The Electrification of Natural Gas-Based District Heating Systems in Denmark

A case study on Oksbøl combined heat and power plant

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Abstract:

This thesis examines the possibility of electrifying natural gas-based district heating systems in Denmark, which is necessary both to reach the Danish climate goals for 2030, and to integrate fluctuating renewable electricity. Firstly, an analysis is made based on EnergyPLAN, which focuses on whether the natural gas-based combined heat and power capacity can be reduced without security of electricity supply being compromised. The analysis shows that a reduction cannot be done unless it is replaced with another electric capacity, provided that all the coal-fired power plants are phased out. Secondly, a paradigmatic case study on Oksbøl combined heat and power plant is used to investigate economic and institutional barriers in an electrification of the district heating sector. Using the modelling tool energyPRO, it is concluded that electric boilers are both business- and socio-economically feasible. However, it is found that biomass boilers are cheaper than heat pumps, which may imply the need of a tax on biomass if a large-scale electrification is wanted. The results of the institutional analysis, which are based on a qualitative interview, show how the relations between- and power of actors strongly impact the transition away from natural gas and also demonstrate the need for innovative democracy if a transition is wanted.

Dansk Resumé

Dette speciale omhandler elektrificeringen af naturgasfyrede fjernvarmeværker i Danmark. For at leve op til det danske mål om 90% vedvarende energi i fjernvarmen i 2030 - og for mere overordnet at begrænse klimaforandringer - er det vigtigt at naturgasforbruget i fjernvarmesektoren reduceres. Idet der kommer til at foregå en kraftig udbygning af vindmøller og solceller i Danmark i de kommende år, så er det vigtigt at det sikres, at den resulterende øgede mængde flukturerende elproduktion udnyttes fornuftigt. Eksperter peger på sektorintegration, altså elektrificering af bl.a. fjernvarmesektoren, som den bedste metode. Elektrificeringen af naturgasfyrede kraftvarmeværker kan imidlertid risikere at føre til en forringelse af Danmarks elforsyningssikkerhed, hvis elektrificeringen medfører en reduktion af deres elproduktionskapacitet.

Formålet med specialet er derfor dels at besvare i hvilket omfang elproduktionskapaciteten fra de naturgasfyrede kraftvarmeværker kan undværes, og dels at besvare hvordan elektrificeringen af disse værker - som er fordelagtig pga. integrationen af vedvarende energi og opnåelse af fjernvarme-målet - udføres på en selskabs- og samfunds-økonomisk fornuftig måde. Det undersøges desuden hvorvidt der er nogen institutionelle- og/eller politiske hindringer af denne elektrificering. Henrik Lunds 'Choice Awareness'-teori bruges som teoretisk ramme for specialet, som består af tre analyser.

Den første analyse, som handler om konsekvenserne for elforsyningssikkerheden ved en eventuel reduktion af kraftvarmekapaciteten i Danmark, tager udgangspunkt i fire scenarier for det danske energisystem i 2030, da der findes vidt forskellige bud på dettes udvikling. Disse scenarier modelleres i programmet EnergyPLAN, som er velegnet til nationale energisystemanalyser. Derefter ændres kraftvarmekapaciteten i scenarierne og effekten på nogle vigtige parametre for elforsyningssikkerhed undersøges. Når disse resultater sammenholdes med Danmarks ambitioner om fortsat at have et lavt antal afbrudsminutter i 2030, og når det samtidig forudsættes at kulkraftværkerne udfases, er konklusionen at den naturgasfyrede kraftvarmekapacitet ikke kan fjernes uden at blive erstattet med en anden elproduktionskapacitet.

I den anden analyse, som er en selskabs- og samfundsøkonomisk analyse af forskellige scenarier for elektrificering af fjernvarmeværker, og i den tredje analyse, som er en institutionel analyse, tages der udgangspunkt i en case. Det vælges at casen skal være et decentralt værk, da resultaterne derved bliver relevante for mange værker i Danmark. Den valgte case er Oksbøl Varmeværk, som anses for at være paradigmatisk, da det er et størrelsesmæssigt gennemsnitligt værk, som hverken udnytter industriel overskudsvarme eller gør brug af usædvanlige teknologier.

I anden analyse bruges teknisk data fra Oksbøl Varmeværk til at udvikle en række scenarier, hvori der indgår forskellige kombinationer af en fliskedel, en varmepumpe og en elkedel. Dette gøres i programmet energyPRO, som er velegnet til analyser på værk-niveau. Kapaciteterne for de pågældende teknologier optimeres i hvert scenarie for at opnå den laveste selskabsøkonomiske omkostning. De vigtigste resultater i denne analyse er, at referencescenariet, samt et scenarie hvor der kun tilføjes en fliskedel, er de dyreste både selskabs- og samfundsøkonomisk. De billigste scenarier er, fra selskabsøkonomisk

perspektiv, scenarierne med hhv. en elkedel- og fliskedel-kombination og en elkedel- og varmepumpe-kombination. Førstnævnte er dog billigst, og der kræves en biomasseafgift på omtrent 10 DKK/GJ for at ændre dette. Samfundsøkonomisk er disse scenarier også blandt de tre billigste, men her er det allerbilligste scenarie et med kun en elkedel, hvilket bl.a. skyldes et mindre skatteforvridningstab pga. større naturgasforbrug. Det undersøges også hvorvidt Oksbøl Varmeværk har økonomisk fordel af at droppe deres gasmotorer, men dette er ikke tilfældet, hvilket er godt ift. resultaterne af den forrige analyse. Dog vil det ikke give mening for værket at købe nye motorer, når de nuværende ikke længere kan bruges. Afslutningsvis diskuteres det, hvordan de bedste scenarier påvirker klimamålene når samme løsninger anvendes på mange decentrale værker, og her bestemmes det at en elkedel- og varmepumpe-løsning på f.eks. 50 decentrale værker kan øge andelen af vedvarende energi i fjernvarmesektoren med ca. fire procentpoint.

Tredje analyse tager udganspunkt i et kvalitativt interview med driftslederen for Oksbøl Varmeværk, Preben Pedersen. Hans svar bruges til at udarbejde den institutionelle analyse, som bruges til at identificere hindringer i elektrificeringen af fjernvarmesektoren. På baggrund af disse hindringer gives anbefalinger til ændringer. Blandt de vigtige hindringer, der bliver fundet i analysen, er følgende. Gasdistributøren har tidligere forhindret en omstilling af Oksbøl Varmeværk ved at appellere til manglende samfundsøkonomisk gevinst. Ydermere blev det konkluderet at kompleksiteten i dansk fjernvarmelovgivning, samt hyppige ændringer, gør det svært for værker at følge med. Der mangler desuden klarhed over, hvordan afgifter i fjernvarmesektoren vil udvikle sig i de kommende år.

Preface

The authors would first and foremost like to thank the operations manager of Oksbøl CHP plant, Preben Pedersen. Preben has made an important contribution to this thesis by providing data from Oksbøl CHP plant and giving an insightful interview. The authors would also like to thank the thesis supervisor Jakob Zinck Thellufsen for useful feedback throughout the thesis development.

This thesis was written in the period February 1, 2021 to June 4, 2021.

The following software has been used in this thesis:

- **Overleaf**
  Writing the thesis.
- **Spyder**
  Making Python plots.
- **Excel**
  Economic calculations and data processing.
- **EnergyPLAN**
  Modelling the national energy system.
- **energyPRO**
  Modelling Oksbøl CHP plant.
- **Draw.io**
  Making figures.

The bibliography uses the APA reference style.
A file named "Master's thesis - Attached files" is attached to the project. It contains the energyPRO models and a sound recording of the qualitative interview.

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Abbreviations

CHP Combined heat and power

COP Coefficient of performance

DEA Danish Energy Agency

DH District heating

DKK Danish kroner

DSO Distribution system operator

ETS Emission trading system

EU European Union

FFR Fast frequency reserves

GHG Greenhouse gas

HDD Heating degree days

IDA Ingeniørforeningen i Denmark (The Danish Society of Engineers)

NGO Non governmental organisation

NHPC Net heat production cost

NPC Net present cost

NPV Net present value

PV Photovoltaic

RE Renewable energy

TSO Transmission system operator

1 Introduction

One of the biggest challenges faced by humanity in recent years is climate change. The years 2010-2019 were the warmest decade ever recorded and this is a result of the large amount of greenhouse gas emissions especially from fossil fuel consumption. Rising temperatures will eventually lead to more extreme weather conditions, drought, and rising sea levels which will impact millions of lives. To combat climate change, individual countries will have to contribute to the multilateral efforts on improvements in energy efficiency and the transition to renewable energy sources. [United Nations, 2021]

Denmark have been a front-runner country in the transition into renewable energy sources with especially a large-scale implementation of wind power in recent years. Integrating fluctuating energy sources at a large-scale, does however, set heavy requirements for a more flexible energy system and large amounts of energy storage capacity. The ability to store excess electricity production (e.g. in thermal storages, batteries or electrofuels) would require highly integrated electricity-, heat-, and transport sectors. [Danish Energy Agency, 2020e; Lund, 2014]

In the scope of the district heating sector, the Danish climate goal is to be 90% renewable in year 2030 and 100% renewable in 2050. These goals can be reached with various technologies such as solar collectors, heat pumps, electric boilers, and bio-fuelled boilers. Many district heating companies in recent years have changed their fossil fuel consuming technologies (in most cases combined heat and power units) into biomass boilers [Danish Energy Agency, 2020b]. However, this does not result in a more flexible and cross-sector integrated district heating sector as would have been the case with electric boilers and heat pumps. Furthermore, when removing combined heat and power capacity, an electricity sector that is highly dependent on fluctuating renewable energy sources becomes even more vulnerable in hours with no wind or solar energy. Even though studies have shown that cross-sector integration of the electricity and district heating sector can be feasible, questions still arise, such as: Can electric heating solutions be integrated in the district heating sector and potentially replace combined heat and power production without compromising the security of electricity supply in Denmark? And what are the economic and institutional barriers of such an integration?

This thesis will investigate how natural gas consumption can be reduced in the district heating sector by using heating solutions based on electricity without compromising the security of electricity supply. Furthermore, with point of departure in a case study, the benefits of a electrification of the heat production will be evaluated from both a business- and socio-economic perspective.

Problem Analysis 2

This chapter seeks to analyse the challenges with fluctuating electricity production and how these can be resolved with the implementation of district heating technologies based on electricity. The chapter addresses the Danish climate goals, current and future electricity production in Denmark, Danish district heating, and the need of maintaining security of electricity supply. The analysis will be used to specify the problem formulation of the thesis.

2.1 The Danish climate goals

The Danish Parliament manifested Denmark's interest in expanding its international position as front runner in a green transition with the Energy Agreements in 2018 and 2020. The agreements contain specific initiatives that deal with increasing investments in renewable energy (RE), energy conservation, energy regulation and research within the Danish energy sector.

Included in the 2018 Energy Agreement, are more specific goals revolving around the Danish electricity and heating sector. One goal states that the annual electricity production in Denmark from renewable sources must exceed the annual consumption. Another goal is that the district heating (DH) production must utilise 90% of renewable sources in 2030. Here, it is a sub-goal that coal-fired power plants must be phased out by 2030. To achieve these ambitious goals, fuel-binding requirements for natural gas and co-generation requirements were removed for DH systems smaller than 500 TJ. Furthermore, the electric heating tax was lowered. [Danish Ministry of Climate, Energy and Utilities, 2016; The Danish Parliament, 2018; Danish Energy Agency, 2018b]

Finally, the climate law of 2019 states that Denmark should reduce its greenhouse gas (GHG) emissions by 70% in 2030 compared to year 1990. Furthermore, the law committed Denmark to be a net zero emitter by 2050. [Danish Energy Agency, 2020c]

In order for Denmark to be able to reach the climate goals goals, an increase in renewable electricity generation capacity has been a priority ever since the agreements were first published. Especially fluctuating RE sources such as wind- and photovoltaics (PV) have been gaining competitiveness and importance in the Danish Energy Sector.

2.2 The Danish electricity sector

2.2.1 RE capacities and current excess electricity production

To reach the climate goals for 2030 described in section 2.1, Denmark requires a larger renewable electricity generation capacity. Aside from expanding the biomass power plant capacity, the options in Denmark are mainly to further expand the wind turbine and PV capacities. The installed capacities for these technologies in Denmark have increased significantly in recent years, which is illustrated in Figure 2.1.

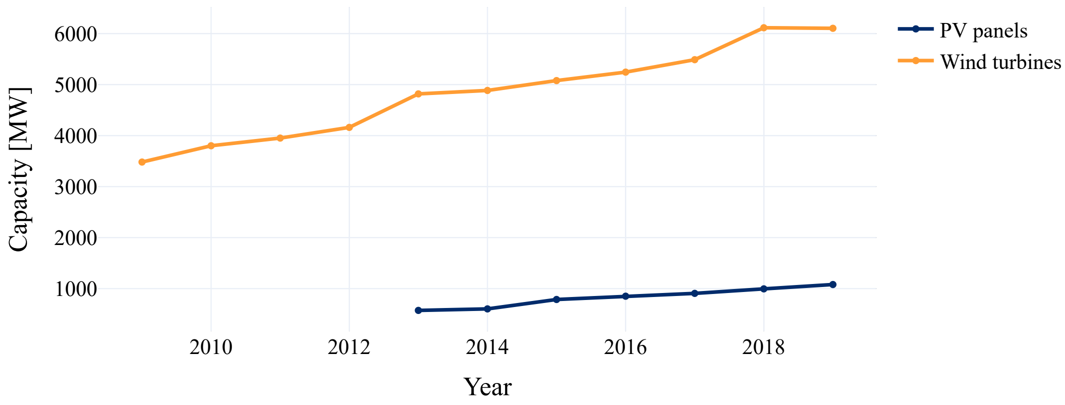

Figure 2.1. Cumulative installed capacities in Denmark for wind turbines and PV panels. As of 2019, the onshore wind turbine capacity was 4.4 GW and the offshore capacity was 1.7 GW [Wind Denmark, 2020a; Statista, 2020].

Even though, the wind turbine capacity is expected to increase in Denmark there are already hours with surplus electricity production from wind turbines in Denmark. This will either result in the turbines being stalled, or electricity being exported to neighboring countries. An example from Western Denmark with differences in electricity production from wind turbines and consumption is shown in Figure 2.2.

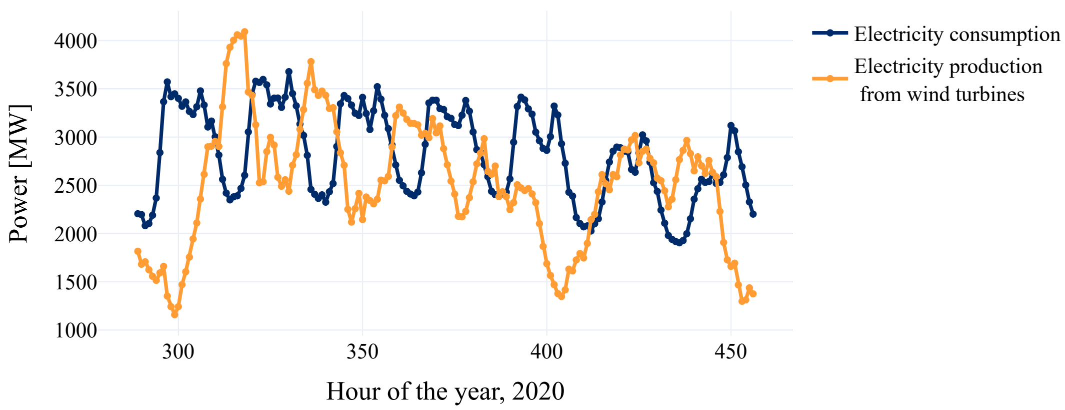

Figure 2.2. Electricity consumption and production from wind turbines in Western Denmark (DK1) in the third week of 2020 [Energi Data Service, 2021].

Excess electricity production from wind turbines is also increasingly a challenge in Northern Germany. Because Northern Germany has problems with bottlenecks in their transmission system, their Transmission System Operator, TenneT, pays Danish wind turbine owners for shutting down wind turbines in Western Denmark. This is because high wind speeds in Denmark and Northern Germany typically occur at the same time. TenneT paying for shutting down wind turbines in Denmark is called 'special regulation'. This is increasingly used, which means that a larger and larger amount of wind energy in Denmark goes to waste. However, it is profitable to deliver special regulation. Therefore, on a windy day in Western Denmark, it can often be observed that many large wind turbines are shut down. [Wind Denmark, 2020b; Energinet, 2020c]

2.2.2 2030 scenarios for the Danish electricity sector

As the installed capacity of wind turbines and PV panels continues to increase in the pursuit of the 2030 climate goals, the challenges with excess electricity production will increase; unless other changes in the electricity system (or more broadly in the energy system) are made. How much these installed capacities are expected to increase in 2030 is a difficult question, as it depends on political decisions, which have not yet been made. In the report, *Denmark's Climate and Energy Outlook 2020*, The Danish Energy Agency (DEA) has made a baseline projection for 2030, which is a so-called 'frozen-policy' scenario. It takes the most recent political decisions into account (including the 2018 Energy Agreement mentioned in Section 2.1), but assumes that new policies are not introduced [Danish Energy Agency, 2020d]. Another approach, which is used by Energinet [2016b], is to make four scenarios for Denmark based on different assumptions about how strongly the goals of the Paris Agreement, mentioned in Section 2.1, will be pursued and also about how much cooperation there will be within the European Union (EU). The definitions of the four Energinet scenarios are illustrated in Figure 2.3.

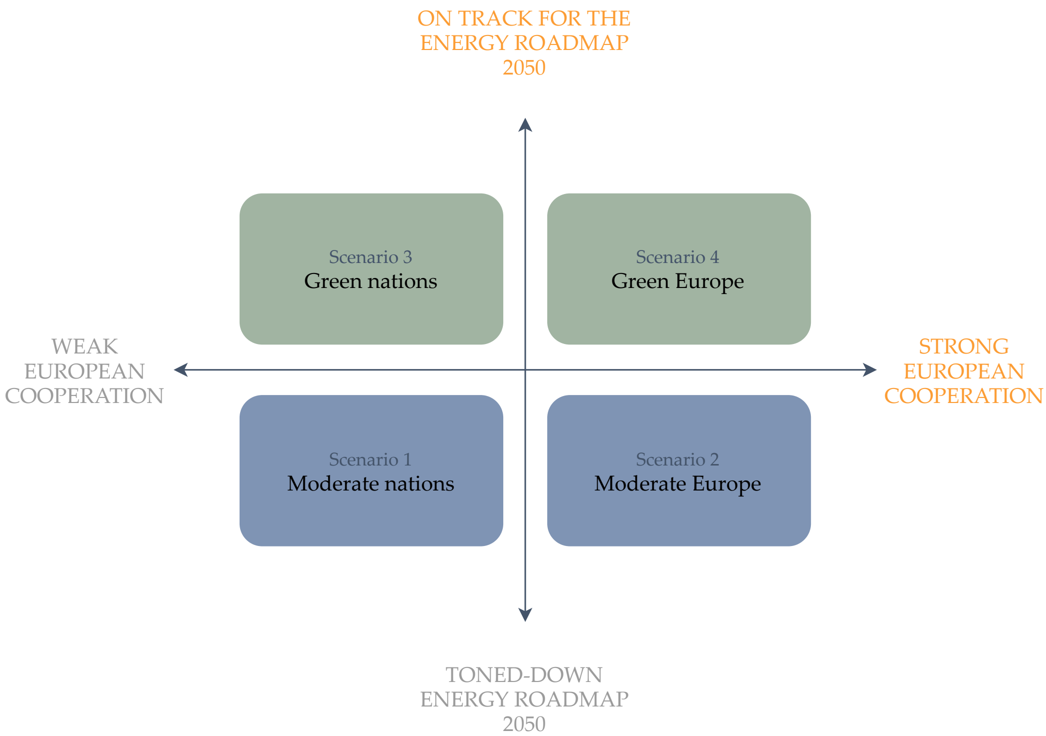

Figure 2.3. Assumptions behind the four scenarios for the Danish energy system in 2030, which Energinet has developed [Energinet, 2016b].

Another scenario, made by the Danish Society of Engineers (IDA), can be found in the report by Lund et al. [2020]. It differentiates itself from the other scenarios by being normative rather than predictive. In other words, the report presents the organisation's opinion on how Denmark should reach the 2030 climate goals [Lund et al., 2020].

The six mentioned scenarios result in significantly different installed wind turbine- and PV capacities in Denmark in 2030. This is shown in Figure 2.4.

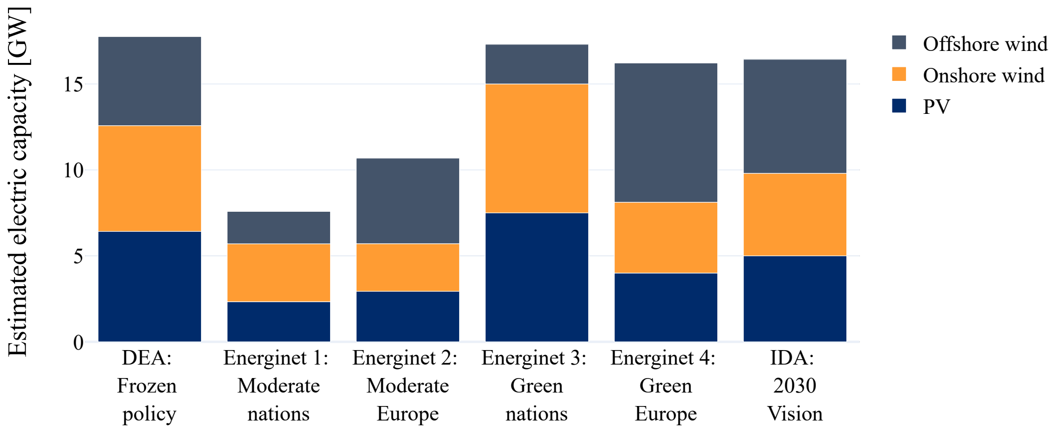

Figure 2.4. Assumed installed capacities of wind turbines and PV panels in Denmark in 2030. Based on scenarios from Danish Energy Agency [2020d], Energinet [2016b], and Lund et al. [2020].

The Energinet scenarios are from 2016, and five years later it is clear that the 'Moderate nations' scenario will not reflect reality. As shown in Figure 2.1, Denmark already has more than 6 GW wind turbine capacity. Furthermore, it is now known that the Danish Government plans to expand offshore wind considerably with the so-called 'energy islands', which are expected to result in an additional 5 GW offshore wind turbine capacity by 2030 [The Danish Parliament, 2020]. This could bring the total wind turbine capacity in Denmark to at least 11 GW in 2030. It should be kept in mind that some of the pre-2008 onshore wind turbines in Denmark are expected to be taken down before 2030; namely around 160 MW/year in the period 2017-2030. However, in the same period, it is expected that around 210 MW/year of onshore capacity will be added [Energinet, 2016a]. Therefore, it is realistic to expect at least 11 GW wind turbine capacity in 2030 in Denmark.

While all scenarios contain large increases in the PV capacity, which is currently around 1 GW, there is significant variation. The emergence of PV in Denmark, which is illustrated in Figure 2.1, has been driven by a considerable reduction in the cost of PV panels. In fact, according to the International Energy Agency [2020], the cost of a PV panel in 2020 is less than 5% of what it was in 2008. The continued expansion of PV capacity will to some extent depend on the evolution of the cost, but another important factor could be potential national political action regarding the placement of PV farms. In recent years, the combination of a low PV cost and a low cost for renting farmland has led to large areas of farmland in Denmark (approximately 10 km^2 in total) being used for PV farms instead of agriculture, and just a single PV project developer has plans for installing PV panels on an additional 38 km^2 of Danish farmland. Brian Vad Mathiesen, professor of energy planning at Aalborg University, points to problems with this approach to PV expansion: areas with farmland have low electricity consumption, so a large production capacity in these areas necessitates expensive upgrades to the electrical grid - and there is strong community opposition to farmland PV projects. Mathiesen points out that a national PV strategy for Denmark is missing, and proposes that PV panels should instead be placed on the large roofs of factories and industrial buildings close to- or within cities. There is broad agreement in the Danish Parliament on the need for more national regulation of the PV expansion, although it has yet to be concretised, which makes it difficult to predict how it will affect the PV capacity in 2030. [Kielgast and Hall, 2019; Dragsted and Solgaard, 2021]

2.2.3 Balancing a Danish RE-based electricity sector

Since Denmark already has periods with excess electricity production, caused by fluctuating wind and solar energy, and a rapid expansion of wind turbine- and PV capacity is expected, it is clear that Denmark has to adapt other parts of the electricity system (or more broadly the energy system) to accommodate the change. Not only should the electricity demand increase, which is expected because of electrification in various sectors and the addition of new, large data centers (according to the frozen-policy scenario from Danish Energy Agency [2020d], the total electricity consumption in Denmark will increase to 46.4 TWh in 2030 compared to 32.4 TWh in 2018, not counting grid losses). The electricity supply and consumption also have to be balanced at all times. With this in mind, not all increases in electricity consumption are equally positive/desirable: flexible demands (such as, to some extent, electric heating solutions with storage or EV charging) are naturally preferred over inflexible demands (like data centers). Furthermore, as argued by Thellufsen and Lund [2015], energy savings are also very important.

The balance of electricity supply and consumption, in a system with a lot of fluctuating electricity production, could be achieved with a combination of technical solutions. Lund [2014] discusses at least three main options: electricity storage, higher interconnector capacities, and cross-sector integration.

Electricity storage This does not refer to battery electric vehicles (which Lund [2014] argues in favor of) but rather to large-scale, stationary electricity storage. This could for instance be compressed-air energy storage or lithium iron phosphate batteries. Lund [2014] specifically investigates the potential role of compressed-air energy storage in Denmark, but his conclusion is that the cost is too high compared to the benefit. This is elaborated on by Lund et al. [2016], where it pointed out how expensive electricity storage is compared to heat-, gas-, and liquid storage. Lund et al. [2016] therefore argue against a narrow focus on the electricity system, and state that cross-sector integration (explained below) is a better approach to accommodate more fluctuating electricity production.

Higher interconnector capacities This refers to the idea of increasing the capacity of transmission lines between Denmark and neighboring countries. These types of transmission lines are referred to as 'interconnectors' here. Of course, interconnectors already play a big role in the Danish electricity system. In 2018, Denmark had a net import of electricity of 5 TWh [Danish Energy Agency, 2020d]. As os 2021, Denmark has interconnectors to Germany, Norway, Sweden, and the Netherlands. Furthermore, when the Viking Link project is completed, Denmark will also be connected to the United Kingdom [Energinet, 2021d]. The Viking Link project is controversial in Denmark: energy planning experts from Aalborg University believe that it is a highly uncertain socio-economic business case, and that investing in heat pumps (cross-sector integration) is a much better alternative [Wittrup, 2016c,b]. While interconnectors certainly help to balance fluctuating electricity production, the socio-economic feasibility of continuing to construct new ones is often called into question; not just in the Viking Link case, but also in the case of the COBRAcable, which now connects Denmark and the Netherlands [Wittrup, 2016a]. According to Becker et al. [2013], it is also clear that interconnectors generally become less useful for integrating more fluctuating renewable electricity production, once the electricity production in surrounding countries is also based on fluctuating RE. The case of special regulation being activated in Northern Germany, which was explained in Subsection 2.2.1, is a good illustration of this.

Cross-sector integration This refers to an integration of the electricity sector and, for instance, the heat- and transport sectors in Denmark. It entails using large heat pumps and electric boilers for DH, individual heat pumps in the countryside and a general electrification of transport. When there is excess electricity production, the integration allows for greater usage of cheap heat storage instead of expensive electricity storage, which is described above. Lund [2014], Lund et al. [2016] and Hvelplund et al. [2019a] all argue for cross-sector integration as the most feasible way to integrate more fluctuating electricity production, and they all state that it should be prioritised above increasing the interconnector capacity.

Although cross-sector integration is considered, by the above-mentioned experts, to be the best way to integrate large amounts of fluctuating electricity production, it is not without its challenges. For example: to integrate the electricity- and transport sectors in Denmark, with a goal of 700.000 battery electric vehicles and 300.000 plug-in hybrid vehicles in 2030, will require investments of 32-48 billion DKK just for upgrading the electrical grid [Dansk Energi, 2019b].

In countries where both combined heat and power (CHP) plants and fluctuating renewable electricity generation are prominent, there are three main steps in cross-sector integration, according to Lund [2014]:

1. Adjust CHP plant operation based on electricity production from fluctuating renewable sources (i.e. turn off CHP plants when fluctuating renewable electricity generation is high and vice versa). This is already done in Denmark, but it causes increased usage of heat-only production (described in Subsection 2.3.1) some of which is based on inefficient boilers.
2. Add large heat pumps and more heat storage in DH systems to solve the problem caused by step 1.
3. Electrify the transport sector.

Considering the Danish climate goals for 2030, including 90% renewable DH production and >100% renewable electricity production (mainly from wind turbines and PV) in addition to the importance of DH in integrating fluctuating renewable electricity production with a cross-sector integration strategy, it is important to understand the Danish DH sector.

2.3 The Danish district heating sector

The oil crisis in 1973 showed vulnerability of a society highly reliant on imported oil for energy production. As a result of this, the Danish government aimed to improve energy efficiency and security of supply. To improve security of supply, an implementation of alternative energy sources such as coal, natural gas and RE was necessary. The early goals of becoming more energy efficient resulted in a large-scale implementation of CHP plants where waste heat from electricity production could be used for residential and industrial heating purposes. This, in combination with improvements in the cost effectiveness and consumer convenience, paved the way for a large-scale implantation of DH in Denmark. [Lund, 2014; Persson and Werner, 2010]

The development in heating installations in Danish dwellings can be seen in Figure 2.5.

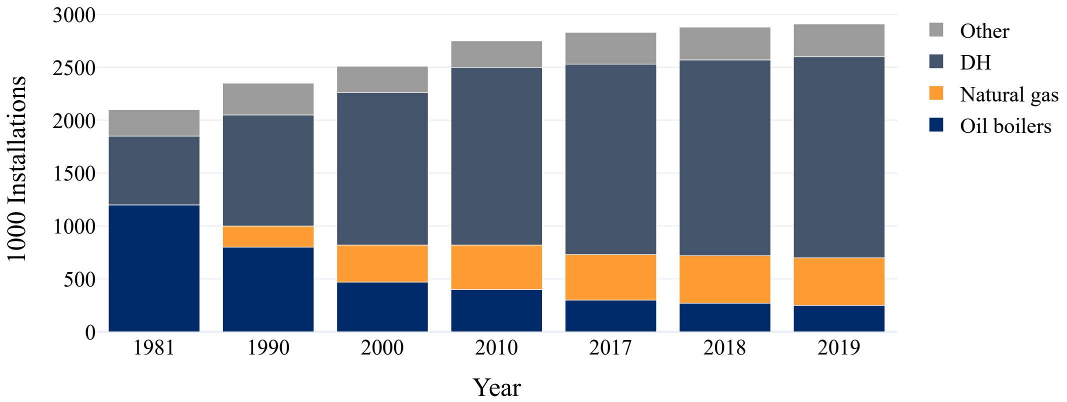

Figure 2.5. The development in heating installations in Danish dwellings from 1981 to 2019 [Danish Energy Agency, 2020e].

As of 2019, 64.8% of Danish dwellings were supplied with DH. The development in fuel usage in the DH sector can be seen in Figure 2.5.

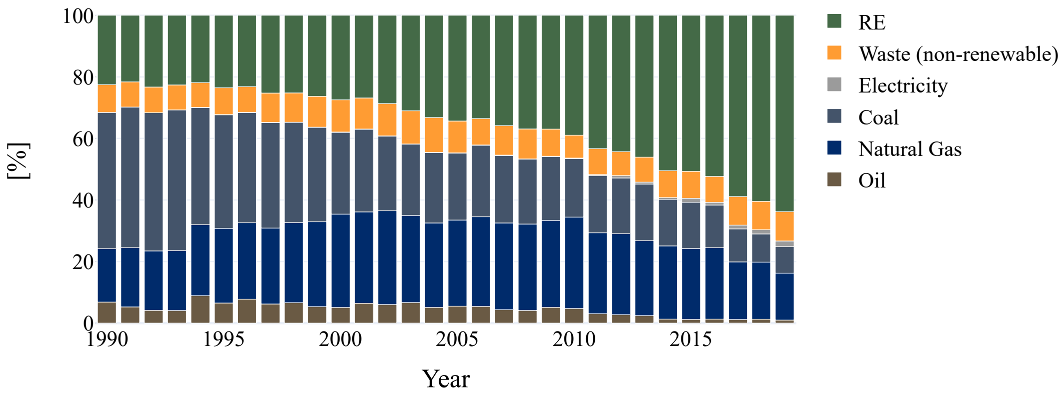

Figure 2.6. The development in fuel usage for the Danish DH sector from year 1990 to 2019 [Danish Energy Agency, 2020e]. The category 'Electricity' accounts for all electricity consumption except that of heat pumps.

From Figure 2.5, it is evident that phasing out coal will not alone reach the goals of a renewable fuel share of 90% in the DH sector. As of 2019, 15.2% of the total fuel consumption for DH production was from natural gas (mainly utilised in CHP plants). Therefore, some of these plants must change fuel in order to be able to reach the Danish climate goals. The RE share in the DH sector has increased rapidly in recent years. This is especially due to an increased use of biomass as a result of the current tax and tariff structure favouring this fuel [Danish Energy Agency, 2020f]. In fact, the usage of biomass in the energy sector has almost tripled from year 2000 to 2019. Even though most renewable DH is from biomass, there has in recent years been an increasing amount of heat production on solar collectors and heat pumps (with renewable electricity) in the sector. [Danish Energy Agency, 2020e]

2.3.1 DH plants

DH in Denmark is produced on different types of DH production plants. These being CHP plants, heat-only plants and autoproducers (waste treatment and industrial waste heat). Aside from autoproducers, DH plants are, in general, categorised into 3 main types of production plants: centralised CHP, decentralised CHP and heat-only plants. The main differences of these plants can be seen in Table 2.1

Table 2.1. DH plants in Denmark as of year 2019 without autoproducers. [Danish Energy Agency, 2017, 2020e, 2018a]

	Centralised CHP	**Decentralised CHP**	**Heat-only**
Primary Fuel	Coal, biomass and natural gas	Biomass and natural gas	Biomass and natural gas
Total electric capacity [MW]	4,721	1,863	-
Number of plants	14	288	557
Area	Larger DH areas	Generally located at smaller DH areas	Smaller DH areas or as supplement to CHP production
Ownership	Often owned by larger energy companies	Owned by municipalities or consumers	Owned by municipalities or consumers

In 2019, 67.7% of the DH production in Denmark was from co-generation with electricity. The development in the production of DH in Denmark from the mentioned production units can be seen in Figure 2.7.

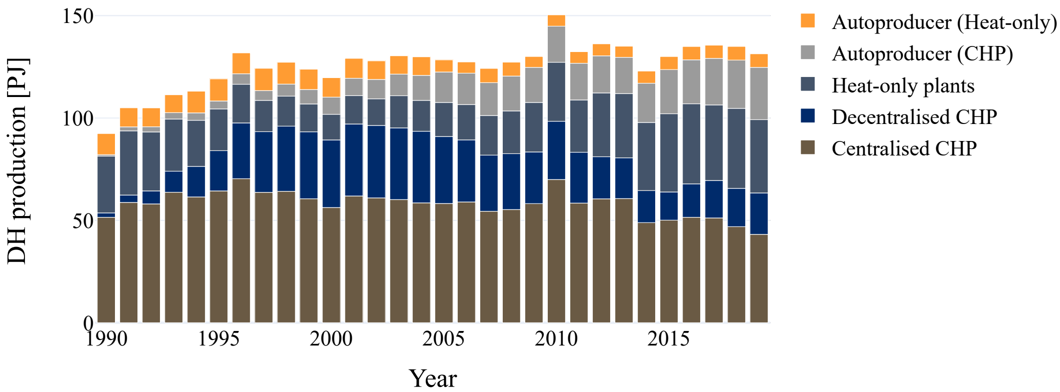

Figure 2.7. Development in DH production in Denmark from year 1990 to 2019. [Danish Energy Agency, 2020e]

From the figure, it is evident that DH from autoproducers has increased significantly. This is especially due to higher amounts of excess heat from industry and waste management. The production of DH from CHP plants has been reduced in recent years, while heat-only production has increased. This is mainly caused by lower electricity prices as a result of increased wind power capacity mentioned in Subsection 2.2.1, making CHP operation less feasible. [Danish Energy Agency, 2020e]

2.3.2 The future of Danish DH

Studies have shown that DH is a competitive solution, also in future energy systems with lower heat intensities. Persson and Werner [2010] conclude that the socio-economic feasibility of DH will depend on future population densities. As a result of lower future heat demand, the feasibility will be challenged in rural areas in Europe. The paper does, however, state that the feasibility is not at risk in high density population areas. Other researchers, such as Lund et al. [2009], analyse the specific case of Danish DH in a 100% RE system. Here, it is concluded that DH can expand in Denmark, while maintaining feasibility even at significantly lower future energy intensities of buildings. The study concludes that a gradual expansion to cover up to 70% of the total heat demand in Denmark with DH could be optimal. To do this, there is a need of improvements in the DH sector to become more efficient by lowering supply temperatures, utilising waste heat and incorporating more RE sources. Another study by Lund et. al [2014] concludes that DH and district cooling will play a significant role in a 100% RE system. However, the study concerns the need of more electric heating solutions such as heat pumps in order to integrate the DH sector with the electricity sector. Furthermore, a step to improve energy efficiency in the DH sector is, as mentioned, to reduce supply temperatures and thereby gradually implement 4th generation district heating. This reduction in temperatures will enable production units such as solar collectors and heat pumps to operate more efficiently while reducing storage and grid losses.

It is evident from these studies, that DH can be expected to play an important role in the future Danish energy system. An electrification of the DH system would enable the utilisation of cheap heat storage and take advantage of otherwise excess electricity production. Thus, utilising cross-sector integration could enable a renewable and socio-economically feasible transformation of the DH sector. However, heat pumps and electric boilers creates an additional electricity demand, which could be a challenge in hours with no wind or PV electricity production. Therefore, Danish CHP capacity cannot just be replaced with electric heating solutions as the impacts on the electricity sector must be evaluated as well.

2.4 Electrification of the district heating sector

2.4.1 The future role of Danish CHP plants

Legislation has had a big impact on how the DH systems have evolved and has especially dictated the choices of CHP plants. As mentioned in Subsection 2.3.1, the feasibility of CHP heat production have been reduced in recent years due to lower electricity prices. Until 2019, all plants were bound by legislation which prevented them from a technological change which resulted in higher consumer heat prices [Danish Ministry of Climate, Energy and Utilities, 2016]. The two main regulations for fuel usage and production requirements for centralised and decentralised CHP plants can be seen in Table 2.2.

Table 2.2. Main elements of regulation regarding fuel binding requirement and co-generation requirement [Danish Ministry of Climate, Energy and Utilities, 2016]

	Decentralised CHP plants	**Centralised CHP plants**
Co-generation requirement	The co-generation requirement depends on which production is the most socio-economically feasible	The co-generation requirement can only be avoided with an exemption
Fuel binding	Free choice of fuel (except coal). In areas with natural gas connected, only co-generation, natural gas or fuel free production is allowed	Free choice of fuel. Fuel free technologies can only be used with exemption as a result of the co-generation requirement

As of 2019, the regulation displayed on Table 2.2 has been abolished for smaller DH systems with a yearly heat production below 500 TJ. These DH systems account for most decentralised DH systems and cover around 600.000 households.

The Danish natural gas- and coal-fired CHP plants will undergo a transition in order to accommodate Danish climate goals. Especially coal-fired power plants will be replaced with other technologies, as it is a sub-goal of the Energy Agreement 2018 that these must be phased out. [The Danish Parliament, 2018] As of 2021, most centralised coal-fired CHP plants already have detailed energy plans for this transition and some are already reconstructing the plant to be able to operate on biomass.

There are four remaining centralised CHP plants in Denmark with coal as their primary fuel. A list of the four CHP plants in Denmark operating on coal (2021) and their respective plans for transitioning into alternative fuels before 2030 can be seen in Table 2.3.

Table 2.3. The four remaining centralised coal-fired CHP plants in Denmark with their respective plans for transitioning into other fuel-types. [Danish Ministry of Climate, Energy and Utilities, 2019]

	Co-generation requirement	**Transitioning plans**	**Expected coal-free**
Nordjyllandsværket (Aalborg)	Expected to be waived	Heat pumps, solar thermal, electric boilers and geothermal heat-only solutions	Year 2028
Esbjergværket (Esbjerg)	Waived	Large-scale heat pump and supplementing technologies	Year 2023
Fynsværket (Odense)	Expected to be waived	Not finalised	Year 2025
Asnæsværket (Kalundborg)	Not waived	Already transitioning to biomass	Year 2023

From Table 2.3, it is evident that some CHP plants have not been exempted from the co-generation requirement. Asnæsværket (seen in the table) and Amagerværket are examples of this, where these plants had to reconstruct in order to utilise biomass for CHP production. However, other coal-fired plants have been exempted from the co-generation requirement. The exemption is from a business-economic perspective favourable for multiple DH companies as they can produce heat without the need of producing electricity when electricity prices are low. Furthermore, the DH plants can utilise technologies that are favourable in specific areas such as geothermal heat [Danish District Heating Association, 2018]. As seen in Table 2.3, Esbjergværket was able to be exempted from the co-generation requirement and the DEA will be able to waive the requirement for the plants: Nordjyllandsværket and Fynsværket. The DEA has in recent years been hesitant with the removal of the co-generation requirement for larger centralised CHP plants. However, recent evaluations have shown that the security of electricity supply would not be significantly impacted by waiving the requirement for just these three plants. [Danish Ministry of Climate, Energy and Utilities, 2019]

Looking at the natural gas CHP plants, it is evident that these are struggling to deliver competitive DH prices for the consumers. This is, as mentioned, due to lower electricity prices and a removal of subsidies which has caused the financial incentive to co-generate heat and electricity to be reduced in recent years [Danish Energy Agency, 2020e]. As mentioned, smaller decentralised CHP plants have been allowed to change technology and be exempted from the fuel binding and co-generation requirements and the same is expected to happen for most of the coal-fired CHP plants. Thereby, coal-fired CHP plants and smaller decentralised natural gas-based CHP plants are able to invest in heat only technologies such as biomass boilers, heat pumps and electric boilers for their main DH production. As a result of this, legislation is needed to ensure some form of dispatchable capacity in the Danish electricity sector to maintain security of electricity supply. [Energinet, 2018a].

One solution to maintain CHP capacity in the future Danish energy system could be to implement more bio-fuelled CHP plants. In recent years, biomass and biogas plants have been favoured by the tax and tariff structure and could be an economically feasible alternative to the current coal- and natural gas-based CHP plants. However, this legislation could be changed in the coming years as politicians and environmental groups have shown an increased skepticism towards biomass. Biomass is accounted as CO_2 neutral in the energy sector, and emissions are calculated in land use, land use change, and forestry (LULUCF). However, most biomass in Denmark is imported, and foreign transport and emissions as a result of foreign LULUCF are not included in the Danish emissions. The life-cycle assessment emissions of biomass can therefore vary significantly depending on the origin, and the fuel is criticised as some emissions are often neglected. [Danish Energy Agency, 2020b]

2.4.2 Electric heating as a business-case

The business-case for electrification of district heating systems has in 2021 been improved considerably, because the tax on electric heating was reduced from 210 DKK/MWh to 4 DKK/MWh. This goes to show that not only experts and researchers believe in cross-sector integration; politicians are also beginning to realise its benefits. [The Danish Parliament, 2018; Lund et al., 2020; The Danish Parliament, 2020; PwC, 2020]

The future electricity prices will play a significant role in the economic feasibility of cross-sector integration. Trømborg et al. [2017] have analysed the future Nordic electricity price variations and levels, and have come to the conclusion that an increase in variability is expected by 2030. Also, an average increase in the electricity price is expected by 2030, as stated by Nordic Energy Research [2019] who estimates around a doubling in electricity prices in this time-frame. From a business-case perspective, an increasing variability and increasing electricity prices could be costly for the DH plants, which use electric heating solutions. However, Trømborg et al. [2017] also found that this variability creates an incentive for incorporating a larger share of thermal storage and electric boilers, as they, in connection with heat pumps, would make for a flexible option.

If DH companies are to convert their production into electric heating solutions, there is a need for a business-economic incentive. DH companies cannot be expected to change their production purely based on a socio-economic perspective, as it must to be feasible to produce heat from a business-economic perspective in order to ensure competitive consumer heat prices. These perspectives may differ, as it could be cheaper for the DH companies from a business-economic perspective, to utilise biomass instead of electric heating solutions, while the reverse may be true from the socio-economic perspective. Whether one solution is feasible from a business-economic perspective, strongly depends on the tax and tariff structure on the different fuels. On the other hand, socio-economic feasibility depends, among other things, on tax distortion, air pollution etc. Furthermore, if the business- and socio-economic results are in conflict, regulatory and institutional changes may be needed in order to reach the climate goals in the most socio-economically feasible way.

Problem Formulation 3

Denmark is committed to a considerable reduction in greenhouse gas emissions by 2030. The 2018 energy agreement formulates specific goals for the Danish electricity supply and fuel usage in DH; namely that coal-fired power plants are phased out, that annual renewable electricity production should exceed the annual demand, and that DH should be 90% renewable. A large increase in wind turbine- and photovoltaic capacity is both needed and expected, but the resulting fluctuating electricity production must be in balance with the demand. Multiple studies conclude that the best way to ensure this balance, and to utilise otherwise wasted excess electricity production, is to utilise electric heating solutions in the DH sector with cross-sector integration. As coal-fired combined heat and power plants in Denmark will be phased out by year 2030 and alternative technology solutions already are in the specific plans for these plants, this thesis will focus on natural gas CHP plants in Denmark. These plants, in the coming years, will have to change their technologies to accommodate the Danish climate goals and increase the business-economic feasibility of operation. Electric heating solutions are increasingly being presented as a feasible alternative to current technologies. However, the electricity sector in Denmark is reliant on electric capacity from natural gas-fired combined heat and power plants and a large-scale implementation of electric heating solutions in the DH sector could challenge security of supply in the electricity sector. Furthermore, there could exist economic, institutional and political barriers that will hinder this implementation.

This leads to the following primary research question:

How can an electrification of the natural gas-based district heating systems be implemented, in order to utilise an increasing amount of fluctuating renewable electricity production and contribute to the achievement of the Danish climate goals of 2030, while maintaining business- and socio-economic feasibility and security of electricity supply?

In order to answer the primary research question, the following underlying research questions have been developed:

1. *To what extent can the electric capacity of natural gas-based combined heat and power plants in Denmark be reduced while maintaining security of electricity supply?*
2. *How can electric heating solutions be used to reduce natural gas consumption in the district heating sector and contribute to the achievement of the Danish climate goals of 2030 while maintaining business- and socio-economic feasibility?*
3. *What are the institutional and political hindrances in the implementation of a socio-economically feasible electrification of the district heating sector in 2030 and how can these be overcome?*

Delimitation

An important aspect of a renewable energy system is improvements in energy efficiency. However, due to a limited ability to generalise the results, improvements in energy efficiency in the district heating grid is not investigated. There likely would be benefits in e.g. renovating buildings which could enable the district heating supply temperatures to be lowered and reduce losses. But, since every district heating system has different characteristics (e.g. age of grids, current supply temperatures, and different building characteristics) it would be difficult to generalise the results to other cases.

Research Design 4

This chapter contains a literature review that examines the novelty of this research, a description of the overall theoretical framework, research development and structure, including a description of how each analysis is carried out.

4.1 Literature review

In order to examine existing research within the field of study and to investigate the relevance and novelty of the thesis, a literature review is made. [Snyder, 2019]

Two scientific research articles and one technical report are analysed below.

Business and socioeconomic assessment of introducing heat pumps with heat storage in small-scale district heating systems
Østergaard et al. [2019] investigates an electrification of biomass-based DH systems. Firstly, EnergyPLAN is used to simulate the impacts of heat pumps in a system-wide analysis, were the key takeaways are the heat pumps' capability of integrating fluctuating renewable electricity and the total system socio-economic costs. Secondly, business-economic feasibility studies are made using energyPRO for designing and running the optimal operation in relation to an external electricity market. Østergaard et al. [2019] concludes that heat pumps are capable of integrating local fluctuating renewable electricity, and that they enable a preservation of biomass reserves for other purposes. However, the paper also concludes that transitioning away from biomass is currently not business-economically feasible, thus Østergaard et al. [2019] advocates the need for business-economic incentives.

The research of Østergaard et al. [2019] has many similarities to the research of this thesis. However, this thesis does not only aim to investigate the impacts of integrating heat pumps in a system-wide analysis, but also, analyses the impact on security of electricity supply when reducing the CHP capacity. The latter gives a more holistic perspective on the research, as security of electricity supply is a concern when electrifying the DH sector. Furthermore, the research of Østergaard et al. [2019] focuses solely on a comparison between biomass and heat pump based DH systems, where this research also focuses on reducing natural gas consumption and potentially natural gas CHP capacity in relation to the Danish 2030 DH goals.

Electrifying the heating sector in Europe: The impact on the power sector
Kavvadias et al. [2019] investigates the possibilities of integrating the heat and power sectors in Europe, and the capability of achieving decarbonisation targets with sector integration. They therefore analyse the impacts of an extreme electrification scenario, where they examine how electrifying the heating will affect the security of supply of electricity sector in Europe. The results show, that such a scenario will significantly increase electricity peak demand in the winter by up to 70%.

The research of Kavvadias et al. [2019], does in contrast to the research of Østergaard et al. [2019], examine the impacts on the security of supply of the power sector. However, Kavvadias et al. [2019] focuses on the European energy system, where as this research project focuses on the Danish energy system. Furthermore, Kavvadias et al. [2019] does not focus on the technical- and economic details of DH plants, which is an essential element in this thesis.

Electrification of the Danish district heating sector

A technical report from Siemens A/S [2018] investigates the potential of electrifying the Danish DH sector by implementing large scale heat pumps. The research includes three analyses; a technical analysis of the potential of implementing electric heat pumps, feasibility studies on the business-economic impacts of this implementation, and lastly, an analysis of the environmental benefits when replacing fossil fuel based DH systems with heat pumps. The results show that, transitioning into large scale heat pumps is feasible, from a business-economic perspective when compared to fossil fuel technologies.

The main elements of the technical report from Siemens A/S [2018] is similar to the research of this thesis. However, both the methodological approach and analyses are highly simplified. Furthermore, the research of Siemens A/S [2018] does not include an analysis on the impacts of a large-scale electrification of the DH sector (security of electricity supply), nor does it include an analysis of the institutional and political hindrances for electrifying the Danish DH sector with heat pumps. Furthermore, they neglect a comparison between heat pumps and alternative solutions. Thus, it is difficult to evaluate whether this is a more feasible solution compared to other alternatives.

Although all these studies have elements that fit the problem of this thesis, it has not been possible to find any papers which combine these elements in a way which would allow the primary research question of this thesis to be answered. With the novelty of this research within the field of study examined, the theoretical framework of the research can be explained.

4.2 Theoretical framework

The research design of this project is based on the methodological framework of the Choice Awareness theory. The Choice Awareness theory seeks to promote and implement a technological change, which is the aim of this project as described in Chapter 3 on page 17. The Choice Awareness theory will be elaborated in Section 5.1 on page 27.

Lund [2014] describes four methodological steps that can be utilised to promote the awareness of choice to society. These can be seen in Figure 4.1.

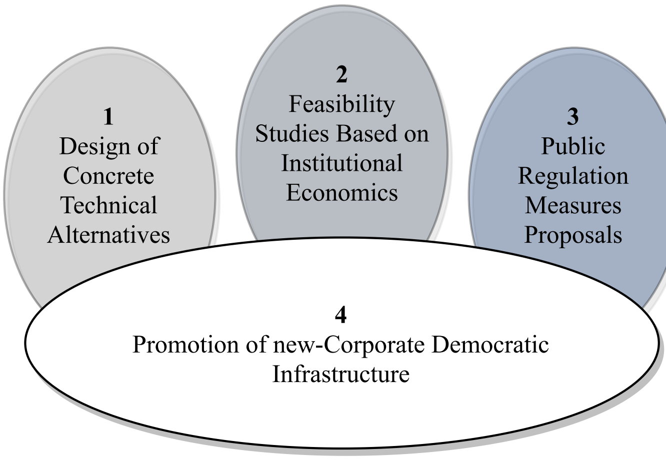

Figure 4.1. The four steps to promote awareness of choice. [Lund, 2014]

The first step of the approach, is to design concrete technical alternatives that promote a radical technological change. Lund [2014] emphasises the importance of this, as society needs to be presented with alternative solutions to choose from. The second step is based on carrying out feasibility studies on the designed alternatives. The purpose of this is to demonstrate their economic viability. Lund [2014] states that this analysis must be made on concrete institutional economics. Thus, this project seeks to investigate both the business- and socio-economic costs of the alternatives. The third step is firstly based on identifying the current market barriers that are preventing a radical technological change, and secondly, proposing new public regulation measures that will promote an implementation. The fourth step takes all the previous steps into account when asking the question: Who should then enforce all of this? Lund [2014] states that one cannot expect a change to happen with the current institutional conditions and advocates a change in the institutional setting. Thus, this step revolves around identifying the current institutional and political hindrances and proposing an institutional change.

As the methodological approach of the Choice Awareness theory has been described, the following seeks to describe how every analysis of this project is going to be carried out. This is done, in order to understand how each analysis contributes to answering the primary research question.

The analysis in Chapter 7 on page 43 seeks to answer the following research question: *To what extent can the electric capacity of natural gas-based combined heat and power plants in Denmark be reduced while maintaining security of electricity supply?*

This analysis is a preliminary technical feasibility study, which is made in order to determine whether it is reasonable to reduce the CHP capacity. This analysis is often neglected in studies where a large scale implementation of electric heating solutions is investigated (see for example the report by Siemens A/S [2018] mentioned in Section 4.1). This is also the case for individual DH companies, which are primarily interested in finding cheap technical alternatives and do not analyse the technical alternatives in the context of the whole energy system. In this analysis, four scenarios of the Danish energy sector in 2030 will be modelled with EnergyPLAN. The conclusion of this analysis will be some general considerations describing to what extent electric capacity of natural gas-based combined heat and power plants in Denmark can be reduced while maintaining security of supply in the electricity sector. The reasons for choosing EnergyPLAN are given in Subsection 6.2.

The analysis in Chapter 8 on page 59 seeks to answer the following research question: *How can electric heating solutions be used to reduce natural gas consumption in the district heating sector and contribute to the achievement of the Danish climate goals of 2030 while maintaining business- and socio-economic feasibility?*

This analysis is performed in accordance with the first three methodological steps from the Choice Awareness theory. The analysis therefore contains models of technical alternatives at plant level, feasibility studies, and an examination of how changes in public regulation affects the designed alternatives. This is all done to raise choice awareness to society as advocated by Lund [2014]. As it is unrealistic to carry out all of the aforementioned steps for all natural gas-based combined heat and power plants in Denmark, it has been chosen to work with one paradigmatic case. The paradigmatic case theory and case study selection are explained further in Subsection 4.3.2 and Section 6.1, respectively.

Performing the analysis, a natural gas-fired CHP plant is modelled in energyPRO as explained in Subsection 6.3. Here, different alternative technological solutions will be evaluated and compared based on feasibility studies including their business- and socio-economic costs. Lastly, energyPRO will be used to examine public regulation measures that either hinder or promote the designed technical alternatives.

The analysis in Chapter 9 on page 83 seeks to answer the following research question: *What are the institutional and political hindrances in the implementation of a socio-economically feasible electrification of the district heating sector in 2030 and how can these be overcome?*

This analysis is performed in accordance with step four of the Choice Awareness theory. Lund [2014] advocates that a change in the current institutional and political structure is needed, in order to actually implement a technological change. Therefore, that is the topic of the third analysis. The course of action in the analysis of Chapter 9, will take point of departure in the methodological approach of an institutional analysis. This approach is explained further in Section 6.5 on page 40. The analysis is also based on political economy- and power theory as elaborated in Section 5.2 and Section 5.3.

4.3 Research development

As the theoretical framework has been described, this section seeks to describe the research development and overall structure. Thus, this section includes the research approach, research strategy, choice of method for data collection and the overall structure of the project. The choices made within the research development can be seen in Figure 4.2.

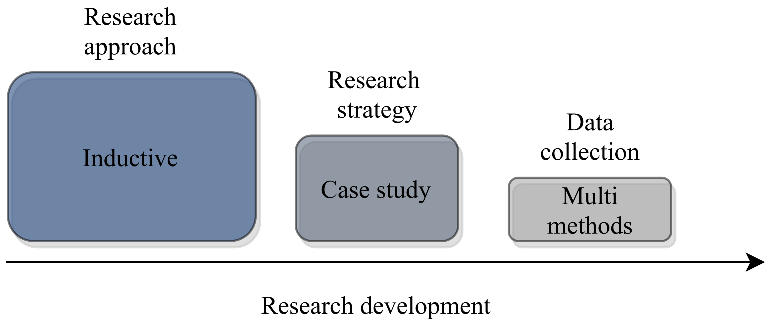

Figure 4.2. The research developments' three steps.

4.3.1 Inductive research approach

A research approach is categorised into three types, respectively: Deductive, inductive and abductive. This project utilises the inductive research approach as seen in Figure 4.2. The inductive research approach is based on making tests and/or observations which becomes the basis of a theory. [Business Research Methodology, 2020]

The steps of the inductive research approach and how they are applied in this project, can be seen in Figure 4.3.

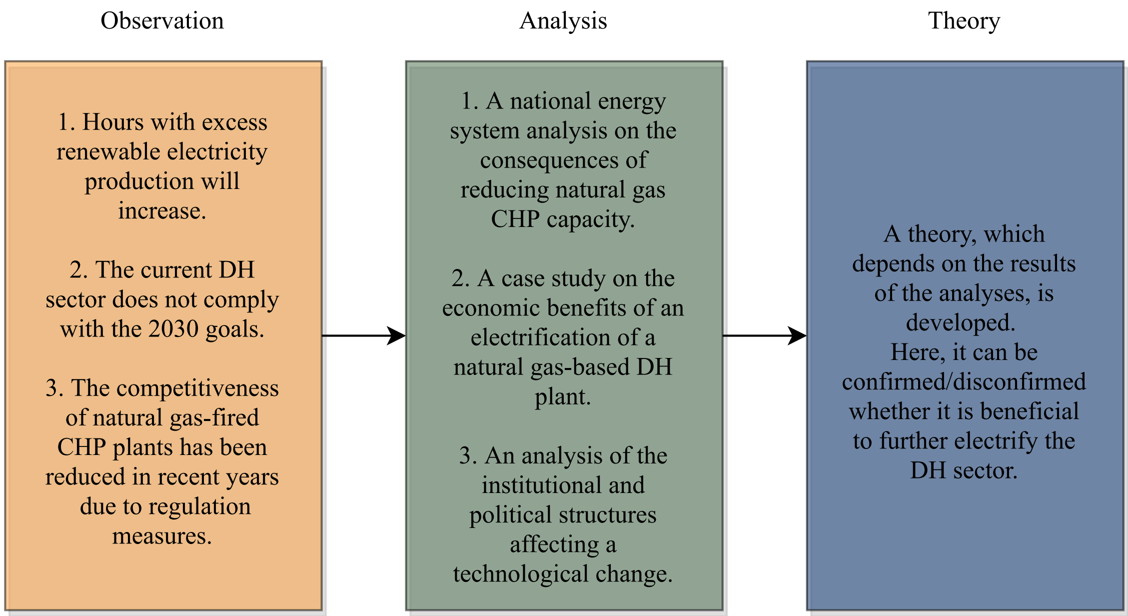

Figure 4.3. The inductive steps taken in this research development [Business Research Methodology, 2020].

4.3.2 Case study

The research strategy that the aforementioned inductive research approach is based on, is a case study. The framework of the case study theory is based upon a detailed examination of a single entity, with the goal of exploring certain phenomena within this entity. Thus, the entity is referred to as a "case". The case can either be chosen based on specific parameters or randomly, depending on the intention behind the research. [Flyvbjerg, 2006]

Flyvbjerg [2006] highlights that a case study and the results found, can be used to generalise to a broader spectrum if the case selection and examination is done right. As the case study of this project uses the information oriented selection, the four types of selection, outlined by Flyvbjerg [2006], are listed below:

- Extreme/deviant case
- Maximum variation cases
- Critical cases
- Paradigmatic cases

The extreme/deviant case selection is used to obtain knowledge about a more unusual entity. This abnormality could be based on some atypical successes or failures, that other cases have not had. The maximum variation case selection is used to obtain knowledge from multiple cases that purposely vary on defined parameters (e.g. emissions, capacity etc.) This is often used, in order to conduct research within a larger scale/range, as the researcher selects cases which differ as much as possible. The critical case selection is used to logically deduct the results and thus, permits a generalisation (e.g. if this energy system configuration is the most feasible in this case, then it will be the most feasible for all cases). The paradigmatic case selection is used to establish an example that can represent multiple entities. [Flyvbjerg, 2006] This project utilises the paradigmatic case, as it is a goal of the analysis to utilise a case with an average size CHP plant in order to be able to generalise the results to multiple typical CHP plants in Denmark. The case selection and how it is applied, will be described further in Section 6.1 on page 31.

4.3.3 Multi methods

As seen in Figure 4.2, the data collection method chosen is multi methods. Multi methods is based on the researcher utilising both qualitative (descriptive) and quantitative (numeric) data to carry out the research. Also, multi methods deviates from other data collection methods, as the qualitative and quantitative data collection does not intertwine in order to create a data set. These methods are instead, in this project, tied up to collecting the data needed to carry out its respective analysis (e.g. quantitative data is used to carry out the analyses in Chapters 7 and 8, where as qualitative data is used to carry out the analysis in Chapter 9). [Saunders et al., 2007]

4.4 Research structure

Figure 4.4 creates an understanding of the research design as a whole, including which theories and methods that are applied in order to carry out the three analyses.

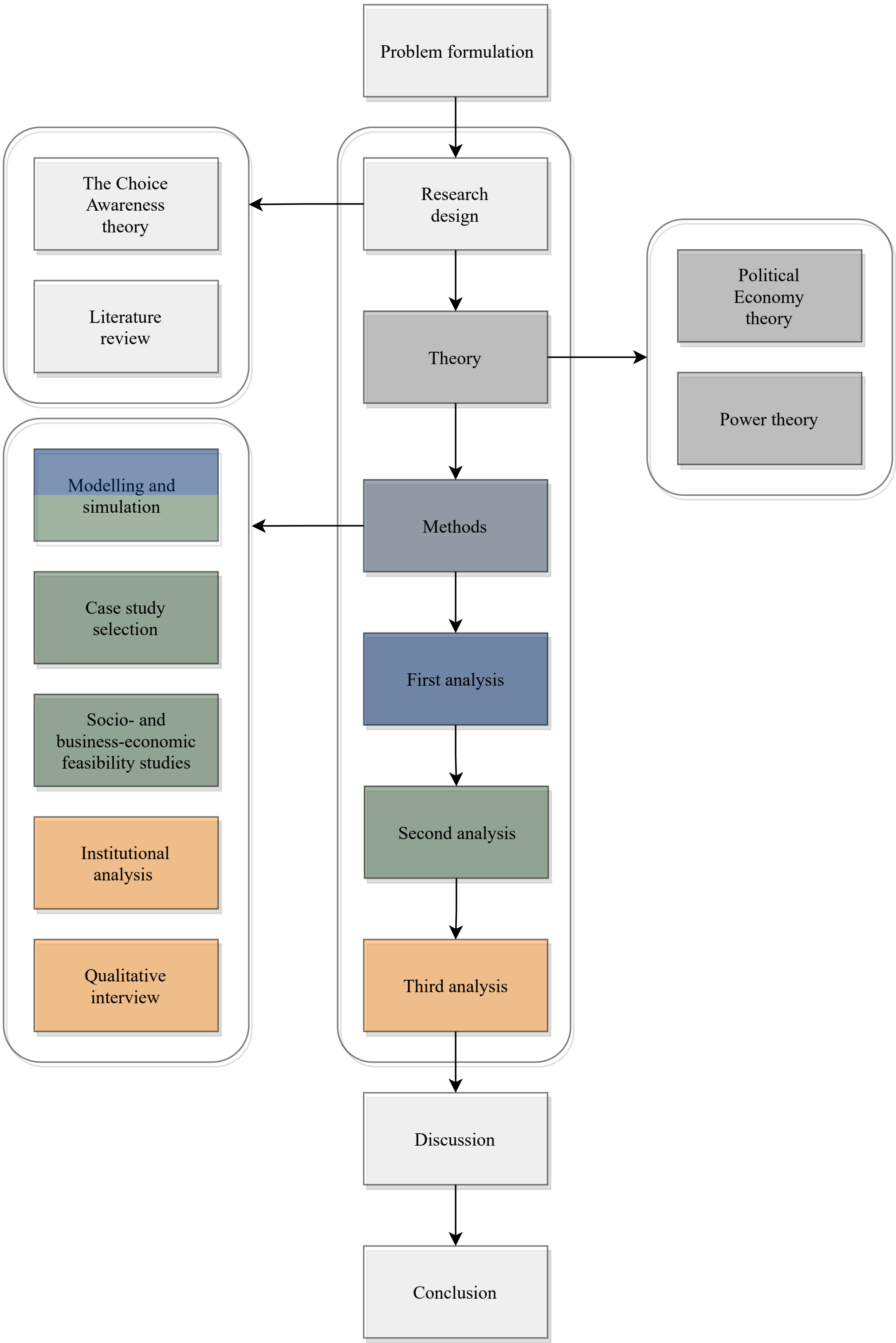

Figure 4.4. The overall research structure of this project.

Theory 5

The Choice Awareness theory is applied as the overall theoretical framework of this project, with the underlying theories; Political Economy theory and Power theory. The following chapter therefore seeks to describe the Choice Awareness theory and the underlying theories, including how they are applied to answer the research question described in Chapter 3 on page 17.

5.1 The Choice Awareness theory

The Choice Awareness theory is based on two overall theses. The first thesis of the theory, revolves around understanding the current institutional setting and how organizations within this setting are trying to eliminate an implementation of a radical technological change. The thesis is connected to Power and Discourse theories, as it emphasises that every organisation sees things differently. These organisations will therefore, on an institutional level, seek to eliminate the implementation of change in society. It is an underlying assumption in the Choice Awareness Theory that radical technological change cannot happen within the current institutional setting and that it must be changed. To keep their position of power and influence, the old market dependent organisations will try to avoid a radical technological change, by eliminating alternative solutions in the decision making. Often, this will lead to a 'no-choice' perception from society, as alternative solutions have been eliminated from the agenda. The second thesis within the Choice Awareness theory, is based on raising awareness within the society about the alternative solutions for an implementation of a radical technological change. Lund [2014] explains that society will benefit from becoming aware of the selection of choices. He therefore emphasises, not only the importance of finding alternatives solutions but also the importance of making feasibility studies and examining public regulation measures and institutional barriers for alternative solutions. [Lund, 2014]

5.2 Political Economy theory

As the analysis in Chapter 9 on page 83 examines the political structure of DH in Denmark, there is a need to shed a light on the Political Economy theory and the paradigms it contains. Thus, the article *Innovative democracy, political economy, and the transition to renewable energy* by Hvelplund [2014] has been used as a part of the theoretical framework, to carry out the analysis in Chapter 9 on page 83. Hvelplund distinguishes between three types of political economy paradigms: Neoclassical approach, Concrete Institutional approach and Innovative Democracy.

The Neoclassical approach is generally based on a 'free market' structure, where RE companies should enter the market when they are ready to be competitive. Nonetheless, neoclassicism recognises the impact of externalities, and deals with them through e.g. CO_2 quotas etc. All of the aforementioned leads to a 'free market' structure, with the perception that the market will regulate itself without almost any interference. This though, hinders the implementation of RE technologies as RE companies do not necessarily have the ability to be competitive under the current market conditions. [Hvelplund, 2014]

The Concrete Institutional approach is expert based, meaning that it can be seen as technocratic and takes a step forward from neoclassicism. It acknowledges that the Neoclassical approach is not adequate for energy planning, by recognising that the market structure and conditions can be changed and/or redesigned. However, this paradigm does not significantly interfere with the market structure. The Concrete Institutional approach assumes that a technological change will happen at a certain stage, when the RE technologies have become more business-economically feasible and thereby competitive. [Hvelplund, 2014]

Innovative Democracy is a paradigm that recognises that the current market structures and political processes need to be redesigned to favour the 'new market dependent organisations' and thereby the implementation of RE technologies. This should be done, to enable the companies to be a strong opposition against the fossil fuel path dependent companies, who currently have an advantage within the current market. Hvelplund [2014] advocates the need for Innovative Democracy, if a technological change is wanted, which correlates with Lund [2014]. Similar to the Choice Awareness theory, Innovative Democracy realises that without any institutional interference, the RE companies will meet a great resistance, which can be assumed to hinder a technological change. [Hvelplund, 2014]

5.3 Power theory

As Chapter 9 on page 83 deals with identifying the current institutional hindrances, it is important for the researcher to understand the current power structures that exist within the institutional setting. Also, this project seeks to discuss whether these power structures are adequate for promoting a technological change. Thus, the Power theory has been applied. Power theory can in a research related perspective be defined in different ways, depending on the purpose of the research. This research seeks to use Barnett and Duvall [2005], to dissect the different layers of relational power that exist within the current institutional setting in order to locate institutional hindrances as described in the Choice Awareness theory's fourth step. Barnett and Duvall [2005] distinguishes between four different taxonomies of power in order to describe the power relations that exist between the different actors. These actors have in this research been defined as the organisations that exist within the institutional setting, in order to make it correlate with the Choice Awareness theory. The different taxonomies of power can be seen in Figure 5.1.

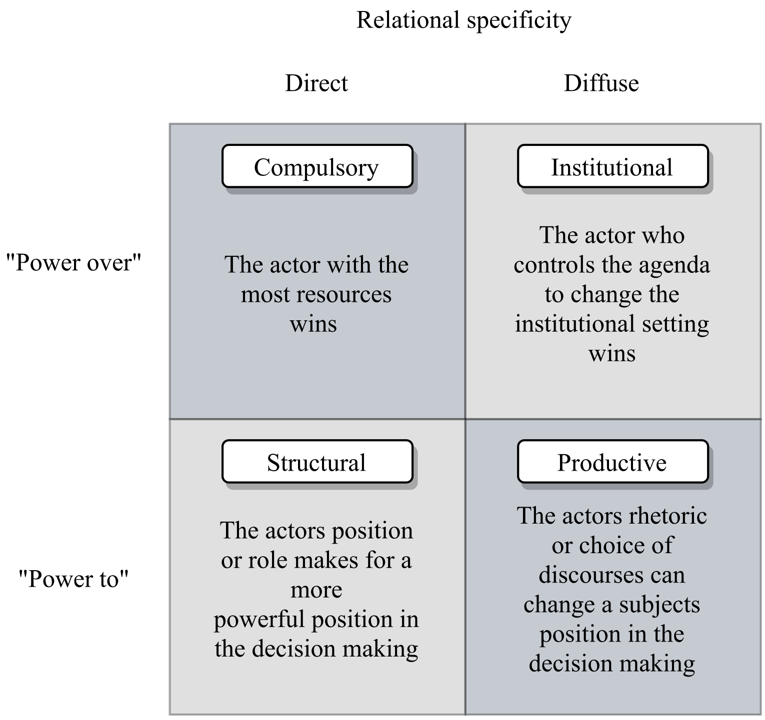

Figure 5.1. The four taxonomies of power [Barnett and Duvall, 2005].

As seen in Figure 5.1, a fourfold power taxonomy is described by Barnett and Duvall [2005] where each box visualises a conceptual type of power. Compulsory power exists when an actor has the power to change an actor's existence or actions (e.g. behavioral change). This relation of power is defined as direct where the actor with the most resources has the most power. Institutional power exists through an actor's ability to indirectly affect other distant actors' conditions (e.g. public regulation). This type of relation is therefore defined as more diffuse. Structural power exists in internal social structures and constitutions, where an actors' social relations makes for a more powerful position (e.g. the relation between decision making parties and the consumers of a DH company). This type of power differentiates from the institutional power, as it is defined as more direct. The productive power exists, in the same matter as the structural power, as it is also constructed socially. However, it differs as the power occurs not through relations but through an actor's knowledge or choice of discourses. Also, the productive power is defined as diffuse, in contrast to structural power, as it refers to a broad and more general social constitution, not only internally within an institution but to all actors (e.g. through social networks). [Barnett and Duvall, 2005].

Methods 6

This chapter contains descriptions of the methods used in this thesis including the case selection, modelling and simulation, feasibility studies, institutional analysis, and the qualitative interview method.

6.1 Case selection

As mentioned in Subsection 4.3.2, the paradigmatic case study is used to represent multiple entities within the same domain [Flyvbjerg, 2006]. In year 2018, there were 190 CHP plants in Denmark with natural gas as the primary fuel, and only two of these plants were located in centralised areas. Thus, to make a case study that represents as many entities as possible, only decentralised CHP plants will be investigated. Furthermore, it is a criteria, that no significant amount of the DH production comes from excess heat from industry or heat production based on electric heating solutions (no more than 25%).

The remaining 183 decentralised natural gas-based CHP plants, that do meet the criteria, have an average electric capacity of 5.5 MW, an average thermal capacity of 16.7 MW, and an average natural gas share of the heat production at 93%. A case that represents multiple other decentralised natural gas-based CHP plants is Oksbøl Varmeværk a.m.b.a (in this project referred to as Oksbøl CHP plant). Oksbøl CHP plant has an electric capacity of 5.5 MW, a thermal capacity of 24.7 MW, and an natural gas share of the heat production at 81%. Furthermore, Oksbøl CHP plant currently does not have electric heating solutions, nor any excess heat from industry. The electric- and heat capacities compared to the other 182 decentralised CHP plants in Denmark, that meet the criteria, can be seen in Figure 6.1. [Danish Energy Agency, 2018a]

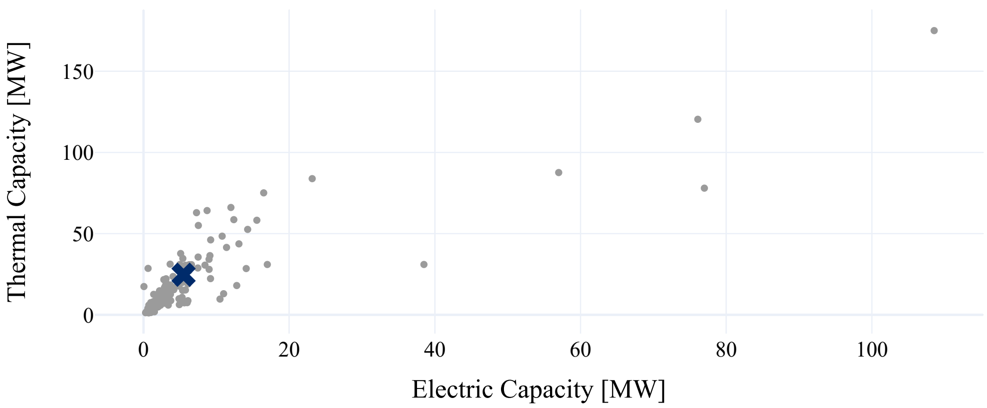

Figure 6.1. Electric- and heat capacity of Oksbøl CHP plant compared to other plants that fit the criteria. Oksbøl CHP plant is represented with the X.

The main parameter for choosing Oksbøl CHP plant as a representative case is the electric capacity which is exactly at the average of all the CHP plants within the criteria. The heat capacity is a higher than the average thermal capacity of the 183 CHP plants. However, as seen in Figure 6.1 the thermal capacity at the plants does vary more than the electric capacity and the impacts of a higher thermal capacity it estimated to have a minor impact on the ability to generalise the results form the case study. Thus the selection can be verified as adequate for the paradigmatic case type. It should be noted that Oksbøl CHP plant has an annual heat production of less than 500 TJ like the majority of the decentralised CHP plants in Denmark. Therefore, the plant is not obligated to comply with the co-generation and fuel binding requirements (see Subsection 2.4.1 on page 13). A detailed case description will be presented in Section 8.2 on page 60.

6.2 EnergyPLAN

The energy system analysis tool *EnergyPLAN* is used in Chapter 7 on page 43, which is made to answer the first underlying research question. There are two main reasons why EnergyPLAN has been chosen:

1. EnergyPLAN is designed for national energy system analyses, and it takes the heat and transport sectors into account [Lund and Thellufsen, 2020]. *This is appropriate in the first analysis, because maintaining security of electricity supply in Denmark is a national concern, and all electricity production and consumption units - regardless of sector - need to be taken into account to get a representative result.*

2. EnergyPLAN is a simulation/scenario model, as opposed to an optimisation model, which means that it is meant for comparing energy system scenarios on several criteria, rather than finding *the* optimal (e.g. least cost) energy system configuration [Lund et al., 2017]. *A scenario model is appropriate for the first analysis, because the researchers wish to compare a number of scenarios on several criteria or 'key parameters'. It is not the main purpose of the analysis to determine which scenario is superior. Rather, the usage of multiple scenarios is a form of sensitivity analysis - to investigate the extent to which the ability to reduce the CHP electric capacity, while maintaining security of electricity supply, is dependent on the uncertain evolution of the Danish energy system toward 2030 (partly illustrated on Figure 2.4).*

EnergyPLAN, which simulates one year of operation based on hourly steps, has a number of inputs and a number of outputs. Inputs include: electricity demands; heat and cooling demands (individual and DH); fuel consumption in both transport and industry; installed capacities for boilers, CHP plants, other power plants, and RE technologies; biofuel/biogas production; electrolyser capacity; storage; and a number of hourly distribution profiles. Outputs, which are based on energy balances, include: CO_2 emissions; total fuel consumption; annual costs; electricity import and export, among other things. [Lund and Thellufsen, 2020]

EnergyPLAN has two overall simulation strategies: a technical simulation strategy and a market-economic simuation strategy, and these are fundamentally different. With the technical simulation strategy, the consumption of fossil fuel is minimised, which is done by e.g. covering as much of the electricity- and heat demands as possible with renewable technology (e.g. wind turbines, PV panels, solar collectors), and only covering the remainder with fossil fuel-based technology. Electricity is only imported/exported if it cannot be produced/consumed nationally. With the market-economic simulation strategy, the operation cost is minimised. Wind and solar for electricity- and heat production is still prioritised, but with this strategy it is because of the assumption that their marginal production costs are zero. Power production with condensing power plants, geothermal power plants and nuclear power plants only occurs in the hours where the electricity price on the external market exceeds their variable operation costs. [Connolly, 2015; Lund and Thellufsen, 2020]

In the analysis in Chapter 7 on page 43, the technical simulation strategy is used. This is because the total system cost is irrelevant, as the analysis only seeks to investigate the energy system's technical capability to ensure security of electricity supply.

6.3 energyPRO

The energy project analysis tool *energyPRO* is used in Chapter 8 on page 59, which is made to answer the second underlying research question. There are four main reasons why energyPRO has been chosen:

1. energyPRO is designed for, among other things, the analysis of DH projects at the plant level. It makes it possible to define detailed specifications of units (heat pumps, solar collectors, heat storage etc.) and it can take O&M costs, taxes and tariffs, and emissions into account [EMD International, 2017]. *This is appropriate in the second analysis, because the researchers wish to carry out detailed analyses of a specific CHP plant in Denmark.*
2. Unless defined differently, the operation strategy in energyPRO is based on minimising the net heat production cost (NHPC) [EMD International, 2017]. *As this research is based on comparing the economic feasibility of a number of scenarios, it is important that the operation strategy in all scenarios is based on achieving the lowest possible heat cost.*
3. energyPRO allows the user to choose the FINANCE calculation module, which enables multiyear analyses taking into account investments and financing. By using indexes, various time series (electricity prices, gas prices, wood chip prices etc.) can be set to develop over the years [EMD International, 2017]. *This is appropriate, as the researchers wish to evaluate the scenarios over the entire lifetime of the new technologies, while using the projection from the Danish Energy Agency [2020a] to define future electricity prices, gas prices etc..*
4. Utilising the INTERFACE module, a single energyPRO model can be set to run multiple times with each run changing one or several values in the model, such as capacities of units, fixed O&M costs, taxes etc., and the output can, for instance, be the financial key figures [EMD International, 2021]. *The ability to vary the capacities of multiple new technologies, simultaneously, is important. It allows the researchers to 'optimise' the new capacities - meaning to find the combination (out of those investigated) which results in the lowest costs - without having to manually make and run, for instance, 25-30 energyPRO models for each scenario.*

A comprehensive explanation of the calculations behind the operation strategy in energyPRO can be found in the *energyPRO User's Guide* (see EMD International [2017]).

6.3.1 Modelling the reference scenario

The reference scenario of the case study on Oksbøl CHP plant contains the following technologies: natural gas engines and boilers, solar collectors, and heat storage. A detailed description of the case-specific inputs is given in Section 8.2 on page 60 (e.g. capacities, efficiencies, and external conditions). The reference scenario technologies are modelled in energyPRO as follows.

Natural engines and boilers

The efficiency of natural gas engines and boilers will vary slightly throughout the year due to differences in DH return temperature, part-load operation and different external conditions [Danish Energy Agency, 2020g]. However, in this model the efficiencies are assumed constant throughout the year at an average efficiency taken from previous years of operation in Oksbøl CHP plant. The electric and thermal output of the natural gas engines is shown in Equation 6.1 and 6.2:

$$P_e = \eta_e Q_{ng} \quad (6.1) \qquad P_h = \eta_{th} Q_{ng} \quad (6.2)$$

Where:

Q_{ng} = natural gas input [MW]
η_e = electric efficiency [-]
η_{th} = thermal efficiency [-]

The heat production of the natural gas boilers is simply given with:

$$P_b = \eta_b Q_{ng} \quad (6.3)$$

Where:

Q_{ng} = natural gas input [MW]
η_b = overall boiler efficiency [-]

Solar collectors

When modelling the solar collectors of Oksbøl CHP plant, the Incidence Angle Modifier (K_θ) is used [EMD International, 2017]. This modifier describes the efficiency reduction when the sun is not directly perpendicular to the solar collector e.g. the incidence angle changes during the day and year. The incidence angle modifier (K_θ) can be found with Equation 6.4:

$$K_\theta = 1 - tan^a\left(\frac{\theta}{2}\right) \quad (6.4)$$

Where:

θ = incidence angle on the collector [-]
a = measured coefficient [-]

The angle of incidence from direct radiation is calculated by energyPRO with time of the day, the location of the CHP plant and the orientation and inclination angle (tilt) of the solar collectors (see EMD International [2017]). The inclination angle of the solar collectors is assumed to be 40° and the the solar collectors are facing south. The coefficient a is a measured value and can be found through tests of the solar collector (Arcon-Sunmark HT-SolarBoost 35/10) [SPF Institute for Solar Technology, 2017].

The thermal power output of the solar collectors, as modelled in energyPRO, is given by Equation 6.5:

$$P_{sc} = A_{sc}\left[\left(I_{direct}K_{\theta} + I_{diffuse}K_{60^{\circ}}\right)\eta_o - a_1(T_m - T_a) - a_2(T_m - T_a)^2\right] \tag{6.5}$$

Where:

I_{direct} = direct solar radiation $[W/m^2]$
$I_{diffuse}$ = diffuse solar radiation $[W/m^2]$
A_{sc} = solar collector area $[m^2]$
T_m = average solar collector temperature $[C^{\circ}]$
T_a = ambient temperature $[C^{\circ}]$
η_o = maximum collector efficiency (also called conversion factor) [-]
a_1 = first-degree heat loss coefficient of solar collector $[W/(m^2C^{\circ})]$
a_2 = second-degree heat loss coefficient of solar collector $[W/(m^2C^{\circ})]$
$K_{60^{\circ}}$ = Incidence Angle Modifier used for diffuse radiation is $60C^{\circ}$[-]

The supply and return temperatures of the solar collectors will vary throughout the year, but is in this model assumed to be constant at 70C° and 40C°, respectively. The three parameters that define the solar collector efficiency (η_o, a_1 and a_2) are found in the fact sheet of the solar collectors used in Oksbøl CHP plant [SPF Institute for Solar Technology, 2017].

Heat storage

When modelling the thermal energy storage content, energyPRO uses the temperature difference of the top and bottom of the storage tank. In this project, constant temperatures of 80C° in the top and 32C° in the bottom are used, taken from average storage temperatures at Oksbøl CHP plant [Oksbøl Varmeværk, 2021]. In practise, not all energy content in the thermal storage tank can be utilised. It is assumed that 90% of the stored energy capacity can be utilised, thus slightly reducing the available storage capacity per volume [Danish Energy Agency, 2018c].

Losses of 0.2% per day as advocated by [Danish Energy Agency, 2018c] is not included as in the energyPRO model. The heat loss as a result of storage is on the other hand included in the total system losses as the data provided by Oksbøl CHP plant is heat production and not consumption.

The power outflow (and inflow if negative) of the storage units can be expressed as:

$$P_s(t_i) = S_t(t_{i-1}) - S_t(t_i) \tag{6.6}$$

Where:

$P_s(t_i)$ = thermal output of storage [MW]
$S_t(t_i)$ = stored thermal energy [MWh]

All production units are allowed to produce heat to the thermal energy storage. [EMD International, 2017] [Carpaneto et al., 2015]

6.3.2 Modelling the alternative scenarios

The alternative technologies modelled for the alternative scenarios in the case study of Oksbøl CHP plant are: electric boiler, wood chip boiler, and heat pump. The arguments for the chosen technologies and the development of the alternative scenarios are described in Section 8.5 on page 66.

Electric boiler

The thermal output of the electric boiler is simply given with:

$$P_{eb} = \eta_{eb} P_{el} \tag{6.7}$$

Where:

P_{el} = power input to the electric boiler [MW]
η_{eb} = overall boiler efficiency [-]

The boiler efficiency is assumed to be 100% and the operation strategy is dependent on the DK1 spot and regulating power markets [Danish Energy Agency, 2020g]. The operation strategy of the electric boiler in the downward regulating power market is modelled as:

$$\textbf{IF } DK1_{Spot} > DK1_{reg,d} \textbf{ AND } \text{NHPC}(DK1_{reg,d}) < \text{NHPC}(Alternative) \quad \textbf{THEN } P_{eb,reg} = P_{eb} = \eta_{eb} P_{el,reg} \tag{6.8}$$

Where:

$DK1_{Spot}$ = hourly spot marked price [DKK]
$DK1_{reg,d}$ = hourly downwards regulating power price in DK1 [DKK]
$NHPC(DK1_{reg,d})$ = heat production cost on regulating power market [DKK]
$NHPC(Alternative)$ = alternative heat production cost on other units [DKK]

If, on the other hand, $DK1_{spot}$ prices are lower than or equal to $DK1_{reg,d}$ prices, the electric boiler will operate on the spot market if feasible compared to heat production on other DH producing technologies. Modelling the correct operation strategy of the electric boiler on the regulating power market is a difficult task and assumptions are made in the process. In practice, a DH plant with electric boilers submit a regulating power bid to the TSO depending on the alternative heat production cost from other units. Here the downward regulation bids from multiple bidders will be activated in price order. The method used when modelling the electric boiler assumes an ideal market, where bids are activated when needed - at the regulating power prices in DK1 (on average 45 DKK/MWh lower than the spot market price). However, there may be periods where the bid is not activated e.g. if the bidding price from the plant does not represent the activating bidding price or if regulating power is not needed. In this case the heat demand must be covered by other units which may make the operation expenditures of the system higher in reality than suggested by the model. On the other hand, the market for special regulation (see Subsection 2.2.1) is not included in the analysis. This market historically has been a highly feasible for DH plants with electric boilers to participate in and might result in lower heat production costs if included. [Energinet, 2017; Detlefsen, 2016]

As a result of the mentioned uncertainties in the model of the electric boiler on the regulating power market, both a scenario on the spot market alone and a scenario on the spot market and regulating power market is modelled.

Biomass boiler

Wood chip boilers are usually the most favourable type of biomass boiler for smaller DH purposes (below 20 MW), and thus, this is the most popular option. [Danish Energy Agency, 2020g]

The thermal power production of a wood chip biomass boiler is given by:

$$P_{bb} = \eta_{bb} Q_{bio} \tag{6.9}$$

Where:

η_{bb} = overall biomass boiler efficiency [-]
Q_{bio} = fuel input (wood chips) to the biomass boiler [MW]

It is assumed that the biomass boiler comes with flue gas condensation resulting in an efficiency of 114% [Danish Energy Agency, 2020g].

Heat pump

The coefficient of performance (COP) of heat pumps is in energyPRO modelled with a Lorentz heat pump model:

$$COP_{Lor} = \frac{T_{lm,H}}{T_{lm,H} - T_{lm,L}} \tag{6.10}$$

Where:

$T_{lm,H}$ = is the logarithmic mean temperature of the provided hot water [K]
$T_{lm,L}$ = is the logarithmic mean temperature of the heat source [K]

The logarithmic mean temperature is be expressed as:

$$T_{lm,H} = \frac{T_{H,o} - T_{H,i}}{\ln T_{H,o} - \ln T_{H,i}} \tag{6.11}$$

$$T_{lm,L} = \frac{T_{L,o} - T_{L,i}}{\ln T_{L,o} - \ln T_{L,i}} \tag{6.12}$$

Where:

$T_{H,o}$ = temperature of the water delivered by the heat pump [K]
$T_{H,i}$ = temperature of the water entering the heat pump [K]
$T_{L,o}$ = outflow temperature of the heat source (air) [K]
$T_{L,i}$ = inflow temperature of the heat source (air) [K]

A Lorentz efficiency is calculated as $\eta_{Lor} = \frac{COP_{HP}}{COP_{Lor}}$ from the COP and design parameters of an actual compression heat pump with a COP of 3.4 [Danish Energy Agency, 2020g]. This efficiency is used to convert the theoretical (ideal) Lorentz cycle into an actual heat pump cycle.

The hourly Lorentz COP is calculated from the supply and return DH temperatures as well as the ambient temperatures which is cooled with 5 K. Thus, the hourly heat output of the heat pump is given with equation 6.13:

$$P_{hp} = COP_{Lor}\eta_{Lor}P_{el} \tag{6.13}$$

Where:

COP_{Lor} = calculated Lorentz COP in a given hour [-]
η_{Lor} = Lorentz efficiency [-]
P_{el} = power input to the heat pump [MW]

The assumed supply- and return temperatures are estimated to be between 74.5-80.3 °C and 31.8-35.1 °C, respectively. These temperatures are taken on a monthly basis from 2020 data at Oksbøl CHP plant.

6.4 Socio- and business-economic feasibility studies

As stated in the research question, an important aspect of this project is to make sure that the solutions for electrifying DH systems, which are developed here, are socio-economically feasible. Therefore, to help answer the second underlying research question in particular, socio-economic analyses of various possible solutions are made.

While socio-economic analyses can reveal the least expensive solution for society, that solution will not necessarily result in the lowest DH price. Therefore, business-economic analyses of the solutions are also made.

The Danish Energy Agency [2018d] has made a detailed guide (with particular focus on the heating sector) for carrying out socio-economic analyses of energy projects, and it will be used in this project. The guide also contains a comparison of socio-economic and business-economic analyses. Certain elements are included in both, while others are only included in one or the other. This is shown in Table 6.1.

Table 6.1. Comparison: elements in socio-economic and business-/user-economic analyses [Danish Energy Agency, 2018d].

	Business- and user-economic analyses	**Socio-economic analyses**
Investment costs	X	X
Operation and maintenance costs	X	X
Fuel costs	X	X
Electricity costs	X	X
CO_2 quota costs	X	X
Other air emissions and externalities		X
Taxes and subsidies	X	
Energy savings	X	X
Tax distortion losses from taxes and subsidies		X
Net tax factor		X

The category 'Other air emissions and externalities' encompasses emissions such as methane (CH_4) and nitrous oxide (N_2O) (which are both GHGs) as well as nitrogen oxides (NO_x) and sulfur dioxide (SO_2) (which are air pollutants). These four are all included in this project, and their socio-economic costs are estimated by Danish Energy Agency [2019b]. It should be noted that the emissions from a certain amount of fuel consumption is technology-dependent, meaning for instance that the CH_4 emission is far greater when using natural gas in an engine compared to using it in a boiler. Production of electricity consumed at a DH plant has also caused emissions (with the current power generation mix) and these emissions are also taken into account. [Danish Energy Agency, 2019b]

Taxes, which are taken into account in the business-economic analysis, are comprised of the energy tax, the CO_2 tax, the NO_x tax, and the CH_4 tax (see Table D.1 on page 133).

If a project results in lower tax income due to a change to e.g. less taxed fuels such as biomass, a tax distortion loss must be included in a socio-economic assessment. The lost tax income is not in itself a socio-economic cost as the funds will be found elsewhere. The redistribution of funds will have a societal cost and is estimated by the Danish Ministry of Finance to be at 10% of the lost tax revenues.

The net tax factor is currently 1.325, as defined by the Danish Ministry of Finance. It is used to calculate market prices from so-called factor prices (which are prices without taxes and subsidies). In socio-economic analyses, the following values (if expressed in factor prices) need to be multiplied with the net tax factor: investment costs, O&M costs, fuel costs, and CO_2 quota costs. [Danish Energy Agency, 2018d]

Once all of the income and costs of each solution have been determined, the *net present value* (NPV) of each solution can be calculated. This makes it possible to compare their socio-economic or business-economic feasibility. The NPV is calculated as shown in Eq. 6.14.

$$NPV_{t=0} = \sum_{t=1}^{T} \frac{B_t - C_t}{(1+r)^t} \tag{6.14}$$

Where T is the lifetime of the solution, while B_t and C_t are, respectively, the income and costs in the period t, and r is the discount rate. In January, 2021, the discount rate for socio-economic analyses was lowered from 4% to 3.5% by the Danish Ministry of Finance [2021]. Lowering the socio-economic discount rate is generally favourable for RE projects.

The term *net present cost* (NPC) is also used, and it is simply defined as follows:

$$NPC = -NPV \tag{6.15}$$

6.5 Institutional analysis

In order to answer the research question, it is necessary to carry out an institutional analysis, that takes point of departure in the methodological approach from Arts and Tatenhove [2006]. The four steps of the institutional analysis are described below.

Step 1: Define political modernisation processes

The first step of the analysis is based on selecting political modernisation processes. In this case, the relevant political modernisation processes are the Energy Agreements and climate law mentioned in Section 2.1 on page 3, because these affect the possible electrification of Oksbøl CHP plant.

Step 2: Analyse structural properties - Actor analysis

The second step of the analysis is based on examining the institutional setting and the actors within. Here, actors with an interest/influence on the defined political modernisation process and specifically interest/influence on the future transition of Oksbøl CHP plant are defined. The actors are shown on a mind map to give a general overview. From the mind map, the most relevant actors are selected and only these actors are in focus in the rest of the analysis. This is done, in order to enable a more thorough relation/interaction and power analysis of the defined actors for the remainder of the actor analysis. The methodological approach of this step, is to place the actors within an interest and power matrix as seen in Figure 6.2.

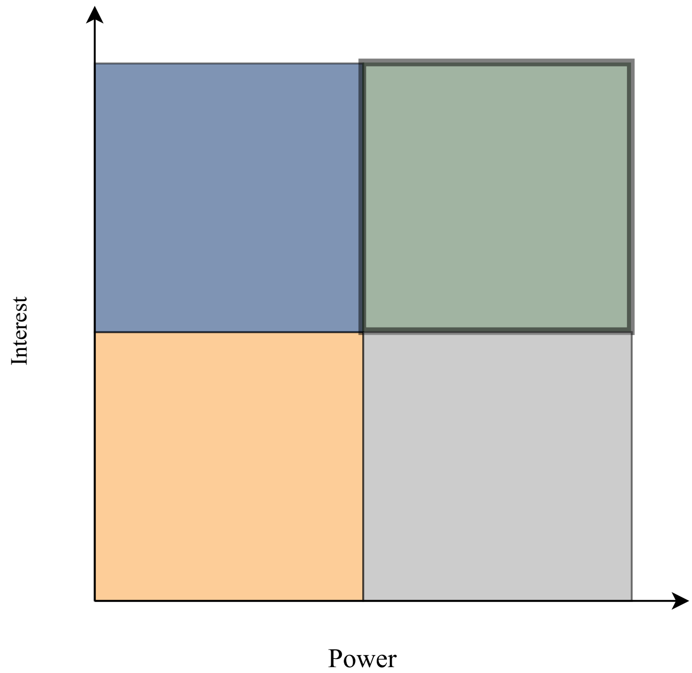

Figure 6.2. The interest/power matrix used to define the most relevant actors for the remaining part of the actor analysis [Mitchell et al., 1997].

The actors are placed by combining and comparing their interest and power on the defined political modernisation process and on the future transition of Oksbøl CHP plant.

Step 3: Actor Interaction

Following the definition of the most relevant actors, the actors' relation/interaction is analysed. This is done by examining the actors' direct and indirect interaction. Direct interaction is defined as a two way interaction where the actors purposely interact through conversation, meetings, hearings etc. Indirect interaction is defined as a one way interaction where the actors indirectly interact through e.g. regulation. It is necessary to analyse the actor interactions to enable an analysis of the power structures. The theoretical and methodological approach described in Section 5.3 on page 28 is used to analyse the taxonomies of power between the actors, by defining their power to influence the decision making of Oksbøl CHP plant. This is done, in order to enable a discussion of whether the current power structures within the institutional setting will either promote or hinder an electrification of the DH in Denmark.

Step 4: Political structure and hindrances

The fourth step of the institutional analysis is based on examining the past and present political paradigms to see how these have affected the promotion of RE. This part takes a point of departure in the Political Economy theory described in Section 5.2 on page 27 and aims to showcase how the different governments have either hindered or promoted a RE transition. When the past and present political paradigms are identified and examined, a discussion of the influence of innovative democracy in relation to an electrification of the DH in Denmark is enabled.

Lastly, all of the identified institutional and political hindrances for electrifying the DH in Denmark are listed and discussed. Also, recommendations, if needed, are made in order to overcome the found hindrances. This is defined as a promotion of a new-corporate democratic infrastructure as advocated by Lund [2014].

6.6 Qualitative interview

The qualitative interview method is used as the primary data collection method used to carry out Chapter 9 on page 83. Brinkmann and Tanggaard [2010] states the different ways to perform qualitative interviews and distinguishes between fully structured, semi-structured and unstructured interviews. The type of qualitative interview approach should be chosen, depending on the intention behind the research. This project utilises the semi-structured interview approach, as the researchers want to dictate the direction of the interview, but also to have the ability to ask follow up questions, if necessary. Thus, the interviewee is allowed to elaborate when answering. The questions asked are therefore made beforehand, and the interviewer follows a premade interview guide (see Appendix A on page 119). This approach is chosen in order to avoid distorting information from the interviewee, as an effect of the interviewee not being allowed to speak freely or feeling too controlled by the interviewer. Lastly, the researchers avoid asking 'yes' or 'no' questions, as this does not correlate with the qualitative semi-structured interview method. [Brinkmann and Tanggaard, 2010]

It is chosen to interview Preben Pedersen, the operations manager at Oksbøl CHP plant. Preben Pedersen operates the technical part of the plant, but is also in charge of the management and decision making together with the board of directors. Also, it is assumed that he has contact to the other relevant actors, that are included and examined in the institutional analysis.

A summary of the interview can be found in Appendix B on page 121, and a sound recording of the full interview is attached to the project in a separate file.

Developments in the National Electricity System 7

The purpose of this chapter is to answer the first underlying research question. It contains national energy system analyses of four 2030 scenarios for Denmark, using the tool EnergyPLAN, with focus on key parameters for security of electricity supply. These analyses lead to a discussion of the prospect that natural gas-based CHP capacity is reduced.

7.1 EnergyPLAN analysis: procedure and inputs

As explained in Section 4.2 on page 21, the researchers find it important to have a holistic view of the energy system while considering further electrifying the DH system. Specifically, this means that if a suggestion of replacing some natural gas-based CHP capacity with heat pump capacity or electric boiler capacity is made, consideration should not only be given to the DH price or cost of the DH system; consideration must also be given to potential negative consequences in the electricity system as a whole - namely potential problems with security of electricity supply if CHP capacity is reduced.

Security of electricity supply in Denmark and the electrification of the DH sector are in focus in this analysis. Thus, it is necessary to use a tool which is appropriate for energy system analyses on a national scale, taking into account both the heat sector and all other sectors which consume and/or produce electricity. Therefore, EnergyPLAN is chosen, and a more detailed explanation of this choice, as well as some background information, can be found in Subsection 6.2 on page 32.

There are two overall goals of this analysis. One is to investigate how the key parameters for security of electricity supply, which EnergyPLAN takes into account, are affected when varying the CHP capacity in different 2030 scenarios. The other is to investigate how much surplus electricity is available for DH electrification purposes in 2030.

7.1.1 Key parameters for security of electricity supply

Grid stabilisation share

Because of grid stability, Lund [2014] advocates that no less than 30% of power production at all times must be delivered by ancillary service-capable units. These ancillary services continue to be strongly reliant on centralised CHP plants [Energinet, 2020d]. In EnergyPLAN, it is possible to define a so-called *minimum grid stabilisation share.* If this is set to 0.30, grid stabilising units must be responsible for 30% of the total electricity production in all hours of the year. In EnergyPLAN, grid stabilising units are defined as: centralised CHP plants (i.e. those in EnergyPLAN's group 3), condensing power plants (named PP2), nuclear power plants, geothermal power plants, and dammed hydropower stations. Decentralised CHP plants (i.e. those in EnergyPLAN's group 2), various renewable electricity generation units (wind turbines etc.), and interconnectors can also be manually defined as grid stabilising units. [Lund and Thellufsen, 2020]

In this analysis, the *maximum possible* grid stabilisation share from CHP is calculated, by comparing the peak power production of the year with the capacity of the units, which are assumed to be grid stabilising (in this case, that means CHP plants both in group 2 and 3 - the argument is given in Section 7.2).

The grid stabilisation share is relevant for the security of electricity supply because of *power grid robustness*. A detailed explanation is given in Section 7.3.

Annual import and peak import

As explained in Subsection 6.2, there are two overall simulation strategies in EnergyPLAN: the technical simulation and the market economic simulation as well as a number of options within each strategy. As this analysis uses the technical simulation strategy, import and export of electricity is minimised. Therefore, if electricity is imported in a given hour, when using the technical simulation strategy, the units within the Danish electricity system cannot produce enough electricity to cover the demand.

In this analysis, both the annual (i.e. total) import of electricity and the peak import is investigated. The latter gives a minimum requirement for the interconnector capacity (not considering export), while the former indicates how much of the time Denmark would have to rely on imported electricity.

Annual import and peak import are, clearly, relevant for the security of electricity supply as the size of these values can give an indication of the likelihood of *power shortfalls*. A detailed explanation is given in Section 7.4.

Annual export

As mentioned above, using the technical simulation strategy in EnergyPLAN entails minimising export. In energy systems with high wind power- and PV capacities, as all the scenarios this analysis includes have, export will occur when there is a high electricity production from these units.

Export of electricity is less of a concern for the security of supply than the previously mentioned key parameters, provided that the electricity output from the wind turbines and/or PV panels can be reduced. But the amount of electricity exported gives an indication of how much additional electrification of, say, transport or heating, that can happen. However, to properly utilise excess electricity production in the DH sector, the distribution profile of the electricity export throughout the year must also be taken into consideration.

7.1.2 2030 scenarios

It has been chosen to simulate four out of the total six scenarios for the 2030 Danish energy system, which were mentioned in Subsection 2.2.2. These are the 'frozen-policy' scenario (referred to as 'DEA' in the rest of this analysis) from the DEA, two of the four scenarios made by Energinet - namely 'Moderate Europe' and 'Green Europe' ('EN2' and

'EN4', respectively) - and finally the scenario made by the Danish Society of Engineers ('IDA'). The two other scenarios from Energinet, 'Moderate nations' and 'Green nations', are excluded because they are both judged to be unrealistic due to their low offshore wind turbine capacities which contradicts the already developed plans mentioned in Subsection 2.2.2.

Fortunately, the data behind each of the chosen scenarios is available, although the level of detail varies (see Danish Energy Agency [2020a], Energinet [2016b], and Lund et al. [2020]). The IDA scenario is already modelled in EnergyPLAN by Lund et al. [2020], and their version can be found on the EnergyPLAN website.

The procedure for making these EnergyPLAN models is described in the following. First, the DEA scenario is modelled on the basis of the highly detailed background data referenced above. As the analysis is not concerned with CO_2 emissions, fuel consumption, or annual costs, all inputs which are not related to electricity or heating are set to zero (e.g. fuel consumption in industry and use of petrol/diesel in transport). All distribution profiles are taken from the IDA EnergyPLAN model made by Lund et al. [2020] (e.g. distributions for electricity demands, heat demands, electric vehicle charging, wind turbine- and PV production) which corresponds to actual measured data in year 2013 [Lund et al., 2020].

The background data for the DEA scenario does not specify a thermal storage capacity in DH, which is a crucial value in the EnergyPLAN model. According to Koch [2020], this value was around 100 GWh as of 2020. In this analysis, the DH thermal storage capacity is assumed to increase to 120 GWh in 2030 (distributed in group 2 and 3 according to their respective CHP thermal capacities) which is a relatively conservative estimate. The actual interconnector capacity in Denmark, including the Viking Link mentioned in Subsection 2.2.3 on page 7, will be approximately 10 GW [Energinet, 2018b]. However, the interconnector capacity is set to zero in the model. This simply means that any import/export will show up as 'Import problems'/'Critical excess'. This is done to limit the results to only account for indispensable import power.

The category 'PP2' in EnergyPLAN, which accounts for power plants with no waste heat utilisation, is also set to zero. According to the background data for the DEA scenario, the correct value for 2030 would be 825 MW. This accounts mainly for oil-based back-up generator capacity. The problem with including this in the model would be that it is prioritised above import when using the technical simulation strategy, which means that the back-up generators would often be active - and this is not realistic.

Regarding the heat pumps in DH, the coefficients of performance (COP) for group 2 and 3 are calculated as weighted averages based on the ratios between the heat production and electricity consumption values found in the DEA background data.

With the DEA scenario modelled, it is used as the foundation for modelling the other scenarios including a modified version of the IDA scenario. The DH demands and baseline CHP capacities, industrial excess electricity, and waste incineration (for both group 2 and 3) from the DEA model are therefore reused in the other models. Here, it is important to again emphasise (as pointed out in Subsection 2.2.2) that the IDA scenario is normative, while the other scenarios are predictive. Therefore, the various installed capacities which Lund et al. [2020] propose are not designed for the heat demand used in the modified version of the IDA scenario. Thus, in this analysis, the remaining installed capacities and electricity demands from the IDA scenario are simply treated as another way in which the Danish energy system could evolve.

The inputs for the EnergyPLAN models of the four scenarios can be seen in Tables 7.1 and 7.2.

Table 7.1. EnergyPLAN demand inputs. All scenarios use distribution profiles from the IDA scenario.

	DEA	**EN2**	**EN4**	**IDA**	**Characteristics**
Electricity [TWh$_e$]	**49.06**	**43.94**	**47.78**	**55.93**	Sum
General electricity demand	37.87	32.86	33.66	30.22	
Additional electricity demand	6.80	6.11	4.11	9.30	
Electricity for transport	1.20	0.96	4.53	5.54	Dump charge + smart charge
Heat pumps, individual	0.65	1.47	2.94	3.96	COP = 3.9
Electric heating, individual	2.54	2.54	2.54	2.54	
Electric cooling, individual	0	0	0	1.63	
Biomass conversion	0	0	0	0.02	
Flexible demands	0	0	0	2.72	
DH [TWh$_{th}$]	**28.80**	**28.80**	**28.80**	**28.80**	Sum
DH group 2 demand	11.12	11.12	11.12	11.12	Network losses: 20%
DH group 3 demand	17.68	17.68	17.68	17.68	Network losses: 20%

Table 7.2. EnergyPLAN capacity inputs. All scenarios use distribution profiles from the IDA scenario.

	DEA	**EN2**	**EN4**	**IDA**	**Characteristics**
Installed capacities [MW$_e$]					
Offshore wind	5180	4972	8100	6630	
Onshore wind	6154	2770	4118	4800	
PV	6421	2939	4000	5000	
River hydro	7	0	0	0	
Wave power	0	0	0	132	
Power plants (PP2)	0	0	0	0	Not included
CHP, group 2	677	677	677	677	$\eta_e = 0.45$ and $\eta_{th} = 0.53$
CHP, group 3	2149	2149	2149	2149	$\eta_e = 0.39$ (0.44) and $\eta_{th} = 0.51$
Industrial excess electricity, group 2	0	0	0	0	
Industrial excess electricity, group 3	49	49	49	49	Based on annual production
Waste incineration, group 2	34	34	34	34	Based on annual production
Waste incineration, group 3	100	100	100	100	Based on annual production
Heat pumps, DH, group 2	173	27	300	237	COP=3.54
Heat pumps, DH, group 3	88	10	186	315	COP=4.46
Electrolysers	0	0	0	1223	
Interconnectors	0	0	0	0	Not included

It is important to understand exactly how the DEA scenario expects the CHP capacities, based on different fuels, to change from 2020 to 2030, as this change in itself represents a considerable reduction in the natural gas-based CHP capacity. This is shown in Table 7.3.

Table 7.3. CHP electric capacities in 2020 and 2030 according to the DEA scenario. Group 2 covers decentralised CHP and group 3 covers centralised CHP [Danish Energy Agency, 2020a].

		CHP capacity using given fuel type [MW$_e$]					
	Year	Biogas	Biomass	Coal	Natural gas	Oil	**Sum**
Group 2	**2020**	50	72	0	1150	18	**1290**
	2030	48	55	0	574	0	**677**
Group 3	**2020**	13	1396	2209	627	65	**4310**
	2030	13	1416	0	695	24	**2149**

As seen, the main changes are that natural gas-based decentralised CHP electric capacity will be halved, and that coal based centralised CHP electric capacity is removed.

7.2 EnergyPLAN analysis: results

With all of the scenarios modelled, the simulations can be carried out. As mentioned, there are several options within the technical simulation strategy in EnergyPLAN. In this analysis, technical simulation strategy 3 is chosen. This strategy is titled 'Balancing both heat and electricity demands', and it entails a minimisation of electricity export. This is done by using heat pumps to cover the heat demand in DH before activating the CHP plants (in hours with electricity production, which would otherwise have been in excess) [Lund and Thellufsen, 2020].

As mentioned, the purpose of the analysis is to vary the CHP capacity in each of the modelled 2030 scenarios, and then determine how the key parameters mentioned in Subsection 7.1.1 are affected.

When reducing the CHP capacity (relative to the baseline value) it is chosen that decentralised CHP capacity is removed first. Conversely, when increasing the CHP capacity, it is done by increasing only the centralised CHP capacity. This is because, from the perspective of maintaining a robust power grid, centralised CHP plants are more important than the others because of inertia. The reasons for this choice is elaborated in Subsection 7.3.1. When changing the CHP capacities, the original DEA ratios between the electric- and thermal capacities are retained. For centralised CHP, the ratio between the electric capacity in condensing mode operation and the electric capacity in back pressure mode operation is also retained.

In the calculation of 'maximum possible grid stabilisation share from CHP', it is assumed that decentralised CHP plants can contribute to grid stability. This is because smaller plants can also provide certain ancillary services. The electric capacities from 'PP2' and waste incineration are, on the other hand, not included. The results are shown in Table 7.4, and the printed results can be found in Appendix C on page 123.

Table 7.4. Results from the EnergyPLAN simulations of the 2030 scenarios with varied CHP capacities. *Assuming that CHP plants in group 2 can also provide grid stabilisation. **2020 capacity according to the Danish Energy Agency [2020a].

Scenario with specified total CHP electric capacity	**Maximum possible grid stabilisation share from CHP***	**Import [TWh]**	**Export [TWh]**	**Peak import [MW]**
DEA				
- 2000 MW	0.12	3.98	8.7	5771
- 2500 MW	0.14	2.86	8.9	5291
- Baseline (2826 MW)	0.16	2.29	9.0	4945
- 3000 MW	0.16	1.99	9.0	4771
- 3500 MW	0.19	1.28	9.0	4271
- 4000 MW	0.21	0.78	9.0	3771
- 5600 MW**	0.27	0.09	9.0	1998
EN2				
- 2000 MW	0.17	4.04	2.85	4862
- 2500 MW	0.21	2.70	2.85	4362
- Baseline (2826 MW)	0.23	2.05	2.85	4036
- 3000 MW	0.24	1.72	2.85	3862
- 3500 MW	0.27	0.99	2.85	3362
- 4000 MW	0.30	0.53	2.85	2862
- 5600 MW**	0.37	0.04	2.85	1254
EN4				
- 2000 MW	0.12	3.33	12.54	5411
- 2500 MW	0.15	2.29	12.70	4911
- Baseline (2826 MW)	0.16	1.80	12.79	4553
- 3000 MW	0.17	1.56	12.79	4379
- 3500 MW	0.19	0.98	12.79	3879
- 4000 MW	0.22	0.58	12.79	3379
- 5600 MW**	0.28	0.05	12.81	1530
IDA				
- 2000 MW	0.12	5.97	2.64	6222
- 2500 MW	0.15	4.42	2.88	5683
- Baseline (2826 MW)	0.16	3.70	2.94	5244
- 3000 MW	0.17	3.30	2.94	5071
- 3500 MW	0.19	2.31	2.94	4571
- 4000 MW	0.22	1.56	2.94	4071
- 5600 MW**	0.28	0.36	3.01	2261

The first thing to note about the results is that, with the baseline CHP capacities, and assuming that only decentralised and centralised CHP plants can provide grid stabilisation, the maximum possible grid stabilisation share is in most cases far from the recommended 30%. Naturally, it is the most conservative scenario with respect to wind turbine- and PV expansion (namely 'EN2') that has the highest possible grid stabilisation share and lowest export. In all scenarios, except 'EN2', a grid stabilisation share of 30% cannot be reached, even if the 2020 CHP capacities shown in Table 7.3 were retained. To what extent this challenge can be solved with new technical solutions is discussed in Section 7.3.

Regarding the peak import, it can be seen that it - in all cases - is below the expected 10 GW interconnector capacity in Denmark in 2030. However, lower values such as 5 or

6 GW could also be a problem - it depends on the electricity production in the countries Denmark is connected to.

The annual export is a reflection of the amount of electricity generation from renewable sources, which is not used nationally. It can therefore indicate if there is room for additional electrification. However, as mentioned in Subsection 7.1.1, the distribution of the export is crucial. If export only occurs in the summer, it is not very useful for the electrification of the heating sector. Figure 7.1 shows the export split into the months of the year, for all scenarios, with baseline CHP capacity. As shown in Table 7.4, the export is barely affected by varying the CHP capacity.

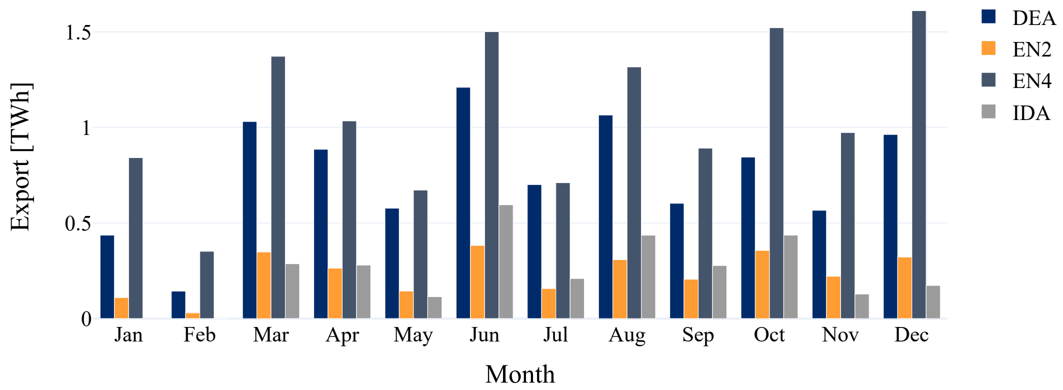

Figure 7.1. Monthly export in each 2030 scenario with baseline CHP capacity.

It can be seen on Figure 7.1 that the export in the IDA scenario (which, again, is a modified version of the IDA scenario made by Lund et al. [2020]) is quite low compared with DEA and EN4, even though they all have very large wind turbine- and PV capacities. This is mainly because the IDA scenario has more cross-sector integration: more heat pumps in DH, more individual heat pumps, more electric vehicles, all of which result in a larger electricity demand.

As shown in Table 7.4, the annual import, with the baseline CHP capacity, is quite high in all scenarios. Varying the CHP capacity naturally has a strong impact on the results. The higher the annual (forced) import, the higher the likelihood of hours with a power shortfall which leads to power outages. This is discussed in depth in Section 7.4. Ultimately, establishing an allowable annual import value is a question of deciding how much Denmark is willing to rely on electricity generation in neighbouring countries and thereby risk power outages.

The large heat pump capacity in DH in the IDA scenario leads to an especially high import in January and February, because EnergyPLAN imports electricity for the heat pumps before the non-electric DH boilers are activated. This is shown in Figure 7.2.

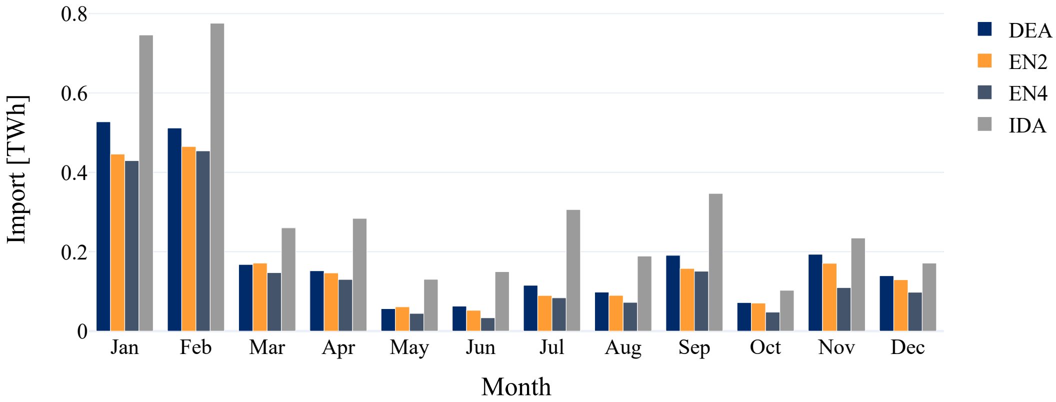

Figure 7.2. Monthly import in each 2030 scenario with baseline CHP capacity.

Before these findings can be discussed further, it is important to explain the possible implications of having a low grid stabilisation share (and how this might be avoided) as well as the implications of having a high import of electricity. This is is done in Sections 7.3 and 7.4.

7.3 Maintaining robust power grids

In this thesis, two properties of a robust power grid are considered, namely *frequency stability* and *voltage stability*. These are explained below.

7.3.1 Frequency stability

Frequency stability is needed in the electricity grid to maintain an adequate active power balance. This stability is provided by ancillary services with the main role of maintaining a certain frequency when there are unexpected events affecting the transmission grid (e.g. a production unit outage). Thus, ancillary services can be defined as active power reserves with the ability to up- or down regulate power production and consumption to maintain power quality in the electricity sector. In Denmark, ancillary services can have different purposes with different response times and can be defined in three control reserve categories seen in Table 7.5

Table 7.5. Different types of frequency and balancing reserves in Denmark Energinet [2020c]

	Control	**Terminology**
Primary reserves	Automatic reserve delivering reserve power at frequency changes	Fast Frequency Reserve (FFR - only in DK2) and Frequency Containment Reserves (FCR)
Secondary reserves	Controlled automatically by the TSO (Energinet)	Automatic Frequency Restoration Reserves (aFRR)
Tertiary reserves	Manual control	Manual Frequency Restoration Reserves (mFRR)

Even though the terminologies are the same, West- (DK1) and East- (DK2) Denmark operate under different synchronous electrical grids, respectively the Continental Synchronous Area and Nordic Synchronous Area. Thus, the requirements for ancillary services are different depending on the investigated area. Energinet [2020c] however, estimates that the requirements will be increasingly unified in the future as the EU aims to further internationalise the market's structure.

In future energy systems with high amounts of RE, it can be assumed that some CHP capacity will be phased out and that CHP in general will have less operating hours. This can result in problems for the grid robustness, as both the removal of reserve capacity and inertia will make the frequency more vulnerable to changes. As the large rotating mass in a synchronous generator is connected directly to the grid, the inertia of this rotating body will instantaneously counteract changes in frequency and thereby help to ensure stable grid frequency. Wind turbines, which also have a rotating mass, are inverter-based and do not directly affect the grid frequency. [Energinet, 2020a]

The EU requires that an outage of the largest power producing unit does not result in a maximum instantaneous frequency deviation of more than 0.8 Hz in DK1 and 1 Hz in DK2. In the European continental system, an outage of the largest power producing unit would result in a lack of power of around 3 GW. However, the large amount of inertia in this system means that this will not become a risk for the power quality in the short term. Conversely, in the Nordic Synchronous Area, an outage of a large-scale power plant can at hours result in a lack of rotational inertia in DK2. This has been solved with the implementation of FFR, which can respond with a power output within 1.3 seconds to ensure frequency stability in this region. [Energinet, 2020a]

Replacing large thermal power plants with inverter-based units will reduce inertia and thereby impact the grid robustness. However, studies have shown that wind farms can imitate the inertia provided from spinning rotating components seen in power plants. This can be done by reprogramming the connected inverters to imitate the behaviour of spinning objects connected directly to the grid. Simplified, a wind farm would deliver synthetic inertia by quickly outputting a spike in power. This spike in power could be delivered by the rotating mass of the wind turbines but will result in a recovering time for the wind turbines as the blades are slowed down. This recovering time can result in a lack of power and could in itself cause grid stability problems. However, researchers within this field are developing intelligent control units enabling fast re-acceleration to the optimal rotor speed. [IEEE Spectrum, 2016]

The technical aspects of synthetic inertia and the implementation of this to stabilise the grid frequency is complex and not fully developed. Pilot projects, however, have shown promising results for inverter based power producing units which can provide synthetic inertia to the grid. Furthermore, FFR control reserves can also limit the need for inertia. This is seen in DK2 where the need of inertia is replaced with FFR balancing reserves.

Further technical analysis on this topic is out of scope of this project. It is, however, an important aspect to consider when removing CHP capacity on a national scale as the frequency stability will be dependent on future technological solutions and the amount of available inertia from neighboring countries in the future. Energinet is prioritising to solve issues of lower grid inertia in the future and the EU has set requirements for new RE technologies to be able to stabilise the frequency. Thus, it is expected that RE technologies with synthetic inertia and developments in the market structure for ancillary services can contribute in stabilising the grid frequency in future energy systems. [IEEE Spectrum, 2016] [Energinet, 2020d] [The European Comission, 2016]

7.3.2 Voltage stability

To maintain an efficient and robust electricity grid, and to prevent damages in electrical installations, the voltage in the transmission grids must be kept within certain ranges. As of 2021, voltage stability is provided by Energinet through Flexible AC Transmission Systems, high-voltage DC converters and centralised power plants.

Inverter-based units do not contribute to this stabilisation, even though they have the necessary technical capabilities. *Requirements for grid connection of generators* made by The European Comission [2016] requires RE sources connected to the grid to be able to regulate the grid voltage. Energinet [2020a] addresses these issues in terms of a 100% RE system, where they assume that all power generating units will be able to provide voltage stability. Thus, Energinet estimates that further regulation in this field is not necessary as RE sources would be able to provide stability in both normal operation and in situations with power grid failures. [Energinet, 2020a]

It is therefore, assumed that the removal of CHP capacity in Denmark would either have no impact or a minor impact on the voltage stability in the grid. Especially if decentralised CHP plants are removed as first priority.

7.4 Power shortfalls

As concluded in Section 7.3, the removal of especially decentralised CHP plants is expected to have minor impacts on the robustness of the electricity grid. However, reducing the electric capacity of decentralised CHP plants could result in power shortfalls in hours with no or minor electricity production from wind turbines and PV. Most decentralised CHP units (mainly turbines and engines) also have a shorter start-up time than larger centralised thermal CHP units, which is beneficial to counteract power shortfalls.

Energinet [2020d] estimates an increasing amount of power outages towards year 2030. This is especially a result of higher electricity consumption, ageing grid connections and a lower electricity production from CHP plants. Here, it is estimated that the amount of power outage as a result of power shortfalls will increase from 1 minute in 2025 to 35 minutes on average in 2030. The developments in power outage minutes can be seen in Figure 7.3.

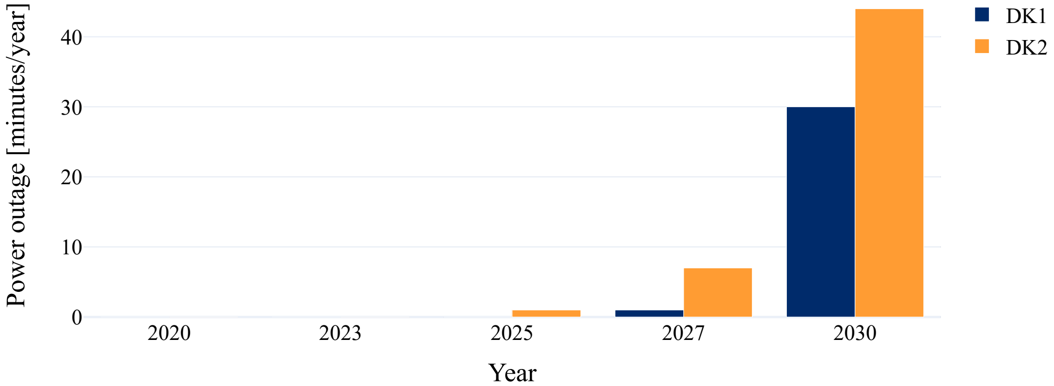

Figure 7.3. Expected development in power outage minutes as a result of power shortfalls [Energinet, 2020d].

The increasing power outage minutes is highly dependent on the ability to import power from neighboring countries in hours where the national electricity production is not sufficient to meet the demand. Denmark already has a relatively high interconnector capacity of around 8 GW, and it is expected to increase to more than 10 GW in year 2030 [Energinet, 2018b]. As shown in Section 7.2, the peak import for all scenarios was below 6.2 GW meaning that the interconnector capacity, in principle, allows the needed power to be imported in hours with no wind and solar power production. However, even though the interconnector capacity allows the needed import, it strongly depends on the ability of neighboring countries to deliver the power. Most of the interconnected neighboring countries are, as Denmark, converting their electricity production from thermal power plants to fluctuating RE sources which will further reduce dispatchable electric capacity. Norway is the exception, because the country uses hydro power for most of its electricity production (e.g. 93.4% in 2019 - see Statistics Norway [2020]).

The analysis by Energinet [2020d] is based on assumptions on the general development of the European energy system. These assumptions are associated with high uncertainty, and specific goals of the interconnected countries could change. An example of this is the renewed national goals of Germany to reduce coal-fired power capacity by 2030, which by Energinet [2020d] is estimated to result in more than a doubling in the Danish power outage minutes in 2030 compared to Figure 7.3. Conversely, the nuclear power capacity in France is estimated to be higher in 2030 than first expected by Energinet, thus resulting in around 20 GW more available nuclear capacity than used to calculate the outage minutes shown in Figure 7.3. If the larger amount of nuclear power capacity in France and the lower amount of coal-fired power capacity in Germany are both taken into account, the outage minutes are expected to be almost halved compared to Figure 7.3.

Energinet [2020d] recommends that the maximum annual power outage minutes in Denmark should be lower than 5 minutes. According to their analysis, this can be achieved by having a power generating capacity to around 5,400 MW in Denmark including peak load capacities and waste incineration. It should be noted that the analysis performed by Energinet [2020d], is based on a 2030 scenario, developed by the DEA, which is not evaluated in this project [Danish Energy Agency, 2019a]. Thus, the results in needed thermal power generating capacity might be slightly different in the scenarios evaluated in Section 7.2.

Following the recommendations of Energinet [2020d], requiring a total capacity of 5,400 MW, a removal of around 1.5 GW of CHP capacity compared to 2020 would be allowed [Danish Energy Agency, 2020d]. As shown in Table 7.3 on page 47, removing the remaining Danish coal-fired power plants before year 2030 means removing 2.2 GW electric capacity. Thus, to comply with the recommendation, an additional electric capacity of 700 MW would be needed in 2030. This presupposes that all other capacities remain the same and that all coal-fired plants will be substituted by technologies without power production capacities. As mentioned in Chapter 2 on page 3, some centralised CHP plants are converting into biomass-based CHP production. Furthermore, Nordjyllandsværket and Fynsværket have, as of 2021, not yet been granted permission to waive the co-generation requirement. It could be necessary to replace some coal-fired plants with biomass-based CHP capacity in Denmark as these will have the ability to maintain a low amount of power shortfalls and improve the robustness in the electricity grid. Furthermore, the Danish Energy Agreement 2018 provided the ability to further subsidise an increase in biomass- and biogas capacity for electricity production to maintain domestic electric capacity while phasing out coal and natural gas fired CHP plants [Danish Energy Agency, 2020b].

With a more integrated electricity grid in Europe, it is expected that the amount of imported and exported electricity will increase, and it is not in itself a goal to be self-sufficient in hours with no domestic renewable electricity production. But if the recommendation regarding outage minutes from Energinet [2020d] is to be accommodated, Denmark will have to expand the thermal power generation capacity. If the national goal of having a net 100% renewable electricity production is also to be accommodated, this expansion could be in the form of biomass- or biogas-based CHP units, which can replace natural gas capacity.

It should be noted that the recommendations of Energinet [2020d] are quite ambitious as Energinet aims to maintain a high security of electricity supply in Denmark. Countries such as France, Great Britain and Belgium have a goal of a Loss of Load Expectation (LOLE) at 3 hours/year. For comparison, the estimated LOLE from the outage minutes in 2030 seen in Figure 7.3 would be around 3.8 hours/year for DK1 and 2.5 hours/year for DK2. Thus, if Denmark had the same requirements as these other countries in Europe, only a dispatchable electric capacity of 4,200 MW is needed instead of the 5,400 MW recommended by Energinet [2020d].

The general recommendations from Energinet [2020d] to maintain a sufficient power supply and reduce the amount of outage minutes in 2030 are listed below:

- Reinvestments in the transmission grid and interconnectors
- Implement market incentives to improve flexibility on both demand and production side of the electricity sector.
- Implementing strategic electricity generating reserves or expand the power plant capacity

7.5 Results

Removing grid stabilising units, such as CHP plants, will result in a reduced capacity capable of providing ancillary services in Denmark. Here, the main challenges will be to maintain frequency stability if the operating CHP units providing inertia are replaced with fluctuating RE sources. As mentioned in 7.3.1, this can be solved with FFR and/or synthetic inertia, which could be supplied by inverter based power producing units. However, these solutions are still at an experimental level and full utilisation of such solutions may take years. In EnergyPLAN terms, the possibility of creating synthetic inertia with wind turbines means that it could be realistic to increase the grid stabilisation share by defining a certain wind turbine capacity as grid stabilising.

Voltage stabilisation is, as mentioned, not provided by decentralised CHP plants, and can, if needed, be provided by RE sources in the future. Thus, a reduction in decentralised CHP capacity would impact the robustness of the electricity grid less than a reduction in centralised CHP capacity. This is especially due to the lower amount of inertia provided by decentralised CHP plants, and the fact that these provide no voltage stability.

The removal of decentralised CHP plants may, however, increase the amount of power shortfalls as peak load capacity is reduced. Energinet [2020d] states the need of increasing the amount of peak load capacities in year 2030, as CHP plants are phased out and are replaced with fluctuating RE sources. To maintain the ambitious goal of no more than 5 power outage minutes per year, Energinet [2020d] estimates a need of around 5,400 MW thermal power generating capacity by year 2030. However, it is strongly dependent on the development in neighboring countries. This expansion is in line with the recommendations from Lund et al. [2020], where it is stated that Denmark has a responsibility to uphold its part of the European peak load capacity.

The estimated amount of import in each scenario modelled in EnergyPLAN - depending on the available CHP capacity in Denmark - can be seen in Figure 7.4.

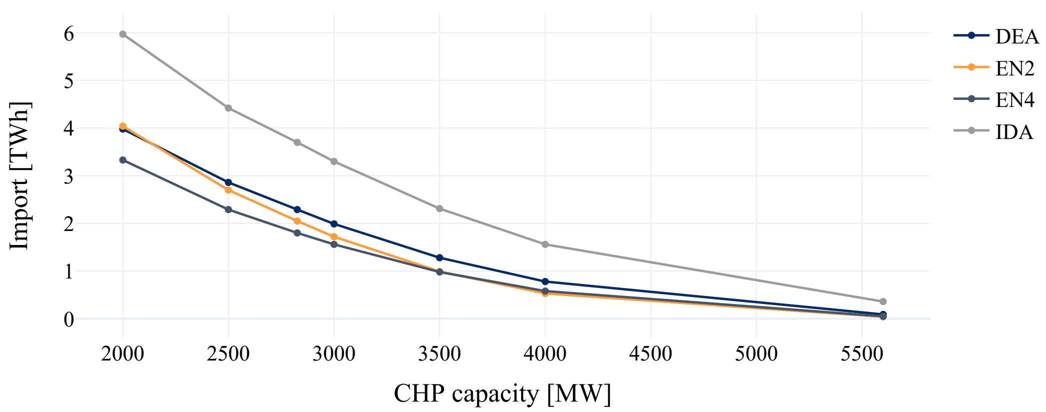

Figure 7.4. Total annual import of electricity at different CHP capacities (not counting the 200 MW_e waste incineration capacity) for the four scenarios for 2030 modelled in EnergyPLAN.

The import value at at CHP electric capacity of 5,400 MW, seen in Figure 7.4, is low in all scenarios, which indicates that following the recommendation of Energinet [2020d] will lead to a high level of security of supply in all scenarios.

As mentioned, it may be feasible in the perspective of grid robustness to retain existing centralised CHP capacity (apart from the coal-fired capacity). Furthermore, it could be expanded with additional biomass- or biogas-based CHP capacity in order to minimise outage minutes. An alternative to this is to expand the power peak load capacities. Regardless, natural gas decentralised CHP plant capacity could be reduced if a feasible replacement of their power generating capacity is found. Decentralised CHP plants have a priority of meeting the DH demand, where lower and more fluctuating electricity prices have significantly reduced business-economic feasibility of operation. One solution to maintain electric capacity in the grids, and to improve feasibility of operation for decentralised CHP plants, may be to retain natural gas CHP units at the plants in addition to implementing alternative heating solutions. Thereby, the natural gas CHP can be used when peak load capacity is needed and electricity prices are high.

Regarding electricity export in the modelled scenarios, shown in Figure 7.1 on page 49, it can be seen that there may be an ability to implement additional heat pumps in Denmark. In the IDA scenario, there is no electricity export in January and February. However, in the other scenarios each month has a surplus electricity production. These scenarios are not as well cross-sector integrated as the IDA scenario, implying that e.g. more heat pumps could be implemented to take advantage of the surplus electricity production from RE sources.

The expansion of electric heating solutions depends heavily on the ability to import power from neighboring countries, fluctuating RE capacities, and the amount of electric vehicles, electrofuel production and electricity demands in general. In the IDA scenario for 2030, an expansion of more than 500 MW_e heat pump capacity is implemented compared to 2020 levels. This scenario, with a large amount of electric vehicles and a large electrolyser capacity thereby, as mentioned, utilises all excess electricity production in January and February. However, the scenario EN4, also expands the heat pump capacity with more than 450 MW_e. This scenario has a lower amount of electric vehicles and no electrolysis in addition to a a larger off-shore wind turbine capacity. As a result of this, EN4 has surplus electricity production in January and February implying that further cross-sector integration is possible in that scenario.

From the results of the analyses performed in EnergyPLAN, it can be seen that electrification of the DH and individual heating sector especially requires large wind power capacities. As seen in scenario EN4, large amounts of wind power enables high electricity production in winter months where the heat demand is at its highest. Comparing this scenario to the DEA scenario with more PV capacity, it can be seen that the EN4 scenario has less import power in winter months even with larger heat pump capacities.

7.6 Subconclusion

The preceding analysis sought to answer the following subquestion:

To what extent can the electric capacity of natural gas-based combined heat and power plants in Denmark be reduced while maintaining security of electricity supply?

To answer this, four scenarios for 2030 were modelled in EnergyPLAN, which made it possible to investigate the impact on key parameters for security of electricity supply, when varying the CHP capacity. These parameters were the grid stabilisation share, the annual- and peak import, and the annual export. Modelling four scenarios showed that the answer to the question is strongly dependent on the other installed capacities and various demands in the Danish energy system, and also strongly dependent on available electricity import from neighboring countries.

It was concluded that it is possible to maintain a robust power grid while reducing the CHP capacity through various technical solutions - for instance FFR and synthetic inertia using wind turbines. The prospect of power shortfalls is by far the bigger issue when considering a reduction of the CHP capacity. If the ambitious recommendation (compared to e.g. France) for maximum power outage minutes, which is given by Energinet, is to be followed, the conclusion is that the electric capacity of natural gas-based CHP plants in Denmark *cannot* be reduced if coal-fired CHP plants are phased out - unless it is replaced with a different dispatchable electric capacity. However, if the goal of 90% RE in DH by 2030 is to be reached, and most of the expected large increase in fluctuating electricity production is to be used nationally through cross-sector integration, the usage of natural gas in DH must be reduced and could be replaced by electric heating solutions. It is an open question if it is better to A) retain all of the current natural gas-based CHP capacity (while also installing heat pumps and electric boilers, ensuring that the usage of natural gas is greatly reduced) or B) reduce the natural gas-based CHP capacity, while increasing the biogas- or biomass-based CHP capacity (preferably centralised because of superior grid stabilising properties) or C) reduce the natural gas-based CHP capacity (while installing heat pumps and electric boilers) and investing in a strategic electricity generating reserve. If the natural gas-based CHP capacity is to be reduced, the reduction should occur in decentralised CHP to minimise the impact on grid robustness. Finally, the EnergyPLAN simulations showed that the integration of heat pumps in DH is an effective way of reducing excess electricity production.

Business- and Socio-economic Analysis 8

The purpose of this chapter is to answer the second underlying research question. It contains detailed business- and socio-economic analyses of various scenarios for the paradigmatic case of Oksbøl CHP plant using the tool energyPRO. These analyses lead to a comparison of the most socio-economically- and business-economically feasible ways to electrify Oksbøl CHP plant and reduce its natural gas consumption, as well as a discussion on the scalability of the results.

8.1 Introduction

As explained in Section 4.2 on page 21, this analysis follows the first three methodological steps of Choice Awareness, namely the design of concrete technical alternatives, feasibility studies and, finally, proposals for regulatory changes.

The analysis in Chapter 7 on page 43 showed that - in various future scenarios for the Danish energy system - there will at times be significant excess electricity production. However, the analysis also showed that it is possible to reduce the excess electricity considerably by, among other things, electrifying the DH sector. This enables a reduction in the usage of natural gas in DH. Furthermore, the need for CHP capacity was investigated, and it was concluded that - due to potential power shortfalls - a relatively high dispatchable electric capacity is needed in order to comply with the Energinet goal for power outage minutes. Since centralised CHP plants contribute more to grid robustness than decentralised CHP plants, it was concluded that reductions (if any) of CHP capacity should preferably occur in decentralised plants. Conversely, potential new CHP capacity should be added in centralised areas, not just because of grid robustness, but also because it is favourable for power production units to be located close to consumers in order to minimise the costs of upgrades to the electrical grid (see Subsection 2.2.2).

In this analysis, from a case study perspective, it will be analysed whether it is business-economically feasible to implement electric heating solutions at a decentralised CHP plant, or if another solution is superior - and crucially what this means for the plant's consumption of natural gas. Afterwards, the analysis is repeated with a socio-economic perspective, and it it also discussed whether any regulatory changes are needed to get the most socio-economically feasible solution to also be the most business-economically feasible solution.

8.2 Case description

As mentioned in the Section 6.1, the paradigmatic case chosen for this analysis is the case of Oksbøl Varmeværk a.m.b.a (in this project referred to as Oksbøl CHP plant). Oksbøl is a Danish town with around 2800 citizens located in western Jutland. Around 1300 dwellings including Oksbøl Barracks are connected to Oksbøl CHP plant and it is therefore the main heat supplier in the town. [Oksbøl Varmeværk, 2021]

The location of Oksbøl can be seen in Figure 8.1.

Figure 8.1. Location of Oksbøl in Denmark represented with the black dot.

The fuel consuming technologies with thermal input and efficiencies of Oksbøl CHP plant can be seen in Table 8.1.

	Thermal input	**Overall Efficiency**	**Electric Efficiency**	**Thermal Efficiency**
Gas engine 1	6.7 MW	≈ 94%	≈ 40%	≈ 54%
Gas engine 2	6.7 MW	≈ 94%	≈ 40%	≈ 54%
Natural gas boiler 1	4.4 MW	≈ 105%	-	≈ 105%
Natural gas boiler 2	6.3 MW	≈ 92%	-	≈ 92%

Table 8.1. Thermal input capacities and efficiencies of the existing Natural gas engines and boilers at Oksbøl CHP plant. Note: Natural gas boiler 1 is equipped with an economiser. [Oksbøl Varmeværk, 2021]

Oksbøl CHP plant, furthermore, has a solar collector field with a total area of 14,745 m^2 from year 2010 and a total hot water storage capacity of 4,200 m^3.

The heat demand of Oksbøl City and Oksbøl Barracks in a normal year has been estimated from the actual heat demand in the period March 2020 to March 2021 (March is the starting point as Oksbøl Barracks were connected in March 2020). This heat demand (Q_{period}) is heating degree day (HDD) corrected for the entire period.

The number of HDD in the period have been estimated as shown in Equation 8.1.

$$HDD_{period} = \sum_{i=1}^{n} (T_{balance} - T_{ambient,i})^{+} \tag{8.1}$$

Here, $T_{balance}$ is the balance temperature of 17 °C (industry standard in Denmark). For all ambient temperatures above 17 °C, the HDD method assumes no space heating demand. However, in reality, the balance temperature will vary depending on the building and heating type. It is assumed that 30% of the heat consumption in Oksbøl and Oksbøl barracks are from hot water consumption and would not be dependent on the ambient temperature. Thus, 30% of the consumption is not HDD corrected. [Bøhm et al., 2009; Danish Technological Institute, 2021]

With the total number of HDDs in a measured period (HDD_{period}) calculated, it is possible to normalise the heat consumption. Thus, making it possible to multiply normalised temperature dependent heat demand with the HDD of a normal period, HDD_{normal} (temperatures and HDDs data used in this estimation can be found in Danish Meteorological Institute [2021]). The temperature dependent heat demand of Oksbøl city and Oksbøl Barracks in a normal year can be expressed with Equation 8.2.

$$Q_{normal} = \frac{Q_{period}}{HDD_{period}} HDD_{normal} \tag{8.2}$$

The total HDD corrected heat demand (including losses and hot water consumption) from Oksbøl town and barracks is 39,320 MWh and the hourly distribution can be seen in Figure 8.2.

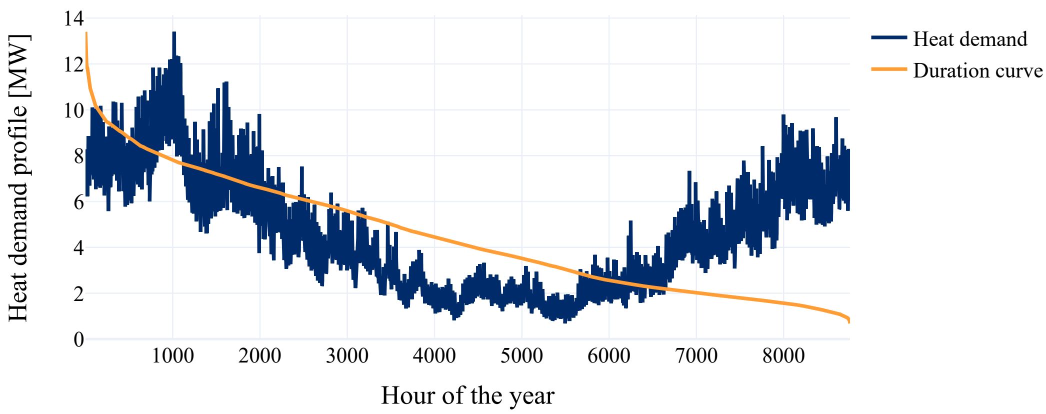

Figure 8.2. HDD corrected hourly heat demand with duration curve from Oksbøl town and barracks including grid losses. [Oksbøl Varmeværk, 2021]

Oksbøl CHP plant has been in contact with the engineering consultant company COWI, and are planning to transition some of their natural gas DH production into other sources. COWI has already made recommendations to Oksbøl CHP plant, however, specific details on the recommendations by COWI cannot be disclosed in this thesis. The recommended technologies are not implemented yet, and are not included when modelling the reference scenario. As a result of this, the scenarios developed for Oksbøl CHP plant will be of no influence by the recommendations of COWI.

All data needed for modelling the plant was provided by Oksbøl CHP plant and includes: specific details on technology data, supply/return temperatures, and losses.

8.3 General modelling assumptions

As mentioned in Subsection 6.3 on page 33, the modelling tool energyPRO with the FINANCE module is used to model the entire projected lifetime of the developed scenarios. The scenarios will consist of different alternative technology solutions for Oksbøl CHP plant and will be used to evaluate the business- and socio-economic benefits of using electric heating solutions to reduce the natural gas consumption of the plant.

The lifetime of DH producing technologies is typically 20-30 years and will vary depending on multiple factors. Therefore, a conservative lifetime of 20 years for the project lifetime is evaluated in the years 2021-2040. Investments and re-investments in new technologies are assumed to be financed in a 15 year period at an interest rate of 3% p.a. Regarding the existing technologies at Oksbøl CHP plant, re-investments and refurbishments are assumed on, respectively, the natural gas boilers and engines. The current natural gas engines were refurbished in 2020 and the operations manager of Oksbøl CHP plant estimates that they can operate for 10-15 years without refurbishments. For the scenarios that include natural gas engines, an additional refurbishment in year 2030 is assumed to be needed to ensure reliable operation until year 2040 (in this unique case, the financing period of the refurbishment is 10 years). The existing natural gas boilers are in the end of their life expectancy and are, for scenarios where these are included, assumed to be replaced with new natural gas boilers with the same capacity. The solar collectors, DH pipes and storage units are included in all scenarios and assumed to operate throughout the lifetime of the project.

The general economic assumptions when modelling both business- and socio-economic scenarios can be seen in Table 8.2.

Table 8.2. Economic assumptions used in the energyPRO analysis [Danish Energy Agency, 2018d].

	Value
Loan interest rate	3%
Inflation rate	2%
Project lifetime	20 years

In general, price developments used in this analysis will follow Denmark's Energy and Climate Outlook 2020 which provides projected gas, electricity, and CO_2 quota prices until year 2040 [Danish Energy Agency, 2020a].

The development in electricity spot prices according to Danish Energy Agency [2020a] for DK1 (Western Denmark) can be seen in Figure 8.3.

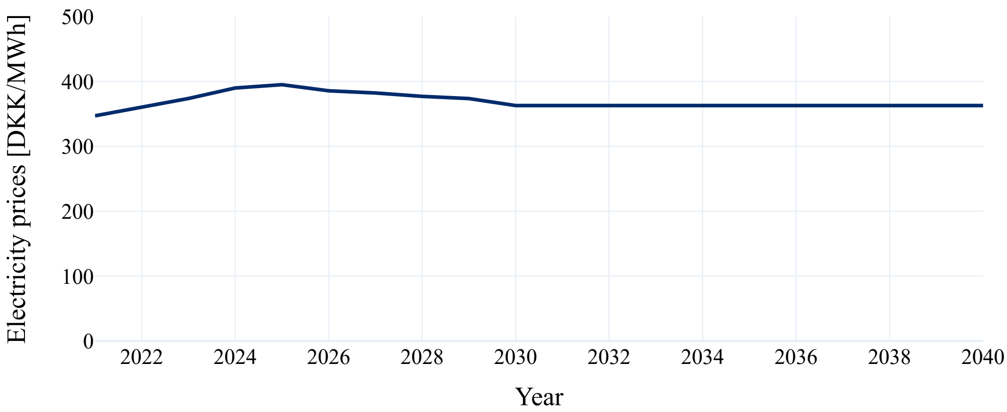

Figure 8.3. Assumed development in electricity spot market prices from year 2021 to 2040 in DK1 [Danish Energy Agency, 2020a]

As distribution, the hourly Nordpool spot market prices for DK1 in 2020 are used [Nordpool, 2021]. These hourly values will then follow an index of the average electricity prices shown in Figure 8.3. DK1 spot market prices in 2020 were relatively low at an average of around 187 DKK/MWh which is almost 50% lower than the projected 2021 prices. This may imply that electricity prices in the coming years could be lower than projected by Danish Energy Agency [2020a]. However, to keep consistency in the projections, the impacts of lower electricity prices will only be investigated in the sensitivity analysis.

The assumed natural gas price increase in the project lifetime from a business-economic perspective can be seen in Figure 8.4. Regarding the term 'natural gas', it should be clarified that this - in all cases - refers to *pipeline* gas, irrespective of what the share of upgraded biogas in the gas grid may be. However, the CO_2 emissions from gas consumption in the scenarios are based on a projected increased share of biogas in the gas grid (see Danish Energy Agency [2020a]).

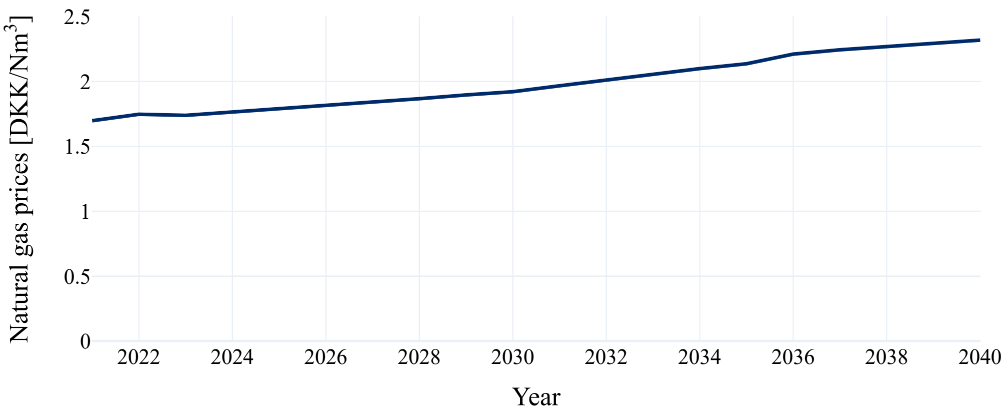

Figure 8.4. Assumed development in business-economic natural gas prices from year 2021 to 2040 in Denmark (excl. VAT, taxes and transport costs). [Danish Energy Agency, 2020a]

The daily natural gas import prices in Denmark from 2020 is used as distribution following the index shown in Figure 8.4. The impacts on the results from fluctuations in the natural gas price will be investigated in the sensitivity analysis.

Oksbøl CHP plant is covered by the EU Emission Trading System (ETS) where the plant has to buy CO_2 emission quotas. The assumed CO_2 quota price and the estimated development in the prices can be seen in Figure 8.5.

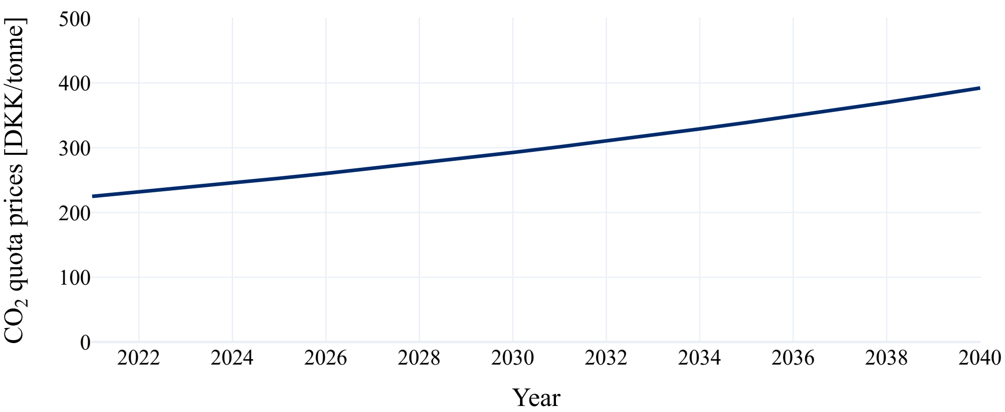

Figure 8.5. Assumed development in CO_2 quota prices from year 2021 to 2040 [Danish Energy Agency, 2020a]

As with electricity and natural gas prices, the impacts on the results from fluctuations in the CO_2 quota price will be investigated in the sensitivity analysis.
Taxes and tariffs used in the energyPRO models are assumed to be at 2021 levels and can be seen in Table D.1 in Appendix D on page 133. For temperatures and solar radiation, time series of a Danish Design Reference Year (DRY) is used for the area of Oksbøl.

8.4 Reference scenario

The first step in evaluating alternative scenarios for Oksbøl CHP plant is to model the current system configuration of Oksbøl CHP plant (in this analysis referred to as the 'reference scenario'). A graphical overview of the modelled reference scenario in energyPRO can be seen in Figure 8.6.

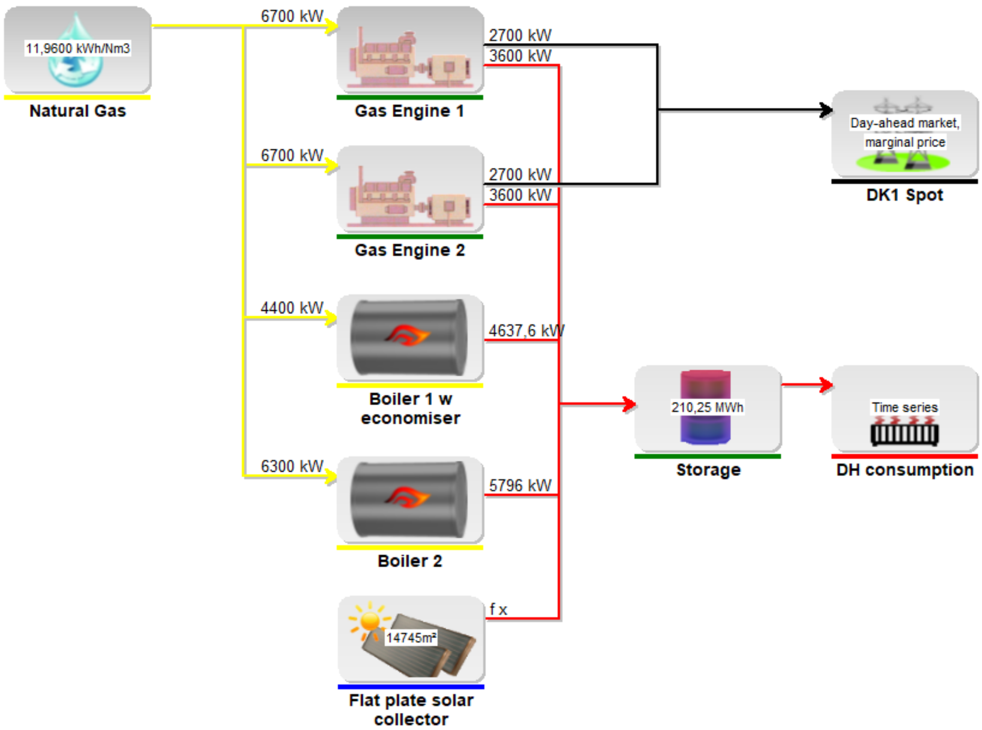

Figure 8.6. Graphical overview of the reference scenario of Oksbøl CHP plant.

A description on the mathematical modelling assumptions on each technology is outlined in Subsection 6.3.1 on page 34.

8.4.1 Reference scenario results

The NPC in a 20 year period from the perspective of Oksbøl CHP plant, if it is decided to reinvest in- and refurbish existing technologies, can be seen in Table 8.3.

Table 8.3. Business-economic results for reference scenario in the period 2021-2040.

Scenario	**NPC [1000 DKK]**	**Average consumer heat price [DKK/MWh]**	**Average annual natural gas consumption [Nm^3/year]**	**Average annual exported electricity [MWh/year]**
Reference scenario	205,655	327	4,032,286	14,844

The average consumer heat price seen in Table 8.3 is defined as the NPV of the heat production cost per MWh which takes an average grid loss of 20% into account. An example of the heat production at Oksbøl CHP plant as modelled in year 2021 can be seen in Figure 8.7.

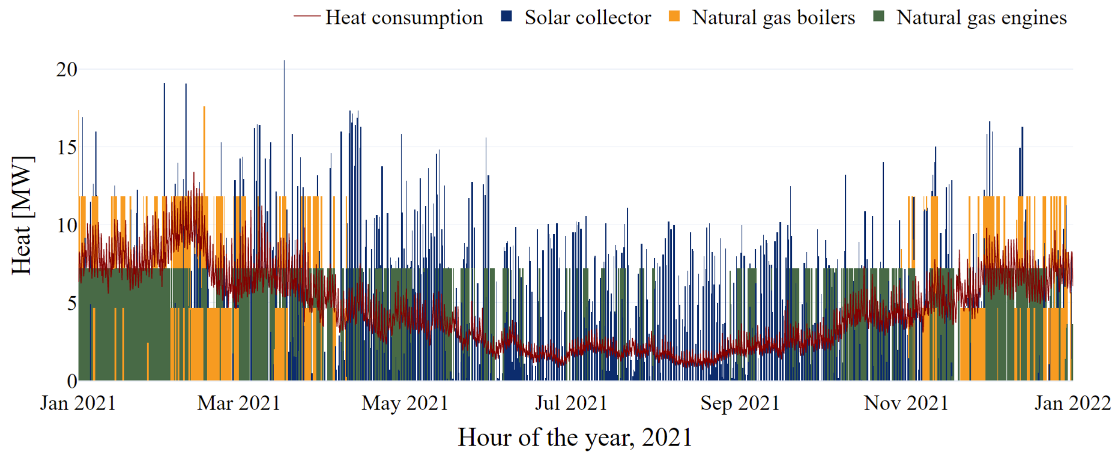

Figure 8.7. Modelled heat production at Oksbøl CHP plant in year 2021.

As it can be seen in Figure 8.7, the solar collectors are the main heat producing technology in the summer months. In the winter months, the heat demand is covered by the natural gas boilers and engines depending on the DK1 spot market prices.

The results of the operation strategy, natural gas usage, and electricity generation have been compared to actual data delivered by Oksbøl CHP plant on operation in previous years. Here, when accounting for the higher future electricity prices assumed in the model, changes in heat demands, and previous refurbishment outages on the engines, the results of the developed energyPRO model appear to be a good representation of the actual operation at Oksbøl CHP plant.

8.5 Alternative scenarios

The goal of this analysis is to investigate how the natural gas consumption can be reduced in decentralised CHP plants. It is not in itself a goal to reduce natural gas CHP capacity. Therefore, the reference case of Oksbøl CHP plant will be modelled with existing technologies including alternative technologies as a supplement to the natural gas units. It will then later be investigated whether it is feasible to remove the natural gas engines and boilers at Oksbøl CHP plant.

The thermal storage capacity at Oksbøl CHP plant was expanded in year 2010 in combination with the implementation of solar collectors. The two hot water tanks with a combined volume of 4,200 m^2 is above average for this plant size and the operations manager of Oksbøl CHP plant has not expressed interest (to the researchers) in expanding this capacity [Oksbøl Varmeværk, 2021] [Danish Energy Agency, 2018c]. Expanding the thermal storage at Oksbøl CHP plant is therefore not investigated. It should, however, be noted that an increase in thermal storage capacity in general may be feasible in an electrification of DH plants as low electricity prices can be utilised to a higher degree for heat production. Likewise, solar collector expansion is not investigated as the current solar collector field already is able to cover most of the heat demand in summer months. As found in Chapter 7 on page 43, a CHP expansion would be more desirable in larger centralised areas. Thus, heat-only technologies are considered and not CHP units. Furthermore, to accommodate the goals set by the Danish government, only renewable heat-only technologies are investigated. Lastly, to follow the principles of the Choice Awareness theory, electric heating solutions (electric boilers and heat pumps) will be compared to scenarios which include a wood chip boiler in order to compare the electric heating units to a well-established and in many cases economically feasible alternative [Danish Energy Agency, 2020g].

The seven developed alternative scenarios are listed below:

1. Reference scenario with electric boiler (spot market)
2. Reference scenario with electric boiler (regulating power + spot market)
3. Reference scenario with heat pump
4. Reference scenario with wood chip boiler
5. Reference scenario with electric boiler (regulating power + spot market) and wood chip boiler
6. Reference scenario with heat pump and wood chip boiler
7. Reference scenario with electric boiler (regulating power + spot market) and heat pump

A description on the modelling assumptions on each alternative technology is outlined in Subsection 6.3.2 on page 36. All investments and O&M costs can be found in Appendix D on page 133. The energyPRO model files are attached to the project in a separate file.

8.6 Business-economic results

These results are based on the method behind business-economic feasibility studies, which is described in Section 6.4 on page 38.

The first results of the business-economic analysis are the optimal capacities - meaning the combination of capacities which result in the lowest NPC - for the new technologies in each of the alternative scenarios. These have been found using the energyPRO INTERFACE module, and the method for this is explained in Section 6.3. It should be noted, that in the process of optimising the capacities, a new electrical substation is included in the investments at 10 MDKK when the total power input to the electricity consuming units are above 7 MW. This assumption is made from dialogue with the operations manager of Oksbøl CHP plant regarding the capacity limitation on the electricity grid [Oksbøl Varmeværk, 2021]. The electric boiler and wood chip boiler capacities have been optimised with the constraint that their capacities have to be an integer (expressed in MW), while the heat pump electric capacity is varied in steps of 0.5 MW_e. This is done in order to reduce the computation time. The results are shown in Table 8.4.

Table 8.4. Business-economic optimal capacities and investment costs for the new technologies.

Scenario	**Optimal electric boiler capacity [MW$_e$]**	**Optimal heat pump capacity [MW$_e$]**	**Optimal wood chip boiler capacity [MW$_{th}$]**	**New technologies total investment cost [1000 DKK]**
1. Reference with electric boiler (spot)	7	-	-	5,100
2. Reference with electric boiler (reg. + spot)	7	-	-	5,100
3. Reference with heat pump	-	2.0	-	48,400
4. Reference with wood chip boiler	-	-	3	17,775
5. Reference with electric boiler (reg. + spot) and wood chip boiler	7	-	2	16,950
6. Reference with heat pump and wood chip boiler	-	1.5	1	42,225
7. Reference with electric boiler (reg. + spot) and heat pump	6	1.0	-	28,571

Having found the optimal combination of capacities for new technologies in each alternative scenario, the resulting business-economic NPC, consumer heat price, fuel consumption, and electricity import/export can be examined. The results are shown in Table 8.5. The scenario with the highest NPC, by far, is the reference scenario. The scenario with the lowest NPC is scenario 5, followed closely by scenario 7. Scenario 5 leads to a 62% reduction of average natural gas consumption in the period 2021-2040 (compared to the reference scenario), while scenario 7 leads to a 64% reduction.

Table 8.5. Business-economic results for the period 2021-2040.

Scenario	**NPC [1000 DKK]**	**Average consumer heat price [DKK/MWh]**	**Average annual natural gas consumption [Nm^3/year]**	**Average annual imported electricity [MWh/year]**	**Average annual wood chip consumption [tonnes/year]**	**Average annual exported electricity [MWh/year]**
Reference	205,655	327	4,032,286	0	0	14,844
1. Reference with electric boiler (spot)	177,114	282	2,559,016	14,121	0	11,460
2. Reference with electric boiler (reg. + spot)	162,906	259	2,110,939	17,509	0	9,697
3. Reference with heat pump	161,129	256	1,330,056	7,165	0	4,998
4. Reference with wood chip boiler	179,328	285	2,525,476	0	4,523	10,629
5. Reference with electric boiler (reg. + spot) and wood chip boiler	156,386	249	1,516,516	10,734	3,677	7,284
6. Reference with heat pump and wood chip boiler	162,285	258	1,400,225	5,682	1,362	5,447
7. Reference with electric boiler (reg. + spot) and heat pump	159,231	253	1,431,696	12,972	0	6,189

The remaining part of Section 8.6 will focus on scenarios 5 and 7 as they have the lowest business-economic NPC values. Figures 8.8 and 8.9 show an example of the operation strategies for the two scenarios, which is calculated by energyPRO and is what determines in which order the units are activated. Naturally, high electricity prices are favourable for the engines, low electricity prices are favourable for the electric boiler and heat pump, while the NHPC for the natural gas boilers and wood chip boiler is independent of the electricity spot price.

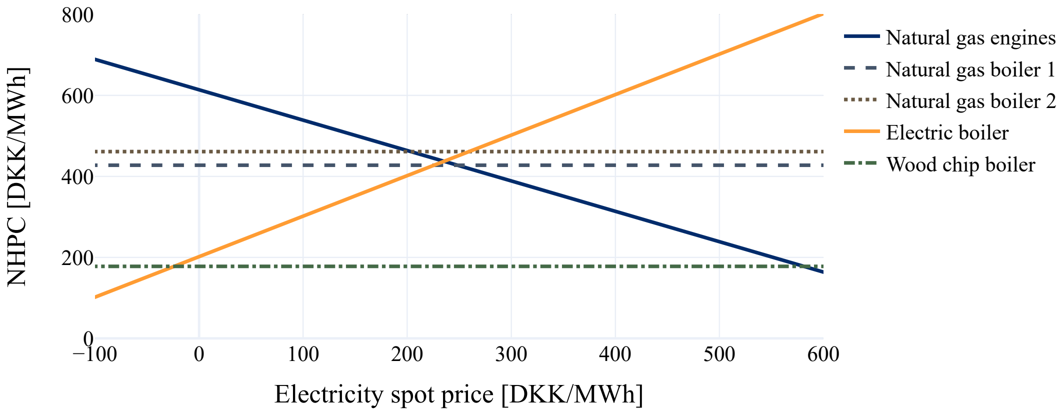

Figure 8.8. Scenario 5 operation strategy for January 2021.

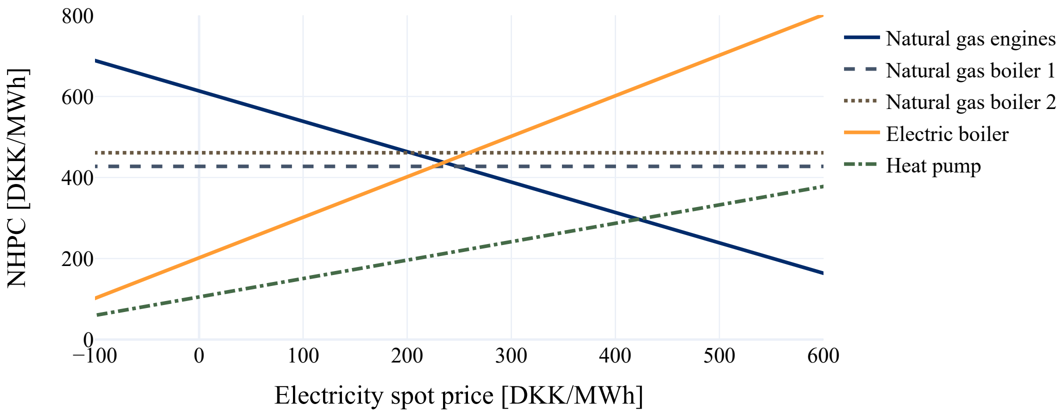

Figure 8.9. Scenario 7 operation strategy for January 2021.

8.6.1 Sensitivity analysis

In order to determine how sensitive the results are to changes in various parameters, a sensitivity analysis is made. The chosen variation magnitudes are based on the researchers' estimate of likely uncertainty. The results are shown in Figure 8.10. The most interesting results are those where scenario 5 becomes more expensive than scenario 7. This occurs in two cases: if the wood chip price is 20% higher than expected, and if the electricity price is 20% lower than expected. It is also worth noting that if the investment costs for new technologies decreases with just 10%, the NPC for the scenarios is almost the same.

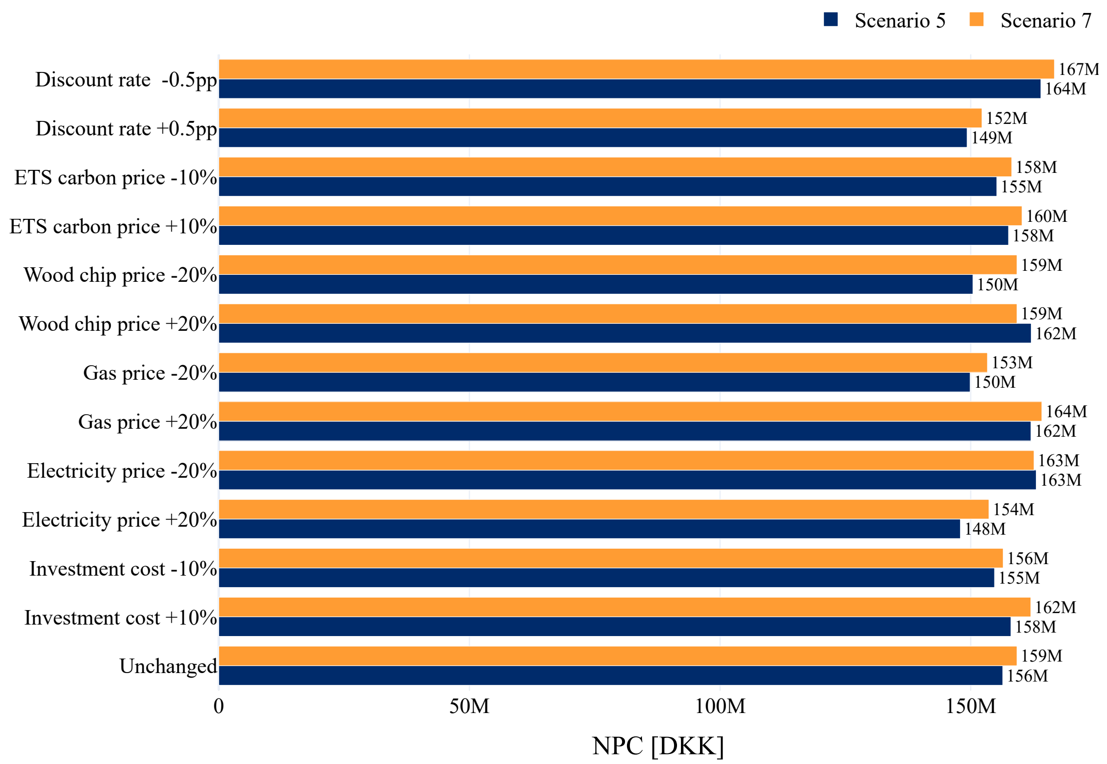

Figure 8.10. Sensitivity analysis of the business-economic results.

The considerable change of the results, which a 20% higher wood chip price causes, is interesting, because it is not at all unlikely that a biomass tax will be implemented in the near future (see Energy Supply [2021]). Also, as mentioned in Section 8.3, the electricity price projection used in these scenarios results in a relatively high electricity price in the future which is in contrast with the generally low electricity price of recent years, so a 20% lower electricity price is not implausible. Therefore, scenario 7 could easily end up being less expensive than scenario 5.

8.6.2 Removal of natural gas boilers

All of the previously analysed scenarios have included the technologies from the reference scenario. This means that they all include costs of a reinvestment in natural gas boilers in 2021 (see costs in Table D.3 on page 134). However, the possibility that it is cheaper to phase out the natural gas boilers needs to be considered as they have a low amount of operating hours. The removal of natural gas boilers has been found to have no impact on the optimal capacities of the alternative technologies due to the low amount of heat production.

The results are shown in Table 8.6. It can be seen that, both for scenario 5 and scenario 7, the NPC is lowered considerably by removing the natural gas boilers. This can be explained by examining the operation strategies shown in Figures 8.8 and 8.9: due to the placement of the intersection of the NHPC lines for the natural gas engines and the electric boiler, the natural gas boilers are almost always the lowest priority. This also explains why the natural gas consumption is not noticeably changed when removing the natural gas boilers. Therefore, the only downside to removing and not reinvesting in natural gas boilers is a reduced peak load capacity and possibly reduced security of supply if there is an outage on other units due to maintenance or breakdowns.

Table 8.6. Business-economic results for the period 2021-2040 with natural gas boilers removed.

Scenario	**NPC [1000 DKK]**	**Average consumer heat price [DKK/MWh]**	**Average annual natural gas consumption [Nm3/year]**	**Average annual imported electricity [MWh/year]**	**Average annual wood chip consumption [tonnes/year]**	**Average annual exported electricity [MWh/year]**
5. Reference with electric boiler (reg. + spot) and wood chip boiler - no natural gas boilers	149,223	237	1,517,159	10,762	3,677	7,312
7. Reference with electric boiler (reg. + spot) and heat pump - no natural gas boilers	152,097	242	1,431,862	13,001	0	6,211

8.6.3 Removal of natural gas engines

Following the conclusions made in Chapter 7 on page 43 is should be investigated if a CHP plant like Oksbøl CHP plant would have business-economic benefits from removing their natural gas engines and thereby reduce the electric CHP capacity in Denmark. Removing the natural gas engines at Oksbøl CHP plant, and thereby a large amount of heat producing capacity, a new optimisation process using the INTERFACE module must be performed on the optimal capacities of alternative units. In this optimisation process, it is assumed that the daily operation should consist of only renewable heat production. To maintain reliable heat supply, the natural gas boilers are kept as backup capacity and will only operate if there is an outage on the renewable technologies due to maintenance or malfunctions (which is not included in the energyPRO model). As the natural gas boilers at Oksbøl CHP plant are in the end of their lifetime, but still operable, there is not assumed to be a need of an investment in new natural gas boilers as there will be only a few operating hours during the year. If however, there is a malfunction in the old natural gas boilers and there is a need of a reinvestment in order to ensure security of heat supply in Oksbøl, the worst case scenario would be an additional investment cost in e.g. a new natural gas boiler or preferably an electric boiler for backup capacity.

Since the natural gas engines are not at the end of their lifetime, they are assumed to have a total scrap value of 7.7 million DKK, which is approximately 20% of the investment cost of new engines with the same capacities [Danish Energy Agency, 2020g]. The results of scenario 5 and 7 without natural gas engines are shown in Table 8.7.

Table 8.7. Business-economic results and optimal capacities for Oksbøl CHP plant in the period 2021-2040 without natural gas engines.

Scenario	**NPC [1000 DKK]**	**Average consumer heat price [DKK/MWh]**	**Average annual imported electricity [MWh/year]**	**Average annual wood chip consumption [tonnes/year]**
5. Reference with 7MW electric boiler (reg. + spot) and 4MW wood chip boiler - no natural gas engines	160,463	255	10,417	7,204
7. Reference with 11MW electric boiler (reg. + spot) and 1.5MW$_e$ heat pump - no natural gas engines	160,138	255	18,690	0

The results show that removing the natural gas engines increases the NPC in both scenarios, while it naturally causes a large increase in electricity and biomass consumption. Furthermore, it can be seen that scenario 7 becomes slightly more feasible than scenario 5 when removing the natural gas engines (even though it has an investment of 10 MDKK in a new electrical substation). This is due to the larger electric boiler capacity which enables more operation on the favourable regulating power market.

It is important to point out that the results presented in Table 8.7 have some uncertainty. They will strongly depend on both future electricity prices and the resale/scrap value of the engines. As the scenarios presented in Table 8.5 on page 68 only assume an inexpensive refurbishment on the engines in 2030, the result may differ in other another CHP plants. If the natural gas engines in a CHP plant are in the end of their lifetime, then a removal of the natural gas engines will be feasible from a business-economic perspective. This can be concluded, as an investment in new natural gas engines, of approximately 38.5 MDKK, will significantly increase the NPC of the scenarios that include these.

In the following section, the scenarios shown in Table 8.4 - with the same installed capacities - will be analysed from a socio-economic perspective.

8.7 Socio-economic results

These results are based on the method behind socio-economic feasibility studies, which is described in Section 6.4 on page 38.

The first results of the socio-economic analysis are the socio-economic NPC values for each scenario which all include the natural gas units. These are shown in Table 8.8. There are three scenarios, which are considerably less costly than the others, namely scenario 5 and scenario 7 (which also have the lowest business-economic NPC values) and finally scenario 2, which has the lowest socio-economic NPC value of all.

Table 8.8. Socio-economic results for the period 2021-2040.

Scenario	**NPC [1000 DKK]**
Reference	215,085
1. Reference with electric boiler (spot)	211,070
2. Reference with electric boiler (reg. + spot)	201,667
3. Reference with heat pump	214,147
4. Reference with wood chip boiler	218,401
5. Reference with electric boiler (reg. + spot) and wood chip boiler	203,292
6. Reference with heat pump and wood chip boiler	214,404
7. Reference with electric boiler (reg. + spot) and heat pump	205,092

It is found that the NPC of scenario 2 is lower mainly because the tax distortion loss is lower than in scenarios 5 and 7. The reduced tax distortion loss in scenario 2 is a result of consuming, on average, approximately 600,000 Nm^3 extra of natural gas per year - compared with scenarios 5 and 7 (see Table 8.5) - and this results in higher tax payments. The socio-economic cost distribution in each scenario can be seen in Figure 8.11.

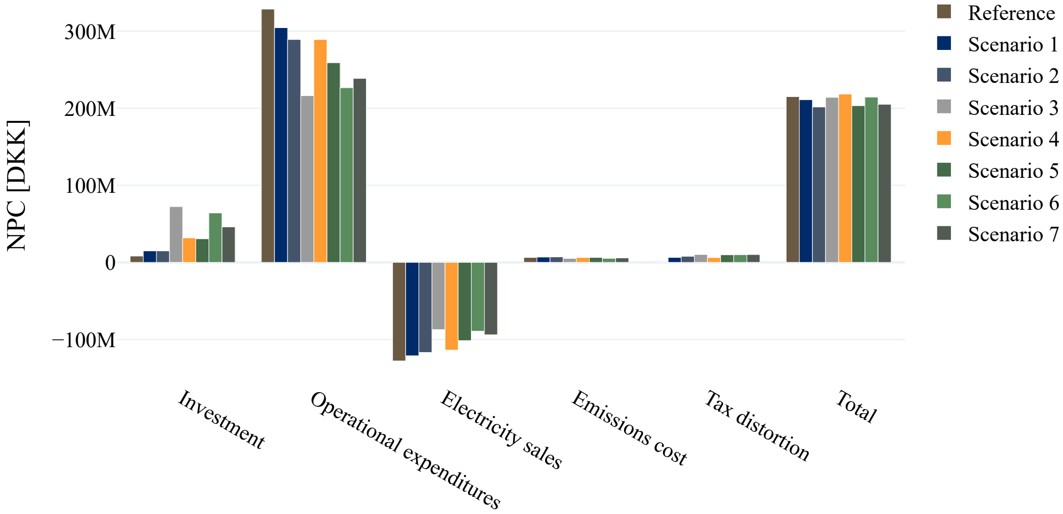

Figure 8.11. Socio-economic cost distribution for each scenario.

As scenarios 2, 5, and 7 are much cheaper than the others, they will be in focus in the remainder of this analysis.

8.7.1 Sensitivity analysis

As with the business-economic results, a sensitivity analysis has been made, and it can be seen in Figure 8.12. It is again those changes, which result in a different scenario becoming the cheapest, which are of particular interest. In this case, that applies to the following parameter changes: wood chip price -20%, wood chip price +20%, gas price +20%, and electricity price -20%.

As pointed out in the sensitivity analysis of the business-economic results, an increased wood chip price and a decreased electricity price are both plausible. In this case, if the electricity price is 20% lower, scenario 7 is the cheapest (as it was in the business-economic case). Also important is the fact that scenario 2 is more vulnerable to an increased natural gas price than the other scenarios. For scenario 5, it can be seen that this scenario naturally is highly dependent on the wood chip price where the scenario becomes the most expensive of the three at an increase of 20% in wood chip price. On the other hand, a decrease of 20% in wood chip price would make scenario 5 the cheapest scenario by far. This shows that, changes in the wood chip price has a significant impact on the feasibility of scenario 5 and it is the scenario which is most vulnerable to changes in one specific parameter.

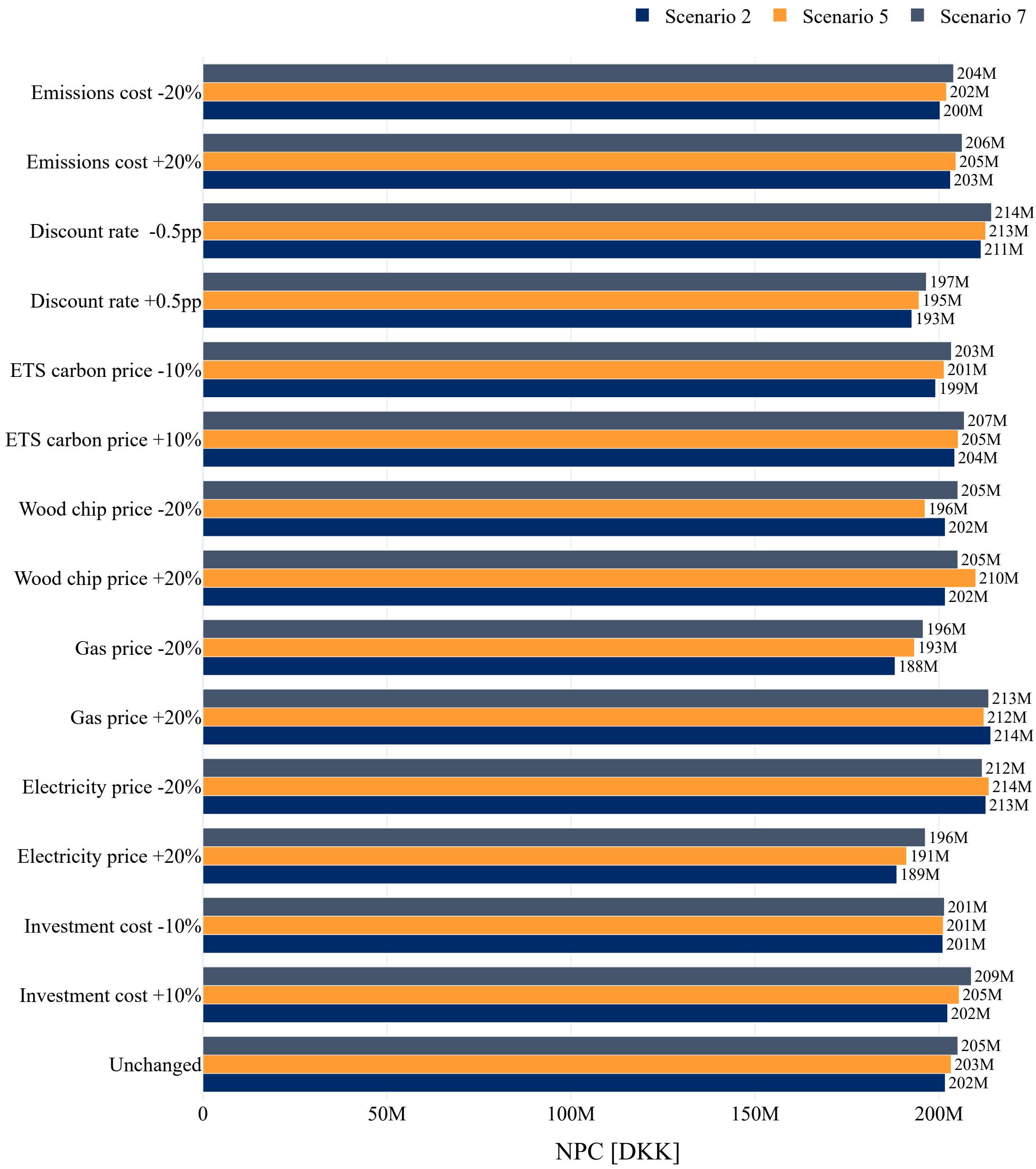

Figure 8.12. Sensitivity analysis of the socio-economic results.

8.7.2 Removal of natural gas boilers

In Subsection 8.6.2 it was investigated whether it - from a business-economic perspective - is feasible to remove the natural gas boilers from the system. It was concluded that it is not worthwhile to reinvest in the boilers. The same analysis is carried out with a socio-economic perspective, and the results are shown in Table 8.9.

Table 8.9. Socio-economic results for the period 2021-2040 with natural gas boilers removed.

Scenario	**NPC [1000 DKK]**
2. Reference with electric boiler (reg. + spot) - no natural gas boilers	216,347
5. Reference with electric boiler (reg. + spot) and wood chip boiler - no natural gas boilers	208,739
7. Reference with electric boiler (reg. + spot) and heat pump - no natural gas boilers	213,662

Removing the natural gas boilers results in an increased NPC in all three scenarios. The biggest impact of removing natural gas boilers occurs in scenario 2, because it has less alternative units (i.e. no wood chip boiler and no heat pump) to produce heat. The impact is lowest in scenario 5, because it has an alternative unit which is not dependent on electricity prices. The distribution of the costs is shown in Figure 8.13.

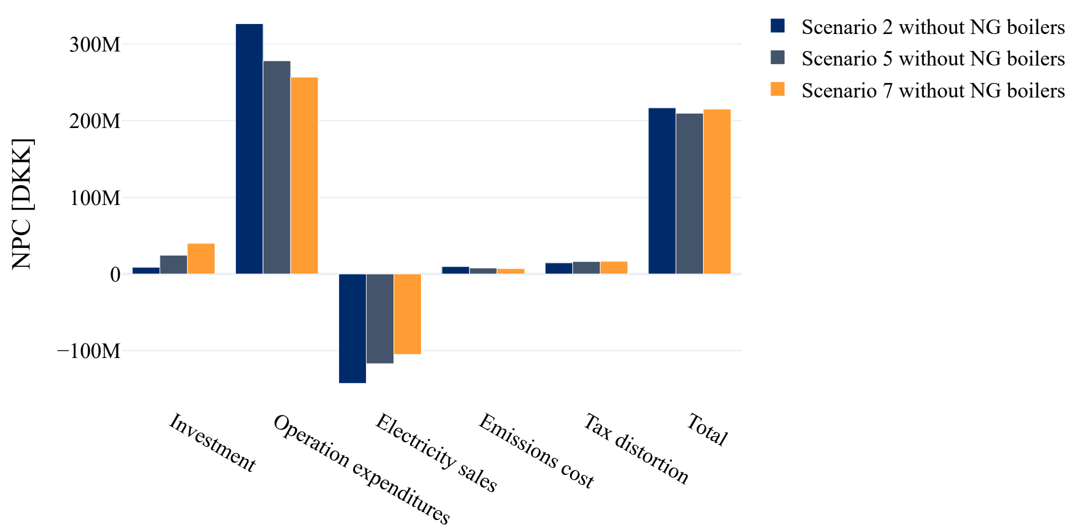

Figure 8.13. Socio-economic cost distribution for scenarios without natural gas (referred to as NG in the figure) boilers.

When removing the natural gas boilers the tax distortion loss increases, thereby reducing the socio-economic feasibility. This is due to the natural gas consumption being solely on the engines. A lower amount of taxes in general is payed for heat production on the engines than the boilers due to the tax benefits on co-generation of heat and electricity PwC [2020]. Furthermore, emissions of CH_4 and NO_x are greater when natural gas is used in an engine resulting in the environmental impact costs being higher. [Danish Energy Agency, 2019b]

8.7.3 Removal of natural gas engines

In Subsection 8.6.3 it was concluded that it would not be business-economically feasible for Oksbøl CHP plant to get rid of their natural gas engines, even if larger capacities of RE technologies are implemented. The same analysis must be carried out with a socio-economic perspective. As electric boilers usually are installed as peak load units, scenario 2 will not be investigated with the removal of natural gas engines as it would be unfeasible to have an electric boiler as the sole DH heating capacity (not accounting for the backup natural gas boilers) [Danish Energy Agency, 2020g]. The results of scenario 5 and 7 without natural gas engines are shown in Table 8.10.

Table 8.10. Socio-economic results and optimal capacities for Oksbøl CHP plant in the period 2021-2040 with natural gas engines removed.

Scenario	**NPC [1000 DKK]**
5. Reference with 7MW electric boiler (reg. + spot) and 4MW wood chip boiler - no natural gas engines	232,892
7. Reference with 11MW electric boiler (reg. + spot) and 1.5MW$_e$ heat pump - no natural gas engines	234,448

There is a significant socio-economic cost increase when removing the natural gas units which mainly is as a result of tax distortion losses and higher operational costs. When the natural gas engines are removed, the revenues of electricity sales are lost and there will be more heat production on e.g. the electric boiler in hours where the electricity prices are high. The reason that the business-economic results are not affected to the same degree by this, is that the higher heat production costs are evened out by the lower amount of taxes payed.

8.8 Comparison of business- and socio-economic feasibility

When comparing the results of the business- and socio-economic analyses, there is fortunately a lot of agreement. It is clear from both perspectives that continuing business-as-usual (i.e. as in the reference scenario) is not economically feasible. The scenarios with the lowest NPC are also, from both perspectives, those where electrification occurs. However, because reducing natural gas consumption causes a large tax distortion loss, scenario 2 becomes the cheapest in the socio-economic analysis (although the cost differences between scenarios 2, 5, and 7 are quite low).

Achieving the very lowest socio-economic NPC is, however, not the only factor which should be taken into account, because the Danish climate goals have to be reached. In the RE transition, it is recognised that there will be a socio-economic burden. For instance, the plan to get 775.000 electric-/plug-in hybrid vehicles on the Danish roads by 2030 is estimated to result in a socio-economic cost of several billion DKK [Bahn and Sindberg, 2020; Ertmann, 2020]. Therefore, the extent to which scenarios 2, 5, and 7 each help to reach the Danish climate goals of 2030 (see Section 2.1) also needs to be considered before a recommendation can be made.

As Oksbøl CHP plant is considered a paradigmatic case, multiple decentralised CHP plants in Denmark should be able to reduce their natural gas consumption, and thereby CO_2 emissions, by implementing solutions similar to those of either scenario 2, scenario 5, or scenario 7, all including natural gas boilers and engines. Assuming the results of Oksbøl CHP plant can be generalised (see Section 6.1), the CO_2 reduction as a function of number of CHP plants willing to transition in a similar manner as Oksbøl CHP plant can be seen in Figure 8.14

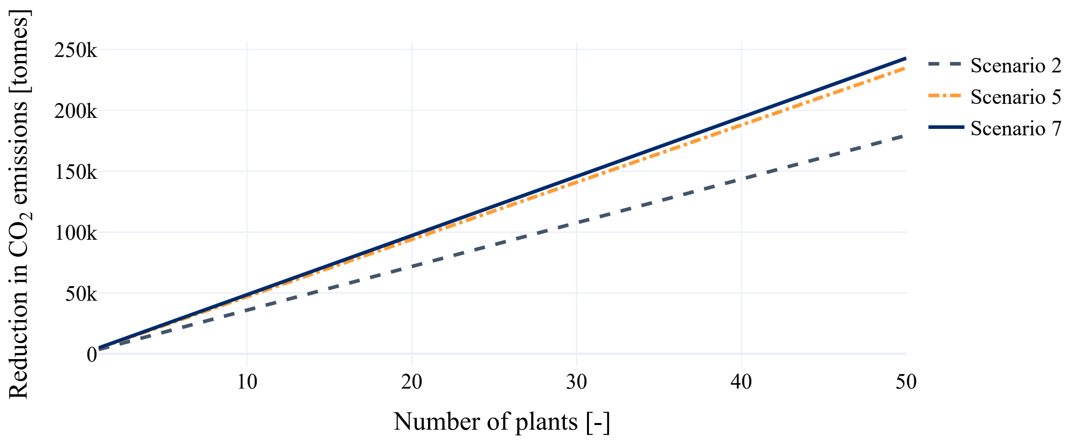

Figure 8.14. Yearly CO_2 reduction in Denmark as function of the number of plants willing and able to transition into an electrified heat production.

As seen in Figure 8.14 the implementation of scenario 7 on 50 decentralised CHP plants would result in a reduction in CO_2 emissions of nearly 250,000 tonnes per year (about 60,000 tonnes more than scenario 2). Denmark needs to reduce the annual CO_2-eq emissions with around 23.8M tonnes (compared to 2019 numbers) to accommodate the

70% reduction target in 2030 [Danish Energy Agency, 2020e]. Not accounting for other GHG emissions from the natural gas consumption in the scenarios, a CO_2-eq reduction of 250,000 tonnes will result in approximately 1% of the emission reduction that remains to be achieved [Danish Energy Agency, 2020e]. It is to be noted that the results in CO_2 emissions are made with the assumption that Oksbøl CHP plant represents an average decentralised natural gas fired CHP plant in Denmark. As multiple plants, smaller and larger, are assumed to benefit from the transition there may be differences between theory and practice.

A reduction in natural gas usage, as a result of the alternative scenarios, will also help achieving the goal of the Danish Government concerning a 90% RE share in the DH sector by 2030. Calculating impact from the scenarios on this goal, the fuel consumption for electricity and heat production on the engines must be separated. Here, the recommendation from the DEA is to use a thermal efficiency of 125%. This method puts losses from co-generation on the electricity side of the production (for more information see Energinet [2020b]). The RE share in the DH sector as a function of the number of CHP plants implementing the electrification scenarios can be seen in Figure 8.15.

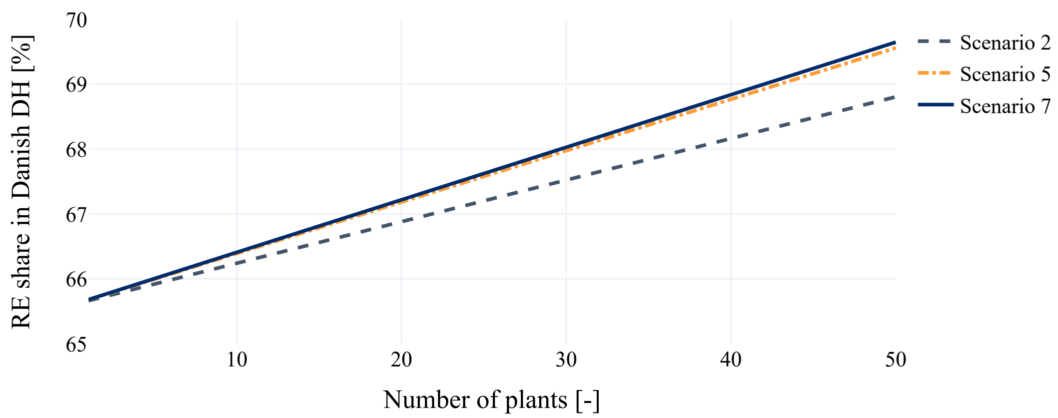

Figure 8.15. RE share in the Danish DH sector (2019 values [Danish Energy Agency, 2020e]). Note: RE share includes electricity consumption from electric boilers and heat pumps.

As previously mentioned, it is a goal to phase out coal by 2030 which will also increase the RE share in the DH sector.

Since scenarios 5 and 7 are - on paper - approximately equal in terms of helping to reach the climate goals, and scenario 5 results in a slightly lower both business-economic- and socio-economic NPC, scenario 5 might be the solution to recommend. With current taxes, investment costs, O&M cost etc., a wood chip boiler and electric boiler combination will probably be implemented at many decentralised CHP plants in Denmark. However, as pointed out in Subsection 8.6.1, implementation of a biomass tax in Denmark is not unlikely, and there could be good reasons for such a tax. Not only is the sustainability of using biomass for electricity and/or heat production often called into question (see Subsection 2.4.1 on page 13), using a wood chip boiler instead of a heat pump also means not utilising as much otherwise excess electricity in DH (which is substantial in some of the scenarios for the Danish energy system analysed in Chapter 7 - see Figure 7.1 on page 49). If sufficient storage capacity is available, scenario 7 with a heat pump and electric boiler, would be able to utilise excess electricity much better.

Oksbøl CHP plant, as mentioned, has a large storage capacity, and it is rarely utilised to the full capacity in the investigated scenarios. An example of the storage content throughout the year in scenario 7 from year 2021 can be seen in Figure 8.16. This scenario is highly dependent on a flexible heat production due to varying electricity prices and yet, the heat storage is almost never fully utilised.

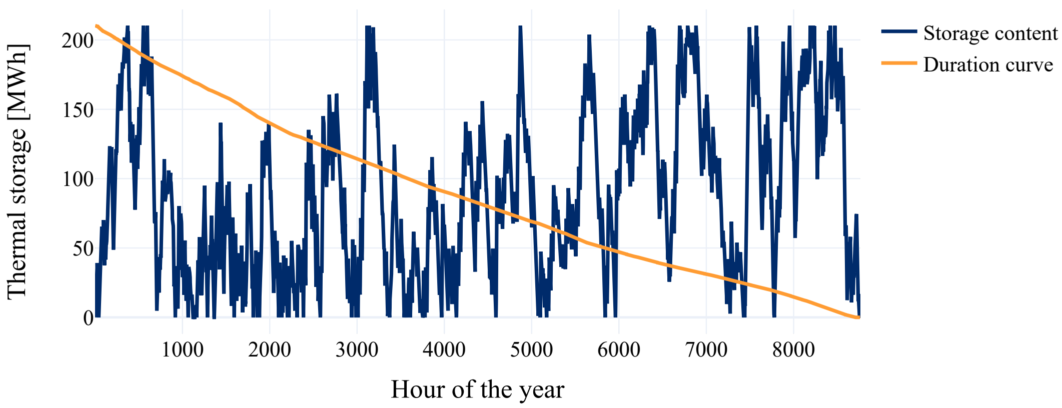

Figure 8.16. Thermal storage content of Oksbøl CHP plant in year 2021 - scenario 7.

For other plants, an electrification of the DH production might result in the need of a larger storage capacity to take advantage of low electricity prices when there is a surplus in e.g. wind production to maintain business- as well as socio-economically feasible operation.

As of 2021, due to a favourable tax structure, there are no public regulation measures that hinder natural gas CHP plants with an annual heat production of less than 500 TJ in reducing their natural gas consumption and transition to a more renewable heat production. However, if the Danish Government wants further electrify the heating sector and incentivise decentralised CHP plants to implement heat pumps rather than wood chip boilers, it must be business-economically feasible. If desired, this can simply be done by making it - for instance - 20% more expensive to use biomass in DH. This is demonstrated in Figure 8.10 and would specifically mean placing a tax of 10 DKK/GJ on biomass. This measure would not result in the most socio-economically feasible alternative. However, for a low additional socio-economic cost it will result in the alternative with a lower natural gas consumption and thereby lower CO_2 emissions, as well as a better integration of fluctuating electricity production.

8.9 Subconclusion

The preceding analysis sought to answer the following subquestion:

How can electric heating solutions be used to reduce natural gas consumption in the district heating sector and contribute to the achievement of the Danish climate goals of 2030 while maintaining business- and socio-economic feasibility?

To answer this, a number of scenarios for the paradigmatic case of Oksbøl CHP plant were made. These scenarios, for the period 2021-2040, included a reference scenario as well as a number of other scenarios, where new RE technologies - used in different combinations - were added, namely an electric boiler, a wood chip boiler, and a heat pump. These scenarios were modelled in energyPRO, and the capacities of the new technologies were optimised with the energyPRO INTERFACE module to minimise the business-economic NPC. The key results were the business- and socio-economic NPC values of each scenario as well as the consumption of natural gas in each scenario.

From the business-economic perspective, the reference scenario had the highest NPC by far, and it also had a high socio-economic NPC. The two scenarios with the lowest business-economic NPC values were those with, respectively, a wood chip boiler and electric boiler combination and a heat pump and electric boiler combination, with the former having a slightly lower NPC. These two scenarios were also in the top three least expensive from the socio-economic perspective, although the very least expensive scenario here was the one with just an electric boiler capable of participating in the regulating power market. Interestingly, the low socio-economic NPC of the electric boiler scenario was due to a higher natural gas consumption which limits the tax distortion loss compared with the two other scenarios.

Sensitivity analyses were made both on the business-economic- and socio-economic results, and these showed that the scenario with a heat pump/EB combination could easily become the least expensive from both perspectives, if the electricity price is just 20% lower than assumed in this analysis (which uses high electricity prices compared with recent years).

It was argued that, even though the heat pump/EB scenario has a slightly higher socio-economic NPC than the electric boiler scenario, it should not be ruled out as a recommendation, because other factors should be taken into account. For instance, to which degree the scenario helps to achieve the Danish climate goals or how well it takes advantage of otherwise excess electricity. Minimising the consumption of biomass in boilers could also be considered favourable, as this finite resource might be put to better use in co-generation. To incentivise implementation of heat pumps rather than wood chip boilers, it was determined that a tax of 10 DKK/GJ could be placed on biomass.

It was also investigated, for certain scenarios, whether the NPC could be lowered by removing the natural gas units at Oksbøl CHP plant. From a business-economic perspective, it is feasible not to reinvest in natural gas boilers. From a socio-economic perspective, it is not favourable, as it entails more usage of the engines, which have higher emissions and cause a lower tax revenue. From both a business- and socio-economic perspective, it is not feasible for Oksbøl CHP plant to scrap their existing natural gas engines.

Institutional Analysis 9

The purpose of this chapter is to answer the third underlying research question. This chapter will therefore examine the institutional and political structures that either hinder or favor actors in achieving an implementation of a socio-economically feasible electrification of the DH sector. The course of action will take a point of departure in the methodological approach explained in Section 6.5 on page 40, using Oksbøl CHP plant as case.

9.1 Political modernisation processes

The first step of the analysis is to select political modernisation processes that will define the object of study. The political processes chosen are the Danish 2018 and 2020 Energy Agreements and the climate law. These processes contain an array of goals, with the most relevant for the institutional analysis being the goal of a 70% GHG emission reduction by 2030 compared to 1990 and that 90% of the DH production in Denmark should come from renewable sources in 2030. [The Danish Parliament, 2018]

This thesis seeks to examine how electrifying the natural gas-based DH production in Denmark can help to reach the climate goals. Thus, it is necessary to investigate the institutional and political structures that either hinder or promote an implementation of such a technological change. Oksbøl CHP plant has been selected as a paradigmatic case as described in Subsection 6.1 on page 31. The institutional setting, and actors within, are therefore identified by taking a point of departure in the future transition of Oksbøl CHP plant.

9.2 Actor analysis

The second step of this analysis, is to map all of the relevant actors within the institutional setting of Oksbøl CHP plant. Thus, the actors are identified based on their interest in, or possible influence on, the future transition of Oksbøl CHP plant. All of the actors are identified through the interview with the operations manager of Oksbøl CHP plant, Preben Pedersen, as described in Section 6.6 on page 42. The mind map is shown in Figure 9.1.

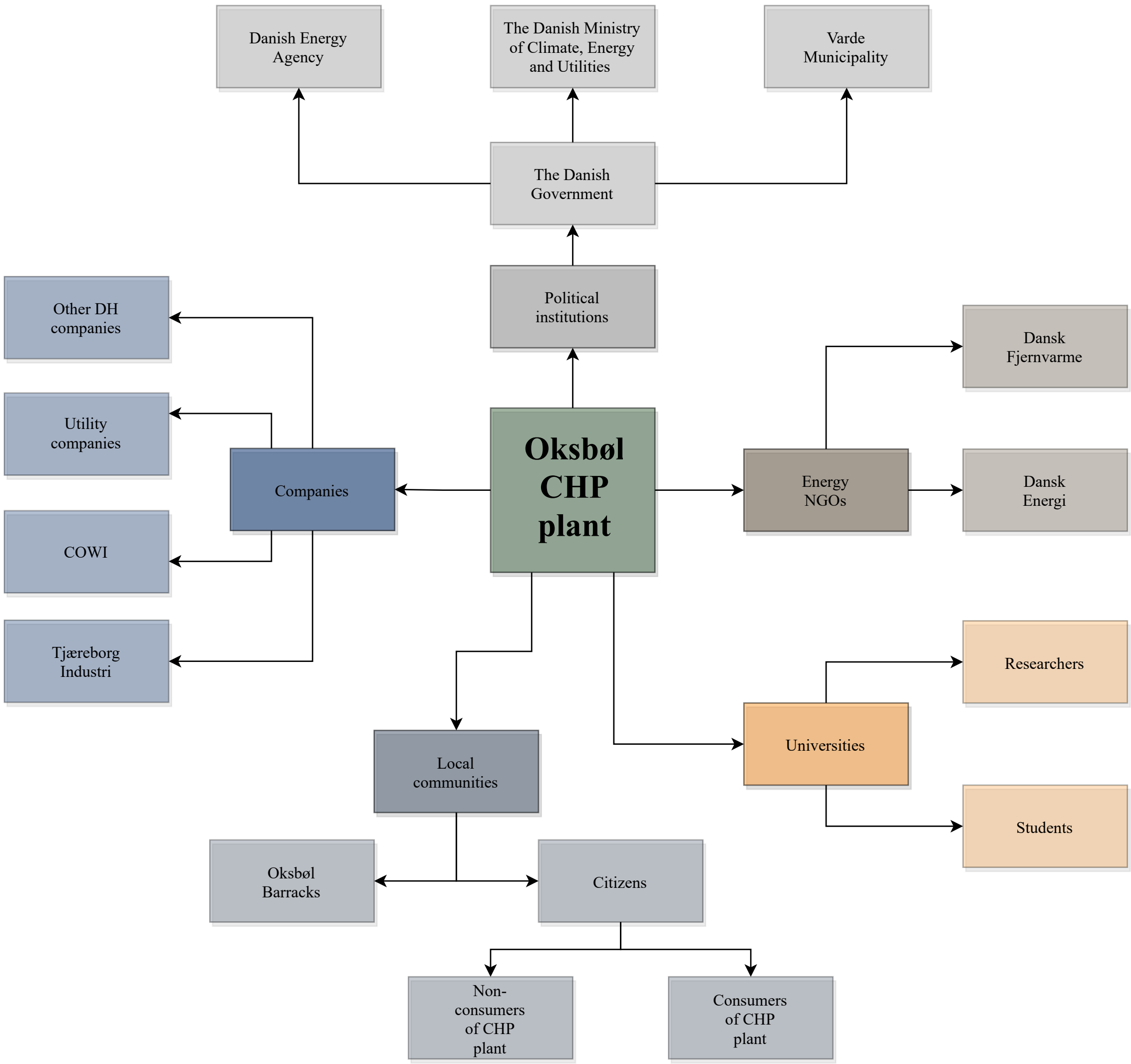

Figure 9.1. Actor mindmap illustrating all of the identified actors relevant for this analysis.

As it can be seen in Figure 9.1, the identified actors have been divided into five branches; Companies, Political institutions, Local communities, Universities and Energy non-governmental organisations (NGOs). A definition and elaboration of each actor is done in the following sections.

9.2.1 Companies

Oksbøl CHP plant is the DH heating company chosen as the case for this research as explained in Section 6.1 on page 31. Oksbøl CHP plant is a consumer owned (limited liability company (a.m.b.a)) decentralised CHP plant which currently uses natural gas engines, natural gas boilers, and solar collectors as explained in Subsection 8.4 on page 65. The operations manager of Oksbøl CHP plant mentions that they have already made plans for implementing new technologies which will reduce their natural gas consumption in the near future, which manifests their interest in this research. (See Appendix B)

Other DH companies have contact and idea exchange with Oksbøl CHP plant. They work as sparring partners, where they exchange thoughts, experiences and ideas, so that they can all benefit from each other. Furthermore, the operations manager of Oksbøl CHP plant mentions that the DH cooperative in general, is very open and extensive, which works in favour of everyone involved. (See Appendix B)

COWI have provided the primary consultant work for Oksbøl CHP plant regarding their transition. They first contacted COWI back in 2014, when they decided to look into expanding their capacity in correlation with the plant's opportunity to connect its production to the Oksbøl Barracks. COWI has since then analysed alternative solutions and made recommendations, which Oksbøl CHP plant intends to follow. COWI therefore has a high influence on the decision making of Oksbøl CHP plant. (See Appendix B)

Tjæreborg Industri has worked closely together with Oksbøl CHP plant regarding the transition, as it is a trusted partner. Tjæreborg Industri provides DH installation services and also provides maintenance services to Oksbøl CHP plant regarding the old and recent modifications of the plant. The operations manager of Oksbøl CHP plant mentions that he values the cooperation with Tjæreborg Industri, which has a lot of experience within the field:

> *"We have a lot of contact with them because we use their service for maintenance of our technologies or if something is to be put out to tender as they have a high competence in this field and an even larger experience. The ones you know well and feel comfortable working with are the ones you listen to."* - The operations manager of Oksbøl CHP plant (see Appendix B).

This also manifests Tjæreborg Industri's ability to influence the decision making, as the company's opinions/advice is prioritised. [Tjæreborg Industri, 2021] (See Appendix B)

Utility companies. This definition distinguishes between three utility companies: the gas distributor, DSO (N1) and TSO (Energinet). The gas distributor is defined as an actor as it has an interest in maintaining the current demand for natural gas and it has previously influenced the decision making of Oksbøl CHP plant by advocating that the proposed alternative solutions were not socio-economically feasible (e.g. tax distortion). As the gas distributor's business-case is largely based on the continued usage of natural gas, it will try to avoid a technological change that makes its product obsolete and makes it lose its position of power. Lund [2014] states, that old market dependent organisations will try eliminate choice to society, which manifests both their interest and influence in this research. The operations manager of Oksbøl CHP plant mentions that the gas distributor did influence the decision making by claiming that Oksbøl CHP plant's alternative solutions were not socio-economically feasible:

> *"In the first three years, it was the gas distributor that hindered our plans, so, yes, you could call it an opposition. They complained about the arguments we had, which they then appealed to the Energy Appeals Board. This provoked a lot of frustrations. However, this interference is mostly gone now. I do not know if someone has told the gas distributor to stop it."* - The operations manager of Oksbøl CHP plant (see Appendix B).

Thus, the gas distributor influenced the decision making of Oksbøl CHP plant. This raises frustration for the operations manager as he expresses the following:

> *"If it was not a semi-state-owned company, then I would not mind them attempting to protect their interests. I have a hard time understanding why I have to pay taxes to finance a semi-state-owned company hindering the the green transition that has been imposed on us by the government."* - The operations manager of Oksbøl CHP plant (see Appendix B).

Since Oksbøl CHP plant has an annual heat production of less than 500 TJ, they are no longer subject to the fuel binding- and co-generation requirements (see Table 2.2 on page 13). This probably explains why the interference from the gas distributor has lessened. However, the example shows that the gas distributor will try to influence the decision making in order to protect their own interests.

N1 manages and maintains the electricity distribution grid in Oksbøl. Its interest in this research and the electrification of the CHP plant, exists in the grid reinforcement that Oksbøl CHP plant needs to apply, in order for it to be adequate for their future electricity consumption. It can be assumed that N1 is interested in the solution that economically benefits N1. Thus, N1 will try to influence the decision making (e.g. the operations manager of Oksbøl CHP plant mentions that he has been in contact with N1 regarding expanding their electric heating solutions, but purchasing a new transformer was found to be too expensive). [N1, 2021] (See Appendix B)

Energinet are in charge of the electricity- and gas transmission grids in Denmark and has an interest in maintaining security of supply in these grids. Energinet is a state-owned company and is a subject to the Danish Ministry of Climate, Energy and Utilities. Thus, it has an interest in adhering to goals of the government in a similar way as this research does. Energinet is defined as an actor, as parts of this research revolves around removing CHP capacity in the Danish energy system as a result of an electrification of the DH, which could affect the security of electricity supply. Thus, Energinet are interested in solutions, that do not contradict one of their main tasks as a company. Energinet has the ability to influence this transition, as it is in charge of the whole infrastructure needed to electrify the DH in Denmark. [Energinet, 2021b]

9.2.2 Political institutions

The Danish Government has a an interest in reducing the GHG emissions in Denmark as stated in the 2018 Energy Agreement The Danish Parliament [2018]. Furthermore, as elaborated in Section 2.1 on page 3, the Danish Government is interested in 90% of the DH production in Denmark, coming from renewable sources, which manifests its interest in the technological transition of Oksbøl CHP plant. Denmark is a member of the EU, which can affect the Danish energy/climate policy. The influence exists through the government's ability to either hinder or promote the transition by law and climate policies.

The Danish Ministry of Climate, Energy and Utilities' goals including its sub agencies and institutions, correlates with the purpose of this research of reducing GHG emissions in Denmark. Also, the ministry can influence the decision making of the Danish Government, which is important if an electrification of the DH in Denmark is wanted. The ministry works as mediator between Energinet, the DEA and the Danish Government. Thus, its interest in this research is manifested through the tasks of the aforementioned agency and institution. [Danish Ministry of Climate, Energy and Utilities, 2021]

Danish Energy Agency's primary task is to assist Denmark towards a green transition and a reduction in GHG emissions. The agency has a variety of tasks ranging from energy planning and management to waste and water management. The agency is subject to the Danish Ministry of Climate, Energy and Utilities, and does therefore have to adhere to the ministry and to the Danish Government. The agency has an interest in electrifying the DH in Denmark, as this transition correlates with their visions as an agency. They furthermore have the ability to influence this transition through their areas of responsibility. [Danish Energy Agency, 2021]

Varde Municipality is identified as an actor, as Oksbøl CHP plant is subject to municipal case processing. (e.g. when implementing new technologies or connecting new areas to DH.) However, at the same time, the municipality is subject to both the regional and governmental plans, which could affect its influence on the decision making of Oksbøl CHP plant. The operations manager of Oksbøl CHP plant mentions that they have been in contact with the municipality, but often without much yield:

> *"I do not think that I can say that we have been directly influenced by Varde Municipality. They have made a fine strategic energy plan, where we participated in meetings and so on. It is fine that the municipality makes a plan for what they think we should do, but it does not help if the regulation points in a different direction."* - The operations manager of Oksbøl CHP plant (see Appendix B).

The municipal planning process is sometimes very extensive and prolonged, which may hinder both the decision making and implementation process of DH companies. This was also the case between Varde Municipality and Oksbøl CHP plant. Municipalities in general, conduct strategic energy plans that to some degree will influence the decision making of the DH plants. [Varde Kommune, 2014] (See Appendix B)

9.2.3 Local communities

Non consumers of Oksbøl CHP plant could be interested in the DH prices, if they live in an area where a DH grid expansion is feasible. However, changes in the DH producing technologies will currently not affect their heating costs.

Consumers of Oksbøl CHP plant are highly interested in the feasibility of the production as this will directly influence their heating costs. The plant is a limited liability cooperative (in Danish: a.m.b.a.), meaning that they have the possibility to directly influence the decision making of the plant through the board of directors. This board of directors is chosen by the consumers, and is therefore working as mediator between the consumers and the plant. Also, the board of directors chooses the personnel in charge of operating and managing the plant. While some citizens care whether or not the heat production is based on renewable sources, it can be assumed that most citizens have an interest in the cheapest heating solution. (See Appendix B)

Oksbøl Barracks has recently been connected to the DH production from Oksbøl CHP plant. The operations manager of Oksbøl CHP plant mentions that their initial thoughts about purchasing a wood chip boiler in 2014, began with the opportunity for them to connect to Oksbøl Barracks. The facility is rather large, and it therefore influences the overall heat demand significantly (25% increase). The increased heat demand made it more economically feasible to expand the heat production capacity. Also, the agency owning the facility has an interest in low heating costs. Oksbøl Barracks will therefore from now on be defined as a consumer of the CHP plant. (See Appendix B)

9.2.4 Universities

Researchers and **Students** have the ability to allocate resources to Oksbøl CHP plant and DH companies in general, through their research. Often, DH companies lack sufficient resources to carry out an adequate analysis for finding the solutions which benefit them the most, which is why they often hire consultants. This was also the case for Oksbøl CHP plant, where they hired consultants from COWI to find alternative solutions. Thus, if students allocate their time and knowledge, this could be beneficial for the DH companies. This thesis is an example of this, as the researchers analyse the case of Oksbøl CHP plant, and gives the operations manager an insight of their findings. However, this cooperative work does not happen by itself, as the researchers in this case, reached out to Oksbøl CHP plant themselves. A suggestion could be that the Energy NGOs or universities encourage the DH companies to propose project ideas that the students would find interesting to study. Also, the students have a natural interest in doing their best work, as it is a part of their study.

9.2.5 Energy NGOs

Dansk Fjernvarme and **Dansk Energi** are identified as the two NGOs relevant for this analysis. Dansk Fjernvarme deals with all DH companies in Denmark, as it is defined as the Danish DH companies' main interest NGO. Thus, it has a natural interest in making sure that these companies are satisfied with their treatment, environmental care, security of supply and equal terms etc. Furthermore, one of Dansk Fjernvarme's flagships deals with green heating solutions, which manifests their interest in electrifying the DH in Denmark. [Danish District Heating Association, 2021]

Dansk Energi on the other hand, is the main interest NGO for electricity companies in Denmark. The organisation's main flagship is to maintain security of supply whilst also ensuring competitive prices for electricity. Their main area of tasks therefore revolves around political framework, collectively solving problems in the Danish Energy Sector and lastly, being a central cooperative platform for the Danish electricity companies. Their interest in this research is manifested by their interest in maintaining security of supply in the Danish electricity sector. As this research examines whether electrifying the Danish DH sector will harm the security of supply, Dansk Energi will have an interest in- and will try to influence the proposed electrification. [Danish Energy, 2021]

Other NGOs like DN (Danmarks Naturfredningsforening) or Concito could also be defined as actors. However, it has been chosen not to include them, as their interest in a possible electrification of Oksbøl CHP plant is assumed to be insignificant. Furthermore, they do not have ability to influence the decision making of the plant, while it is assumed that both Dansk Fjernvarme and Dansk Energi do.

9.2.6 Actor delimitation

As all of the identified actors have been accounted for, the most relevant actors will be chosen for the remaining part of the actor analysis. This will be done by defining the actors' interest and power in a possible electrification of Oksbøl CHP plant. The results of this definition is therefore based on the interview with Oksbøl CHP plant. To showcase the actors' interest and power, a matrix has been made. This can be seen in Figure 9.2.

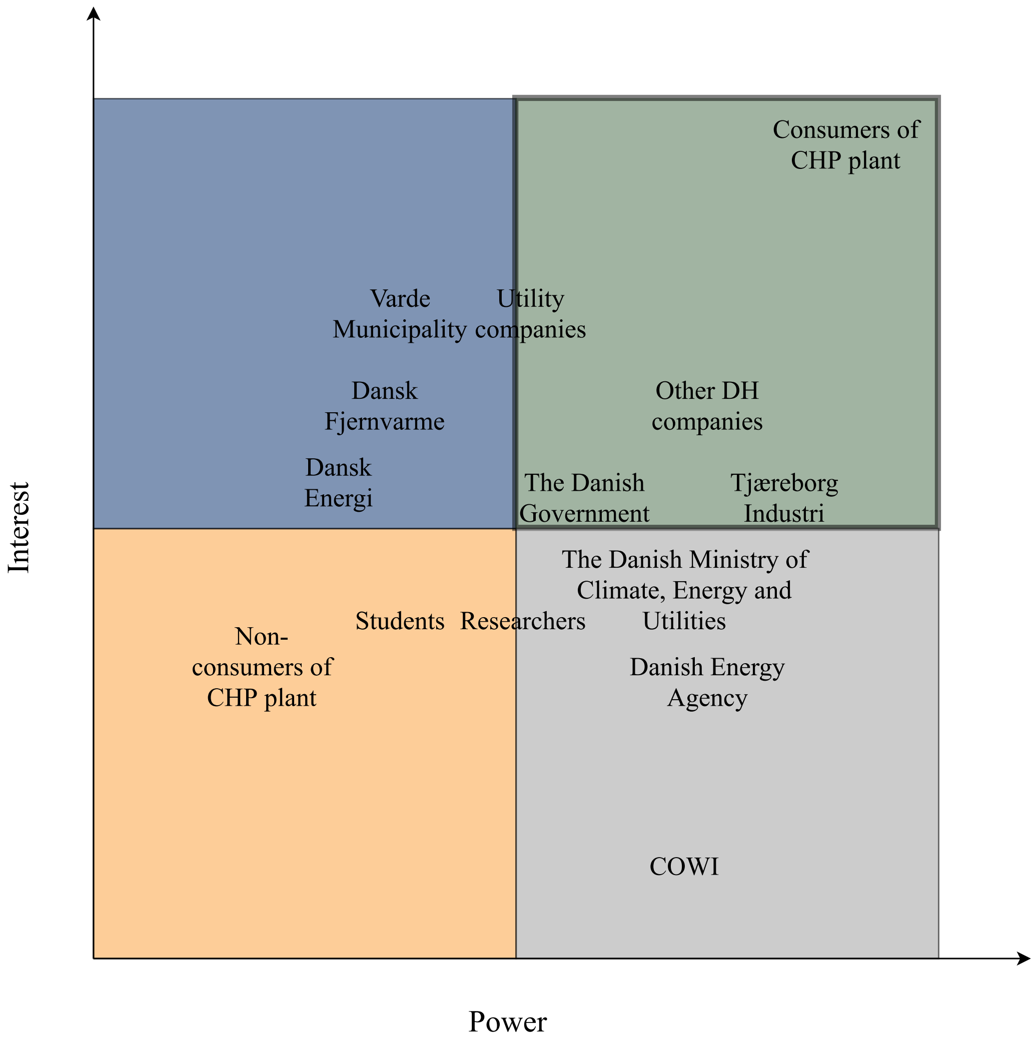

Figure 9.2. The identified actors' interest/power in a future transition of Oksbøl CHP plant.

As it can be seen in Figure 9.2, the actors with the most interest and power have been placed in the green upper right square within the matrix. This square has been highlighted, as it contains the most relevant actors for the remaining part of this analysis. The following will therefore only deal with these actors.

9.3 Actor relation/interaction

In order to understand the relation/interaction that the most relevant actors have, the actor interaction has been outlined in Figure 9.3. The figure distinguishes between to types of interaction: Direct and indirect. Direct interaction is defined as a two way interaction, where the actors purposely interact by e.g. speaking, having meetings etc. This interaction is visualised in the figure by a orange line with a double arrowhead. Indirect interaction is defined as an one way interaction, where the actors indirectly interact through e.g. regulation, policy, law, plans etc. This interaction is visualised in the figure by a blue line with a single arrowhead showing the direction of the interaction. All of the relations/interactions were identified through the interview with the operations manager of Oksbøl CHP plant.

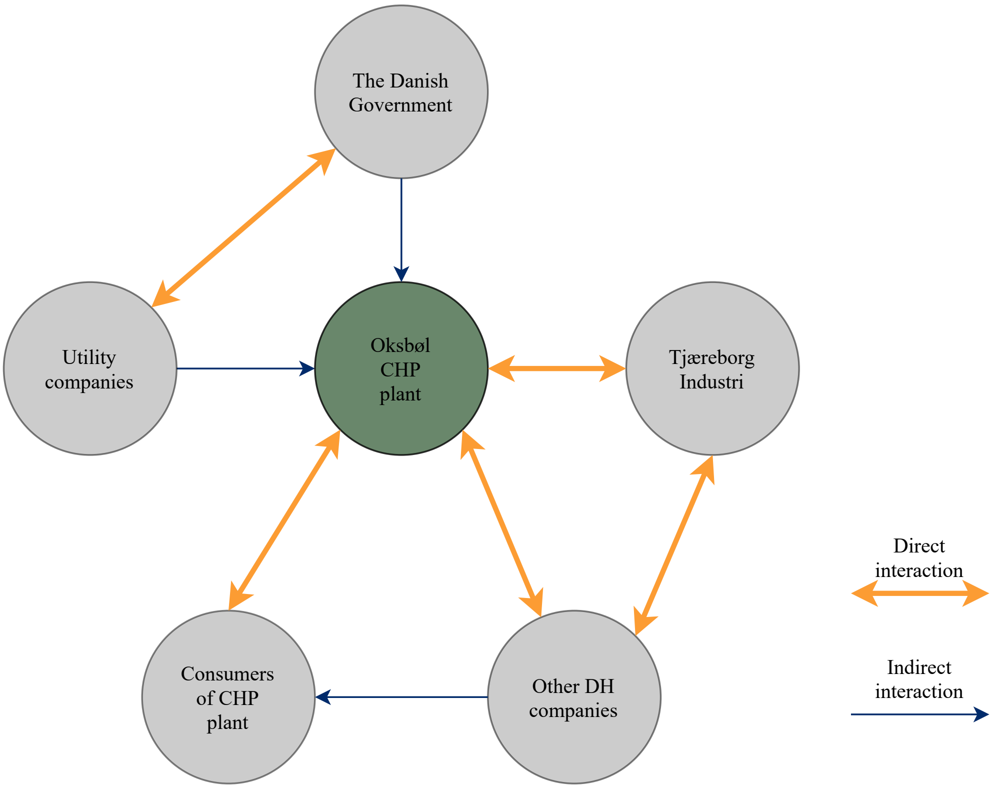

Figure 9.3. The actors' direct and indirect interactions.

As it can be seen in Figure 9.3, three indirect and five direct interactions exists in the case of a future transition of Oksbøl CHP plant. The purpose of this figure is to identify the relations/interactions that happen between the actors, in order to understand the power structures that are exercised through these relations/interactions.

9.3.1 Division of power

Taking a point of departure in the relations/interactions between the actors, the division of power can be analysed. This will be done by using the power theory as outlined by Barnett and Duvall [2005], to describe the actors' taxonomy of power as explained in Section 6.5 on page 40. The actors' power can be seen in Figure 9.4.

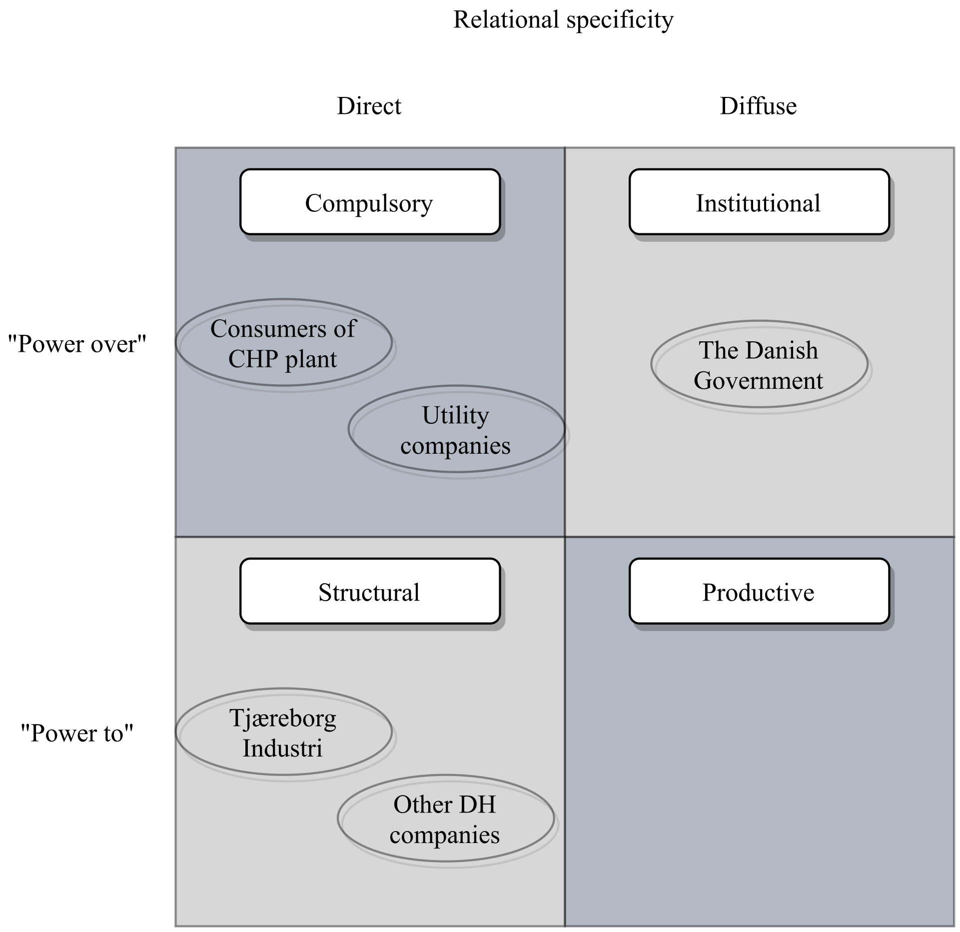

Figure 9.4. The actors' power taxonomies. [Barnett and Duvall, 2005]

As it can be seen in Figure 9.4, three types of power exists through the interactions identified in Figure 9.3. The following paragraph seeks to examine the different taxonomies of power that is being exercised by the different actors.

Tjæreborg Industri exercises structural power, as their role as partners with Oksbøl CHP plant gives them a powerful ability to influence the decision making. As mentioned during the interview, Tjæreborg Industri is the first actor that Oksbøl CHP plant includes when a new decision is considered. This shows that, even though they might not have the most resources or any institutional power, they override other actors' interaction and/or power due to personal relations. However, this might be an unusual situation, that only exists in this relation and not in other cases.

Similar to the power of Tjæreborg Industri, is the power of the other DH companies. They also exercise structural power, as Oksbøl CHP plant seeks guidance and idea exchange with these companies. However, this power is not as prominent as with Tjæreborg Industri, as it is more of an idea exchange rather than an initial or final saying.

The utility companies exercise compulsory power, as their power derives from their resources. Larger companies are able to allocate large amounts of resources to influence the decision making and influence a technological change. As mentioned, the gas distributor already exercised this power, during the early stage of the planning phase of the technological change at Oksbøl CHP plant. However, the operations manager of Oksbøl CHP plant mentions that the gas distributor has not interfered in recent years. Thus, it seems that the regulatory changes of the Energy Agreement 2020 have worked as intended. The gas distributor in Denmark, as of 2021, is called Evida and they are owned by the Ministry of Finance [Evida, 2021]. Therefore, if the gas distributor still counteracts the phase out of natural gas at plants with an annual heat production of more than 500 TJ, a new interaction and power structure between the Danish Government and the gas distributor could be proposed. (See Appendix B)

The consumers of the CHP plant exercise compulsory power, as their ability to influence Oksbøl CHP plant revolves around the share of liable deposits they have in the company, and also their influence on the board of directors. Therefore, the consumers have a strong ability to influence the decision making of the plant. This company structure, where the consumers have influence, can be seen as democratic. However, this is not necessarily always a good thing, when a transition is wanted. As mentioned by the operations manager of Oksbøl CHP plant, the consumers are most likely to agree with the production solutions that result in the lowest heating costs, which could hinder the wanted transition for the plant. Also, when including consumers in the decision making, Oksbøl CHP plant and the board of directors have to take their opinions into account, which can hinder in a transition. (See Appendix B)

The Danish Government exercises institutional power. The Danish Government 'controls the agenda' of the institutional setting, and therefore has a strong ability to influence the decision making of Oksbøl CHP plant. However, the Danish Government needs to exercise this power with caution and with clear and understandable communication. The operations manager of Oksbøl CHP plant mentions that he finds the interaction between them and the Danish Government confusing, as they have had a hard time keeping up with new regulations and climate policies. This misunderstanding can be assumed to happen through most of the Danish Government's interaction with smaller DH companies that do not have the personnel nor resources to fully examine and engage in new regulation. This could harm the transition of these natural gas-fired DH companies, as they might find it easier not to look into a transition. An interesting example of the aforementioned confusion which could lead to a delayed transition is that the operations manager of Oksbøl CHP plant was not aware of the reasons behind the lessened interference from the gas distributor (see Subsection 9.2.1).

Furthermore, the operations manager of Oksbøl CHP plant mentions that they are worried about sudden changes in regulation e.g. a change in taxation on biomass:

> *"This is our biggest concern. They are very erratic. This is the reason why we do not yet have a wood chip boiler. The board of directors is nervous about what the Danish Parliament will do. There is no advantage in having a wood chip boiler installed and then suddenly a tax on biomass is adopted."* - The operations manager of Oksbøl CHP plant (see Appendix B).

In relation to a future biomass tax being adopted, an example of the past natural gas taxation can be given. A natural gas tax was adopted in 1996, and the income from this tax rose from 6 million DKK in 1996 to 3.8 billion DKK in 2001, which shows a large increase within a short time span [Danish Ministry of Taxation, 2018]. This is not unlikely to be repeated with an implementation of a biomass tax, as Dan Jørgensen pronounced that he is not dismissive about such a change in regulation [Energy Supply, 2021].

The operations manager of Oksbøl CHP plant advocates clear instructions from the government regarding long term plans for regulation and taxation for achieving the climate goals. This could be assumed, based on the mentions from the operations manager of Oksbøl CHP plant, to ease the general natural gas fired CHP plants, into a green transition. However, again, this does not seem like the case as of now. Even though a relativity large change in electricity taxation has happened in the last year, the future uncertainty could halt the reduction of natural gas usage. (See Appendix B)

9.4 Political structure and innovative democracy

As the institutional structures and the actors within have been examined, this section seeks to identify and analyse the past, current and future political paradigms regarding energy planning in Denmark. This in accordance with the last step of an institutional analysis as advocated by Arts and Tatenhove [2006], in order to shed a light on the possible hindrances for an electrification of the DH in Denmark as an effect of the political orientation and paradigms. This section will therefore take a point of departure in the article *Innovative democracy, political economy, and the transition to renewable energy* by Hvelplund [2014], and its theoretical framework to examine the political structures and how these have affected a promotion of innovative democracy. The theory is elaborated in Section 5.2 on page 27.

Hvelplund [2014] uses a table to show how the energy planning approach has differed from 1974 until 2013 depending on the Danish Government's political orientation and composition. This table has been expanded to include the most recent governments, and they have been evaluated based on the researchers' own analysis. This can be seen in Table 9.1.

Table 9.1. The Danish Government's political economy paradigms from 1974-2021 [Hvelplund, 2014].

	Government	Neoclassical	Concrete Institutional	Innovative Democracy
1974-1979	Right/liberal	xx	x	x
1980-1983	Center/left	x	x	xx
1984-1989	Right/green	(-)	x	xxx
1990-1991	Right	xx	x	x
1992-2002	Center/left	x	(-)	xxx
2002-2007	Right	xxxx	(-)	(-)
2007-2011	Right	xxx	x	(-)
2011-2015	Center/left	x	xx	x
2016-2019	Right	x	x	xx
2019-	Center/left	(-)	xx	xx

As it can be seen in Table 9.1, Hvelplund [2014] distinguishes between three political paradigms: Neoclassical approach, Concrete Institutional approach and Innovative Democracy. The number of x's (ranking from zero to four) placed in the boxes represents the amount of influence the respective approach had on energy planning in Denmark, during that time period. The table is used to show how the approach has differed in the last 50 years, with a few clear examples standing out.

The worlds' first heat supply act was made by the Danish Government in 1979, with the purpose of promoting a socio-economically feasible heat supply, energy conservation in buildings and to decrease the dependency on oil in the Danish energy system. [Folketinget, 1979]. This is an early example of the innovative democracy paradigm. The Government decided to interfere with the market, in order to lower the overall dependency on the 'old market dependent companies' (oil suppliers) by law. These companies, at the time, were the market dominant companies, which created the incentive and need for innovative democracy.

The Poul Nyrup Rasmussen Government (1993-2001) promoted the focus on RE and especially wind turbines. In this period the expansion of the wind turbine capacity in Denmark was clear, which is illustrated in Figure 9.5.

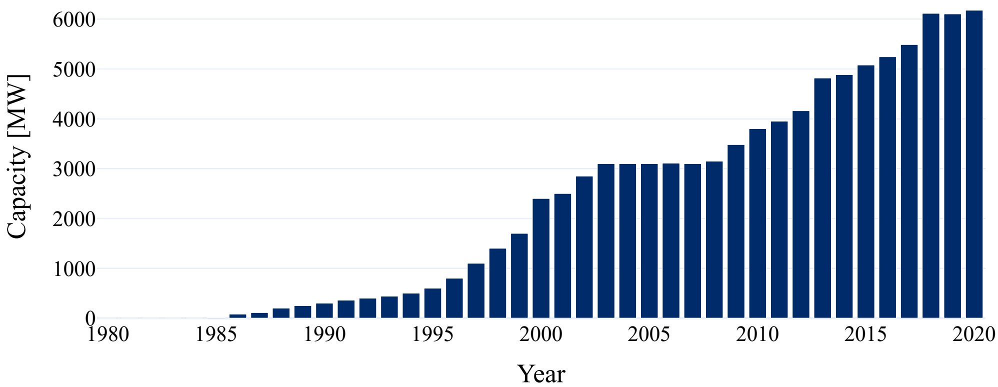

Figure 9.5. The wind turbine capacity expansion in Denmark [Mundaca et al., 2012; Wind Denmark, 2020a].

This expansion correlates with the respective level of innovative democracy during that period, which again, manifests its importance. However, this changed in late 2001 when the right wing Anders Fogh Rasmussen Government was formed. This government fully believed in the Neoclassical approach, which affected the promotion of RE immensely and brought the expansion of wind power to a halt. The preceding example shows how drastically energy policy can be changed because of the governmental change - in this case from 1993 (large influence of innovative democracy) to 2001 (large influence of neoclassicism). However, as seen in Table 9.1, innovative democracy has been prioritised more in recent years. The last election was labelled the "climate election" by the media and researchers, and more citizens were voting based on the climate proposals from the respective parties [Kallestrup and Eller, 2019]. This was also manifested by the climate law in 2019 and the plans for two new energy islands included in the Energy Agreement 2020. Ultimately, the attention to the climate and a green transition has increased, which should affect the promotion and implementation of RE immensely. However, the government is still reliant on the 'old market dependent organisations', which can be seen as an opposition to a green transition and innovative democracy. An example of this is the newly planned gas pipe, which will connect Zealand and Lolland. Here, large GHG emitting factories on Lolland needed to transition away from coal and oil. The industry on Lolland thought that the best solution was to construct a gas pipe, that at first would provide natural gas, and then later on could be used for biogas. However, many experts came to the conclusion that this solution was socio-economically infeasible. Ultimately, the minister for Climate, Energy and Utilities, Dan Jørgensen, decided to choose the gas pipe solution without investigating alternative solutions like heat pumps, which experts claim would be the most socio-economically feasible solution. [Sæhl et al., 2020]

As it can be seen in Table 9.1, much of the most recent government's orientation is based on the Concrete Institutional approach. This means that not much actual interference with the market structures is done. One could argue that the Danish Government needs to prioritise innovative democracy even more, if the goals for 2030 are to be achieved. Especially regarding an electrification of the DH in Denmark, where innovative democracy is needed to empower the DH companies to challenge the 'old market dependent organisations' and transition into RE sources.

An example of innovative democracy recently, is the decrease in electricity taxation and the waiving of the fuel binding for the smaller CHP plants as elaborated in Subsection 2.4.1 on page 13. Here, the Danish Government has interfered with the market structures, to promote and favour the 'new market dependent organisations' by redesigning processes and changing the 'rules of the game'. This is assumed to favour a green transition, if done adequately as advocated by both Lund [2014] and Hvelplund et al. [2019a].

The aforementioned examples show governments making decisions that point in different directions and causes uncertainty about the future governments and their willingness to promote innovative democracy and whether this could be a hindrance for an electrification of the DH in Denmark. As mentioned by Oksbøl CHP plant, this uncertainty is a barrier for them regarding their transition, and it can be assumed to be a general concern for most of the natural gas-fired CHP plants in Denmark.

9.5 Identification of hindrances

Taking point of departure in the first three steps of the institutional analysis as well as Section 8.8 on page 78, this section seeks to identify and discuss both the institutional and political hindrances for electrifying the DH sector in Denmark. The hindrances are identified based on the actor analysis and the political structure analysis. Thus the power theory and the political economy theory has been applied to carry out this remaining section of the institutional analysis. The hindrances are listed below.

- Old market dependent organisations (including the gas distributor) exercise power to interfere with the decision making of the DH companies.
- The DH regulation and policies in Denmark are complex, and companies which lack the resources to study the policy in detail may be hindered in a transition.
- The long term plans for the DH sector in Denmark lack concrete guidelines and time frames.
- It is currently more business-economically feasible to purchase a wood chip boiler/electric boiler combination than to purchase a heat pump/electric boiler combination due to a lack of a biomass tax.

The first hindrance identified is rooted in the division of power between Oksbøl CHP plant and the gas distributor. The interview with Oksbøl CHP plant and the division of power analysis enlightened the relation of power between the gas distributor and the plant. The operations manager of Oksbøl CHP plant mentioned that the interaction between the two brought the plans of a transition to a halt. The gas distributor interfered with the decision making in the early stage of the planning process, by advocating that their alternatives were not socio-economically feasible. However, with the regulatory changes as a result of the Energy Agreement 2020, the power of the gas distributor over the decentralised CHP plants with an annual heat production of less than 500 TJ is reduced. It is uncertain whether the gas distributor still exercises its power to interfere with the decision making of CHP plants or if other old-market dependent organisations exercise compulsory power. Nonetheless, the power structure can be seen as a barrier that may hinder an electrification of the Danish DH sector, and this therefore needs to be assessed.

The second hindrance was identified through the relation between the Danish Government and Oksbøl CHP plant. During the interview, the operations manager of Oksbøl CHP plant mentioned that the decision making parties struggle to keep up with the changing and complex DH policy, which affects the decision making. This can be assumed to be a general concern for most of the smaller DH companies, that do not have the resources to fully engage in the policies of the Danish Government. While the significance of this hindrance is debatable, it should not be a concern, and can easily be amended through clear instructions and application-orientated policy making.

The third hindrance is rooted in Oksbøl CHP plant's demand for a long term governmental plan regarding the DH sector in Denmark. During the interview, it was mentioned that they lack a long term plan with concrete guidelines and time frames, that would help them in their decision making. Preferably such a plan should be adopted by a broad majority in the Danish parliament, and should guide smaller DH in plants in the direction wanted, and thus enable a technological change and electrification of the DH in Denmark. Furthermore, this hindrance is rooted in Oksbøl CHP plant's concern regarding the government's future attitude towards biomass taxation. It is not possible for the DH plants to determine what the most business-economically feasible solution is for them in the next decades, if the government does not make a clear statement of intent. If a plan with broad support in the Danish parliament and with concrete guidelines and time frames for changes in taxation and subsidies was made, the DH plants could comfortably decide and analyse their alternative solutions, knowing how taxation, regulation etc. would affect their business-economic case in the future.

The last hindrance is found by taking point of departure in the results of Chapter 8 on page 59. Here it was found that it currently is more business-economically feasible to purchase a wood chip boiler/electric boiler combination than to purchase a heat pump/electric boiler combination. If the goal is to have a more cross-sector integrated energy sector, and to utilise otherwise wasted excess electricity production, a biomass tax on heat-only solutions should be adopted. The uncertainty of biomass taxation causes plants to stagnate in their development, which manifests the importance of long term plans and adequate regulation as mentioned above. Also, it is important to mention that there are plants that have recently purchased a biomass boiler, and their heat production costs will increase if a biomass tax is implemented. Thus, it could be argued that the taxation should be differentiated based on the time of investment in order to establish fairness in the market.

9.6 Promotion of new-corporate democratic infrastructure

As the institutional and political hindrances have been found and discussed, this section seeks to promote a new-corporate democratic infrastructure in correlation with the Choice Awareness theory by Lund [2014]. These recommendations will be based on the the four hindrances found, and are listed below.

- To the extent that old-market dependent organisations are still exercising their power to interfere with the decision making of natural gas fired CHP plants, the Danish Government needs to exercise its power to reduce their influence.
- DH policy should be less complex and should not be changed as frequently.
- Long term plans for taxation and subsidies within the DH sector need to be made, including concrete guidelines and time frames. Preferably this should be adopted by a broad majority in the Danish parliament.
- A biomass tax on heat-only solutions should be adopted if an electrification of the DH sector, which is also based on heat pumps, is wanted. This would ensure a high integration of fluctuating electricity production, the best compliance with the 2030 climate goals, minimal usage of biomass, and a relatively low socio-economic cost.

9.7 Subconclusion

The preceding analysis sought to answer the following subquestion:

What are the institutional and political hindrances in the implementation of a socio-economically feasible electrification of the district heating sector in 2030 and how can these be overcome?

To answer this, an institutional and political structure analysis was made, taking point of departure in the analytical framework of Arts and Tatenhove [2006] and the theoretical framework of Barnett and Duvall [2005] and Hvelplund [2014]. This made it possible to identify hindrances of the DH sector in Denmark.

The primary object of study was the Danish 2018 and 2020 Energy Agreements and the climate law.

It was concluded that the institutional setting for a future transition of Oksbøl CHP plant, contains an array of actors, with the most relevant being; the consumers of the CHP plant, other DH companies, Tjæreborg Industri, the Danish Government, and utility companies. The most relevant actors were found based on the actors' interest and power to influence the decision making of Oksbøl CHP plant. Furthermore, it was concluded, through an analysis of the actor interaction, that the most noticeable power structures, was the exercised power from the gas distributor and Tjæreborg Industri on Oksbøl CHP plant. Moving away from the institutional structure, the political structure and innovative democracy was analysed. Here it was concluded that the government's political orientation and composition has played a major part in the implementation and promotion of RE technologies. Both the past and present political economy paradigms were analysed, which enabled a discussion of the importance of innovative democracy. Here, the demand for innovative democracy was manifested, if a technological change is wanted. This again correlates with the Choice Awareness theory and Political Economy theory. Lastly, the following four recommendations for promoting a technological change were made:

- Favour new-market dependent organisations
- Simplify DH policy
- Make long term plans for taxation and subsidies within the DH sector
- Tax biomass consumption for heat-only purposes

10 Discussion

The purpose of this chapter is to discuss both the theories and methods, which have been used in this research, as well as the results of the analyses. The discussion is structured around the methodological steps of the Choice Awareness theory.

10.1 Theories and methods

As this research is based on a paradigmatic case study, the case type and case selection can be discussed. As mentioned in Subsection 4.3.2 on page 24, the case type should be chosen based on the intention behind the research. Thus, it is worth considering how the results could have been different if another case type was chosen. For example, using the maximum variation case type, multiple decentralised natural gas-based CHP plants, with e.g. a large variation in heat capacities, could have been selected as cases to enable an even broader generalisation. However, this was not done, as the researchers focused their resources on a single entity to enable a more thorough analysis. Furthermore, like the paradigmatic case study might have issues in representing the extremes, it is not guaranteed that a maximum variation case study would represent an average natural gas-based decentralised CHP plant.

As the primary data to conduct the institutional analysis was gathered through the interview with the operations manager of Oksbøl CHP plant, the interview method should be discussed. It was chosen to make a semi-structured qualitative interview where the researcher followed a premade interview guide. The semi-structured qualitative interview method allows the interviewee to speak and elaborate freely, and thereby avoid misunderstandings. It can be discussed whether only conducting one interview has given the adequate knowledge to carry out the institutional analysis. One could argue that, in order to enable a more holistic perspective of the institutional and political setting, more interviews should have been conducted. When conducting the analyses in Chapter 8 and 9, a few assumptions were made, which could have been verified if more interviews were conducted. A few examples can be given: multiple CHP plants could have been asked whether they have experienced an influence from either the gas distributor or other old-market dependent organisations. Multiple CHP plants could have been asked to elaborate on the actors that have influenced their decision making, to investigate whether the close relation between Oksbøl CHP plant and Tjæreborg Industri is an unusual situation. Lastly, multiple CHP plants could have been asked about the expected remaining lifetime of their gas engines, in order to find out how urgent the problem of losing dispatchable electric capacity in decentralised CHP plants is. These examples would require a detailed quantitative study which is out of scope for this case study analysis.

The actor identification and delimitation is based on only a single case. Thus, it can be discussed whether selecting a different case would have changed the identification and delimitation of actors for the institutional analysis. However, most of the actors identified in Figure 9.1 on page 84 are also relevant for other decentralised natural gas-based CHP plants.

In the analysis in Chapter 7 on page 43, it was chosen to use EnergyPLAN in order to investigate four 2030 scenarios for the Danish energy system in depth. Specifically, it was investigated how the grid stabilisation share, annual import and peak import, and annual export were impacted when the CHP capacity was varied. This was done to be able to discuss the technical feasibility of reducing the CHP capacity in Denmark, which was relevant in the analysis in Chapter 8 on page 59. Using EnergyPLAN, rather than just studying the documentation for these scenarios, was necessary because it allowed the researchers to examine parameters which had not been considered/documented by the other researchers/organisations - and furthermore allowed the researchers to change the CHP capacity and examine the impact. However, since the security of electricity supply was in focus in Chapter 7 on page 43, it must also be said that certain aspects are not possible to investigate with EnergyPLAN: as it uses hourly steps, it does not take frequency- and voltage stability into account (only indirectly through the grid stabilisation share). It is also difficult to make a strong conclusion regarding the relation between power shortfalls and imported electricity, because the results will depend on the developments in neighbouring countries.

Regarding the modelling assumptions of the analysis in Chapter 8 on page 59, the most consequential parameter is the electricity price. The electricity price projection from the Danish Energy Agency [2020a] has been used throughout the research, and sensitivity analyses have been made, because the price is highly uncertain. There are many uncertainties of future electricity prices in Northwestern Europe. For example: the degree of wind turbine and PV expansion, the development of electricity consumption, the construction of transmission lines, the development of fuel prices, and the emergence of electricity storage [Dansk Energi, 2019a]. How different electricity price levels would affect the results of this research is discussed in Section 10.2. The future natural gas prices and wood chip prices are likewise uncertain. These price developments could for instance depend on the amount of CHP plants which use these fuels.

The distribution profiles for electricity prices and gas prices, which have been used in this research, are actual distributions from 2020. When using the index method, described in Section 8.3 on page 62, the size of the fluctuations is determined by the index value. Dansk Energi [2019a] expects larger fluctuations in future electricity prices, and this may not be fully captured with the index method.

Regarding the assumptions of the business- and socio-economic calculations, there are several topics to discuss. Firstly, the taxes and tariffs which have been used, which can be found in Appendix D on page 133, could (and will most likely) change in the coming 20 years. This uncertainty has, in part, been taken into account by making sensitivity analyses on electricity prices, gas prices, and wood chip prices.

Secondly, there is the issue of tax distortion losses in the socio-economic calculations. This has been included, because it is a part of the guidance for socio-economic assessments made by Danish Energy Agency [2018d], which has been followed without deviations in this research. Tax distortion losses affect the results considerably, which is explained in Section

10.2, and according to Djørup [2014] they cause a bias against technological changes and favour fossil fuel in socio-economic assessments. The true social cost of emissions of, for instance, SO_2 and NO_x is also debated, with Shindell [2015] estimating significantly higher social costs than the Danish Energy Agency [2018d].

Finally, there are some elements, which are sometimes included in socio-economic analyses, which have not been considered here, such as balance of payments and job creation - however these are also not included in the guidance from the Danish Energy Agency [2018d]. In the scenarios where the gas engines are removed, the socio-economic cost of losing some electric capacity (potentially leading to more power outage minutes or forcing Energinet to invest in a strategic reserve if many plants remove their engines) has also not been priced in.

10.2 Technical alternatives and feasibility studies

The analysis in Chapter 7 on page 43 ended with an open question about the best way to maintain security of electricity supply while reaching the 2030 climate goals. Specifically, whether the natural gas-based CHP capacity should be kept, or be replaced with centralised bio-fuelled CHP capacity, or be replaced with strategic electricity generating reserves. Answering this question would require a detailed socio-economic analysis, which includes the impacts of electric heating solutions also being used for base-load heat production. It is clear from Chapter 7 on page 43 that the natural gas CHP capacity should not be reduced without it being replaced with another dispatchable electric capacity. The analysis in Chapter 8 on page 59 showed that, both from a business- and socio-economic perspective, it is not feasible to remove existing natural gas engines that have any lifetime remaining (assuming that the electricity price projection is accurate). From the security of electricity supply perspective, this is a good result. However, it was also shown that it is not at all business-economically feasible to invest in new engines, once the old ones are no longer functional, and this is why a detailed socio-economic analysis of the options for maintaining the dispatchable electric capacity is needed in the future. It could be that it is socio-economically feasible to subsidise the investment of engines in DH rather than investing in strategic reserves. In an analysis of these options, merely maintaining the electric capacity is not the only aspect which should be considered. There is also the issue of grid robustness. As emphasised in Chapter 7 on page 43, large centralised CHP plants are important for inertia and voltage stability. However, decentralised CHP plants can also play an important role, because their start-up time on engines and turbines often is shorter.

Regarding the technologies, which were chosen for the alternative scenarios in Chapter 8 on page 59, there is an important point to be made about the electric boiler. The choice of taking the regulating power market into account, but not special regulation, could be questioned. The argument for this is that the researchers do not find it probable that the transmission grid problems in Northern Germany (see Section 2.2) will persist for the next 20 years. Regarding the heat pumps, an important delimitation in this research is that the possibility of lowering the DH temperatures in Oksbøl has not been considered. A lower flow temperature would ensure a better system efficiency, but especially a higher heat pump COP, which could result in lower consumer heat prices. Depending on the temperature reduction, such a system could require low energy buildings, and this would probably mean that many buildings in Oksbøl would need to be renovated. As mentioned in Subsection 2.2.3 on page 7, energy savings are very important in a RE system. However, the argument for not investigating this is that there are currently many barriers for energy renovations of residential buildings [Meyer et al., 2014; Hvelplund et al., 2019b]. For example, not all house owners are able to take out a loan to finance an energy renovation, and this is often the case outside the larger cities of Denmark [Finans Danmark, 2020]. It is beyond the scope of this research to analyse how to overcome these barriers.

There are some important points to be made about the results of the analysis in Chapter 8 on page 59. As explained in Section 10.1, tax distortion losses have a big influence on the results. For instance, in the case of Oksbøl CHP plant, they cause the removal of natural gas boilers to be socio-economically infeasible. The tax distortion loss may be used by old market dependent organisations to hinder a technological change. It should therefore be strongly considered, if the current guidelines for socio-economic calculations by Danish Energy Agency [2018d] are indeed too biased against technological changes, as argued by Djørup [2014].

As mentioned in Section 10.1, the electricity price is the most consequential parameter for the results of this research. The sensitivity analyses have shown that changing the electricity price with ±20% can change whether a wood chip boiler or heat pump should be bought (in addition to an electric boiler). Furthermore, changing the electricity price would likely also change the optimal capacities for new technologies, and it certainly changes the natural gas consumption.

10.3 Public regulation and the need of new-corporate democratic infrastructure

Taking a point of departure in the results from the analyses in Chapters 8 and 9, the proposed public regulation measures and democratic infrastructure can be discussed. The results indicated that there is no need for any radical changes in regards to the new-corporate democratic infrastructure, if an electrification of the Danish DH sector is wanted and the 2030 climate goals are to be reached. Also, it was shown that there is no reason to further incentivise the implementation of electric boilers, as they are already business-economically feasible (although the business case depends on the regulating power market). However, the results from Chapter 8 on page 59 showed that there is a need for a tax on biomass, if it is prioritised to shift into heat pumps instead of wood chip boilers. One could argue that the adoption of a biomass tax needs to happen relatively soon, in order to avoid a loss for the DH companies that are planning to invest in a wood chip boiler. It will be highly problematic for the DH companies that have recently shifted to biomass, as their consumers will experience increased heat prices. Therefore it can be discussed, whether the biomass tax should only apply to the plants which invest in biomass boilers after the tax is adopted. The tax could be differentiated based on the origin of the biomass and/or whether it is used in boilers or in co-generation. However, this would imply a more complex regulation which could be socio-economically expensive to enforce.

The aforementioned proposal correlates with the results from Chapter 9 on page 83. Here it was concluded that there is a demand for long term plans, with concrete time frames regarding future regulation and taxation, in order to minimise the uncertainty from the DH companies. Long term plans should be made, even if it is currently not the plan to adopt a biomass tax, so that the DH companies can choose strategy based on what is going to happen. The current uncertainty, results in the DH companies delaying their technological transition, which delays the green transition. Furthermore, the results from Chapter 9 on page 83 showed, that the interference from the gas distributor to Oksbøl CHP plant, also caused a delay. The aforementioned correlates with the Choice Awareness theory, as it shows an example of an old market dependent institution that seeks to remain in power in the market.

Regarding the generalisability of the results, there are a few points to be made. For the analysis in Chapter 8 on page 59, the most important points are that the investment costs are generally impacted by *economy of scale*, and that some larger DH areas utilise industrial excess heat. Both of these facts can lead to different results for larger plants. However, the results are estimated to be scalable to the majority of the decentralised, natural gas-based CHP plants in Denmark. For the analysis in Chapter 9 on page 83, the only finding which perhaps would not apply to all plants is that DH legislation needs to be less complex, and have less frequent changes, because it is difficult to keep up with. This is surely true for most smaller plants with a small staff. However, larger DH companies may have the resources to study complex legislation in more detail.

If the Danish DH sector is electrified, there is going to be a need for upgrades and reinforcements of the electricity grid. This is assumed to be an expensive cost and one could ask the question: Who should pay for these upgrades and reinforcements? As shown by the interaction between Oksbøl CHP plant and N1, the latter gave the plant the option to buy a new electrical substation if they were to implement an electric boiler of more than 7 MW. However, the investment of a substation was considered too expensive by the operations manager at Oksbøl CHP plant. The discussion about who should pay for grid reinforcements also happens in the transport sector and regarding the expansion of wind turbine- and PV capacity. A recent example of this is that the reinforcements in the transmission- and distribution electricity grids, which are necessitated by the expansion of wind turbines and PV panels, are imposed on the project developers. While the project developers consider it fair that they pay for the direct connection of their wind- or solar power plants, they argue that the DSOs (and consequently the electricity consumers) should pay for the upgrades to the electrical grid. [Wittrup, 2021]

11 Conclusion

The purpose of this research was to answer the following primary research question:

How can an electrification of the natural gas-based district heating systems be implemented, in order to utilise an increasing amount of fluctuating renewable electricity production and contribute to the achievement of the Danish climate goals of 2030, while maintaining business- and socio-economic feasibility and security of electricity supply?

By analysing the impacts of an electrification of the DH sector, it was concluded that reducing decentralised CHP capacity would not impact grid robustness. However, there is a need of dispatchable power generating capacity to meet the requirements for maximum outage minutes set by Energinet. It was also concluded that - if the Danish DH goals for 2030 are to be achieved - the natural gas consumption must be reduced. One way to reduce natural gas consumption is to implement electric heating solutions which can utilise excess electricity production from fluctuating RE sources.

The ability to both reduce natural gas consumption and utilise excess electricity production was investigated in a paradigmatic case study on Oksbøl CHP plant. From a business-economic perspective, it was concluded that the scenarios with a wood chip boiler/electric boiler- and a heat pump/electric boiler combination, in a 20 year period, had the lowest NPCs at 156 MDKK and 159 MDKK, respectively. The two aforementioned scenarios also had the second and third lowest socio-economic NPCs at 203 MDKK and 205 MDKK, respectively. However, the electric boiler scenario had the lowest socio-economic NPC at 202 MDKK due to lower tax distortion losses. Through sensitivity analyses, it was concluded that the electricity- and wood chip prices had a large impact on the results, and it changed which scenario resulted in the lowest NPC. If it is a goal to utilise otherwise excess electricity production in the DH sector, a biomass tax should be adopted to make heat pumps more favourable than wood chip boilers. Lastly, it was concluded that in the case study for Oksbøl CHP plant, it is not business- nor socio-economically feasible to scrap their working natural gas engines.

Through the institutional analysis and the interview with the operations manager of Oksbøl CHP plant, it was concluded that the most relevant actors for a transition of Oksbøl CHP plant were: the consumers of Oksbøl CHP plant, other DH companies, Tjæreborg Industri, the Danish Government and utility companies. The most noticeable relation and power structure was between Oksbøl CHP plant and the gas distributor, which delayed the plant's transition. Also, it was concluded that the political orientation and composition of the government has played a major role in the promotion of RE and that innovative democracy is needed, if a technological change is wanted. Lastly, four recommendations were made based on the found hindrances, which created the foundation for the promotion of a new-corporate democratic infrastructure. These recommendations will enable a further electrification of natural gas-based DH systems and thereby help achieving the Danish climate goals of 2030.

Bibliography

Arts, B. and Tatenhove, J. V. (2006). Political Modernisation. *Institutional Dynamics in Environmental Governance*, pages 21–43.

Bahn, M. and Sindberg, M. (2020). »Helt absurd«: Elbilkommissionen udelod klimagevinst ved grønne biler i sine beregninger ['Absolutely absurd': The Electric Car Commission omitted the climate benefits of green cars in its calculations]. https://www.information.dk/indland/2020/09/helt-absurd-elbilkommissionen-udelod-klimagevinst-ved-groenne-biler-beregninger.

Barnett, M. and Duvall, R. (2005). Power in international politics. https://www.cambridge.org/core/journals/international-organization/article/power-in-international-politics/F5F3C74D30A12A5C4CC9B4EFEA152967.

Becker, S., Rodriguez, R., Andresen, G. B., Schramm, S., and Greiner, M. (2013). Transmission grid extensions during the build-up of a fully renewable pan-european electricity supply. *Energy*, 64:p. 404–418.

Brinkmann, S. and Tanggaard, L. (2010). *Kvalitative metoder [Qualitative methods]*. Number ISBN: 978-87-412-5255-1. Hans Reitzels Forlag.

Business Research Methodology (2020). Research approach. https://research-methodology.net/research-methodology/research-approach/.

Bøhm, B., Schrøder, F., and Bergsøe, N. (2009). Varmt brugsvand [Domestic hot water]. https://vbn.aau.dk/ws/portalfiles/portal/17689984/SBi_2009-10.pdf.

Carpaneto, E., Lazzeroni, P., and Repetto, M. (2015). Optimal integration of solar energy in a district heating network. *Renewable Energy 75*, Journal 3/2006:714–721.

Connolly, D. (2015). Finding and Inputting Data into EnergyPLAN.

Danish District Heating Association (2018). Aalborg: Dispensation er minimum [Aalborg: Exemption is a minimum]. https://www.danskfjernvarme.dk/nyheder/nyt-fra-dansk-fjernvarme/arkiv/2018/180626-aalborg-dispensation-er-minimum.

Danish District Heating Association (2021). Om os [About us]. https://www.danskfjernvarme.dk/om-os.

Danish Energy (2021). Om Dansk Energi [About Danish Energy]. https://www.danskenergi.dk/om-dansk-energi.

Danish Energy Agency (2017). Regulation and planning of district heating in Denmark. https://ens.dk/sites/ens.dk/files/Globalcooperation/regulation_and_planning_of_district_heating_in_denmark.pdf.

Danish Energy Agency (2018a). Data: Oversigt over energisektoren [Data: Overview of the energy sector]. https://ens.dk/service/statistik-data-noegletal-og-kort/data-oversigt-over-energisektoren.

Danish Energy Agency (2018b). Høring om udkast til ændring af bekendtgørelse om godkendelse af projekter for kollektive varmeforsyningsanlæg [Consultation on a draft amendment to the executive order on approval of projects for collective heat supply systems]. https://www.ft.dk/samling/20181/almdel/efk/bilag/49/1962461/index.htm.

Danish Energy Agency (2018c). Technology data for energy storage . https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-energy-storage.

Danish Energy Agency (2018d). Vejledning i samfundsøkonomiske analyser på energiområdet, juni 2018 [Guide in socio-economic analyses in the energy sector, June 2018]. https://ens.dk/sites/ens.dk/files/Analyser/vejledning_i_samfundsoekonomiske_analyser_paa_energiomraadet_-_juni_2018_v1.1.pdf.

Danish Energy Agency (2019a). Analyseforudsætninger til Energinet [Analysis prerequisites for Energinet]. https://ens.dk/service/fremskrivninger-analyser-modeller/analyseforudsaetninger-til-energinet.

Danish Energy Agency (2019b). Samfundsøkonomiske beregningsforudsætninger for energipriser og emissioner [Socio-economic calculation assumptions for energy prices and emissions]. https://ens.dk/sites/ens.dk/files/Analyser/samfundsoekonomiske_beregningsforudsaetninger_for_energipriser_og_emissioner_2019.pdf.

Danish Energy Agency (2020a). Basisfremskrivninger [Denmark's Energy and Climate Outlook]. https://ens.dk/service/fremskrivninger-analyser-modeller/basisfremskrivninger.

Danish Energy Agency (2020b). Biomasseanalyse [Biomass analysis]. https://ens.dk/sites/ens.dk/files/Bioenergi/biomasseanalyse_final_ren.pdf.

Danish Energy Agency (2020c). Dansk Klimapolitik [Danish Climate Policy]. https://ens.dk/ansvarsomraader/energi-klimapolitik/fakta-om-dansk-energi-klimapolitik/dansk-klimapolitik.

Danish Energy Agency (2020d). Denmark's climate and energy outlook 2020.

Danish Energy Agency (2020e). Energistatistik 2019 [Energy Statistics 2019]. https://ens.dk/sites/ens.dk/files/Statistik/energistatistik2019_dk-webtilg.pdf.

Danish Energy Agency (2020f). Fakta om bioenergi i Danmark [Bio-energy in Denmark]. https://ens.dk/ansvarsomraader/bioenergi/bioenergi-i-danmark.

Danish Energy Agency (2020g). Technology Data - Energy Plants for Electricity and District heating generation. https://ens.dk/sites/ens.dk/files/Analyser/technology_data_catalogue_for_el_and_dh.pdf.

Danish Energy Agency (2021). Om os [About us]. https://ens.dk/om-os.

Danish Meteorological Institute (2021). *Tabeller [Tables]*.

Danish Ministry of Climate, Energy and Utilities (2016). Bedre rammer for investeringer i fjernvarmesektoren [Better conditions for investments in the district heating sector]. https://ens.dk/sites/ens.dk/files/Forsyning/investeringer_i_fjernvarmesektoren.pdf.

Danish Ministry of Climate, Energy and Utilities (2019). Kuludfasning [Phasing out coal]. https://www.ft.dk/samling/20191/almdel/KEF/bilag/147/2129003/index.htm.

Danish Ministry of Climate, Energy and Utilities (2021). Klima-, Energi og Forsyningsministeriet [Danish Ministry for Climate, Energy and Utilities]. https://kefm.dk/ministeriet.

Danish Ministry of Finance (2021). Dokumentationsnotat – den samfundsøkonomiske diskonteringsrente [Documentation note - the socio-economic discount rate]. https://fm.dk/media/18371/dokumentationsnotat-for-den-samfundsoekonomiske-diskonteringsrente_7-januar-2021.pdf.

Danish Ministry of Taxation (2018). Skattetryk for grønne afgifter [Tax burden for green charges]. https://www.skm.dk/skattetal/statistik/arkiv/skattetryk-for-groenne-afgifter/.

Danish Technological Institute (2021). *Graddage [Heating degree days]*.

Dansk Energi (2019a). Elpris outlook 2019 [Electricity price outlook 2019]. https://www.danskenergi.dk/sites/danskenergi.dk/files/media/dokumenter/2019-06/Elpris_Outlook_2019.pdf.

Dansk Energi (2019b). Er elnettet klar til elbilerne? [Is the electricity grid ready for electric vehicles?]. https://www.danskenergi.dk/sites/danskenergi.dk/files/media/dokumenter/2019-05/Er_elnettet_klar_til_elbilerne_Analyse_af_effekt-og_investeringsbehov_i_eldistributionsnettet.pdf.

Detlefsen, N. (2016). Specialregulering i fjernvarmen [Special regulation in the district heating sector]. https://www.danskfjernvarme.dk/groen-energi/analyser/160402-specialregulering.

Djørup, S. (2014). The tax distortion loss and its structural influence in the Danish energy sector. https://www.4dh.eu/resources/presentations.

Dragsted, S. K. and Solgaard, A. (2021). Solcelleparker boomer: Politikere presser på for national regulering [PV plants are booming: Politicians push for national regulation]. https://www.radio4.dk/nyheder/solcelleparker-boomer-politikere-presser-paa-for-national-regulering/.

EMD International (2017). User's guide energyPRO. https://www.emd.dk/energyPRO/Tutorials%20and%20How%20To%20Guides/energyPROHlpEng-4.5%20Nov.%2017.pdf.

EMD International (2021). INTERFACE.
https://www.emd.dk/energypro/modules/interface/.

Energi Data Service (2021). Electricity balance.
https://www.energidataservice.dk/tso-electricity/electricitybalance.

Energinet (2016a). Analyse: Nedtagning af gamle landmøller [Analysis: Removal of old onshore wind turbines].
https://energinet.dk/Om-publikationer/Publikationer/RS-Analyse-Juni-2016-Nedtagning-af-gammel-landvind.

Energinet (2016b). Energiscenarier for 2030 [Energy scenarios for 2030].
https://energinet.dk/Om-publikationer/Publikationer/RS-Analyse-Energiscenarier-for-2030.

Energinet (2017). Forskrift C2 balancemarked og balanceafregning [Regulation C2 balance market and balance settlement].
https://energinet.dk/-/media/A7B52A9681DD4206A392D6CB62374CE3.pdf.

Energinet (2018a). Redegørelse for elforsyningssikkerhed 2018 [Statement on security of electricity supply 2018].
https://energinet.dk/-/media/50205A49C7404053889E358C6A078D19.pdf.

Energinet (2018b). Tekniske problemstillinger forbundet med nye transmissionsforbindelser i Danmark [Technical issues associated with new transmission lines in Denmark].
https://energinet.dk/-/media/05230627DCC644A781CDC81D16967D60.pdf?la=da&hash=6F5470A6C04A974B31412BFD17EEDB727B1B8253.

Energinet (2020a). Behovsvurdering for systemydelser 2021 [Needs assessment for ancillary services].
https://energinet.dk/-/media/5A1B09F29DE749B3967EB17CEC4AA616.PDF?la=da&hash=3761939CD0B84476CEC225A78CE086E1A2FDE734.

Energinet (2020b). Deklarationer af el [Declarations of electricity].
https://energinet.dk/-/media/94DFF11261FD4F2A936A7AFBCAA6996E.pdf.

Energinet (2020c). Introduktion til systemydelser [Introduction to ancillary services].
https://energinet.dk/-/media/8F2B403B3A724197A179FF6DFD9A926C.pdf.

Energinet (2020d). Redegørelse for elforsyningssikkerhed 2020 [Statement on security of electricity supply 2020].
https://energinet.dk/-/media/480ED137F0884FDE918563DB04171FEA.pdf.

Energinet (2021a). Gældende gastariffer [Gas tariffs].
https://energinet.dk/Gas/Tariffer-for-gastransport/Gaeldende-tariffer.

Energinet (2021b). Om os [About us]. https://ens.dk/om-os.

Energinet (2021c). Tariffer of gebyrer [Tariffs and fees].
https://energinet.dk/El/Elmarkedet/Tariffer.

Energinet (2021d). Viking Link: Elforbindelse til Storbritannien [Viking Link: Electric grid connection to Great Britain]. https://energinet.dk/Anlaeg-og-projekter/Projektliste/Viking-Link.

Energy Supply (2021). Dan Jørgensen: Biomasse må og skal kun bruges i en overgang [Dan Jørgensen: Biomass can and must only be used in a transition]. https://www.energy-supply.dk/article/view/776059/dan_jorgensen_biomasse_ma_og_skal_kun_bruges_i_en_overgang.

Ertmann, B. (2020). Aftalen er på plads: 775.000 el- og hybridbiler i Danmark i 2030 [The agreement is in place: 775,000 electric and hybrid cars in Denmark in 2030]. https://finans.dk/politik/ECE12607129/aftalen-er-paa-plads-775000-el-og-hybridbiler-i-danmark-i-2030/.

Evida (2021). Historien bag Evida [The story behind Evida]. https://evida.dk/om-evida/historien-bag-evida/.

Finans Danmark (2020). Finansiering af grønne investeringer [Financing green investments]. http://finansdanmark.dk/media/47260/finans-danmark-og-ldf-finansiering-af-groenne-investeringer.pdf.

Flyvbjerg, B. (2006). Five misunderstandings about case-study research. *Qualitative Inquiry*, 12:p. 219–245.

Folketinget (1979). Forslag til lov om varmeforsyning [Proposal for a law on heat supply]. https://www.folketingstidende.dk/samling/19781/lovforslag/L206/19781_L206_som_vedtaget.pdf.

Hvelplund, F. (2014). Innovative democracy, political economy, and the transition to renewable energy. A full-scale experiment in Denmark 1976-2013. *Environmental Research Engineering and Management*, 4:p. 5–21.

Hvelplund, F., Djørup, S., and Sperling, K. (2019a). Fossil fuel systems to 100 per cent renewable energy-based smart energy systems: lessons from the case of Denmark, 1973–2017. Chapter 13 in the book 'In Search of Good Energy Policy'. ISBN: 9781108639439.

Hvelplund, F., Krog, L., Nielsen, S., Terkelsen, E., and Madsen, K. B. (2019b). Policy paradigms for optimal residential heat savings in a transition to 100% renewable energy systems. *Energy Policy*, 134:p. 1–11.

IEEE Spectrum (2016). Can synthetic inertia from wind power stabilize grids? https://spectrum.ieee.org/energywise/energy/renewables/can-synthetic-inertia-stabilize-power-grids.

International Energy Agency (2020). Evolution of solar PV module cost by data source, 1970-2020. https://www.iea.org/data-and-statistics/charts/evolution-of-solar-pv-module-cost-by-data-source-1970-2020.

Kallestrup, C. and Eller, E. (2019). Forskerne har talt: Ja, det blev et klimavalg [Researchers have spoken: Yes, it became a climate election].

https://www.dr.dk/nyheder/politik/folketingsvalg/forskerne-har-talt-ja-det-blev-et-klimavalg.

Kavvadias, K., Thomassen, G., Pavičević, M., and Quoilinc, S. (2019). Electrifying the heating sector in Europe: The impact on the power sector. *ECOS 2019 - the 32nd international conference on efficiency, cost, optimization, simulation and environmental impact of energy systems*, pages 3859–3870.

Kielgast, N. and Hall, O. (2019). Dropper kornmarkerne: Solceller er blevet en hot afgrøde [Ditching the corn fields: PV panels have become a hot crop]. https://www.dr.dk/nyheder/penge/dropper-kornmarkerne-solceller-er-blevet-en-hot-afgroede.

Koch, J. (2020). Elektrificering af fjernvarmen [Electrification of the district heating sector]. https://www.danskfjernvarme.dk/viden/moedematerialer/2020-01-30-hvordan-faar-vi-el-ind-i-fjernvarmen.

Lund, H. (2014). *Renewable Energy Systems: A Smart Energy Systems Approach to the Choice and Modeling of 100% Renewable Solutions, 2nd edition.* Number ISBN: 9780124104235 in Hardback. Elsevier Science & Technology.

Lund, H., Arler, F., Østergaard, P. A., Hvelplund, F., Connolly, D., Mathiesen, B. V., and Karnøe, P. (2017). Simulation versus Optimisation: Theoretical Positions in Energy System Modelling. *Energies*, 10:p. 840.

Lund, H., Mathiesen, B. V., Thellufsen, J. Z., Sorknæs, P., and Skov, I. R. (2020). IDAs klimasvar: Transport- og energiløsninger 2030 [IDAs climate response: Transport and energy solutions 2030].

Lund, H., Möller, B., Mathiesen, B., and Dyrelund, A. (2009). The role of district heating in future renewable energy systems. *Energy*, 35:p. 1381–1390.

Lund, H. and Thellufsen, J. Z. (2020). EnergyPLAN: Advanced energy systems analysis computer model. Documentation version 15.1. https://www.energyplan.eu/wp-content/uploads/2020/09/documentation.pdf.

Lund, H., Østergaard, P. A., Connolly, D., Ridjan, I., Mathiesen, B. V., Hvelplund, F., Thellufsen, J. Z., and Sorknæs, P. (2016). Energy storage and smart energy systems. *International Journal of Sustainable Energy Planning and Management*, 11:p. 3–14.

Lund et. al (2014). 4th generation district heating (4GDH). https://www.sdu.dk/-/media/files/om_sdu/institutter/iti/forskning/nato+arw/literature/4th+generation+district+heating+4gdh.pdf.

Meyer, N. I., Mathiesen, B. V., and Hvelplund, F. (2014). Barriers and Potential Solutions for Energy Renovation of Buildings in Denmark. *International journal of Sustainable Energy Planning and Management*, 1:p. 59–66.

Mitchell, R., Agle, B., and Wood, D. (1997). Toward a theory of stakeholder identification and salience: Defining the principle of who and what really counts. https://www.jstor.org/stable/259247?origin=JSTOR-pdf&seq=1#metadata_info_tab_contents.

Mundaca, L., Dalhammar, C., and Harnesk, D. (2012). The integrated nordic power market and the deployment of renewable energy technologies: key lessons and potential implications for the future ASEAN integrated power market. *Energy Market Integration in East Asia: Renewable Energy and its Deployment into the Power System*, 2:p. 25–97.

N1 (2020). Priser og vilkår for N1 [Prices and terms for N1]. `https://n1.dk/media/yeooa41f/n1-priser-og-vilkaar_a5_januar2020.pdf?fbclid=IwAR3qePbVHcsrnoSSG7P-2QnZq8plpUi53cinSvdkM4NTXbv1y-D0ws5hgyA`.

N1 (2021). Om N1 [About N1]. `https://n1.dk/om-n1`.

Nordic Energy Research (2019). Will electricity prices in Norway double? `https://www.nordicenergy.org/article/will-the-electricity-price-in-norway-double/`.

Nordpool (2021). History market data. `https://www.nordpoolgroup.com/historical-market-data/`.

Oksbøl Varmeværk (2021). Om os [About us]. `https://www.oksboelvarmevaerk.dk/profil/om-os/`.

Persson, U. and Werner, S. (2010). Heat distribution and the future competitiveness of district heating. *Applied Energy*, 88:p. 568–576.

PwC (2020). 2021 – nye afgiftssatser med relevans for forsyningsvirksomheder [2021 - new tax rates relevant to utility companies]. `https://www.pwc.dk/da/artikler/2020/11/2021---nye-afgiftssatser-med-relevans-for-kraftvarmebranchen.html?fbclid=IwAR1m45K4rSagW-RSh2maZXRH9K2n4ArrBdammpalS09UD_H4b9i_phxWhtM`.

Saunders, M., Lewis, P., and Thornhil, A. (2007). *Research methods for business students*. Number ISBN: 978-12-920-1664-1. London: Pearson.

Shindell, D. T. (2015). The social cost of atmospheric release. `https://energyinnovation.org/wp-content/uploads/2015/03/SocialCostAtmRelease.pdf`.

Siemens A/S (2018). Elektrificering af Danmarks fjernvarmesektor [Electrification of the Danish district heating sector].

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, 104:333–339.

SPF Institute for Solar Technology (2017). Solar collector factsheet Arcon-Sunmark HT-SolarBoost 35/10). `https://serv.spf.ch/spftesting/collectors/pdfs/scf1735en.pdf`.

Statista (2020). Cumulative solar photovoltaic capacity in Denmark from 2013 to 2019. `https://www.statista.com/statistics/497491/connected-and-cumulated-photovoltaic-capacity-in-denmark/`.

Statistics Norway (2020). Electricity.
https://www.ssb.no/en/energi-og-industri/statistikker/elektrisitet/aar.

Sæhl, M., Andersen, K. S., and Olsgaard, D. (2020). KLIMA Eksperter: 115 kilometer lang gasledning til Lolland giver "dundrende underskud" [Climate Experts: 115 kilometer gas pipeline to Lolland leads to a deficit].
https://www.dr.dk/nyheder/viden/klima/eksperter-115-kilometer-lang-gasledning-til-lolland-giver-dundrende-underskud.

The Danish Parliament (2018). Energiaftale [Energy Agreement].
https://kefm.dk/media/6646/energiaftale2018.pdf.

The Danish Parliament (2020). Klimaaftale for energi og industri mv. 2020 [Climate Agreement for energy and industry 2020].
https://fm.dk/media/18085/klimaaftale-for-energi-og-industri-mv-2020.pdf.

The European Comission (2016). Commission Regulation (EU) 2016/631. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016R0631&from=EN.

Thellufsen, J. Z. and Lund, H. (2015). Energy saving synergies in national energy systems. *Energy Conversion and Management*, 103:p. 259–265.

Tjæreborg Industri (2021). Virksomshedsprofil [Company profile].
https://www.tji.dk/index.php/info/virksomhedsprofil/.

Trømborg, E., Havskjold, M., Bolkesjø, T. F., Kirkerud, J. G., and Åsa Grytli Tveten (2017). Flexible use of electricity in heat-only district heating plants. *International Journal of Sustainable Energy Planning and Management*, 17:p. 29–46.

United Nations (2021). Climate action.
https://www.un.org/sustainabledevelopment/climate-change/.

Varde Kommune (2014). Strategisk energiplan 2014-2018 [Strategic energy plan 2014-2018].

Wind Denmark (2020a). Antal vindmøller og kapacitet [Number of wind turbines and capacity]. https://winddenmark.dk/tal-fakta/fakta-om-vind-danmark/antal-vindmoeller-kapacitet.

Wind Denmark (2020b). Rekordstor dansk hjælp til det tyske energisystem [Record in Danish assistance to the German energy system]. https://winddenmark.dk/nyheder/rekordstor-dansk-hjaelp-til-tyske-energisystem.

Wittrup, S. (2016a). Mørkelagt businesscase forhindrer debat om elkabel til England [Covered up business case prevents debate over power cable to England].
https://ing.dk/artikel/moerkelagt-businesscase-forhindrer-debat-elkabel-england-186710.

Wittrup, S. (2016b). Professorer frygter kæmpe fejlinvestering: Drop kabel til England og invester i varmepumper herhjemme [Professors fear huge misinvestment: Cancel cable to England and invest in heat pumps at home].

https://ing.dk/artikel/professorer-frygter-kaempe-fejlinvestering-drop-kabel-england-invester-varmepumper-herhjemme.

Wittrup, S. (2016c). Varmepumper en langt bedre forretning end milliardkabel til England [Heat pumps are a better business-case than grid connections to England]. https://ing.dk/artikel/varmepumper-langt-bedre-forretning-end-milliardkabel-england-186659.

Wittrup, S. (2021). Strid om betaling for elnettet kan true den grønne omstilling [Dispute about the payment for the electrical grid can threaten the green transition]. https://ing.dk/artikel/strid-betaling-elnettet-kan-true-gronne-omstilling-246401.

Østergaard, P. A., Jantzen, J., Marczinkowski, H. M., and Kristensen, M. (2019). Renewable Energy Business and socioeconomic assessment of introducing heat pumps with heat storage in small-scale district heating systems. *Renewable Energy*, 139:904–914.

Interview guide A

Guide for interview with Preben Pedersen, operations manager of Oksbøl CHP plant	
Briefing	
Introduction of the interviewers Explanation of the purpose of the interview	
Research question	**Interview questions**
What are the institutional and political hindrances in the implementation of a socio-economically feasible electrification of the district heating sector in 2030 and how can these be overcome?	*Are you familiar with the Energy Agreement from 2018, and the DH goals for 2030?* *Do you as a company feel obligated to change your production to use more RE sources because of the goals?* *How much do you take the 2030 DH goals into account, when thinking about the future of Oksbøl CHP plant?* *How is the ownership structure of Oksbøl CHP plant?* *Who has the power to make and/or veto decisions?* *And how are the decision processes?* *What influence does Oksbøl Barracks have on your heat production?* *How did you first come up with the idea of transitioning your production to use more RE?* *Were you affected by any actors into changing your production?* *If yes, which actors were these and how did they affect you?* *Have you experienced any opposition against reducing your usage of natural gas?* *Do you as a company feel obligated to choose a specific technology when transitioning?* *If yes, why?* *Aside from electric boilers, why did you choose to look only at heat pumps and woodchip boilers as solutions, and were you affected by COWI in any way?* *How were the scenarios in the COWI report chosen?* *What do you think are the main pros and cons of the electrification of your plant?* *Are you concerned about sudden changes in legislation? (e.g. a tax on biomass)* *Apart from COWI, have you worked together with anyone regarding the transition of your plant?* *Have you had any dialogue with other DH companies about the options?* *Have you worked together with- or been influenced by Varde municipality?* *You have already decided to purchase a 7 MW electric boiler.* *What about grid reinforcement?* *Do you have to pay a fee to the DSO?*
Debriefing	

Interview summary B

A sound recording of the full interview is attached to the project in a separate file.

Question(s): *Are you familiar with the Energy Agreement from 2018, and the DH goals for 2030? Do you as a company feel obligated to change your production to use more RE sources because of the goals?*

Summary of answer: The operations manager answers that he is not familiar with all the details of the Energy Agreement, but that they are taking the goals into consideration and that they want to be 100% renewable. He uses their solar collectors as an example. However, he also mentions that they are obligated to deliver the cheapest possible heat to their consumers, and that certain legislation can hinder their ambitions.

Question(s): *How is the ownership structure of Oksbøl CHP plant? Who has the power to make and/or veto decisions? How are the decision processes? And what influence does Oksbøl Barracks have on your heat production?*

Summary of answer: The operations manager answers that they are an a.m.b.a company and that they have approximately 1300 consumers. He explains that the consumers select a board of directors which takes the overall decisions and choose the operations manager, who gives inputs for decisions. He also explains that connecting Oksbøl CHP plant to Oksbøl Barracks gave them an option to shift to biomass because of a 20-25% increase in the heat demand.

Question(s): *How did you first come up with the idea of transitioning your production to use more RE? Were you affected by any actors into changing your production? If yes, which actors were these and how did they affect you? Have you experienced any opposition against reducing your usage of natural gas?*

Summary of answer: The operations manager answers that it started with the installation of solar collectors in 2010 because of economic considerations and wanting to be more 'green'. Then, in 2014, they wanted to get connected to Oksbøl Barracks, but many advisors said that it was not possible. Then a consultant from COWI argued that they should try it, and it finally happened in 2020. Tjæreborg Industri, he explains, are among their main partners, because they trust them and have worked with them for a long time. Lastly, he mentions that the gas distributor hindered their plans of shifting to biomass in the first three years of the planning phase, as the gas distributor argued against the socio-economic feasibility of the transition and filed complaints.

Question(s): *Aside from electric boilers, why did you choose to look only at heat pumps and woodchip boilers as solutions, and were you affected by COWI in any way? How were the scenarios in the COWI report chosen?*

Summary of answer: The operations manager answers that the proposed scenarios were chosen based on guidance from COWI. He adds that the given technologies make the most sense, as the plant is not connected to any industrial excess heat, and that there are no other obvious choices.

Question(s): *What do you think are the main pros and cons of the electrification of your plant?*

Summary of answer: The operations manager answers that the purpose of an electric boiler is to produce cheap heat, when the electricity price is low, and that it is a cheap peak load reserve. He explains that a heat pump would be used for the base load and that it would produce cheap heat in the summer months, but that a heat pump might not be as attractive for Oksbøl CHP plant, since their solar collectors cover the demand in the summer. He sees the potential of high electricity prices as a big drawback/risk when using a heat pump for the base load.

Question(s): *Are you concerned about sudden changes in legislation? (e.g. a tax on biomass)*

Summary of answer: The operations manager answers that a sudden tax on biomass is his- and the board of directors' biggest concern and that it is the reason why they have not yet invested in a wood chip boiler.

Question(s): *Apart from COWI, have you worked together with anyone regarding the transition of your plant? Have you had any dialogue with other DH companies about the options? Have you worked together with- or been influenced by Varde municipality?*

Summary of answer: The operations manager answers that they constantly share ideas with- and talk to the other DH companies, especially those who are nearby. He explains that Varde Municipality took a very long time to approve the Oksbøl Barracks project, which he found frustrating, but that they have been quick to approve the electric boiler. He also says that the strategic energy plan of the municipality has not affected Oksbøl CHP plant significantly.

Question(s): *You have already decided to purchase a 7 MW electric boiler. What about grid reinforcement? Do you have to pay a fee to the DSO?*

Summary of answer: The operations manager answers that they are disconnectable, which makes their grid reinforcement payment significantly lower. He explains that they asked N1 about the possibility of installing an additional electrical substation so that the plant would get its own, to which N1 replied that it would cost Oksbøl CHP plant approximately 10 MDKK, which they were not willing to pay.

EnergyPLAN - printed results C

The printed results from the EnergyPLAN simulations carried out in Chapter 7 are shown in the following pages.

Input DEA.txt — The EnergyPLAN model 15.0

Electricity demand (TWh/year):		Flexible demand	0,00
Fixed demand	44,67	Fixed imp/exp.	0,00
Electric heating + HP	3,19	Transportation	1,20
Electric cooling	0,00	Total	49,06

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0,00	13,90	22,10	36,00
Solar Thermal	0,00	1,00	0,00	1,00
Industrial CHP (CSHP)	0,00	0,00	0,00	0,00
Demand after solar and CSHP	0,00	12,90	22,10	35,00

Wind	6154 MW	19,85	TWh/year	0,00	Grid
Offshore Wind	5180 MW	23,14	TWh/year	0,00	stabili-
Photo Voltaic	6421 MW	7,81	TWh/year	0,00	sation
River Hydro	7 MW	0,03	TWh/year	0,00	share
Hydro Power	0 MW	0	TWh/year		
Geothermal/Nuclear	0 MW	0	TWh/year		

	Capacities MW-e	Capacities MJ/s	Efficiencies elec.	Efficiencies Ther	COP
Group 2:					
CHP	677	974	0,45	0,53	
Heat Pump	173	613			3,54
Boiler		6864		1,00	
Group 3:					
CHP	1827	3705	0,39	0,51	
Heat Pump	88	390			4,46
Boiler		6196		1,00	
Condensing	2149		0,44		

Heatstorage: gr.2:25 GWh gr.95 GWh
Fixed Boiler: gr.2:0,2 Per cent gr.0,2 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0,00	0,00
Gr.2:	0,00	0,30
Gr.3:	0,43	0,88

Regulation Strate(Technical regulation no. 3
CEEP regulation 234500000
Minimum Stabilisation share 0,00
Stabilisation share of CHP 0,00
Minimum CHP gr 3 load 0 MW
Minimum PP 0 MW
Heat Pump maximum share 1,00
Maximum import/export 0 MW

Nord_pool_system_2013_EUR.TXT
Addition factor 1,00 EUR/MWh
Multiplication factor 1,30
Dependency factor 0,00 EUR/MWh pr. MW
Average Market Price 51 EUR/MWh
Gas Storage 4500 GWh
Syngas capacity 0 MW
Biogas max to grid 0 MW

Fuel Price level:

	Capacities MW-e	Storage GWh	Efficiencies elec.	Ther.
Hydro Pump:	0	0	0,80	
Hydro Turbine:	0		0,90	
Electrol. Gr.2:	0	0	0,80	0,10
Electrol. Gr.3:	0	0	0,80	0,10
Electrol. trans.:	0	0	0,61	
Ely. MicroCHP:	0	0	0,80	
CAES fuel ratio:	0,000			

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0,00	0,00	0,00	0,00
Household	0,00	1,06	6,58	13,75
Industry	0,00	0,00	0,00	0,00
Various	0,00	0,00	0,00	0,00

Output WARNING!!: (1) Critical Excess; (3) PP/Import problem

	District Heating: Demand	Production									Electricity: Consumption						Production							Balance					Exchange: Payment	
	Distr. heating MW	Solar MW	Waste CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Balance MW	Elec. demand MW	Flex.& Transp MW	HP MW	Electrolyser MW	EH MW	Hydro Pump MW	Turbine MW	RES MW	Hydro MW	Geothermal MW	Waste CSHP MW	CHP MW	PP MW	Stab-Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Imp Million EUR	Exp Million EUR
January	6134	44	1064	0	2177	851	0	1655	402	0	5804	136	346	0	867	0	0	5552	0	0	183	1171	125	100	709	586	586	0	48	14
February	6258	93	1067	0	2652	817	0	1430	263	-4	5666	135	340	0	739	0	0	4597	0	0	183	1425	147	100	735	206	206	0	38	5
March	5443	105	1039	0	1570	887	0	1405	522	-26	5457	134	338	0	928	0	0	6913	0	0	183	845	75	100	226	1385	1385	0	14	26
April	4512	164	993	0	1623	806	0	448	531	5	5000	139	296	0	856	0	0	6178	0	0	183	876	71	100	211	1230	1230	0	13	23
May	3704	173	936	0	1445	714	0	58	468	-31	4675	138	252	0	723	0	0	5473	0	0	183	785	46	100	76	776	776	0	3	15
June	2092	158	900	0	475	539	0	1	205	-127	4665	135	167	0	321	0	0	6042	0	0	183	273	382	100	87	1679	1679	0	4	20
July	2092	183	887	0	629	368	0	0	109	-26	4482	135	122	0	224	0	0	4576	0	0	183	365	625	100	155	942	942	0	6	14
August	2092	163	893	0	499	477	0	0	139	-19	4667	140	151	0	254	0	0	5559	0	0	183	290	478	100	132	1431	1431	0	6	21
September	2807	125	925	0	1078	479	0	2	255	2	4833	134	169	0	432	0	0	4849	0	0	183	615	493	100	265	837	837	0	13	14
October	3810	78	963	0	999	809	0	271	595	155	5063	138	279	0	859	0	0	6572	0	0	183	548	75	100	97	1135	1135	0	5	24
November	4764	50	1009	0	1830	814	0	700	420	0	5341	137	304	0	766	0	0	5732	0	0	183	996	154	100	269	786	786	0	13	15
December	5540	30	1045	0	1021	921	0	1900	682	0	5394	137	348	0	1096	0	0	7302	0	0	183	551	45	100	187	1294	1294	0	10	24
Average	4098	114	977	0	1327	707	0	656	383	-6	5085	137	259	0	673	0	0	5786	0	0	183	725	226	100	260	1027	1027	0	Average price	
Maximum	10164	1401	1245	0	4679	1003	0	7594	1054	3619	7622	315	529	0	1815	0	0	15318	0	0	183	2504	1886	100	4945	8728	8728	0	(EUR/MWh)	
Minimum	1926	0	830	0	0	8	0	0	0	-3148	3337	68	28	0	101	0	0	4	0	0	183	0	0	100	0	0	0	0	75	24
TWh/year	36,00	1,00	8,58	0,00	11,66	6,21	0,00	5,76	3,37	-0,05	44,67	1,20	2,28	0,00	5,91	0,00	0,00	50,83	0,00	0,00	1,61	6,37	1,99		2,29	9,02	9,02	0,00	171	214

FUEL BALANCE (TWh/year):

	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu	Hydro	Waste	CAES Elc.ly.	BioCon version	Electro Fuel	Wind	PV and Wind off CSP	Wave	Hydro	Solar.Th	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Net	CO2 emission (Mt): Total	Net
Coal	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Oil	-	0,02	-	-	0,13	-	-	-	-	-	-	-	-	-	-	-	-	-	1,06	-	1,20	0,00	1,20	0,32	0,32
N.Gas	-	0,78	0,51	0,13	0,48	0,14	-	-	-	-	-	-	-	-	-	-	-	-	6,58	-	8,60	-0,46	8,15	1,76	1,66
Biomass	-	5,05	16,33	2,45	2,58	4,38	-	-	8,86	-	-	-	-	-	-	-	-	-	13,75	-	53,40	-14,85	38,55	0,00	0,00
Renewable	-	-	-	-	-	-	-	-	-	-	-	-	19,85	7,81	23,14	0,03	1,00	-	-	-	51,83	0,00	51,83	0,00	0,00
H2 etc.	-	0,00	0,00	-	-	0,00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Biofuel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Nuclear/CCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Total	-	5,85	16,84	2,57	3,19	4,51	-	-	8,86	-	-	-	19,85	7,81	23,14	0,03	1,00	-	21,39	-	115,03	-15,31	99,72	2,08	1,98

26-maj-2021 [16:31]

Output specifications DEA.txt The EnergyPLAN model 15.0

District Heating Production

	Gr.1				Gr.2									
	District heating MW	Solar MW	CSHP MW	DHP MW	District heating MW	Solar MW	CSHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Stor-age MW	Ba-lance MW
January	0	0	59	0	2368	44	250	482	612	0	805	176	0	0
February	0	0	59	0	2416	93	251	579	603	0	781	109	0	0
March	0	0	59	0	2102	105	243	352	610	0	560	232	26	0
April	0	0	59	0	1742	164	230	376	544	0	198	238	944	-8
May	0	0	59	0	1430	173	214	360	448	0	26	206	4432	4
June	0	0	59	0	808	158	204	190	281	0	0	24	24716	-49
July	0	0	59	0	808	183	200	271	177	0	0	1	25198	-26
August	0	0	59	0	808	163	202	214	247	0	0	2	25198	-20
September	0	0	59	0	1084	125	211	412	274	0	1	65	24712	-4
October	0	0	59	0	1471	78	222	272	509	0	101	257	7977	33
November	0	0	59	0	1839	50	235	465	568	0	336	186	62	0
December	0	0	59	0	2139	30	245	235	601	0	721	307	2	0
Average	0	0	59	0	1582	114	225	349	456	0	293	151	9456	-6
Maximum	0	0	59	0	3924	1401	302	974	613	0	2887	495	25200	976
Minimum	0	0	59	0	744	0	184	0	3	0	0	0	0	-1336
Total for the whole year														
TWh/year	0,00	0,00	0,52	0,00	13,90	1,00	1,98	3,07	4,00	0,00	2,57	1,32		-0,05

	Gr.3										RES specification				
	District heating MW	Solar MW	CSHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Stor-age MW	Ba-lance MW	RES1 Wind MW	RES2 Offshc MW	RES3 Photo MW	RES 4-7 MW	Total aic MW
January	3766	0	754	1695	240	0	851	226	18015	0	2400	2970	179	4	5552
February	3842	0	757	2073	214	0	649	154	22300	-4	1756	2452	385	4	4597
March	3342	0	737	1217	278	0	846	291	12685	-26	2825	3044	1041	4	6913
April	2770	0	704	1247	262	0	251	293	17846	14	2431	2368	1375	4	6178
May	2274	0	663	1085	266	0	32	262	45673	-35	1869	2140	1461	4	5473
June	1284	0	637	285	258	0	1	181	90183	-78	2149	2439	1451	4	6042
July	1284	0	628	358	190	0	0	107	94652	0	1419	1589	1565	4	4576
August	1284	0	632	285	230	0	0	137	94638	0	1942	2282	1331	4	5559
September	1723	0	655	666	205	0	2	190	90625	5	1682	2171	993	4	4849
October	2339	0	682	728	300	0	170	338	56645	122	2688	3386	495	4	6572
November	2925	0	715	1365	246	0	365	234	33694	0	2396	3074	258	4	5732
December	3401	0	741	786	320	0	1179	375	4048	0	3512	3667	119	4	7302
Average	2516	0	692	978	251	0	363	233	48454	0	2260	2634	889	4	5786
Maximum	6239	0	885	3705	390	0	4746	559	94800	3619	6097	5117	5576	4	15318
Minimum	1182	0	587	0	5	0	0	0	0	-3148	0	0	0	4	4
Total for the whole year															
TWh/year	22,10	0,00	6,08	8,59	2,20	0,00	3,19	2,05		0,00	19,85	23,14	7,81	0,03	50,83

Own use of heat from industrial CH0,00 TWh/year

ANNUAL COSTS (Million EUR)

Total Fuel ex Ngas exchange =		1922
Uranium =	0	
Coal =	0	
FuelOil =	6	
Gasoil/Diesel=	70	
Petrol/JP =	0	
Gas handling =	56	
Biomass =	1791	
Food income =	0	
Waste =	0	
Total Ngas Exchange costs =		204
Marginal operation costs =		32
Total Electricity exchange =		171
Import =	171	
Export =	-214	
Bottleneck =	214	
Fixed imp/ex=	0	
Total CO2 emission costs =		0
Total variable costs =		2330
Fixed operation costs =		3783
Annual Investment costs =		14163
TOTAL ANNUAL COSTS =		20276

NATURAL GAS EXCHANGE

	DHP & Boilers MW	CHP2 CHP3 MW	PP CAES MW	Indi-vidual MW	Trans port MW	Indu. Var. MW	Demand Sum MW	Bio-gas MW	Syn-gas MW	CO2Hy gas MW	SynHy gas MW	SynHy gas MW	Stor-age MW	Sum MW	Im-port MW	Ex-port MW
January	168	222	9	1205	0	0	1604	0	0	0	0	0	624	980	980	0
February	136	269	10	1233	0	0	1648	0	0	0	0	0	669	980	980	0
March	155	161	5	1051	0	0	1372	0	0	0	0	0	392	980	980	0
April	47	169	5	842	0	0	1063	0	0	0	0	0	83	980	980	0
May	6	155	3	661	0	0	825	0	0	0	0	0	-155	980	980	0
June	0	65	26	299	0	0	390	0	0	0	0	0	-589	980	980	0
July	0	90	43	299	0	0	432	0	0	0	0	0	-548	980	980	0
August	0	71	33	299	0	0	403	0	0	0	0	0	-577	980	980	0
September	0	144	34	460	0	0	637	0	0	0	0	0	-343	980	980	0
October	31	112	5	684	0	0	832	0	0	0	0	0	-148	980	980	0
November	71	198	10	898	0	0	1178	0	0	0	0	0	199	980	980	0
December	213	106	3	1072	0	0	1394	0	0	0	0	0	414	980	980	0
Average	69	146	15	749	0	0	980	0	0	0	0	0	0	980	980	0
Maximum	854	465	129	2105	0	0	2996	0	0	0	0	0	2017	980	980	0
Minimum	0	0	0	262	0	0	262	0	0	0	0	0	-717	980	980	0
Total for the whole year																
TWh/year	0,61	1,28	0,14	6,58	0,00	0,00	8,60	0,00	0,00	0,00	0,00	0,00	0,00	8,60	8,60	0,00

RES Share: 91,5 Percent of Primary Energ126,1 Percent of Electricity 59,9 TWh electricity from RES 26-maj-2021 [16:31]

Input EN2.txt

The EnergyPLAN model 15.0

Electricity demand (TWh/year):		Flexible demand	0,00
Fixed demand	38,97	Fixed imp/exp.	0,00
Electric heating + HP	4,01	Transportation	0,96
Electric cooling	0,00	Total	43,95

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0,00	13,90	22,10	36,00
Solar Thermal	0,00	0,20	0,00	0,20
Industrial CHP (CSHP)	0,00	0,00	0,00	0,00
Demand after solar and CSHP	0,00	13,70	22,10	35,80

Wind	2770 MW	8,93	TWh/year	0,00	Grid
Offshore Wind	4972 MW	22,21	TWh/year	0,00	stabili-
Photo Voltaic	2939 MW	3,57	TWh/year	0,00	sation
River Hydro	0 MW	0	TWh/year	0,00	share
Hydro Power	0 MW	0	TWh/year		
Geothermal/Nuclear	0 MW	0	TWh/year		

	Capacities MW-e	Capacities MJ/s	Efficiencies elec.	Efficiencies Ther	COP
Group 2:					
CHP	677	974	0,45	0,53	
Heat Pump	27	96			3,54
Boiler		6864		1,00	
Group 3:					
CHP	1827	3705	0,39	0,51	
Heat Pump	10	45			4,46
Boiler		6196		1,00	
Condensing	2149		0,44		

Heatstorage: gr.2:25 GWh gr.95 GWh
Fixed Boiler: gr.2:0,2 Per cent gr.0,2 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0,00	0,00
Gr.2:	0,00	0,30
Gr.3:	0,43	0,88

Regulation Strateg Technical regulation no. 3
CEEP regulation 234500000
Minimum Stabilisation share 0,00
Stabilisation share of CHP 0,00
Minimum CHP gr 3 load 0 MW
Minimum PP 0 MW
Heat Pump maximum share 1,00
Maximum import/export 0 MW

Nord_pool_system_2013_EUR.TXT
Addition factor 1,00 EUR/MWh
Multiplication factor 1,30
Dependency factor 0,00 EUR/MWh pr. MW
Average Market Price 51 EUR/MWh
Gas Storage 4500 GWh
Syngas capacity 0 MW
Biogas max to grid 0 MW

Fuel Price level:

	Capacities MW-e	Storage GWh	Efficiencies elec.	Efficiencies Ther.
Hydro Pump:	0	0	0,80	
Hydro Turbine:	0		0,90	
Electrol. Gr.2:	0	0	0,80	0,10
Electrol. Gr.3:	0	0	0,80	0,10
Electrol. trans.:	0	0	0,61	
Ely. MicroCHP:	0	0	0,80	
CAES fuel ratio:	0,000			

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0,00	0,00	0,00	0,00
Household	0,00	0,00	4,01	13,90
Industry	0,00	0,00	0,00	0,00
Various	0,00	0,00	0,00	0,00

Output WARNING!!: (1) Critical Excess; (3) PP/Import problem

	District Heating										Electricity																		Exchange	
	Demand	Production									Consumption						Production							Balance						
	Distr. heating MW	Solar MW	Waste-CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Ba-lance MW	Elec. demand MW	Flex.& Transp MW	HP MW	Elec-trolyser MW	EH MW	Hydro Pump MW	Tur-bine MW	RES MW	Hy-dro MW	Geo-thermal MW	Waste-CSHP MW	CHP MW	PP MW	Stab-Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Payment Imp Million EUR	Payment Exp Million EUR
January	6134	9	1064	0	2461	124	0	2369	167	0	5060	109	304	0	632	0	0	4013	0	0	183	1323	135	100	599	147	147	0	39	4
February	6258	18	1067	0	3022	122	0	2016	78	-5	4940	107	309	0	554	0	0	3320	0	0	183	1622	159	100	668	42	42	0	33	1
March	5443	21	1039	0	1997	126	0	2150	249	-80	4759	109	269	0	655	0	0	4670	0	0	183	1077	100	100	230	468	468	0	14	14
April	4512	32	993	0	2077	122	0	1064	230	52	4362	111	222	0	555	0	0	3997	0	0	183	1124	108	100	204	366	366	0	12	11
May	3704	34	936	0	1959	115	0	545	173	1	4080	110	179	0	428	0	0	3564	0	0	183	1073	88	100	82	193	193	0	4	5
June	2092	31	900	0	946	82	0	37	262	-107	4072	109	89	0	378	0	0	3972	0	0	183	543	407	100	73	531	531	0	3	10
July	2092	36	887	0	1058	52	0	11	132	-24	3913	109	81	0	247	0	0	2880	0	0	183	622	754	100	121	211	211	0	5	5
August	2092	32	893	0	876	72	0	17	236	25	4073	113	86	0	351	0	0	3674	0	0	183	512	546	100	121	414	414	0	5	10
September	2807	25	925	0	1536	70	0	129	174	8	4218	106	121	0	351	0	0	3295	0	0	183	874	510	100	219	285	285	0	10	7
October	3810	15	963	0	1325	123	0	1011	303	129	4417	112	186	0	567	0	0	4686	0	0	183	726	71	100	95	479	479	0	5	13
November	4764	10	1009	0	2078	124	0	1397	205	0	4658	110	235	0	552	0	0	4148	0	0	183	1130	163	100	237	307	307	0	11	8
December	5540	6	1045	0	1291	132	0	2797	329	0	4705	110	275	0	742	0	0	5155	0	0	183	696	56	100	174	432	432	0	8	10
Average	4098	22	977	0	1712	105	0	1129	212	0	4437	110	196	0	501	0	0	3952	0	0	183	940	258	100	233	324	324	0	Average price	
Maximum	10164	276	1245	0	4679	140	0	7768	637	4186	6638	253	645	0	1398	0	0	9518	0	0	183	2504	1887	100	4036	4161	4161	0	(EUR/MWh)	
Minimum	1926	0	830	0	0	8	0	0	0	-3600	2920	55	61	0	101	0	0	0	0	0	183	0	0	100	0	0	0	0	72	35
TWh/year	36,00	0,20	8,58	0,00	15,04	0,93	0,00	9,92	1,86	0,00	38,97	0,96	1,72	0,00	4,40	0,00	0,00	34,72	0,00	0,00	1,61	8,26	2,27		2,05	2,85	2,85	0,00	148	100

FUEL BALANCE (TWh/year):

	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu	Hydro	Waste	CAES Elc.ly.	BioCon version	Electro-Fuel	Wind	PV and CSP	Wind off Wave	Hydro	Solar.Th	Transp.	Industry househ.	Various	Total	Imp/Exp Corrected Imp/Exp	Net	CO2 emission (Mt): Total	Net
Coal	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Oil	-	0,02	-	-	0,15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,18	0,00	0,18	0,05	0,05
N.Gas	-	1,06	0,64	0,30	0,58	0,15	-	-	-	-	-	-	-	-	-	-	-	-	4,01	-	6,74	-0,05	6,69	1,38	1,36
Biomass	-	6,86	20,68	5,75	3,13	5,00	-	-	8,86	-	-	-	-	-	-	-	-	-	13,90	-	64,18	-1,75	62,42	0,00	0,00
Renewable	-	-	-	-	-	-	-	-	-	-	-	-	8,93	3,57	22,21	-	0,20	-	-	-	34,91	0,00	34,91	0,00	0,00
H2 etc.	-	0,00	0,00	-	-	0,00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Biofuel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Nuclear/CCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Total	-	7,94	21,32	6,06	3,86	5,15	-	-	8,86	-	-	-	8,93	3,57	22,21	-	0,20	-	17,91	-	106,01	-1,81	104,20	1,42	1,41

26-maj-2021 [16:39]

Output specifications EN2.txt The EnergyPLAN model 15.0

District Heating Production

Gr.1	District heating MW	Solar MW	CSHP MW	DHP MW
January	0	0	59	0
February	0	0	59	0
March	0	0	59	0
April	0	0	59	0
May	0	0	59	0
June	0	0	59	0
July	0	0	59	0
August	0	0	59	0
September	0	0	59	0
October	0	0	59	0
November	0	0	59	0
December	0	0	59	0
Average	0	0	59	0
Maximum	0	0	59	0
Minimum	0	0	59	0
Total for the whole year TWh/year	0,00	0,00	0,52	0,00

Gr.2	District heating MW	Solar MW	CSHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Stor-age MW	Ba-lance MW
January	2368	9	250	541	96	0	1402	71	0	0
February	2416	18	251	656	96	0	1364	32	0	0
March	2102	21	243	456	96	0	1173	113	0	0
April	1742	32	230	495	94	0	789	102	0	0
May	1430	34	214	530	85	0	493	74	15	0
June	808	31	204	378	55	0	34	116	11744	-10
July	808	36	200	497	33	0	9	57	19111	-24
August	808	32	202	396	48	0	15	105	17475	10
September	1084	25	211	578	47	0	127	78	4752	19
October	1471	15	222	360	90	0	646	133	17	5
November	1839	10	235	523	96	0	886	91	0	0
December	2139	6	245	296	96	0	1352	145	0	0
Average	1582	22	225	474	77	0	690	93	4454	0
Maximum	3924	276	302	974	96	0	3177	299	25200	940
Minimum	744	0	184	0	3	0	0	0	0	-615
Total for the whole year TWh/year	13,90	0,20	1,98	4,17	0,68	0,00	6,06	0,82		0,00

Gr.3	District heating MW	Solar MW	CSHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Stor-age MW	Ba-lance MW
January	3766	0	754	1920	28	0	967	96	19077	0
February	3842	0	757	2366	26	0	652	47	27039	-5
March	3342	0	737	1541	30	0	977	136	18607	-80
April	2770	0	704	1582	29	0	275	129	34678	52
May	2274	0	663	1429	29	0	52	100	48343	1
June	1284	0	637	568	27	0	3	146	79698	-97
July	1284	0	628	561	18	0	2	75	90558	0
August	1284	0	632	480	24	0	2	131	89421	15
September	1723	0	655	958	23	0	2	96	80701	-11
October	2339	0	682	965	34	0	365	170	37573	124
November	2925	0	715	1555	29	0	511	114	30560	0
December	3401	0	741	995	37	0	1445	184	5243	0
Average	2516	0	692	1238	28	0	439	119	46794	0
Maximum	6239	0	885	3705	45	0	4725	338	94800	4186
Minimum	1182	0	587	0	5	0	0	0	0	-3163
Total for the whole year TWh/year	22,10	0,00	6,08	10,87	0,24	0,00	3,86	1,04		0,00

RES specification	RES1 Wind MW	RES2 Offshc MW	RES3 Photo MW	RES 4-7 aic MW	Total MW
January	1080	2851	82	0	4013
February	791	2354	176	0	3320
March	1271	2922	476	0	4670
April	1094	2273	630	0	3997
May	841	2054	669	0	3564
June	967	2341	664	0	3972
July	639	1525	716	0	2880
August	874	2191	609	0	3674
September	757	2083	455	0	3295
October	1210	3250	226	0	4686
November	1079	2951	118	0	4148
December	1581	3520	55	0	5155
Average	1017	2528	407	0	3952
Maximum	2744	4911	2552	0	9518
Minimum	0	0	0	0	0
Total for the whole year TWh/year	8,93	22,21	3,57	0,00	34,72

Own use of heat from industrial CH0,00 TWh/year

ANNUAL COSTS (Million EUR)	
Total Fuel ex Ngas exchange =	2240
Uranium =	0
Coal =	0
FuelOil =	7
Gasoil/Diesel=	0
Petrol/JP =	0
Gas handling =	37
Biomass =	2196
Food income =	0
Waste =	0
Total Ngas Exchange costs =	160
Marginal operation costs =	40
Total Electricity exchange =	148
Import =	148
Export =	-100
Bottleneck =	100
Fixed imp/ex=	0
Total CO2 emission costs =	0
Total variable costs =	2589
Fixed operation costs =	3624
Annual Investment costs =	13843
TOTAL ANNUAL COSTS =	20056

NATURAL GAS EXCHANGE

	DHP & Boilers MW	CHP2 CHP3 MW	PP CAES MW	Indi-vidual MW	Trans port MW	Indu. Var. MW	Demand Sum MW	Bio-gas MW	Syn-gas MW	CO2Hy gas MW	SynHy gas MW	SynHy gas MW	Stor-age MW	Sum MW	Im-port MW	Ex-port MW
January	215	250	9	735	0	0	1209	0	0	0	0	0	442	767	767	0
February	166	305	11	752	0	0	1234	0	0	0	0	0	466	767	767	0
March	205	206	7	640	0	0	1059	0	0	0	0	0	291	767	767	0
April	81	218	7	513	0	0	820	0	0	0	0	0	52	767	767	0
May	32	218	6	403	0	0	659	0	0	0	0	0	-108	767	767	0
June	2	129	28	182	0	0	342	0	0	0	0	0	-426	767	767	0
July	1	159	51	182	0	0	393	0	0	0	0	0	-374	767	767	0
August	1	129	37	182	0	0	349	0	0	0	0	0	-418	767	767	0
September	7	203	35	280	0	0	524	0	0	0	0	0	-243	767	767	0
October	87	148	5	417	0	0	657	0	0	0	0	0	-110	767	767	0
November	121	224	11	547	0	0	903	0	0	0	0	0	136	767	767	0
December	284	133	4	653	0	0	1075	0	0	0	0	0	308	767	767	0
Average	100	193	18	457	0	0	767	0	0	0	0	0	0	767	767	0
Maximum	861	465	129	1283	0	0	2181	0	0	0	0	0	1413	767	767	0
Minimum	0	0	0	160	0	0	161	0	0	0	0	0	-607	767	767	0
Total for the whole year TWh/year	0,88	1,70	0,15	4,01	0,00	0,00	6,74	0,00	0,00	0,00	0,00	0,00	0,00	6,74	6,74	0,00

RES Share: 93,5 Percent of Primary Energ114,0 Percent of Electricity 45,8 TWh electricity from RES 26-maj-2021 [16:39]

Input EN4.txt

The EnergyPLAN model 15.0

Electricity demand (TWh/year):		Flexible demand	0,00
Fixed demand	37,77	Fixed imp/exp.	0,00
Electric heating + HP	5,48	Transportation	4,53
Electric cooling	0,00	Total	47,78

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0,00	13,90	22,10	36,00
Solar Thermal	0,00	0,35	0,00	0,35
Industrial CHP (CSHP)	0,00	0,00	0,00	0,00
Demand after solar and CSHP	0,00	13,55	22,10	35,65

Wind	4118 MW	13,28	TWh/year	0,00	Grid
Offshore Wind	8100 MW	36,18	TWh/year	0,00	stabili-
Photo Voltaic	4000 MW	4,87	TWh/year	0,00	sation
River Hydro	0 MW	0	TWh/year	0,00	share
Hydro Power	0 MW	0	TWh/year		
Geothermal/Nuclear	0 MW	0	TWh/year		

	Capacities		Efficiencies		
Group 2:	MW-e	MJ/s	elec.	Ther	COP
CHP	677	974	0,45	0,53	
Heat Pump	300	1062			3,54
Boiler		6864		1,00	
Group 3:					
CHP	1827	3705	0,39	0,51	
Heat Pump	186	830			4,46
Boiler		6196		1,00	
Condensing	2149		0,44		

Heatstorage: gr.2:25 GWh gr.95 GWh
Fixed Boiler: gr.2:0,2 Per cent gr.0,2 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0,00	0,00
Gr.2:	0,00	0,30
Gr.3:	0,43	0,88

Regulation Strateg Technical regulation no. 3
CEEP regulation 234500000
Minimum Stabilisation share 0,00
Stabilisation share of CHP 0,00
Minimum CHP gr 3 load 0 MW
Minimum PP 0 MW
Heat Pump maximum share 1,00
Maximum import/export 0 MW

Nord_pool_system_2013_EUR.TXT
Addition factor 1,00 EUR/MWh
Multiplication factor 1,30
Dependency factor 0,00 EUR/MWh pr. MW
Average Market Price 51 EUR/MWh
Gas Storage 4500 GWh
Syngas capacity 0 MW
Biogas max to grid 0 MW

Fuel Price level:

	Capacities MW-e	Storage GWh	Efficiencies elec.	Ther.
Hydro Pump:	0	0	0,80	
Hydro Turbine:	0		0,90	
Electrol. Gr.2:	0	0	0,80	0,10
Electrol. Gr.3:	0	0	0,80	0,10
Electrol. trans.:	0	0	0,61	
Ely. MicroCHP:	0	0	0,80	
CAES fuel ratio:	0,000			

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0,00	0,00	0,00	0,00
Household	0,00	0,00	0,00	11,78
Industry	0,00	0,00	0,00	0,00
Various	0,00	0,00	0,00	0,00

Output WARNING!!: (1) Critical Excess; (3) PP/Import problem

	District Heating										Electricity																			Exchange	
	Demand	Production									Consumption						Production							Balance						Payment	
	Distr. heating MW	Solar MW	Waste-CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Ba-lance MW	Elec. demand MW	Flex.& Transp MW	HP MW	Elec-trolyser MW	EH MW	Hydro Pump MW	Tur-bine MW	RES MW	Hy-dro MW	Geo-thermal MW	Waste-CSHP MW	CHP MW	PP MW	Stab-Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Imp Million EUR	Exp Million EUR
January	6134	15	1064	0	1855	1572	0	1447	240	0	4938	517	952	0	705	0	0	6361	0	0	183	997	124	100	577	1131	1131	0	38	23
February	6258	33	1067	0	2254	1506	0	1278	182	-3	4816	511	949	0	658	0	0	5249	0	0	183	1212	142	100	652	505	505	0	33	11
March	5443	37	1039	0	1462	1583	0	1148	279	-44	4630	505	882	0	684	0	0	7299	0	0	183	789	75	100	198	1843	1843	0	12	30
April	4512	57	993	0	1606	1410	0	243	248	14	4224	521	743	0	573	0	0	6186	0	0	183	868	78	100	181	1436	1436	0	11	26
May	3704	60	936	0	1245	1343	0	12	222	-54	3935	526	641	0	477	0	0	5507	0	0	183	678	54	100	60	903	903	0	3	16
June	2092	55	900	0	441	806	0	1	25	-76	3926	511	335	0	141	0	0	6156	0	0	183	256	355	100	47	2084	2084	0	2	21
July	2092	64	887	0	610	589	0	0	0	0	3763	512	281	0	116	0	0	4409	0	0	183	358	564	100	113	955	955	0	4	13
August	2092	57	893	0	448	752	0	0	0	0	3928	524	322	0	116	0	0	5698	0	0	183	263	418	100	97	1769	1769	0	4	22
September	2807	44	925	0	900	914	0	1	77	3	4076	515	437	0	255	0	0	5139	0	0	183	518	470	100	209	1238	1238	0	10	18
October	3810	27	963	0	729	1543	0	154	294	158	4280	516	702	0	559	0	0	7401	0	0	183	399	53	100	64	2045	2045	0	4	33
November	4764	17	1009	0	1430	1512	0	610	245	0	4527	515	794	0	592	0	0	6572	0	0	183	776	96	100	152	1351	1351	0	7	21
December	5540	10	1045	0	826	1720	0	1637	361	0	4575	517	924	0	775	0	0	8159	0	0	183	446	35	100	132	2164	2164	0	6	31
Average	4098	40	977	0	1145	1271	0	544	181	0	4300	516	663	0	471	0	0	6185	0	0	183	627	205	100	205	1456	1456	0	Average price	
Maximum	10164	490	1245	0	4679	1892	0	6858	486	3481	6555	1190	1700	0	1252	0	0	14599	0	0	183	2504	1886	100	4553	8794	8794	0	(EUR/MWh)	
Minimum	1926	0	830	0	0	8	0	0	0	-3148	2746	258	119	0	101	0	0	0	0	0	183	0	0	100	0	0	0	0	75	21
TWh/year	36,00	0,35	8,58	0,00	10,06	11,16	0,00	4,78	1,59	0,00	37,77	4,53	5,82	0,00	4,13	0,00	0,00	54,33	0,00	0,00	1,61	5,51	1,80		1,80	12,79	12,79	0,00	135	264

FUEL BALANCE (TWh/year):

	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu	Hydro	Waste	CAES Elc.ly.	BioCon-version	Electro-Fuel	Wind	PV and CSP	Wind off Wave	Hydro	Solar.Th	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Net	CO2 emission (Mt): Total	Net
Coal	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Oil	-	0,02	-	-	0,12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,14	0,00	0,14	0,04	0,04
N.Gas	-	0,69	0,43	0,08	0,47	0,12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1,79	-0,75	1,04	0,37	0,21
Biomass	-	4,46	13,97	1,59	2,51	3,98	-	-	8,86	-	-	-	-	-	-	-	-	-	11,78	-	47,15	-24,23	22,92	0,00	0,00
Renewable	-	-	-	-	-	-	-	-	-	-	-	-	13,28	4,87	36,18	-	0,35	-	-	-	54,68	0,00	54,68	0,00	0,00
H2 etc.	-	0,00	0,00	-	-	0,00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Biofuel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Nuclear/CCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Total	-	5,17	14,41	1,67	3,10	4,10	-	-	8,86	-	-	-	13,28	4,87	36,18	-	0,35	-	11,78	-	103,76	-24,98	78,78	0,40	0,25

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Output specifications EN4.txt The EnergyPLAN model 15.0

District Heating Production

	Gr.1 District heating MW	Gr.1 Solar MW	Gr.1 CSHP MW	Gr.1 DHP MW	Gr.2 District heating MW	Gr.2 Solar MW	Gr.2 CSHP MW	Gr.2 CHP MW	Gr.2 HP MW	Gr.2 ELT MW	Gr.2 Boiler MW	Gr.2 EH MW	Gr.2 Storage MW	Gr.2 Balance MW
January	0	0	59	0	2368	15	250	408	1028	0	557	110	0	0
February	0	0	59	0	2416	33	251	496	1020	0	535	82	0	0
March	0	0	59	0	2102	37	243	338	985	0	370	129	0	0
April	0	0	59	0	1742	57	230	378	867	0	100	115	930	-5
May	0	0	59	0	1430	60	214	318	766	0	8	88	17187	-25
June	0	0	59	0	808	55	204	192	360	0	0	1	25193	-4
July	0	0	59	0	808	64	200	280	263	0	0	0	25200	0
August	0	0	59	0	808	57	202	207	342	0	0	0	25200	0
September	0	0	59	0	1084	44	211	368	457	0	0	4	25166	0
October	0	0	59	0	1471	27	222	195	864	0	14	115	14061	34
November	0	0	59	0	1839	17	235	349	923	0	202	113	80	0
December	0	0	59	0	2139	10	245	190	1018	0	509	168	0	0
Average	0	0	59	0	1582	40	225	309	740	0	191	77	11126	0
Maximum	0	0	59	0	3924	490	302	974	1062	0	2470	228	25200	791
Minimum	0	0	59	0	744	0	184	0	3	0	0	0	0	-759
Total for the whole year TWh/year	0,00	0,00	0,52	0,00	13,90	0,35	1,98	2,71	6,50	0,00	1,67	0,68		0,00

	Gr.3 District heating MW	Gr.3 Solar MW	Gr.3 CSHP MW	Gr.3 CHP MW	Gr.3 HP MW	Gr.3 ELT MW	Gr.3 Boiler MW	Gr.3 EH MW	Gr.3 Storage MW	Gr.3 Balance MW	RES1 Wind MW	RES2 Offshc MW	RES3 Photo MW	RES 4-7 MW	Total MW
January	3766	0	754	1448	544	0	889	130	11588	0	1606	4644	111	0	6361
February	3842	0	757	1759	486	0	743	100	12070	-3	1175	3834	240	0	5249
March	3342	0	737	1124	598	0	778	149	13420	-44	1890	4760	648	0	7299
April	2770	0	704	1228	543	0	143	133	27095	19	1627	3702	857	0	6186
May	2274	0	663	926	577	0	3	134	50022	-29	1250	3346	910	0	5507
June	1284	0	637	249	446	0	0	24	91350	-72	1438	3814	904	0	6156
July	1284	0	628	330	326	0	0	0	94800	0	950	2485	975	0	4409
August	1284	0	632	242	410	0	0	0	94799	0	1300	3569	829	0	5698
September	1723	0	655	533	458	0	1	73	92454	3	1126	3394	619	0	5139
October	2339	0	682	534	679	0	140	179	60050	124	1799	5294	308	0	7401
November	2925	0	715	1081	589	0	408	132	28880	0	1604	4808	161	0	6572
December	3401	0	741	636	702	0	1128	193	2733	0	2350	5735	74	0	8159
Average	2516	0	692	836	530	0	353	104	48342	0	1512	4119	554	0	6185
Maximum	6239	0	885	3705	830	0	4389	258	94800	3481	4080	8001	3473	0	14599
Minimum	1182	0	587	0	5	0	0	0	0	-3148	0	0	0	0	0
Total for the whole year TWh/year	22,10	0,00	6,08	7,35	4,66	0,00	3,10	0,92		0,00	13,28	36,18	4,87	0,00	54,33

Own use of heat from industrial CH0,00 TWh/year

ANNUAL COSTS (Million EUR)

Total Fuel ex Ngas exchange = 1548
Uranium = 0
Coal = 0
FuelOil = 5
Gasoil/Diesel= 0
Petrol/JP = 0
Gas handling = 3
Biomass = 1539
Food income = 0
Waste = 0

Total Ngas Exchange costs = 43

Marginal operation costs = 28

Total Electricity exchange = 135
Import = 135
Export = -264
Bottleneck = 264
Fixed imp/ex= 0

Total CO2 emission costs = 0

Total variable costs = 1753
Fixed operation costs = 3657

Annual Investment costs = 14462

TOTAL ANNUAL COSTS = 19872

NATURAL GAS EXCHANGE

	DHP & Boilers MW	CHP2 CHP3 MW	PP CAES MW	Indi-vidual MW	Trans port MW	Indu. Var. MW	Demand Sum MW	Bio-gas MW	Syn-gas MW	CO2Hy gas MW	SynHy gas MW	SynHy gas MW	Stor-age MW	Sum MW	Im-port MW	Ex-port MW
January	161	188	8	0	0	0	358	0	0	0	0	0	154	204	204	0
February	138	229	10	0	0	0	377	0	0	0	0	0	173	204	204	0
March	135	152	5	0	0	0	292	0	0	0	0	0	88	204	204	0
April	26	168	5	0	0	0	200	0	0	0	0	0	-4	204	204	0
May	1	135	4	0	0	0	140	0	0	0	0	0	-64	204	204	0
June	0	63	24	0	0	0	88	0	0	0	0	0	-116	204	204	0
July	0	90	38	0	0	0	129	0	0	0	0	0	-75	204	204	0
August	0	67	29	0	0	0	95	0	0	0	0	0	-109	204	204	0
September	0	124	32	0	0	0	157	0	0	0	0	0	-47	204	204	0
October	22	81	4	0	0	0	106	0	0	0	0	0	-98	204	204	0
November	71	152	7	0	0	0	230	0	0	0	0	0	26	204	204	0
December	195	85	2	0	0	0	283	0	0	0	0	0	79	204	204	0
Average	63	127	14	0	0	0	204	0	0	0	0	0	0	204	204	0
Maximum	782	465	129	0	0	0	782	0	0	0	0	0	578	204	204	0
Minimum	0	0	0	0	0	0	0	0	0	0	0	0	-204	204	204	0
Total for the whole year TWh/year	0,55	1,12	0,12	0,00	0,00	0,00	1,79	0,00	0,00	0,00	0,00	0,00	0,00	1,79	1,79	0,00

RES Share: 98,1 Percent of Primary Energ138,1 Percent of Electricity 62,4 TWh electricity from RES 26-maj-2021 [16:44]

Input IDA (researchers' version).txt — The EnergyPLAN model 15.0

Electricity demand (TWh/year):		Flexible demand	2,72
Fixed demand	39,54	Fixed imp/exp.	0,00
Electric heating + HP	6,50	Transportation	5,54
Electric cooling	1,63	Total	55,93

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0,00	13,90	22,10	36,00
Solar Thermal	0,00	1,38	0,00	1,38
Industrial CHP (CSHP)	0,00	0,00	0,00	0,00
Demand after solar and CSHP	0,00	12,52	22,10	34,62

Wind	4800 MW	15,48	TWh/year	0,00	Grid
Offshore Wind	6630 MW	29,62	TWh/year	0,00	stabili-
Photo Voltaic	5000 MW	6,08	TWh/year	0,00	sation
River Hydro	0 MW	0,46	TWh/year	0,00	share
Hydro Power	0 MW	0	TWh/year		
Geothermal/Nuclear	0 MW	0	TWh/year		

	Capacities MW-e	Capacities MJ/s	Efficiencies elec.	Efficiencies Ther	COP
Group 2:					
CHP	677	974	0,45	0,53	
Heat Pump	237	839			3,54
Boiler		6864		1,00	
Group 3:					
CHP	1827	3705	0,39	0,51	
Heat Pump	315	1405			4,46
Boiler		6196		1,00	
Condensing	2149		0,44		

Heatstorage: gr.2:25 GWh gr.95 GWh
Fixed Boiler: gr.2:0,2 Per cent gr.0,2 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0,00	0,00
Gr.2:	0,00	0,30
Gr.3:	0,43	0,88

Regulation Strateg Technical regulation no. 3
CEEP regulation 234500000
Minimum Stabilisation share 0,00
Stabilisation share of CHP 0,00
Minimum CHP gr 3 load 0 MW
Minimum PP 0 MW
Heat Pump maximum share 1,00
Maximum import/export 0 MW

Nord_pool_system_2013_EUR.TXT
Addition factor 1,00 EUR/MWh
Multiplication factor 1,30
Dependency factor 0,00 EUR/MWh pr. MW
Average Market Price 51 EUR/MWh
Gas Storage 4500 GWh
Syngas capacity 159 MW
Biogas max to grid 1107 MW

Fuel Price level:

	Capacities MW-e	Storage GWh	Efficiencies elec.	Efficiencies Ther.
Hydro Pump:	0	0	0,80	
Hydro Turbine:	0		0,90	
Electrol. Gr.2:	0	0	0,80	0,10
Electrol. Gr.3:	0	0	0,80	0,10
Electrol. trans.:	1223	40	0,61	
Ely. MicroCHP:	0	0	0,80	
CAES fuel ratio:	0,000			

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0,00	0,00	0,00	0,00
Household	0,00	0,00	0,00	7,36
Industry	0,00	0,00	0,00	0,00
Various	0,00	0,00	0,00	0,00

Output WARNING!!: (1) Critical Excess; (3) PP/Import problem

	District Heating: Demand	Production									Electricity: Consumption						Production							Balance					Exchange	
	Distr. heating MW	Solar MW	Waste+CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Balance MW	Elec. demand MW	Flex.& Transp MW	HP MW	Elec- trolyser MW	EH MW	Hydro Pump MW	Tur- bine MW	RES MW	Hy- dro MW	Geo- thermal MW	Waste+ CSHP MW	CHP MW	PP MW	Stab- Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Payment Imp Million EUR	Payment Exp Million EUR
January	6134	61	2312	0	1916	1361	19	313	221	-9	5260	933	1073	627	686	0	0	5864	0	0	183	1062	473	100	1003	6	6	0	66	0
February	6258	128	2324	0	2461	1120	19	246	57	-38	5150	924	1032	489	533	0	0	4895	0	0	183	1360	577	100	1114	2	2	0	59	0
March	5443	145	2211	0	1406	1350	19	78	353	-60	4983	947	971	664	758	0	0	6975	0	0	183	790	412	100	350	385	385	0	21	11
April	4512	227	2025	0	1193	1008	19	12	133	-45	4618	951	758	666	458	0	0	6035	0	0	183	682	545	100	394	388	388	0	25	10
May	3704	239	1791	0	1003	718	19	1	27	-32	4359	931	576	569	282	0	0	5369	0	0	183	582	562	100	175	154	154	0	8	4
June	2092	218	1643	0	201	165	19	0	0	-95	4351	946	224	692	116	0	0	5960	0	0	183	126	678	100	208	826	826	0	9	13
July	2092	253	1590	0	284	111	19	0	0	-106	4205	930	209	501	116	0	0	4388	0	0	183	177	1082	100	411	281	281	0	17	6
August	2092	224	1613	0	210	183	19	0	0	-98	4353	963	228	641	116	0	0	5513	0	0	183	133	804	100	254	586	586	0	11	13
September	2807	173	1745	0	623	352	19	0	1	-47	4485	917	366	547	179	0	0	4916	0	0	183	373	925	100	482	385	385	0	23	9
October	3810	108	1900	0	724	1052	19	1	73	-6	4669	951	676	780	337	0	0	6886	0	0	183	423	368	100	138	586	586	0	7	15
November	4764	69	2089	0	1396	1028	19	43	169	11	4891	950	799	595	515	0	0	6077	0	0	183	800	543	100	326	178	178	0	15	4
December	5540	41	2235	0	928	1644	19	204	404	125	4933	939	1054	810	818	0	0	7583	0	0	183	526	265	100	230	232	232	0	11	5
Average	4098	157	1955	0	1023	842	19	75	121	-33	4687	940	663	633	410	0	0	5878	0	0	183	583	602	100	421	335	335	0	Average price	
Maximum	10164	1933	3054	0	4679	2244	19	2656	1054	3520	6711	3054	2164	1258	1740	0	0	14570	0	0	183	2504	2149	100	5244	5998	5998	0	(EUR/MWh)	
Minimum	1926	0	1358	0	0	8	19	0	0	-2416	3292	278	160	20	101	0	0	2	0	0	183	0	0	100	0	0	0	0	74	31
TWh/year	36,00	1,38	17,18	0,00	8,98	7,39	0,16	0,65	1,06	-0,29	41,17	8,26	5,83	5,56	3,60	0,00	0,00	51,64	0,00	0,00	1,61	5,12	5,29		3,70	2,94	2,94	0,00	274	91

FUEL BALANCE (TWh/year):	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Waste	CAES Elc.ly.	BioCon- version	Electro- Fuel	Wind	PV and Wind off CSP	Wave	Hydro	Solar.Th.	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Net	CO2 emission (Mt): Total	Net
Coal	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Oil	-	0,02	-	-	0,00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,02	0,00	0,02	0,01	0,01
N.Gas	-	0,87	0,33	0,03	0,00	0,36	-	-	-	-	-10,80	-	-	-	-	-	-	-	-	-	-9,21	0,05	-9,16	-1,88	-1,87
Biomass	-	5,62	10,59	0,60	0,02	11,66	-	-	8,86	-	11,40	-	-	-	-	-	-	-	7,36	-	56,11	1,66	57,77	0,00	0,00
Renewable	-	-	-	-	-	-	-	-	-	-	-	-	15,48	6,08	30,07	-	1,38	-	-	-	53,02	0,00	53,02	0,00	0,00
H2 etc.	-	0,00	0,00	-	-	0,00	-	-	-	-3,29	-0,32	3,61	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Biofuel	-	-	-	-	-	-	-	-	-	-	-	-3,06	-	-	-	-	-	2,92	-	-	-0,14	0,00	-0,14	0,00	0,00
Nuclear/CCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Total	-	6,51	10,92	0,63	0,03	12,02	-	-	8,86	-3,29	0,28	0,55	15,48	6,08	30,07	-	1,38	2,92	7,36	-	99,80	1,72	101,51	-1,87	-1,86

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Output specifications IDA (researchers' version).txt The EnergyPLAN model 15.0

District Heating Production

	Gr.1 District heating MW	Gr.1 Solar MW	Gr.1 CSHP MW	Gr.1 DHP MW	Gr.2 District heating MW	Gr.2 Solar MW	Gr.2 CSHP MW	Gr.2 CHP MW	Gr.2 HP MW	Gr.2 ELT MW	Gr.2 Boiler MW	Gr.2 EH MW	Gr.2 Stor-age MW	Gr.2 Ba-lance MW
January	0	0	59	0	2368	61	645	581	706	0	282	94	87	0
February	0	0	59	0	2416	128	649	728	645	0	246	19	492	0
March	0	0	59	0	2102	145	612	477	612	0	77	179	3139	0
April	0	0	59	0	1742	227	550	463	431	0	12	105	12909	-45
May	0	0	59	0	1430	239	473	433	295	0	0	23	24001	-32
June	0	0	59	0	808	218	424	134	120	0	0	0	25195	-89
July	0	0	59	0	808	253	406	182	70	0	0	0	25199	-104
August	0	0	59	0	808	224	414	144	119	0	0	0	25199	-94
September	0	0	59	0	1084	173	458	326	172	0	0	1	25197	-46
October	0	0	59	0	1471	108	509	328	473	0	0	60	24573	-6
November	0	0	59	0	1839	69	571	552	469	0	42	125	9643	10
December	0	0	59	0	2139	41	620	337	692	0	202	225	1922	22
Average	0	0	59	0	1582	157	527	389	400	0	71	70	14837	-32
Maximum	0	0	59	0	3924	1933	891	974	839	0	2191	495	25200	1627
Minimum	0	0	59	0	744	0	329	0	3	0	0	0	0	-1687
Total for the whole year TWh/year	0,00	0,00	0,52	0,00	13,90	1,38	4,63	3,42	3,51	0,00	0,63	0,61		-0,28

	Gr.3 District heating MW	Gr.3 Solar MW	Gr.3 CSHP MW	Gr.3 CHP MW	Gr.3 HP MW	Gr.3 ELT MW	Gr.3 Boiler MW	Gr.3 EH MW	Gr.3 Stor-age MW	Gr.3 Ba-lance MW	RES1 Wind MW	RES2 Offshc MW	RES3 Photo MW	RES 4-7 MW	Total aic MW
January	3766	0	1608	1335	655	19	31	126	69654	-9	1872	3801	139	52	5864
February	3842	0	1616	1732	474	19	0	38	73947	-38	1370	3138	300	87	4895
March	3342	0	1540	929	738	19	2	174	84705	-60	2203	3896	811	65	6975
April	2770	0	1416	730	577	19	0	28	94655	0	1897	3031	1071	37	6035
May	2274	0	1259	569	423	19	0	4	94741	0	1457	2739	1138	35	5369
June	1284	0	1160	67	45	19	0	0	94784	-6	1676	3122	1130	32	5960
July	1284	0	1124	102	41	19	0	0	94794	-1	1107	2034	1218	29	4388
August	1284	0	1140	66	64	19	0	0	94783	-5	1515	2921	1037	40	5513
September	1723	0	1229	298	180	19	0	0	94785	-2	1312	2778	773	52	4916
October	2339	0	1332	396	580	19	0	13	94719	0	2096	4334	385	71	6886
November	2925	0	1458	844	559	19	0	43	93447	1	1869	3935	201	72	6077
December	3401	0	1556	591	951	19	2	179	84541	103	2739	4694	93	57	7583
Average	2516	0	1369	634	441	19	3	51	89155	-1	1762	3371	692	52	5878
Maximum	6239	0	2104	3705	1405	19	1692	559	94800	2859	4756	6549	4342	132	14570
Minimum	1182	0	969	0	5	19	0	0	0	-2416	0	0	0	1	2
Total for the whole year TWh/year	22,10	0,00	12,03	5,57	3,88	0,16	0,03	0,45		-0,01	15,48	29,62	6,08	0,46	51,64

Own use of heat from industrial CH0,00 TWh/year

ANNUAL COSTS (Million EUR)

Total Fuel ex Ngas exchange = 1490
Uranium = 0
Coal = 0
FuelOil = 1
Gasoil/Diesel= 34
Petrol/JP = 0
Gas handling = 3
Biomass = 1452
Food income = 0
Waste = 0

Total Ngas Exchange costs = -219

Marginal operation costs = 34

Total Electricity exchange = 274
Import = 274
Export = -91
Bottleneck = 91
Fixed imp/ex= 0

Total CO2 emission costs = 0

Total variable costs = 1579
Fixed operation costs = 3946

Annual Investment costs = 14894

TOTAL ANNUAL COSTS = 20419

NATURAL GAS EXCHANGE

	DHP & Boilers MW	CHP2 CHP3 MW	PP CAES MW	Indi-vidual MW	Trans port MW	Indu. Var. MW	Demand Sum MW	Bio-gas MW	Syn-gas MW	CO2Hy gas MW	SynHy gas MW	SynHy gas MW	Stor-age MW	Sum MW	Im-port MW	Ex-port MW
January	19	226	32	0	0	0	277	1107	123	0	0	0	96	-1048	0	1048
February	12	286	39	0	0	0	338	1107	123	0	0	0	157	-1048	0	1048
March	4	176	28	0	0	0	208	1107	123	0	0	0	27	-1048	0	1048
April	1	160	37	0	0	0	198	1107	123	0	0	0	17	-1048	0	1048
May	0	143	38	0	0	0	182	1107	123	0	0	0	1	-1048	0	1048
June	0	38	46	0	0	0	84	1107	123	0	0	0	-97	-1048	0	1048
July	0	52	74	0	0	0	126	1107	123	0	0	0	-55	-1048	0	1048
August	0	40	55	0	0	0	95	1107	123	0	0	0	-86	-1048	0	1048
September	0	100	63	0	0	0	163	1107	123	0	0	0	-18	-1048	0	1048
October	0	106	25	0	0	0	131	1107	123	0	0	0	-49	-1048	0	1048
November	2	189	37	0	0	0	229	1107	123	0	0	0	48	-1048	0	1048
December	10	120	18	0	0	0	149	1107	123	0	0	0	-32	-1048	0	1048
Average	4	136	41	0	0	0	181	1107	123	0	0	0	0	-1048	0	1048
Maximum	302	465	147	0	0	0	543	1107	123	0	0	0	362	-1048	0	1048
Minimum	0	0	0	0	0	0	0	1107	123	0	0	0	-181	-1048	0	1048
Total for the whole year TWh/year	0,04	1,19	0,36	0,00	0,00	0,00	1,59	9,72	1,08	0,00	0,00	0,00	0,00	-9,21	0,00	9,21

RES Share: 109,3 Percent of Primary Energ113,5 Percent of Electricity 62,7 TWh electricity from RES 26-maj-2021 [16:51]

energyPRO - economic inputs D

Table D.1. Danish taxes and tariffs in 2021 used in the energyPRO models [PwC, 2020; Energinet, 2021a,c; N1, 2020].

	Value	**Unit**	**Payment Concerns**
Energy tax	2.486	DKK/Nm^3	Natural gas consumption (Engine)
Energy tax	52.3	DKK/GJ	Natural gas consumption (Boiler)
Energy tax	4.0	DKK/MWh	Electricity consumption
CO_2 tax	0.403	DKK/Nm^3	Natural gas consumption
NO_x tax	0.029	DKK/Nm^3	Natural gas consumption (Engine)
NO_x tax	0.008	DKK/Nm^3	Natural gas consumption (Boiler)
NO_x tax	0.5	DKK/GJ	Wood chip consumption
CH_4 tax	0.069	DKK/Nm^3	Natural gas consumption (Engine)
Payback energy tax	-2.486	DKK/Nm^3	Electricity production (Engine)
Payback CO_2 tax	-0.403	DKK/Nm^3	Electricity production (Engine)
Gas transport tariff	0.22	DKK/Nm^3	Natural gas consumption
Balance and feed in tariff	4.23	DKK/MWh	Electricity production
TSO tariff	112.29	DKK/MWh	Electricity consumption
DSO tariff	78.7	DKK/MWh	Electricity consumption

Table D.2. Assumed O&M costs of the investigated technologies at Oksbøl CHP plant [Danish Energy Agency, 2020g].

	Value	**Unit**	**Payment Concerns**
O&M (fixed)	400,000	DKK/year	Natural gas engines (5.5 MW_e)
O&M (variable)	40.5	DKK/MWh	Natural gas engines
O&M (fixed)	153,500	DKK/year	Natural gas boilers (10.5 MW_{th})
O&M (variable)	8.25	DKK/MWh	Natural gas boilers
O&M (fixed)	1,620	DKK/year	Heat storage (4,200 m^3)
O&M (fixed)	4,500	DKK/year	Solar collectors (14,745 m^2)
O&M (fixed)	8,025	DKK/MW_e/year	Electric boiler
O&M (variable)	6.75	DKK/MWh	Electric boiler
O&M (fixed)	51,000	DKK/MW_e/year	Heat pump
O&M (variable)	16.5	DKK/MWh	Heat pump
O&M (fixed)	278,250	DKK/MW/year	Wood chip boiler
O&M (variable)	23.25	DKK/MWh	Wood chip boiler

Table D.3. Assumed investment costs of the investigated technologies at Oksbøl CHP plant. All investments will be made in year 2021 except the refurbishment of natural gas engines [Danish Energy Agency, 2020g; Oksbøl Varmeværk, 2021].

	Value	**Unit**	**Payment Concerns**
Refurbishment	2,000,000	DKK	Natural gas engines (year 2030)
Reinvestment	4,700,000	DKK	Natural gas boilers (10.4 MW_{th})
Investment	728,600	DKK/MW_e	Electric boiler
Investment	5,925,000	DKK/MW	Wood chip boiler
Investment	24,200,000	DKK/MW_e	Heat pump