing out on wind turbine expansion. Barriers that Frede Hvelplund et al. have highlighted in [11]. One of the barriers mentioned by Hvelplund et al. is an economic barrier connected to the merit order effect, which conflicts with the fact that the onshore wind turbine is the cheapest electricity source.

1.5.1 Economic barriers for wind turbine expansion

As mentioned in Section 1.5 one of the barriers to the expansion of onshore wind turbines is the economic barrier related to the merit order effect that forces lower electricity prices. The specific problem is as follows. If the price of electricity is too low, future investors cannot sell wind electricity at a sufficient price and, therefore, the business case is bad investing in wind turbines [12].

Wind turbine income depends on the LCOE and the electricity price, and the electricity price and the LCOE for wind turbines depend on each other. Therefore, it is difficult to calculate a specific LCOE for wind turbines. The LCOE depends on the variation in electricity prices and geographical conditions. If the price pr. MWh electricity is lower than the LCOE, wind turbines will earn less than the wind turbine produces electricity for, which will make the business case for wind turbines bad. In Europe, the LCOE for onshore wind turbines ranges from 50 to 65 €/MWh [13] and in Figure 1.5 the number of hours with electricity prices below 50 €/MWh and 65 €/MWh in DK2 can be seen.

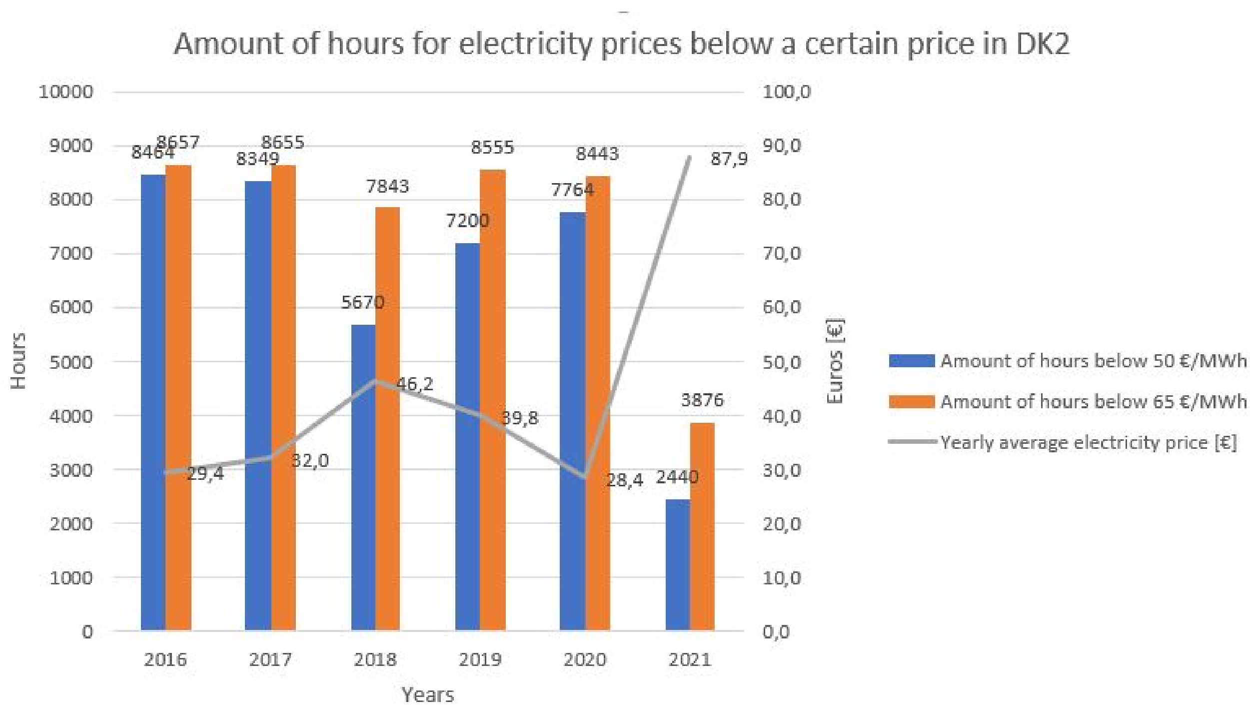

Figure 1.5: Amount of hours for electricity prices below a certain price in DK2 [14]

Figure 1.5 shows how many hours a year an onshore wind turbine will not make a profit from selling electricity on the DK2 grid. The blue and orange pillars show the number of hours for an onshore wind turbine with a high or low LCOE. 2021 is not considered a representative year due to the increase in natural gas prices, bad weather conditions for renewable energy sources, increased carbon taxes and an economy that restarts after the corona pandemic [15]. On figure 1.5 the average electricity price is shown for different years. The average electricity price is not representative for 2021, but for all previous years, the average is below the range for the LCOE of the wind turbine.

The low price of electricity is bad for the economic situation of wind turbines. However, the lower price of electricity is forced by renewable energy sources and the merit-order effect. The reason the merit order effect is bad for the wind turbines is because when wind turbines bid at the elspot marked, they offer electricity to 0 €/MWh. They bid 0 €/MWh because it is better for the wind turbine to sell and be a part of the market rather than being excluded and therefore not be able to sell their electricity. When there is a high percentage of renewable energy sources in the grid, the electricity price will therefore be low [11].

1.6 Attractiveness to make cross-sector integration

An appropriate solution to the economic barriers mentioned in 1.5.1 could be cross-sector integration. A solution to the missing incentives for wind turbines, on which Hvelplund et al. agree by coming to this statement: *Cross-sector integration with increasing electricity demands in heating and transportation sectors may increase electricity prices* [11].

Cross-sector integration is about establishing cooperation between different energy sectors and creating a synergy effect. For district heating system, cross-sector integration is to electrify the heat production, which could be cooperation with a wind turbine and a heat pump. By combining these two units, heat pumps do not necessarily buy electricity if the heat demand is high and the electricity price is high, or the wind turbine is not running. This is because the hot water storage is hopefully filled while the wind turbine is running or the electricity price is low. Hvelplund et al. also agree that this district heating combination is the solution to lower electricity prices with the following statement: *The decrease in wind power prices at the spot market will continue and within less than 10 years. The first step of this future infrastructure is to use wind power in district heating systems in combination with heat pumps and hot water heat storage to support flexible demand* [11].

An advantage of cross-sector integration, especially when an electricity producing unit is directly combined with an electricity consuming unit, is the possibility of not paying tariffs to the TSO and the state. In technical terms, this is called Behind-the-meter integration. The difference between a traditional system and a behind-the-meter system can be seen in Figure 1.6

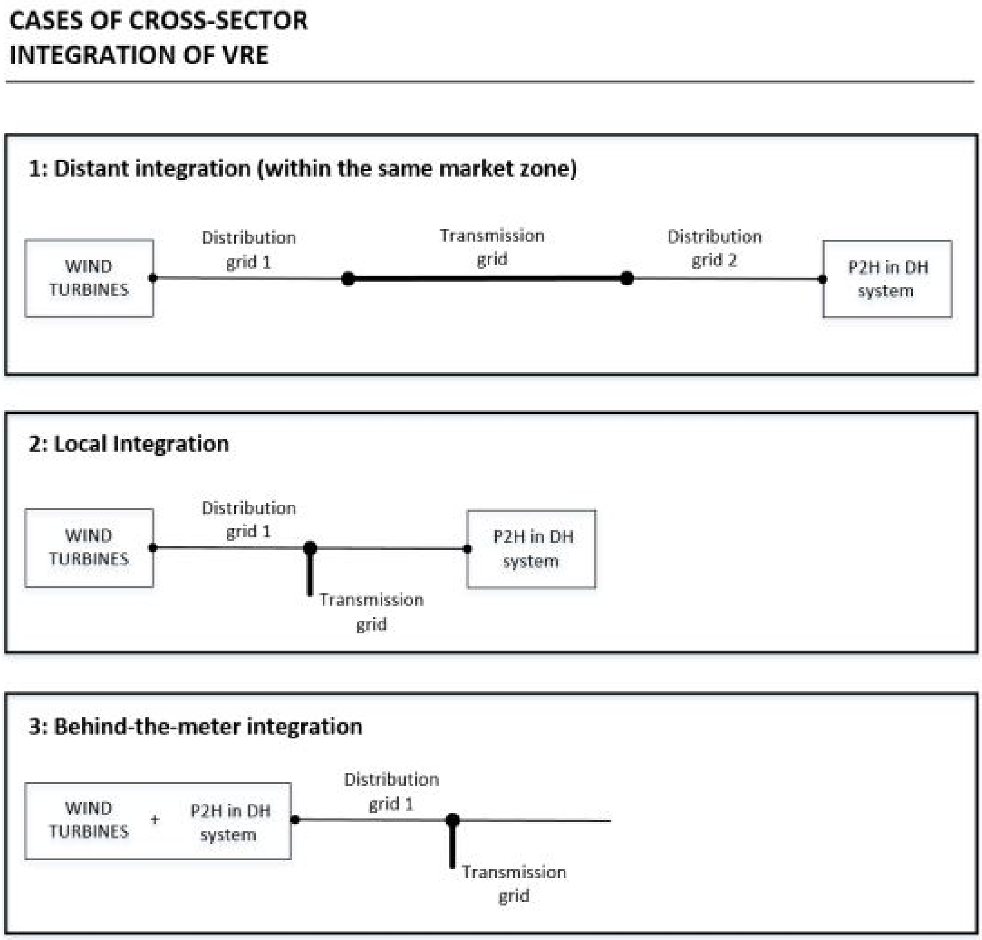

Figure 1.6: Illustration of how to integrate a wind turbine in district heating production [12]

Figure 1.6 shows the three possible solutions for cross-sector integration with electricity flow through both the TSO and DSO, only the DSO and no flow through the DSO and TSO. For a behind-the-meter solution, it means that the electricity flow will not run through the DSO or TSO electricity grid before reaching each other, but will run directly from one unit to the other in a self-owned cable [12]. By avoiding tariffs, the LCOE for wind turbines will also drop, making a better business case for wind turbines.

In Denmark, cross-sector integration is not widespread. Most district heating in Denmark is produced from biomass or natural gas, and the heating produced from electricity is not significant yet [16]. The only case where heating produced from electricity and cross-sector integration have been achieved is in Hvide Sande district heating. Hvide Sande District Heating has an energy system with a heat pump and an electric boiler that operates on some local wind turbines they have bought, which means that they operate a behind-the-meter integration of a wind turbine [12]. Hvide sande has now shown a possible solution for future renewable production of district heating that should be possible to follow from other district heating companies.

1.7 Mørkøv district heating as case

In Holbæk municipality the district heating system of Mørkøv is located. Before picking Mørkøv as an appropriate case for this project, there are some specific requirements for the district heating system that would fit into the work of cross-sector integration and the green transition, the requirements were:

- The district heating system applies natural gas or natural gas and biomass.
- Open for the application of heat pumps and cross-sector integration.

Based on these requirements, Mørkøv district heating is applied as a case. Mørkøv district heating, located in Holbæk municipality, produces 11.940 MW-heat every year for district heating consumers. Mørkøv district heating company operates a heat pump, a biomass boiler, a gas boiler, and a gas engine. Therefore, Mørkøv district heating is ideal for the requirements.

Since Mørkøv is part of Holbæk municipality, the direction and goals for future energy planning are located in Holbæk's strategic energy plan. In this plan, different themes are presented for each of the different energy consuming and producing sectors. These goals will be elaborated in Section 8.1.

2 Research question

Section 1 determined the overall national and international climate goals. To achieve the national climate goal, Section 1 has highlighted some of the difficulties and problems in the current district heating system and barriers to the expansion of wind energy as the main resource to solve problems related to district heating systems. Section 1 also determined that a suitable approach to solving the problems of district heating systems and wind turbines could be cross-sector integration. Based on the previous points, the following research question has been formed.

- **How can a local energy system based on behind-the-meter cross-sector integration make it possible for Mørkøv district heating to achieve the national and Holbæk municipality's climate goal with an economically feasible approach in 2030?**

The research question, which is the general question to answer, is determined to be answered by a feasibility study. A feasibility study is performed containing three different analyses, WWW-analysis, Diamond-E analysis and calculation, each of these analyses has a sub-question related, which is seen below.

- What should be studied, for whom, and why should the feasibility study be performed?
- What is the current technical and institutional situation for the cross-sector integration related to Mørkøv district heating?
- How can a model simulation, based on cross-sector integration, become a business economical feasible alternative for Mørkøv district heating, to achieve Mørkøv's Climate goals for 2030

3 Research design

This section presents the research design for this project. The research design aims to illustrate the overall structure of the report to visualize how the different sections of the report support each other and connect with each other. The research design is shown below.

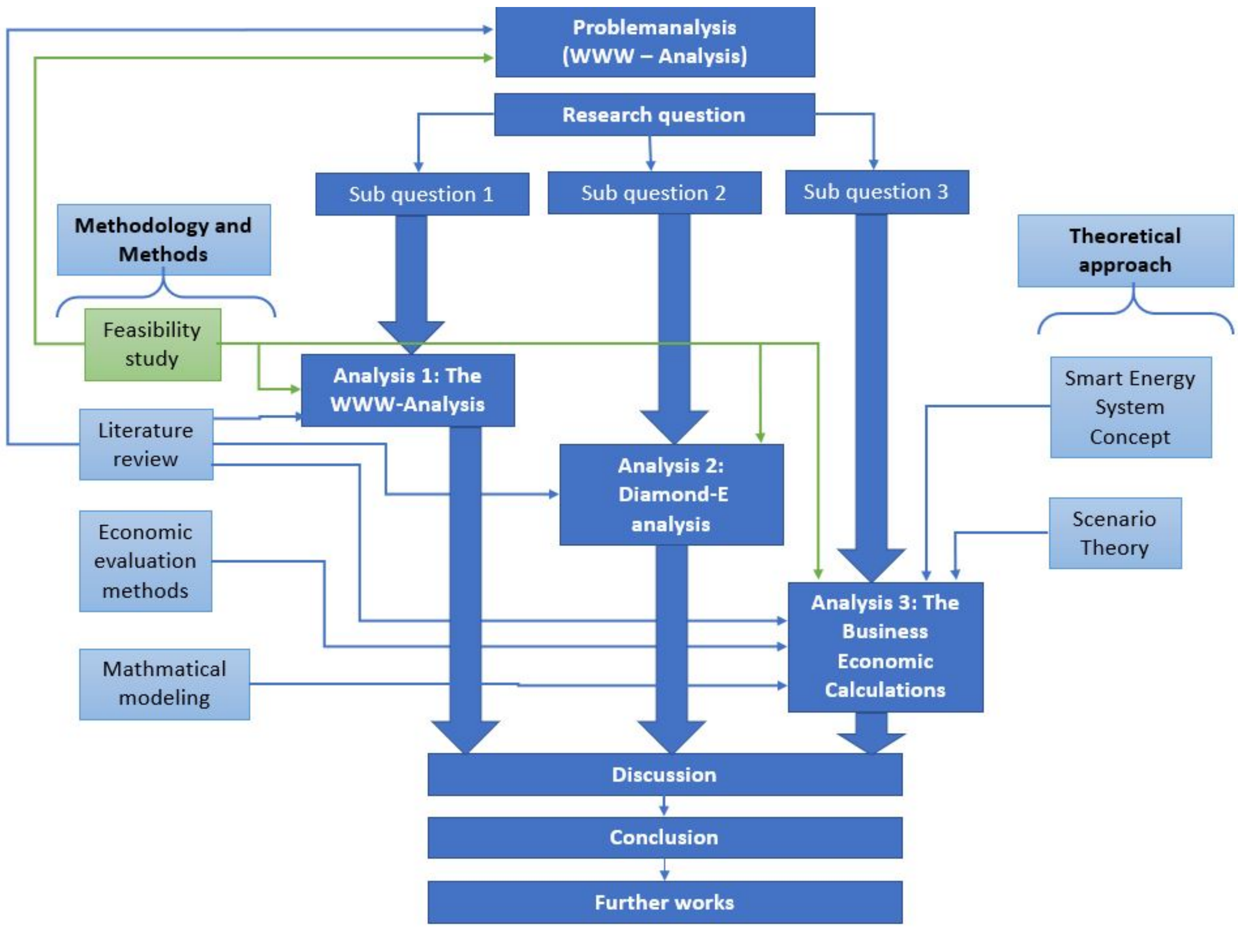

Figure 3.1: Research design

Figure 3 clearly shows how the different parts are connected to each other. The overall flow and empirical analysis are shown as the dark blue stream of boxes in the middle. It is notable how it illustrates that the research question stands as a concentrated part that spreads out in three subquestion, and then the analysis narrows again in the conclusion to be answered. The general methodology for the report is the feasibility study, which is illustrated as a green box. Illustrated as the light blue boxes in Figure 3 methods and the theoretical approach, the arrows show in which specific parts the methods are applied.

4 Theoretical approach

In this report Scenario theory and The Smart Energy System Concept have been applied as theoretical approaches for the third step of the feasibility study regarding the calculation in Section 9. Scenario theory has been applied as a theory to support the overall approach to go from a starting point to an ending point that achieves certain goals. The smart energy concept has been applied to determine the more specific technical steps to achieve sustainability.

4.1 Scenario theory

Predicting what will happen in the future is a difficult exercise. Several factors have an impact on future development that can significantly change the situation [17]. Recently, events such as the corona pandemic and the war in Ukraine have had a great impact on future predictions. To study the future and predict how different events can have an impact on the future, scenario theory can be applied. This section aims to discuss scenario theory and how it has been applied in Section 9.

There are several different approaches to analyzing what will happen in the future. One of the approaches is backcasting, which is applied in this report. Backcasting has been applied because it is required that the scenario achieves the national goals in Section 1 and Section 7. To understand the argument for producing backcasting scenarios, it is essential to understand how backcasting and forecasting depend on each other. At the beginning of backcasting studies, there is a vision of a future for one or more reliable forecasts. These forecasts are compared with the desired vision and if the vision is not achieved, a backcasting scenario is generated [17]. This is illustrated in Figure 4.1.

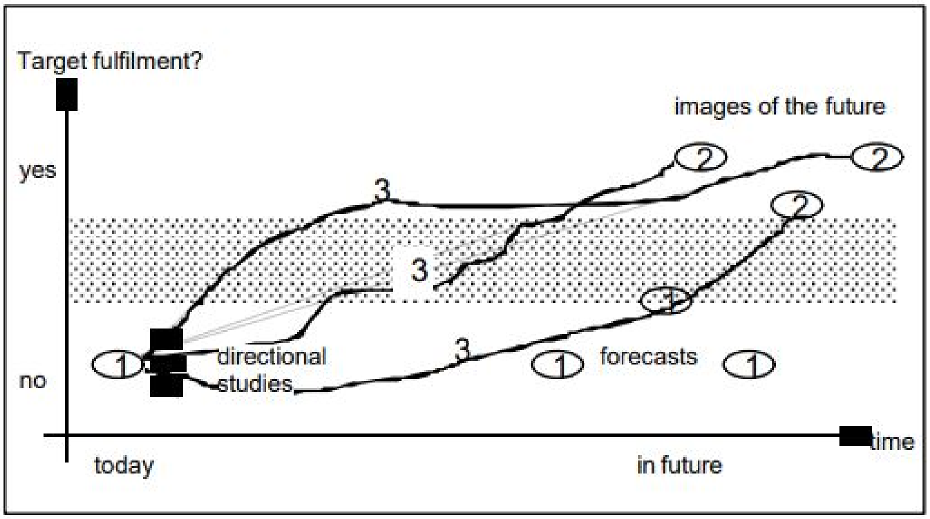

Figure 4.1: Backcasting framework [17]

On figure 4.1 point 1 indicates that the different forecasts do not meet the targets, which indicates that there is a need for a backcasting scenario. Point 2 is the specific target that specifies the different solutions to fulfill the targets, and finally point 3 shows the different approaches on how to fulfill the targets and achieve the goals.

The steps in Figure 4.1 can all be related to this report. The forecasts, at point 1, can be found in Section 1 that determines that problematic situations will appear if no changes are made. The objectives of the report, at point 2, are presented in Section 1 as national climate goals and in Section 7 as specific goals for Mørkøv district heating. The different direction, point 3, will be generated in section 9 to avoid the undesired forecast, at point 1, and achieve the targets at point 2.

In Section 9 not all the scenarios fulfill the point 2 goals. The development of the scenarios will be a flow of improvements until the targets at point 2 are fulfilled. This is done instead of creating fixed scenarios from the beginning that meet the targets. The argumentation for this scenario development approach is to apply experience from the scenario development process in future scenarios and not make the scenarios fixed from the start.

4.2 The Smart Energy System Concept

Before modeling and construction of an energy system starts, it can be necessary to find a clear direction and approach for the energy system. There are many directions and approaches in the modeling and construction of energy systems and it is essential to determine. One of the approaches can be The Smart Energy System concept. The definition of The Smart

Energy System concept is: *"an approach in which smart Electricity, Thermal and Gas Grids are combined with storage technologies and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system"* [18]. The Smart Energy System concept and definition of The Smart Energy System are visualized in Figure 4.2

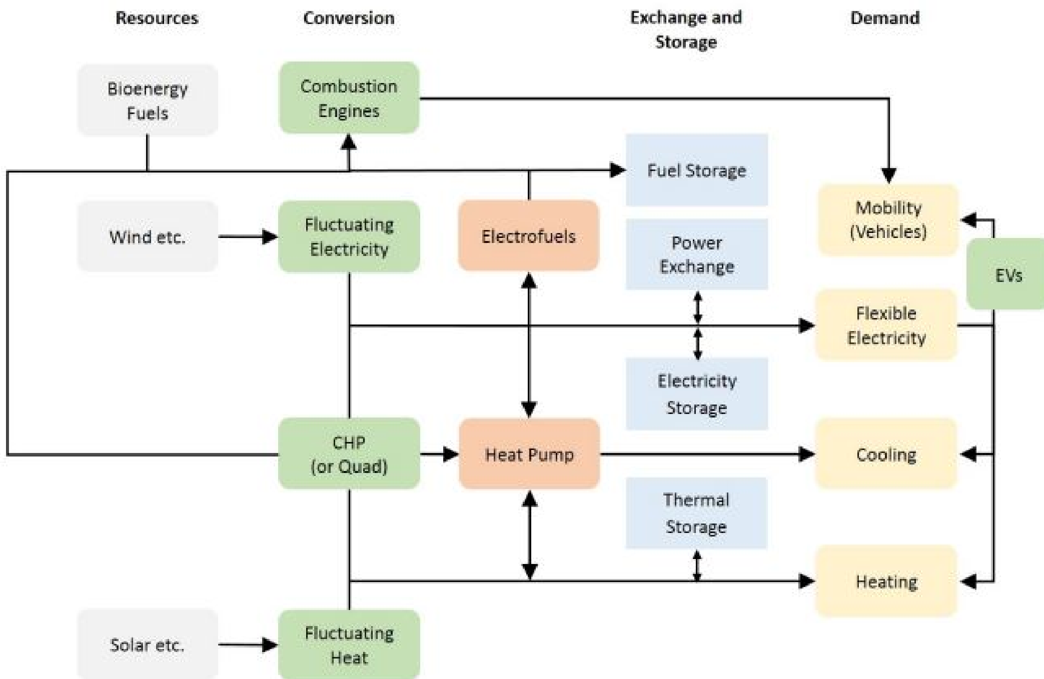

Figure 4.2: Illustration of *The Smart Energy System* concept [18].

One of the key forms of energy production in The Smart Energy System concept is fluctuating energy, which can be seen in figure 4.2 supported by wind energy. Fluctuating energy is a difficult production form to manage and is highly prioritized in The Smart Energy System concept. The common feature of all grids in the The Smart Energy System concept is to connect to each other. This connection will enable better utilization of storage in different grids and greater flexibility. This flexibility will establish a better starting point for the utilization of fluctuating energy and for The Smart Thermal Grid it is especially the heat storage that will create additional flexibility. By following this approach in the modeling and construction of energy systems, fluctuating energy can become much more integrated in future energy systems and displace fossil fuels [18].

In the further calculation in Section 9 will The Smart Energy System concept be applied. Argumentation for applying The Smart Energy System concept is due to the motivation in the transition from the present energy system to a 100 pct. renewable energy system. The two main points that will define the direction and approach in Section 9 are the following:

- Wind turbine and heat pump must complement each other as much as possible, with the purpose of creating synenergy between them.
- Storage must be an essential factor to make it possible for the heat pump and the wind turbine to complement each other.

5 Methodology

In this report, feasibility studies have been applied as a methodology and as a contextual framework that guides the choices of research for the analysis. This section will describe the purpose and content of feasibility studies and how feasibility studies are applied as the overall structure of the analysis.

5.1 Feasibility Study

A feasibility study can be created in many different ways. The structured methodical framework for this feasibility study will be used in an approach by Hvelplund et al. [19]. This approach focuses on how to conduct solutions depending on concerns for the specific case areas requirements, and not only economic concerns.

The general purpose of a feasibility study and the main question to be answered is *Which alternative is the most feasible for solving a given problem?* If this question is seen isolated, it is a pretty simple question which can be answered by some calculations. However, before establishing the calculation to answer the question, it is necessary to define and specify the question. This approach is what makes a feasibility study different from a purely cost-effectiveness or cost-benefit analysis. The question can be defined and specified by answering the following questions:

- Most feasible compared to which alternatives?
- Most feasible to whom?
- Most feasible to meet which objectives?
- Most feasible within what time horizon?
- Most feasible including which consequences?

In feasibility studies, the conclusion can be very sensitive to such issues as mentioned above. Consequently, a feasibility study on the same energy planning project or investment could lead to different conclusions if such issues are not defined in the same way. For example, if a feasibility study is conducted for the same project with two different objectives, which could be economic or environmental issues, the conclusion of the feasibility study could be different due to the objectives [19].

Feasibility studies can be performed to support decision making in public and private institutions. Therefore, it is important to distinguish between socioeconomic and business economic feasibility studies. In socioeconomic feasibility studies, the calculations are based on externalities that have an impact on society as a whole, and for business economic feasibility studies, the calculations are considered feasible from a narrow business perspective [19]. Although it is possible to establish a feasibility study, either as a business economic feasibility study or a socioeconomic feasibility study, Hvelplund et al. recommend that both studies be conducted to evaluate the possible corresponding business or socioeconomic feasibility study [20]. This report exercises only a business economic feasibility study, but is still classified as a feasibility study.

The structure of a feasibility study consisting of three steps is divided into three analyses. The analysis consists of The WWW-analysis, The Diamond-E analysis, and The Calculations.

5.1.1 The WWW-analysis

The first analysis for a feasibility study is the WWW-analysis, which consists of an identification of what should be studied, for whom, and why it should be studied. In particular, the analysis will answer the following.

- What should be studied?
- For whom should it be studied?
- Why are the feasibility study made?
- Which time horizon is used?

These questions are part of a systematically designed feasibility study and must be answered in a context in a time horizon, where the time horizon for the specific feasibility study is defined. [19]

What should be studied?

In relation to the question: What should be studied? It is necessary to distinguish between single project analysis and system analysis. The single project analysis is related to an analysis of a specific unit in a system, and system analyses is about analyzing a set of technologies that are included in the scenario. It is important to note that single project analyses may be outdated for the current feasibility studies conducted. This is argued because sustainability is often on the agenda in project development and sustainability cannot be achieved by optimizing one sector alone without considering the other sectors [19].

For Whom should it be studied?

Feasibility studies can be performed for many different interests. The interests could be national governments, municipalities, supply companies, industries, private companies, etc. As mentioned above, the feasibility study is performed for either a business or a socioeconomic evaluation. The determination of the economical evaluation of the given feasibility study is determined by who the recipient of the feasibility study is. For example, if a feasibility study is conducted for the government, it is likely to be conducted for some socioeconomic results, and for smaller companies, such as supply plants, it is often conducted for economic business evaluations [19].

Why are feasibility study made?

As mentioned, feasibility studies are performed as business or socioeconomic feasibility studies with two different approaches for specific calculations. The reason why business or socioeconomic feasibility studies are made is due to their relevance in democratic processes and future decision-making. Calculations based on business economic purposes can be applied by governments that have the power to change public regulation and regulate the market economy. Figure 5.1 shows the connection between the business economy, socio economy, and public regulation in the present and the future.

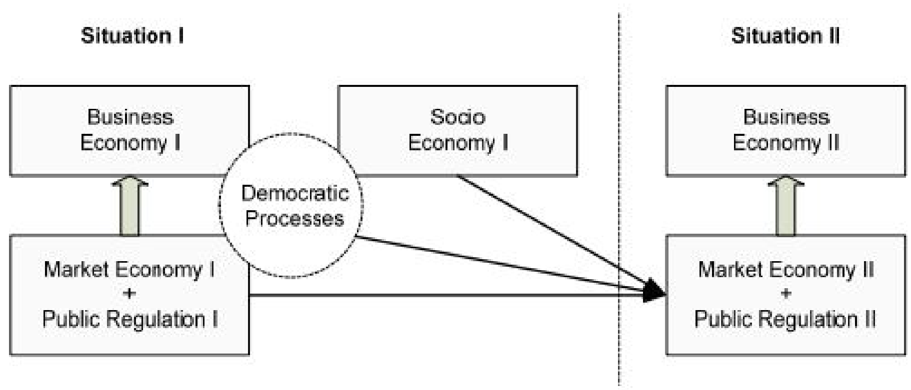

Figure 5.1: The relationship between business economy, socio economy and public regulation [19]

In situation I in figure 5.1 it can be seen which calculations, regulations, and processes can have an impact on regulation and economics in situation II, which is the future. From figure 5.1 it is relevant to note that the business economic calculation may have an impact on the democratic process when there is a change in public regulation. In general, both business and socioeconomic feasibility studies have a great impact on future decisions and should be elaborated in democratic processes. [19]

Which time horizon should be used

The time horizon must be related to the calculation in a feasibility study. To determine the specific time horizon, it is relevant to take into account the kind of project studied. If the study relates to a single project investment, the time horizon should be related to the expected lifespan of the investment, but if we are dealing with the system infrastructure and the development of scenarios, the time horizon of a project should be determined by the specific purpose of the study [19].

5.1.2 The Diamond-E Analysis

The second step of a feasibility study is the Diamond-E analysis. Diamond-E analysis is a detailed design of the content of the feasibility study that may then be passed through an examination of each of these areas, shown in Figure 5.2, in order to understand the current technical and institutional situation. In this analysis, the consequences of a project must be identified, and the feasibility study must analyze how these consequences can be carried out. The framework for the Diamond-E analysis is systemised in Figure 5.2

Figure 5.2: The diamond-E framework [19]

Organisational goals (Box 1)

The organizational goals must relate to the goals for whom the feasibility study is conducted, as done in the WWW-analysis. The goals must be explicit, and an overview must be easy to obtain. For governments, organizational goals could be related to social equality, national climate goals, economic growth, etc., if the organization is smaller, the goals could relate to the goals related specific to the municipality.

Organisational resources (Box2)

In a feasibility study, organizational resources must be located. Organizational resources are linked to key characteristics that connect to the specific implementations of a project. For example, if there is available labor to manufacture a plant or available resources, such as biomass, to supply the new energy producing unit, this must be highlighted.

Financial resources (Box3)

The financial resources related to the key financial characteristics related to the implementation of the given project. This is both about the financial possibilities that investors have in realizing the project and also about a risk assessment of the project based on the economical factors. For example, if consumers have a low ability to pay bills or the cost of energy resources is unstable, the feasibility study must highlight this. This risk assessment will also be an argument to establish a sensitivity analysis of these parameters in the calculations.

Natural and socioeconomic environment (box5)

The last part of the Diamond-E analysis is the Natural and socioeconomic and environmental impacts. This part is an assessment of the current national and international agenda, and the project has to be in context with these political agendas. This could be about legislation on air pollution, etc.

5.1.3 Calculations

The third analysis of a feasibility study is the calculation of solving the previously expanded concrete problem, which requires the major part of the feasibility study work. For the calculations, it is important to provide an explicit overview of the data and information applied. This will make the whole analysis more reliable when all the right and necessary data are shown. The calculations can be conducted in many different ways, and what is most common for energy system analysis is mathematical modeling software. The software applied and the arguments for this report will be elaborated in Section 6.2.1

5.1.4 Business economic evaluation method

To evaluate and measure business economic results, different evaluation methods can be applied. A common evaluation method for investments in energy projects, energy systems, and energy technologies is NPV or LCOE. NPV and LCOE are fundamentally similar to each other; both include investment, cash flows, and the discount rate, but LCOE also applies the amount of energy produced by the energy system [21]. In this project, only NPV has been applied, which will be argued in the following paragraph.

Net present Value

NPV is applied to value an investment with all future cash flows in the period of the investment lifetime discounted to the present. NPV is an ideal business economic evaluation method to help determine the value of an investment or project to compare other possible projects [22]. To calculate the NPV, this project applied the NPV function in excel.

Both NPV and LCOE have been considered applicable as the business economic evaluation method in this project. However, NPV has been chosen as the only method to evaluate the results of Section 9. The reason why LCOE will not be applied is due to the different amount of energy units produced in the different scenarios, while the total heat demand remains the same. This is because in some of the scenarios, the storage is larger, which means that the heat loss is also greater. This demands a higher heat production, and hence a distortion in the comparison of the results, which NPV manage better by not determining the cost of each energy unit.

6 Methods

This section has on purpose of elaborate how the basics of each method are applied and in addition discuss the experience and thoughts that have appeared during the working process.

6.1 Literature Review

In any form of research, the literature review plays an important role as a foundation for research. The literature review has also been a main method applied for this report, this section will elaborate on how the scientific literature review is performed and how it is done in the analysis included in this report. Considerations when using the prior literature are essential to increase the validity of a scientific report and should be related to the approach to the search for literature and the quality of the literature found [23].

In this report, channels and databases such as ScienceDirect, Scopus, and Aalborg University Library have been applied as literature sources. The articles, books, etc. from these databases have all undergone peer review, which means that scientific, academic, or professional work has been evaluated by others working in the same field and gives validity and quality to the sources applied. To find relevant sources in these databases, keywords such as *cross-sector integration, smart energy system, district heating, and renewable energy system* have been applied. For the analysis, the necessary data and literature could not be obtained from scientific databases. Therefore, some knowledge is found on the official websites of the relevant authorities. This is found on websites such as Holbæk municipality, The Danish Energy Agency, and Nordpool, which all seem to have reliable and accurate data.

6.2 Mathematical Modeling

This section aims to describe the methodical background for mathematical modeling and also to describe how it is applied in Section 9. Mathematical modeling is a method that is applied to describe a real-world problem in mathematical terms. Mathematical modeling is applied to understand the real world by allowing engineers to design technology for the future in mathematical terms, which is usually done by a flow of equations dependent on each other. In other, more specific terms, the mathematical model is: *a representation in mathematical terms of the behavior of real devices and objects* [24]. To describe and understand mathematical modeling as a scientific method, figure 6.1 will be applied.

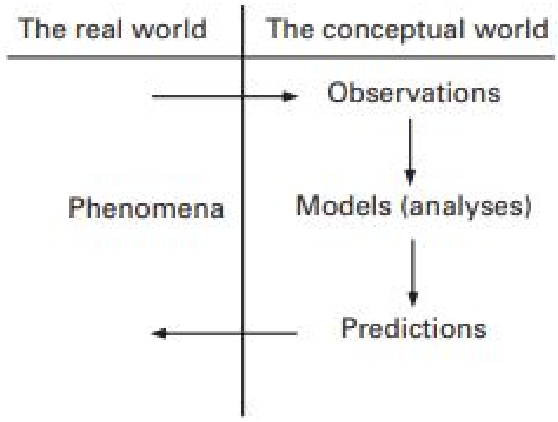

Figure 6.1: An elementary depiction of the scientific method of mathematic modelling [24]
.

Figure 6.1 shows two different worlds, the real world and the conceptual world. The real world is where observations of various phenomena and behaviors are made. The conceptual world is the world of mind, where mathematical modeling examines the real world and attempts to understand it. In mathematical modeling, the conceptual world consists of three stages: Observations, Models and Prediction. The first stage of the scientific method is observation. In observation, the real world is measured and empirical evidence is gathered. In energy planning terms, this stage could be about gathering energy demand, geografical conditions, economic parameters, etc. The second stage is about the actual modeling and this part will examine and analyze the previous observations. The rational emergence in this part is about: *models that allow us to predict future behaviors*. In the prediction part, the model is exercised to get a prediction on how the model will work on events in the real work. These predictions should then be followed up by observations that either validate the model or tell if the model is insufficient. After the prediction stage, the iterative process starts and the phenomena triggered by the models are investigated and observed in the real world [24].

6.2.1 Excel tool for mathematic modeling

The tool applied for the calculations in Section 9 is excel. Excel is a tool that uses spreadsheets to organize numbers and data with formulas and functions, and is not considered a typical tool for energy system analyses [25]. In a typical energy system tool, the system is already established, and units, capacities, and other parameters of the system only need some values, and as soon as the values are given, the units operate together in the system. A typical software for energy system analysis could be energyPRO or energyPLAN. Excel is more difficult to apply for energy system analysis because the cooperation and dependence on the units must be determined by manual made functions and formulas.

6.2.2 Model building

This section aims to explain and elaborate how the Excel model has been built to get some valid results. The model is mainly built up in two sections, the technical and the economical, where the model begins in the technical part and then ends up with economical results. The Excel models can be found in the Appendix 13.7.

- The purpose of the technical part is to make the model work and to make the technical input and output accurate. The model started by setting up the uncontrollable conditions like hourly- elspot price, temperature, and heat demand; the further work has been to model the energy units applied to meet the heat demands and the electricity demands. To make the energy system model work in Excel, the results of different cells must depend on the results of other cells. This cannot be done with a simple mathematical equation but is only possible with the IF function. The IF function allows one to make a logical test of an equation that picks two different values depending on whether a statement is true or false. An example of an IF statement in the model could be as follows. *If there is a heat demand and there is no heat in the storage, then run the heat pump; if not, do not run the heat pump.* To explain and validate how the model is built, the operation graphs for Scenario 2, from hour 400 to 500, in Figure 6.2 are applied.

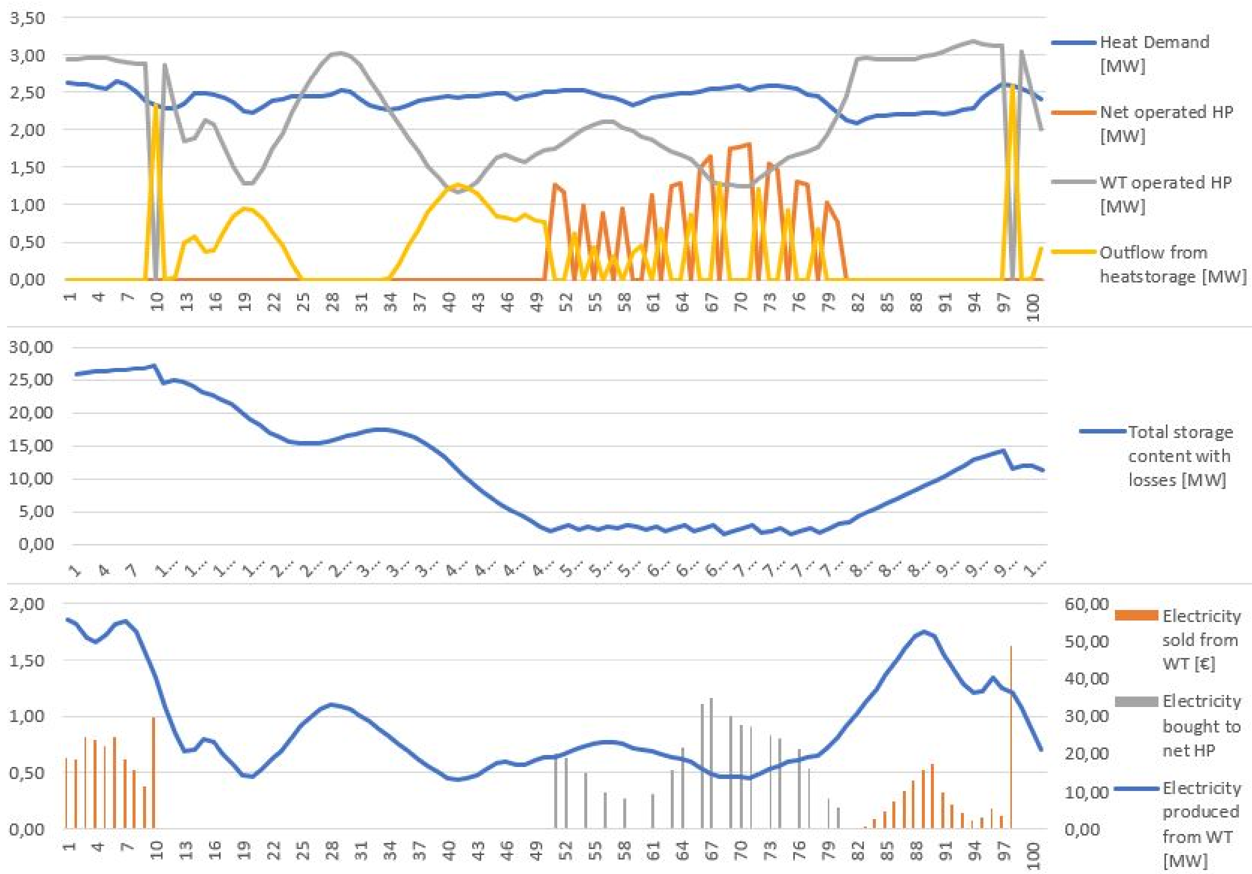

Figure 6.2: Operation of Scenario 2 from hour 400 to 500

- The top graph of Figure 6.2 shows the different units that produce heat according to the heat demand. This shows that the wind turbine-operated heat pump operates whenever it is possible except when the storage is full, the outflow from storage is applied when the wind turbine operated heat pump cannot meet the demand by itself, and the network operated heat pump is operating when the heat storage is close to being emptied.
- The middle graph of Figure 6.2 shows the storage content. The storage content depends on the outflow from the storage and the wind turbine-operated heat pump, which is the only unit to produce excess heat. In the middle graph, it is clearly shown how the total content is determined by the gray and yellow lines in the top graph.
- The bottom graph of Figure 6.2 is a combined graph that shows the electricity sold and bought and the electricity produced by the wind turbine. For this graph, it is notable that excess electricity from the wind turbine is sold when the wind turbine

operated heat pump cannot consume all the electricity and that there is bought electricity from the network when the network-operated heat pump is operated.

The operation of the graphs in Figure 6.2 would not have been possible if the IF function was not available in Excel.

- The economic part is simpler compared to the technical part; this part is basically the technical data multiplied with some economical data obtained from a different source that gives the economic results. This could, for example, be the capacity of the heat pump multiplied by the investment cost or the bought electricity multiplied by the tariffs on the bought electricity. This is also the part where the NPV is calculated with the NPV function in Excel.

6.2.3 Model of compression air-source heat pump

To model the heat pump, it is mainly the variation of the COP value that is necessary to model because the COP value determines the output of heat related to the input of electricity. The COP value for the heat pump is modeled using the calculation method presented by the Danish Energy Agency in the Technology Catalog for the production of district electricity and heating [26].

$$T_{\text{lm,sink}} = \frac{T_{\text{out}} - T_{\text{in}}}{\ln\left(\frac{T_{\text{out}}}{T_{\text{in}}}\right)}$$

$$T_{\text{lm,source}} = \frac{T_{\text{in}} - T_{out}}{\ln\left(\frac{T_{\text{in}}}{T_{\text{out}}}\right)}$$

$$\text{COP}_{\text{Lorenz}} = \frac{T_{\text{lm,sink}}}{T_{\text{lm,sink}} - T_{\text{lm,source}}}$$

$$\text{COP}_{\text{real}} = \text{COP}_{\text{Lorenz}} \cdot \eta_{\text{Lorenz}}$$

Figure 6.3: Equation to calculate the COP value

To calculate the COP value the necessary data are the ambient temperature, the forward and return temperature for the district heating pipes, the temperature difference for the source and the efficiency Lorenz. All applied data can be found in the Appendix 13.7.

6.2.4 Model of wind turbine

To model the wind turbine, the Renewables.ninja website has been applied. Renewables.ninja is an easy applicable website to simulate the hourly wind production depending on different heights, models, capacities and location of the wind turbine. When the parameters are determined, the hourly wind production data are easy to import as an Excel file and apply as electricity for the heat pump and the grid. Wind production is calculated by converting wind speed in a Virtual Wind Farm model [27].

7 The WWW-Analysis

The first part of the business economic feasibility study is to conduct the WWW-analysis. The purpose of the WWW-analysis is to create the foundation of doing a feasibility study to highlight what the purpose of doing the feasibility study is. This WWW-analysis aims to answer the following sub-question.

- *What should be studied, for whom, and why, should the feasibility study be performed?*

Some of the questions answered in this analysis, as part of the feasibility study, are also answered in Section 1, which could be perceived as repetition. This repetition is considered, but it is assumed that it is necessary to make the structure of the feasibility study clear and straightforward.

7.1 What should be studied?

What will be studied in this business economic feasibility study is how cross-sector integration can solve the problems, argued in Section 1, related to Mørkøv district heating system. Specifically, this report will study how to displace natural gas by a system in combination of a heat pump and a wind turbine, and also how it can become attractive to establish wind turbines for a district heating company. This synergy in the energy system seems appropriate to solve different environmental and economic problems, which is argued in Section 1.

This project is classified as a system analysis, because the calculation in Section 9 is performed as an energy system analysis. In the energy system, units from both the heating sector and the electricity sector are in operation, categorizing the system as a cross-sector system. The calculation is based on the analysis of all units in the systems and not a single one. Therefore, this project is not classified as a single project analysis but rather as a system analysis.

7.2 For whom is this feasibility study made?

This feasibility study is conducted as an alternative solution for the district heating system in Mørkøv. Since Mørkøv district heating is located in Holbæk municipality, both of these actors could be interested in this business economic feasibility study.

7.3 Why is this feasibility study made?

Why this feasibility is performed is mainly argued in Section 1. The three main points for why this feasibility study is carried out are mentioned below.

- The district heating system should strive to phase out natural gas due to carbon pollution, but also to become independent of foreign energy resources.
- Biomass should be phased out due to the high amount of imported energy with the same argument as in order to avoid unexpected economic and supply problems in the energy sector.
- The low expansion of onshore wind turbines is due to the lack of economic incentives to invest in wind turbines, which is assumed that cross-sector integration can solve.

7.4 Which time horizon and time priority should be used?

The time horizon is determined whenever it is a socio- or business-economic feasibility study. For this report the focus of this is on the business economics and therefore the time horizon will be based on the lifespan of the technologies applied in the calculations. In the district heating and electricity production technology catalog [26] the lifespan of a heat pump is 25 years, for an onshore wind turbine 27 years and for hot water storage 40 years.

Taking all this into account, the time horizon for this feasibility study will be based on the lifespan for technology with the shortest lifespan, which is the heat pump's 25 years lifespan.

8 The Diamond-E Analysis

The purpose of this analysis is to answer the following sub-question:

- *What is the current technical and institutional situation for the cross-sector integration related to Mørkøv district heating?*

This sub-question will be answered by performing a Diamond-E analysis. The Diamond-E analysis will go in depth with the institutional framework established for Mørkøv district heating by Holbæk municipality, the technical criteria for the establishment of cross-sector integration, the risk assessment of the financial resources applied and, finally, understand the socioeconomic environment related to cross-sector integration.

8.1 Organizational goals

Mørkøv district heating is located in Holbæk municipality and therefore the organizational goals for Mørkøv will be related to the goals in Holbæk's strategic energyplan [28]. The goal of Holbæk municipality is the same as the national goal of 70 pct. reduction in greenhouse gas emissions for the whole municipality in 2030. To achieve this goal, Holbæk municipality has created action plans for six sectors. The action plans for district heating and electricity are called *Theme 1: Green heat* and *Theme 2: Green electricity* [28].

For heating and electricity production, the goal is not to reduce greenhouse emissions by 70 pct. but is even more ambitious, and in 2030 the reduction in greenhouse emissions must be 100% in the electricity and heating production sector [29]. The specific action related to cross-sector integration for Mørkøv district heating can be seen in 8.1.1 and 8.1.2.

8.1.1 Theme 1: Green Heat

The action plan *Theme 1: Green Heat*, includes the action for heating in Holbæk municipality. In the plan, there are measures related to individual heating, centralized and decentralized district heating, and since Mørkøv district heating is classified as decentral, the measures for decentralized are relevant. The action plan specifications for decentralized district heating are: "Decentralized district heating solutions based on air heat pumps", which makes cross-sector integration ideal for Mørkøv district heating [29].

8.1.2 Theme 2: Green Electricity

In *Theme 2: Green Electricity* the action plan relates to a geographical plan for renewable energy plants. The action point here is to map the different possibilities to build renewable plants. The maps for wind turbines and solar panels can be seen in [28].

8.2 Organizational resources

In this feasibility study, it is investigated how Mørkøv district heating can establish an energy system based on a heat pump, wind turbine, and storage. Therefore, this section will assess the key characteristics of the specific implementation related to these three units.

- In the Danish context, wind turbines are one of the best developed energy producing units. The concern about the immature level of readiness or the lack of labor to establish wind turbines appears non-existent [26]. In relation to wind turbines as a resource, the main concern relates to whether there are existing wind turbines or if there are any possibilities to establish any wind turbines close to Mørkøv's district heating grid. Holbæk municipality has already done an analysis of possible areas, which is shown in figure 8.1

Figure 8.1: Overview of existing wind turbine and possible areas for new ones close to Mørkøv [28].

Figure 8.1 shows that east of Mørkøv there are three existing wind turbines, marked with red crosses, and there is an orange area next to it, which is marked as a possible area for new wind turbines with a height of 130 meter. The area east of Mørkøv seems to be the most appropriate for obtaining wind energy for the heat pump located in the middle of Mørkøv.

- Heat pumps do not have the same problem of space requirement as wind turbines, because heat pumps require a relatively small amount of space. According to [26] compression heat pumps, ambient air is a "commercial technology with moderate deployment so far and significant development potential" that is assumed to be a mature technology.

- Heat storage does not require a lot of space and the Danish Energy Agency categorizes large-scale hot water tanks as mature and proven commercial technologies [30].

8.3 Financial resources

The operational and economic complexity is huge for heat pumps and wind turbines. This is because heat pumps and wind turbines are so sensitive and depend on the weather conditions and the elspot price. The price of electricity is one of the most unstable prices of any goods and can change significantly over short periods of time. Also, for wind turbines, the economic situation is very difficult to predict because of changed weather conditions that decide the amount of electricity produced. This can be seen in figure 8.2

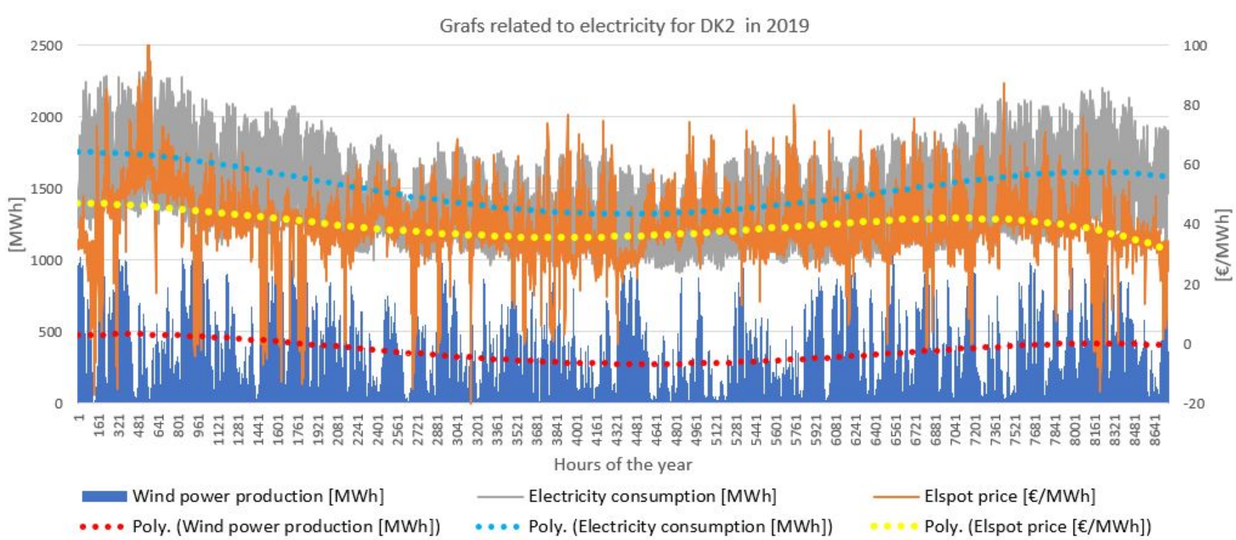

Figure 8.2: Grafs related to windpower production, electricity consumption and elspot price for DK2 in 2019. Data obtained from [14]

Figure 8.2 shows the yearly distribution for wind power production, electricity consumption and elspot price for DK2 in 2019. In figure 8.2 it is clear how unstable and fluctuating these three elements are and how quickly they can change. The polynomial regression lines in figure 8.2 show how the elspot price depends on wind power production and electricity consumption by having an almost similar curve related to each other. In some hours it is clear that when the wind power production increases, the elspot price decreases. But at certain hours the elspot price does not seem to be completely dependent on wind power production, the reason could be the impact of interconnectors, CHPs, PV panels, etc.

Due to this unstable economic and operational situation for the two main units of the energy system, a sensitivity analysis will be performed in Section 9.5 for both the wind power production and the elspot price.

8.4 Natural and socioeconomic environment

In relation to cross-sector integration, it has not been possible to find any specific regulation on that field. But for the units included in cross-sector integration, like heat pumps and wind turbines, different public regulations have had an impact on the development, which will be elaborated in this section.

8.4.1 The lowered electricity to heat tariff

In the past, one of the main barriers to the electrified district heating system has been the electricity-to-heat tariff. But since 2021 this tariff has been reduced from 20.8 €/MWh to 0.53 €/MWh . This tariff reduction has given heat pumps an economic advantage from a public and political side, and now the economic incentives for heat pumps in district heating system seem to make heat pumps competitive [31].

8.4.2 Subsidies for wind turbines

Since 1984, wind turbines have been offered economic support from the public, which is obviously the initiative of the greatest importance in the establishment of private wind turbines. Economic support changed later to the PSO-tariff, but in 2018 the PSO-tariff was phased out, and now wind turbines are not offered any subsidy schemes if the wind turbine is established after 2018 [32] [33].

9 The Business Economic Calculations

The calculations are the main part of a feasibility study and will be the part that solves the question related to a feasibility study. To answer the sub-question, the calculations will be performed by applying Excel as a tool. The Excel models performed can be found in the Appendix 13.7. The question answered by this analysis is sub-question 3, which is as follows.

- *How can a model simulation, based on cross-sector integration, become a business economical feasible alternative for Mørkøv district heating, to achieve Mørkøv's climate goals for 2030*

For the overall structure and the actions taken in the scenarios for this analysis, the following theories have been applied.

- Scenario theory is applied as an approach to develop the general structure of the calculations. Explained in Section 4.1.
- The concept of a Smart Energy System is applied as a guide for actions to improve the scenarios as the technical approach to the development of each individual scenario. Explained in Section 4.2.

9.1 Model assumptions and limitations

Since the model is predictions of the future and not part of the real world yet, some assumption is made that the model performs as realistically as possible. The assumption is as follows.

- If the wind turbine produces less than 25% heat pump capacity, the net-operated heat pump produces the rest of the 25%
- If the wind turbine produces less than 25% heat pump capacity and there is less than X% storage, then the net-operated heat pump will produce full load minus how much heat the wind turbine-operated heat pump produces.
- At the beginning of the year, the storage was half full no matter what capacity.
- The hourly storage losses will be 0.83% of the storage content [30].
- Discount rate on 4 % as recommended by [34]

In this project, different unknown parameters and uncertainties have limited the results, which have been part of the limitation of the model. The limitations are as follows.

- There is no planned or forced outage time for units.
- The data for the specific years are fixed, no projections related to wind production, elspot price, temperature change, etc. are applied.

9.2 Data applied

For this analysis, different economic, technical and natural data have been applied. All the specific data applied can be found in Appendix 13.3 and Appendix 13.7 and a list of the data that have been applied can be found below.

- Technology data catalog for electricity and DH from the Danish Energy Agency [26].
- Technology data catalog for storage from the Danish Energy Agency [30].
- Technology Data for energy transport from the Danish Energy Agency [35]
- Tariffs from TSO - Energinet.dk [36]
- Electricity to heat tariff - Dansk Energi[31]
- Elspot price 2020 from Nordpool [37]
- Wind and temperature data from renewables.ninja [38]
- Specific data from Mørkøv district heating from Jesper Graa Andreasen from Niras. Data can be seen in Appendix 13.1

9.2.1 Demand applied

The heat demand for the applied scenarios is 11,940 MWh, which are total heat demand data for 2021 [Appendix 13.1]. The hourly distribution of heat demand was not achievable, so the hourly distribution was made in EnergyPRO based on the total heat demand and temperature conditions for 2020. The hourly distribution can be seen in figure 9.1.

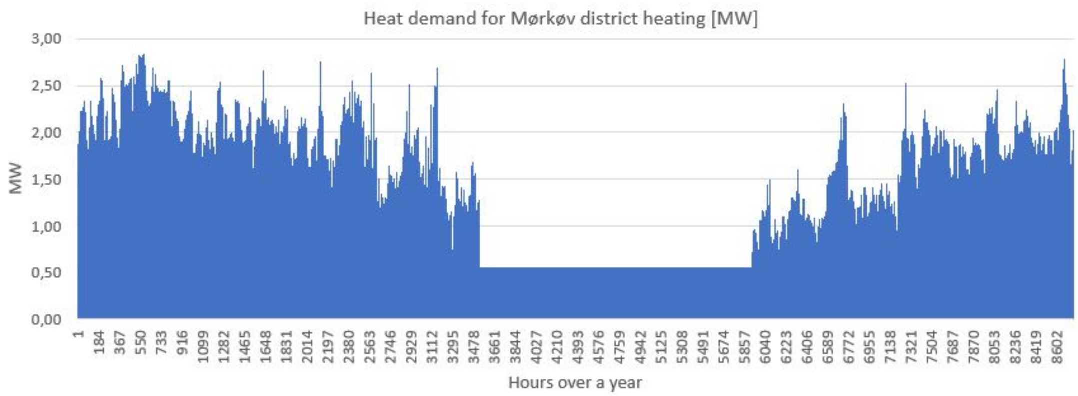

Figure 9.1: Heat demand for Mørkøv

In Holbæk municipality, the population is expected to grow by approximately 5% by 2030, but the benchmark is to keep total heat consumption calm [28]. Although Holbæk municipality expects the heat demand to be static, an unexpected increase could occur if more households are connected to the grid. Therefore, the heat demand will be part of the sensitivity analysis in Section 9.5.

9.3 Scenario description

This section aims to explain how the different scenarios are established and what underlies the decisions made in the construction of the scenarios. This section will only elaborate on the purpose of the different decisions made in the scenario and the results can be seen in Section 9.4. The different scenarios that will be analyzed and the specific actions for each scenario are listed below.

- **Reference scenario:** Current units in the district heating system, which are a heat pump, a biomass boiler, gas boiler, gas engine and a heat storage. The illustration of the reference scenario can be seen in Appendix 13.2

- **Scenario 1:** Investment in 0.76 MW-electricity of the heat pump capacity. Units are marked with a red and yellow frame in Figure 9.2

- **Scenario 2:** Investment in 0.76 MW-electricity of heat pump capacity + 2.5 MW wind turbine and a 1600 meter electric cable. Units are marked with a red, yellow, and blue frame in Figure 9.2

- **Scenario 3**: Investment in 1.26 MW-electricity heat pump capacity + 4 MW wind turbine and a 1600 meter electric cable + 75 MWh of heat storage. Units are marked with a blue and yellow frame in Figure 9.2

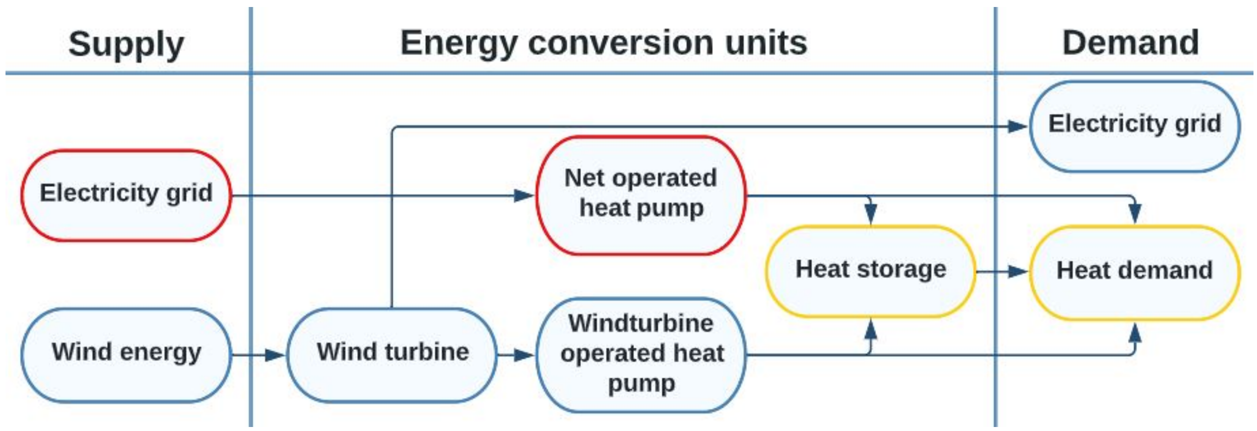

Figure 9.2: Flowchart of Scenario 1 to 3

9.3.1 Reference Scenario

The current energy system for Mørkøv district heating, also known as the reference scenario, is modeled in EnergyPRO. The reference scenario is applied as the baseline for the energy system to determine whether there are any advantages in the modeled scenarios. The specific and relevant numbers included in the reference scenario can be seen in Table 9.1.

Table 9.1: Table of Mørkøv district heating's key numbers for the reference scenario

Unit	**Capasity [MW-heat]**	**Efficiency [Pct.]**	**Heat production [MWh/year]**	**Heat production [Pct.]**	**Capasity [MWh-heat]**
Heat pump	1.1	3.2 - heat	7,240	60.63	-
Biomass boiler	0.95	0.92 - heat	3,703	31.01	-
Gas boiler	3.25	0.92 - heat	860	7.20	-
Gas engine	2.05	0.55 - heat 0.4 - electricity	136	1.13	-
Heat storage	-	0.95 - heat	-	-	35
Total	7,35	-	11,940	100	35

Table 9.1 shows that the heat pump is the most active unit in the system and that biomass and gas are less applied.

9.3.2 Scenario 1

The purpose of Scenario 1 and the first step in the development of the scenarios is to exclude biomass and gas, so that the system operates only on electricity. To meet the demand for heat, the necessary action has been as follows.

- Investment in 0.76 MW-electricity heat pump capacity.

To optimize the use of storage and to improve the NPV, two operation strategies have been tested.

- An operation strategy is to put a price limit on the electricity bought to operate the heat pump. The idea regarding the maximum limit for elspot price has been to avoid expensive electricity. To meet demand, the maximum limit has been set at 96 €/MWh.
- Another strategy of operation has been to reduce storage capacity. Since storage is almost full every hour and storage losses are calculated as percentages, storage losses might be smaller with less storage capacity.

The optimized Scenario 1 shows that a smaller storage has significant improvements in NPV compared to the limit on the electricity price, which can be seen in the Appendix 13.4 and will be included in Results 9.4. Therefore, both a limit on the price of electricity and storage losses will be considered in future scenario developments.

9.3.3 Scenario 2

Scenario 2 will implement the wind turbine to accommodate the behind-the-meter structure and to provide electricity to the heat pump or sell to the electricity marked. For Scenario 2, only the wind turbine capacity will be simulated and then determined on the highest NPV. The actions taken for Scenario 2 are the following:

- Investment in 0.76 MW-electricity heat pump
- Investment in a 2.5 MW wind turbine and a 1600 meter electric cable.

In Scenario 2, the storage is almost full for the entire year, which means that the net-operated heat pump is independent of the storage content. To make Scenario 2 more efficient and improve storage usage and the use of cheap fluctuating wind energy, storage should be filled with heat only when the wind turbine allows it. This will be done by making the net-operated heat pump dependent on the storage content and making it possible for only the wind turbine-operated heat pump to fill the storage. This strategy has improved the operation of storage, the use of fluctuating wind energy and the NPV of the energy system. The results and operation over a year for the independent and dependent can be seen in Appendix 13.5

9.3.4 Scenario 3

As argued in Section 1, the import of fuel constitutes a great risk in the variations in fuel prices, which have been clear by historical events and the current situation with the war in Ukraine. Therefore, Scenario 3 will achieve self-sufficientness and not even dependence on the electricity grid. To become self-sufficient, Scenario 3 will simulate different capacities for wind turbine, heat pump, and heat storage to find a balance between NPV and investment cost that applies electricity from wind turbines only. The reason why Scenario 3 will be evaluated in terms of both NPV and investment cost is that the greater the wind turbine capacity, the more NPV will improve, but the investment cost will increase. Therefore, the simulations of Scenario 3 will be balanced between NPV and investment cost, which can be seen in the Appendix 13.6

The actions made in Scenario 3 are the following:

- Invest in 1.26 MW-electricity heat pump capacity.
- Investment in 4 MW wind turbine and a 1600 meter electric cable.
- Invest in 75 MWh of heat storage.

To improve the operation of Scenario 3, the approach has been to find periods of the year in which the demand for heat, storage, and the wind turbine-operated heat pump are less dependent on each other. To do that, the hourly heat demand in Figure 9.1 and the storage content for Scenario 3 in Appendix 13.6 have been analyzed. The comparison of heat demand and storage content shows that in the summer period, when the heat demand is constant and stable, the use of all storage is less necessary. Therefore, the wind turbine-operated heat pump will produce heat at a heat content of 20% instead of 90%. in the period when the heat demand is low and stable. The operation of the improved scenario can be seen in Appendix 13.6. In some periods of unstable heat demand, the needed heat storage could be reduced, but since there is a great risk of empty storage in unstable periods, the lower storage content will not be tested.

9.4 Results

This section is intended to evaluate and compare the results from the scenarios. The results that will be evaluated are as follows:

- Net present value (NPV)
- Yearly income and expenses
- Investment cost
- Electricity flows

9.4.1 Net present value

The NPV results are applied to determine the cheapest business economic scenario.

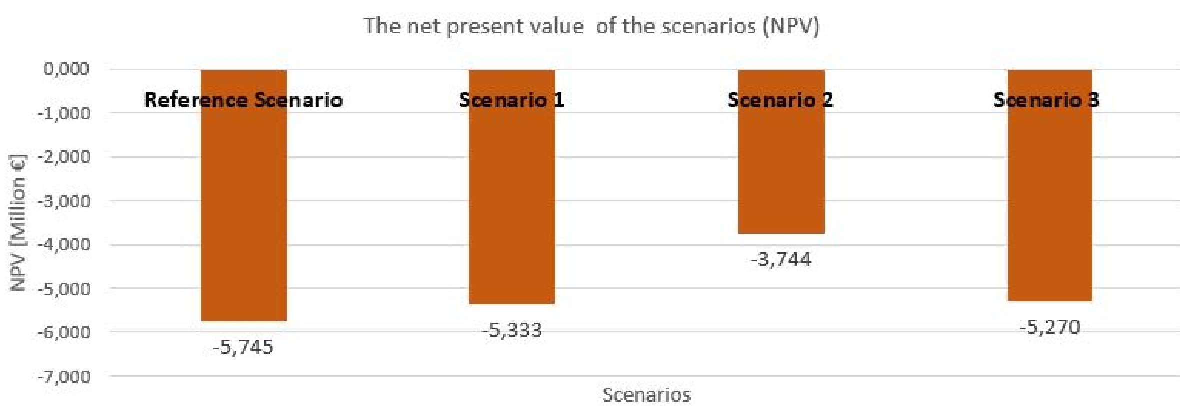

Figure 9.3: The net present value of the scenarios

Figure 9.3 shows that the reference scenario is the most expensive business economic scenario with a NPV of -5,745 mill. €. Scenario 1 and 3 are pretty even with approximately -5,3 mill € and the cheapest is Scenario 2 with a NPV on -3,744 mill €.

9.4.2 Yearly income and expenses

Figure 9.4 shows the specific yearly income and expenses for each scenario and the total cost when expenses and income are deducted.

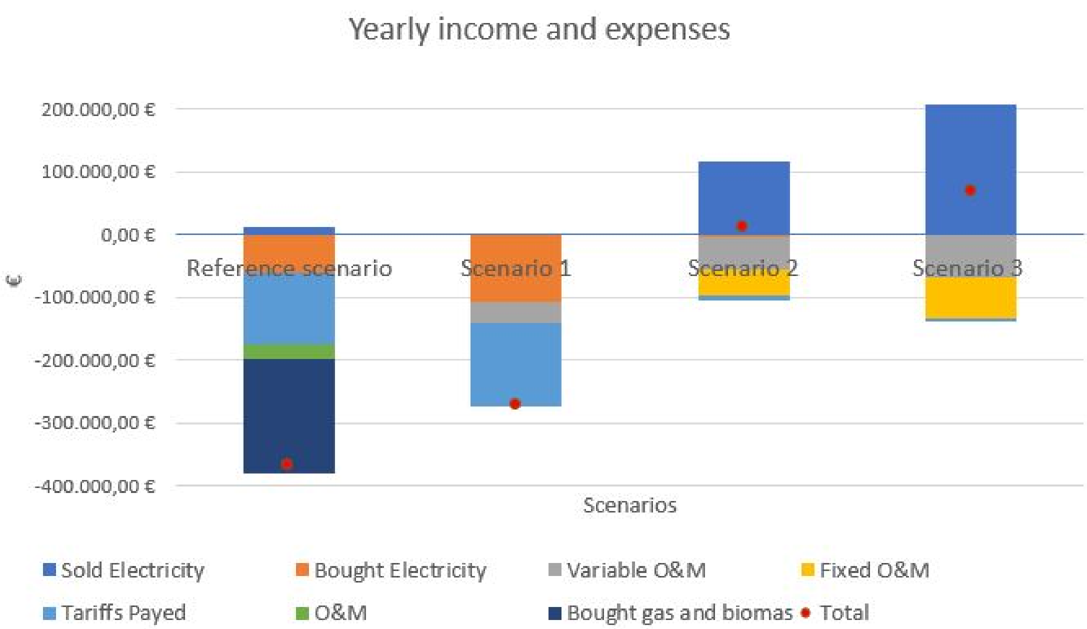

Figure 9.4: Yearly Income and expenses for the scenarios

Figure 9.4 gives a lot of data related to the scenario. What is notable is the impact of fuel consumption and electricity production on the total and also the part of the tariffs paid in the reference scenario and scenario 1 compared to Scenario 2 and 3.

9.4.3 Investment cost

Figure 9.5 shows the investment cost for each scenario.

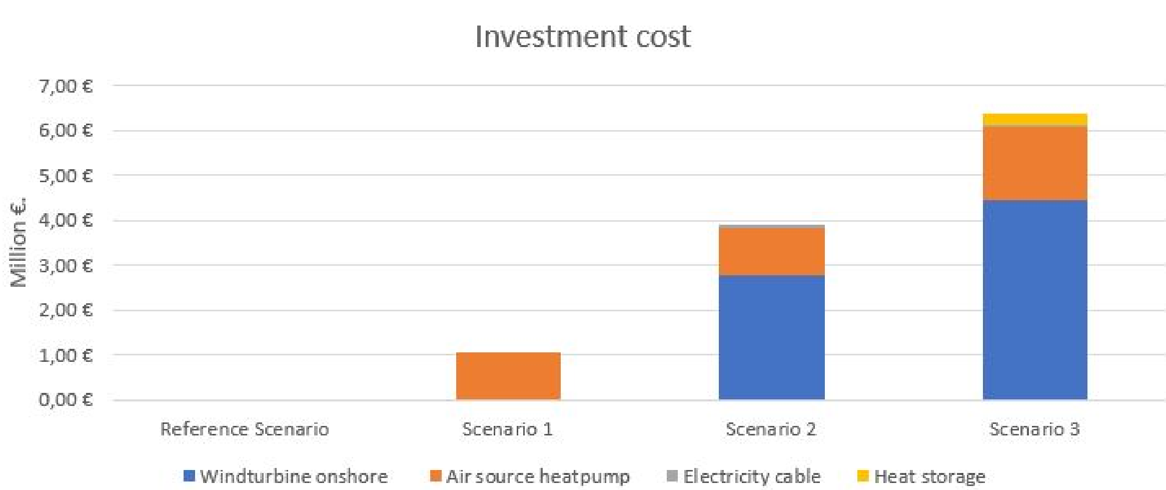

Figure 9.5: Investment cost for each scenario

Figure 9.5 shows that the development of each scenario gives an higher investment cost. Wind turbines especially contribute a huge part of the investment cost when implemented in Scenarios 2 and 3. Notable is that investment in 75 MWh heat storage has a minor impact on the total investment cost compared to the heat pump and wind turbine.

9.4.4 Electricity flows

Figure 9.6 shows the flows of electricity from the different scenarios, which is included is the electricity bought from the grid, sold to the grid, the electricity produced to the grid and the total consumed electricity from the wind turbine and the grid.

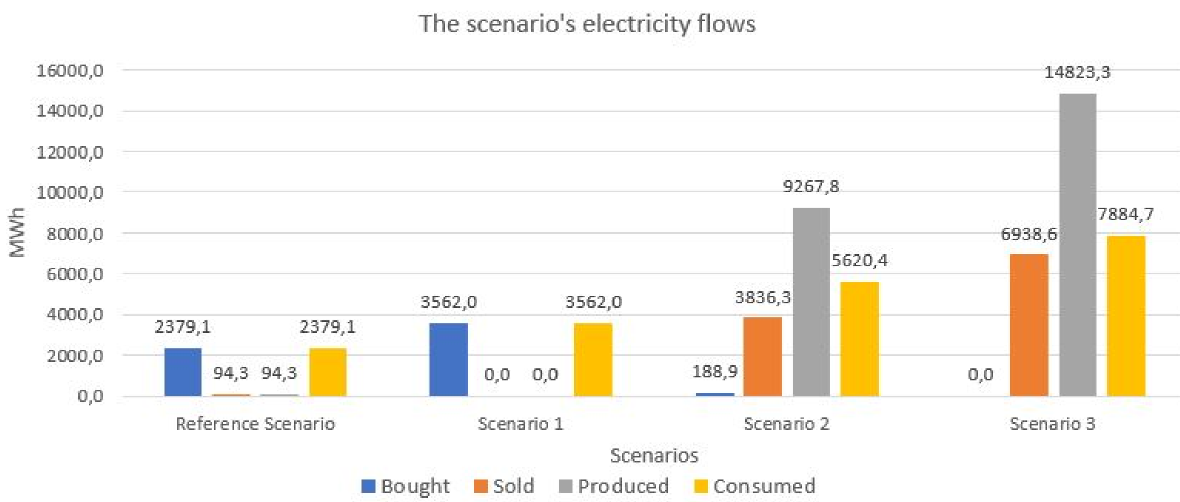

Figure 9.6: The scenario's electricity flows

In Scenario 2, 188,9 MWh of electricity is bought from the grid, which is not considered carbon neutral, and an excess of 3836,3 MWh of renewable electricity is produced to the grid. Taking into account this ratio between consumed and produced electricity, Scenario 2 is considered as a carbon neutral scenario, because renewable electricity most likely displaces non-carbon neutral electricity in the grid.

The purpose of Scenario 3 is to become self-sufficient by producing the 188,9 MWh electricity that is bought in Scenario 2. It is notable that such a minor part of the bought electricity can have such a great impact on the three other electricity flows in Scenario 3.

9.5 Sensitivity analysis

As part of the calculations, each scenario will also be assessed for its sensitivity to regulation under different parameters. These parameters are wind production, elspot price, heat demand, natural gas price, and biomass price. Each scenario will be simulated by +/-10%, to determine how sensitive each scenario is to each parameter. Furthermore, different values will simulate the scenarios affected by some historical data or projections, which are argued in the following:

- The historical data from Nordpool show that since 2016 the change in wind production from year to year has been at a maximum of 25% from 2018 to 2019. Calculations and historical numbers can be seen in the Appendix 13.7. Therefore, the sensitivity analysis of wind power production will simulate a change of +/-10% and +/-25%.
- Since 2016 the change in the price of the elspot has a maximum of 50% between 2017 and 2018, if 2021 is not taken into account, as seen in Figure 1.5. Calculations and historical numbers can be seen in the Appendix 13.7. Therefore, the sensitivity analysis of the elspot price will simulate a change of +/-10% and +/-50%.
- The sensitivity of heat demand will be determined by the argument in Section 9.2.1. Section 9.2.1 concludes an expected population growth of 5% to 2030, which will be three times that much over a 25-year time horizon. Furthermore, there is a population consensus that connecting to a district heating grid is smart since the war in Ukraine started. Therefore, the simulated heat demand will change by +/-10% and +/-15%.
- Since 2016 the most significant price change has a price increase of 90% from 2020 to 2021 for consumers of 500 - 1.999 MWh natural gas. [39]. Therefore, the analysis of the sensitivity of the natural gas price will simulate a change of +/-10% and +/-90%.
- According to the Danish Energy Agency, the price of wood pellets for industry will increase from 8.7 €/GJ in 2022 to 9.1 €/GJ in 2040 which is an increase of 4.5% [40]. Instead of applying 4.5% as expected by the Danish Energy Agency, a scenario similar to the unexpected increase in natural gas of 90% is applied. Therefore, the simulated change will be +/-10% and +/-90%.

9.5.1 Results for fixed sensitivity regulation

In the following figures 9.7 and 9.8 the results of the sensitivity analysis can be seen. The percentage change shown in figures 9.7 and 9.8 is related to the NPV in figure 9.3

The sensitivity analysis of the fixed -/+10% change can be seen in Figure 9.7

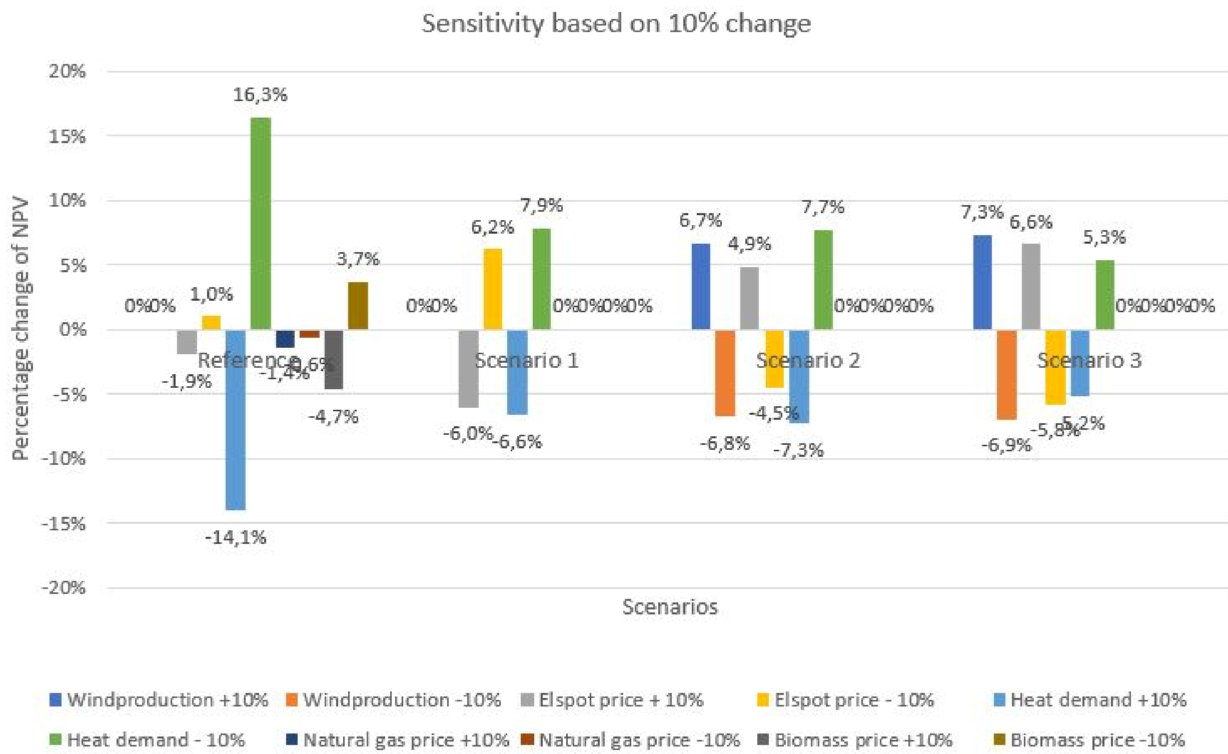

Figure 9.7: Graph that shows the percentage change of the NPV when different parameters is changed 10%

9.5.2 Results for variable sensitivity regulation

The sensitivity analysis of the variable values, based on historical data and projections, can be seen in Figure 9.8.

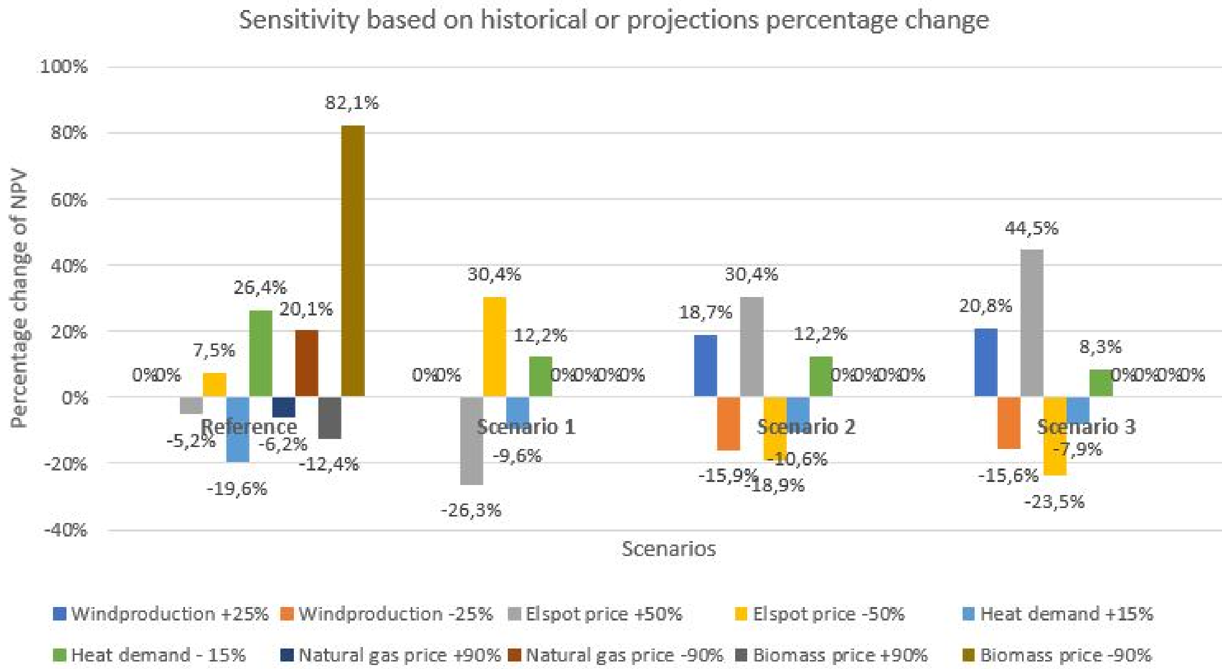

Figure 9.8: Graph that shows the percentage change of the NPV when different parameters with variable values

9.5.3 Reflection's on the results of the sensitivity analysis

In Figures 9.7 and 9.8, it should be noted that Scenarios 1 and 2 cannot meet the heat demand if the heat demand increases +10% and +15%, therefore the NPV will probably increase even more due to higher unit capacities to meet the demand. For Scenario 3 it is possible to meet the heat demand, but the electricity will be consumed from the grid and not from the wind turbine, which is the purpose of Scenario 3.

In Section 9.4 it was concluded that Scenario 2 has the cheapest NPV of the simulated scenarios. After regulating the parameters for the sensitivity analysis, it is only two regulated parameters that can compete with the basic of scenario 2. These two scenarios are the reference scenario with a reduction in biomass prices of 90% and scenario 3 with an increase in the price of the elspot of 50%.

What is notable about the sensitivity analysis is how the NPV changes depending on the elspot price after the wind turbine is established. After the wind turbine is established the NPV actually becomes cheaper when the elspot prices increase. The reason behind this phenomenon in Scenario 2 and 3 is that more electricity is sold electricity compared to electricity bought for a higher price.

10 Discussion

This section has on purpose to reflect and discuss some of the parts that have caught one's attention and started wondering over certain difficulties or relevant topics related to the project.

10.1 The uncertainties of future studies and applied data

The following section will discuss the accuracy and validity of the data applied in the calculations and the development of the scenario in Section 9 from a future perspective. There is no doubt that the data applied in Section 9 come from valid sources that have provided data that are of high accuracy and match historical data. What will be discussed are the uncertainties about how historical numbers can be valid in the context of the development of future predictions. In particular, the parameters applied in the sensitivity analysis are some of the most considerable parameters with the highest uncertainty. As shown in the sensitivity analysis, some small adjustments in the data can completely change the outcome of the analysis and give some results that do not match the future.

It might be possible to predict inflation and the development of prices of goods to some degree if no impact from events occurs. To produce a more accurate scenario, it should be possible to apply projections of change in prices, conditions, etc. But how should it be possible to predict events such as the corona pandemic and the war in Ukraine, and how is it possible to predict the impact of those events? The last years have shown how minor events and adjustments can have a huge impact on the electricity prices etc. This gives great uncertainty in all scenario development, which underlines the importance of performing sensitivity analysis and reflecting on the results.

10.2 The financial barrier of a high investment cost

When considering the appropriate scenario for a particular energy system, all technical and financial results must be taken into account. In some systems, the investment cost can be high and the yearly expenses can be low and vice versa. In Section 9.4 the NPV and investment cost for each scenario were concluded, and from Figures 9.5 and 9.3 it was clear that scenario 2 has the cheapest NPV, but an investment cost of almost 4 million euros. This investment cost is considered quite high for such a small district heating system in Mørkøv, making it unrealistic for a district heating company to invest in such a system, since the district heating company does not have the capital for such an investment, even though the system with the highest investment cost might have the best business case in the long term.

To accommodate a barrier such as high investment cost, possible solutions must be considered. Since many of the district heating companies are owned by consumers, consumers could have a great interest in a low district heating price, and therefore a consumer ownership of energy units, like a wind turbine, could be considered. An exercise to provide consumers with the opportunity to invest in a wind turbine related to the district heating company might be difficult, but if such ownership succeeds, it might have some very economic benefits. By highlighting this point on the application of consumers as a resource in the development of district heating systems, it might also be considered possible to apply consumers for other purposes in the development of district heating. To address this barrier to connecting more consumers to the district heating network, a possible consideration could be to cooperate with citizens to promote the expansion of the district heating network.

10.3 War in Ukraine's impact on politics on energy import

Since the beginning of the war in Ukraine, the Danish and European energy consumption have been in focus. The reason is mainly because European countries do not want to support the Russian war economically by buying Russian energy. The whole situation is really heated because, on one site, European countries will not buy energy, but at the same time they are so dependent on the energy that a cut in the supply will have domestic consequences. There is no doubt that the approach for European countries is to become independent of Russian energy, but what is exciting is how the opinions on import of energy will be affected in the future.

Over a long period, the main focus of energy has been on the green transition from fossil fuels to renewable energy. But the war in Ukraine has now put a focus on the questions of supply security from imported energy. A relevant topic that has probably been out of sight for many people believing in the globalization of the world. The last time the security of supply was heavily in focus was in the 1970s. Now the war in Ukraine has reattached it to the agenda and, in situations like this, it is important to consider all possible scenarios of a cut in supply. To address future supply problems, it must be considered to regulate imported energy marked in Denmark.

Energy has become such an important resource for the infrastructure of all countries that missing energy can create catastrophic situations. Therefore, it is necessary to think about the dependency of energy in all aspects of planning.

11 Conclusion

The purpose of this report has been to answer the research question that is.

- *How can a local energy system based on behind-the-meter cross-sector integration make it possible for Mørkøv district heating to achieve the national and Holbæk municipality's climate goal with an economically feasible approach in 2030?*

To answer the research question in this report, a business economic feasibility study has been conducted. From the business economic feasibility study performed, it can be concluded that the Mørkøv district heating system is capable of reducing greenhouse gas emissions by 100% and improving the business economic NPV for the current district heating system in Mørkøv, by establishing a district heating system based on cross-sector integration with a behind-the-meter structure. This means that a heat pump powered by an owner wind turbine is more competitive than a heat pump powered by the grid. This can be concluded from the scenario modeling performed in Excel that Scenarios 2 achieve the goal for Mørkøv and Holbæk municipality and achieve an improved NPV. The actions performed in Scenario 2 is.

- **Scenario 2:** Investment in 0.76 MW-electricity of heat pump capacity + 2.5 MW wind turbine and a 1600 meter electric cable.

Scenario 2 consumes a small amount of grid electricity and produces a greater amount of renewable electricity, making Scenario 2 considered carbon neutral. The recommendation of this report is to establish Scenario 2 as the cheapest business economic alternative to achieve the organizational goals of Mørkøv district heating and Holbæk municipality.

In the sensitivity analysis, it can be concluded that scenario 2 is roughly robust but is most sensitive to variations in heat demand, which seems like an advantage, as the municipality has a greater opportunity to have an impact on heat demand compared to wind production and electricity prices.

12 Further works

In the process of this report, different ideas have emerged for further work. The ideas emerged due to a possible direction of project development, but it was determined that these directions were either outside the scope or too time consuming and could instead be part of further work. The related research question and the description of the idea in the further work are as follows.

- *What will the socioeconomic results of the scenarios be, based on the guide of the socioeconomic analysis of the Danish Energy Agency?*

As mentioned in Section 5, it is recommended that a business economic feasibility study is not performed alone, but a corresponding socioeconomic feasibility study is carried out in the business economic feasibility study. Therefore, further work for this report could be a socioeconomic feasibility study for the scenario. By making socioeconomic results, the feasibility will be fully finished and it will be possible to come up with some recommendations for public regulation on accommodating cross-sector integration.

- *What would the results be if the business-economic calculations of the scenarios were performed with the MILP solver in EnergyPRO?*

Since EnergyPRO is a highly recognized energy system software, a comparison of the scenarios modeled in EnergyPRO and Excel could be relevant. In a mail correspondence with Anders Andersen, Head of Research and Development for EMD International, he recommended using the mixed-integer linear programming (MILP) solver to conduct the cross-sector integration scenarios.

- *How will the local opposition accommodate wind turbines if the wind turbine is put in relation to cross-sector integration in Mørkøv?*

According to [12] it is argued that cross-sector integration could be a possible method to accommodate the local opposition to the wind turbine. To investigate this phenomenon, it could be possible to make interviews or collect other forms of social knowledge in the field in Mørkøv.

- *How is it possible to make Scenario 2 and Scenario 3 cheaper from a business economic perspective?*

This research question would be highly related to choice awareness theory, because from a theoretical point of view, it is never certain that the scenarios performed are the cheapest economic or the best for the climate and environment when not all possible scenarios are performed [41]. Therefore, further work could be done to optimize the NPV of Scenarios 2 and 3, actions such as the optimized summer period and the implementation of an electric boiler could be possible direction.

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13 Appendix

13.1 Appendix - Data about reference scenario

Følgende generelle antagelser er benyttet i modellen:

- Varmeproduktionsgrundlag, normalår: 11.940 MWh-varme/år
- Elpriser:
  - Faste omkostninger (afgifter og tariffer): 247 kr./MWh-el
  - Spotpriser fra år 2020
- Produktionsomkostninger, biokedel: 330 kr./MWh-varme
- Produktionsomkostninger, gaskedler: 420 kr./MWh-varme
- Produktionsomkostninger, gasmotor: 931 kr./MWh-varme

Tabel 4.1: Resultater fra simulering af referencecasen

**Eksl. elsalg*

Produktionsenhed	Varmeproduktion [MWh/år]	Produktionsomkostninger [kr./år]
Varmepumpe	7.240	1.145.000
Biokedel	3.703	1.221.000
Gaskedler	860	361.000
Gasmotor*	136	126.000
Samlet	**11.940**	**2.751.000**

Figure 13.1: Data about reference scenario

13.2 Appendix - Illustration of reference scenario

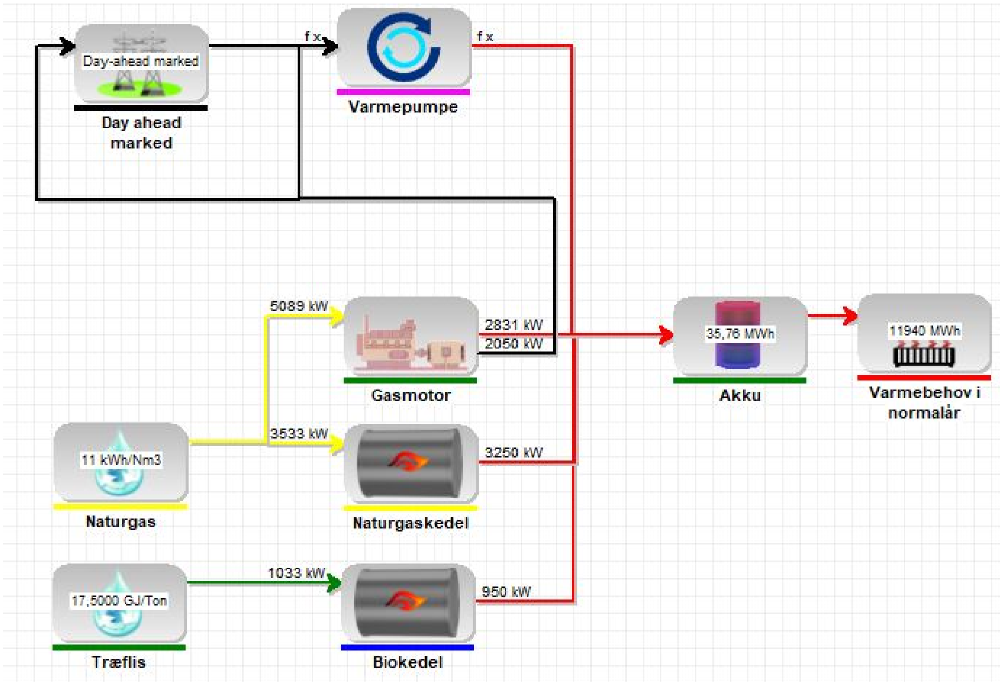

Figure 13.2: Illustration of reference scenario

13.3 Appendix - Data applied

Units	Investmentcost [€/MW]	Fixed O&M [€/MW]	Variable O&M [€/MWh]	Source
Windturbine onshore	1.120.000,00 €	14.000,00 €	1,50 €	Electricity and DH Technology catalog page 224
Air source heatpump 1MW	1.400.000,00 €	2.000,00 €	2,70 €	Electricity and DH Technology catalog page 297
Storage	3.000,00 €	8,60 €		Storage technology catalog page 59
Cable - Electricity distribution, Rural |	41,00 €	1.605,00 €		Technology catalog energy transport

Consumer tariffs	[€/MWh]	Source
TRANSMISSIONSNETTARIF (TSO)	6,53	Energinet.dk
SYSTEMTARIF (TSO)	8,13	Energinet.dk
BALANCETARIF FOR FORBRUG (TSO)	0,31	Energinet.dk
Eletricity to heat tariff (elafgiften)	0,53	Danskenergi.dk
Tariff to DSO	18	Cerius
Producer tariff	**[€/MWh]**	
INDFØDNINGSTARIF	0,40	Energinet.dk
BALANCETARIF FOR PRODUKTION	0,15	Energinet.dk

Figure 13.3: Technical data and tariffs

13.4 Appendix - Scenario 1

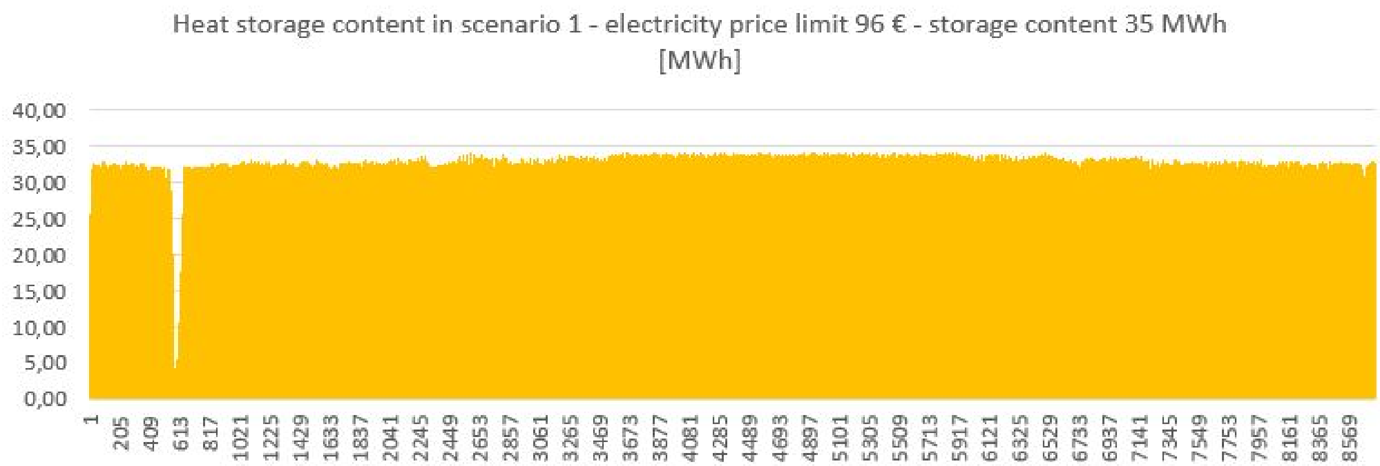

Figure 13.4: Heat storage content in scenario 1 - electricity price limit 96 € - storage content 35 MWh [MWh]

Table 13.1: Actions to optimize Scenario 1

Actions to optimize Scenario 1	Heating produced from heat pump [MWh]	Storage losses [MWh]	NPV [Mill. €]
Unlimit price - 35 MWh storage	14,271	2,308	-6.061
Limit to 96 € - 35 MWh storage	14,259	2,297	-5.988
Unlimit price - 7 MWh storage	12,226	276	-5.333

13.5 Appendix - Scenario 2

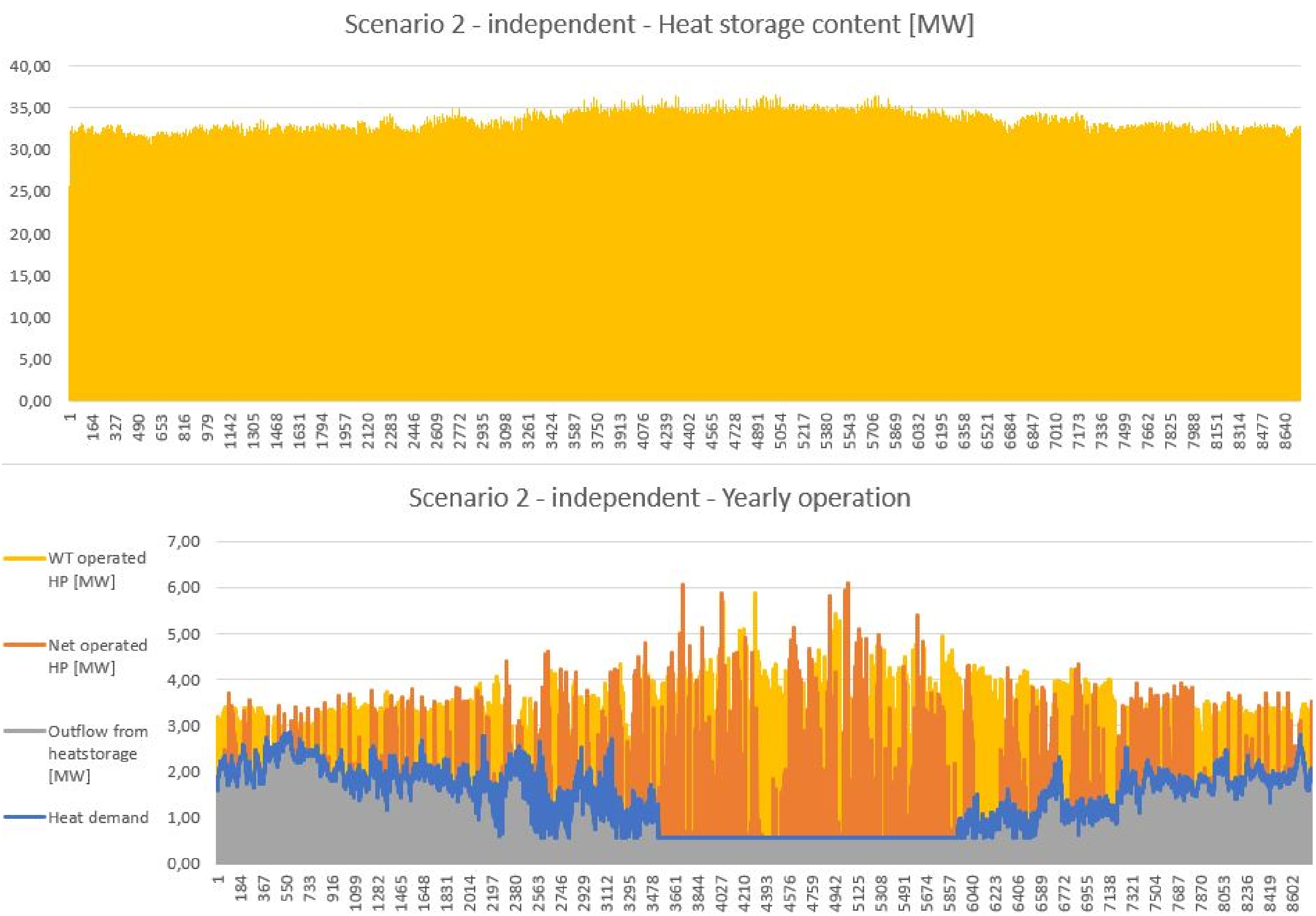

Figure 13.5: Storage content and yearly operation for Scenario 2 - Undependent

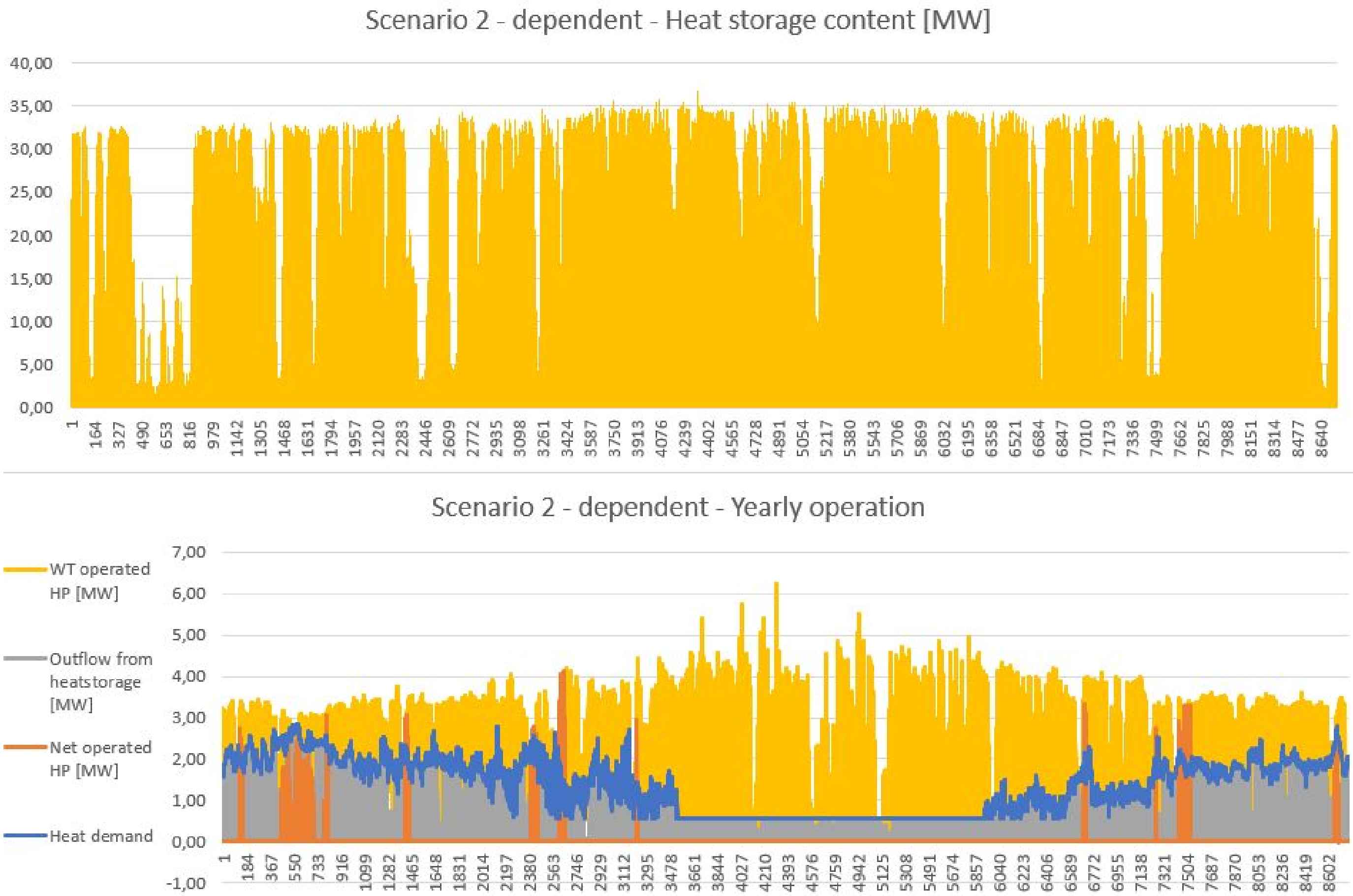

Figure 13.6: Storage content and yearly operation for Scenario 2 - dependent

Table 13.2: Results for scenario 2

Actions to optimize Scenario 2	Total electricity bought [€]	Total electricity sold [€]	Storage losses [MWh]	NPV [Mill. €]
Independent net HP	39,176	153,401	2,337	-4.476
Dependent net HP	4,469	116,202	1,953	-3.743

13.6 Appendix - Scenario 3

NPV [Million €]

WT capacity 3,5 MW

Storage \ Heat pump [MW]	1,5	2	2,5	3
130	-	-	-	-
140	-	-	-	-
150	-	-6,62	7,32	-6,94
160	-	-6,65	7,35	-7,06
170	-	-6,68	7,38	7,18
180	-6,01	-6,71	7,41	7,28

WT capacity 4 MW

Storage \ Heat pump [MW]	1,1	1,5	2	2,5
100	-	-	-	-
110	-	-5,27	5,42	-5,88
120	-	-5,43	-5,55	-6
130	-	-5,6	-5,7	-6,15
140	-	-5,73	-5,83	-6,26

WT capacity 4,5 MW

Storage \ Heat pump [MW]	1,1	1,5	2	2,5
80	-	-	-	-
90	-	-	5,24	-5,63
100	-	-6,88	-5,38	-5,78
110	-	-6,91	-5,54	-5,9
120	-	-6,94	-5,67	-6,03
130	-	-6,97	-5,81	-6,17

Investment [Million €]

WT capacity 3,5 MW

Storage \ Heat pump [MW]	1,5	2	2,5	3
130	-	-	-	-
140	-	-	-	-
150	-	6,62	7,32	8,02
160	-	6,65	7,35	8,05
170	-	6,68	7,38	8,08
180	6,01	6,71	7,41	8,11

WT capacity 4 MW

Storage \ Heat pump [MW]	1,1	1,5	2	2,5
100	-	-	-	-
110	-	6,36	7,06	7,76
120	-	6,39	7,09	7,79
130	-	6,42	7,12	7,82
140	-	6,45	7,15	7,85

WT capacity 4,5 MW

Storage \ Heat pump [MW]	1,1	1,5	2	2,5
80	-	-	-	-
90	-	-	7,55	8,25
100	-	6,88	7,58	8,28
110	-	6,91	7,61	8,31
120	-	6,94	7,64	8,34
130	-	6,97	7,67	8,37

Figure 13.7: Simulation Scenario 3

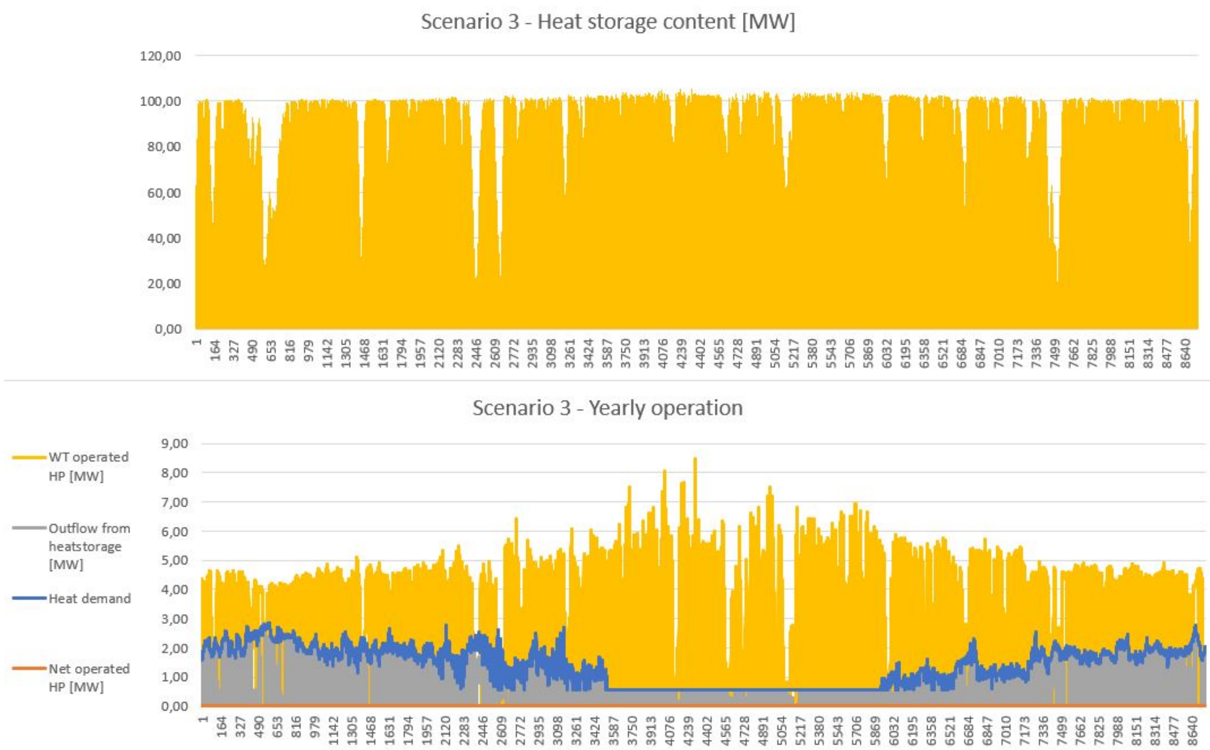

Figure 13.8: Storage and yearly operation for Scenario 3

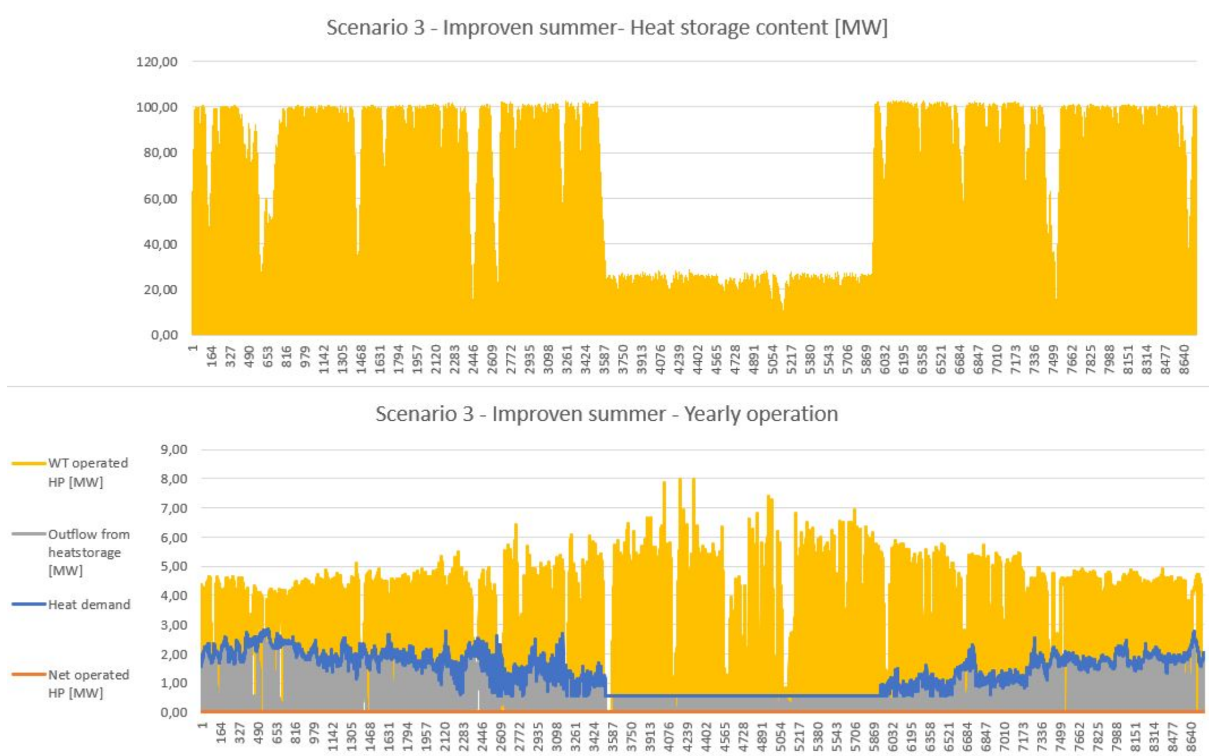

Figure 13.9: Storage and yearly operation for Scenario 3 - Improven Summer

13.7 Appendix Excel models

The Excel sheets and models can be access through the link.

https://drive.google.com/drive/folders/1zP7sUvyJEQfg6GDLGe6Uc3QFm-9M_r5e