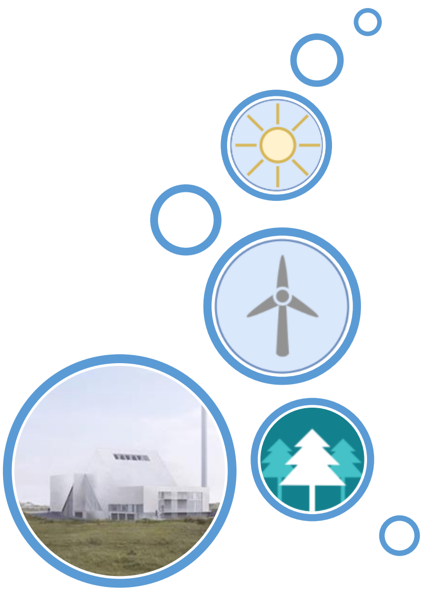
AALBORG UNIVERSITY
STUDENT REPORT

Local Wind to Heat Integration

A techno-economic analysis of wind to heat integration in the context of Aabybro District Heating

Master's Thesis
Sustainable Energy Planning and Management
Toke Kjær Christensen
June 2019



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STUDENT REPORT

Fourth Semester of the Master's Programme of *Sustainable Energy Planning and Management*

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Title
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- A techno-economic analysis of wind to heat integration in the context of Aabybro district heating

Project
4th Semester, Master Thesis

Project Period
February 2019 – June 2019

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Pages: 82 (94)

Hand in date: 07-06-2019

Abstract:

An ever-changing development within the Danish District Heating sector along with changing framework conditions incentivizes new innovative solutions in order to secure the future heat supply while reducing CO_2 emissions and use of limited resources. With a widely spread district heating network along with a large amount of on-shore wind turbines in Denmark, the potential of integrating wind for heating purposes is substantial.

This Master Thesis seeks to address the potential benefits of *wind to heat* integration in terms of reducing the overall system costs and biomass consumption. This is done in a local context of Aabybro, looking into eight scenarios of indirect- and directly grid-connection options, which includes the investment of local wind turbines in combination with electric boilers and heat pumps for heating purposes.

The annual energy production of the wind turbines included, are modelled using the simulation tool windPRO whereas the operation of each district heating scenario is modelled using energyPRO.

The main result of the analysis show that most scenarios are able to reduce both the operation costs and biomass consumption, but is however in many cases challenged by relatively large investment costs in a system which mainly comprises of biomass and solar thermal. It is furthermore found that *wind to heat* is on a local basis potentially related to certain barriers and uncertainties regarding the legislative framework, but also opportunities of increased local acceptance.

Preface

This Master's Thesis is written by a 4th semester student of the Masters Programme of Sustainable Energy Planning and Management (SEPM) at Aalborg University. First and foremost I would like to thank my supervisor Peter Sorknæs for a thorough and proper guidance throughout this final semester of the Masters Programme. A special thanks for all the valuable inputs and ideas and for always being flexible and quick to respond when needed. I would also like to express a sincere thanks to NIRAS and team ENRG for providing external guidance, knowledge and inputs. Furthermore, I would like to express my gratitude to Aabybro District Heating, Torben Stenbroen and Benny Klemar, for collaborating and providing the data needed. Finally, I would like to thank all of those who have contributed with information and data, either through face-to-face interviews, by phone or e-mail.

Reading guide

Throughout the report, Tables and Figures are numbered according to the Chapter in which they appear. For example will the second Figure in Chapter 1 be numbered 1.2 and the same applies for Tables. Furthermore, will all Tables and Figures be linked with a caption, briefly explaining the content of which is presented. When equations appear in the report, these will be followed by a nomenclature explaining the different variables included. Throughout the report several abbreviations will also appear. The first time an abbreviation appear in the text, it will be written in full followed by its abbreviation in a parenthesis (..). A list providing an overview of the applied abbreviations in this report, can be seen on the following page.

Throughout the report source references will be appearing in brackets [..] noted according to the Harvard method. The reference will be stating the authors last name, followed by the year it has been publicized. An example of this is [Author, Year]. If no specific author appears in the source, the company or organization of which it has been published, will appear instead. If no specific year appears in the source, n.d. (no date) will be stated instead. If more sources have the same author and are published the same year, the reference are separated alphabetically, e.g. [Hvelplund, 2015A]. The reference notes refers to the *Bibliography* in the end of this report, which presents a complete list of all references included. In here all the specific details such as full title, publisher, ISBN etc. can be seen. If a reference statement appear *in* the sentence only the year will be in brackets after the authors name. When a reference appear outside a dot of a sentence, the source refers to the whole section or back to the previous reference. Contrary, If a reference by the end of a sentence is within the dot, it refers to only this specific sentence. All references will appear in English if an English name appears in the source or can be directly translated, otherwise the Danish name will be noted.

Nomenclature

Abbreviations:

AEP	*Annual Energy Production*
COP	*Coefficient of Performance*
CHP	*Combined Heat and Power*
DDHA	*Danish District Heating Association*
DEA	*Danish Energy Agency*
DKK	*Danish Kroner*
DSO	*Distribution System Operator*
DH	*District Heating*
EB	*Electric Boiler*
HOB	*Heat Only Boilers*
HP	*Heat Pump*
Ngas	*Natural Gas*
NPV	*Net Present Value*
O&M	*Operation and Maintenance*
RE	*Renewable Energy*
RES	*Renewable Energy Sources*
STMC	*Short-term marginal cost*
SPB	*Simple Payback Time*
TSO	*Transmission System Operator*
WtH	*Wind to Heat*
WTG	*Wind Turbine Generator*

Resumé

Nærværende speciale beskæftiger sig med potentialet i at integrere vind til fjernvarmeformål på lokalt niveau. På baggrund af de nuværende institutionelle betingelser er der udarbejdet en tekno-økonomisk energisystems analyse for vind til varme i Aabybro.

Med skiftende politikker, markedsvilkår samt teknologisk udvikling, er det danske energisystem i konstant forandring. I fjernvarmen har der over senere år været en tendens mod reduceret samproduktion af el-og varme og en overvejende stigning i produktionen fra kun varmeproducerende kedler, hvilket kan siges at reducere den overordnede effektivitet i sektoren samt lægge pres på resurser, såsom biomasse, der betragtes begrænsede. Samtidig ses på el-siden, at en stigende mængde vind udfordrer samspillet mellem produktion og forbrug, hvilket resulterer i øgede overskudsproduktion og påvirkede markedspriser. Overskudsproduktion af vind har i flere år været argumenteret for en effektiv udnyttelse i den danske varmesektor, ved benyttelse af de allerede eksisterende og veletablerede fjernvarmenetværk og lagerkapacitet.

Samtidig stiller en stigende politisk interesse i at modernisere og effektivisere fjernvarmen krav til fjernvarmeselskabernes fremtidige forsyning. Hvor adskillige fjernvarmeværker retter interessen mod konventionelle løsninger, motiverer de nuværende institutionelle rammer samtidig andre fjernvarmeværker til at se mod nye innovative løsninger til sikring af den fremtidige fjernvarmeforsyning, samtidig med at brændselsforbrug og emissioner reduceres. Sådanne løsninger er f.eks. hvor der investeres i lokale vindmøller i direkte sammenkobling med varmepumper eller elkedler til produktion af fjernvarme, hvilket overvejende er en ny måde at tænke lokal kraftvarme på.

Med en stor mængde landbaserede vindmøller og et bredt funderet fjernvarmenet i Danmark, har potentialet for lokal udnyttelse af vindkapacitet til varmeformål, vist sig at være substantiel. Med udgangspunkt i Aabybro Fjernvarme undersøger nærværende speciale potentielle fordele ved lokal integration af *vind til varme*, i form af at reducere systemomkostningerne og biomasseforbruget. Ud fra de nuværende lovgivningsmæssige- og institutionelle strukturer adresseres tre forskellige opkoblingsmuligheder for *vind til varme* i Aabybro;

- Fuldt forbundet, hvor nuværende afgifter og tariffer gælder (konventionel tilslutning)
- Delvis tilsluttet, hvor en reduceret tarif og ingen afgifter gør sig gældende. Undersøges med og uden salg af overskydende el produktion.
- Ø-drift, hvor vindmølle og varmepumpe/elkedel er direkte forbundet uden tilslutning til offentligt net. Heri er afgifter og tariffer afskaffet

Scenarierne er undersøgt ud fra de lokale muligheder og ressourcer tilgængelige i Aabybro, og tager derfor udgangspunkt i én ny forventet vindmølle samt én eksisterende vindmølle, i kombination med elkedler og varmepumper med udnyttelse af forskellige varmekilder. Generelt fremgår det af analysen at den sæsonmæssige variation af vindproduktion overvejende stemmer overens med den sæsonmæssige variation i varmebehovet, hvilket danner grundlag for at reducere brændselsforbruget. Disse reduktioner kan direkte kan overføres til en økonomisk besparelse i

driften, og med udgangspunkt i økonomiske analyser baseret på beregninger fra modelleringsværktøjerne energyPRO og windPRO, demonstrerer nærværende speciale således et stort omkostningsmæssig besparelsespotentiale ved lokal *vind til varme* integration. Den relative høje investering i kombination med en forholdsvis lav marginal produktionspris for referencen, udfordrer dog business casen for en ny vindmølle, i et system der primært er baseret på biomasse sol. Dog ses der modsat et mindre økonomisk potentiale i at investere i den eksisterende vindmølle, der grundet kortere afstand til værket og alder har reducerede kapitalomkostninger. Den forholdsvise beskedne virksomhedsøkonomiske gevinst er dog relateret til væsentlige usikkerheder omkring investeringen og forventede levetid for møllen, set i forhold til et relativt beskedent bidrag til den samlede produktion i denne case. Hvis der dog ses på det samlede besparelsespotentiale lokal *vind til varme* potentielt set kan generere, er chancerne for, at det ved andre fjernvarmeselskaber hvis primære produktion ikke er baseret på afgiftsfritaget biomasse og sol, kan være et gavnligt supplement til den eksisterende forsyning eller et potentielt alternativ til en ny investering.

Gennem processen og foretagede interviews synes at være identificeret en række potentielle fordele og barrierer, der afhængig af opsætningen kan forventes at påvirke beslutningsgrundlaget og planlægningsprocessen. Eksempelvis vil egenproduktion og forbrug i en direkte kombination kunne betragtes 100% vedvarende og samlet set bidrage til at reducere CO_2 emissioner. Samtidig ses et potentiale i lokalt ejerskab af vindmøller for fjernvarmeselskaber, der kan være med til at fremme accept i lokalområdet.

Der synes dog samtidig at skulle være en række forudsætninger til stede under de nuværende vilkår og almindelig regulering for, at sådanne systemer kan blive en realitet. Disse angår så vidt som regulativ uklarhed, praktisk timing og tilladelser samt tekniske udfordringer. Disse potentielle barrierer kan medføre at sådanne systemer bliver hindret i praksis. Samtidig stilles der spørgsmålstegn ved hvor vidt, selve idégrundlaget om at udbygge individuelle systemer giver mening, eller om det blot medvirker til en øget suboptimering, der ikke bidrager til energisystemet som helhed og det reelle behov for systemintegration. Det kan dog samtidig indikere, at de nuværende lovgivningsmæssige og institutionelle strukturer stadig ikke understøtter *vind til varme* fuldt ud. Såfremt *vind til varme* skal erkendes for den værdi den potentielt set kan være med til at skabe, bør den som udgangspunkt ligestilles med biomasse, hvilket kræver en ny afgifts- og tarifmæssig struktur.

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1 Introduction

Globally, climate change and the associated environmental consequences are receiving ever more attention on the political agenda. However, in order to keep the temperature below 2°C compared to pre-industrial level, which was historically agreed upon by almost 200 countries at COP16 in Paris, action is needed. [UNFCCC, 2016] IPPC stated in their recent report [IPPC, 2018] that even being able to keep the temperature increase at a level of 1.5°C instead of 2°C will have major benefits for the global environment. Denmark is also committed to take part in reducing CO_2 emissions through both international as well as national agreements. [DEA, 2019] In 2006 the Danish prime minister stated for the first time in history, that Denmark was to be independent of fossil fuels by 2050. [Government, 2006] Over the years the specific details of this goal have varied, but the current government states the aim of Denmark achieving a low carbon society by 2050. [Government, 2016]

The Danish Energy System which play a major role in the national CO_2 emissions has changed considerably over the years. Due to the 1970'ties oil crisis, a paradigm shift towards *Renewable Energy Sources* (RES) occurred in Denmark to increase the national security of supply. It was now evident that saving energy was critical to reduce the dependency of the imported fossil fuels. [DEA, 2017] Due to natural gas findings in the Danish part of the North Sea and as a part of the Danish energy policy, Denmark expanded its share of *District Heating* (DH), mainly consisting of decentral natural gas based *Combined Heat and Power* (CHP) plants. [DEA, 2017] Today, the share of households connected to DH is around 64%, which makes Denmark one of the countries in Europe with the highest share of DH. [DEA, 2017] The development of *Renewable Energy* (RE) in the Danish energy system can according to Østergaard [2015] be divided into three phases;

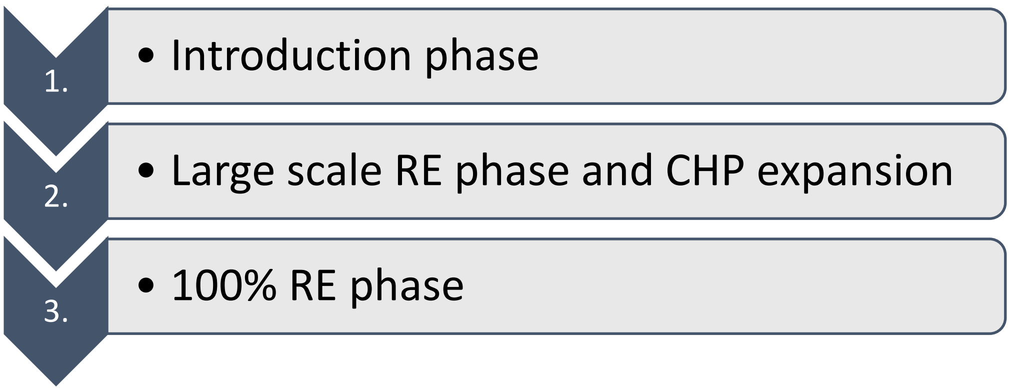

Figure 1.1 - Three phases in the development of the Danish energy system [Østergaard, 2015]

The policy of expanding with decentral CHP for DH along with introducing intermittent power production, especially on-shore wind turbines, can be characterised as the first phase [Østergaard, 2015]. This first phase was an introduction phase where the RE-technologies were to be developed, and the marked share was so small that no major infrastructural changes were necessary in order to integrate the more intermittent RE in the system. Between 2003 and 2010 a slow development in the expansion of RE in Denmark was present, and is therefore not characterised as a phase on its own. However, during the last decade, Denmark has intensively increased the share of RE and have thus entered the second phase in the development of the Danish energy system. [Østergaard, 2015] A phase where the energy system is no longer a fossil-based system supplemented by RE, but rather a RE system supplemented by fossil fuels. [Djørup, 2016] The second phase however requires significant changes in the electricity and heating infrastructure. According to Østergaard [2015] and Lund et al. [2015], decentral CHP plants and other flexible technologies, such as *heat pumps* (HP), are to be brought into play in order to regulate and balance production and consumption when needed (sector integration). The third phase that is yet to come, is characterised by moving towards a 100% renewable energy system, having RE and energy savings contributing to the major part of the energy consumption. This is however expected to result in infrastructural challenges regarding system adaption. [Østergaard, 2015]

1.1 District Heating in Denmark

The Danish DH system has, as described above, been a cornerstone in the Danish heat supply and have enabled a more energy efficient energy system exploiting excess heat from power production with CO_2 reductions as a result. [DEA, 2017] District heating in Denmark has however also developed significantly over the years. Today, the production of heat for DH in Denmark consist of different technologies but is mainly produced on CHP and *Heat Only Boilers* (HOB) fuelled by coal, natural gas and biomass. [DEA, 2017] The production of DH by type of producer, can be seen on Figure 1.2.

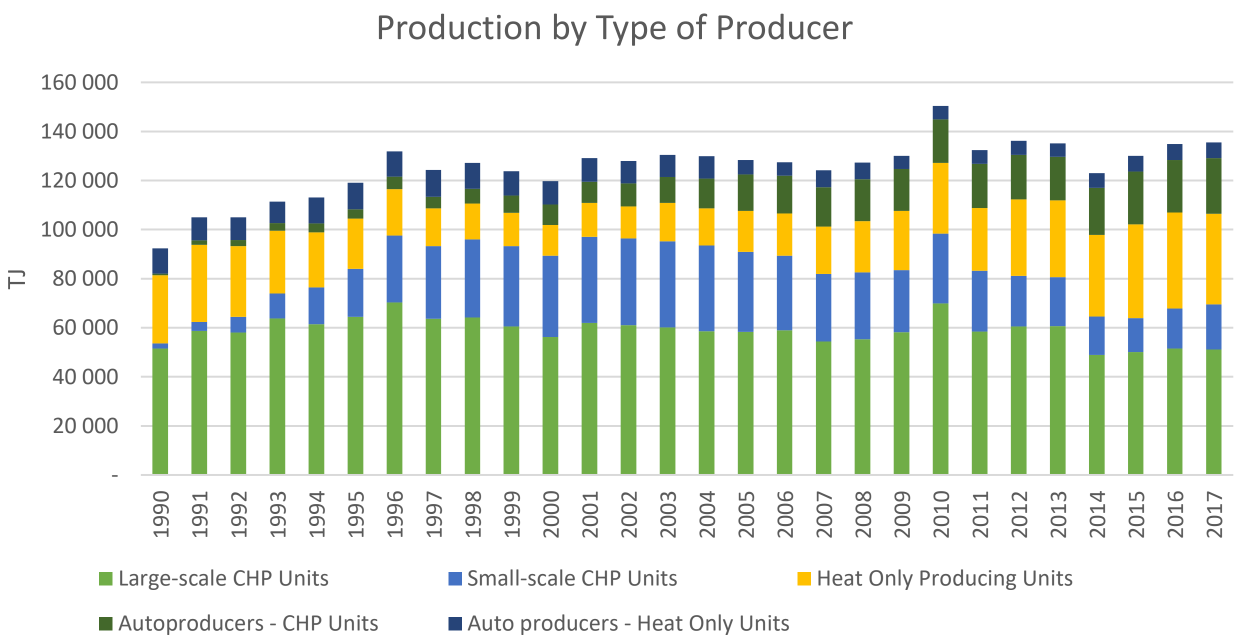

Figure 1.2 - Heat production by type of producer. Own made Figure based on data from [DEA, 2018]

As illustrated on Figure 1.2 DH production from small scale CHP and HOB has changed rather significant over the last decades. Due to the age and development in electricity prices, later described in this Chapter, the production from small scale CHP units has decreased from around 2004 and onwards, whereas DH production on HOB's has increased correspondingly. Heat produced on the so-called auto-producers has also increased from year 2000 and onwards. Unless the fuels are efficiently used, the potential result of moving towards heat-only production will be an overall efficiency loss of the DH sector. [Djørup, 2016] Hence, a tendency is seen where fuel efficiency does not create sufficient economic value for the DH companies. [Djørup, 2016]

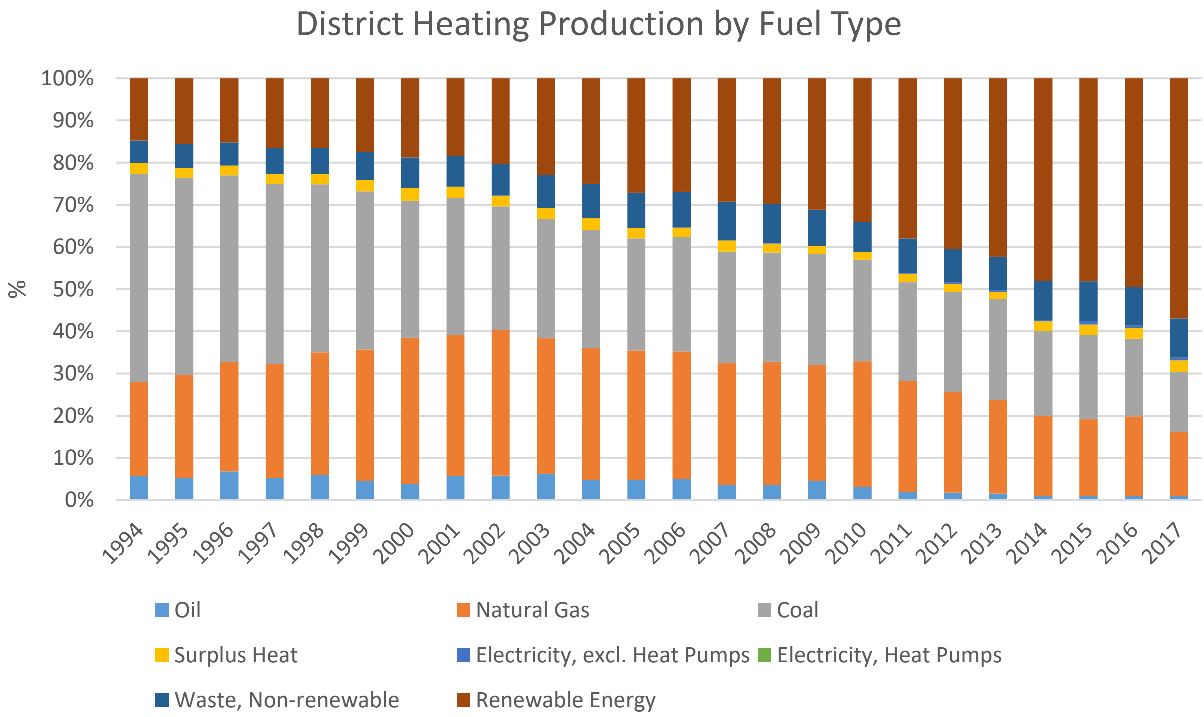

Figure 1.3 - Production of district heating by type of fuel. Own made Figure based on data from [DEA, 2018]

The use of fuels for production of DH in Denmark mainly comprises of both fossil fuels such as coal and natural gas but also non-fossil fuels such as biomass, waste and solar, whereas electricity only amounts for a small part of the total production. Biomass for energy has been a part of Denmark's energy profile which is one of the reasons why biomass for DH has been supported by subsidies, tax exemption etc. [DEA, 2017] The rapidly growing use of biomass in Denmark is mainly due to these benefits in the tax and subsidy system, but also due to the regulative framework of pubic heating. As biomass is and have been exempt from energy taxes, it is a fuel many DH companies prefer, which can also be seen on the development on Figure 1.3. [Grøn Energi, 2016] [Klimarådet, 2018] Despite being considered CO_2 neutral the sustainability and use of biomass as fuel for DH purposes has however been discussed for several years and can according to Mathiesen et. al [2012] and the Danish Climate Panel [2018] among others be considered a limited resource and should therefore mainly be prioritized in sectors where most needed or where no other option is available. Biomass is however still considered important in the transition towards- and in a future 100% RE system. [Lund et. al., 2015] [DEA, 2017]

As described in the beginning of this Chapter, Denmark has intensively expanded its share of wind turbines which has also contributed in changing conditions for DH in Denmark. Just in the last decade wind power has more than doubled its share of the total consumption, from below 20% in 2009 to 40,7% in 2018. [Danish Wind Industry Association, 2019] However, while there is a political interest in increasing wind power-based capacity, wind turbines are still in many cases subject to local resistance, which is why the main expansion of wind capacity in the future is expected off-shore. [Hvelplund & Djørup, 2017] [Government, 2018]

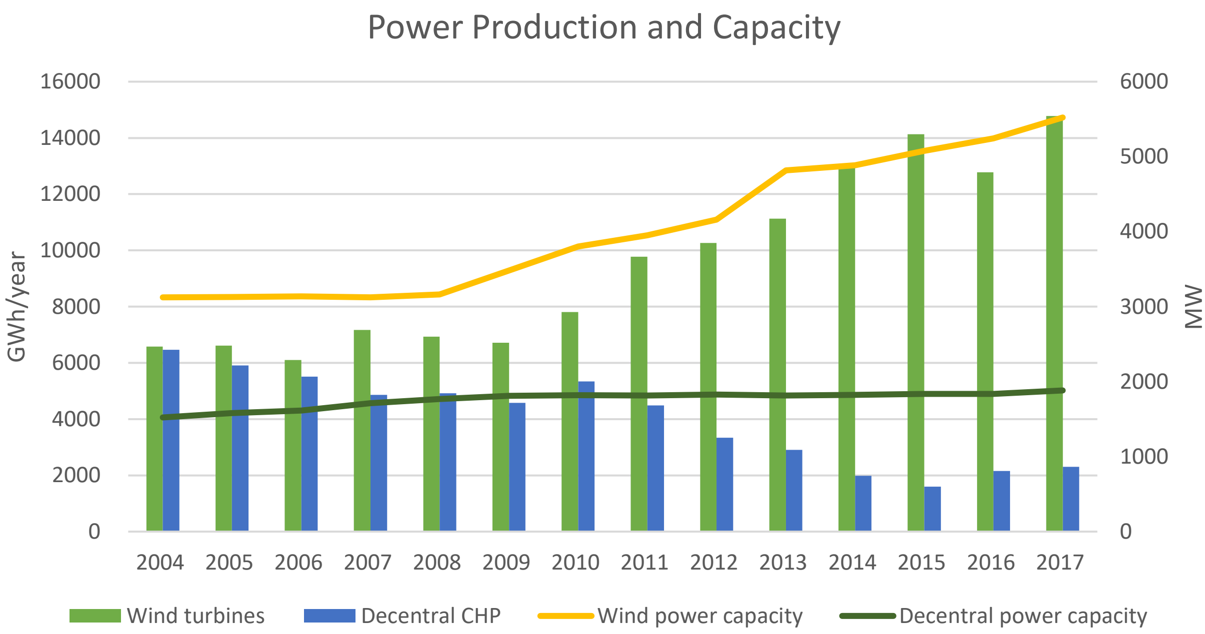

Figure 1.4 - Electricity production (left axis) and available capacity (right axis) of wind turbines and decentral CHP. Own made Figure based on [DEA, 2018]

Figure 1.4 illustrates the annual capacity and development of electricity produced on decentral CHP and wind turbines. Decentral CHP is here defined as units which are not under the definition of a central CHP and where co-production of electricity and heat is the main activity. [DEA, 2018] As it can be seen, the decentral CHP plants' electricity production has decreased almost proportionally with the increase in wind power, despite a more or less constant CHP capacity available. When the decentral CHP plants in Denmark moved towards producing electricity on market conditions instead of receiving a fixed price, the so-called *Capacity Payment* was introduced. [Danish Energy Regulatory, 2014] The capacity payment was given as a temporary production-independent subsidy for decentral CHP plants to compensate for lower electricity prices and thus ensure lower heat prices as well. [Dansk Energi, 2016] The expectation was that the electricity price was going to increase and the capacity payment was set to expire in the end of 2018. [Dansk Energi, 2016] [Danish Energy Regulatory, 2014] However as it can be seen on Figure 1.5 this has in general not been the case, and with this expiration many DH networks are facing higher heat prices. [Grøn Energi, 2015]

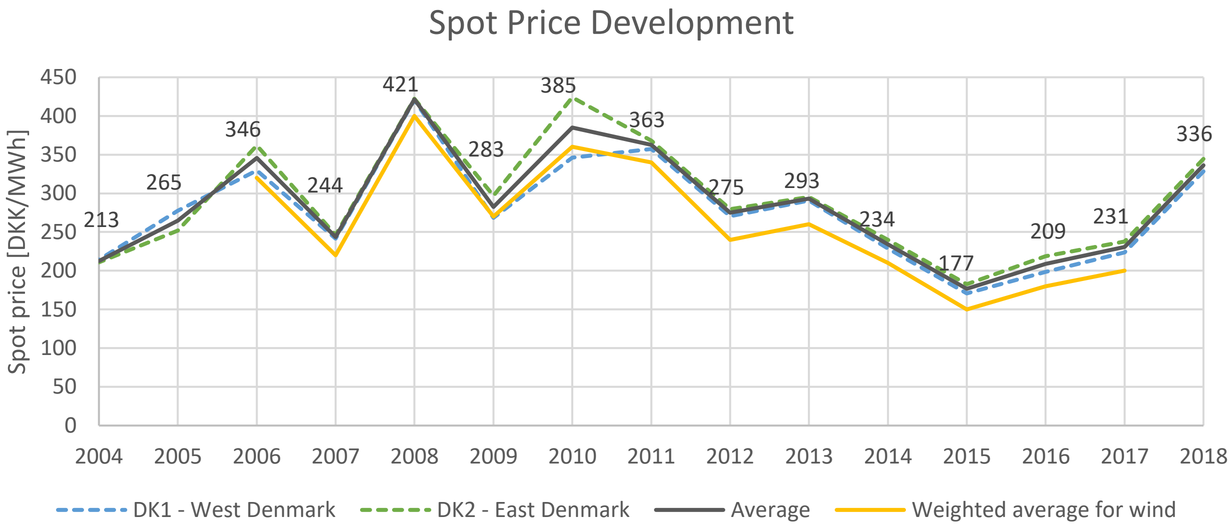

Figure 1.5 - Annual Spot prices from 2004-2018. Own Figure based on data from [Nord Pool, 2019] [DWIA, 2018]

On the North Pool Spot Market, where the prices for electricity are affected by the *short-term marginal costs* (STMC) of the electricity suppliers operating on the market, wind power will in many cases act as the price setter. This is due to the character of wind power which includes almost close to zero STMC despite the relatively high investment costs. This means that with more wind capacity in the system, the supply curve will be pushed to the right, which consequently will affect the price in windy periods. [EA Energianalyse, 2014] The principle of this dynamic is exemplified on Figure 1.6.

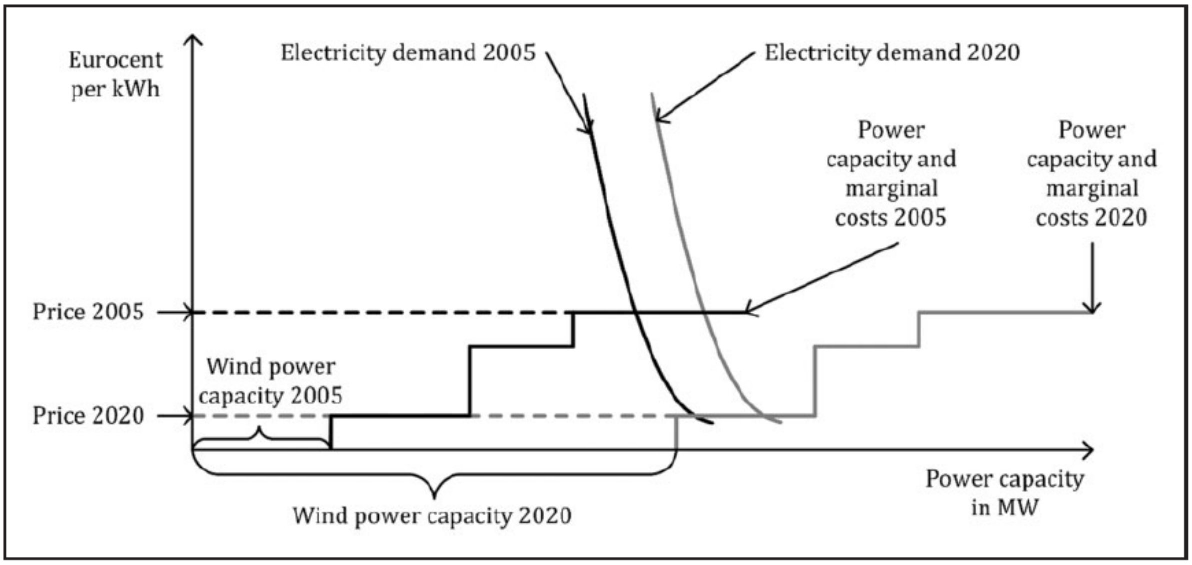

Figure 1.6 - Merit order effect [Hvelplund & Djørup, 2017]

As illustrated on Figure 1.6 the settlement price for wind is affected by the electricity demand and amount of wind power being present in the system (nationally as well as internationally) and hence also the availability of cross border interconnections as well as the energy systems ability to balance production and consumption. A lack of this ability to balance the consumption to the wind power production will consequently lead to lower and at times negative market prices. [EA Energianalyse, 2014] This dynamic and development in wind power capacity has according to [EA Energianalyse, 2014] and [Hvelplund & Djørup, 2017] in general lowered the market price for electricity produced on wind turbines over the last decade, which can be a challenge for both owners of the wind turbines as well as for the DH companies operating on the electricity market. The excess production occurs in times with high wind and low power demand. Just in 2015 wind power produced what was equal to 42,1% of the Danish electricity consumption and produced in that way more power than the total consumption in more than 1460 hours over the year. [Energinet, 2016] In hours with excess electricity production from wind turbines, electricity either have to be exported or the wind turbines to be shut down, unless the electricity can be stored. Not utilising the excess electricity and shutting down wind turbines is arguably a waste of energy. However, being able to store the energy from the more intermittent power production from *Renewable Energy Sources* (RES) has been a challenge for several years. Whereas batteries are often receiving the main attention and are seen as one of the major solutions to this issue, Lund et al. [2016] argues that storing electricity into heat by use of HP's, exploiting the already existing DH networks and thermal storages, is by far still one of the cheapest ways of storing energy as well as enabling flexibility between production and consumption. Djørup [2016] also argues that downregulating by shutting down wind turbines will result in an economic efficiency loss due to the STMC being close to zero which instead could be used in an integrated energy system to reduce fuel consumption. Hence, it is argued that DH play a major role in reaching a 100% RE system in Denmark and that DH is the major link for integrating the heat and electricity sector as well as meeting the future heat demand. [Lund et. al., 2015]

1.2 Alternative Ways of Securing the Future Heat Supply

With the described development within the DH sector along with the more recent *Energy Political Agreement* and political interest in the need for modernization of DH in Denmark, it is reasonable to believe that further change can be expected in the near future. [Danish Parliament, 2018] These changing framework conditions along with the development of the DH sector incentives many DH companies to look at alternative ways of securing the future heat supply. This can either be by reinvesting in new production technology or by interconnecting to other DH networks, which has been an increasing tendency. Between 2010-2016, 110 DH companies interconnected to neighbouring DH networks in order to reduce the system costs regarding production and distribution as well as to reduce costs for service and administration. [DDHA, 2017] The *Danish District Heating Association* (DDHA) draws a line between the increasing number of interconnections and savings of 18% in DH within the same period. [DDHA, 2017] While some DH networks are looking into the opportunity of interconnecting, others are looking into reinvesting in new production technologies. According to a survey conducted by Grøn Energi [2016] the main part of the participating DH companies expected to invest in biomass boilers and solar thermal. However, recent changes in framework conditions along a political interest in electrifying the heating sector resulted in a reduction of electricity to heat tax. [Danish Parliament, 2018] This has made several DH companies to investigate in HP's and *Electric Boilers* (EB) as potential investments. Despite the reduction in the electricity tax and PSO tariff, electricity for heating purposes is still heavily taxed when compared to other fuel types. This is illustrated on the following Table 1.1:

Biomass [DKK/MWh]	Natural gas [DKK/MWh]	Electricity [DKK/MWh]	Solar heating [DKK/MWh]
< 5	> 250	> 320	0

Table 1.1 – Taxes and tariffs by selected "fuel" types. The table illustrates the tax level in DKK per MWh fuel consumption. The tax level for biomass and natural gas is based on boiler production. The costs per MWh electricity is with the expected reduced tax of 2021 and excluding PSO tariff. Numbers are excluding fuel prices. Based on [PWC, 2019] [SKAT, 2019] [Energinet, 2019] [Dansk Energi, 2018] [Danish Parliament, 2018]

According to Djørup [2018] and Lund et. al. [2018], taxes and high tariffs for using the grid has been the two major barriers for implementing HP's in Denmark. Furthermore, Djørup [2018] argues that not only is local and regional wind to heat exchange taxed by the Danish Government, but short distance trading of electricity carries costs of long-distance trading through grid tariffs. While excess supply of wind creates the need of integration, which can either be by interconnecting or integrating internally in the Danish DH system, tariffs does not reward short term integration. [Djørup, 2018] Hence, it can be argued that the current tax and tariff structure still doesn't to same extend favour integration of electricity to heat compared to other fuels for heat, especially biomass.

Consequently, the profitability of using either HP's or EB's for heat, is dependent on the electricity price and taxation level as well as the efficiency, the latter only for HP's. [DEA, 2017] [Grøn Energi, 2017] The efficiency of the HP's is furthermore dependent on the available heat source and quality of such, later described in Chapter 4. Whereas some DH companies are looking into traditional technological reinvestments others are looking new innovative ways of producing heat while reducing the environmental impact in terms of fuel consumption and CO_2 emissions. Such systems are for instance where DH companies invest in local wind turbines used for own-production of electricity utilized directly in combination with HB's and EB's for DH purposes. Among these DH companies are for instance; Hvide Sande DH, Assens DH, Aabybro DH and Fjerritslev DH. However, due to unclear framework conditions and (limited experiences) as there are no fully operational DH systems in Denmark with this direct combination, it is an area that is not yet completely covered, which also leads to uncertainties regarding the business case. Yet WtH can be expected to be associated with potential benefits.

1.3 Potential Benefits of Power to Heat

The above sections highlight some of the challenges that are present both in terms of the general development and framework conditions within the DH sector, but also in terms of integrating more intermittent RE in the energy system. However, *Wind to Heat* (WtH) can be expected to be associated with some potential benefits, highlighted in the following.

As described in the above sections on-shore wind turbines are receiving major resistance due to not only the at times non-transparent process, but also implications that in many cases wind turbines only benefit the owners and not the local area to same extend. [Hvelplund & Djørup, 2017] Still wind turbines are considered important in the national policy to achieve a low carbon society and in order to reduce CO_2 emissions, which is also why increased capacity is expected. [Danish Parliament, 2018] However, by being able to produce electricity for local heating purposes may potentially lower the heat price, which will benefit a major part of the local area and thus, also potentially raise the local acceptance. Depending on the different options for grid connection, heat delivered from a HP or EB in combination with a wind turbine can be considered 100 % renewable. Not only is this in line with the aim of reducing the national CO_2 emissions from the energy sector, but it will also be able to reduce the fuel consumption for heat, whether this is coal, natural gas or biomass. Exactly this is also a goal in the energy political agreement of 2018 of having 90% of the DH consumption based on other fuel types than coal, oil and gas by 2030 and a total RE share of 55% in 2030 [Danish Parliament, 2018].

As described in the beginning of this Chapter, Denmark has intensively expanded its share of wind power. During this expansion, various schemes have subsidised power production from wind turbines. Depending on when the wind turbines were originally grid connected, these will at some point come to an end. When no longer receiving subsidies, wind turbines must compete on a market with others who may still receive a subsidy. Not only will WtH potentially increase the lifespan of the wind turbine but chances are, that that the real value of electricity produced will be reflected. As described earlier in this chapter, certain challenges occur when the production of electricity from wind turbines exceed the demand, which Lund et. al. [2015] argues potentially could be exploited within the Danish DH sector. This was also stated by the DDHA [2015] who argues that wind is far better utilised in the Danish DH sector as exporting the production at low prices is a lost opportunity of saving fuels. Hence, it is argued that WtH promotes sector integration in situations with high wind if utilised for DH purposes, exploiting the already existing heat storages and networks. Finally, it was argued that storing electricity into heat is yet one of the cheapest alternatives of storing electricity while keeping the electricity local instead of exporting state subsidised excess electricity.

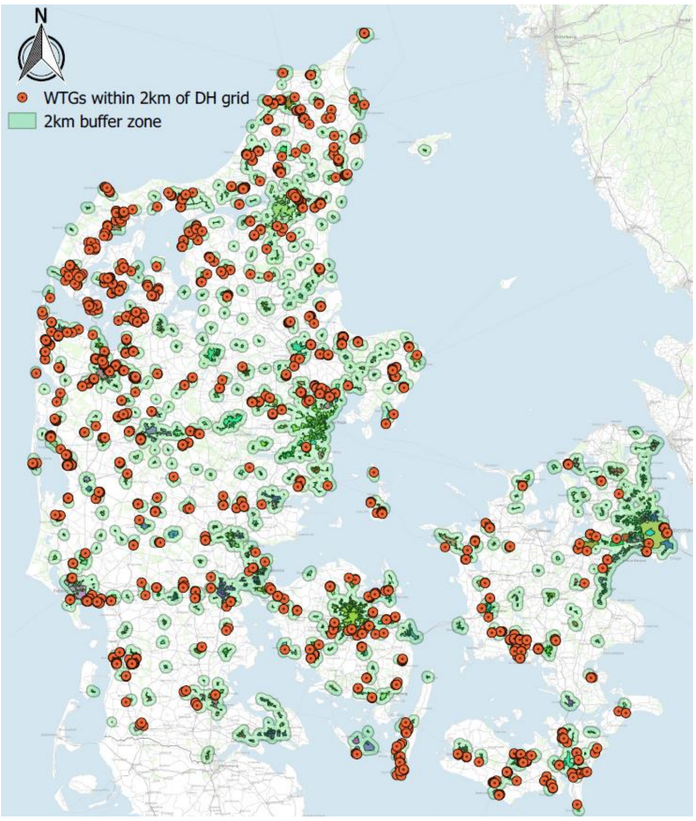

Figure 1.7 - Map of potential wind turbine capacity within 2 km of district heating networks. Own made map using QGIS, based on data from [DEA, 2019A], [DEA, 2019B] [Kortforsyningen, 2019] and [Planinfo, 2019]

With a large amount of on-shore wind turbines and a widely spread DH network in Denmark, the potential of integrating wind in local DH systems is considered substantial. Figure 1.7 illustrates an example of the potential available wind power capacity within 2 km of a DH network. Table 1.2 illustrates this potential capacity within a distance of 1, 2 and 3km of a DH network.

Distance	Potential Capacity
1 km	345 MW
2 km	1,157 MW
3 km	2,258 MW

Table 1.2 – Potential wind capacity within 1, 2 and 3 km of a DH network. Based on own made QGIS screening

In appendix 1 larger images of the screening for 1, 2 and 3km can be seen. As it can be seen on Table 1.2, the potential can be considered substantial. In combination with HP's this could efficiently be utilised for heating purposes in the DH sector. The above screening is however, only an example of the potential available capacity based on WTG's near areas designated for DH purposes, where as in reality the available capacity may be lower due to restrictions in the networks, ownership, etc. This *Thesis* will take point of departure in Aabybro, as a specific case looking into the potential of integrating WtH in a local DH network applying various grid connection options.

1.4 Case Description

Aabybro is located on the north-western part of Denmark in the municipality of Jammerbugt, illustrated on Figure 1.8.

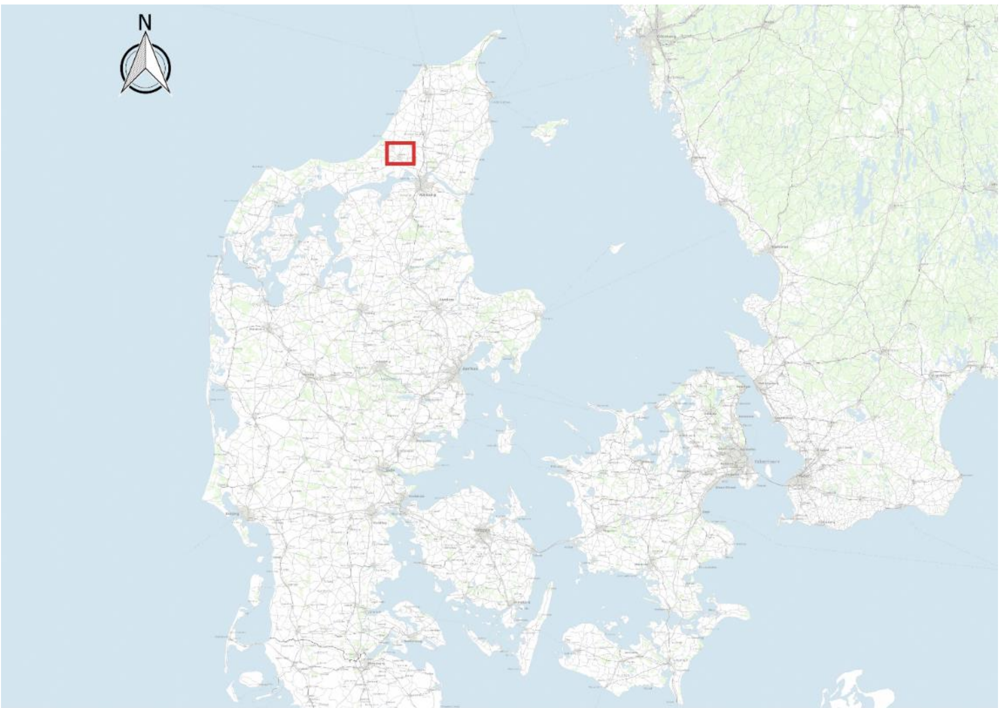

Figure 1.8 - Map of Denmark. Aabybro highlighted with red square. Own Figure made using QGIS, based on data from [Kortforsyningen, 2019]

Aabybro DH, which has been in operation since 1958, is a consumer owned company with around 2.200 consumers connected. [Aabybro, 2019] Aabybro DH has an annual degree-day corrected heat demand of around 60,000 MWh which currently mainly is produced on a wood chip boiler along with a solar collector field of around 26,000 m2. The solar collector field was installed in 2018 along with a 6000m3 heat storage and is expected to produce between 20-25% of the annual heat demand. For backup capacity Aabybro DH have two gas boilers. With biomass-based heating in the production mix, the marginal production costs are today kept at a minimum. [Aabybro DH, 2019] However, in order to reduce the risk of a potential price increase of biomass and keeping a stable heat price while pursuing a DH system based 100% on RE, the DH board of Aabybro are interested in investigating the opportunity of integrating wind power into the system. Figure 1.9 illustrates the current DH setup of Aabybro, and a potential future in a scenario where wind power is integrated. [Aabybro DH, 2019]

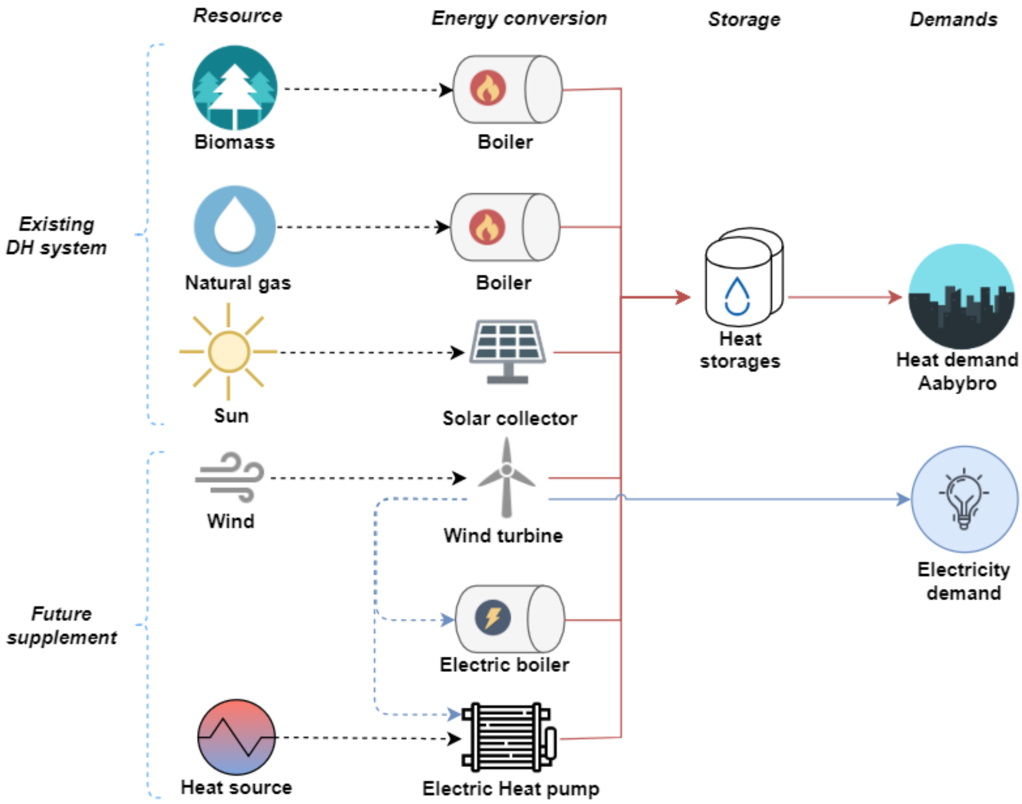

Figure 1.9 - Diagram of existing DH system and potential future supplement. Own Figure.

A more detailed description of the DH system of Aabybro can be seen in Chapter 6.

1.5 Choice of Case

Besides the fact that Aabybro DH are interested in looking into the opportunity of integrating wind to the system, similarities between Aabybro DH and other DH networks makes Aabybro a relevant case. Around 71% of the DH networks, including Aabybro DH, are located in "other urbanization" defined as DH networks which are not located in the 20 largest cities in Denmark or are green field plants. [Danish Energy Regulatory, 2017] Despite the fact that most smaller decentral DH companies are fuelled by natural gas, the majority of the DH networks are, as Aabybro, today fuelled by biofuels

(56%) which also stands for about 55% of the total DH supply. [Danish Energy Regulatory, 2017] Due to former restrictions for decentral natural gas-based DH companies regarding choice of fuel, most DH companies have only been allowed to install solar thermal based capacity, which is also in the production mix of Aabybro. [Retsinformation, 2016] This is relevant to consider as it's another intermittent RE source, which may be important when integrating WtH. Furthermore, Aabybro DH is a consumer owned company, which is also what the major part of the Danish DH companies are (83%) [Danish Energy Regulatory, 2017]. Aabybro is located in the western part of Denmark where both the major amount of decentral DH companies as well as wind power capacity is located, illustrated on Figure 1.10.

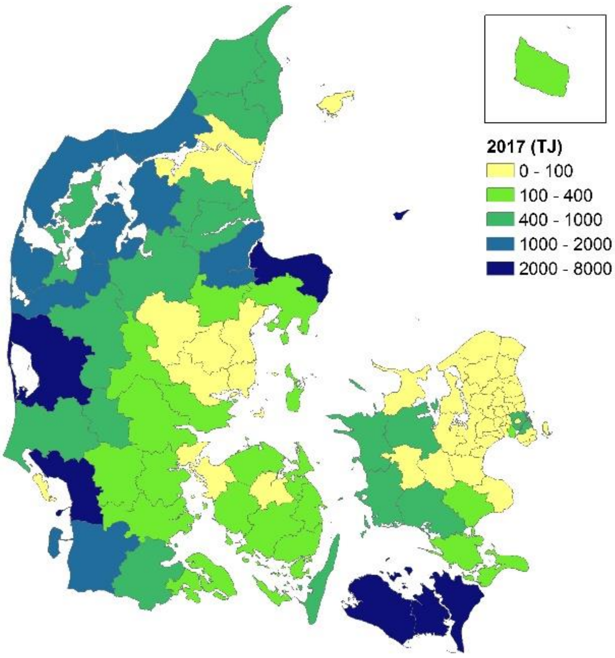

Figure 1.10 - Wind power in 2017, distributed on municipalities [DEA, 2018]

Despite the fact that Aabybro DH is not a decentral natural gas based CHP plant, who are challenged by the expiration of the capacity payment, as previously mentioned, it can however be argued that if such a solution can compete with biomass, chances are that this would also be the case for many of the decentral DH companies who have been restricted to use natural gas.

Another factor that makes Aabybro an interesting case is, that the consequences of integrating both new as well as existing wind turbines can be investigated (later described in Chapter 4). This is considered relevant as it can be expected that some older turbines will be replaced by new larger ones [Danish Parliament, 2018], where as other will continue to be in operation for years to come. Furthermore, it can be expected that there will be a difference in the business case between new and existing wind turbines as well as regarding available heat sources for HP production. Consequently, the similarities between Aabybro DH and most other DH networks can be considered of reasonable character, which is why Aabybro is considered a representative case for this type of analysis.

2 Research Question

As highlighted in the introduction the Danish District Heating system is considered important in the existing as well as future energy system. However, with changing policies and an on-going development, the Danish energy system is facing a paradigm shift. Furthermore, a tendency of moving away from co-generation and towards heat only production is seen, which arguably reduces the overall efficiency of the DH sector. In the meantime, Denmark has rapidly expanded its share of on-shore wind turbines which consequently affects the market prices, while the intermittent production challenges a flexible consumption, with the result of excess electricity at times not being utilized. Furthermore, certain challenges are related to the increasing use of biomass which questions the sustainability and use of the resource for heat-only purposes. Where some DH companies are looking into reinvesting in conventional production technologies, few DH companies are looking into new innovative solutions to secure the future heat supply, while reducing the fuel consumptions and CO_2 emissions. Such systems may involve various options for integrating wind, either by a conventional grid connection or by investing in local wind turbines in direct combination with heat pumps and electric boilers. Through a preliminary screening a substantial wind capacity is found to be located within a close distance to a district heating network. With a widely spread DH network and a large amount of on-shore wind capacity, Denmark has a unique opportunity to utilize the already existing district heating networks and heat storages for added flexibility while rethinking co-generation. This *Thesis* seeks to address some of the potential benefits of integrating wind to heat for district heating purposes in Denmark. This is done in the context of Aabybro District Heating, looking into various options for local wind integration. Consequently, the research question of this *Thesis* is as followed;

How can local wind to heat integration benefit the District Heating system of Aabybro in terms of reducing the overall system costs and biomass consumption, and what are the potential barriers and opportunities for such systems?

Subquestions

1. *What are the opportunities for integrating wind to heat in the district heating system of Aabybro, under the current framework conditions?*
2. *What is the business economic potential?*
3. *What are the potential barriers and opportunities for wind to heat integration?*

2.1 Delimitation and Clarification

This *Thesis* is delimited from looking at the more technical solutions that may be needed for such systems to work and is rather to be seen as a specific techno-economic energy system analysis, for wind to heat in the case of Aabybro. This research is also delimited from looking into potential environmental issues and permissions which may be needed.

3 Methodology

The purpose of this chapter is to present and elaborate on the methods that are used to answer the Research Question of this Thesis. The Chapter starts with an overview of the general structure of the Thesis, followed by a description of the qualitative and quantitative methods applied.

3.1 Research Design

The structure of the *Thesis* is illustrated on Figure 3.1. In the middle of the figure the main structure is shown by the order of the main chapters throughout the report. On the Figure it can also be seen where the different sub questions are answered (left) as well as where the methods are applied (right).

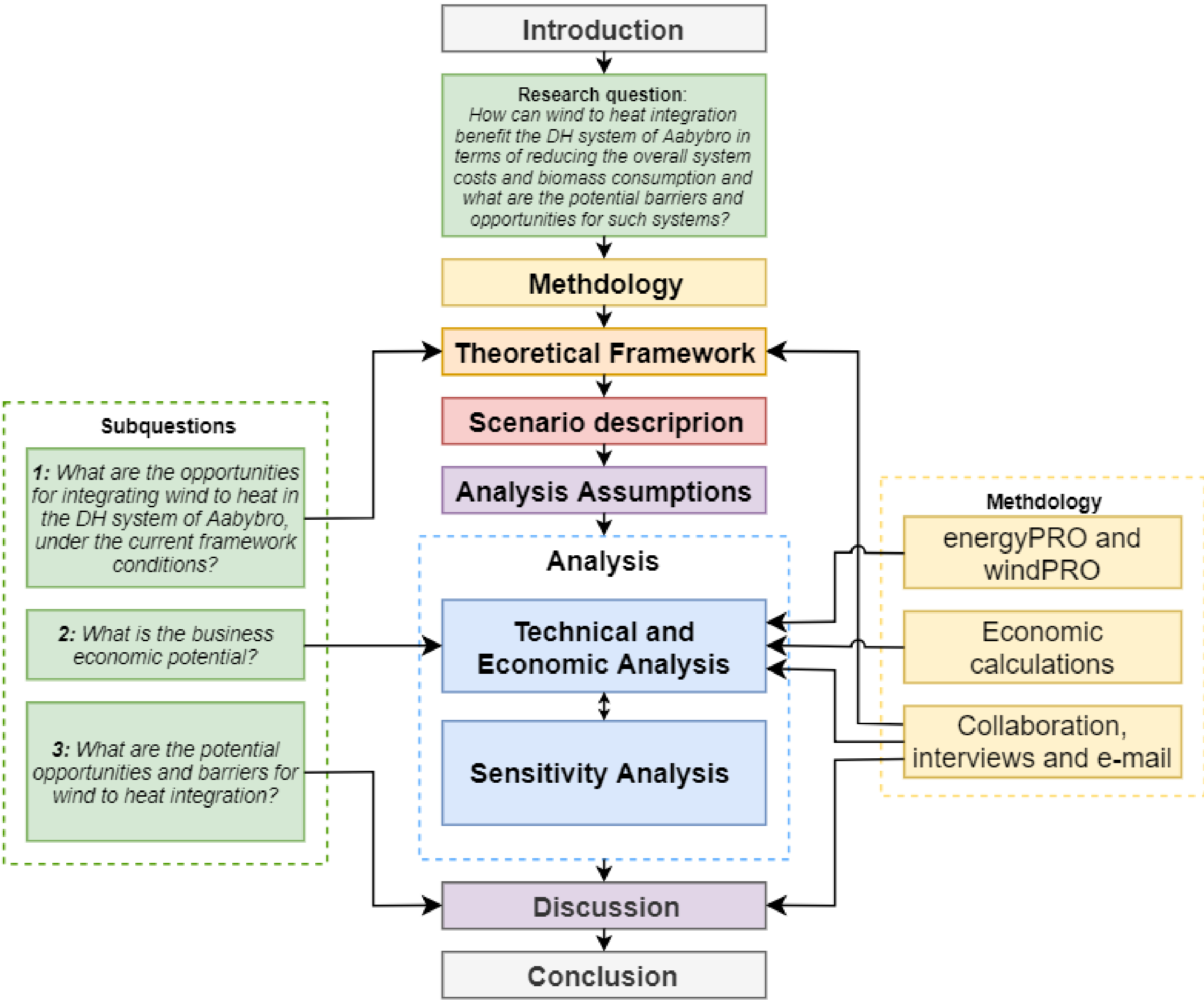

Figure 3.1 - Research design of Thesis. Own Figure

Whereas the dotted lines indicate an elaboration of some of the different chapters the colour code refers to which specific section of the report that is elaborated. The purpose of this is to enablable the reader to get an overview of where the different methods and tools are applied and where the different sub questions are answered. The different sub questions are for instance within a dotted line due to be an elaboration of the main research question (green box), which will be answered in different sections throughout the report. The Theoretical Framework (described in Chapter 4) is used for mapping and defining potential factors that influence both wind to heat integration in Aabybro as well as how technological changes occur.

3.2 Research Approach

The main research approach in this *Thesis* is a mixed research approach, characterised by combining both qualitative and quantitative methods in its study. [AU, 2017] Johnson et. al. [2007] defines mixed methods research as being a type of research in which the researcher combines elements from quantitative and qualitative research approaches (e.g. viewpoints, data collection etc.) for the purpose of breadth and depth of understanding the research. The use of qualitative and quantitative methods applied in the *Thesis* are illustrated on the following Figure 3.2 and elaborated in the following sections (starting from left).

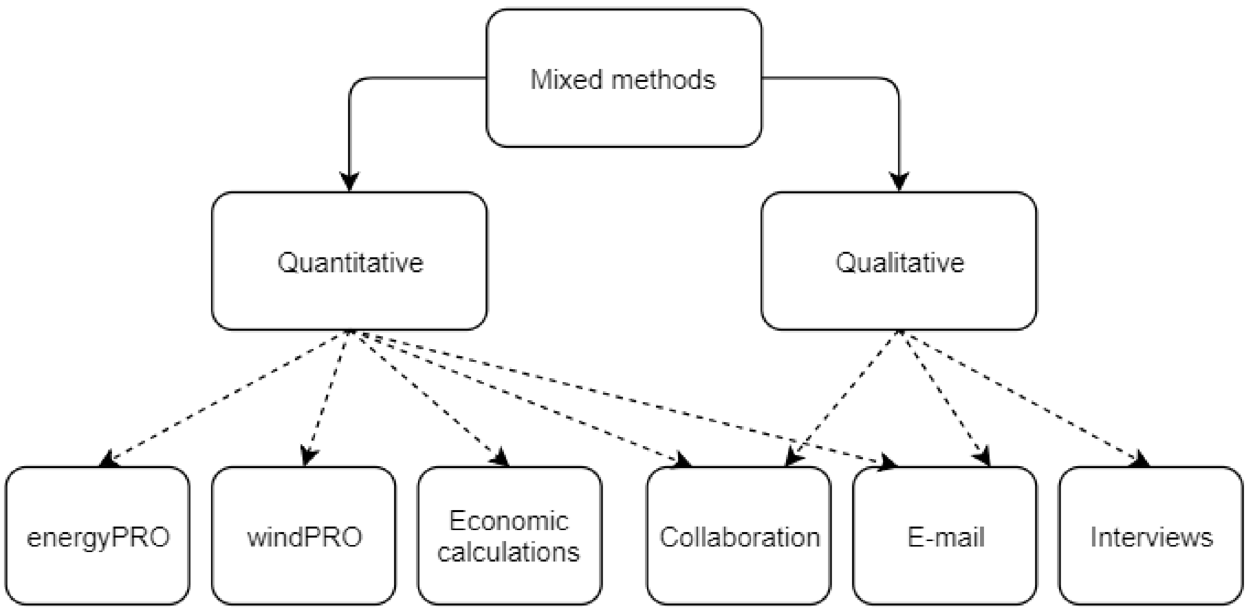

Figure 3.2 - Mixed method approach. Own Figure

As seen on Figure 3.2, the mixed method approach allows for simultaneous appliance of quantitative and qualitative methods in order to answer the *Research Question*, enabling the methods to complement and validate each other. [Johnson et. al., 2007] Consequently, limitations the methods may have when applied alone are minimised, and together they contribute to a better understanding and thorough research. However, a disadvantage of using the mixed method approach is that it can be resource demanding. [Bryman & Bell, 2007] The main quantitative method used in this *Thesis* is modelling and simulation of different DH scenarios of integrating WtH in Aabybro. The main qualitative methods applied are interviews. Despite the use of a mixed method approach, this *Thesis* applies a research approach which is considered quantitatively dominant. Yet, qualitative methods are used to broaden the understanding of the research question and context.

3.3 Energy System Analysis

3.3.1 energyPRO.

The purpose of the energy system analysis is to detect, evaluate and quantify the potential consequences of integrating WtH in the case of Aabybro technically as well as economically. For this purpose, the modelling tool energyPRO is chosen. energyPRO is a modelling software, used for techno-economic energy system analysis which can be used for the modelling of various energy demands, production technologies and storages. [EMD International A/S, 2019A] As energyPRO can calculate the annual operation expenses and optimal operation strategy for a DH system, energyPRO is considered a relevant tool for the purpose of this *Thesis*. energyPRO enables calculations for various time steps, but in this *Thesis,* calculations are made for one year with hourly intervals. One-hour intervals are chosen as the production in such an analysis in considered relevant, due to the intermittent character of wind power production, which in every hour should be balanced with the heat demand and other production units in the system. Shorter time steps could also have been chosen but is kept on an hourly basis due to having most input data, such as electricity prices etc. in this time step.

Thus, in this *Thesis* energyPRO is used for modelling and simulation of Aabybro DH, investigating the potential effects introducing wind power production and electricity consuming heat units will have on the system, in terms of fuel consumption and operation costs. An example of the reference setup in energyPRO can be seen on Figure 3.3.

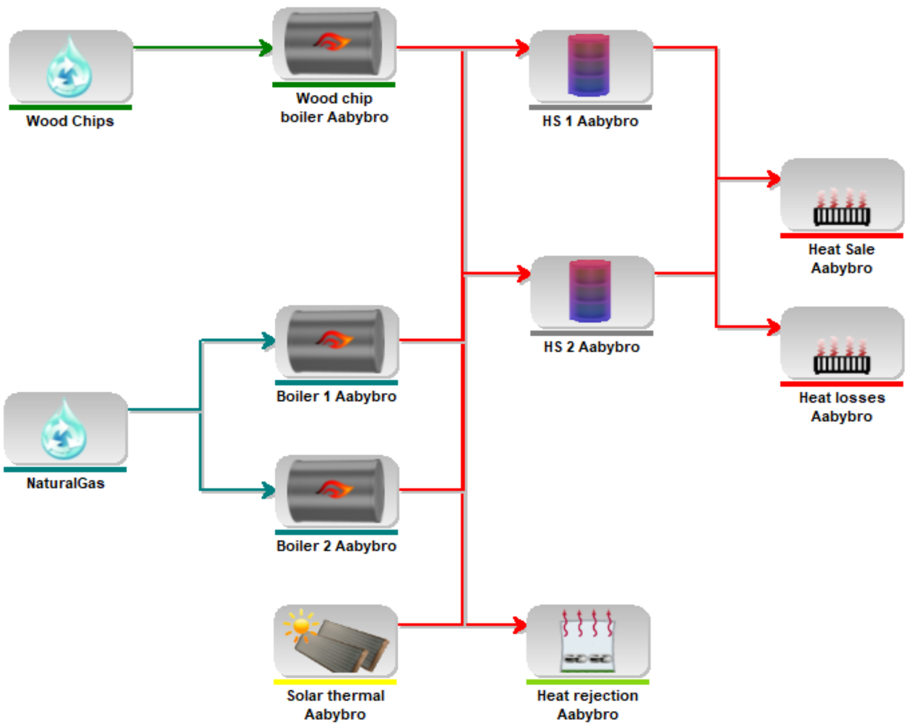

Figure 3.3 - Example of production setup in energyPRO, showing the reference system of Aabybrp DH [EMD International A/S, 2019A]

The annual operation expenses calculated in energyPRO are combined with the investment costs in each scenario (described in section 3.4) in order to determine the business economic feasibility. In order to calculate an hourly heat production and thus also the expenses, energyPRO requires a set of input, which among others can include:

- Time series containing whether data for ambient temperatures, wind, radiation etc.
- Fuel prices and O&M costs
- Relevant taxes, tariffs and subsidies
- Production unit specifications

A description of the applied input for energyPRO can be seen in Chapter 6. energyPRO has various predefined production units, however it is also possible to manually define units and formulas for production curves. This has been applied for the HP's included in this *Thesis*, later described in Chapter 6. In energyPRO it is possible to choose between two main operation strategies; "Minimizing Net Production Costs (NPC)" and "User Defined Operation Strategy". In the NPC strategy all economic values, (operation costs and revenues) are calculated based on the above-mentioned input data for each of the production units in the system. [EMD International A/S, 2019A] The operation strategy is then calculated for each hour where the production unit with the lowest operation cost per MWh-heat is given first priority, having as much of the production placed at the cheapest units in the system. If this unit isn't able to fulfil the heat demand in the specific hour, the production unit with the second lowest operation costs is allowed to produce heat etc. In this way the annual production is simulated in a way that the heat demand is fulfilled in each hour, utilising the cheapest production units available. [EMD International A/S, 2019A] Doing so, accurate data for expenditures, revenues and unit specifications are important. In the user defined operation strategy energyPRO calculates the hourly production based on a manual prioritisation of the units. [EMD International A/S, 2019A] As one of the purpose of this thesis is to minimise the production costs, the NPC operation strategy is chosen unless other stated.

Another relevant feature is the opportunity of adding heat storages, which can be expected important when implementing intermittent production, for increased flexibility. Due to the more detailed and case specific character of the *Thesis* in combination with the available features the tool offers, energyPRO is considered relevant for this analysis and for answering the *Research Question*.

3.3.2 windPRO.

To calculate the annual and hourly power production of the wind turbines in the area of Aabybro, windPRO is chosen. windPRO is, like energyPRO, a modelling software developed by EMD International used for project design and planning of both single wind turbines as well as large scale wind farms. [EMD International, 2019B] Figure 3.4 illustrates an example a wind rose in windPRO with the applied wind data.

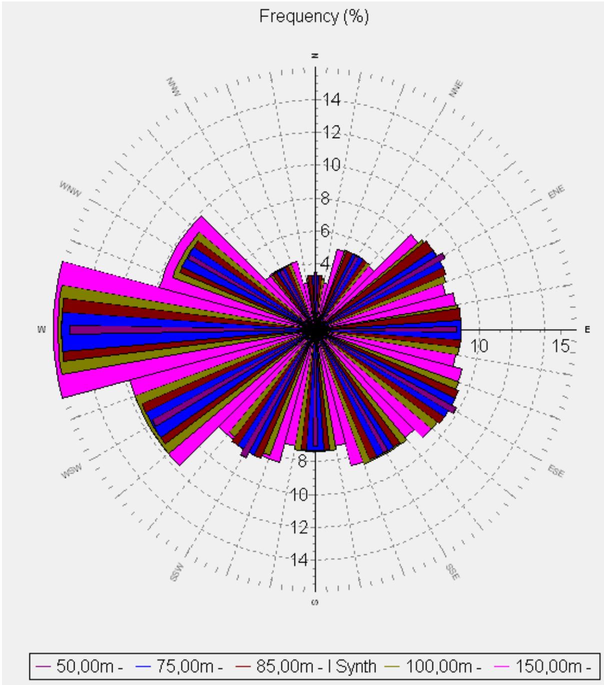

Figure 3.4 - Example of wind rose in windPRO with the applied wind data, illustrating the frequency of the wind direction. A primary wind from west can be seen [EMD International, 2019B]

windPRO is used to calculate the hourly production from relevant wind turbines in the local area of Aabybro. A PARK calculation in windPRO calculates the *Annual Energy Production* (AEP) based on specific wind data for each wind turbine included in the park calculation. Wind turbine specifications used in PARK calculations (hub height, rotor diameter, power curves) are available in windPRO through a regularly updated register for almost all types of wind turbines. Furthermore, in the AEP a PARK calculation calculates the wake effect from other turbines resulting in wake losses. For wake calculations windPRO offer different choices of wake models. For on-shore calculations N.O. Jensen is usually used. [EMD International A/S, 2018] For PARK calculations in this *Thesis* N.O. Jensen is chosen as the default wake model. As for energyPRO, windPRO also allows for hourly calculations for power production. windPRO offers various options for PARK calculations with hourly values. One way is to make a PARK calculation using WAsP with time varying, which is commonly used for PARK calculations. WAsP is a calculation software from Risø DTU, that does the model calculations used for a PARK calculation based on roughness, orography, obstacles and wind statistics. Alternatively, if WAsP isn't available a PARK calculation with time varying can for instance also be made using a calculated resource file for the wind turbine area. A resource file is also calculated in windPRO based on wind data measurement, wake loss, power curves, scaling etc. [EMD International A/S, 2018]

windPRO is used as a modelling tool for the wind turbines included in the *Thesis*, as the software is considered more accurate when compared to using the build in wind park feature of energyPRO, both in terms of having more wind data available but also in terms of including wake losses, specific power curves, accurate positioning etc. in the calculations. Furthermore, for this specific case where the actual heat production is dependent on the output from the wind turbine in each hour, representative hourly values is considered important.

The hourly values/distribution and production file is then used as a time series in energyPRO, as described in the previous section. The validation of the time series and production can be seen in Chapter 6, section 6.5.

3.4 Economic Calculations

To evaluate and compare the different scenarios included in this *Thesis*, various economic calculations are applied. The purpose of applying the following economic calculations is to help answer the *Research Question* and second sub question, investigating the feasibility and business economic potential of integrating wind into the DH system of Aabybro. In the following sections, the different economic calculations applied in this *Thesis* is presented.

3.4.1 Simple Payback Time

The Simple Payback Time (SPB) calculation is, what the name also imply, a simple calculation for scenario comparison. In this *Thesis* it is used as a method for evaluating risk of each scenario as a part of the feasibility study. The SPB illustrates the amount of years it takes before the accumulated in-payments correspond to the total investment costs. Thus, the investment will show profitable when the SPB is shorter than the lifespan of the specific investment. [Serup et. al. 2010] The following expression is used:

$$\mathrm{SPB} = \frac{Investment}{Annual\ Net\ Payments}$$

Another reason for including the SPB is that, it's a simple way of illustrating the DH board of Aabybro the amount of years it takes for the different investments to be paid back. This is important in Aabybro as a short SPB minimises the risk of the investment which allows for at fast return of the investment. One of the limitations of the calculation method is that, neither does it include return payments after the payback period nor does it take the value of time into account. However, in combination with the other economic calculation methods applied in this *Thesis*, the limitations of the SPB method are considered minimised. [Serup et. al. 2010]

3.4.2 Heat price

A heat price calculation is used as a tool to compare the different scenarios included in this *Thesis*, by the price per MWh-heat produced. The calculated heat price of each of the scenarios are compared to the heat price of the reference system (today). As one of the main goals for Aabybro DH is to secure a stable and competitive heat price in the future whilst reducing the biomass consumption, described in section 1.4, a heat price comparison is considered relevant. Furthermore, it is a simple way of comparing different scenarios, finding the most feasible solution in a business economic perspective while allocating the different costs.

As the relation between the different production units in the system is considered important, the heat price is calculated based on the total costs for operating the system and not only for a single production technology. As mentioned in section 3.3.1, the annual expenses are calculated using energyPRO and Excel. As it is expected that the investment will require a loan, an annual payment of the specific loan for each scenario is included in the heat price. The following expression is used for calculating the heat price.

$$Heat\ Price = \frac{\text{Annual Operation Expences} + \text{Annual Payment of Loan}}{\text{Annual Heat Demand}}$$

As it is expected that the loan will be paid back in *X* equally large amounts on an annual basis, the annuity loan equation is applied. To calculate the annual payment of the loan, the following expression is used [Serup et. al. 2010]:

$$\text{Annual Payment of Loan} = Size\ of\ loan * \frac{\frac{i}{100}}{1 - \left(1 + \frac{i}{100}\right)^{-n}}$$

Where,

Size of loan	The total investment cost of each scenario [DKK]
n	The expected timespan of the loan [years]
i	Interest rate of the loan [%]

Generally, the lower the heat price is, the more favourable the scenario is. Consequently, if the heat price of a specific scenario is lower than the heat price of the reference system, the investment is considered is considered feasible and vice versa.

3.4.3 Net present value

For improving the foundation of more qualified decisions for future investments in Aabybro, the Net Present Value (NPV) calculation method is used. The NPV calculation is in this *Thesis* used to compare the different scenarios for wind integration in Aabybro, taking the value of time into account. A NPV calculation sums up the discounted value of all net-payments related to an investment, negative as well as positive, over a calculation period. [Serup et. al. 2010] Thus, in this *Thesis* the NPV sums up all the net payments related to operating the DH system of Aabybro, in each scenario. The payments (annual expenses) are, as described in section 3.3.1, calculated in energyPRO. If the NPV is positive, the investment is considered profitable [Serup et. al. 2010]. However, the larger the NPV, the more feasible the investment can be considered. Hence, if the NPV doesn't prove to be positive, the investment is considered unprofitable. [Serup et. al. 2010] For the NPV, the following expression is used:

$$Net\ Present\ Value = \sum_{t=0}^{n} NP_t * (1 + r)^{-t}$$

Where,

NP_t	Net payment at time t [DKK]
r	Discount rate [%]

[Serup et. al. 2010]

3.4.4 Fuel consumption

Next to the economical evaluation the scenarios included in this *Thesis* are evaluated in terms of biomass consumption. An evaluation of the biomass consumption is included due to the factors mentioned in Chapter 1, regarding the limitations of biomass as a resource, as well as the importance of saving energy within the energy sector. The accumulated biomass consumption is based on calculations made in energyPRO.

$$Annual\ Biomass\ Consumption = \sum_{t=1}^{n} Bio_{con.}$$

3.5 Qualitative Methods

To broaden the understanding of the *Research,* qualitative methods are also applied, in terms of interviews, collaboration and correspondence. These are elaborated in the following

3.5.1 Collaboration and data collection

Collaboration with Aabybro DH is conducted using both qualitative and quantitative methods. Qualitative methods are applied in the form of preliminary and mid-way semi-structured face-to-face interviews to obtain local knowledge and to clarify challenges as well as important criterions to include in the planning process of integrating WtH in Aabybro, later described in Chapter 5. Quantitatively, the collaboration is used to gather data regarding the existing DH system of Aabybro in terms of heat demand, production unit specifications etc. Furthermore, collaboration gives the opportunity to validate the data used with the actual data measurements for a more accurate model simulation. A potential consequence of collaborating with a specific DH company is that the choice of scenarios, assumptions etc. can be subjectively influenced by the DH company rather than objectively considered, which may affect the outcome and conclusions of the research.

3.5.2 Interviews

Interviews are chosen as a qualitative method with the purpose of gaining an in-depth insight in some of the potential barriers and opportunities for wind-to-heat integration in DH systems, as there yet still is limited knowledge and experiences within this area. The interviews are conducted as face-to-face interviews and by phone using interview guides. All interviews are conducted as semi-structured interviews, enabling the interviewee the opportunity to answer the questions freely, allowing for small deviation from the interview guide for a broaden inclusion of relevant related subjects whilst still covering the main topic. [Kvale & Brinkmann, 2009] As for the relatively limited experiences for WtH in district heating networks the variety of the interviews are furthermore used validate each other, seeking to understand the potential challenges and regulative framework. General is, that all knowingly DH companies of which is currently looking into or planning to look into WtH solutions have been contacted but is not only limited to these. On Table 3.1 and overview of the interviews conducted can be seen.

3.5.3 E-mail correspondence.

E-mail correspondence is used as a method for gathering of both qualitative and quantitative data. The main purpose of using e-mail correspondence is to follow up on questions and build upon data gathered through the interviews. This allows both the researcher and respondent to have time to think before sending an answer or question. Furthermore, e-mail correspondence is used for gathering of more specific quantitative data used in the modelling and economic calculations. The following main contacts have been established:

Company/Organisation	Description (Main purpose)	Interviewee(s)
Face-to-face interview		
Hvide Sande District Heating	*Insight and experiences in an on-going wind to heat project. Barriers and opportunities*	Martin Halkjær Kristensen
Energinet	*Current legislative framework and barriers for wind-to-heat integration. Current as well as future tariff structure*	Jesper Stryhn, Katja Birr-Pedersen, Carsten Vittrup
Aalborg University	*Local ownership of wind turbines. Alternative taxes and tariffs*	Frede Hvelplund
Tangeværket	*Information regarding off-grid options for own-producers of electricity. Heat uptake using water.*	Rasmus Lambert
Nykøbing Mors District Heating	*Challenges of using electricity for heat and thoughts on differentiated tariff system*	Bjarne Østergaard
Frederikshavn District Heating (utility company)	*Legislative framework. Reasons for not continuing with a wind to heat project and experiences.*	Jes Vad Thomsen, Kim Arp
Interview by phone		
Evonet	*Tariff options and challenges of integrating intermittent RE production*	Poul Erik Skødt Bork, Erik Østergaard
Tjæreborg Industri	*Technical options for off-grid solutions and experiences in Hvide Sande*	John Dam
European Energy	*Experiences with the planning process and legislative framework in Frederikshavn DH.*	Søren Hartz
Johnson Controls	*Heat pump specifications and Information regarding options when connected to a wind turbine*.	Claus P. Thomsen
Fjerritslev District Heating	*Thoughts on barriers and opportunities for off-grid WtH, which they are currently planning*	Kenny Lundtoft
E-mail correspondence		
Orbicon A/S	*Gathering of yearly data for temperatures in Ryå*	Morten Engholm Larsen
Atcho Engineering	*Options for heat exchangers in Ryå*	Willy Van Well
Danish Energy Agency	*Legislative framework for wind-to-heat. Net settlement and electricity sale for own-producers*	Helena Jakobsen

Table 3.1 - Table overview of conducted interviews and mail correspondence

4 Theoretical Framework

The following chapter presents and defines the *Theoretical Framework used to identify important factors influencing the planning process of integrating wind to DH in Aabybro. The theoretical framework is furthermore, used to identify the relevant options in the local context of Aabybro as well as and understanding of the interrelation between the national energy system development and down to a local system point of view. The theoretical framework is based on the authors understanding and interpretation of theories developed by Lund [2014], Hvelplund & Lund [1998], Hvelplund [2014], [Djørup, 2016] and Patil & Herder [2010].*

This chapter is not only to be understood as a theoretical framework alone, but also as a preliminary planning tool to identify relevant factors to include in the planning process and feasibility study. Furthermore it is used to investigate potential scenario opportunities for wind to heat (now referred to as WtH) in Aabybro and implementation measures for technological changes. In order to be able to do so, interviews and an examination of local and national conditions is made. The purpose of this is to map and define possible scenarios based on all relevant factors affecting the choice of technology. These will be described in Chapter 5. The scenarios are then to be modelled and investigated, quantitatively using energyPRO, windPRO and economic calculations, as described in Chapter 3. To exemplify and get an overview of how different factors relate and influence the choice of technology as well as how technological changes are implemented, pushed from both a local as well as national perspective a figure illustrating this, is made. Figure 4.1 is divided into two main spheres; a Local Sphere and a National Sphere. In between, interrelating these two spheres is transitioning and implementation theory of technological changes and policies.

The Local Sphere primarily focuses on factors that may be important in the planning process from a local point of view in Aabybro, and thereby not necessarily factors that are important beyond the context of Aabybro. This could for instance be available resources in the area and specific financial conditions for Aabybro. The national perspective primarily focuses on national factors that influence the present market setup and choice of technology and thus, also the development within the energy sector. This could for instance be public regulation and legislation as a result of societal goals. The interaction and relation between the local and national perspective also illustrates how the two are affected by each other, both in terms of choice of technology but also in terms of changes in the energy system. Hence, both perspectives are important to consider. The Figure furthermore illustrates the interrelation between the local and national perspective resulting in “Situation I”, but also how a true choice of technology is ensured (Situation II). The figure furthermore illustrates the complexity of integrating changes in the current energy system as well as new solutions.

The Following sections elaborate on the different parts of Figure 4.1. Not all elements on the figure will be equally analyzed in-depth but are still considered relevant.

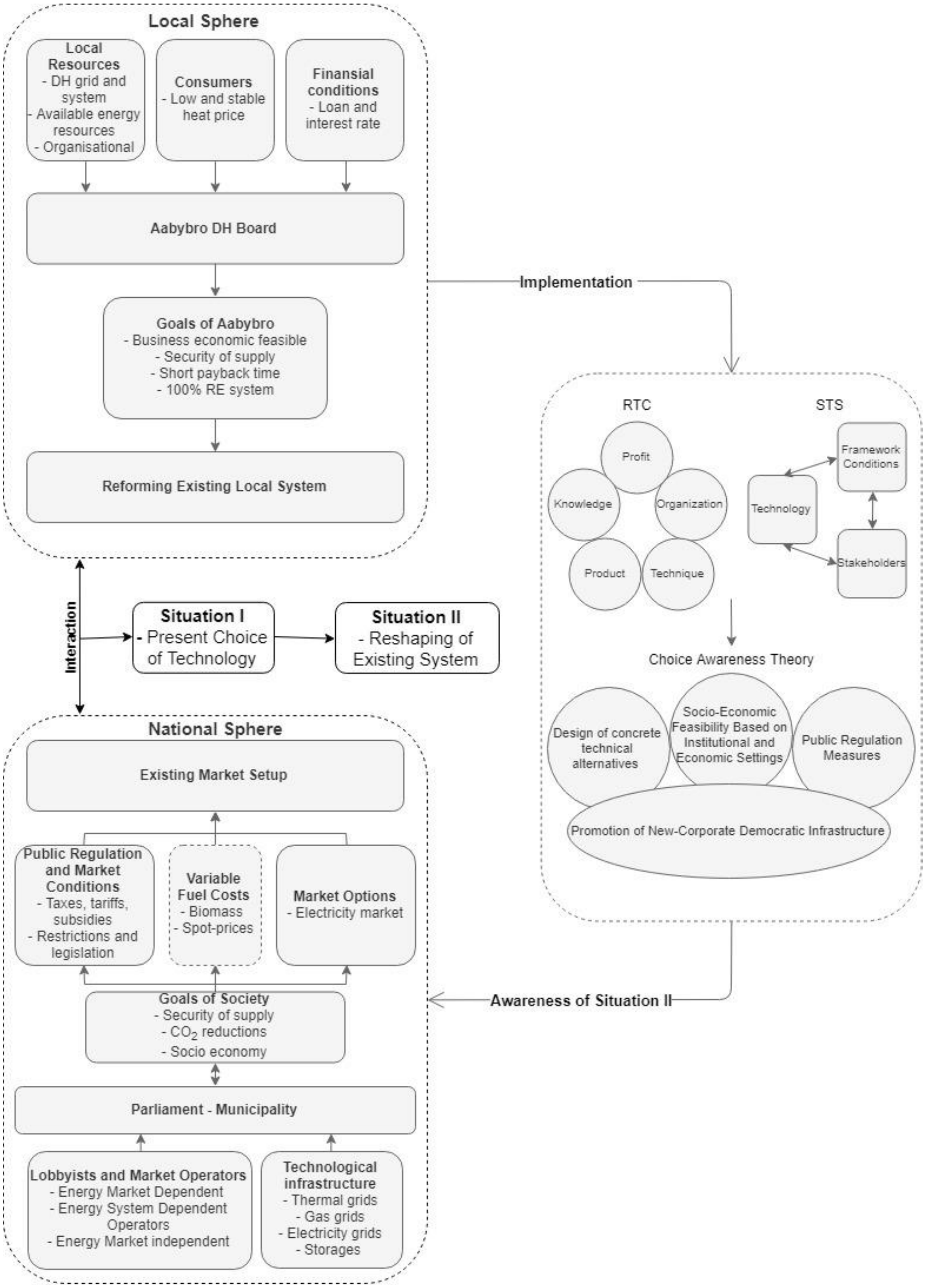

Figure 4.1 - Theoretical Framework and preliminary planning tool. Illustrating different levels in the planning process and energy system development. Situation I illustrate the current choice of technology as a result of the current market conditions. A reshaping of the current structures may however be needed, possible due to a mismatch between the local and national spheres. The right box Illustrates how technological changes are pursued and raised awareness upon, which can affect a change to Situation II. Own made Figure based on [Lund 2014], [Hvelplund & Lund, 1998], [Hvelplund, 2014], [Djørup, 2016] and [Patil & Herder, 2010]

4.1 Local Sphere

The *Local Sphere* consist of the following main aspects; *Local Resources, Consumers, Financial Conditions, Aabybro DH Board, Goals of Aabybro, Reformation of Existing DH System*. First and foremost, the local interests, resources and conditions of Aabybro must be uncovered. A recap of the Local Sphere can be seen on Figure 4.2

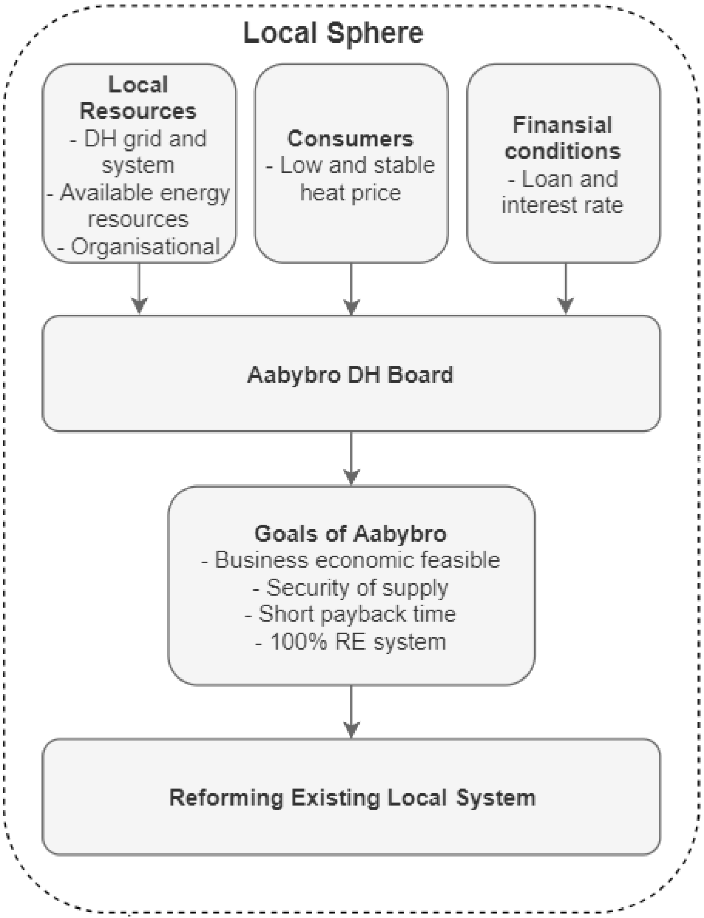

Figure 4.2 - Overview of the local Sphere (micro level)

4.1.1 Local Resources

The *Local Resources* consist of the availability of energy resources and current DH infrastructure- and system. Energy resources could for instance be the availability of local produced biomass, geothermal energy, excess heat from industry etc. However, as the primary scope in this case is wind to heat, focus is thus upon the availability of wind turbines, wind resources and heat sources in the area. As for wind resources, Figure 4.3 indicates that Aabybro is in an area of medium resources, why the potential of integrating wind to DH in Aabybro is considered reasonable.

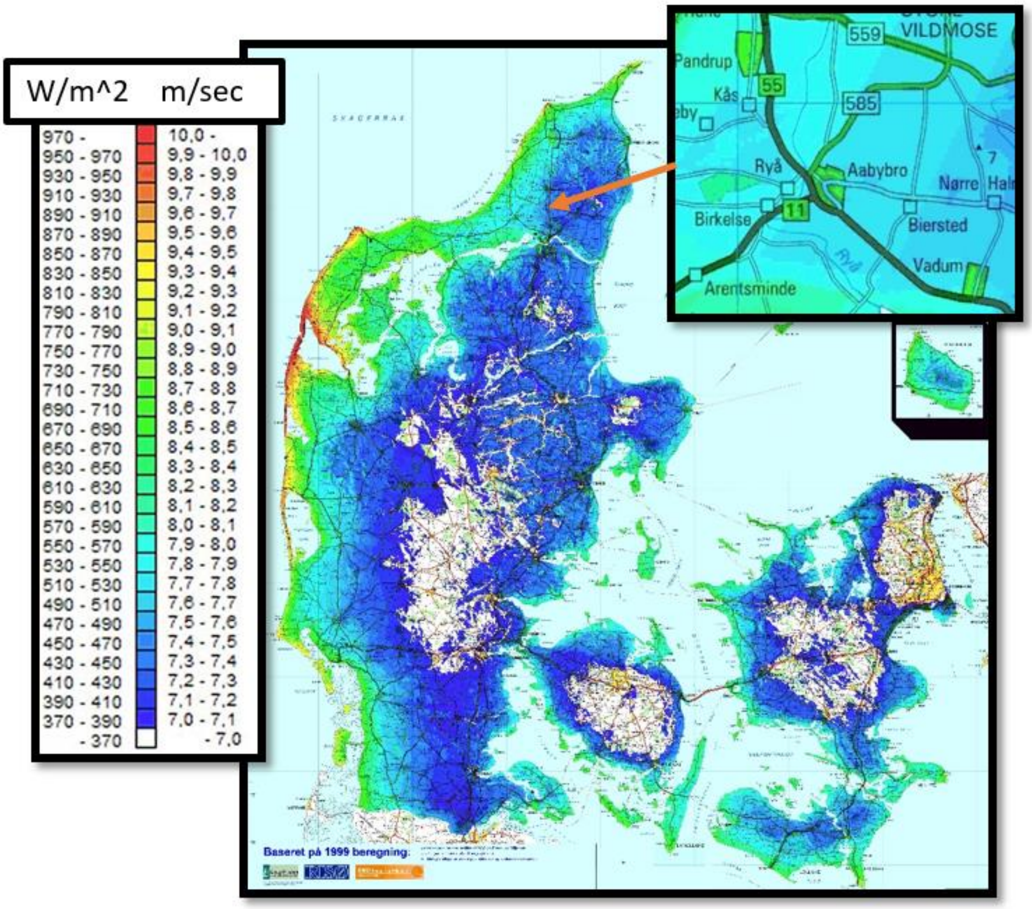

Figure 4.3 - Wind resource map, 100m. [EMD International, 2019C]

When investigating WtH, it is also relevant to consider, how the wind energy varies throughout the seasons in comparison to the heat demand. Figure 4.4 illustrates the monthly variation in wind energy for a "normal" year in northern Jutland.

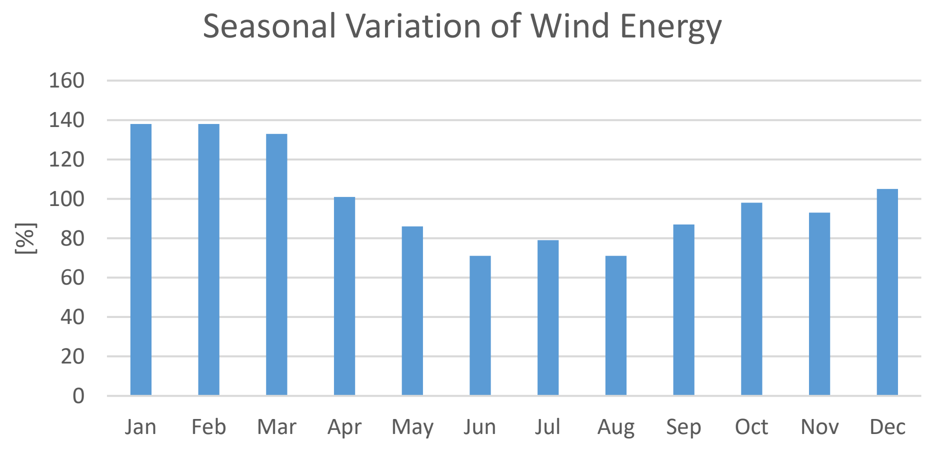

Figure 4.4 - Seasonal variation of wind energy for a normal year, Northern Jutland, index100 [EMD International, 2019D]

As it can be seen on Figure 4.4, the typical power production from wind energy is highest during the winter season where the heat demand usually also is at its highest, and opposite lower during the summer when the heat demand usually also is lower. Hence, preliminary speaking is a match between the power production from wind and the heat demand of Aabybro expected.

A preliminary screening show that one existing wind turbine is located around 700m from the DH grid of Aabybro. The existing wind turbine is a Micon from 1996 with a rated power capacity of 600 kW. [DEA, 2019A] Currently there are no new wind turbines in the area. However, Jammerbugt Municipality has published a replacement proposal for wind turbines in Renbæk Øst, north of Aabybro. The project will include that 12 existing wind turbines are replaced with 16 new wind turbines, each with a total height of 150m. The location of the existing as well as the expected wind turbines can be seen on Figure 4.5.

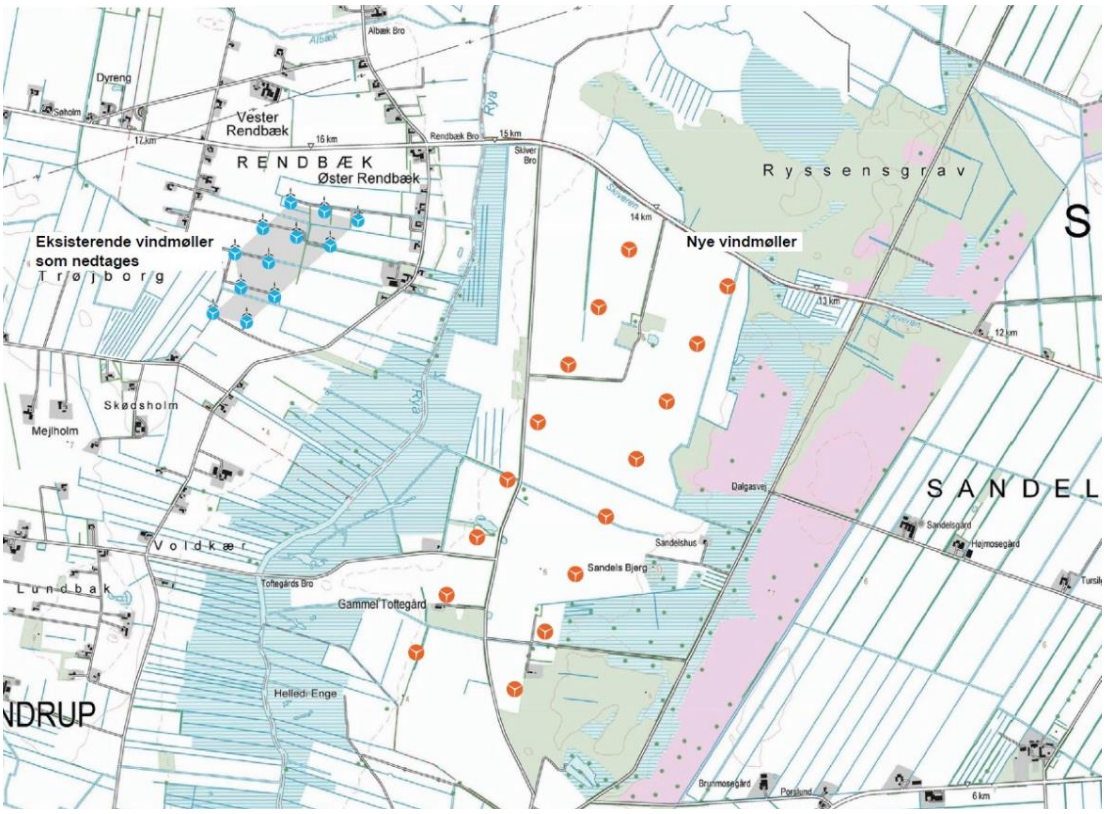

Figure 4.5 - Project proposal overview of new wind park [Dansk Vindenergi, 2019]

The project is developed by Dansk Vindenergi ApS in collaboration with the municipality and landowner. It has not yet been fully decided which type of wind turbine the wind farm is going to consist of. However, it is expected to be one of the following types;

- Siemens SWT-130 DD 4.3MW
- Vestas V126 3.6MW
- Vestas V136 4.2MW

All wind turbines have a total height of 150m and is expected to produce between 189,000-210,000 MWh annually. The wind turbines are expected to be placed in two rows with 8 turbines in each row, as illustrated on Figure 4.5. [Dansk Vindenergi, 2019] Producing electricity either EB's and HB's can be used as electricity consuming units for heat production. EB's usually have lower investment costs when compared to HP's and therefore only requires fewer operation hours. EB's are fast regulating but cannot reach an efficiency above 100% opposite HP's that can reach an efficiency of above 400% depending on the heat source. [DEA, 2017A] For EB's no heat source is needed, however the efficiency, or *Coefficient of Performance* (COP), of a HP on the other hand depends on the heat source and the "quality" of such. [DEA, 2017] [DEA, 2018] According to Aabybro DH [2019] no high-quality heat source, such as industrial excess heat, is available in the area. However, near Aabybro a stream, called Ryå runs. According to DEA [2017] using a stream as heat source for HP's are considered of medium quality. Alternatively, air can also be used as heat source for HP's. Air is usually considered a lower quality heat source, [DEA 2017] but can potentially also reduce the total investment costs, as no specific location is required. Whereas air can almost be utilized everywhere, Ryå is closest to the expected new wind turbine park. A total overview of the stream, connection points, existing and expected wind turbine park can be seen on Figure 4.6.

Figure 4.6 - Overview of potential production options and transmission. Purple line indicates a possible trace for heat transmission. Blue lines indicate potential electrical transmission. Own made Figure using QGIS, data based on [DEA, 2019A], [Kortforsyningen, 2019]

The current DH infrastructure and system is also relevant to consider when looking at solutions. As Aabybro has a well-functioning DH grid and system, DH solutions are in general considered favorable. However, other factors such as dependencies in the production system setup are considered important to include when integrating intermittent WtH production. This can include factors such as the startup time and minimum operation hours for existing production capacity, solar thermal production in the summer, as well as available heat storage opportunities. Specifications and applied assumptions for the above mentioned are further described in Chapter 6. Organizational resources refer to the manpower and consumer base of the DH organization. An analysis of the organizational resources is not included in this *Thesis* but is yet still considered relevant when looking into available options, as the potential options may be limited by a lack of resources.

4.1.2 Consumers

As Aabybro is a consumer owned company with around 2.200 consumers connected, the planning- and decision process is to some extend influenced by all of the “owners”. As Aabybro DH board represent the *consumers* interests this should be taken into consideration when planning for the future. According to Aabybro DH [2019], the consumers primary interest is a low and stable heat price. While there may be other aspects relevant to consider, other consumer specific interests are not investigated further in this *Thesis*.

4.1.3 Financial Conditions

Financial conditions are also relevant to consider in a local perspective as these are expected to vary between DH companies, which potentially will influence the feasibility study. Aabybro DH can potentially apply for a so-called *municipality guaranteed loan* for the investment. [Aabybro DH, 2019] A municipality guaranteed loan can in many cases be provided for public owned non-profit organizations such as DH companies with a public purpose. The municipality loan usually, if granted, provide a relatively low interest rate. [DDHA, 2017B] However, experiences from Hvide Sande DH show that such a loan was not an option when investing in WTG’s due to an argue of the DH company then becoming a competitive and commercial business. [Hvide Sande DH, 2019] Despite not being able to obtain a loan from the municipality for the WTG’s in Hvide Sande, an interest rate at the same level was still possible. [Hvide Sande DH, 2019]

4.1.4 Goals of Aabybro

As illustrated on Figure 4.2 the above factors influence the decision making of the Aabybro DH board, who is primarily in charge of managing these conditions. In the articles of association of Aabybro it is stated that they must deliver the cheapest supply of heat. [Aabybro DH, 2019] Thus, *the Goal of Aabybro* is that the future choice of technology, hence WtH, provides a business economic feasible supplement to the existing system enabling a stable heat price, whilst maintaining the security of supply. This is, as mentioned in section 1.4, mainly due to concerns regarding the future price of biomass. Consequently, a reduction of the biomass consumption is of this reason also a goal of Aabybro. Secondly, having a DH system based 100% on RE, fully independent of natural gas is a target, yet not the primary one. [Aabybro DH, 2019] To lower the economic risk and uncertainty of the project, Aabybro DH is also looking for a solution with a reasonable payback time. A low heat price and economic risk is furthermore preferred in order to maintain attractiveness for the existing as well as future consumers in terms of having a competitive heat supply.

4.1.5 Reforming of Existing Local Energy System

With the above mentioned local factors and goals of Aabybro, a *Reforming of the Local Existing Energy System* can be pursued. A Reforming of the existing energy system is not necessarily only pushed by local factors and goals but can also be triggered by the national sphere in terms of changing framework condition and goals of Society. Hence, this is also where the energy planning process and potential critique towards existing market structures takes place. This is also where the *Local Sphere* can try to influence and change the institutional setup in the *National Sphere* in order to meet both local as well as societal goals. However, one might find that reforming the existing energy system and the implementation of technological changes may be implicated by the current setup, further elaborated in section 4.2.9 and 4.3. The need to reform the existing energy system of Aabybro is caused by a combination of both.

The present as well as future choice of technology is not in all cases single handed determined by the local factors and goals but is also a result of national policy and market structures, hereby the *National Sphere.*

4.2 National Sphere

The *National Sphere* is where the framework conditions for the *Existing Market Setup* and present choice of technology are established. In other words, the *National Sphere* can also be defined as an energy market process. The National Sphere consist of *Lobbyists and Market Operators, Parliament-Municipality, Goals of Society, Public Regulation and Market Conditions, Market Options, Variable Fuel Costs and Existing Market Setup*.

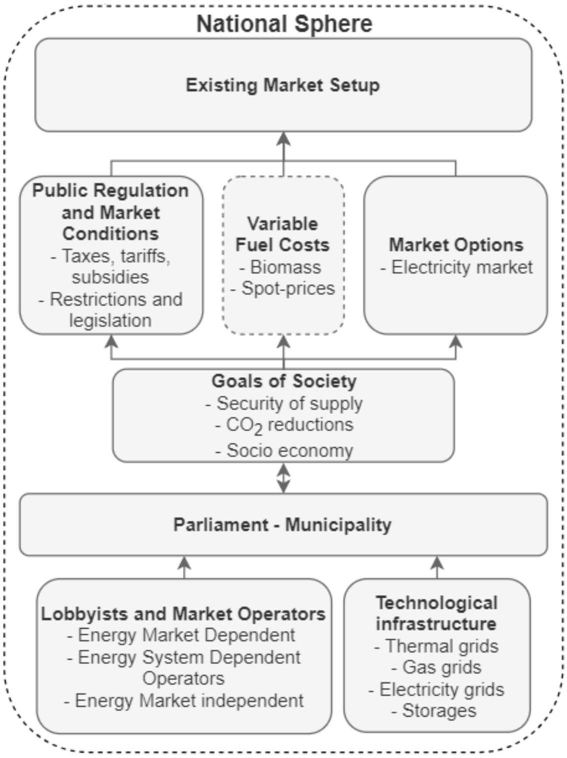

Figure 4.7 - Overview of National Sphere (macro level)

4.2.1 Lobbyists and Market Operators

On a national level various lobbyists and market operators can influence the political agenda of the parliament and municipality. The *Energy System Dependent Operators consist* of the Danish *Distribution system operators* (DSO) and *Transmission system operators* (TSO). The Danish TSO, Energinet, is a state-owned public organization who is responsible for operating and managing the national electricity grid as well as maintaining the security of supply [Energinet, 2019]. In Aabybro, Evonet is the DSO who is responsible for the distribution grid. [Evonet, 2019] The *Energy Market Dependent* actors can be divided into *old* and *new* market lobbyists. *New Market RE Lobbyists* are defined as governmental as well as non-governmental organizations and actors who lobby for RE production technologies- and systems. This could for instance be RE producers or technologies. *Old Market Dependent Lobbyists* are similar organizations and actors lobbying for a continuance of fossil fuels such as gas and oil companies. [Hvelplund, 2014] However, the division between these New and Old Market Dependent Lobbyists are not entirely clear and does also consist of external actors lobbying for different sectors of the energy system, with each and their own interests. This can for instance be Dansk Energi, Dansk Fjernvarme and other organizations of interest. As these types of organizations are usually financed by their members, they usually have well defined interests and discourses. The *Market Independent Lobbyists* are defined as public lobby groups and consumers, who, despite being consumers, doesn't directly operate on or are dependent on the energy market. These different actors and organizations can actively or non-actively try to influence the parliament and municipal policies, and thus also the existing market conditions and regulative framework. Consequently, these different actors are relevant to consider as they can play a role in the shaping and decision-making process of reforming the political agenda, on a municipal and governmental level. [Hvelplund, 2014] Whereas many of the above mentioned stakeholders are included in this *Thesis*, not all are included despite they may be involved in the planning process.

4.2.2 Technological Infrastructure

Technological infrastructure relates to the established infrastructure of the energy system, such as Thermal grids (DH), Gas grids, Electricity grids and Storages, which are all spread over Denmark. The Current infrastructure is relevant to consider as solutions utilizing these may be favored or pursued from a national policy point of view.

4.2.3 Parliament – Municipality

The Parliament is where goals of society are defined, which creates the basis for the current public regulation and market conditions. [Hvelplund, 2014] Also, indirectly affecting the Parliament is the above described technological infrastructure. [Djørup, 2016] The Parliament also consist of various institutions such as the Danish Ministry of Finance, Ministry of Energy, Utility and Climate etc. who affect, regulate and interpret the framework conditions within the energy sector. The specific legislative framework of WtH will be described in section 354.2.7.

4.2.4 Goals of Society

Goals of Society relates to societal goals of the energy sector, which, as described in Chapter 1, can be goals of increasing the RE share and reduce CO_2 emissions while maintaining the security of supply and ensuring socio economic feasibility. The Goals of Society is primarily defined by the

Danish parliament and affected by the different lobbyists, stakeholders, market operators and current infrastructure.

4.2.5 Variable fuel costs

Variable Fuel Costs (excl. taxes) are on Figure 4.7 placed within a dotted line because they are not directly affected by the Parliament but is rather a result of external factors such as the availability of the fuel, supply and demand on the national and international market, which is not directly under the influence of the parliament. Now, the Parliament still have certain regulation measures to affect the total cost of using a fuel and thereby also the consumption, which is further elaborated later in this Chapter. Both present and future variations in the fuel prices can have a major influence on the feasibility of operating existing systems as well as for future technologies. An example of this is seen on Figure 1.5 in chapter 1, where the electricity price has varied significantly since 2004, which consequently also affect the profitability of using electricity for heat. Future variations in the price for biomass can also be expected to influence the feasibility of WtH in Aabybro.

4.2.6 Market Options

Market Options for heat can be considered limited as the DH networks usually are natural monopolies, delimited by the local area. However, when producing or consuming electricity, various market options are available. As described briefly in Chapter 1, the major electricity consumed and produced is bought and sold on the spot market, where prices are settled on an hourly basis. For Aabybro the DK1 spot prices for western Denmark applies. On the stock exchange consumers (buyers) and producers (sellers) make their bid and a price per unit is calculated according to the supply and demand. [Energinet, 2018] Purchase of electricity on the spot market for grid connected HP's usually happens through an electricity supplier following the hourly spot prices [DDHA, 2017A].

As Energinet, as the Danish TSO, is responsible for balancing the electricity grid, several system services is offered (Ancillary services). One of these are called the Regulation Power Market where producers and consumers make their bid on an hourly basis according to the electricity price they want to be regulated down or up to. The hourly activation price is calculated similar to the spot market where all activated bids receive the same price per MWh-electricity. Two major requirements apply for the regulation power market; the regulation must be fully completed within 15 min and the lowest bid is for 5MW-electricity, for both up and down regulation. However, if the HP or EB can't deliver 5MW-el the capacity it is possible to be combined with other units from other companies. [Energinet, 2018] The market for manual reserves (mFRR) is the same as the power regulating market, but with a "capacity payment" ensuring that Energinet have the required reserves for regulation available throughout the day. [Energinet, 2018] During recent years EB's have been very active on the Special regulation market in DK1 caused by grid capacity issues in the northern part of Germany as a result of increasing wind power production. The special regulation is usually activated as downregulation and the price is settled as "pay as bid". [Energinet, 2018] Due to the high variation and less proactive character of the special regulation market, the economic potential for operating on this market can be difficult to predict. [Grøn Energi, 2017] The Frequency Containment Reserve (FCR), formerly called The Primary Reserve, consists of production and consumption units, that automatically reacts to imbalances in the grid. [Energinet, 2018] The FCR is the fastest regulating reserve of the services as it requires activation of the bidding capacity within

30 seconds, where as 50% is to be activated within 15 seconds. The FCR is primarily for in-operation units as the activation happens automatically by deviations in the frequency. [Energinet, 2018] FCR requires permission from Energinet and amounts for a total of +/- 20MW. FCR is singlehanded supposed to deliver capacity until aFRR (secondary reserve) and mFRR (Manual reserves) can take over. This fast regulation is mainly considered suitable for EB's due to the characteristics of HP's. The automatic Frequency Restoration Reserve (aFRR), previously called the Load Frequency Control (LFC), is an automatic 15 minutes capacity regulation reserve. aFRR is almost always activated and is delivered by units on partial load and fast activated units. The activation of aFRR is not triggered by a deviation in the frequency but is automatically activated from Energinet and through the power balance responsible. [Energinet, 2018] aFRR is considered less relevant in the case of Aabybro. Based on the above, the spot market and power regulation market is considered most relevant for Aabybro.

4.2.7 Public Regulation and Market Conditions

Public Regulation and *Market conditions* are important to uncover and include when assessing the feasibility and implementation of energy projects. Public regulation is in this *Thesis* defined as regulation measures (legislation) and restrictions enforced by law. In the following, only the major public regulation measures in relation to WtH integration in Aabybro is uncovered. As the legislative framework for WtH in general is found to be a "grey zone" the following sections are based on an interpretation and experiences from the interviews included. However, this also means that there may potentially be several aspects that is not included or understood correctly. In general, for all project proposals for heat is that, c.f. the Danish heat supply act and project declaration, they need to be socioeconomic feasible to be approved. [Retsinformation, 2019] [Retsinformation, 2018]

In this *Thesis, Market Conditions* are defined as all relevant taxes, tariffs and subsidies. Market Conditions is considered to play an important role in designing both the present and future energy system, as it can affect the feasibility of new investments (also described in Chapter 1). Taxes are in general used as a tool to affect and constrain the behavior of companies and consumers (E.g. fuel consumption), whereas subsidies are oppositely used the affect/promote the behavior in a positive way. [Christensen, 2006] Tariffs are usually allocated for certain purposes, and is not necessary a payment for the Danish state.

As described in Chapter 1, electricity and fossil-based energy for heat is heavily taxed, whereas biomass is almost exempt. The DH system in Aabybro is mainly based on biomass and solar thermal, which in general lowers the marginal production costs. For historic reasons taxes and tariffs for electricity are mainly placed on the consumption side whereas subsidies are placed on the production side. [Klimarådet, 2016] For electricity to heat using the public grid in Aabybro, the following taxes and tariffs applies:

Electricity tax	Danish government
Transmission tariff	Energinet
System tariff	Energinet
PSO tariff	Energinet (soon out phased)
Local net tariff	Local DSO (Evonet)

As the feasibility of HP's and EB's are dependent on the electricity price as well as the current tax level, it is relevant to uncover the opportunities for minimizing these. When integrating WtH various grid-connection opportunities potentially applies, which will be uncovered in the following.

4.2.7.1 Electricity tax

According to "*Law of tax for electricity*" §2 Litra C [Retsinformation, 2016], electricity is exempt from taxes when produced on production units based on RE sources such as wind power, and which is consumed by the electricity producer itself. It is addressed that wind power production which the wind power producer consumes for the operation of HP's or EB's is exempt from electricity tax. However, it is a condition that it is a *direct* own consumption, meaning that the wind turbine and HP/EB must be connected via an internal cable. The wind turbine and HP/EB must also belong to the same legal entity. [SKAT, 2019] If the wind power producers' internal cable, which the wind turbine and HP/EB are connected to, also is connected to the local electricity grid of the DSO, excess electricity production is allowed to be delivered on the public grid, without being taxed. If the wind power producer both supplies wind power to the public grid and receives electricity from the public grid for the operation of the HP/EB, the wind power can still be delivered to the public grid without being taxed. [SKAT, 2019] Electricity delivered to the wind power producer (consumed from the public grid) is taxed regardless of the amount of wind power delivered to the public grid. There must be separate measurements of the wind power delivered to the public grid and power delivered from the public grid to the producer. [SKAT, 2019] A binding answer for he above exemption of tax for own consumption of electricity produced on WTG's and used in HP's/EB' was by Hvide Sande DH [2019] retrieved in 2016.

4.2.7.2 Tariffs - TSO

In the following, options for net settlement and relevant tariffs of such, will be described. For own-producers and consumers of electricity two main net settlement options are available*; Momentary settlement* and *Hourly settlement*. The two settlement groups are quite similar. If qualified for net settlement one has the opportunity to supply the producer itself with all the electricity which can be consumed. The capacity/effect which can't be consumed by the producer himself, can be sold to the public grid. [DEA, 2019]

To be able to net settle as a consumer, one will have to be classified as an *own-consumer*. An own-consumer is defined as an electricity consumer who is 100% the same legal entity or person as the one who produces electricity with the purpose of fully or partly covering the own energy consumption. [Retsinformation, 2016] Own-consumption of electricity is defined as the part of the electricity consumption the own-producer itself produces. [Retsinformation, 2016] To make use of net settlement the electricity producing unit (WTG) must be connected to the installation (consumer installation) or be located on the same place of consumption, which in many cases is the same cadastral. [DEA, 2019D] The WTG is required to be 100% owned by the same legal entity (owner in Stamdata register is to be the same person/company as the consumer). According to §3 in Retsinformation [2016] and §3 in Retsinformation [2019B], own production of electricity on wind turbines with a capacity of more than 25kW are exempt from paying the full amount for *Public Service Obligations* (PSO) for the own consumption of electricity. Hence a reduced PSO applies for both own consumers of momentary settlement and hourly settlement. For WTG's under 25 kW, no PSO payment is required. However, despite this definition the DEA [2019D] states that, in some cases where CHP plants produces electricity for own consumption in boilers used for heating purposes for end users, often these will not be considered as an "own producer" which is often up for an individual valuation. [DEA, 2019B] Net settled own producers are according to Energinet [2019C] exempt from paying transmission and system tariffs. The DEA has furthermore confirmed that there is no difference in payments of tariffs and taxes between the momentary settlement and the hourly settlement. [DEA, 2019D] According to Grøn Energi [2015B] the exemption of tariffs for own production and consumption is explained by the consumer not making use of the public grid to transmit and transform the own produced effect.

The major difference between the momentary and hourly settlement is the amount of time the produced electricity can be "saved". An example is that a potential excess production can be "stored" in one hour, within this hour the power can be consumed. If the power isn't consumed within this specific hour, the electricity is sold to the electricity grid at spot prices. Both momentary and hourly settlement can sell electricity to the grid, but being able to do so, an "Electricity production supplier" is required. [DEA, 2019D] However, if it is wished to sell electricity to the grid it is preferred to have hourly settlement, as this increases the flexibility, and will reduce the risk of delivering electricity to the grid "for free". [European Energy, 2019] In order to become net settled on an hourly basis, it is however a requirement to apply for this before project start of a new wind turbine park. [Retsinformation, 2016] Finally, for conventional grid connected HP's and EB full tariffs and taxes applies, whereas for completely off-grid no tariffs seems to apply. [Hvide Sande DH, 2019] [Evonet, 2019] [European Energy, 2019] [Fjerritslev DH, 2019]

4.2.7.3 Tariffs – DSO

When a consumer is also an own-producer and is partly connected to the grid for net settlement, one can be exempt from paying the full net-tariff to the local DSO. [Evonet, 2019B] Being able to do so, the production unit, hence WTG, must also be instalment-connected, meaning that the WTG needs to be directly connected to the installation of the consumer. In such a case, the own-producer, will be charged a reduced tariff, referred to as a *"capacity tariff".* [Evonet, 2019B] The capacity payment is charged for the electricity the consumer produces and consumes, to ensure that the consumer have the opportunity to draw similar effect from the local grid. For instance, if the WTG stops to produce power, due to a lack of wind, the effect will have to be delivered from the local grid. For Evonet In Aabybro, the capacity payment is usually a few øre/kWh lower than the regular net-tariff [Evonet, 2019B]. For conventional fully grid connected HP's/EB's a full tariff payment applies, where as if completely off-grid no tariffs are charged.

The following Table 4.1 gives an overview of the different taxes and tariffs charged for each grid-connection option.

	Full grid-connection	Partly connected	Off-grid
Government			
Electricity tax	Full	Zero	Zero
TSO – Energinet			
PSO - Tariff	Full	Reduced	Zero
Transmission – tariff	Full	Zero	Zero
System – Tariff	Full	Zero	Zero
DSO - Evonet			
Capacity payment – Tariff	Full	Reduced	Zero

Table 4.1 - Overview of different options for taxes and tariffs

Here it can be seen that, if no tariff and tax payment is to be charged, a full off-grid solution is the only way. However, reduced tariffs are also possible, if certain requirements are fulfilled. The following Table 4.2 gives an overview of the specific requirements for the above three categories of grid connections.

	Full grid connection	Partly connected - Momentary	Partly connected - Hourly	Off-grid
Same legal entity – 100% same owner of power unit and consumer	No	Yes	Yes	No
Consumer installation/Direct connection	No	Yes	Yes	Yes
Classified as "own-producer"	No	Yes	Yes	No
Heat unit on same cadastral as WTG	No	Yes	Yes	Yes
Application before project start (DEA)	No	No	Yes	No
Electricity production supplier required	No	Yes	Yes	No

Table 4.2 - Overview of specific requirements for grid connection

4.2.8 Existing Market Setup

The Existing Market Setup can be said to be a result of the *Goals of Society* through *Public Regulation and Market Conditions* as well as *Variable Fuel Prices (external) and Market Options*. These are the main framework conditions for the establishment of Situation I.

4.2.9 Socio-Technical Regime (Situation I and Situation II)

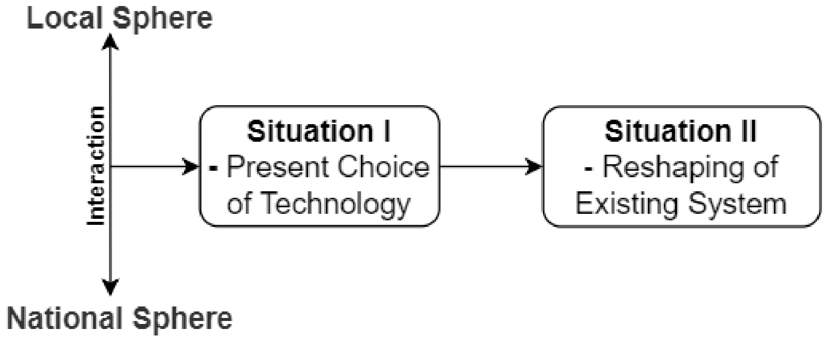

Figure 4.8 - Interaction between the Local and National Spheres result in Situation I and the present choice of technology. A mismatch between the Spheres may however create the need of Situation II and a reshaping of the existing system. [Hvelplund & Lund, 1998]

Situation I represent the well-established socio-technical regime of the energy system, consisting of the current framework conditions of the *Local*- and *National sphere,* resulting in the present choice of technology. However, a feasibility study may find that what is business economic feasible, is not necessarily what is socioeconomic feasible and vice versa, resulting in a mismatch in Situation I [Hvelplund & Lund, 1998]. However, not only can there potentially be a mismatch between the goals of the *Local Sphere* and *National Sphere*, but there can also be a mismatch internally. This could for instance be between the *Goals of Society* and the current *Market Regulation and Conditions,* not having the current regulations measures and market conditions supporting the societal goals. As the *National Sphere* function as the framework, in terms of both market and regulative conditions that Aabybro must conform and operate in accordance with, the *National Sphere* will consequently also affect the *Local Sphere* in terms of reforming the energy system in terms of which solutions that are both possible as well as feasible. This is illustrated as the "interaction" arrow on Figure 4.8. In order to implement technological changes and reshape the existing energy system and choice of technology, relevant measures may be needed.

4.3 Radical Technological Changes and Choice awareness

Technology in this *Thesis* is understood in a broader sense than just single production technologies and its technical and physical prospects, but rather, as Hvelplund [2017] describes it, something that comprises five elements; *Technique, Profit, Organization, Product and Knowledge.*

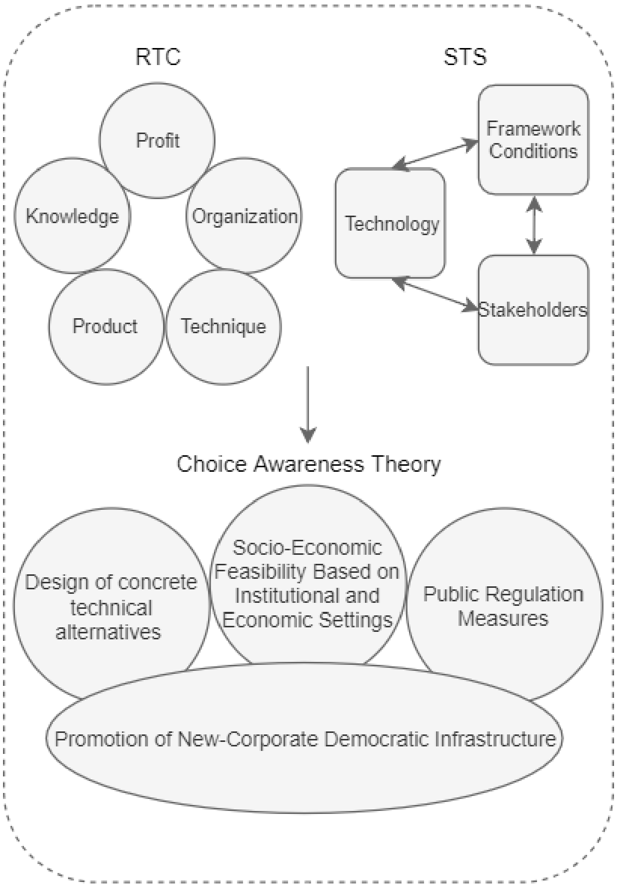

Figure 4.9 - Overview of transition and technological change. RTC: Radical Technological Change, STS: Socio-technical system [Hvelplund, 2017], [Lund, 2014], [Patil & herder, 2010]

This definition of technology is used to illustrate that there are various factors influencing the planning process and implementation of radical technological changes, which are also closely linked to the local and national context. According to Hvelplund [2017] a technological change can be considered substantial (radical) when two or more of the before mentioned elements are changed. Generally, integrating WtH in Aabybro can be considered a substantial change locally, where most elements are affected. Not only is Aabybro DH used to have a solid fuel instead of electricity, nor are they used to have electricity consuming and producing units such as wind turbines, EB's or HP's in the production setup. If such are implemented it would mean changes in *technique, knowledge* and *profit*. Depending on the ownership structure, the organizational structure can potentially also change. Consequently, despite the different technologies are well known individually, integrating WtH can be considered a radical technological change from a local perspective of Aabybro. Finally, it changes the whole perception of being a power and heat producing DH company. In relation to the understanding of *Technology*, the energy system can in relation to the theory of Pertil & Herder [2010] be considered a complex system, that does not only consist of technological aspects but also of more societal aspects, also defined as a "*Socio-Technical-System*" (STS). This comprehension implies that the development of a technology or technical system isn't necessary singlehanded enough to create changes in the existing system, but also that the right framework conditions and stakeholders ought to be present for such a change to occur. Thus, a STS consist of three mutual dependent aspects; *Technology*, *Stakeholders* and *Framework conditions*. [Patil & Herder, 2010] Thus, in order to affect the current STS (Situation I) it is not just enough for the technology to be present, but the implementation of such is dependent of having the right stakeholders and framework conditions supporting this. [Patil & Herder, 2010] This is closely linked to the *Choice Awareness Theory*.

The theory *Choice Awareness*, developed by Lund [2014], is a theory that deals with the implementation of *Radical Technological Changes*. The theory addresses the societal level and collective decision-making process, which involves various organizations and individuals, who not only represent different levels of power, but also different interests and discourses. [Lund, 2014] The Choice Awareness Theory emphasizes that, in many cases, these organizations see things from a from a different point of view and that often/many cases, their interests are reflected through their actions. The theory is built upon the fact that the decision-maker must have a *true choice,* meaning that there must be more than on "real" option available, enabling the decision-maker to judge the merits between alternatives. [Lund, 2014] Contrary to a *true choice*, a situation where no real options are available, referred to as a *false choice*. In relation to this, The *Choice Awareness Theory is based* on an observation that, in many cases, there is a collective perception of *no choice* in the communities. However, according to the theory it's important to raise awareness that society *do* have a choice, and that alternatives are existing. [Lund, 2014] On Figure 4.1 this is illustrated by the arrow from the choice awareness theory to the National Sphere, raising awareness of a Situation II.

The theory also emphasizes that existing organizational interests and institutional perceptions often seeks to keep radical technological changes out of the agenda, for instance by eliminating certain options from the political decision-making process, in order to maintain the current market conditions and policies (maintaining Situation I). The relatively non-transparent and unclear legislative framework for WtH in DH systems can be considered as an elimination of choices. As there isn't always a match between the local and national spheres, one might find that in order to reform the existing energy system and implement radical technological changes, strategies ought to be applied. The theory presents four *counter strategies* to improve the decision-making process and to raise public awareness that alternatives do exist [Lund, 2015], potentially leading to Situation II and a change in the STS.

4.4 Summary

As highlighted in the above sections various factors influence the opportunities for WtH in Aabybro. The *Existing Market Setup* and *Present Choice of Technology* (Situation I) can be said to be a result of the current market Conditions and regulative framework, as well as well as the societal goals. These are, as illustrated on Figure 4.1 defined by the Parliament, but influenced by various stakeholders and lobbyists as well as the current technological infrastructure. The interaction between the institutional and technological infrastructure potentially creates some issues. The energy political action and goals of society result in changes in the institutional infrastructure regarding market conditions, taxes, tariffs etc., which usually influence the technological infrastructure. [Djørup, 2016] The public regulation and market conditions should according to [Hvelplund & Lund, 1998] assure that what is best from a societal point of view is also best from a business economic perspective. If such a situation is established, the market companies will act in accordance with not only the business economy, but also with what is best for society. [Hvelplund & Lund, 1998] As described and illustrated on Figure 4.1, it is clear that in *Situation I*, there are specific legislation and conditions in the market which may favor the existing technologies, leading to the present choices of technology. In the meantime, these conditions may also disfavor the implementation of new technologies which is also seen regarding the implementation of WtH. In the light of Aabybro DH, the existing market conditions seems to favor the use of biomass, whereas WtH for DH companies are not to the same extend favored. However, a more detailed analysis investigating this is to be applied. As the business economic feasibility in many cases determine whether to pursue a certain solution for a DH company, the first step is to asses this. To improve the decision-making and to raise the public awareness of alternative choices, the *Choice Awareness Theory* is used as the background for making and investigating scenarios, presented in the following chapter. Based on the results, in may become clear what type of changes in the current market setup, that could be introduced, which would lead to a Situation II, where the existing energy system and choice of technology is reshaped.

5 Scenario Description and Definition

In the previous chapter the potential for wind to heat integration have been investigated, looking into the local context of Aabybro as well as the current market structures on a national scale. The following chapter presents the included scenarios for wind to heat integration in Aabybro, as a result of the current options and framework conditions presented in the preliminary analysis of chapter 5.

The purpose of investigating different scenarios is to identify possible options for WtH in Aabybro. By investigating various scenarios, not only will the business economic potential be evaluated for different options, but also how this match the current framework conditions is evaluated. If in accordance with societal goals while providing business economic feasibility, an ideal situation is already established, c.f. chapter 4.

As elaborated in chapter 4, local WtH integration in Aabybro is possible through various connection options, also illustrated on Figure 5.1. One way is through a conventional grid connection, exploiting low electricity prices and down regulation that usually occur in windy periods. Another way is by being partly grid-connected, but directly connected to a wind turbine in the area, exploiting reduced tariffs and taxes and producing the electricity for the purpose of own consumption. Finally, a complete off-grid solution, directly connected to a nearby wind turbine, where no taxes and tariffs applies. In the area an existing WTG is located near the DH grid of Aabybro and furthermore, north of Aabybro, a wind park consisting of 16 new WTG's is expected in the near future, whereas one of these potentially could be utilized. Using electricity for heat, EB's and HPs are commonly used for DH purposes and both two technologies are chosen to be included as, it is interesting to investigate how technologies with different technical properties and investments compare.

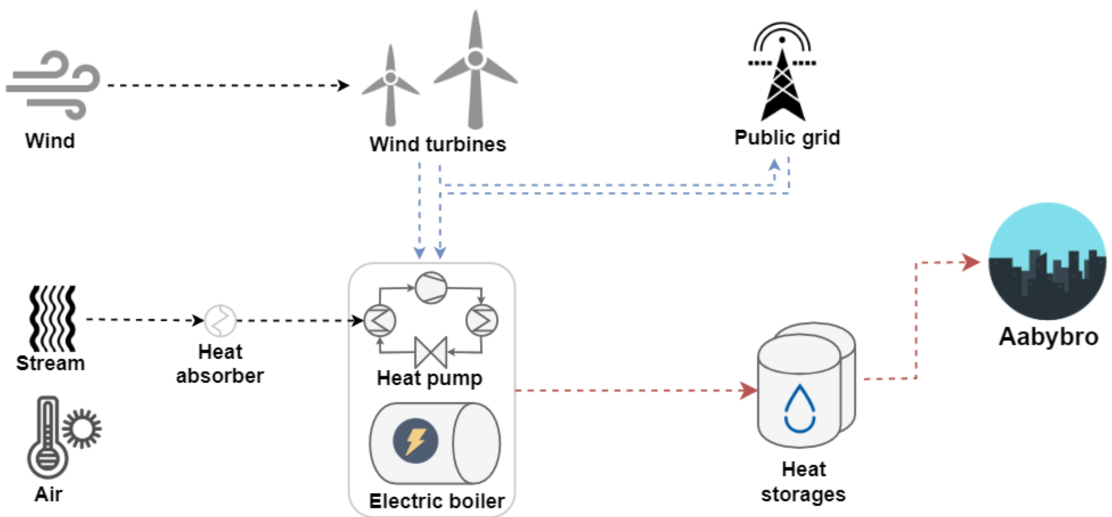

Figure 5.1 - Illustration of different grid- and production options in Aabybro. Own Figure

Whereas an EB directly converts electric energy to thermal energy, a HP exploits a heat source in the process (further elaborated in the following chapter). Of potential heat sources it was found that a nearby stream or the ambient air were qualified options of such. Whereas other heat sources may be present, this *Thesis* is delimited to looking into only these two, comparing a medium quality heat source at higher initial investment costs, with one of lower quality and lower investment costs. Not only can EB's and HP's be seen as separate single technologies but a combination of both in the same DH system can prove interesting, which potentially enables a reduction of the investment costs while ensuring the maximal capacity of the WTG to be exploited. Hence, a scenario containing both will be included. However, due to the lower capacity of the existing WTG, a combination scenario will only be investigated with the new WTG. Due to legislative uncertainties regarding sale of excess electricity (momentary and hourly net settlement) scenarios including a *partly grid-connection* will investigate the economic consequences of both being able to sell the excess electricity and not. However, due to these uncertainties, sale of electricity from the WTG's will not be included in the operation strategy of energyPRO, meaning that the electricity produced on the included WTG's will have the first priority to be utilized in the HP and/or EB. Doing so may however affect the business economic results and thereby also the conclusions of the *Research Question*. As Ryå is closest to the new wind turbine, only air as heat source for the HP connected to existing WTG will be investigated. This also applies for when fully grid-connected. Consequently, the following scenarios have been chosen to be included in this *Thesis*.

Scenarios			
Scenarios	Fully grid-connected	Partly grid-connected (a)	Off-grid (b)
1. New WTG + EB		X	X
2. New WTG + HP-Stream		X	X
3. New WTG + HP-Air		X	X
4. New WTG + HP + EB		X	X
5. Existing WTG + EB		X	X
6. Existing WTG + HP-Air		X	X
7. No WTG + EB	X		
8. No WTG + HP-Air	X		

Table 5.1 - Overview of scenarios included

Notice that some scenarios consist of the same production setup but is investigated with different grid connection solutions. For instance, will Scenario 3 be calculated in a partly grid-connected option (a) and an off-grid option (b). All the above listed scenarios are compared to a reference consisting of the current DH system of Aabybro. The applied assumptions for the reference and scenarios will be elaborated in the following chapter.

6 Analysis Assumptions

The purpose of the following chapter is to describe and present the applied assumptions of the scenarios included in this Thesis. The chapter describes the specifications of the current DH system of Aabybro as well as all external conditions such as temperatures, flow and wind data. Secondly, specifications regarding the HP's, EB's and WTG's are presented along with the financial conditions that applies for Aabybro DH.

6.1 Existing DH System Specifications of Aabybro

As described in Chapter 1, Aabybro has an annual DGD-corrected heat demand of around 45,500 MWh along with heat losses of around 15,000 MWh. A duration curve of the annual heat demand can be seen on Figure 6.1.

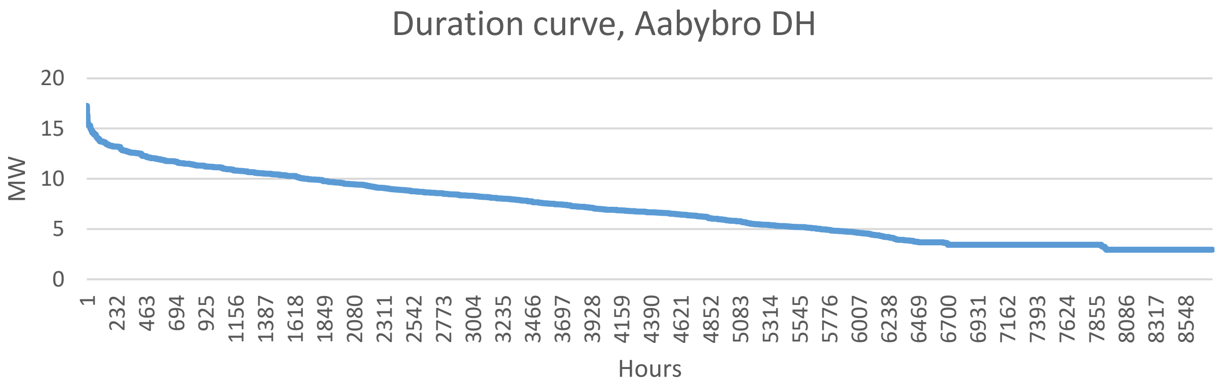

Figure 6.1 - Duration curve of Aabybro DH, illustrating the number of hours a certain heat demand is present. Own figure

Figure 6.1 illustrates the number of hours a specific heat demand is being present in Aabybro. As it can be seen, Aabybro DH has a peak demand of around 17MW. Despite the slightly lower capacity of the wood chip boiler, Aabybro DH has over the last few years been able to cover the heat demand only by the use of the wood chip boiler and heat storage, with no need of natural gas. Table 6.1 gives an overview of the existing fuel-based production units of Aabybro DH.

Production unit	**Capacity - Heat**	**Efficiency**	**Minimum operation hours**	**Remark**
Wood chip boiler	12.5MW	104%	10 hours, 2 hours in between	Incl. flue gas condensation [Aabybro DH, 2019]
Natural gas boiler 1	4MW	92%	0 hours, 0 hours in between	[Aabybro DH, 2019]
Natural gas boiler 2	4MW	92%	0 hours, 0 hours in between	[Aabybro DH, 2019]

Table 6.1 - Overview of existing fuel-based production units in Aabybro

As described in Chapter 1, Aabybro recently installed a solar collector field. Table 6.2, describes the specifications for the solar collectors included.

Solar Collector Specifications		
Area	26.000m2	[Aabybro DH, 2019]
Loss coefficient 1	2,41 W/(m^2*°C)	[Aabybro DH, 2019]
Loss coefficient 2	0,015 W/(m^2*°C)^2	[Aabybro DH, 2019]
Incidence angle modifier	0.92 Kϴ at 50 degree	[Aabybro DH, 2019]
Temperatures from and to collector	Flow and return of Aabybro	[Aabybro DH, 2019]
Losses in pipes	3% of production	Assumed [NIRAS, 2019]

Table 6.2 - Applied assumptions for the solar collector field in Aabybro

As the solar collectors were installed during the summer 2018, no specific production data for a full year is present. Figure 6.2 illustrates the expected production from the solar collector field calculated in energyPRO. The annual production from the solar collectors are with the above specifications and external conditions, later described, calculated to be around 13,000 MWh, which corresponds to around of 22% of the annual heat demand.

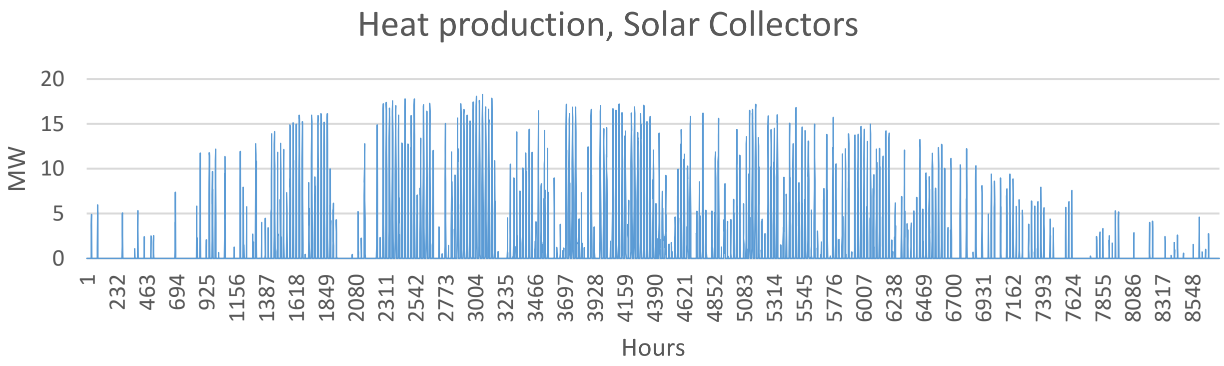

Figure 6.2 - Heat production from solar collectors based on energyPRO simulation

As the production from the solar collectors can't as be switched off as such, the production throughout the year and hence the dependence is important to consider and include when implementing new production units into the system. Due to this intermittent production from solar collectors, a heat storage is often necessary in order to create flexibility between production and demand. In Aabybro two heat storages are installed. Table 6.3 gives an overview of the applied assumptions for the heat storages.

Heat Storage Specifications		
Volume	2.500m^3, 6.000m^3	[Aabybro DH, 2019]
Temperatures	Top 85°C, bottom 35°C	[Aabybro DH, 2019]
Utilization	95%	[Aabybro DH, 2019]

Table 6.3 - Applied assumptions for heat storages

As well as a heat storage is considered important when having solar collectors as a part of the DH system for flexibility, these are also expected to be important when integrating intermittent wind-based heat production to the system.

The above specifications for the DH system of Aabybro will be defined as the reference system for comparison of the scenarios. As the main production units and storage are relatively new, no reinvestments within the calculation period is expected.

6.2 External Conditions

Hourly data sets from a Danish Reference Year (DRY) [DMI, 2013] is used as input for energyPRO regarding solar collectors, heat demand and COP calculations. DRY data represents a typical year in Denmark and is divided into different zones. [DMI, 2013] Due to the location of Aabybro DH DRY data for "Zone 2 – Inland parts of Jutland" is used as hourly values for the ambient temperature. The annual variation of the temperatures can be seen on Figure 6.3.

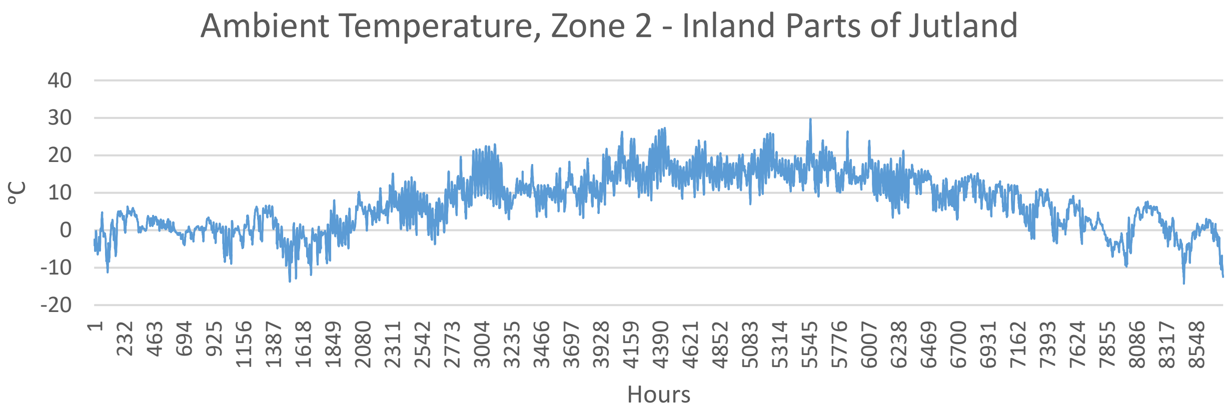

Figure 6.3 - Ambient temperature over a year. Based on data from [EMD International A/S, 2019], [DMI, 2013]

Datasets for global radiation applied as input data for the solar collectors in energyPRO, "Zone 1 – Northern Jutland" is used. The direct and diffuse radiation in W/m^2 can be seen on Figure 6.4. As the DRY data represents a typical year, the data a considered representative for a typical production year of Aabybro DH and is thus used throughout the whole calculation period. However, these external conditions will vary between the years and consequently also the production.

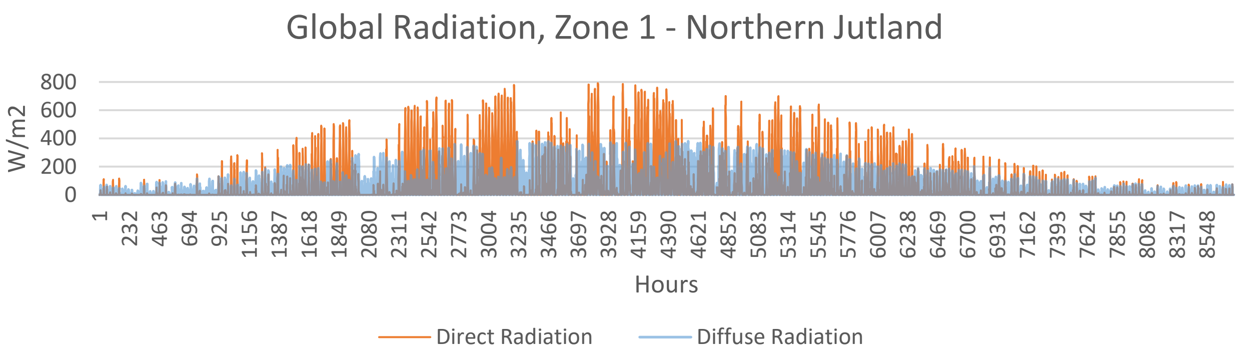

Figure 6.4 - Direct and diffuse radiation. Based on data from [EMD International A/S, 2019] [DMI, 2013]

The actual measured flow and return temperatures of Aabybro DH is used in energyPRO for calculating the annual heat production from the solar collectors and for calculating the theoretical

COP value of the HP’s, later described in this chapter. The flow and return temperature throughout the year can be seen on Figure 6.5.

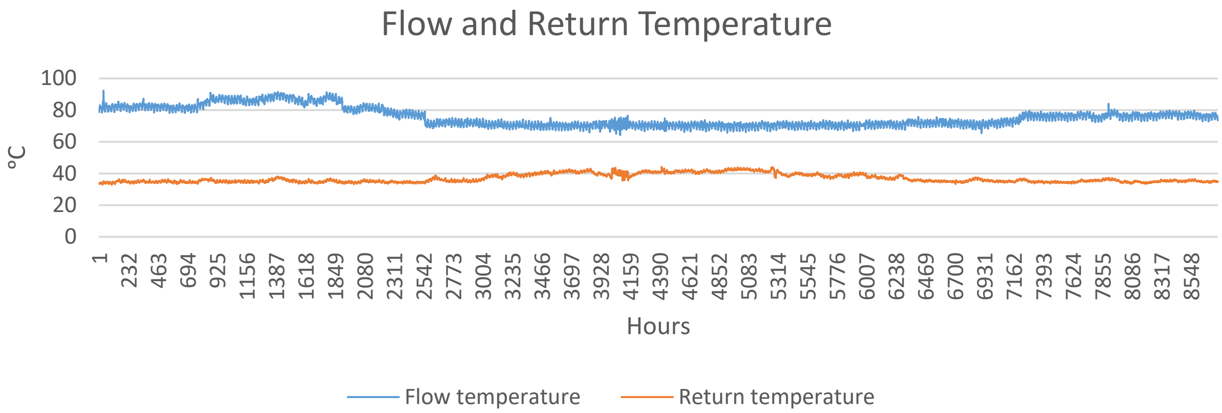

Figure 6.5 - Flow and return temperature of Aabybro DH. [Aabybro DH, 2019]

In order to calculate the hourly COP value of a HP using a stream as heat source, the temperatures of Ryå is needed. The temperatures of Ryå over the past six years has been retrieved from Orbicon [2019] and is illustrated by blue line on Figure 6.6.

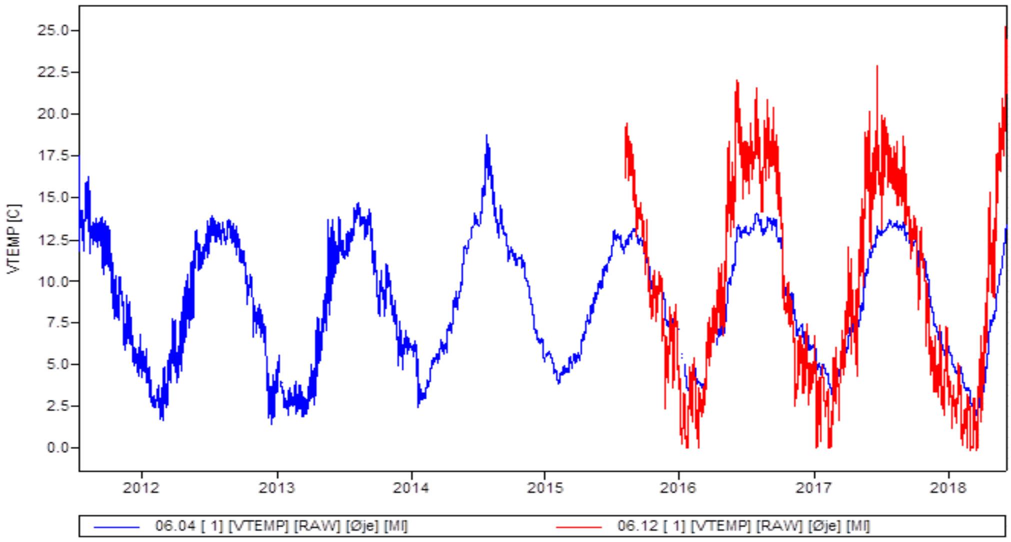

Figure 6.6 - Temperatures Ryå between 2012-2018. Data from [Orbicon, 2019]

As hourly values of the temperature have not been able to be retrieved in Excel format, monthly averages of the above Figure 6.6 temperatures is used. Despite not having the hourly values, the data is still considered representative as the temperatures of a stream in general will not vary as much on an hourly basis compared to the air temperature. The average flow of Ryå, based on daily measurements between 2008-2016, is 6m^3/s.

6.3 Fuel Prices, Tariffs and Taxes

As elaborated earlier, fuel prices, taxes and tariffs are expected to have a major influence on the feasibility of integrating wind in Aabybro. As described in Chapter 1 and as seen on Figure 6.7 the electricity price has fluctuated substantially from 2004 to 2018.

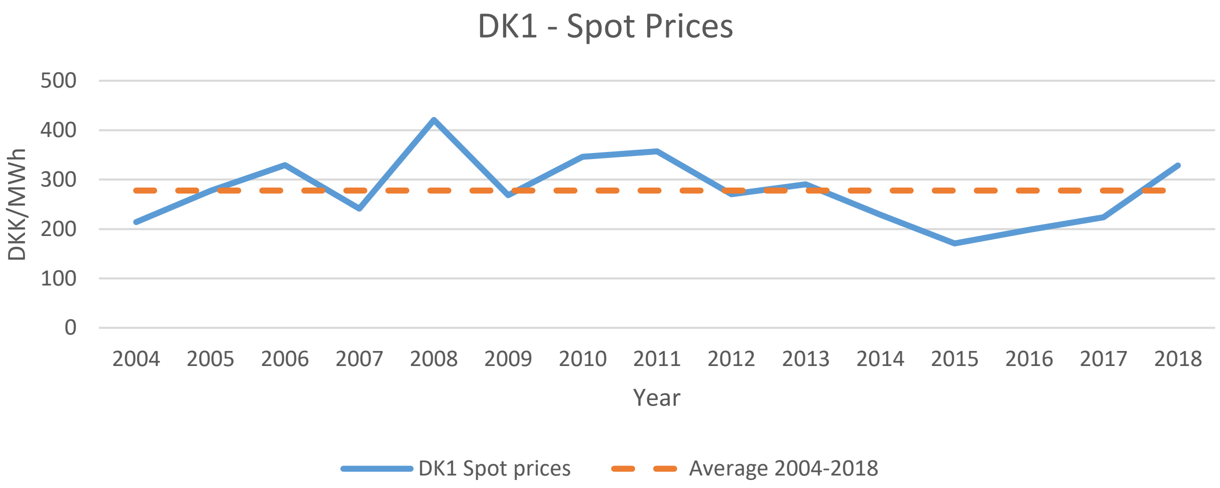

Figure 6.7 - Annual average spot prices and average 2004-2018 [Nord Pool, 2019]

Whereas the electricity price from 2008 and up until 2015 in general have showed a decreasing tendency, the electricity price of recent years has showed a significant increase. As the future electricity price is difficult to predict, while the hourly variations are still considered important, an average electricity price of the years from 2004-2018 with hourly fluctuations of 2018 is used in all scenarios that includes a full or partly grid connection. Using the annual prices will lower the average price compared to using fixed 2018-electricity prices, which may affect the outcome of scenarios where electricity sale and consumption is included. In the reference and basis scenarios the actual average price of wood chips in Aabybro DH is used. Table 6.4 gives an overview of the applied fuel and electricity prices.

Fuel and electricity prices		
Wood chips	169 DKK/MWh	Average of Aabybro DH 2018
Natural gas	183 DKK/MWh	2018 spot prices [Aabybro DH, 2018]
Electricity	278 DKK/MWh	Average DK1 [Nord Pool, 2019]

Table 6.4 - Applied fuel and electricity prices

A tax of 1.8 DKK/MWh for biomass is applied. [SKAT, 2019A] The following table gives an overview of the applied assumptions for electricity taxes and tariffs for each of the grid connection options elaborated in Chapter 4.

	Full connection	Partly connected	Off-grid
Electricity tax [DKK/MWh]	155	0	0
Tariffs – Energinet [DKK/MWh]	80	0	0
Tariffs – Evonet [DKK/MWh]	155.1	129.7	0

Table 6.5 - Applied tariffs and taxes for each grid-connection option [Energinet, 2019] [Evonet, 2019B] [Danish Parliament, 2019]

As it politically has been decided to decrease the electricity tax by 2021, an electricity tax of 155 DKK/MWh is used throughout the calculation period. [Danish Parliament, 2018] The above applied tariffs for Energinet and Evonet will naturally also vary between the years but will also be kept constant in the calculation period due to not knowing the future level.

6.4 Heat Pump and Electric Boiler Specifications

6.4.1 Heat pump

In general HP's move heat from a low-temperature level to a higher. As described in Chapter 4, a HP draws heat from a heat source, the input heat, which is converted to a higher temperature, the output heat, through a closed process. [DEA, 2019C] When using electricity, the type of HP is a compression HP, which typically consist of four main components; An evaporator, a compressor, a condenser and an expansion valve, illustrated on Figure 6.8.

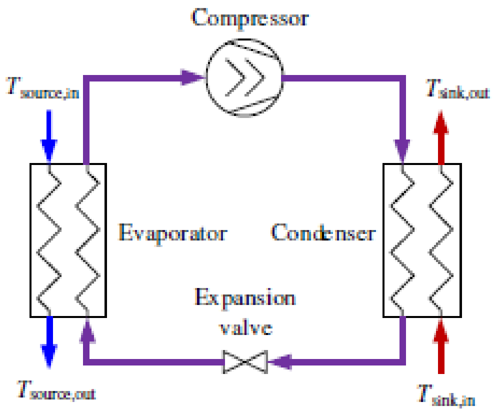

Figure 6.8 - Principle of compression Heat pump [DEA, 2019C]

In a HP the heat uptake and release happen through a circulation of a refrigerant in a closed loop. In the evaporator the refrigerant absorbs heat from the heat source and evaporates at low temperatures. In the compressor the evaporated refrigerant is compressed and led to the condenser at higher temperatures. The compressor is in this case driven by electricity and is therefore, where the main part of electricity is consumed. In the condenser the refrigerant condenses at higher temperatures and heat is released through a heat exchanger to the DH. The condensed refrigerant is now lead through an expansion valve which maintain the pressure difference and leads the condensed refrigerant from the high-pressure side to the evaporator in the low-pressure side. [DEA, 2017A] Due to this process of a HP and the varying power supply from a wind turbine, the sizing and revolutions of the specific HP in praxis is considered important. For a compression HP the COP is usually between 3-5, but will, as described earlier, depend on the efficiency of the specific HP and temperature of the heat source as well as the temperature difference of the DH. [DEA, 2019C] For both the Ryå and the ambient air the theoretical COP value is calculated on an hourly basis, using the Lorenz COP expression which is multiplied with the HP efficiency.

$$COP = COP_{Lorenz} * HP\ effeciency$$

The Lorenz COP is applied as it is commonly used for HP's in DH and is furthermore also the standard method applied for HP's in energyPRO. [DEA, 2017B] [EMD International A/S, 2019E]. The *HP efficiency* depends on the specific HP, but is usually between 40-60% of the theoretical COP. [DEA, 2017A] The specific efficiency is based on data from Johnson Controls [2019] and NIRAS [2019]. The theoretical Lorenz COP depends on the distribution temperatures of Aabybro DH as well as the heat source temperature of Ryå and the ambient air. The COP_{Lorenz} can be calculated using the following expression.

$$COP_{Lorenz} = \frac{T_{HighMean}}{T_{HighMean} - T_{LowMean}}$$

Where,

$T_{HighMean}$	$Average\ supply\ temperature\ of\ DH$ [°C]
$T_{LowMean}$	$Average\ temperature\ of\ heat\ source$ [°C]

$T_{HighMean}$ and $T_{LowMean}$ is calculated using the following expression:

$$T_{HighMean} = \frac{T_{HighOutlet} - T_{HighInlet}}{ln\left(\frac{T_{HighOutlet} + 273.15}{T_{HighInlet} + 273.15}\right)}$$

$$T_{LowMean} = \frac{T_{LowOutlet} - T_{LowInlet}}{ln\left(\frac{T_{LowOutlet} + 273.15}{T_{LowInlet} + 273.15}\right)}$$

Where,

$T_{HighOutlet}$	$Supply\ temperature\ from\ HP$ [°C]
$T_{HighInlet}$	$Return\ temperature\ to\ HP$ [°C]
$T_{LowOutlet}$	$Temperature\ heat\ source\ is\ cooled\ down\ from$ [°C]
$T_{LowInlet}$	$Temperature\ heat\ source\ is\ cooled\ down\ to$ [°C]

[EMD International, 2019E]

Based on the above expression, the COP value is calculated for a HP using Ryå and the ambient air as heat source on an hourly basis. The supply temperature from the HP can according to Aabybro DH [2019] be calculated with a constant of 70°C. The actual hourly return temperatures, presented on Figure 6.5, is applied. The hourly COP values are calculated in Excel and used as time series in energyPRO which are then multiplied with the specific electric capacity of the HP in each scenario, for calculating the potential heat output in each hour. The calculated COP value of air and Ryå can be seen on the following Figure 6.9 and Figure 6.10:

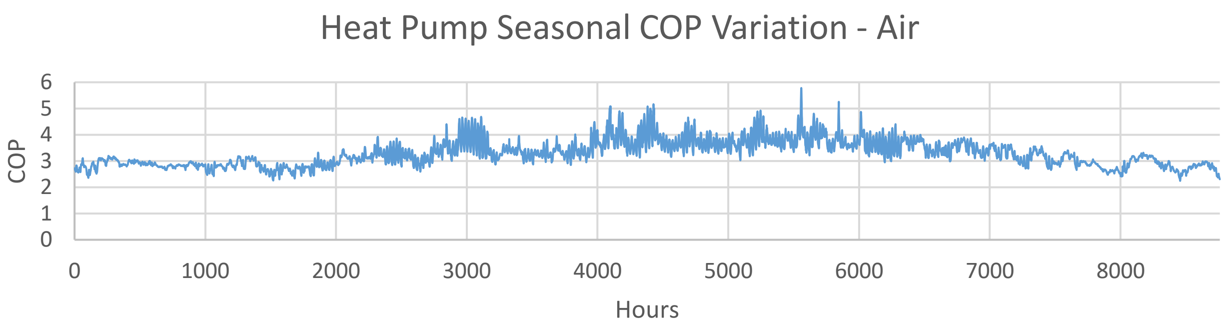

Figure 6.9 - Calculated Heat pump COP - Air

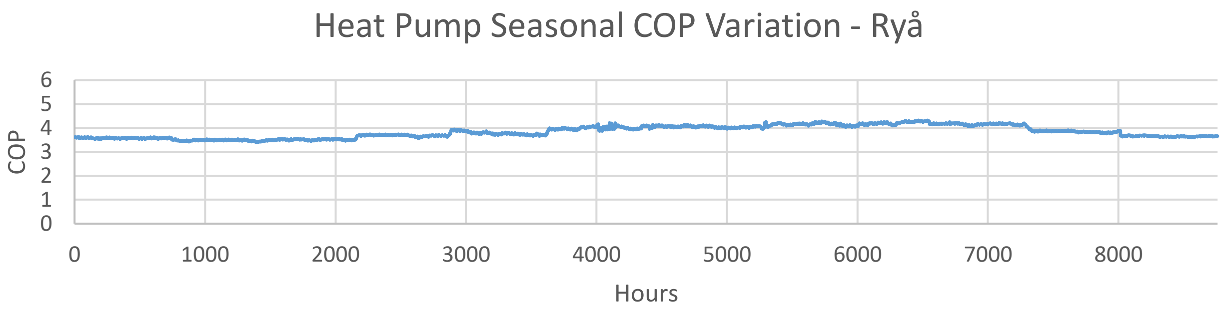

Figure 6.10 - Calculated heat pump COP - Ryå

As it can be seen on the above Figures, the hourly and seasonal variation of the COP value is higher when using the ambient air as heat source when compared to using Ryå. As the temperature of the ambient air is usually lower during the heat season and opposite, higher during the summer, the COP value during the winter is usually lower compared to other heat sources. This also apply to some extend for using a stream as heat source. However, as it could be seen on Figure 6.6 the measured temperature of Ryå, never go below 0 °C and rarely below 2.5 °C, and is thus, in general, a more stable heat source than the ambient air. This can also be seen on Figure 6.10.

Whereas the cooling of the heat source is dependent of the seizing and uptake of the heat absorbers the cooling when using Ryå as heat source, is also affected by the flow. For heat uptake pillow plates can be used [Atcho, 2019] If a separate canal is made for the pillow plates in Ryå, the flow can be expected to be reduced to the half, 3 m3/sec ≈ 2991kg/sec. If for instance an electricity uptake of 1,000kW is expected for the HP and the seasonal COP is 3.84, retrieved from NIRAS [2019] and Johnson Controls [2019], it equals a cooling effect of 2,840kW. By the use of these values can an estimation of the cooling of the heat source can be calculated:

$$Q = m * c * \Delta T$$

Where,

m	$Volume\ (kg)$
c	$Specific\ heat\ capacity\ (kJ/kg * {}^{o}\mathrm{C})$
ΔT	$Temperature\ difference\ ({}^{o}\mathrm{C})$

Thus,

$$Q_{Cooling} = 2991kg./\sec * 4.18\frac{kJ}{kg*°C} * \Delta T \rightarrow 2{,}840kW = 12{,}570\frac{kJ}{sec} * \ \Delta T \rightarrow \Delta T \approx 0.2°C$$

[NIRAS, 2019]

Thus, is the cooling of Ryå calculated to be around 0.2°C. A summary of the specifications for HP's using air and stream as heat sources, are presented in the following Table 6.6:

Heat Pump Specifications			
	Term	*Ryå*	*Ambient air*
DH supply water HP	$T_{HighOutlet}$	70°C	70°C
DH return water HP	$T_{HighInlet}$	$Hourly\ return\ temp$ °C	$Hourly\ return\ temp$ °C
Heat source	$T_{LowOutlet}$	$Temp\ of\ Stream$ °C	$Temp\ of\ ambient\ air$ °C
Heat source cooled	$T_{LowInlet}$	$T_{Stream} - 0.2°C$	$T_{Ambient} - 5°C$
Average Lorenz COP	COP_{Lorenz}	7.39	6.92

Table 6.6 - Applied heat pump specifications. Cooling of air is based on [NIRAS, 2018]

The HP efficiencies applied for the calculated Lorenz COP model is 52% for Ryå and 48% for the ambient air, which is based on the specific HP from Sabroe [Johnson Controls, 2019] under given circumstances. In order to validate and adjust the efficiencies for the COP Lorenz model, the COP value for the specific HP is retrieved for the average monthly temperatures of Ryå and the ambient air as fix points. Using the above mentioned efficiencies, the seasonal COP (SCOP) for using Ryå is 3.84 and 3.30 for using the ambient air, which corresponds to the average of the retrieved COP values of the HP. Of the above values it can also be seen that despite higher peaks of the COP value when using the ambient air as heat source, the COP value over a year is still higher for using Ryå as heat source.

6.4.2 Electric boilers

An EB is a simpler technology that converts electrical energy into thermal energy. Different types of EB's are used for DH purposes in Denmark depending on the seizing, voltage level etc., but will in this *Thesis* be defined under the same term. [DEA, 2019C] Common for most EB's is that the ability to start up- and regulate within few seconds, which allows for flexible production. Opposite an electric driven HP, the technical properties of an EB only allows for a maximum efficiency of 100% but will however typically have lower investment costs. Due to the efficiency and current tax level, EB's are commonly used as peak load units operating at low spot prices or for ancillary services, explained in chapter 4. [Grøn Energi, 2017] [DEA, 2019C]

6.4.3 Capacities and priorities applied

In scenario 1 (New WTG + EB) an electric capacity of 4.3MW for the EB is chosen, which equals the rated output from the WTG. This is chosen as it is expected that most of the electricity can be utilised for heat with a COP of only 1. Furthermore, due to the general lower investment costs of an EB, fewer full load hours is usually required. [Grøn Energi, 2017] In all scenarios including the expected new WTG and a HP (Scenario 2+3), HP's are dimensioned with an electric capacity of 2MW, enabling the HP to potentially cover around of 60-70% of the heat demand of Aabybro. This is done as the investment costs of having an electric capacity of the HP equal to the capacity of the WTG and hence also the peak load of Aabybro, is expected to exceed the savings due to fewer full load operation hours. In the scenario combining both HP's and EB's (scenario 4) an electric capacity of 1MW for the HP and 3.3MW for the EB is applied. In this case, the full capacity of the wind turbine (4.3MW) can potentially be converted to thermal energy, also corresponding to 60-70% of the annual heat demand. This also applies for the existing wind turbine where the electrical capacity of both the HP and EB (scenario 5 + 6) will correspond to the capacity of the wind turbine of 0.6MW. Whereas the optimal capacity in reality may vary from the applied capacities in this *Thesis*, the velocity of the investigated scenarios is considered to give a representative indication of the business economic potential of integrating WtH in Aabybro. The applied capacities can also be seen in Appendix 2 along with the investments.

6.5 Wind Turbine Specifications

As described in Chapter 4, is has not been fully decided which type of WTG's the expected new wind park near Aabybro is going to consist of. For further work in this *Thesis* the SG SWT130-DD is chosen. As there is only one existing WTG near the DH network of Aabybro, this is included in the *Thesis*. The specifications for the two wind turbines can be seen on Table 6.7.

Wind Turbine Specifications		
	SG-130DD	NEG Micon
Rated power	4.3MW	0.6MW
Hub height	85m	40m
Roter diameter	130m	43m
Total height	150m	62m
Type	Synchronous	Asynchronous
Grid frequency	50Hz	50Hz

Table 6.7 - Wind turbine specifications [EMD International, 2019B] [DEA, 2019A]

The power output for a wind turbine at a given wind speed can be calculated using the following expression:

$$P = ½pv^3AC_p$$

Where,

p	Air density
v	Wind speed
A	Rotor area/swept area
C_p	Turbine efficiency

[DEA, 2019C]

The efficiency of the turbine varies with the wind speed, but usually reaches a maximum of 45-50% for modern WTG's. [DEA, 2019C] The actual power output of the two included WTG's at given wind speeds can be described by their power curves, illustrated on the following Figures:

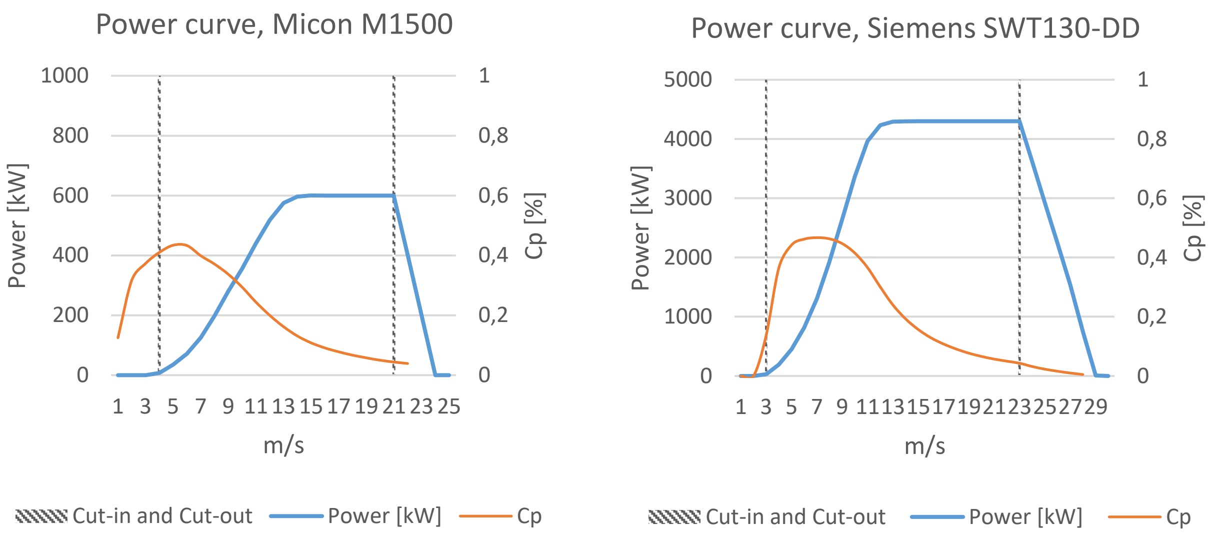

Figure 6.11 - Power curves for included wind turbines, Micon and Siemens [EMD International A/S, 2019B]

For hourly calculation of the power production throughout a year in windPRO, a wind resource file is made based on wind data and distribution from EMD [2019B] (EMD ConWex with WTI for west Denmark and scaler) [EMD International A/S, 2019B]. The official project proposal of [Dansk Vindenergi, 2019] suggests that for a wind park consisting of 16 Siemens WTG's in Renbæk Øst, the *annual energy production* (AEP) is expected to be around of 205,000 MWh. [Dansk Vindenergi, 2019] The AEP of the wind park calculated in windPRO is 204,329 MWh, which corresponds to a deviation of less than 1% compared to the expected AEP of the proposal. The annual AEP for the expected single WTG, seen on Figure 4.6, is calculated to be 13,655 MWh, distributed as seen on Figure 6.12. This corresponds to a capacity factor of 36%, which is also considered acceptable as in Denmark onshore turbines usually have a capacity factor of 35%. [DEA, 2019C] In order to represent a normal year of power production from the existing Micon wind turbine, the average AEP of all years in operation is used for comparison. [DEA, 2019A] The average AEP from the existing wind turbine is 1,190 MWh in reality and using windPRO the AEP is calculated to be 1,150 MWh, distributed as seen on Figure 6.13. This corresponds to a deviation of 3%.

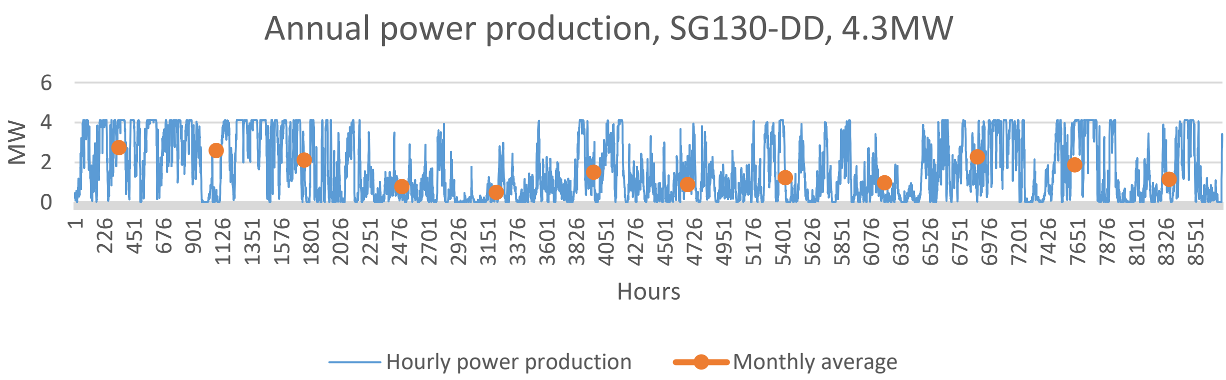

Figure 6.12 - Annual energy production over a year, SG130-DD, 4.3MW. Calculated in windPRO [EMD International A/S, 2019B]

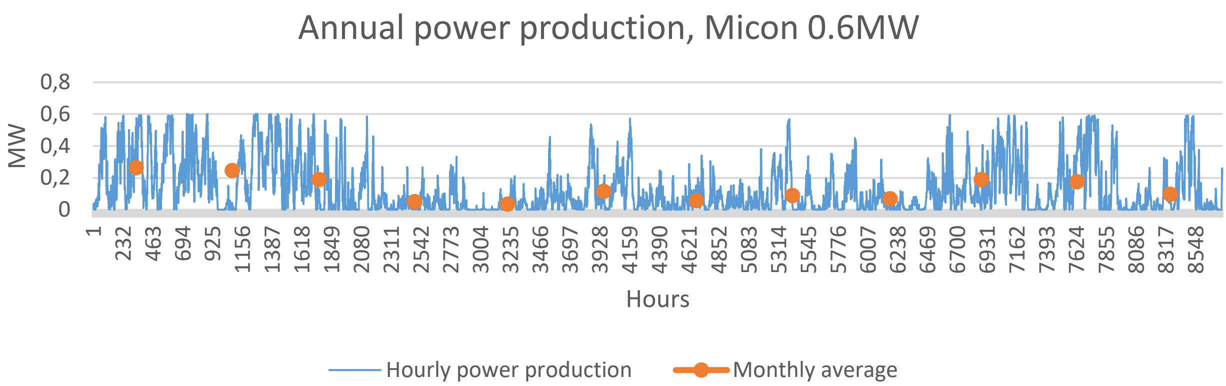

Figure 6.13 - Annual energy production over a year, Micon M1500 0.6MW. Calculated in windPRO [EMD International A/S, 2019B]

As described in Chapter 3 the hourly values of the wind power production are used as time series in energyPRO.

6.6 Financial Conditions

In Aabybro DH it is expected that a loan can be obtained with a fixed interest rate of 1,5% p.a. + 0,5% as a guarantee for the municipality [Aabybro DH, 2019] Hence, in all basis scenarios a real discount rate of 2% is applied and calculated over a 20-year period. All specific investment costs for each scenario can be seen in Appendix 2.

7 Technical and Economic Analysis

In this chapter the previously presented scenarios of Chapter 6, will be analysed. The chapter will start with a technical overview regarding the production distribution of each scenario, followed by an economic analysis based on the evaluation parameters presented in Chapter 4. Finally, the chapter will present the consequences each scenario will have on the overall biomass consumption of Aabybro DH. A recap of the included scenarios can be seen on the following Table 7.1

Scenarios			
Scenarios	Completely grid-connected	Partly grid-connected (a)	Off-grid (b)
1. New WTG + EB		X	X
2. New WTG + HP-Stream		X	X
3. New WTG + HP-Air		X	X
4. New WTG + HP + EB		X	X
5. Existing WTG + EB		X	X
6. Existing WTG + HP-Air		X	X
7. No WTG + EB	X		
8. No WTG + HP-Air	X		

Table 7.1 - Recap of included scenarios

As it could be seen in the previous chapter the main wind power production occur during the heat season, contrary to the solar based production which mainly occurs during the summer, where the heat demand is lower. Due to this seasonal variation of wind power and since the production on the solar collectors usually have the first priority to be used of technical reasons, integrating wind makes sense from a heat production point of view. The following Figure 7.1 illustrates the production distribution of each scenario for one year. The production distribution indicates how well the wind power is being utilised in the DH system of Aabybro.

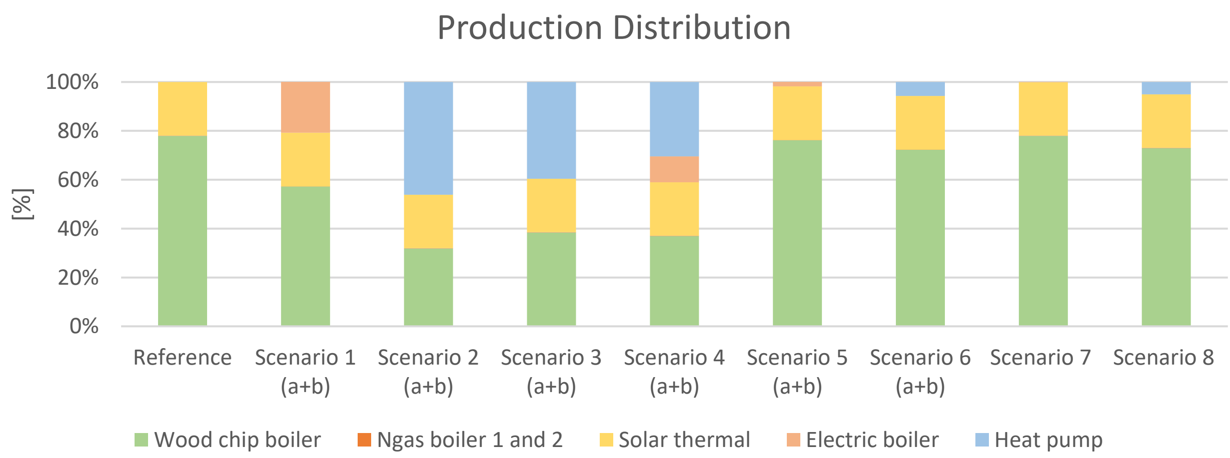

Figure 7.1 - Production distribution of the reference and scenarios.

In the reference it can be seen that the main production is based on their current wood chip boiler whereas around of 22% is produced on their solar collectors. As the solar collectors are given first priority, the production from here will be the same in all scenarios. This means, that it is mainly a displacement of biomass that will occur in the scenarios, which will vary depending on the hourly heat demand, storage opportunities as well as the wind power production and capacity of the heat producing units.

In scenario 1, around of 20% of the heat is being produced on an EB supplied with power from a new WTG where almost all the wind power produced, is being utilised. Only a few hours during the summer where the storage is being filled with heat produced on the solar collectors, potential electricity produced on the WTG is not being utilised for heating purposes. In Scenario 2 and 3 where the wind power is being utilised in HP's, it can be seen that more biomass is being displaced due to the capacity and COP of the HP's. Here it can be seen that due to the efficiency of the HP using Ryå as heat source, more heat from the wood chip boiler is being displaced when compared to a HP using air as heat source. In these scenarios around 55% of the electricity produced is being utilised for heat, producing between 40% and 46% of the annual heat demand. An example of the electricity production and consumption can be seen on Figure 7.2. In scenario 4, where 1MW out of 4.3MW is utilised using a HP and the remaining 3.3MW through an EB, around of 40% of the annual heat demand is being produced based on wind power, utilising 82% of the potential electricity produced.

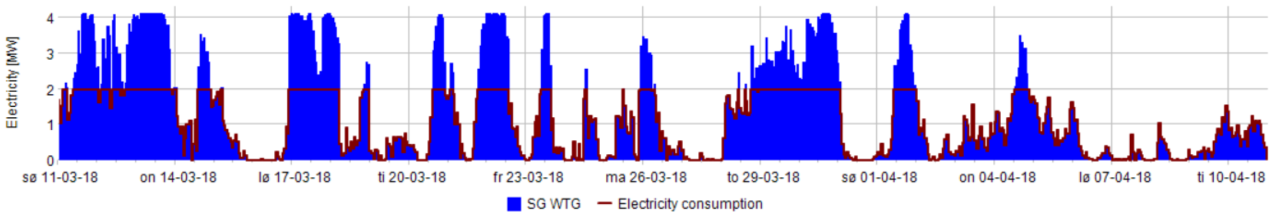

Figure 7.2 - Example of electricity production and consumption in scenario 3 (New WTG + HP-air). Made in energyPRO

In Scenario 5, where electricity is being produced on the existing nearby WTG, 97% of the annual electricity produced is converted directly to thermal energy using an EB. However, despite the high utilisation rate, the EB heat production only contribute to what corresponds to around of 2% of the annual heat demand. This is due to the lower capacity of the existing WTG as well as the limitations of the EB's where electric energy only is converted to thermal energy 1:1. In scenario 6 where electricity produced on the existing WTG is utilised in a HP (air) more heat is being produced. In this scenario almost all electricity is also being utilised resulting in around 3.500MWh of heat being produced. Out of the annual heat demand, this however still only corresponds to 6%.

In scenario 7 and 8, electricity is not produced on a nearby WTG's but rather drawn from the public grid when electricity prices are low. However, due to tariffs, taxes and low marginal production costs of the wood chip boiler, the EB in scenario 7 ends up with having very few operation hours. Due to a higher efficiency of the HP, more heat is being produced in scenario 8, however, this only contribute to a minor part of the annual heat production.

Common for most of the scenarios is that the existing heat storages enable a more flexible production and utilisation of the intermittent production occurring from the WTG's and solar thermal. An example of this can be seen on Figure 7.3, that illustrates the production and storage content over a period of one month in scenario 4.

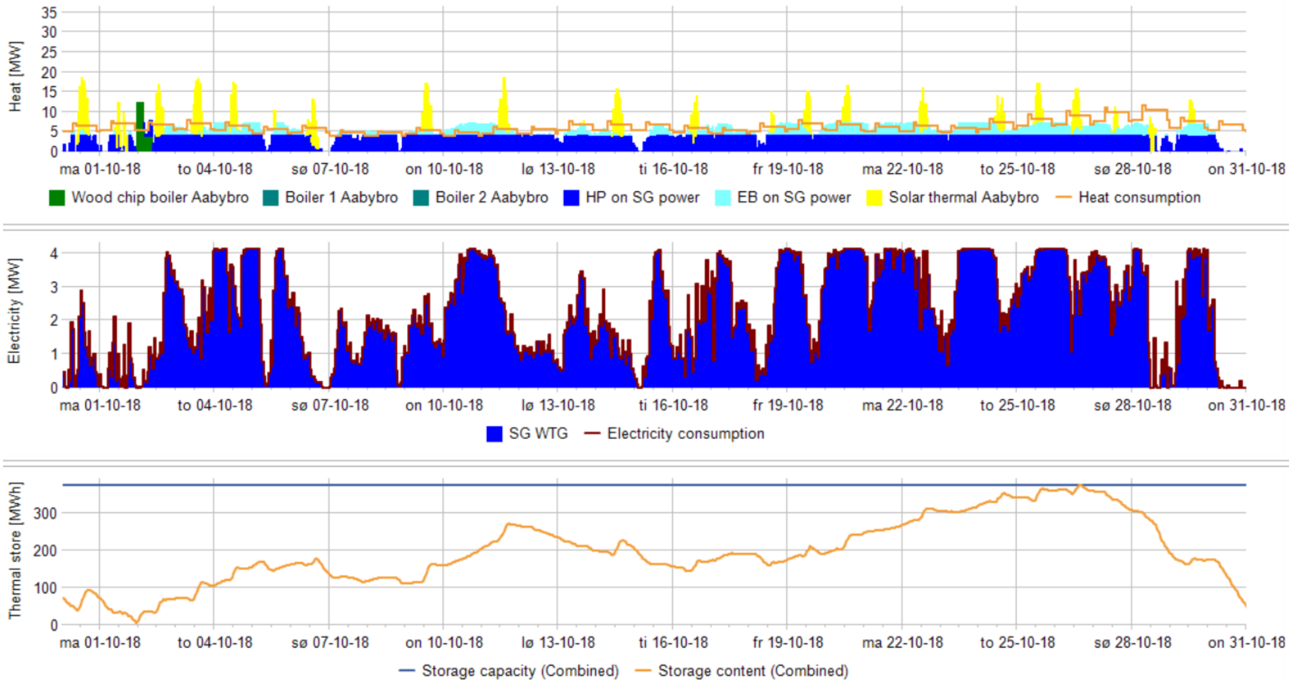

Figure 7.3 - energyPRO example of heat production, electricity consumption and heat storage content for a month in scenario 4 (New WTG + HP and EB)

On Figure 7.3, it can also be seen that in this specific month the storages enable all electricity produced on the WTG to be utilised by the HP and EB. If heat produced on the HP and EB in the displayed scenario was not connected to the heat storages, the heat produced will be reduced by 8%. However, contrary, it can also be seen on Figure 7.3 that there is a chance that the existing heat storages may even be too small when integrating more intermittent RE due to the existing storage capacity only dimensioned to match the existing production setup. However, if the storage capacity in this case, as an example, were to be increased by 50%, the potential heat production would only increase by less than 1%, indicating that, in this case, the existing storage capacity is optimally dimensioned. This is however calculated knowing the forecasts, whereas in reality one might only have an expectation regarding the coming days forecasts and production and operate accordingly, charging and discharging the storage differently. Consequently, a storage in this case could potentially prove to be too small. On Table 7.2 the potential increase and decrease in the production can be seen in a situation where a larger storage is added, a situation with no solar thermal and a situation where the production is not allowed for the storage. Due to almost all of the electricity being utilised in scenario 5 and 6 (existing WTG) no real change in the production is seen.

Potential Production			
	Larger storage [% - increase]	No solar thermal [% - increase]	No production to storage allowed [% - decrease]
New WTG + EB	0	8	6
New WTG + HP-Stream	1	22	9
New WTG + HP-Air	1	23	9
New WTG + HP + EB	0	19	8
Existing WTG + EB	-	-	-
Existing WTG + HP-Air	-	-	7
No WTG + EB	4	9	63
No WTG + HP-Air	3	7	38

Table 7.2 - Potential production with a larger storage, with no solar thermal and with no production to storage allowed. Based on energyPRO calculations

As it can be seen on Table 7.2 a larger storage doesn't increase the production much. However if the HP's and EB's on the other hand are not allowed to deliver heat to the storage, the potential production would decrease rather significant. Note that the rather large percentage decrease in scenario 7 only amounts for a few MWh, due to a few operation hours in the first place. Finally, it is noticeable that the solar thermal actually have a large impact in the potential heat production, despite being seasonally staggered compared to the main heat demand and wind power production. If the solar thermal was not installed the business economic potential for WtH would be increased.

The production distribution is directly connected to the biomass consumption of the scenarios. On Figure 7.4, the annual biomass consumption can be seen.

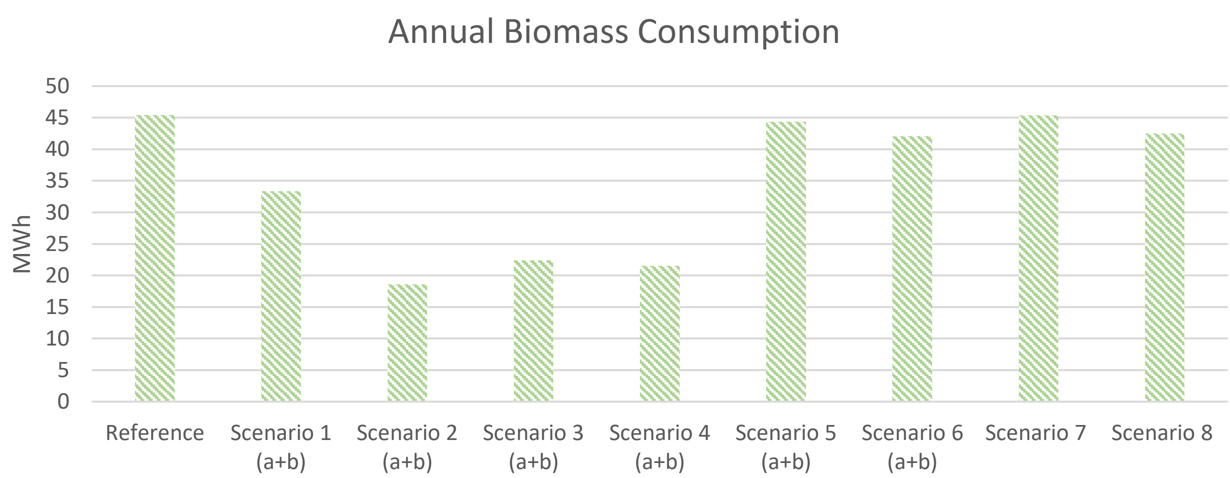

Figure 7.4 - Annual biomass consumption of each scenario and reference

As it can be seen on the above Figure 7.4, Scenario 2 results in the highest biomass reduction of all tested scenarios whereas scenario 7 results in the least. It is not surprising that the biomass reduction depends on the installed capacity (and efficiency) as well as the operation hours. Hence, looking solely at reducing the biomass consumption when integrating wind to the system, scenarios including HP's are preferred in the case of Aabybro. However, as for most projects the business economy also needs to match in order to become a reality. As described in Chapter 4, the main goal of Aabybro is to secure a low heat price in the future, which is why this will be the main economic evaluation parameter. Figure 7.5 illustrates the heat price for all tested scenarios described in Chapter 5, with the applied assumptions described in Chapter 6.

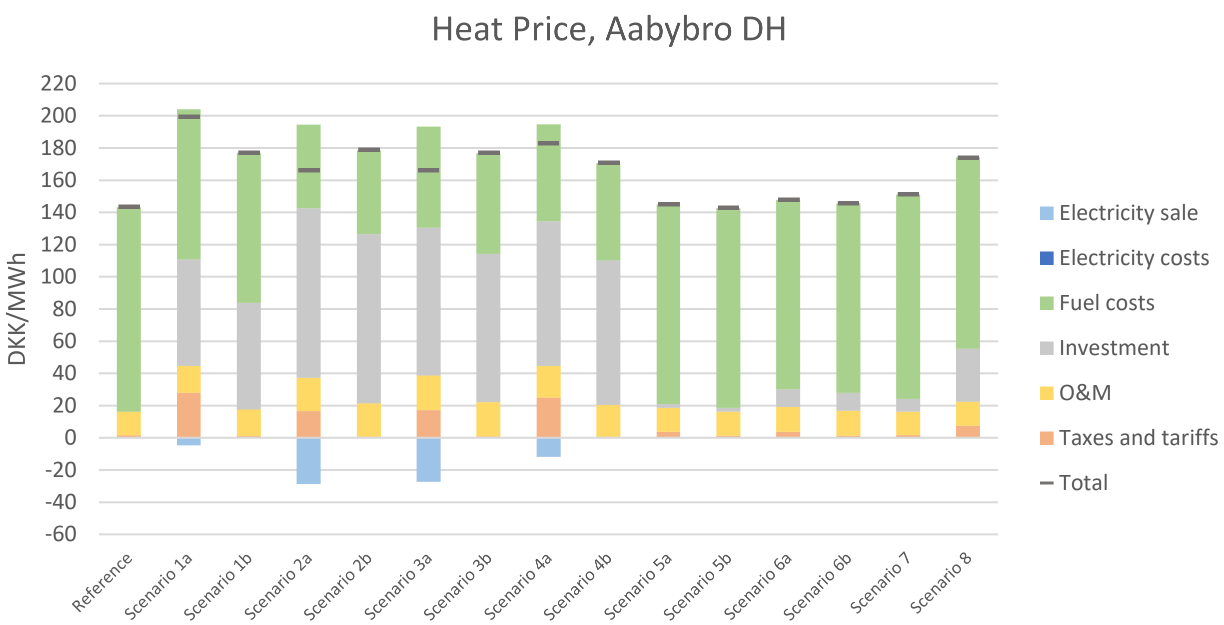

Figure 7.5 - Calculated heat price of each scenario in DKK/MWh, compared to a reference. The black line indicates the resulting heat price which for all partly grid-connected scenarios (a) is with excess electricity sale.

As it can be seen on Figure 7.5, the resulting heat price for the overall system in the reference is 143 DKK/MWh, which can be considered relatively low. The relatively low heat price of the reference is mainly due to biomass and solar based heat production being exempt from taxes, also described in Chapter 1. This means that the main expenses for operating the system are only related to the costs of wood chips and O&M. As presented on Table 5.1 in Chapter 5, all *b* scenarios are off-grid solutions where no taxes and tariffs for electricity consumption applies. Off-grid solutions however also means that sale of electricity is not possible. Due to the different groups of net settlement and uncertainties regarding the sale of excess electricity, explained in Chapter 4, the resulting heat price of both with and without electricity sale (a) can be seen on Figure 7.5, illustrated with the dark line.

Despite a major part of the electricity being consumed by the EB and utilised directly for heat in Scenario 1, the investment costs and tariffs (capacity tariff), have a major impact on the heat price, resulting scenario 1 in having the highest heat price of all scenarios. In an off-grid solution where no taxes and tariffs are included, the heat price is now competitive with all scenarios containing the new WTG, but is, however, still not competitive compared to the reference. In scenario 2 and 3 a major reduction in the fuel costs can be seen due to a larger displacement of biomass, also seen on Figure 7.1. However common for the two scenarios containing only HP's, is that the investment represents a relatively large part of the heat price compared to the scenario with only an EB. Furthermore, in these scenarios there are, as described previously, relatively many hours of excess electricity production, which are not utilised for heat. Consequently, the profitability of these scenarios is relatively sensitive to the sale of excess electricity. Comparing the two HP solutions (stream vs. air), it can be seen that despite a higher COP of the HP using Ryå as heat source, it is not completely enough to weigh up for the additional investment cost when compared to the heat price of a HP using air as heat source. The scenarios, however, result in a matching heat price of 166 DKK/MWh when partly grid-connected. Consequently, in this case it can be seen that HP's in combination with a new WTG results in a lower heat price than when the WTG is connected to an EB, due to an overall higher efficiency which is able to weigh up for the additional investment costs when partly connected. Comparing the off-grid solutions no major big difference in the heat price between the EB solution and HP solution is present, but overall provides a lower heat price if sale of electricity is not included. Consequently, it can be seen that the capacity tariff, despite being reduced compared to the regular net tariff, and the possibility to sell electricity actually have a major impact on the heat price. Scenario 4 will due to a combined high utilization and efficiency result in the lowest heat price of all the scenarios containing a new WTG (1-4) in an off-grid situation. Scenario 5 is the only scenario providing a lower heat price than the reference. This is however only reduced by less than 1 DKK/MWh compared to reference and is therefore not considered a substantial reduction. Despite almost all the electricity being utilised in scenario 6, the scenario results in a higher heat price compared to the reference as well. This is due to the amount of fuel saved not being able to compensate for the relatively larger investment costs.

In scenario 7 it could be seen that the EB almost had no operation hours when fully grid connected. This means that there won't be any major fuel reductions but only added investment costs, resulting in a higher heat price. In scenario 8 it was seen that the HP were able to reduce the fuel consumption to some extent, but due to the current taxes and tariffs when fully grid connected fewer operation hours also occur, and is thus, also not able to weigh up for the additional investment costs.

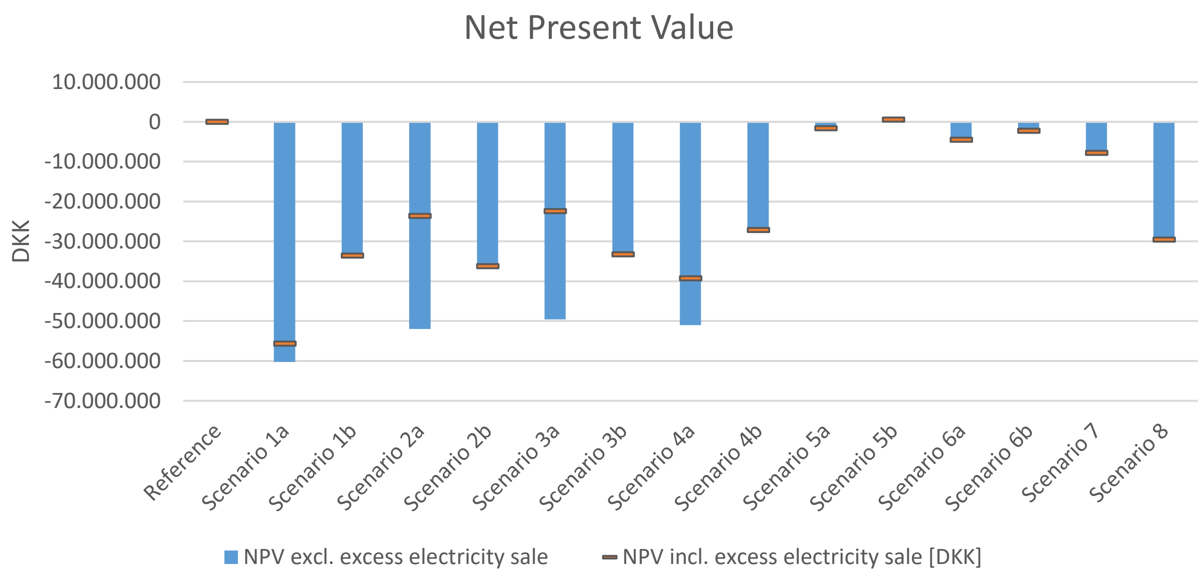

Figure 7.6 - Net Present Value of each scenario compared to the reference.

Comparing the scenarios in a Net Present Value, the same picture as for the heat price can be seen, having the scenario which provide a lower heat price (scenario 5) also providing a positive NPV. However, the slightly lower heat price compared to the reference as well as the only slightly positive

NPV makes the uncertainties related to this scenario relatively high. This specific scenario is also the only scenario to provide a simple payback time of less than 20 years (13 years), as seen on the following table.

Simple Payback time of Scenarios [Years]			
Scenarios	Completely grid-connected	Partly grid-connected (a)	Off-grid (b)
1. New WTG + EB		+20	+20
2. New WTG + HP-Stream		+20	+20
3. New WTG + HP-Air		+20	+20
4. New WTG + HP + EB		+20	+20
5. Existing WTG + EB		+20	13
6. Existing WTG + HP-Air		+20	+20
7. No WTG + EB	+20		
8. No WTG + HP-Air	+20		

Table 7.3 - Overview of simple payback time for each scenario.

7.1 Summary of Technical and Economic Analysis

In the analysis it was found that only one out of eight tested scenarios (5b – Existing WTG + EB, off-grid) provided a positive business economic result. However, the business economic gain in this specific scenario is considered marginal and therefore also related major uncertainties. Consequently, none of the basis scenarios were found to be attractive for WtH in Aabybro with the applied assumptions described in Chapter 6. General is, that scenarios where EB's are included provide a better result when off grid due to the capacity tariff and since most of the electricity produced is utilised for heat, only a relatively low amount of electricity is sold. For scenarios including HP's it is found that sale of excess electricity has a relatively large impact on the business economy and due to a high efficiency of the HP's, the capacity tariff for the DSO represent a minor part of the total heat price. However, if sale of excess electricity is not an option, an off-grid solution provides a better business economic result. In all scenarios it was found that the existing heat storages enable more of the electricity produced to be utilised for heating but also that the existing solar thermal prevent a relatively large amount of heat to be produced. The EB in combination with a new WTG is not entirely able to weigh up for the relatively large investment costs, compared to a HP, which, due to a higher efficiency, provides a better business economic result. Contrary, it can be seen that EB's, due to lower investment costs, provide a better business economic result in combination with an existing WTG's with a closer distance and no capacity tariff. It can furthermore be seen that in partly grid-connected scenarios sale of excess electricity have a relatively high impact on the business economic result. Whereas the EB's are better at utilising most of the electricity produced, especially when integrating a new WTG, HP's are substantially more efficient. Comparing the two heat sources, air and stream, it was found to be resulting in almost the same heat price, which means that added investment costs for a higher COP almost breaks even with one of reduced costs and COP in this case. In the scenarios containing a new WTG (Scenario 1-4) it was seen that despite annual operational savings in the range of 0.6-5 MDKK, the total investment costs of each scenario prevent a competitive heat price in a system which mainly comprises of biomass. However, if the solar collector field was not a part of the DH system, the business economic potential would be increased. Finally, it could be seen that with the current conditions a fully grid connected solution (scenario 7 and 8), is not competitive compared to the reference as well. In all tested scenarios it was found that scenarios including HP's were able to reduce the biomass consumption the most. Not surprisingly this is due to the capacity and efficiency of the HP's and WTG and hence, the ability to displace more biomass. Thus, seen from the point of view of saving biomass, Scenario 2, 3 and 4 are preferred, where HP's and a new WTG are included.

8 Sensitivity Analysis

The analysed scenarios of chapter 8 all depends on various assumptions, which potentially, if altered, can change the business economic feasibility of Wind to Heat integration in Aabybro. Hence, to test the uncertainty and significance of certain assumptions, a sensitivity analysis is carried out in the following chapter.

8.1 Biomass Price

As the DH system of Aabybro mainly consist of biomass-based production, the future price of biomass is expected to have an impact on the feasibility of the scenarios. Hence, a change in the price for wood chips will in this section be investigated. The sensitivity analysis on the price of biomass is conducted using the DEA [2018A] expected price development along with a 50% projected price increase. The applied biomass prices can be seen on Figure 8.1.

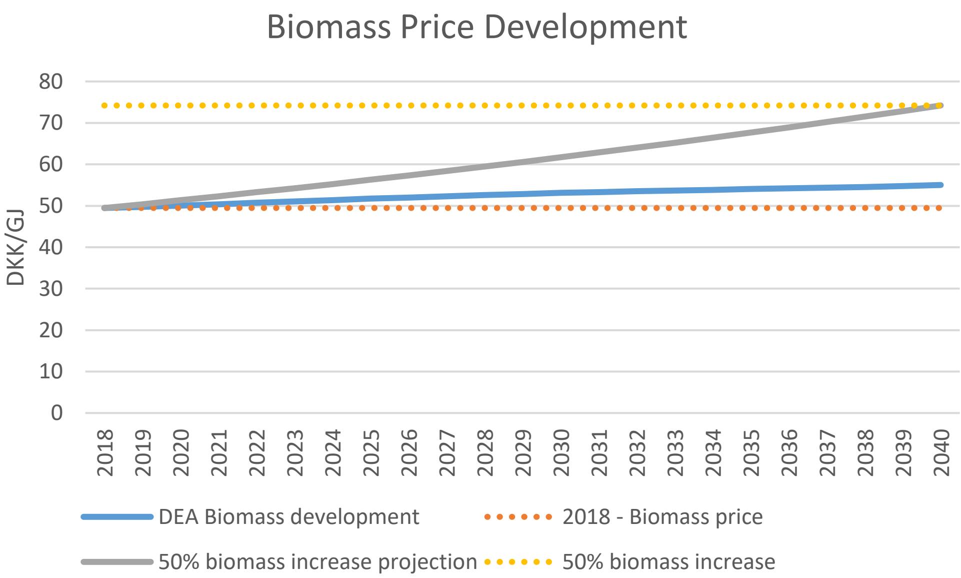

Figure 8.1 - Biomass Price development. Projected price of [DEA, 2018A] and a 50% projected increase

A 50% increase in the future biomass price may seem relatively high, but as biomass is considered a limited resource along with an expected increase in the demand, a more extreme case is chosen. Furthermore, an increase in the price of biomass can reflect the consequence of implementing a tax for the use of biomass in the future. Finally, the price increase could represent another fuel type.

General for the results of the scenarios are, that the more biomass being displaced, the greater the impact will a change in the price have. In the DEA projected biomass price increase, no scenarios result in a lower heat price compared to the reference and will thus also not result in a positive NPV, when looking at the whole calculation period, illustrated on Figure 8.2.

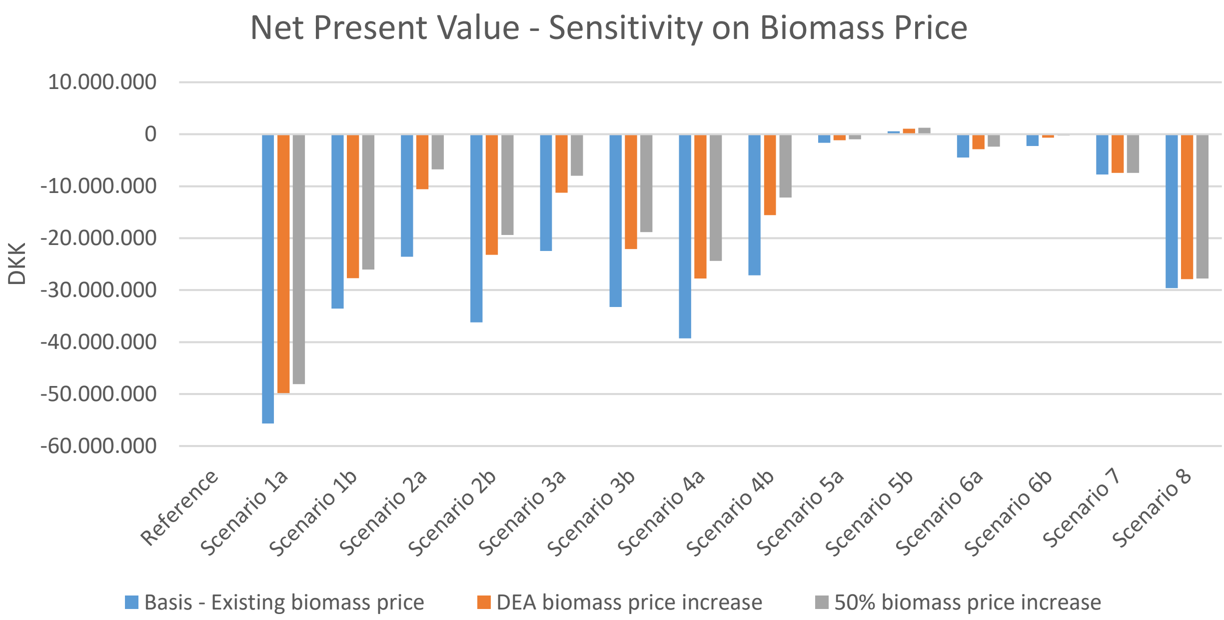

Figure 8.2 - Net present value showing the a sensitivity of different price projections over 20 years

In the 50% biomass increase projection, Scenario 2a+b, 3a, 4b, 5b and 6b provide a lower heat price than the reference by the end of the calculation period, whereas scenario 3b, 5a and 6a result in a matching heat price compared to the reference. Seen over time this price increase is however also not enough to provide a positive NPV, illustrated on Figure 8.2. When compared to the basis scenarios where the 2018-price level (current price) is applied, a relatively high impact can however be seen, providing a better business economic result than the basis scenarios (less negative), but still yet not positive. Hence, unless a sudden biomass increase, or taxation were to occur, the investigated future price increases are not able to provide a positive business economy for WtH in Aabybro. The SPB of an instant biomass increase of 50% can be seen on Table 8.1.

Simple Payback time - 50% biomass increase [Years]			
Scenarios	Completely grid-connected	Partly grid-connected (a)	Off-grid (b)
1. New WTG + EB		+20	+20
2. New WTG + HP-Stream		14	16
3. New WTG + HP-Air		15	16
4. New WTG + HP + EB		17	15
5. Existing WTG + EB		17	9
6. Existing WTG + HP-Air		16	13
7. No WTG + EB	+20		
8. No WTG + HP-Air	+20		

Table 8.1 - Simple payback time with a 50% increase from year one

The simple payback time (SPB) indicates the saving potential compared to the investment. However, neither does the SPB include the loan, nor does it include the value of time, and is therefore only used as a secondary evaluation parameter.

A change in the biomass price will due to the chosen operation strategy not cause any changes in biomass consumption and will thus be the same as illustrated on Figure 7.4.

8.2 Investment Costs

Whereas the marginal production costs of WtH based production in most scenarios proved to be lower than the marginal production costs of the wood chip boiler, it was contrary found that the investment costs of the investigated scenarios represent a relatively large part of the total heat price. Therefore, it is relevant to consider how much the investments are to be reduced in order to match the heat price of the reference. Due to the variety of the scenarios the exact same reduction will not apply for all scenarios, and is thus rather calculated for each individual scenario, illustrated on Figure 8.2.

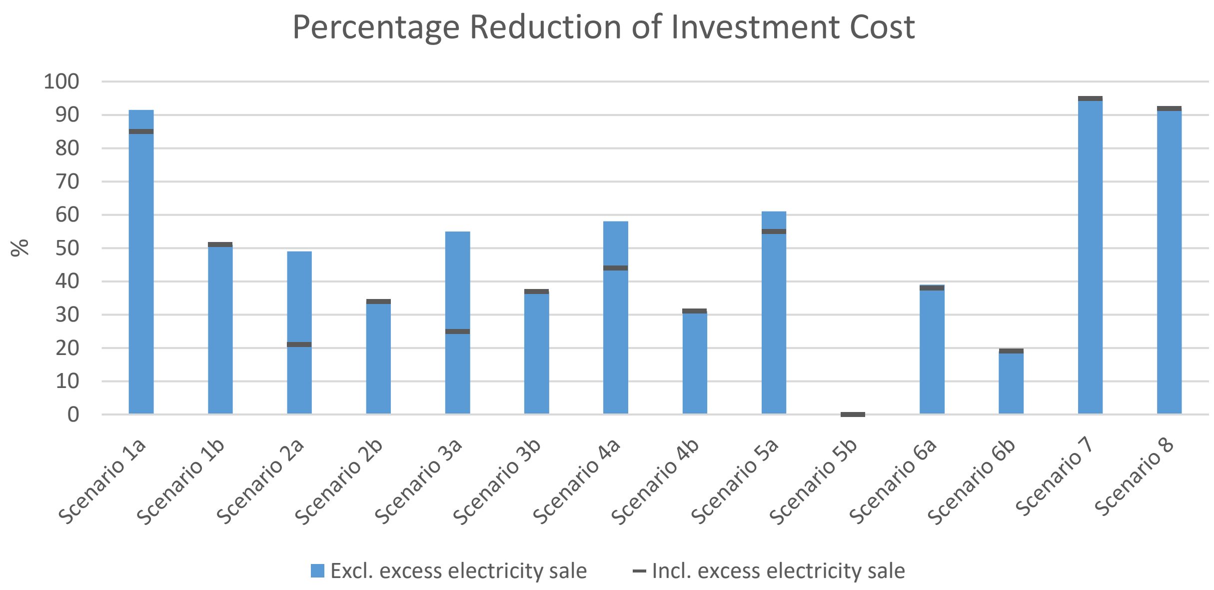

Figure 8.3 - Graph of the required percentage reduction of the investment costs in each scenario for matching the heat price of the reference

As for the relatively high variety in the business economic potential of the scenarios, seen on Figure 7.5 and Figure 7.6 it can be seen that the reduction of the investment costs also varies similar. Generally, it can be seen that the investments will have to be reduced relatively much before being competitive with the heat price of the reference. As seen in Appendix 2, the investment costs of the interconnection to and from the WTG/EB/HP varies between 27%-43% of the total investment, which if reduced, e.g. due to closer distance, would improve the business economic potential rather significant. This indicates that the distance between the WTG's/EB/HP and DH plant is critical when compared to a system where the main heat production is based on biomass and solar. As it can be seen on Figure 8.3, Scenario 2a and 6b require the lowest percentage reduction before resulting in a competitive heat price compared to the reference. However, percentage wise, Scenario 2a (new WTG + HP) may seem similar in comparison to scenario 6b (Existing WTG + HP), but is in a monetary value far greater. As scenario 7 and 8 (full grid connection) only resulted in a minor reduction in the operation costs of the DH system, the investment costs will have to be reduced with more than 90% before being competitive with the heat price of the reference system.

Another relevant parameter to include in a sensitivity analysis can be the discount rate. Regarding the discount rate, it is argued that the applied rate of 2% is a relatively low rate to begin with, which is why a higher rate will be considered most relevant. However, as almost all scenarios provide a higher heat price and negative NPV compared to the reference, a higher rate will only impair the business economic result.

Likewise, the sensitivities made for the future biomass price, reducing the investment costs will not affect the total biomass consumption of the scenarios, and will also thus remain the same as illustrated on Figure 7.4.

8.3 Electricity Sale - Profit Maximisation

As described earlier, sale of electricity is due to uncertainties not included in the operation strategy of the scenarios enabling as much of the electricity produced to be utilised for heating purposes. However, as it could be seen on Figure 7.5, sale of excess electricity still affect the business economic result in all partly grid-connected scenarios. Therefore, it is relevant to consider the consequences of including the hourly electricity prices in the operation strategy. If this is an option for the DH company in reality, this could potentially add flexibility to the production in a situation of future electricity price development.

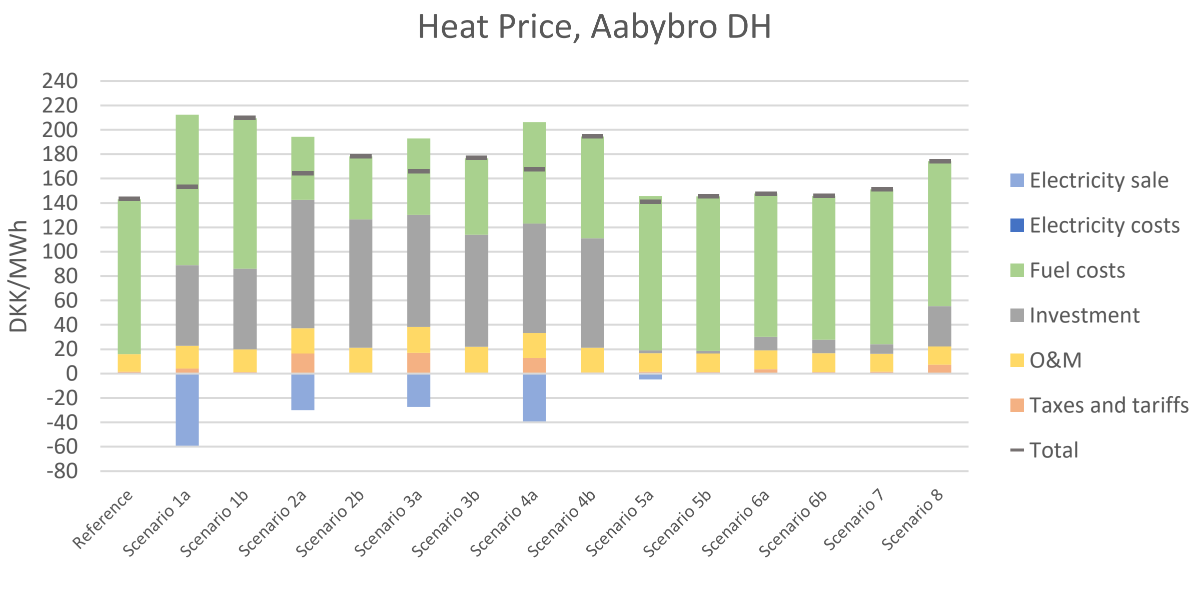

Figure 8.4 - Heat price of each scenario when electricity sale is included as a part of the operation strategy in energyPRO

All off-grid solutions (b) and fully grid connected scenarios will of course not be affected by the change in electricity sale and is therefore rather concentrated to the partly grid-connected scenarios (a), where the heat price can be seen with and without electricity sale. On Figure 8.4 it can be seen that compared to the basis scenarios on Figure 7.5, the electricity sale increases significantly (blue area) in all scenarios containing an EB, with the result of a reduced heat price (black line). This is due to the electricity prices in many cases being higher than the marginal production costs of producing heat on the wood chip boiler, that otherwise should be replaced. Hence, the heat production from the EB's are reduced to a minimum meaning that the EB's almost, to some extent, become unnecessary and the investment could potentially be reduced to only the WTG. However, it should be noticed that this is also a result of the applied electricity and fuel prices and having both (WTG + EB) can potentially add flexibility in terms of future electricity price fluctuations. Despite the reduction in optimised electricity sale is still not able to provide positive NPV and a lower heat price than the reference. Furthermore, the SPB isn't below 20 years. In all partly grid-connected scenarios containing a HP, the production distribution does not change much. This is due to the efficiency of the HP's, adding more value to producing and replacing heat production on the wood chip boiler, rather than selling electricity at spot prices.

If the DH company have the opportunity to profit optimize the electricity sale, the savings in biomass consumption will decrease compared to the basis scenarios, where most of the electricity produced is also utilised for heat. Consequently, the biomass consumption of the scenarios including EB's will increase, illustrated on Figure 8.5.

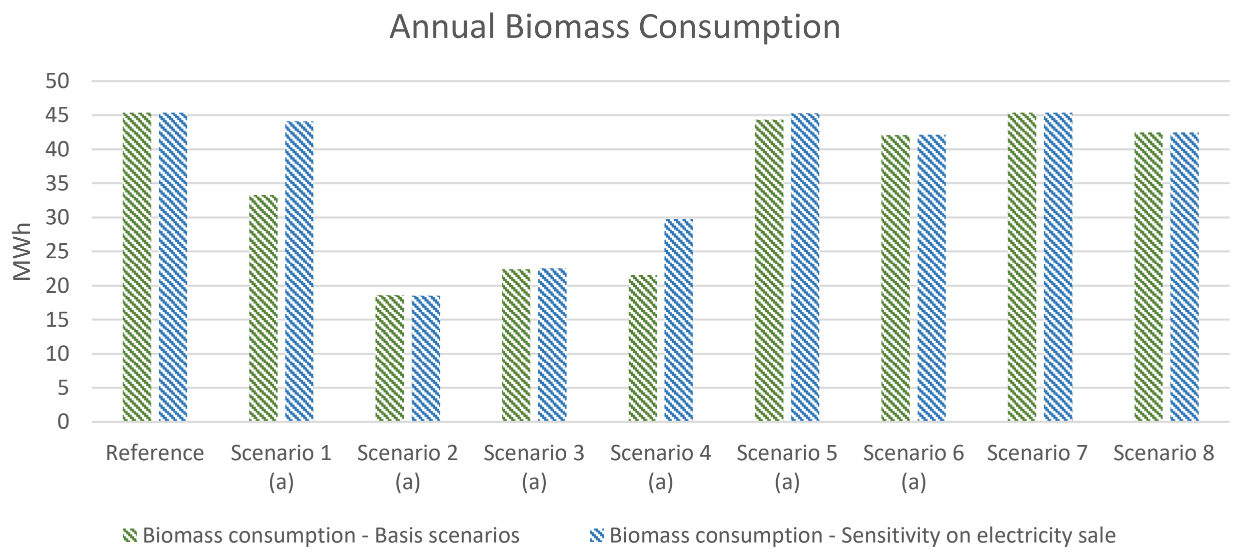

Figure 8.5 - Graph of the annual biomass consumption when electricity sale is included in the operation strategy of energyPRO

8.4 Electric Capacity

As elaborated in Chapter 4, certain assumptions regarding the capacity of the HP's and EB's are made. However, other capacities than the chosen may provide a better business economic result due to the correlation between the investment and energy savings, which especially for HP's, are linked to the operation hours. In scenario 6 (Existing WTG + HP) for instance, an electric capacity of the HP corresponding to the rated power output of the WTG was applied, which potentially may be oversized. On Figure 8.6 the full load hours of the HP in scenario 6 at different capacities can be seen.

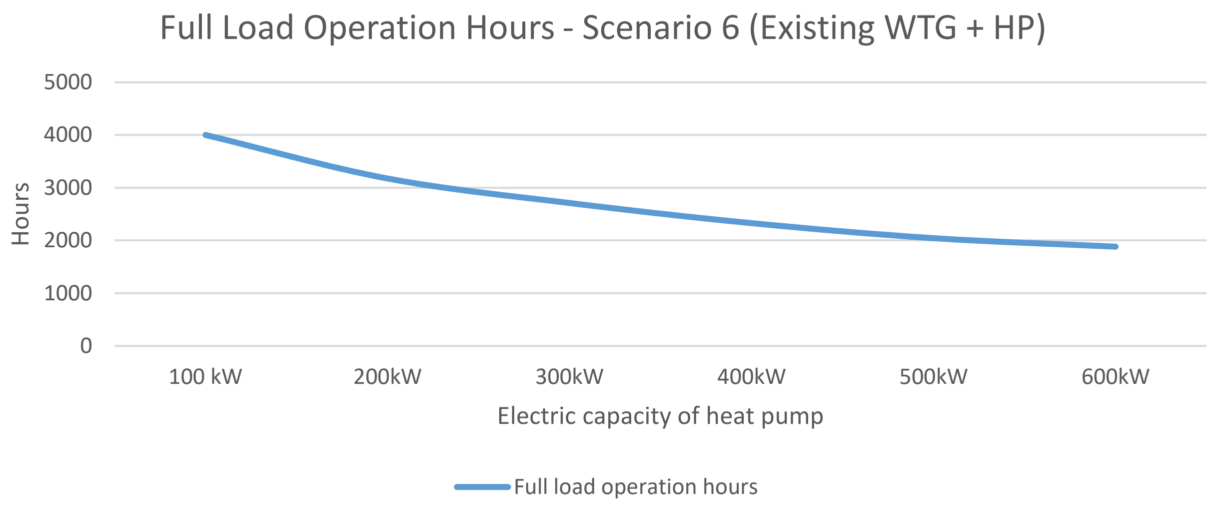

Figure 8.6 - Graph showing the full load hours of the heat pump at different capacities in scenario 6

Not surprisingly will the full load hours for the HP decrease with a higher capacity due to the WTG not producing at the rated capacity throughout the year. On the following Figure 8.7, a NPV of the above tested capacities for scenario 6 (a+b) can be seen.

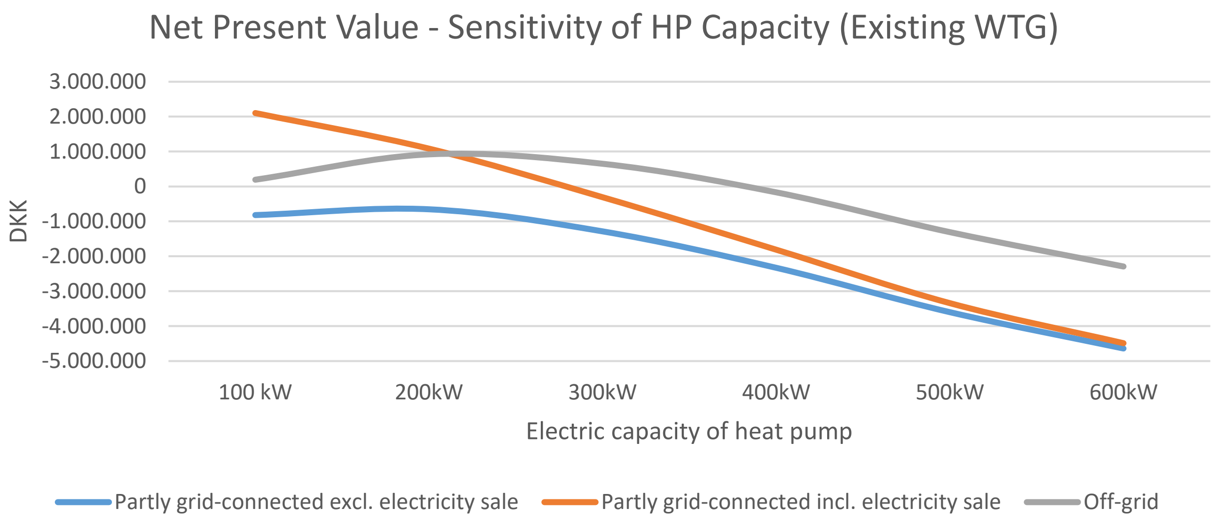

Figure 8.7 - Graph illustrating the net present value of varying the heat pump capacity in scenario 6

Production wise it is still more profitable to utilise the power produced in a HP instead of selling the electricity however, when adding the capacity tariff the savings are not able to weigh up for the additional investment. Hence, in this case it is seen that, if able to sell the electricity, then despite it being better utilised in the HP, the NPV indicates that it isn't profitable to invest in the HP, but only the WTG. Contrary, in an off-grid solution where no taxes and tariffs apply, the capacity providing the best business economic result is a capacity of 200kW, which is also closer to the average production of the WTG as seen on Figure 6.13. This corresponds to one third of the rated power output from the WTG. lowering the HP capacity in scenario 6b (off-grid), the investment is however still related to major uncertainties when compared to the marginal profit it is providing.

For the HP's included in scenario 2 and 3 (New WTG + HP), the already applied electric capacities of 2MW, was found to be optimal. This corresponds to nearly 50% of the rated power output of the WTG which is more than for the existing WTG. This may however be related to the difference in the capacity factor and efficiency of the WTG's as well as the average production when utilised.

Generally, in the case of Aabybro it is also seen that as the price of the existing biomass-based production is low, electricity sale is also given a high value relatively. For example, in a situation where the fuel costs were increased to the double the electricity sale will have lower value relatively speaking compared to the fuel saved. An example of this is shown on Figure 8.8 for scenario 3 (New WTG + HP air).

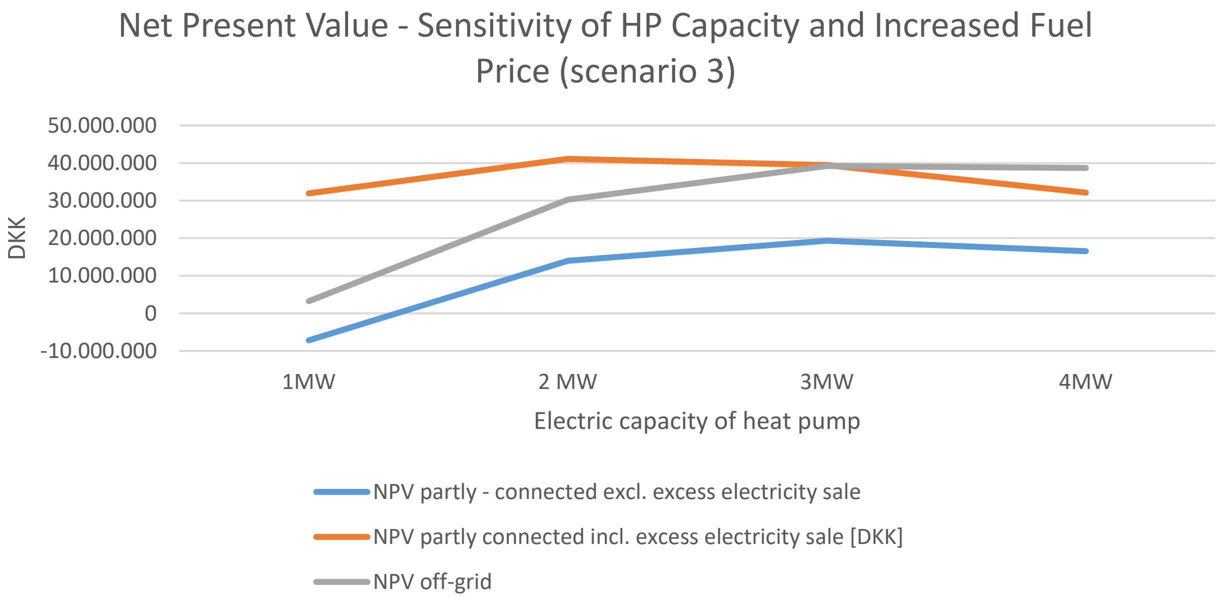

Figure 8.8 - Graph illustrating the net present value of varying the heat pump capacity in a system where the fuel costs is increased to the double.

Here it can be seen that an electric capacity of around 3MW provides the best business economic result. In this case a higher capacity than the capacity applied in the basis scenarios is business economic profitable due to increased savings from the fuels being displaced, which is able to weigh up for the additional investment costs. This means that the "optimal" capacity also varies with the production costs of the existing units as well as the different connection options. Consequently, for HP's it is seen that dimensioning the electric capacity equal to the rated power output of the WTG, as applied for scenario 6, is not in this case optimal.

8.5 Summary of Sensitivity Analysis

Throughout the sensitivity analysis the change of different parameters has been investigated for the scenarios of Chapter 7. An increase in the biomass price was found to improve the business economic result compared to the basis scenarios where a 2018 biomass price is applied. However, none of the applied biomass prices were able to provide a positive business economic result in an NPV. Compared to the reference, a 50% biomass increase is however, over time, able to provide a lower heat price in scenario 2a+b, 3a, 4b, 5b and 6b along with a simple payback time below 20 years. However, unless this full price increase were to occur suddenly, either as an increase in demand or as a tax, it is still not able to provide a positive NPV.

In the analysis it was found that despite significant savings in fuel consumption in most scenarios, the investment cost represented a major part of the total heat price for the system. Hence, a sensitivity analysis investigating how much the investments were to be reduced to match to heat price of the reference was carried out. Here it could be seen that the investments were to be reduced relatively much in general in order to match the heat price of the reference, indicating that everything that potentially could reduce the total costs such as distance etc., could be necessary in a system that comprises of tax-free biomass and solar thermal.

The business economic consequences of Aabybro DH being able to sell electricity at favourable spot prices and not only when the excess electricity isn't able to be utilised for heat was looked into. Here it could be seen that in scenarios where EB's were included, the major part of the electricity produced is now sold instead of being utilised in the EB for heating purposes. Despite an increasing biomass consumption due to less electricity being utilised for heat, a reduction in the heat price was found. However, this reduction, illustrated on Figure 8.4, was still not able to provide a lower heat price than the reference. In the scenarios including a HP, the electricity sale almost remains the same as in the basis scenarios due to the efficiency of the HP. Consequently, the electricity price will have to be relatively high before the electricity being sold on the spot market instead of being utilised in the HP.

Finally, a sensitivity investigating different HP capacities was made. Here it was found that the applied capacity of the HP in scenario 6 (Existing WTG + HP) was oversized resulting in higher costs. By lowering the electric capacity from 600kW to 200kW, the off-grid scenario was found to provide a positive business economic result. Generally, it was also found that the optimal capacity varies according to the different grid- connection options, the efficiency of the different WTG's as well as the price of the fuel being displaced. It was furthermore found that when competing with biomass, off-grid solutions utilising existing WTG's are business economically preferred.

9 Discussion of Barriers and Opportunities for Wind to Heat

The following chapter discusses some of the potential barriers and opportunities for the different WtH options in Aabybro, on a local and national scale. This is done to broaden the understanding of the potential impact WtH solutions can have, as well as to include other aspects than only the business economy. The Chapter is primarily based on the interviews presented in Chapter 3.

9.1 Potential Barriers and Opportunities

Despite the general negative business economic result in the case of Aabybro DH, presented in Chapter 7 and 8, it is considered relevant to investigate the potential consequences of WtH integration more qualitatively. The following sections highlights some of the potential barriers and opportunities being present when integrating different WtH solutions, locally as well as nationally. It is furthermore discussed which solution wind integration that is preferred from a local as well as energy system point of view.

9.1.1 Off-grid WtH

Generally can off-grid solutions be said to directly integrate the wind power produced for heating purposes. Off-grid solutions are furthermore less affected by taxes and tariffs, which, as indicated in the Chapter 1 and 7, represent a major barrier in fully grid connected solutions and also represent a substantial cost in the partly grid-connected solutions. However, contrary, an opportunity is lost in terms of being able to sell electricity as well as the opportunity to draw from the public grid if needed for backup capacity. Thus, for off-grid WtH it is necessary that backup capacity is available, and that this capacity is sufficient to cover the peak demand of the DH system. Consequently, off-grid solutions are therefore mainly relevant as a supplement to the existing production setup in order to reduce the existing fuel consumption.

A disadvantage of off-grid solutions is that is considered a waste if all the electricity isn't utilized as elaborated in chapter 1. Due to the relatively large capacity of the new WTG excess production was seen in most of the scenarios including this. The excess electricity could potentially be used elsewhere in the Danish energy system and benefit in reducing the fuel consumption. Off-grid solutions would therefore also mean that all the potential synergies on a system level will be lost but can however also potentially reduce the need for downregulating ancillary services due to intermittent production removed from the system. Furthermore, it is also considered a waste if the electricity isn't utilized in the most efficient way e.g. by using HP instead of with EB's, which can be argued to increase the efficiency of the DH sector. However, despite scenarios including HP's resulted in reducing the largest amount of biomass, it was also in these scenarios where most of the electricity would be wasted in an off-grid solution, whereas in EB solutions most of the electricity is utilised but at a lower efficiency.

A benefit of off-grid WtH is that all heat produced can be considered 100% renewable, which, despite biomass politically being considered CO_2 neutral, will reduce the actual CO_2 emissions (and other emissions) from the DH company and contribute to both national and international goals regarding CO_2 reductions. Furthermore, biomass will still be replaced which will lower the pressure on the resource, which potentially can be used for other purposes if needed. If natural gas or other fossil fuels are displaced in other DH systems, the impact in CO_2 reductions will naturally be greater. A potential weakness of off-grid solutions is that the DH company is required to maintain the local grid stability and security of supply, which may be associated with some technical challenges, which if connected to the public grid instead, primarily is handled by the local DSO and the national TSO. [TJI, 2019] [Energinet, 2019] General for off-grid solutions utilising HP's, is that load changes of the WTG may challenge the HP in having the right operating pressure which may be associated with some technical issues compared to EB's that are "easy" to up and down regulate according to the production. [TJI, 2019]

9.1.2 Partly grid-connected WtH

Partly grid-connected WtH solutions can likewise off-grid solutions be characterised as direct wind integration if the wind is used internally for own consumption when produced. If able to operate on market terms selling more than just the excess electricity, the heat price will be reduced due to a more flexible operation on the market. This means, that when there are low electricity prices, usually in windy periods, the electricity will still be used for heat, but opposite sold when electricity prices are high (if any production on WTG). For example, if the future electricity prices prove to increase, more electricity will be sold resulting in a higher revenue from the electricity sold, and opposite if the electricity price decreases, more electricity will be utilised for heat. Having this flexibility will enable a more balanced production cost. If this was scaled up, having various DH companies investing in similar production setup with the same market model, it could potentially affect the market prices.

Due to sufficient capacity of the existing system, Aabybro DH doesn't need to consume electricity from the public grid when the wind doesn't blow, meaning that all heat produced on the WTG/HP/EB is considered 100% renewable from a production point of view. In a case where it would be necessary to draw from the public grid, the CO_2 emissions will depend on the production mix of electricity in the specific hour. Consequently, one of the benefits of being partly grid-connected is that, if necessary, electricity can be drawn from the grid in times when the WTG isn't producing electricity. Similar to off-grid WtH, partly grid-connected also have the benefit of having more "fuels" and variety of production units to choose among, which minimises the risk of changes in future prises. In the case of Aabybro a capacity tariff for Evonet is however not considered necessary as there won't be drawn capacity from the grid in case of no wind.

Common for both the off-grid and partly grid-connected WtH solutions is, that the current legislative framework is found to be less transparent and unclear, which potentially may inhibit the implementation of such solutions. Another barrier Hvide Sande DH experienced is that electricity, contrary to heat, can't privately be transported across a third party cadastral serviced by public electricity infrastructure. [Hvide Sande DH, 2019] [Evonet, 2019] The consequence of this is that, all depending on the location and owner(s), chances are that land where the trace of the cable is planned, will have to be bought and made into one single cadastral. [Hvide Sande DH, 2019]

Consequently, this means that, not only are there some legislative barriers, as elaborated in Chapter 4, but there are also certain barriers that can be characterised more technical and practical.

9.1.3 Fully grid-connected WtH

As it was found in the analysis of chapter 7 and 8, fully grid-connected WtH solutions was in this case not able to compete with the existing solar and biomass-based production, with the applied assumptions. One of the major barriers is the taxes and tariffs which despite the efficiency of the HP resulted in relatively few operation hours and was furthermore found not to be able to weigh up for the investment costs. Consequently, due to the additional costs of taxes and tariffs along with the investment costs, the electricity price will have to be fairly low before being able to compete with biomass.

The CO_2 emissions from the electricity consumed in a fully grid-connected solution, will depend on the momentary production mix. However, as the operation mainly will be in hours where the electricity price is low (either spot or down regulation) a relatively high amount of wind is expected to be present in the system. Therefore, in this case, a fully grid connected solution is also considered as a way to integrate WtH while reducing the fuel consumption as well as CO_2 emissions. However, a fully grid-connected solution is rather sensitive to changes in both taxes and tariffs as well as the future development in electricity prices, which for off-grid and partly grid-connected WtH solutions are reduced. Therefore, when comparing the WtH solutions, off-grid and partly grid-connected scenarios are preferred from a business economic point of view. From a societal point of view a fully grid connected option may however be preferred due to state revenue from taxes and will therefore also be the most scalable. General for all grid connection options in the case of Aabybro is that a reduction of biomass will not fuel-wise affect the state revenue, due to biomass being exempt from taxes.

Common for all WtH solutions is that various environmental issues and permissions may apply. Due to a HP's making use of a heat source, permissions regarding noise, §3 and restricted areas etc. (depending on air or stream) may prove to be time demanding while adding a reasonable uncertainty to the individual investments and timing. [DEA, 2017] [Frederikshavn DH, 2019] Furthermore due to legislative uncertainties for off-grid solutions and partly-grid connected solutions, the socio economy may potentially also be a barrier.

9.1.4 New vs. Existing WTG

One of the major risks of investing in an existing WTG is the uncertainty of the remaining lifespan as well as the expected future maintenance costs. Not only does this add a risk to the expected business economy, but it may also add a risk to the security of supply, meaning that unless being able to draw from the public grid when the WTG isn't or can't produce electricity, sufficient backup capacity is needed. On the contrary, can the investment in an existing WTG be expected to reduce the total investment costs compared to a new, which in the analysis also was found to have a major impact on the results. In Hvide Sande the investment costs for existing WTG's were reduced about 50%, despite only being 5 years old at that time. [Hvide Sande DH, 2019] It was furthermore found that all owners of the WTG would have to agree on selling, which can be a potential barrier for investing in existing WTG's. Consequently, in areas where only existing WTG's with multiple owners are present, this may challenge the process and opportunity for off-grid and partly grid-connected WtH solutions. Unless the WTG is invested in as a part of the public regulated 20% that needs to be public offered, agreements with the project developer will also needed to be agreed upon.

In general, it can be argued that DH companies in any case should be allowed to own their own wind turbine despite it being an only electricity producing unit. If the WTG is utilised for heating purposes it could be considered a new way of combining heat and power production which potentially could add flexibility similar to the widely expanded natural gas-based CHP and heat storages while reducing emissions. How the WTG should be connected can however be discussed.

Another opportunity that may not be measured in a monetary value but yet still relevant is that, by enabling consumer owned DH companies to invest in a WTG for heating purposes, existing as well as new, there may be an opportunity of increased local acceptance compared to only having single owners earning a profit. As elaborated in Chapter 1, this has shown to be a major issue for land based WTG's but if used for lowering the heat prices in the local communities instead, the resistance may potentially be minimised. This has also proven to be the case in Hvide Sande, where local ownership increased the local acceptance. [Hvide Sande DH, 2019] The benefits of locally owned WTG's are also promoted by Hvelplund [2019] who argues that a DH company should be able to own a high share of WTG's. Figure 9.1 highlights some of the potential barriers and opportunities for WtH.

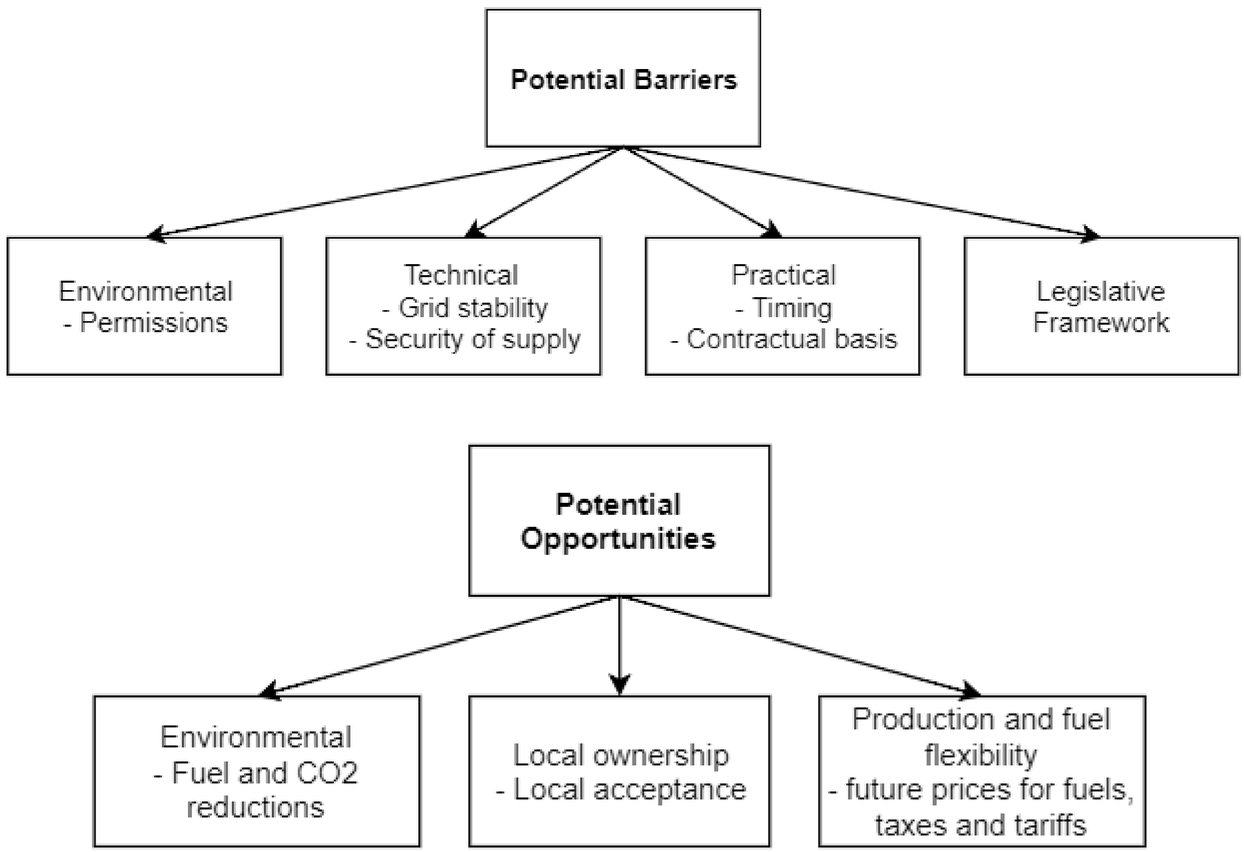

Figure 9.1 - Potential barriers and opportunities of wind to heat.

All the above highlighted potential barriers and opportunities are considered relevant as they may affect the realizability and scalability of WtH solutions. For example, some of the above-mentioned risks and uncertainties were one of the reasons why Frederikshavn DH did not pursue a partly grid-connected solution, but rather moved forward with a conventional fully grid connected solution instead. [Frederikshavn DH, 2019]

9.2 Results and Policy Considerations

Based solely on the results of the analysis, WtH is not recommended in Aabybro under the given circumstances. However, looking at the potential benefits and opportunities of local WtH integration, it can be argued that the current framework conditions should be changed. It can furthermore be argued that despite not providing a positive business economic result in a system primarily consisting of biomass and solar, a chance is that this could be the case in a natural gas-based system where the reference price is closer to the 50% biomass increase tested in the sensitivity analysis.

It can however be argued that making individual cables (mini grids) in order to avoid taxes and tariffs instead of using the already existing and well-established public grid is not necessarily optimal from a societal point of view. It may however indicate that if these alternative solutions are investigated, the existing framework conditions may not sufficiently promote WtH and there may be a need of new structures. It can furthermore be argued that if it ought to be a societal goal to minimize biomass consumption for heat only purposes whilst electrifying the DH sector the analysis indicates a mismatch in the current market setup. If that is to be the case, a situation is found where what is good for society is not good for business (situation I, Figure 4.1) and as it is the case of Aabybro, it is often the case that it should be business economic feasible before a DH company will consider moving forward with such a solution. It does however also indicate what types of changes that could be relevant to introduce. A direct way of balancing the competition between the use of biomass and electricity is to add a tax on biomass. Whereas this may have a positive effect on the state revenue, if may however result in economic consequences for the DH companies who invested in biomass-based heat production in the belief it was exempt. Hvelplund [2019] argues that;

"From an economical point of view I don't believe that wind-based heat should have a higher tax than biomass, but rather a lower tax as there are some associated problems with biomass that wind doesn't have"

[Hvelplund, 2019]

Hence, it is argued that wind-based heat should at a maximum only be taxed the same as biomass and Hvelplund [2019] furthermore argues that, electricity either bought or received from a WTG for DH purposes should be exempt from taxes in order to balance the competition between the two sources for heat. At least to the point where no more electricity is consumed than produced on the WTG.

"I also believe that it's a problem with the current transmission-system tariff at 8 øre/kWh which we all pay no matter if we receive the neighbors own produced electricity or whether it comes from Germany – I believe that is wrong"

[Hvelplund, 2019]

It is thus argued that if it can be documented that i.e. a DH company reduces its load on the total system by consuming the electricity locally or regionally instead of the electricity being delivered to the transmission grid and exported, then the costs should also be reduced. It has previously also been acknowledged that local utilization of electricity will reduce the costs. [Hvelplund, 2019] [Evonet, 2019C], [Energinet, 2019E]

Hence it can be discussed that a DH company should be charged a lower transmission-system tariff if the electricity is consumed closer to where it is produced as the transmission system in these cases will be less affected. This would also seem to be the case of Aabybro, that electricity will only be consumed when there is sufficient wind power production.

"All electricity produced on the local WTG utilized for heating purposes won't add pressure to the system and hence, there is no reason for Aabybro to pay a transmission-system tariff"

[Hvelplund, 2019]

Contrary it can be argued that if a relatively high capacity is needed to be drawn from the grid when there is no wind, the system will also be affected. [Energinet, 2019E] Consequently, if electricity is drawn from the public grid when there is no wind, a corresponding tariff could be argued to be in place. However, due to sufficient capacity of the existing DH system of Aabybro, electricity will only be consumed when there is wind-based production, which argues for no transmission system tariff. [Hvelplund, 2019]

The same applies if the electricity produced isn't utilized locally, then the system will also be affected and higher losses would be present. [Evonet, 2019C] Exactly this dynamic of utilizing the electricity locally when produced is currently not incentivized. [Hvelplund, 2019] Thus, the main point is that EB's and HP's should be recognized for the value they are creating. For instance, if EB's and HP's for DH purposes contribute to added value for the electricity system it should equally be reflected in the taxes and tariffs.

An alternative way of constructing a flexible electricity tax, presented by Djørup [2016], incentivizing electricity consumption when its produced, is a structure where the electricity tax is affected by the amount of wind being present in the system. For instance, if the wind power production represent 60% of the total electricity consumption the electricity tax is reduced correspondingly 60% etc. The benefit of doing so is that, despite the fact that the electricity price in many cases reflect the amount of wind being present, this does not always seem to be the case. Hence by varying the tax level corresponding to the actual wind production will reflect the true amount of wind being present in the system and furthermore incentivize the consumption to when it is needed and potentially reduced when less electricity is produced.

However, local ownership of a WTG is with the above mentioned not promoted and there might be a situation where a local WTG potentially could cover 100% of a DH company's momentary consumption. If for instance the DH company owns this specific local WTG, the momentary electricity consumption (produced on the WTG) is argued to be exempt from electricity tax if used for heating purposes. Thus, if 100% of the electricity produced is utilized for heating purposes this will be exempt from taxes, despite a situation where the total wind production only represents 20% of the total consumption. In this case the electricity tax for everyone else is reduced 20%. If the electricity produced is used locally by the DH company, it is to be subtracted from the total wind production in the system. Contrary, if the electricity produced on the local WTG is not utilized for heat but rather sold and delivered on the public grid, the production would be added to the total amount of wind reducing the general tax level. If electricity is consumed from the public grid when the local WTG isn't producing, the general tax level would apply for the DH company, corresponding to the wind being present in the system. This construction could potentially be argued to add some flexibility to the production and consumption on a general level, while local ownership of WTG's is being promoted. Making use of all the existing heat storages will in the meantime enable more of the power produced by wind energy to be consumed at the same time. Consequently, the consumption will potentially be incentivized in windy periods and reduced in times with lower wind. This could potentially increase the cross sectoral synergies while own electricity cables would be avoided.

A disadvantage of the proposed tax structure is that, not only would it require a relatively accurate forecast of the production and demand in order to actively make use of it, but the amount of wind is also depend on the electricity price and ancillary services.

In a recent report from Energinet [2019D] several grid connection options was investigated for *Power to Gas* (PtX), similar to the ones included in this *Thesis*. As the economic potential of PtX is also relatively sensitive to taxes and tariffs it is here also argued for model that incentivizes high flexibility and interruptibility as well as the value of being geographically closely located. One could argue that this should not only apply for PtX but also for WtH. The DH companies are then to evaluate whether it is economically feasible under the given local circumstances as well. The implementation of such changes can however be inhibited by the described factors of Figure 4.1, needing to make use of relevant measures. On the contrary can such implementations be pursued by various lobby groups and market operators and, if implemented, a Situation II is established where what is best for society is also good for the business. [Hvelplund & Lund, 1998]

10 Conclusion

The Danish energy system is in constant development due to technological development, changing framework conditions and market changes. The development of recent years within the Danish district heating sector has shown reduced co-generation and a tendency of moving towards heat-only biomass-based production, which arguably reduces the overall efficiency of the DH sector along with adding pressure on limited resources. In the meantime, an increasing share of intermittent power production from renewable energy, especially wind turbines, requires increasing system adaption. A potential way of utilising the intermittent electricity production is by use of heat pumps and electric boilers in the district heating sector which, due political attention and changing framework conditions, are receiving an increased interest among district heating companies.

Whereas some DH companies interconnect and reinvest in conventional production technologies in order to stabilize the future heat price while reducing CO_2 emissions, few DH companies are looking into alternative ways of integrating the intermittent wind power production. This is by looking into the opportunity of investing in local wind turbines in combination with heat pumps or electric boilers for heating purposes, while utilizing the already existing heat storages, which arguably still is one of the cheapest ways of storing electricity. With a widely spread district heating network along with a large amount of on-shore wind turbines in Denmark, the potential of integrating wind for heating purposes locally where the electricity is being produced, is found to be substantial. This *Thesis* seeks to address the potential benefits of integrating *wind to heat* for a district heating company in terms of reducing the operation costs and biomass consumption. This is done in the context of Aabybro District Heating looking into 8 different scenarios of indirectly and directly integrating wind for heating purposes.

The analysis takes point of departure in an existing local wind turbine and one new larger wind turbine which is expected in the near future. The wind power production and operation are tested in combination with heat pumps and electric boilers applying various grid connection options for comparison;

- ***Off-grid:*** No taxes and tariffs included
- ***Partly grid-connection***: No taxes and a reduced tariff applies, with and without excess electricity sale
- ***Fully grid-connection:*** Standard tariffs and taxes applies, no investment in a wind turbine

The analysis found that the seasonal variation of electricity produced on wind turbines generally matches the seasonal variation in the heat demand compared to solar based heating. This enables a relatively large amount of fuel to be displaced. The main result of the analysis however showed that only one out of eight tested scenarios provided a positive business economic result with the applied assumptions. Adjusting the capacity in a sensitivity analysis, the analysis however found a business economic potential for one more scenario. Both scenarios providing a positive business economic result were in combination with the existing wind turbine in an off-grid situation.

However, the relatively marginal profit the scenarios are able to provide is related to major uncertainties regarding the investment costs of off-grid solutions.

Despite the largest potential in reducing the biomass consumption, none of the scenarios including a new wind turbine provided a positive business economic result, unless the investment costs are drastically reduced or a sudden taxation on biomass is to occur. Finally, none of the tested scenarios including a full grid-connection provided a positive result due to relatively low production costs of the existing system, resulting in fewer operation hours for the electric boiler and heat pump.

The analysis however still shows that giving the right circumstances, *wind to heat* can benefit Aabybro District Heating in terms of reducing both the overall system costs and biomass consumption, but is however in many cases challenged by the investment costs in a system which mainly comprises of biomass. Furthermore, *wind to heat* in off-grid or partly grid-connected solutions are generally still related to substantial uncertainties both in terms of the legislative framework as well as the future development in electricity- and biomass prices. However, looking at the potential savings *wind to heat* is able to generate in the tested scenarios, it is reasonable to believe that, despite not being beneficial in a business economic perspective of Aabybro, *wind to heat* can still potentially be beneficial in other DH systems where the primary heat production is not based on solar and tax free biomass. Thus, the business economic potential is consequently affected by various local conditions such as distance, available capacity, heat demand, existing production setup etc. as well as regulatory uncertainties, which are all relevant to take into account when looking into *wind to heat* solutions.

The *Thesis* furthermore addresses some of the potential barriers and opportunities *wind to heat* solutions may be related to. Certain barriers are found to be related to the legislative framework, whereas other potential barriers regarding environmental permissions, timing and contractual basis can potentially implicate the planning process. *Wind to heat* may however also, depending on the specific configuration, also be related to potential opportunities regarding local ownership- and acceptance of wind turbines, CO_2 reductions and increased flexibility in the heat production, which potentially reduces the sensitivity of future changes in fuel prices. However, the *Thesis* finally argues that sub optimizing- and investments by implementing individual grids in order to avoid taxes and tariffs is arguably not optimal from a societal point of view. It does however indicate, that the current framework conditions do not fully incentivise *wind to heat* integration in Denmark, especially when compared to biomass. It can furthermore indicate that changes ought to be implemented for *wind to heat* to be fully competitive while exploiting potential cross sectoral synergies.

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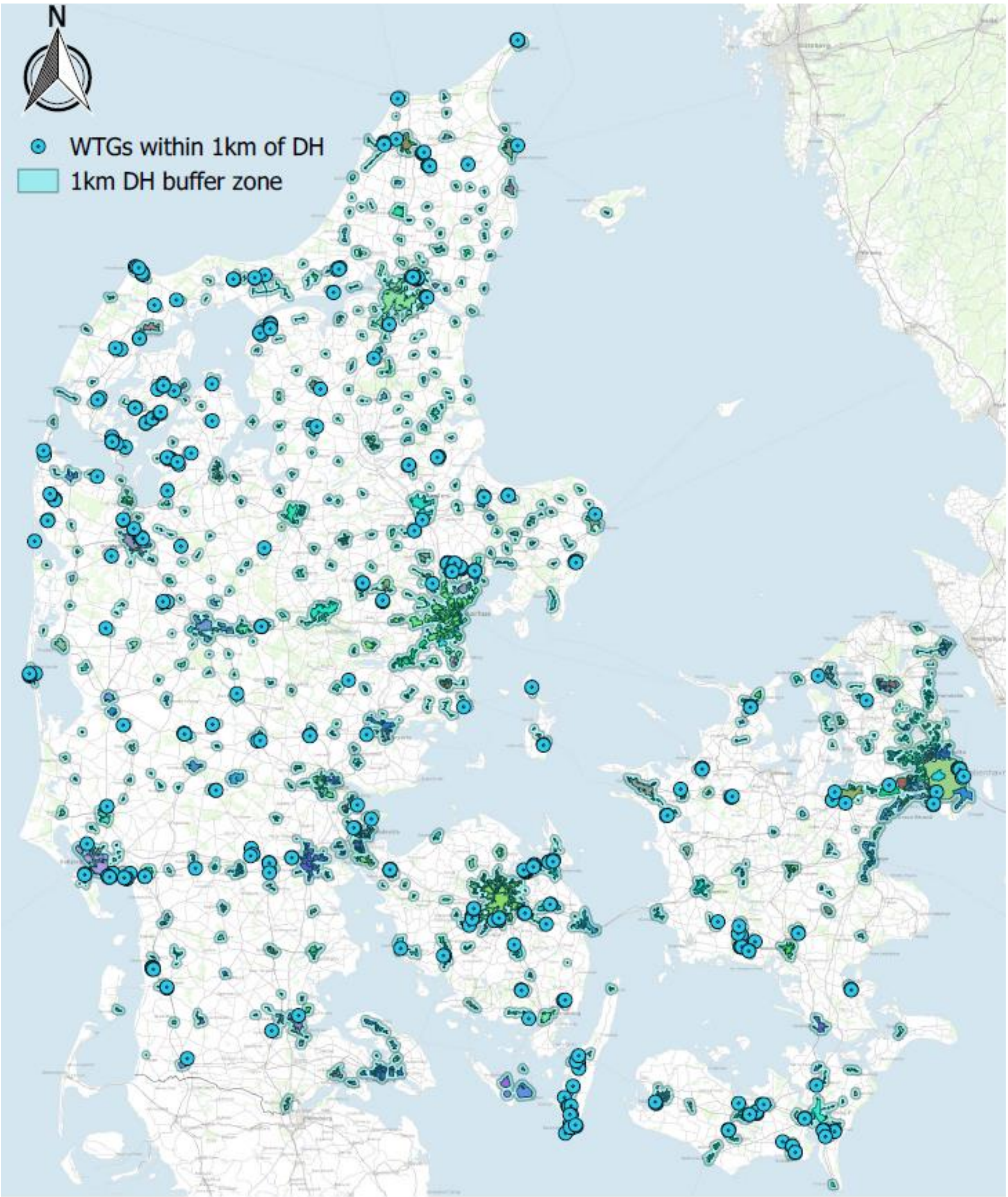
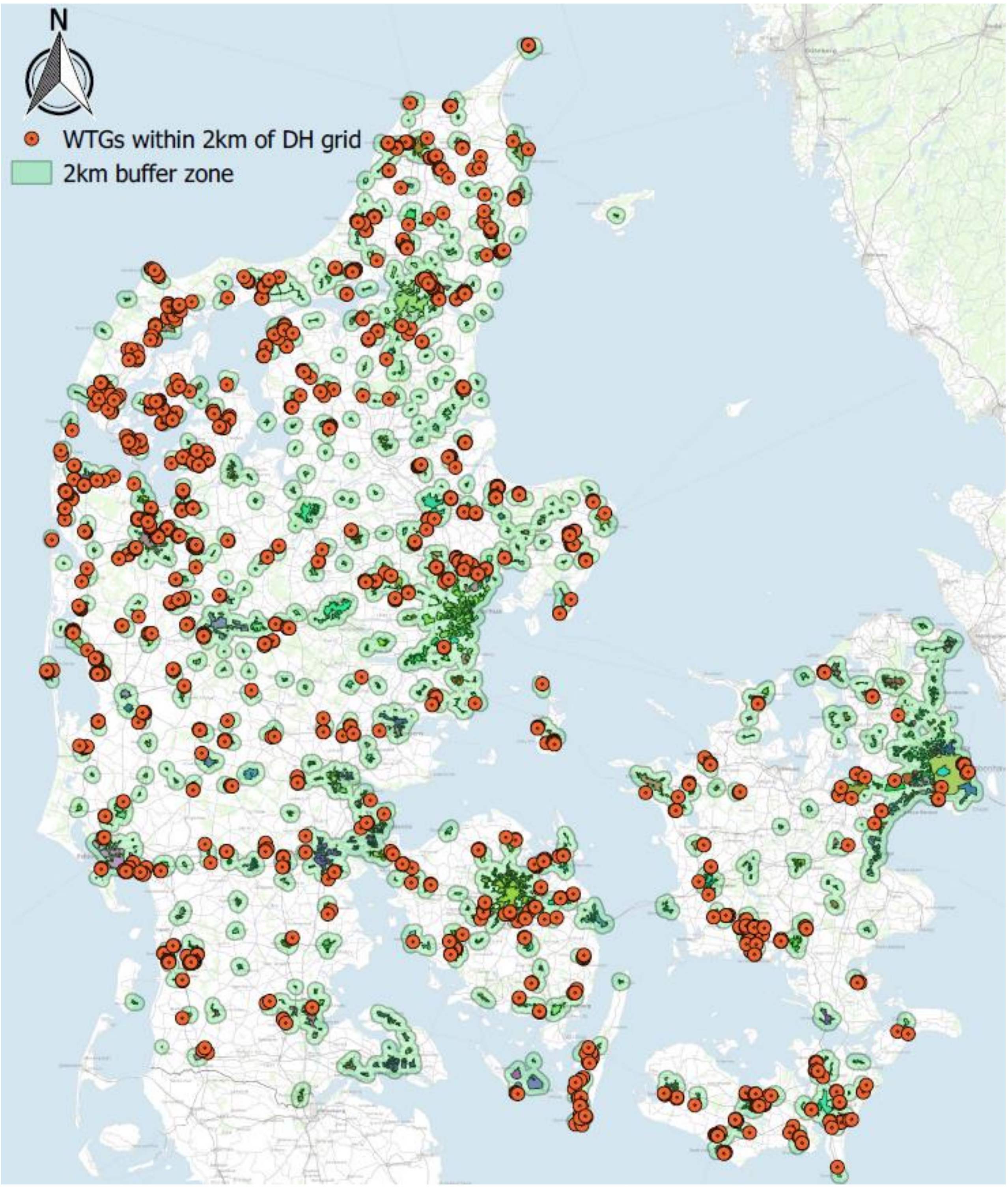
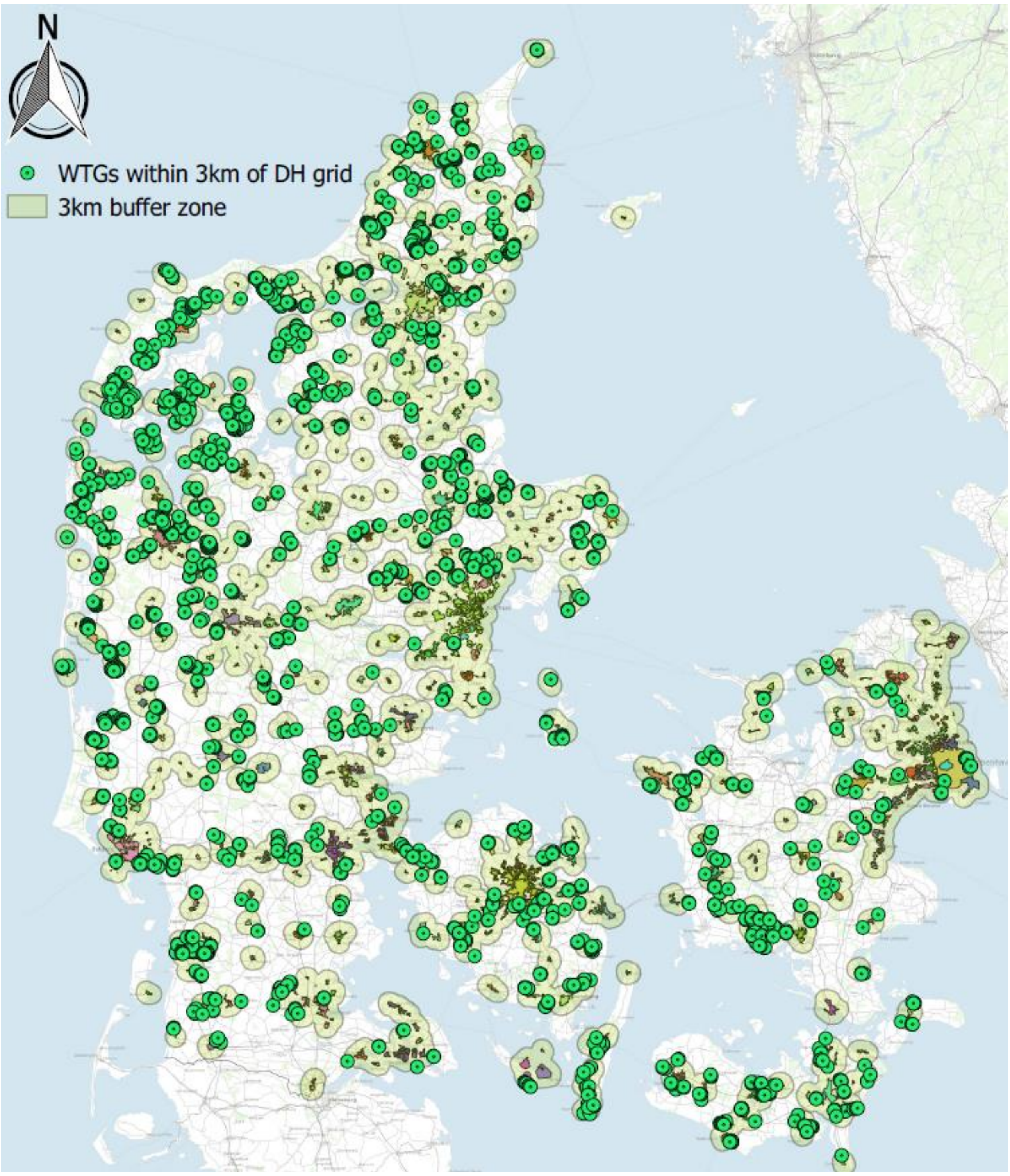
12 Appendix

Appendix 1: Screening of wind turbines within 1, 2 and 3km of district heating network




N
WTGs within 2km of DH grid
2km buffer zone


N
WTGs within 3km of DH grid
3km buffer zone

Appendix 2: Applied investment costs

Scenario 1 - New WTG + EB						
Investment			**Capacity**		**Year**	**Note**
New wind turbine	31.672.080	DKK	4,3	MW	2020	*DEA - technology catalogue*
Electric Boiler	4.798.800	DKK	4,3	MW	2020	*DEA - technology catalogue*
Transmission - Heat	28.425.492	DKK	9	km	2020	*DN150 - NIRAS key numbers*
Transmission - Electricity	663.553	DKK	0,5	km	2020	*DEA - technology catalogue/NIRAS*
Total investment costs	65.559.925	DKK				
Scenario 2 - New WTG + HP Stream						
Investment			**Capacity**		**Year**	**Note**
New wind turbine	31.672.080	DKK	4,3	MW	2020	*DEA - technology catalogue*
Heat pump - Stream	37.711.872	DKK	2 (elec.)	MW	2020	*DEA - technology catalogue*
Transmission - Heat	28.425.492	DKK	9	km	2020	*DN150 - NIRAS key numbers*
Transmission - Electricity	1.327.106	DKK	1	km	2020	*DEA - technology catalogue/NIRAS*
Canal, pipes etc.	5.000.000	DKK		MW	2020	*Estimation, NIRAS*
Total investment costs	104.136.550	DKK				
Scenario 3 - New WTG + HP Air						
Investment			**Capacity**		**Year**	**Note**
New wind turbine	31.672.080	DKK	4,3	MW	2020	*DEA - technology catalogue*
Heat pump - Air	33.390.720	DKK	2 (elec.)	MW	2020	*DEA - technology catalogue*
Transmission - Heat	25.267.104	DKK	8	km	2020	*DN150 - NIRAS key numbers*
Transmission - Electricity	663.553	DKK	0,5	km	2020	*DEA - technology catalogue/NIRAS*
Total investment costs	90.993.457	DKK				
Scenario 4 - New WTG + EB + HP Stream						
Investment			**Capacity**		**Year**	**Note**
New wind turbine	31.672.080	DKK	4,3	MW	2020	*DEA - technology catalogue*
Electric boiler	3.682.800	DKK	3,3	MW	2020	*DEA - technology catalogue*
Heat pump - Stream	18.855.936	DKK	1 (el)	MW	2020	*DEA - technology catalogue*
Transmission - Heat	28.425.492	DKK	9	km	2020	*DN150 - NIRAS key numbers*
Transmission - Electricity	1.327.106	DKK	1	km	2020	*DEA - technology catalogue/NIRAS*
Total investment costs	88.963.414	DKK				

Scenario 5 - Existing WTG + EB						
Investment			**Capacity**		**Year**	**Note**
Existing wind turbine	736.560	DKK	0,6	MW	2020	*DEA technology catalogue and Straight line depreciation (30 years). Resently been upgraded with new gearbox*
Electric boiler	669.600	DKK	0,6	MW	2020	*DEA technology catalogue*
Transmission - Electricity	928.974	DKK	0,7	km	2020	*DEA technology catalogue/NIRAS key numbers*
Total investment costs	2.335.134	DKK				
Scenario 6 - Existing WTG + HP						
Investment			**Capacity**		**Year**	**Note**
Existing wind turbine	736.560	DKK	0,6	MW	2020	*DEA technology catalogue and Straight line depreciation (30 years). Resently been upgraded with new gearbox*
Heat pump	9.329.760	DKK	0,6	MW	2020	*DEA technology catalogue*

Transmission - Electricity	928.974	DKK	0,7	km	2020	*DEA technology catalogue/NIRAS key numbers*
Total investment costs	10.995.294	DKK				
Scenario 7 - Grid connected EB						
Investment			**Capacity**		**Year**	**Note**
Electric boiler	7.812.000	DKK	7	MW	2020	*DEA technology catalogue*
Total investment costs	7.812.000	DKK				
Scenario 8 - Grid connected HP						
Investment			**Capacity**		**Year**	**Note**
Investment 1	32.605.056	DKK	2 (elec.)	MW	2020	*DEA technology catalogue*
Total investment costs	32.605.056	DKK				

Appendix 3: WindPRO prints (attached)