MASTER THESIS

ENERGY TECHNOLOGY

UNIVERSITY OF SOUTHERN DENMARK

Renew Biogas - Reduction of Greenhouse Gas Emissions in Biogas Production

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3^{rd} of June 2019

Preface

The project is a master thesis in Energy Technology written at the University of Southern Denmark. It is intended for peers and others who find interest in the reduction of emissions in biogas production. The project examines the implementation of renewable electricity capacity at a Nature Energy Midtfyn biogas plant, the ability to use own biogas for heating purposes and the future implementation of hydrogenation at biogas plants as a means to reduce carbon emissions and increase the biomethane output.

The authors would like to thank Nature Energy for helping provide data and information.
Lastly, a special thanks to our supervisor Lars Yde as well as to Abid Rabbani for guidance during supervisor meetings and thanks to our supervisors at Nature Energy, Mikkel Kynde and Jonas Svendsen.

Odense, June 3rd 2019.

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Number of characters (including appendix): 116,782 (127,781)
Number of pages occupied by figures and tables: 35

Abstract

Even though the production and use of biogas is considered CO_2 neutral, there are greenhouse gas emissions from biogas production. These emissions primarily stem from electricity and natural gas consumption, methane leakages and the transportation of biomass to and from the biogas plant. The focus of the thesis is on emission reductions from electricity and natural gas usage.
Using Nature Energy Midtfyn as a reference, an analysis of how much the emissions from the biogas production can be reduced by either introducing renewable electricity production on site, use biogas instead of natural gas for heating purposes or introduce electrolysis and methanation on site, will be investigated. Through this, the emission reductions, the socio-economic benefits from the reductions and the feasibility of the different solutions are carried out. The end goal is to provide a better product in the form of "cleaner" biogas.

It was found that the best solution, in terms of feasibility, was to introduce renewable capacity at the biogas plant as 1 MW of wind. This gave an IRR of 14.5 % and yielded an emission reduction of 16.8 % and a socio-economic benefit of 2.58 DKK/MWh produced biomethane. Using own biogas instead of natural gas for heating the biomass would result in an emission reduction of 22.75 % and a socio-economic benefit of at least 2.77 DKK/MWh produced biomethane. Combining the result of the first end second scenario yielded a total reduction of 39.55 % and a minimum socio-economic benefit of 5.35 DKK/MWh produced biomethane. From the end-consumer's perspective, the solution with 1 MW wind installed would decrease the end consumer costs by 2.4 DKK/MWh biomethane, where the combined solution with using own biogas would increase the consumer costs by 20.47 DKK/MWh biomethane.

It was found that through hydrogenation and the addition of quick biomasses the biomethane production could be increased by 84.15 GWh yearly, which is an increase of 67 %. The hydrogenation scenario would however not be feasible due to the high capital costs of electrolysis and electricity expenses. In order to make hydrogenation feasible it was found that an increase in consumer price of 188 DKK/MWh was needed.

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1 Reading Guide

This section will provide the reader with a short introduction of the content and the composition of the thesis. Throughout the report the reader will be introduced to each section and will be able to read a short summary at the end of each section.

Background
The different sub-sections all contribute to explaining why this thesis is relevant and what motivated the project. The background also functions as a literature review where the current status of biogas production in Denmark is explained.

Methods
This section describes the methods which has been used in the project for the simulations and the economic analysis.

Scenarios
This section describes the scenarios which will be simulated in the project. These include the Reference, Photovoltaics and Wind, Biogas Replaces Natural Gas and the Hydrogenation scenario.

Simulation
This section describes how the scenarios have been simulated using energyPRO. The scenarios are simulated over a period of 20 years from 2019-2038.

Results
This section contains the results of the simulations, and the results regarding greenhouse gas emissions, business economics and socioeconomics.

Sensitivity Analysis
This section contains a sensitivity analysis of the main parameters used in the simulations. The parameters are: electricity price, natural gas price, investment costs and CO_2 allowance price.

Discussion
This section contains a discussion of the results, and perspectives of further study.

Conclusion
This section will have the main conclusions drawn from the project and answer the thesis problem proposal.

Appendix
The appendix includes the original problem proposal (Appendix A), an overview of the attached files (Appendix B) and some in-depth explanations for calculations and results.

2 Background

This section will explain the motivation for writing this thesis. Biogas has become an increasingly larger part of the energy system in Denmark, and is considered necessary in order to reach a low-emission society by 2050 [1]. Biogas production does however cause greenhouse gas (GHG) emissions, which this project will attempt to reduce. Finally, Nature Energy, the partner of this project, is interested in reducing their GHG emissions from biogas production in order to be able to provide a better product for their customers.

2.1 Biogas Production in Denmark

In this section the production of biogas is explained together with the development of biogas production in Denmark.

Biogas is a renewable energy source able to substitute natural gas and is produced by letting biomass degas in an oxygen free environment. This is a natural occurring process that is utilised for energy production. The biomass used in the production is typically a composition of wet and dry manure together with energy-crops, wastewater, food waste, and/or industrial waste. This composition however changes from unit to unit. The produced biogas consists of 50-80% methane, 20-50% carbon dioxide and few percentages of H_2S, NO_2 and water vapour [2]. When manure from domestic animals is used for biogas production the GHG emissions are reduced for the owners of the farm animals. When the biomass has been through the biogas production process it is delivered back to the farmers as fertiliser.

Sustainability

The choice of biomass has an effect on the advantages that biogas has on the climate. Because of this, there is a maximum percentage energy crops allowed in the biomass used for biogas production. In a note by the Danish Energy Agency (DEA) [3], it is highlighted that the economic framework regarding biogas production is so good that the production itself will not be dependent on energy crops. The DEA evaluate that it is appropriate to limit the use of energy crops for biogas production. This means that right now, the share of energy-crops in biogas production must not exceed 12 % if a producer is to be eligible for subsidy payments [4].

Circular Economy

When talking about biogas production one will not be able to avoid the term circular economy. Circular economy is what makes biogas production in particular interesting and biogas production is a great real-world application of the principle. Essentially, circular economy revolves around minimising waste and externalities, and maximising the utilisation of the resources. In biogas production, the biomass is returned digested to the farmers, thereby minimising the need for additional resources for fertilisation along with the utilisation of the gas produced.

The current share of biogas in the gas grid

In Figure 1 the percentage share of biogas in the natural gas grid over the course of the last 12 months, as of April 2019, is shown. From the figure it is clear to see that the development in installed biogas plants is increasing and is expected to push the share of biogas even further over the course of the next few years. One of the main reasons to the short term expected increase, is the discontinuation of the subsidy given to biogas producers, who either upgrades biogas or produce electricity or heat from biogas. This elaborated in Section 2.2.

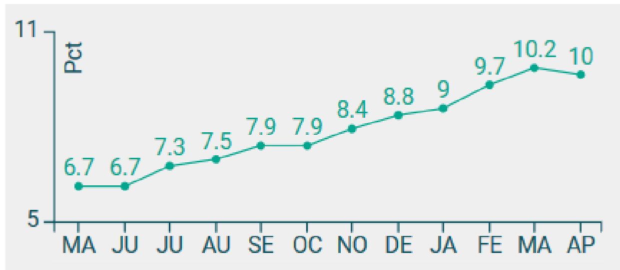


Figure 1: The percentage share of biogas fed to the natural gas grid [5].

Figure 1 shows the development in biogas share of the natural gas grid and as of April 2019 the share of biogas in the natural gas grid was at 10 %. Figure 2 shows the total expected biogas production in Denmark towards 2020.

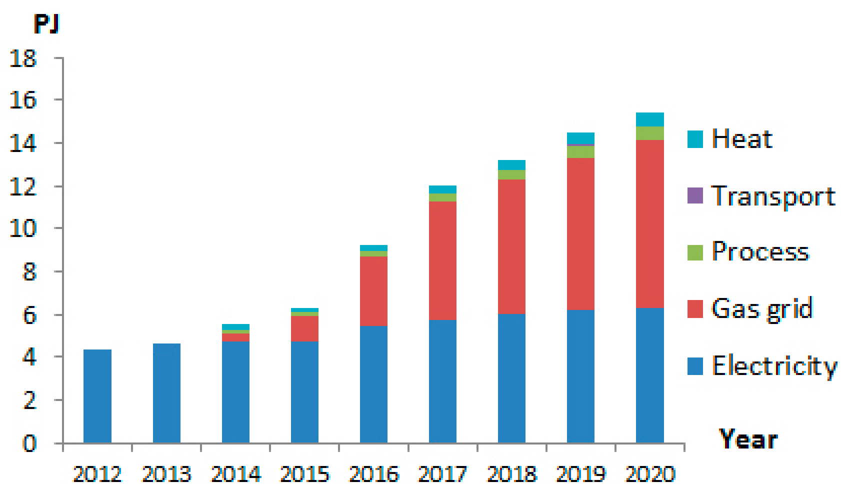


Figure 2: Historical and expected future biogas production and its use in Denmark 2012-2020. Estimations from the DEA from 2016 [6].

As seen in the figure, the biogas production is expected to have tripled by 2020 compared to 2012.

The development of biogas production

The biogas industry in Denmark has moved from smaller decentralised production units, mainly at water treatment plants to stabilise sludge, to larger production units, like common facilities used and owned by several farmers. Today, production units utilising manure from domestic animals represent 90 % of the large common facilities. These facilities have capacities between 100-2000 tons of biomass per day and collectively converts around 15 % of the total amount of manure in Denmark [1]. The smaller facilities at farms have capacities of around 10-100 tons per day. The tendency is that the production of biogas is moving towards larger centralised facilities like the case of Nature Energy. They have established a larger portfolio of production units helping them create better conditions for increased efficiency and operation [1][7]. As seen in Figure 2 the main production of new facilities is expected to produce to the gas grid as upgraded biogas. The numbers for 2018 to 2020 are estimates based on information available in 2016. Today, however, the actual biogas production to the gas grid can be found using live data from Energidataservice [5], and it can be seen in Figure 3 that the production is higher than expected. Furthermore, the first quarter of 2019 was added to highlight the increasing production of biogas to the grid. From the report by the DEA, from November 2018, the total biogas production is expected to reach 19 PJ in 2020 contrary to the expected 16.2 PJ extrapolated in 2012 [1]. Since 2012, biogas has been promoted through public subsidies with different support schemes that includes electricity production, biogas upgrading and biogas usage for process purposes, fuel in transportation and heating purposes. The support rates are elaborated in Section 2.2.

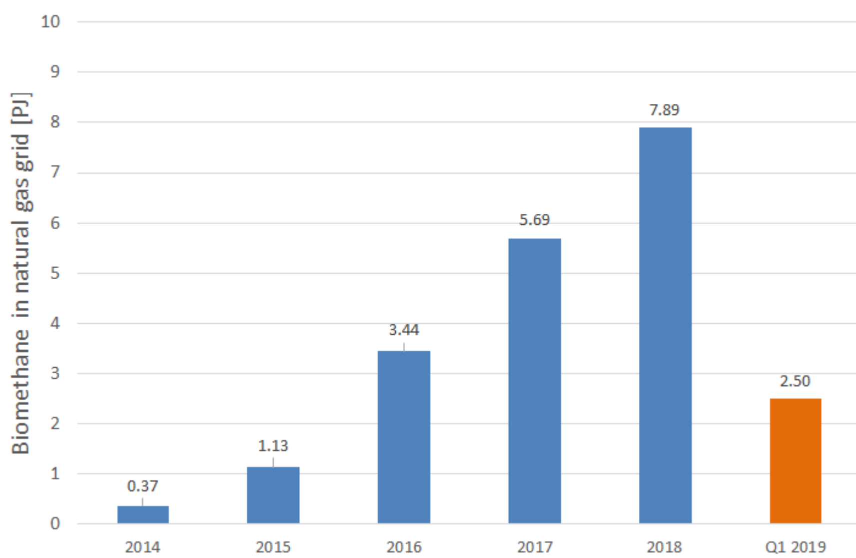


Figure 3: The amount of biomethane fed to the grid in PJ [5].

2.2 Biogas in the Energy System

This section will elaborate on the role of biogas in the future energy system, how biogas is subsidised.

Are we able to have a system without biogas?

According to The Danish Council on Climate Change, biogas is one of the key components to reach the reduction goals in regard to GHG emissions. The council provides recommendations on climate initiatives based on individual analyses of which the centre is a low-emission society by 2050. The council highlights different conversion technologies that will make the goals set for 2050 easier to reach, where biogas is one of the solutions that are recommended by the council, in order to easier reach the goals [9].

The support scheme promoting biogas

As of 2019 the total surcharge for delivering upgraded biogas to the natural gas grid is at 107.6 DKK/GJ [10]. In order to receive subsidies, the production unit has to meet requirements within sustainability and other conditions. The subsidy given to biogas in the form of a grant/GJ and is dependent on the price for natural gas and is therefore changed annually. In 2020 there will be a discontinuation of the current surcharge given to biogas production units delivering electricity or delivering upgraded biogas to the gas grid. Because of this, many producers rush new projects in order to secure subsidies before 1st of January 2020. In order to receive the grant, a project must have completed an irreversible investment before 8th of February 2019. This recently changed from 1st of January [11]. From 2021, 240 million DKK/year has been put aside for an invitation to tender for biogas plants [12].

Politics

The project relevancy can be tied to the decisions of the Danish government and the European Union. Politics cannot be left out when creating a project like this, whether it is climate plans, climate goals or new subsidies, taxes or levies, it all has an effect on the energy system's development in regards to what technologies are used in the transition to a completely renewable grid in the future. As of May 2019, there is no concrete plan of action as to how Denmark is going to reach the goal of a low-emission society by 2050. There is however an agreement [12] between the Danish parties to work towards net zero emissions in accordance with the Paris Agreement [13].

The parties have allocated financial resources towards a renewable share of 55 % in the energy system by 2030 of which the electricity consumption will be 100 % renewable.

2.3 Biomass Potential in Denmark

In the report *Energiscenarier frem mod 2020, 2035 og 2050* from 2014 [14] by The Danish Energy Agency, different bio-energy consumptions are calculated for four different fossil fuel free scenarios. These are wind, biomass, bio+ and hydrogen. In Table 1 the bio-energy consumption for each scenario is listed.

DEA Scenarios	Wind	Biomass	Bio+	Hydrogen
Bio-energy consumption	250 PJ	450 PJ	700 PJ	200 PJ

Table 1: The bio-energy consumption for four different fossil free scenarios by DEA [14].

According to an analysis by Ea Energianalyse [15], the bio-energy that can be produced within the borders of Denmark is estimated to be 148 PJ/year. In a newer report by the DEA [1], they argue that the potential is bound to increase due to better utilisation of land and bi-products.

Looking at the import numbers for biomass in the energy statistics from 2017 [16], 64.6 PJ biomass was imported out of an energy production of 91.8 PJ from biomass. Besides biomass, biogas itself was at 11.2 PJ in 2017.
In the DEA report [1] Henrik B. Møller [17] has set the most ambitious collectively potential for biogas to 105 PJ up from 40-50 PJ. This increase is obtained by increased utilisation of manure, straw, grass and the opportunity to store excess electricity via methanation. In the light of the report by Henrik B. Møller, gas distribution companies have estimated that a realistic level of green gas will be at 80 PJ including methanation, by 2035 [18]. This increase can help reduce the need for other biomass to reach the expected biomass needs in the future. Because of the possibility of storing excess electricity and increase biogas production through electrolysis and methanation (hydrogenation), this is investigated in the project, both in regards of feasibility and creating a cleaner biogas.

2.4 The Emissions in Question

The following section will highlight where in the biogas production the emissions come from and why this project will focus on the reductions of emissions through investments in renewable electricity production.

The production and use of biogas is considered CO_2 neutral, there are however greenhouse gas emissions from biogas production. These emissions primarily stem from electricity and natural gas consumption, methane leakages and the transportation of biomass to and from the biogas plant.
Figure 4 shows the emission distribution as it is right now in the Reference Scenario of Nature Energy Midtfyn, compared to the fossil reference of diesel fuel.

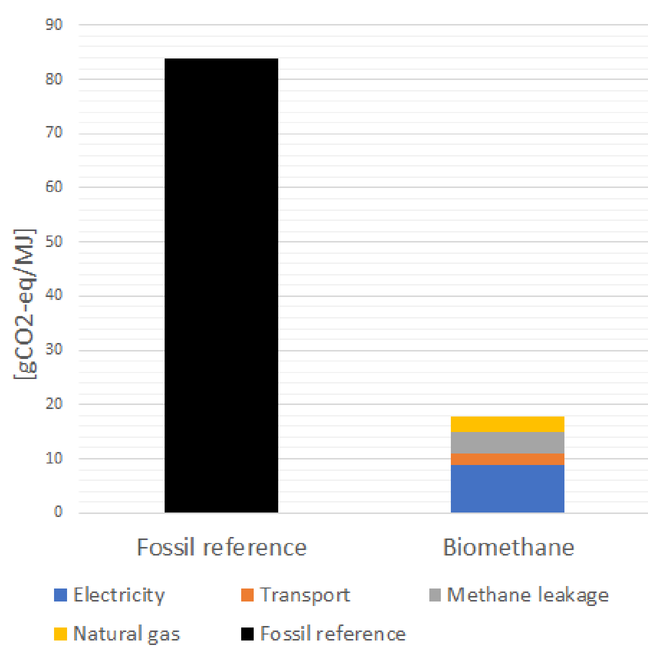


Figure 4: The REDcert fossil reference and the emissions distribution of Nature Energy Midtfyn.

From the figure, it is clear to see that a large part of the emissions tied to biogas production at Nature Energy Midtfyn comes from electricity consumption. Therefore, this project will look into installing renewable electricity capacity at the biogas plant.

2.5 Relevance for Nature Energy

The project is written in cooperation with Nature Energy, a biogas production company situated on Funen in Odense. This section will describe what Nature Energy do and the questions they would like answered. The part of the report which refers to Nature Energy and their problems will mainly have an economic aspect regarding to their business and the feasibility of the solutions. This, however, does not mean that the report will not have any socio-economic aspects to highlight, given that biogas is getting financial support by The Danish Government and will have a key role in the transition to the completely renewable energy grid. For Nature Energy the goal is to reduce the CO_2 emissions from biogas production, thereby offering a better product, cleaner biogas.

REDcert Certificates

Selling biogas is like selling renewable electricity, in order to ensure the origin of the electricity, a certificate of origin is sold with it. This is typically between a producer and either a re-seller or a company striving to reduce their emissions or increasing brand awareness. For biogas, there are different certificates that can be used to document the authenticity of the gas and its emission reduction compared to the fossil reference as showed in Figure 4. The certification criteria varies dependent on which method or what kinds of certificates that are sold along with the biogas. All biogas produced by Nature Energy is certified by Energinet [19] and a great share certified by the REDcert scheme [20].

In order to use REDcert the biogas producer has to document the CO_2 emissions tied to the production. There is a requirement of a 60 % emission reduction in order to get the biogas REDcert certified [21], comparing the biogas to the fossil reference of diesel, which is 83.8 gCO_2-eq/MJ. REDcert has a very strict set of rules for calculating the greenhouse gas (GHG) emissions [21]. As mentioned in Section 2.4 the emissions stem from electricity use, natural gas use, methane leakage and transportation of biomasses. Renewable electricity production can only be included in the calculation, if it is directly connected to the biogas plant, which means that it is not possible to use certificates of origin from renewable electricity production. The producer is also not allowed to include the saved emissions from manure not being used as fertiliser where it releases methane [21].

Another important aspect of REDcert is that, you have to proof that only sustainable biomasses have been used. Sustainable biomasses generally refer to organic waste products. This means that you must be able to trace the biomass all the way back to its origin and document its pathway to the biogas plant and its GHG emissions to the biogas plant.

The guarantee of GHG reductions and a guarantee of sustainable production gives value to the REDcert certificates, since customers value these aspects. According to Nature Energy, customers ask for biogas that have higher GHG reductions than the required 60 %, for example 80 %, while paying more for the REDcert certificates. It is therefore important for Nature Energy to be able to supply a better biogas product, and it is therefore relevant to examine the possibilities of reducing the GHG emissions.

2.6 Section Summary

Through the background section the project foundation is created. The biogas production in Denmark is increasing with a larger portion of the biogas produced going towards the natural gas grid as upgraded biogas or biomethane. Biogas is mentioned as having a key role in the transition towards a low emission society by the Danish Council on Climate Change.

There are many different takes on the biomass potential in Denmark but one thing they have in common is that there is not enough biomass to cover the future energy demands. The biogas potential is set to be around 40-50 PJ. This can be raised to 80 PJ according to Henrik B. Møller who mentions that methanation can be one of the solutions to increase the potential. Therefore, this project will attempt to implement electrolysis and methanation (hydrogenation) at Nature Energy Midtfyn.

Biogas is often seen as CO_2 neutral but there are however emissions tied to the production. Here the greatest sinner is electricity from the grid which stand for 50 % of the emissions in the reference scenario of this project which is Nature Energy Midtfyn. The goal for Nature Energy is to reduce the emissions from the electricity consumption in order to offer a better product to their customers. The product along with the biogas is a guarantee that ensures biogas bought has a reduction effect of minimum 60 % in the form of a REDcert certificate. Therefore, this project will aim to increase the CO_2 reductions through the introduction of renewable electricity production, the use of biogas instead of natural gas for heating biomasses at the biogas plant and electrolysis with methanation (hydrogenation).

3 Methods

In the following section, the simulation tools, assumptions, limitations, data collection and the socio-economic calculation method of the project will be explained.

3.1 Simulation Tools

In this section the main simulation tool energyPRO and the usage of Excel and e!Sankey is explained.

energyPRO

energyPRO is a modeling software which can be used for technological and economic analysis of energy projects. It is able to optimise complex energy systems that include both electricity and heat production from multiple different energy producing units [22]. Additionally, energyPRO can provide the user with a financial plan with all revenues and expenditures and an overview of the energy conversion data. The financial figures is necessary in order to determine the feasibility of the different scenarios in the project and the energy conversion data is necessary for the GHG calculations.

In order to simulate an energy project, energyPRO needs different kinds of data: external conditions (weather, electricity prices, natural gas prices), fuels, demands, the energy conversion units, revenue streams, operation expenditures and investment costs.

Weather data is available directly in energyPRO. energyPRO gets the data from a weather station, which the user can choose on a map. The weather stations available on Funen can be seen in the figure below.

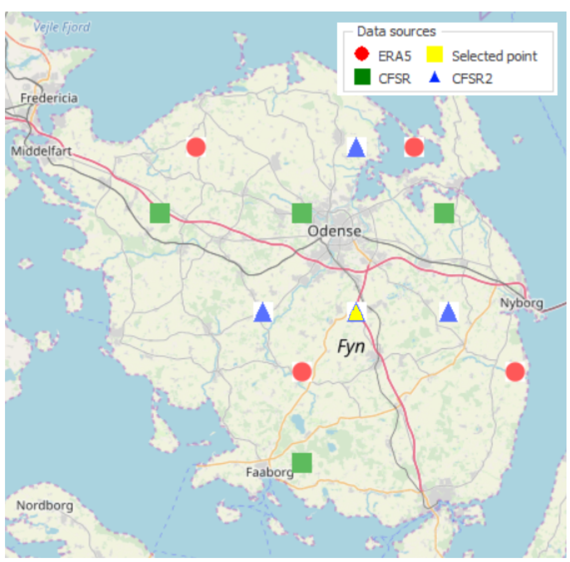


Figure 5: The available weather stations in Funen in energyPRO. Screenshot from energyPRO.

For each weather station it is possible to retrieve data on hourly air temperatures, solar radiation, wind speeds, precipitation and humidity. This data is for example used when energyPRO calculates the electricity production from wind turbines or photovoltaics (PV).

Electricity prices and natural gas prices can be inserted as hourly prices for an entire year. These prices can then be set to follow an index over the lifetime of the project. Demands of electricity and heat can be inserted as a time series or a times series function which can depend on the external conditions.

The revenues and operation expenditures can either be set to a fixed yearly value or it can be a function of different parameters from the energy project. For example, the revenue from a wind farm can be defined as the electricity production multiplied with the electricity spot price.

Excel

Excel is used to process the data from the simulations in energyPRO and to do sensitivity analysis. Excel is also used to make the graphic representation of the results obtained from the energyPRO simulations.

e!Sankey

e!Sankey was used to create illustrations of the energy flows in the different scenarios defined in Section 4. e!Sankey was used for Figure 7, 8 and 10. The input data for the e!Sankey diagrams are from the simulations in energyPRO.

3.2 Assumptions and Limitations

This section will contain the assumptions and limitations applied in this project.

Frozen Policy
It is assumed that the current legislation will stay the same throughout the lifetime of the project.

Constant biomethane production
In Scenario 1 and 2, it is assumed that the production of biomethane is constant. This also means that the consumption of electricity and natural gas is constant in these scenarios.

Weather Data
Weather data from Årslev on Funen from 2015 has been used. This means that the results are not directly applicaple for all locations. The location was chosen because it was the closest weather station to Nature Energy Midtfyn.

3.3 Data Collection

This section will present and review the data and the sources that has been used throughout the project. The data is split into three categories: technological data, economic data and data on external conditions.

Technological Data

The technological data is primarily used for the simulations in energyPRO. Table 2 below, presents what kind of data is used and gives a description of the data together with the source of which the data came from.

Data	Description	Source	Reference
	Biogas Plant and Upgrading		
Production and consumption data	Data regarding electricity consumption, natural gas consumption, biogas production and biomethane delivered to the natural gas grid at Nature Energy's biogas plant in Midtfyn.	Nature Energy	[23]
	Wind Turbines		
Power curve	The electricity production of the wind turbines at different wind speeds.	wind-turbine-models.com Vestas V90 2 MW	[24]
	Photovoltaics		
PV module specifications	Data regarding the specifications of the PV modules.	Suntech STP275S - 20/Wem	[25]
	Electrolysis		
Production and consumption data	Data regarding the electricity input, hydrogen output, district heating output and the heat loss in an alkaline electrolysis cell.	Technology Data for Renewable Fuels	[26]
	Methanation		
Production and consumption data	Data regarding the biogas input, hydrogen input, electricity use, biomethane output, district heating output and heat loss in the methanation plant.	Technology Data for Renewable Fuels	[26]

Table 2: Description and sources for the technological data used in this project.

Economic Data

The economic data is used for calculating revenue and operation expenditures for all scenarios in energyPRO. Table 3 below presents what kind of data is used and gives a description of the data and the source hereof.

Data	Description	Source	Reference
	Electricity Price		
Electricity spot price	The hourly electricity price of DK1 in 2015 is used in the simulations.	Energi Data Service	[8]
Electricity price index	The index that the electricity price follows throughout the lifetime of the project.	Danish Energy Agency	[27]
Electricity taxes	TSO, DSO, PSO and electricity tax payed on the consumption of electricity.	Energinet Nature Energy	[28] [29]
	Natural Gas Price		
Natural gas spot price	The average natural gas price of 2018 has been used in the simulations.	Gaspoint Nordic	[30]
Natural gas price index	The index that the price of natural gas follows throughout the lifetime of the project.	Danish Energy Agency	[31]
Natural gas taxes	CO_2, NO_2, and natural gas tax payed on the consumption of natural gas.	Natural gas bill from Nature Energy	[23]
	Investment Cost		
Investment costs	The investment costs of wind turbines, PV plants, electrolysis plants and methanation plants.	Technology Data Catalogues	[26] [32]
	Operation & Maintenance		
Operation & Maintenance	The cost of O&M for wind turbines, PV plants, electrolysis plants and methanation plants.	Technology Data Catalogues	[26] [32]
	Subsidies		
Subsidies	The amount of subsidies given for biomethane delivered to the gas grid.	Danish Energy Agency	[33]
	Tax on Biogas		
Tax on biogas	The tax on biogas used for heat production.	The Danish Ministry of Taxation	[34]
	Sale of biomethane		
Sale of biomethane	The price Nature Energy gets for selling biomethane.	Nature Energy	[23]
	Damage costs		
Damage costs	Data on cost of damages from different pollutants.	Danish Energy Agency	[35]

Table 3: Description of, and sources for, the economic data used in this project.

Data on External Conditions

The data on external conditions, such as weather data, is used in energyPRO to calculate the electricity production from wind turbines and photovoltaics. Table 4 below presents what kind of data is used and gives a description of the data and the sources hereof.

Data	Description	Source	Reference
	Weather Data		
Weather Data	Temperature, wind speeds and solar radiation from 2015 are used in the simulations.	energyPRO CFSR2	-
	Danish Biomass Potential		
Danish Biomass Potential	Data on the biomass potential available for biogas production in Denmark.	Energy scenarios towards 2020, 2035 and 2050	[14]

Table 4: Description and sources for the data for external conditions used in this project.

The overall validity of the data used in the projects is deemed sufficient since it comes from reputable sources and historic data. The data used mostly originates from public authorities which are considered reputable objective sources. Data about technologies mostly originate from actual data from either Nature Energy Midtfyn or data sheets from manufactures.

3.4 Business Economic Analysis

This section will describe the method used for the calculations of the business economics, and what assumptions have been made.

The general method used for the business economic analysis, is to calculate the expenses and revenue for each year, for each scenario. The revenue minus the expenses is calculated for each year and is referred to as the contribution margin. The net present value (NPV) of the scenarios are found using Equation 1.

$$NPV = \sum_{t=0}^{20} \frac{Cm_t}{(1+r)^t} \tag{1}$$

Equation 1 consists of the following parameters:

- NPV: The net present value of the solution in the scenario.
- 20: Refers to the lifespan of the project, which is set to 20 years in all simulated scenarios.
- t: Refers to each year of the project.

- Cm_t: The contribution margin in each year of the project.
- r: The interest rate used for the business calculations is 10 %.

Other Assumptions Used

In all scenarios, it is assumed that the investment cost is paid off as a loan with a interest rate of 2.75 %. This interest rate originates from a business case from Nature Energy [23]. When it is calculated how much the REDcert price needs to increase in order for the given solution to be attractive for Nature Energy, the REDcert price is increased until the internal rate of return (IRR) reaches 12 %, as per request from Nature Energy [23].

3.5 Socio-economic Analysis

The socio-economic analysis is following the Danish Energy Agency's socio-economic analysis guidelines [36] and the calculation prerequisites used in the guideline [35].
Socio-economic calculations will be carried out for the GHG reductions or increases of the different scenarios in the project. As the scenarios in the project aims to reduce GHG emissions, it is socio-economic benefits that are considered. The result of the calculation will be socio-economic benefit per MWh biomethane produced, DKK/MWh. The valuation of reduced CO_2 emissions is different from reduced SO_x, NO_x and $PPM_{2.5}$ emissions. CO_2 is valued as marginal cost of increasing or decreasing the emission of CO_2, where SO_x, NO_x and $PPM_{2.5}$ is valued as the cost of the loss in years of life. The two valuation methods are elaborated further in the subsequent sections.

Valuation of CO_2

As mentioned, the CO_2 valuation is calculated as marginal cost of increasing or decreasing the emission of CO_2. This is the calculation method recommended by the DEA. Contrary to the valuation of SO_x, NO_x and $PPM_{2.5}$, the CO_2 emission is not based on damage costs, but rather as saved or increased costs tied to the marginal reduction cost.
Following the guidelines, a price approximation of CO_2 quotas is used to valuate GHG. The quota price has however changed drastically since the release of the guidelines in October 2018 - revised 20th of November 2018 [35]. The guidelines' approximation of the quota price in 2019 was set to 119 DKK/t, where today's price, April 15th 2019, is 200 DKK/t [37]. For this project, the latest accessed quota price will be used for the socio-economic calculations concerning CO_2 emissions. The price is, as seen in Figure 6, incredibly volatile, but with an upward trend following the year.

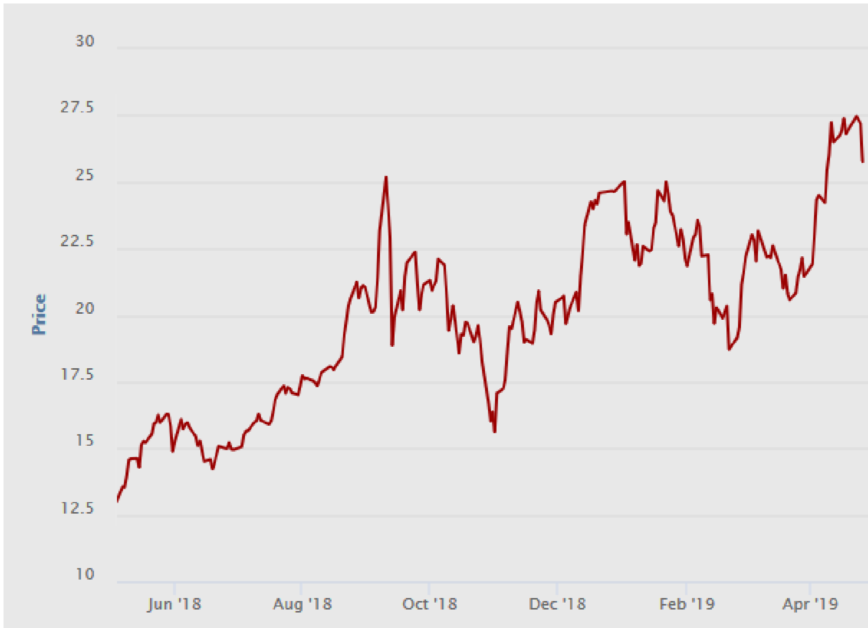


Figure 6: The CO_2 emission allowance price May 2018 - May 2019 in EUR/t [37].

DEA states that the projection of the quota prices is tied with great uncertainty and should be seen as a central approximation. Because of this, it is important to perform sensitivity calculations where alternative conditions for the calculations are used. Additionally, the quota price has to be multiplied with the *net tax factor* when doing socio-economic calculations.

Valuation of SO_x, NO_x and $PPM_{2.5}$

Where CO_2-emissions are dependent on the fuel type when burning fuels, the emissions from SO_x, NO_x, CH_4, N_2O and $PPM_{2.5}$ are both dependant on fuel and the technology used. For this project, the emission coefficient for natural gas from the gas grid and electricity from the electricity grid will be used. These coefficients are found in the calculation prerequisites for socio-economic analyses for emissions, provided by the DEA [35].
For the damage costs related to the emissions, the note *"Miljøøkonomiske beregningspriser for emissioner 3.0"* [38] from DCE is used. DCE is the National Centre for Environment and Energy. The note has calculated damage costs for different sectors and is valued as the cost of lost life years due to the emission.
For this project, the energy sector is used. The settlement for the emissions is calculated following the *impact pathway*-method, which consists of four parts:

1. concentration contributions from emissions,
2. inhabitant's exposure to the emissions based on their placement from GIS-data based on CPR-data,
3. summarised health effects based on exposure

4. monetary valuation based on unit values for each health effect.

From this, the marginal external emissions costs from large incineration plants has the emission costs shown in Table 5:

Damage Cost Values	
Pollutant	[DKK/kg]
SO_x	134
NO_x	137
$PM_{2.5}$	265

Table 5: The emission costs per emitted pollutant in DKK/kg [38].

These values will be used to find the socio-economic benefit, or costs, for the different scenarios in the project. The end comparison parameter will be costs or benefits in DKK/MWh produced biomethane.

3.6 Section Summary

The methods described in this section will be used to calculate the results of the different scenarios of the project, using the data from the energyPRO simulations. The sources of the data inputs of the project is presented in three different tables concerning technological data, economic data and external conditions.
The valuation of emissions includes both the marginal cost of reducing CO_2 emissions and the health effects from particles like SO_2 and NO_2. The CO_2 price used to evaluate the emissions in this project is 200 DKK/t. The health effect valuation use values from the National Centre for Environment and Energy.

4 Scenarios

The following section will introduce and elaborate on the different scenarios of the project. Each scenario will have a description of the system and the expectations of the outcome of the given scenario as well as a system drawing.

Besides the Reference Scenario that describes the current biogas production, there are three different main scenarios. **The first**, a scenario where CO_2 emissions from the production of biogas is reduced by installing renewable electricity production near the site. **The second**, a scenario where the reduction comes from using own biogas instead of natural gas from the grid for heating the biomass. **The third**, a scenario where biogas production is increased with electrolysis and methanation. This scenario will be called the hydrogenation scenario. In addition to the third scenario, there will be a sub-scenario where renewable electricity production is installed alongside the electrolysis and methanation.

4.1 Reference Scenario

The Reference Scenario is built upon the biogas plant Nature Energy Midtfyn located near Ringe. The plant has a capacity of approximately 360,000 tons of biomass every year and produces around 11 million m^3 of biomethane [39]. For the scenario in question, the total production for the reference year, 2018, is 121 GWh biomethane which amounts to roughly 6,700 households yearly heating consumption, at an average consumption of 18.1 MWh/year for each household.
The reasoning behind using Nature Energy Midtfyn as a reference scenario is that it is an example of a modern biogas plant, being built in 2015 [39]. Also, data on Nature Energy Midtfyn was available for use in this project.

The biomethane production is modelled in energyPRO with the following components, except biomass input:

- **The electricity grid:** Electricity is fed to the biogas production unit and the upgrading unit.
- **Biogas production unit:** Biomass is heated in order to accelerate the gasification process using natural gas. The composition of the biogas produced is roughly 60 % CH_4 and 40 % CO_2.
- **Upgrading unit:** The upgrading unit is a water scrubber that purifies the biogas to contain at least 97.3 % methane [40]. In the purification process, H_2S (hydrogen sulfide), O_2 and CO_2 is removed from the biogas. After this process the product is now biomethane.
- **The gas grid:** The upgraded biogas, now biomethane, is fed to the natural gas grid. Simultaneously natural gas is used for the heating process at the biogas plant.
- **Biomass:** The biomass is a mixture of different organic matter primarily from agricultural waste. The biomass feed will not change in the different scenarios and will not be included in the energyPRO model. The biomass input is still included in the figures for visualisation purposes and has been set to be two times the biomethane output, since the efficiency is typically around 50 % [41].

The illustration of the reference scenario is seen in Figure 7.

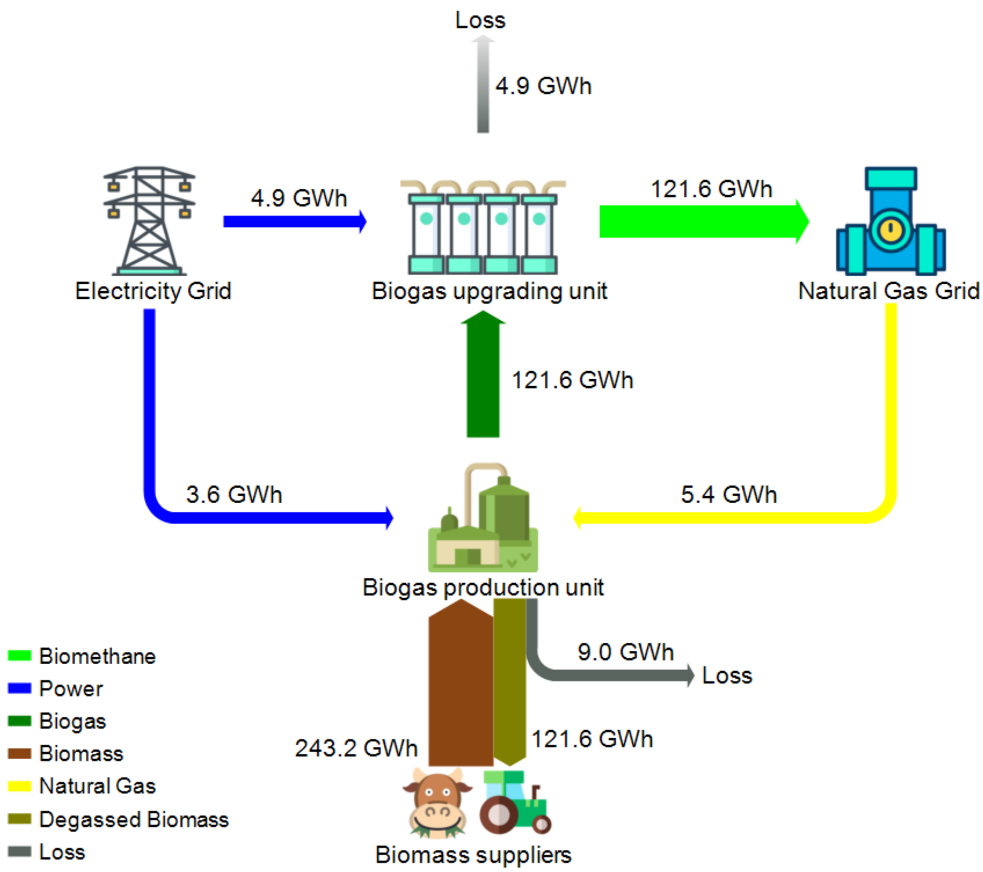


Figure 7: Sankey diagram of the reference scenario. Icons from [42][43].

The expectation for the reference scenario is that it is as close a representation of the reality as possible since data inputs from the plant Nature Energy Midtfyn is used.

4.2 Scenario 1 - Photovoltaics and Wind Power

In this scenario, PV and wind capacity is added to the model in order to create a more renewable biogas production by reducing the share of CO_2 emitted from the used electricity. The share of PV and wind power will depend on whichever is the most economically feasible over the projected period. Sub-scenarios with different capacities of installed wind power and PV will be simulated to find the best solution.

In Figure 8 an illustration of Scenario 1 can be seen. The only difference from the reference scenario in Figure 7 is the added solar and wind capacity. The wind power and PV can be added to the unit list from Section 4.1 with the following:

- **Wind:** A wind turbine between 1-3 MW will produce CO_2 neutral electricity to the biogas plant.
- **Photovoltaics:** Like the wind turbine, the PV-park of 1-3 MW will produce electricity to the biogas plant.
- **Electricity meter:** The meter is an important component regarding keeping the electricity flows to the grid and the plant separated. There is a meter measuring the electricity fed to the grid and to the biogas plant. This ensures that there is no taxation and levy added to the electricity send to the plant directly from the renewable production. Should the renewable on-site power production exceed the demand of the biogas plant and upgrading unit, the electricity will be sold to the grid.

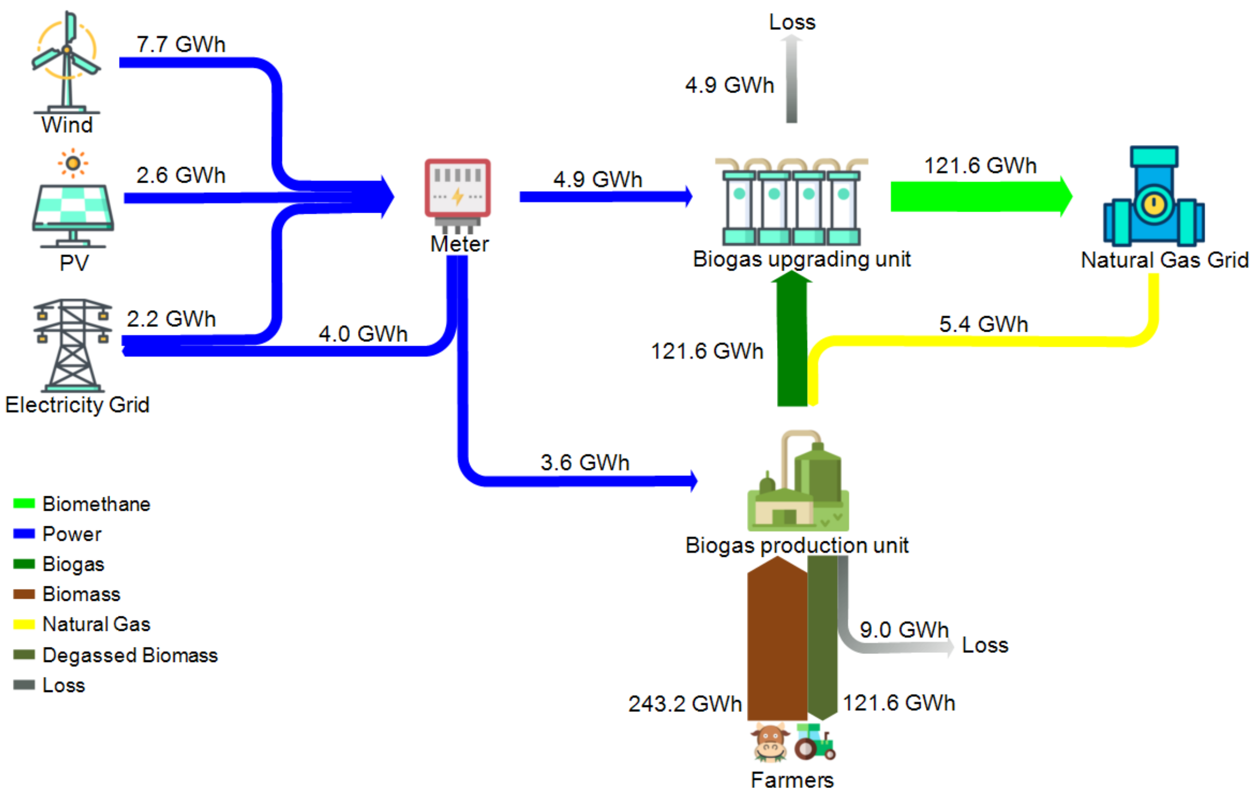


Figure 8: Sankey diagram of Scenario 1, showing the sub-scenario where 2 MW wind power and 2 MW PV is installed. Icons from [42] [43].

The expectations for this scenario will be that the addition of renewable electricity production will have a large enough impact on saved taxes, levies and electricity costs in the production to make it feasible. Regarding the emissions, it is expected that adding renewable electricity production to the biogas production will yield lower emissions per biomethane produced.

4.3 Scenario 2 - Biogas Replaces Natural Gas for Heating

This scenario considers the expenditures and emissions of changing the fuel used for the heating of biomass from natural gas to biogas produced on site. The costs in this scenario will depend on the savings on natural gas, the lost revenue from the smaller biomethane production and the investment in a new biogas boiler. The levy on using natural gas for process heat is 219.9 øre/Nm^3 while the levy for using biogas is only 9.8 øre/Nm^3. Using biogas to heat the biomasses will however result in less total biomethane sold to the natural gas grid. The difference in levies will therefore have to make up for the loss in lost biomethane sales. Figure 9 shows the energy flow in this scenario.

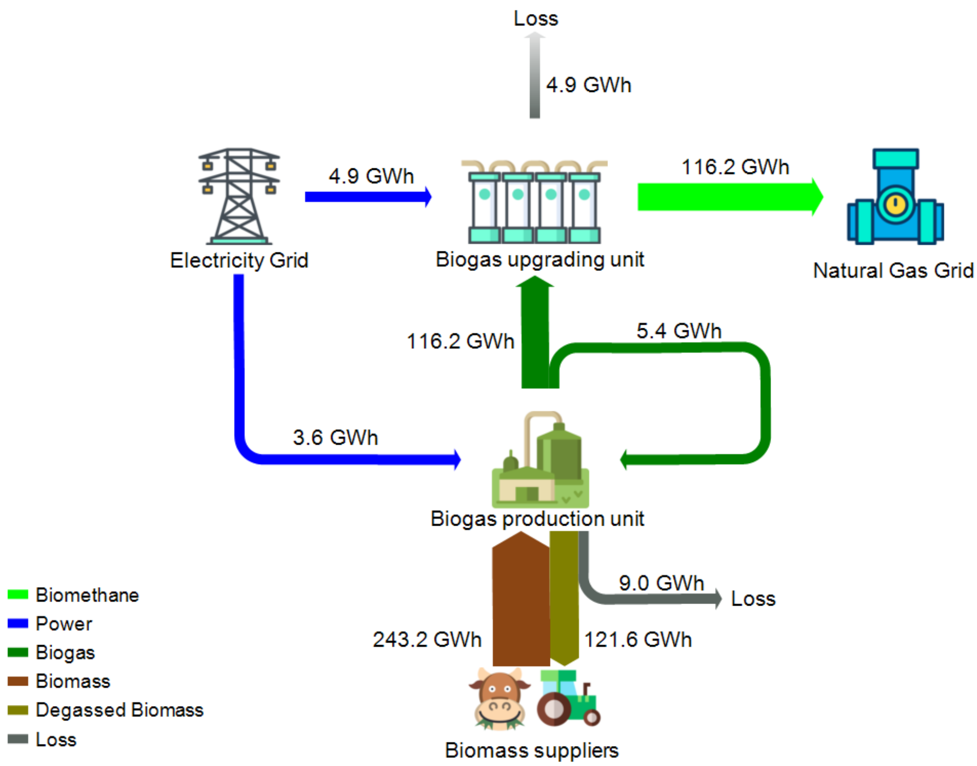


Figure 9: Sankey diagram of Scenario 2 where natural gas is replaced with biogas. Icons from [42][43].

The emissions in CO_2-eq/MWh produced bio methane is expected to decrease given that the biogas used will be considered CO_2 neutral. It is also expected that this scenario will have a socio-economic benefit because of the emission reduction but have a negative effect on revenue because of reduced biomethane sales.

4.4 Scenario 3 - Hydrogenation

The hydrogenation scenario consists of adding an electrolysis unit with related methanation unit in order to increase the biomethane production. When hydrogenation is mentioned further on in the report the meaning is an electrolysis unit in combination with methanation.

The following units have been added to the scenario, as seen on Figure 10:

- **Electrolyser:** The electrolysis unit will produce hydrogen utilising low electricity prices and/or own renewable electricity production. The hydrogen produced will be one of the inputs to the methanation unit. As seen in the figure, there are heat losses and heat that can be used as excess heating in a close by district heating network.
  The size of the electrolysis plant is determined by assuming that 50 % of the biogas will be redirected to the methanation unit. Knowing the CO_2 contents of the biogas, the amount of hydrogen needed is determined using the following energy balance:

  $$CO_2 + 4H_2 \longrightarrow CH_4 + 2H_2O \tag{2}$$

  From the energy balance it can be seen that the needed hydrogen is four times greater than the CO_2 contents of the biogas. From this the needed electricity consumption to create the needed amount of H_2 can be found and then from this, the electric capacity of the electrolysis plant can be found using efficiency data from the technology catalogue [26].

- **Methanation:** The methanation unit will combine the CO_2 from the biogas input and the H_2 from the electrolysis to create additional biomethane. As with the electrolysis, there are some heat losses and heat that can be utilised tied to the unit.
  The capacity of the methanation unit is found using the determined amount of H_2 and CO_2 and use the technology data catalogue for the efficiency [26]. The efficiency for the methanation unit is close to 100 % since the only loss tied to the unit is equal to the electricity input, which is 1 % of the total energy input.

The scenario revolves around feeding the methanation unit with a share of biogas equal to what is needed for the produced hydrogen to merge with the CO_2 in the biogas in order to make more biomethane. The hydrogenation process only runs when the day ahead prices are below or equal to the set maximum electricity price for the unit. This set maximum electricity price is referred to as the *cut-in price*. The intention of using the day ahead price as a switch is that it opens up for the possibility of adding fast biomasses, such as fat- and sugar-containing waste from the industry or glycerine, to the biogas production process and thereby increase the overall biomethane production. This is already a used method for increasing the biogas production within a few hours [44]. To clarify, the day ahead price determines if biogas is redirected to the methanation and if additional fast biomasses that can be added to the production. This scenario was proposed by Nature Energy, as they see it as a potential way of implementing hydrogenation to existing biogas plants.

Figure 10 shows how the flows of the scenario would look like with a cut-in price for the hydrogenation at 250 DKK/MWh electricity. In the sub-scenario shown, no renewable capacity is added but the possibility of this is utilised in the scenario where renewable capacity is added in order to investigate the effects of this.

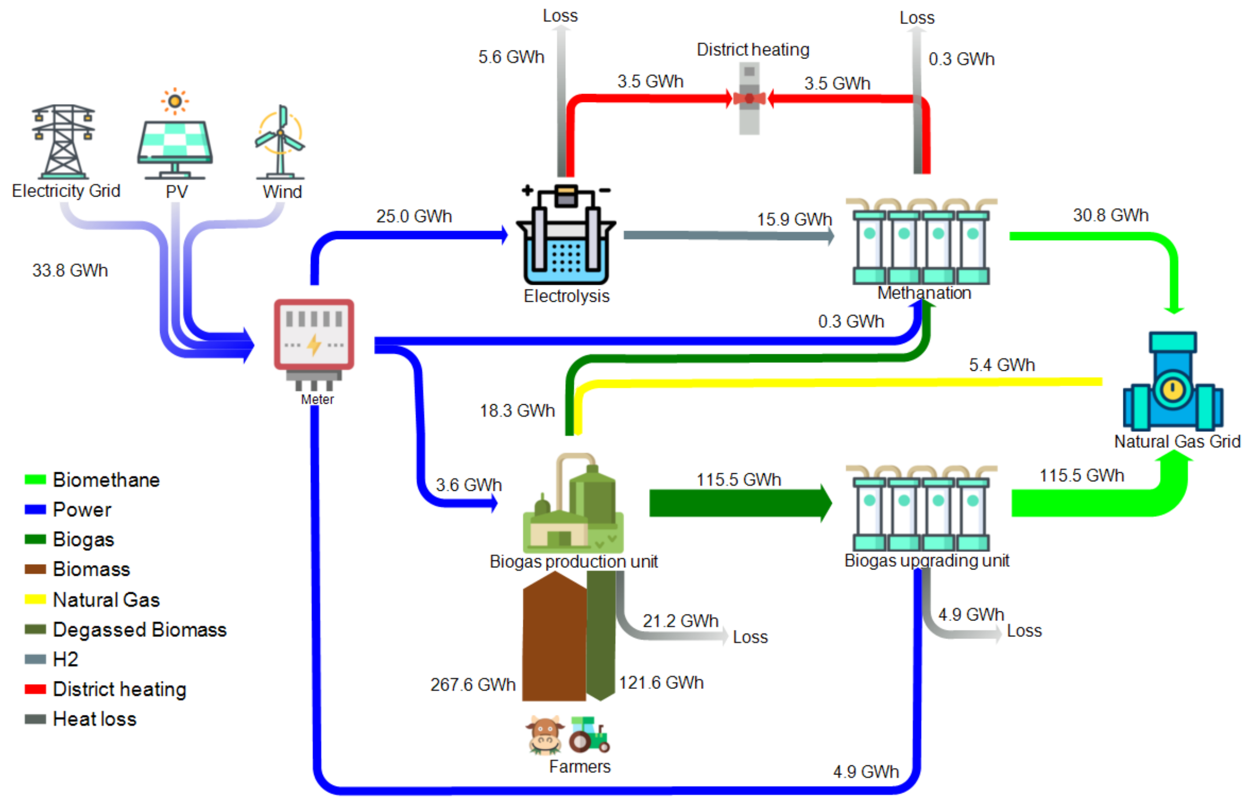


Figure 10: Sankey diagram of Scenario 3 with a cut-in electricity price of 250 DKK/MWh. Icons from [42][43].

The expectation for the hydrogenation scenario is that the added electrolysis and methanation units will be able to increase the total biomethane production. The feasibility of introducing these units is however not expected to be considered great since there are high capital costs attached to this. Furthermore, it is expected that the additional biomethane produced will not be enough to cover the costs of the hydrogenation and the large amounts of electricity bought from the grid. Looking at how the emissions will either increase or reduce in CO_2-eq/MWh biomethane will depend on whether the increased biomethane production and it replacing natural gas will be enough to account for the emissions from the additional electricity usage in the hydrogenation process.

For the hydrogenation scenario with added renewable capacity, the picture is slightly different. Here it is expected that a large part of the expenses to electricity consumption is reduced thereby making the hydrogenation a more likely solution to increase biomethane output. For the emissions it is expected that there will be a large reduction in most of the sub-scenarios due to decreased use of electricity from the grid and increased biomethane production. However, it will not be possible to produce extra biomethane from fast biomasses, and this will likely cause a decrease in revenue, compared to the scenario without wind power.

4.5 Section Summary

Through the scenario section the reference and the three scenarios have been described along with the expected changes in emissions and feasibility in relation to the Reference Scenario. The scenarios will create the basis for the simulations, where the different scenarios will be simulated based on their system descriptions.

5 Simulation

The energyPRO model is elaborated in the following section. Each of the modules and the system will be explained along with the system extensions with wind power, photovoltaics and hydrogenation. The scenarios are simulated over a lifetime of 20 years from 2019-2038.

5.1 Data Choice for the Scenarios

This section explains the simulation method which is identical in all of the scenarios. When choosing data for weather and electricity prices, it is important that these originate from the same period. This is because the weather affects the price of electricity, when a larger part of the electricity production is from wind turbines and photovoltaics [45]. If the data series are not from the same period, it could occur that the electricity production from renewables and the electricity price are both high, and this would not be the case in reality. The year 2015 is chosen since the solar radiation and electricity production from wind power seem to be close to average. This is shown in the sections below.

5.1.1 Solar Radiation Data

In Figure 11 the accumulated hours of bright sunshine from 1920-2017 is shown. It can be seen that the hours of bright sunshine on average has been higher since 2000 than the average from 1981-2010. 2015 is close to the average from 2000-2017. The average hours of bright sunshine were 1,574 hours from 1981-2010 [46].

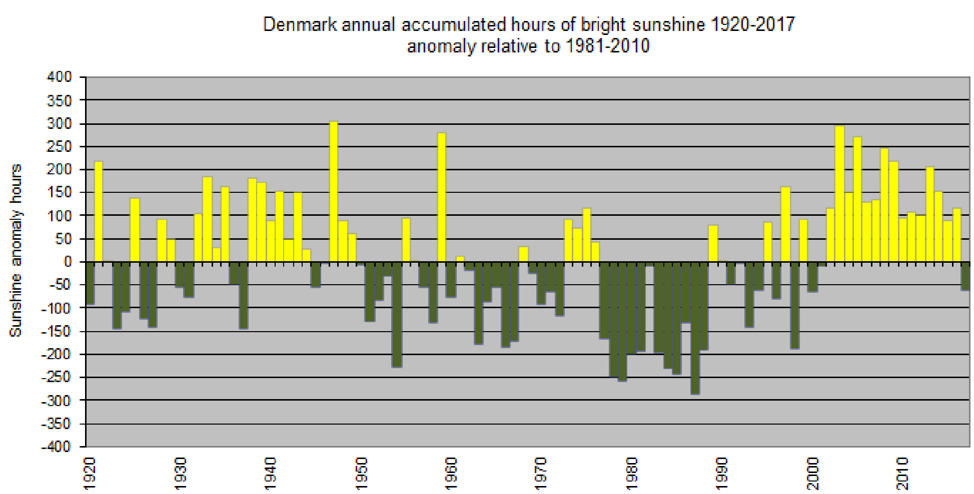


Figure 11: The yearly number of hours with bright sunshine in Denmark from 1920-2017 [46].

5.1.2 Wind Data

In Figure 12 the percentage share of wind power in the Danish power grid is shown. The figure shows a somewhat steady incline from 2009 to 2015, but in 2016 the wind power did not produce as much electricity and therefore the lower share. In 2017 it rose again, back to the tendency that is seen in the Danish electricity grid.

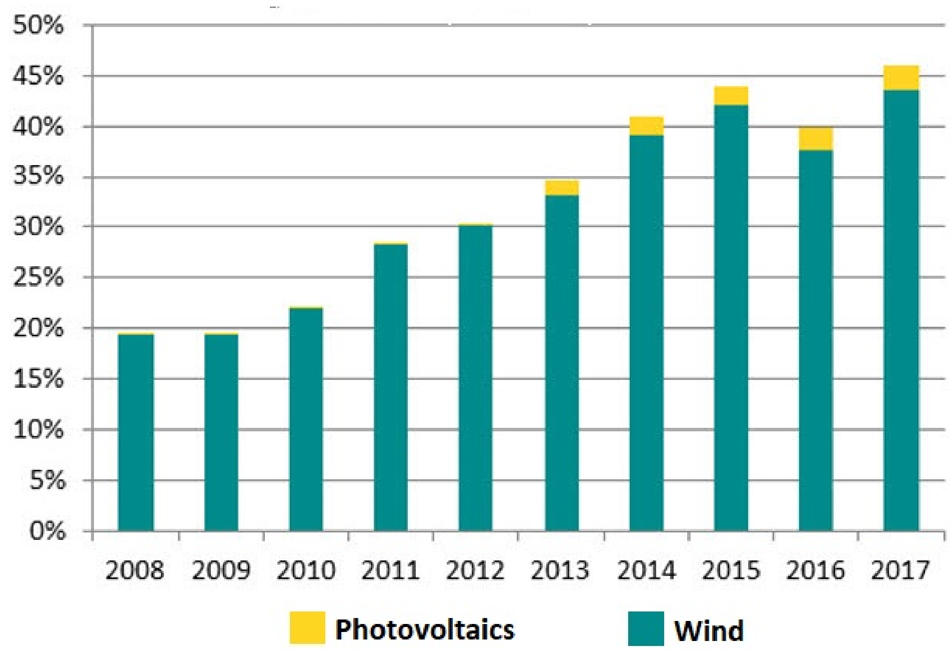


Figure 12: The percentage share of wind in the Danish power grid from 2008 to 2017 [47].

5.1.3 Electricity Spot Price

The spot price data is chosen to be the same year as the wind and solar irradiation data which is 2015. Based on the weather data, the spot price should correlate with the times where the wind turbines and the PV panels produce electricity. This meaning that the electricity prices are often low when PV and wind production is high and vice versa.

The electricity price is following an index which is created using the projection of the electricity price from The Danish Energy Agency [27].

5.1.4 Natural Gas Price

The average gas price of 2018 has been used together with an index based on the projections of future natural gas prices [31]. It is sufficient to use the average value, because the natural gas consumption is assumed to be constant, and therefore, it is not changing anything over using hourly prices.

5.1.5 Production and Upgrading of Biogas

The production and upgrading of biogas are assumed constant. This means that the consumption of natural gas and electricity is constant. Likewise, the flow of biogas from the digester to the biogas upgrading plant (BUP) is constant, and the flow of biomethane from the BUP to the natural gas grid is constant.

5.2 Technology Data Inputs

The following section will provide the technology data used. The data is listed in Table 6.

Technology data table

Production Unit	Data	Amount	Unit
Biogas Digester	Electricity use	3,570	MWh/year
	Natural gas use	5,372	MWh/year
	Biogas production	121,592	MWh/year
Water scrubber	Electricity use	4,927	MWh/year
	Biomethane production	121,592	MWh/year
Wind Turbine	Maximum power	2	MW
	Hub height	85	m
	Wind speed measure height	10	m
	Hellmann exponent	0.20	
Photovoltaics	Module maximum power	275	W
	Inclination	39	°
	Temperature coefficient	-0.440	%/ °C
	NOCT[1]	45	°C
Boiler	Installed Capacity	1.00	MW
Electrolysis	Electricity use	9.47	MW
	H_2 per electricity use	63.6	%
	Hydrogen heat value	3.0	kWh/m^3
	Heat loss	14.0	%
Methanation	Electricity use	0.13	MW
	Biogas input	6.94	MW
	Hydrogen input	6.02	MW
	Biomethane output	11.65	MW
	District heating output	1.31	MW
	Heat loss	0.13	MW

Table 6: The technology data used for the different simulations.

The sources for the data can be found in Tables 2, 3 and 4.

[1] Nominal Operating Cell Temperature

5.3 Financial Data Inputs

The following section will provide the financial data used. The data is listed in Table 7.
The financial data inputs are solely for the additions to the existing plant.

Financial data table

Production Unit	**Data**	**Amount**	**Unit**
Wind turbine	Investment cost	7,365,300	DKK/MW
	Fixed O&M	177,816	DKK/MW/year
	Variable O&M	18.6	DKK/MWh
Photovoltaics	Investment cost	4,612,800	DKK/MW
	Fixed O&M	60,264	DKK/MW/year
Boiler	Investment cost	446,400	DKK/MW
	Fixed O&M	14,508	DKK/MW/year
	Variable O&M	7.44	DKK/MWh
Hydrogenation	Investment cost	6,770,400	DKK/MW SNG
	Fixed O&M	267,840	DKK/MW SNG/year
	Variable O&M	32.14	DKK/MWh SNG
Electricity taxes	TSO tariff	44	DKK/MWh
	DSO tariff	36	DKK/MWh
	PSO tariff	101[2]	DKK/MWh
	Electricity tax	4	DKK/MWh
Gas taxes	CO_2 tax	0.391	DKK/m^3
	NO_2 tax	0.008	DKK/m^3
	Natural gas tax	2.199	DKK/m^3
	Emergency supply tariff	0.0063	DKK/m^3
	Biogas tax	0.098	DKK/m^3
Biogas subsidy	Biogas subsidy	349.1	DKK/MWh

Table 7: The financial data used for the different simulations.

The sources for the data can be found in Tables 2, 3 and 4.

5.4 Reference Scenario

In the simulation of the reference scenario Nature Energy Midtfyn has been simulated using actual values of their production from 2018. The setup in energyPRO can be seen in Figure 13.

[2] The PSO tariff decreases to 46 DKK/MWh in 2020, 11 DKK/MWh in 2021 and is completely phased out by 2022.

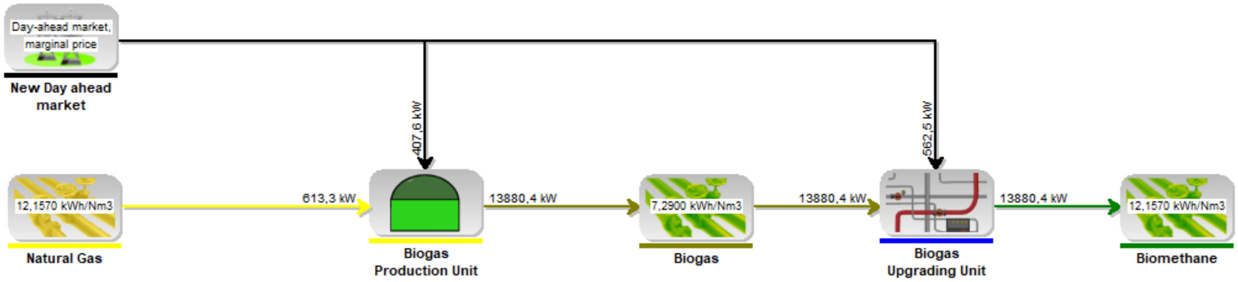


Figure 13: The setup of the reference scenario in energyPRO.

5.5 Scenario 1 - Photovoltaics and Wind Power

In this scenario different sizes of renewable electricity production, in the form of wind turbines and photovoltaics, are installed at the biogas plant. The sizes simulated are 0 MW, 1 MW, 2 MW and 3 MW of photovoltaics and wind turbines and all the possible combinations. This results in 16 different scenarios, where one scenario is equal to the reference scenario (0 MW PV and 0 MW wind power installed).

In the simulations the renewable electricity production will prioritise being used by the biogas plant over being sold to the grid. Therefore, the electricity production will only be sold, if it exceeds the electricity consumption. The biogas plant will prioritise using electricity from the renewable electricity production over electricity from the grid. Therefore, the biogas plant will only purchase electricity from the grid when the renewables cannot supply it. The setup in energyPRO can be seen in Figure 14.

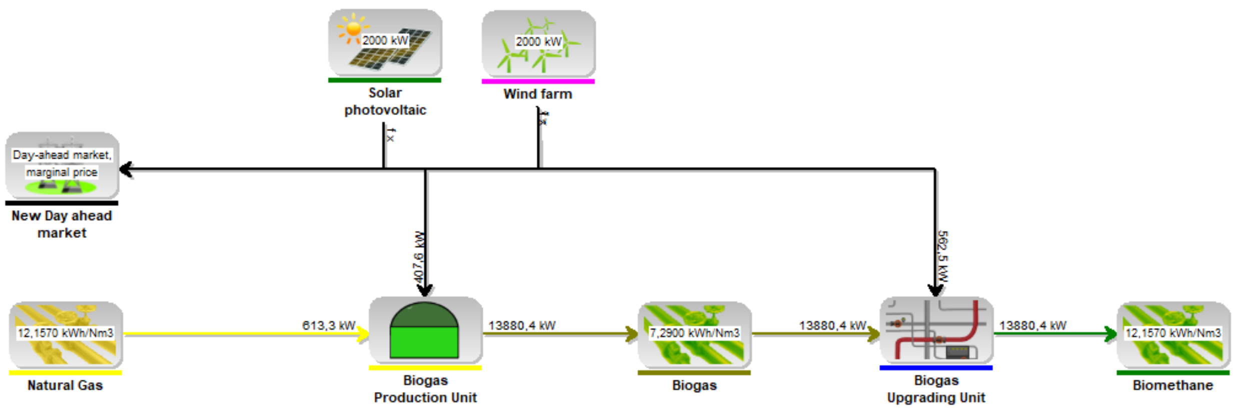


Figure 14: The setup of the wind and photovoltaics scenario in energyPRO.

An example the renewable electricity production of one month can be seen in Figure 15, which shows the simulated production of May, 2019. The figure showcases the scenario with 2 MW photovoltaics and 2 MW wind power.

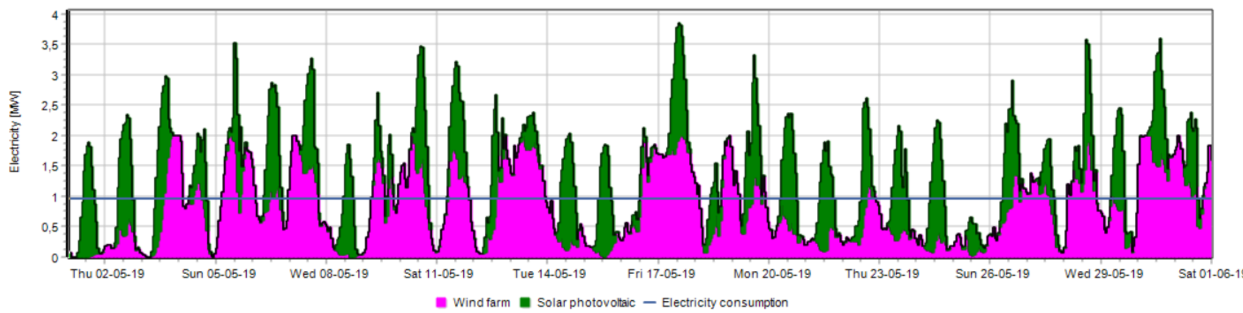


Figure 15: The electricity production and consumption of May 2019.

In Figure 15 the electricity consumption is the constant blue line. The electricity production from wind power is pink and the production of photovoltaics is green.

5.6 Scenario 2 - Biogas Replaces Natural Gas for Heating

This scenario has not been simulated in energyPRO. It was not necessary to simulate each hour, since the consumption of natural gas at the biogas plant is assumed to be constant. Therefore, average yearly values were used to calculate the results in Excel. In the calculations, the average natural gas flow of 613.3 kW of natural gas is replaced by a equivalent amount of biogas, measured in energy. A new biogas boiler of 1 MW is installed in this scenario, in order to utilise the biogas. The boiler is on purpose dimensioned larger than the average consumption, so that it does not have to run at maximum capacity, and in reality, the needed heat production is not completely constant. The results can be found in Section 6.4.

5.7 Scenario 3 - Hydrogenation

When simulating fuel production units, like electrolysers and methanation plants, in energyPRO, it is not possible to have more than one input fuel and one output fuel. Therefore, the methanation process, where biogas and hydrogen are both input and biomethane is output, could not be simulated in energyPRO. Therefore, the electrolysis and methanation is simulated as one unit, called hydrogenation, where the input is electricity and biogas and output is biomethane. The setup in energyPRO for this scenario can be seen in Figure 16.

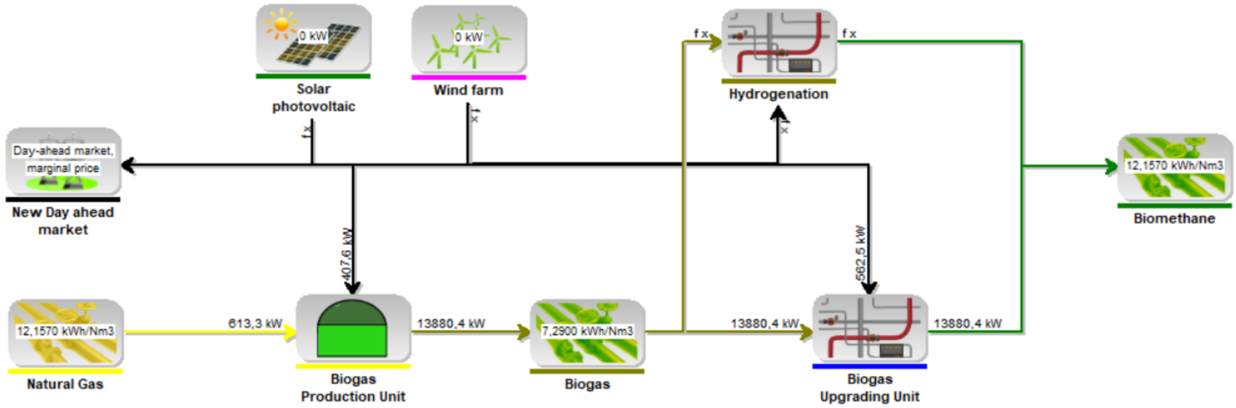


Figure 16: The setup of the hydrogenation scenario in energyPRO.

In the simulations, the hydrogenation is turned on once the average daily electricity price is below a certain threshold. The average daily electricity price is entered in energyPRO as a time series where the electricity price of each hour is the average electricity price of that day.

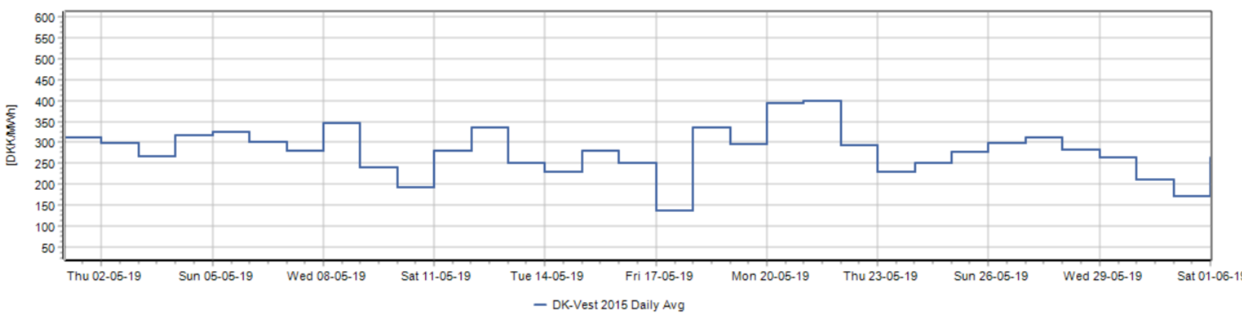


Figure 17: The average daily electricity price of June 2019.

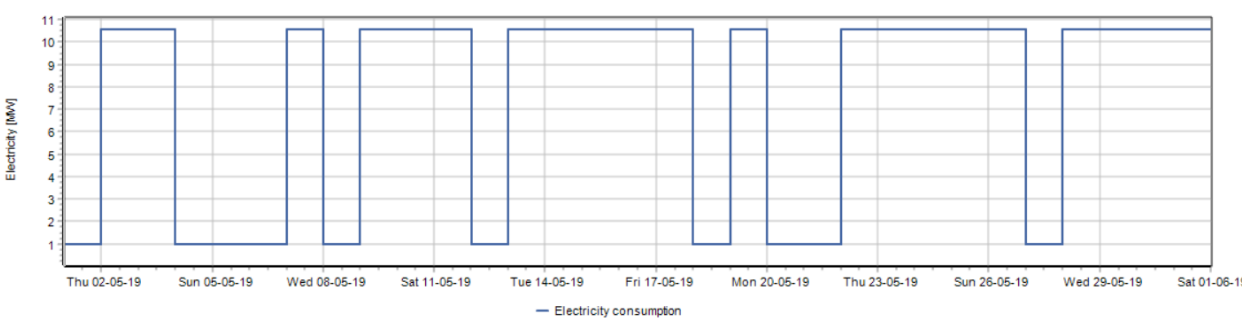


Figure 18: The electricity consumption of the biogas plant with hydrogenation in June 2019.

In Figure 17 and Figure 18, the simulation of June 2019 is shown with a cut-in price of 300 DKK/MWh. This means the hydrogenation process is on, when the daily average electricity price is lower than 300 DKK/MWh.

Sub-scenarios where wind power is installed alongside the hydrogenation has also been simulated. In these scenarios the hydrogenation will run utilising the same capacity as the renewable electricity production if the electricity price is above the cut-in price. If the average daily electricity price is below the cut-in price, the hydrogenation will still run at full capacity.

5.8 Section Summary

The year 2015 was chosen as basis for the wind and solar data since this year provided wind production and solar radiation close to average. The electricity spot price data are also from 2015 in order to have the correlation between electricity price and renewable production. The gas prices however are from 2018. Both the electricity and gas prices are projected using price indexes from 2018 by the Danish Energy Agency.
The different scenario setups in energyPRO are described and simulated and the behaviour of the system was investigated. The key to the simulations was to make sure the system reacted as expected, which it did.

6 Results

In the following section the main results are elaborated. These results and calculations include emissions, business economics and socio-economics for each of the scenarios presented in Section 4. The emission sections will elaborate on the emissions saved or increased in the different scenarios compared to the Reference Scenario. The business economic parts will investigate the feasibility of the scenarios, and how much the price of the REDcert certificates would have to increase to make it feasible. The socio-economic parts will investigate the socio-economic benefit of the reductions or increases in GHG emissions for each scenario. The results for each scenario will be discussed in their respective sub-sections. The foundation for the socio-economic calculations and the emission calculations can be found in Appendix C.

6.1 Overview

This section will give a quick overview of the most important results.

Figure 19 shows the most realistic reduction of GHG emissions from Scenario 1 and Scenario 2 combined. The sub-scenario chosen from Scenario 1 is the one with 1 MW of wind power installed, since it was found to be the most feasible.

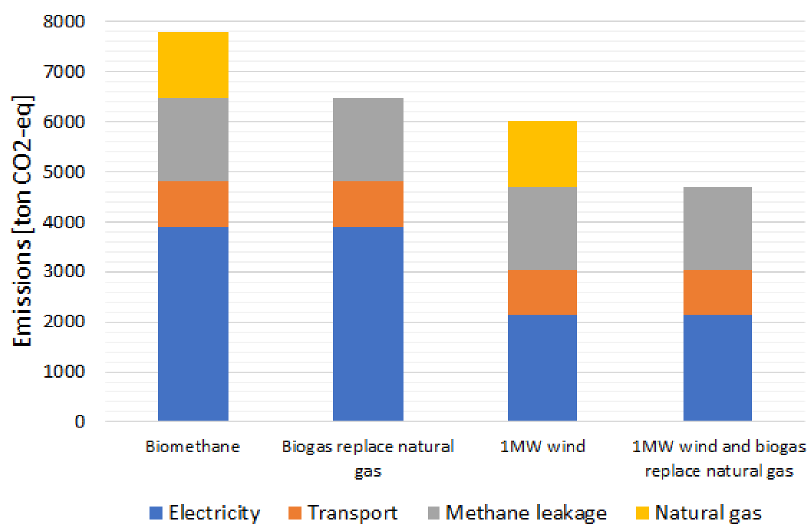


Figure 19: The emission results of Scenario 1 and 2 are compared to the Reference Scenario.

From Figure 19 the emissions From Scenario 1 and 2 can be seen compared to the reference scenario. Replacing the natural gas for heating with biogas decrease the GHG emissions with 16.8 %. Installing 1 MW of wind power decreases the GHG emissions with 22.75 %. Combining both scenarios gives a reduction of 39.55 % and a socio-economic benefit of at least 5.35 DKK/MWh produced biomethane. In Section 8.2 it is discussed how the emissions from methane leakage and transport can be reduced, given that the key focus of the project is reductions through renewable energy capacity.

Using biogas instead of natural gas would increase the consumer costs by 22.87 DKK/MWh, while implementing 1 MW of wind power would decrease them by 2.4 DKK/MWh. The combined scenario would therefore increase the consumer costs by 20.47 DKK/MWh, which corresponds to an increase of 6.3 %.

The results from the hydrogenation scenarios show, that almost all sub-scenarios have a negative NPV, and are therefore not economically feasible. The few scenarios that have a positive NPV have significant socio-economic costs, due to the large amount of electricity consumption. It is therefore concluded that hydrogenation is best suited for being implemented after 2030, where the emissions from electricity are carbon neutral, or in a combination with renewable electricity, in a system that is specifically designed for utilising hydrogenation.

6.2 Reference Scenario

The Reference Scenario will be used to compare results from the calculations for the different scenarios. This is done in order to conclude whether or not there will be benefits of introducing renewable electricity production from PV and wind, use biogas instead of natural gas for heating purposes or integrate hydrogenation in the production in order to boost biomethane production. Table 8 shows the total amount of emissions in CO_2-equivalents over 20 years from electricity and gas consumption for the Reference Scenario, calculated with the emission factors from the DEA [35]. Gas and electricity emissions are the only two highlighted since only these are subject to change in the different scenarios. And the 20 years are in order to have the same time period as simulated in the scenarios.

Emissions from:	Electricity consumption	Natural gas consumption
Ton CO_2-equivalents	11,755	18,258

Table 8: The total emission amount over 20 years from electricity and gas consumption.

The emission reduction or increases in the results will all be in relation to the numbers in Table 8.

The socio-economic benefits will be measured in DKK/MWh produced biomethane. The biomethane production is fixed at 121,592 MWh/year. This number will be the denominator for all the marginal reduction and damage costs tied to the emissions of the scenarios, except for Scenario 3 where the biomethane production is increasing.

6.3 Scenario 1 - Photovoltaics and Wind Power

The calculations and results of introducing own renewable electricity production at the biogas plant for the 16 different compositions of photovoltaics and wind capacity are described and discussed in this section. The notation used for the sub-scenarios is *MW PV/MW wind power*, meaning that the sub-scenario with 0 MW of PV installed and 1 MW of wind power is called *0/1*.

Emissions

The number of emitted CO_2-equivalents in Scenario 1 are shown in Figure 20.

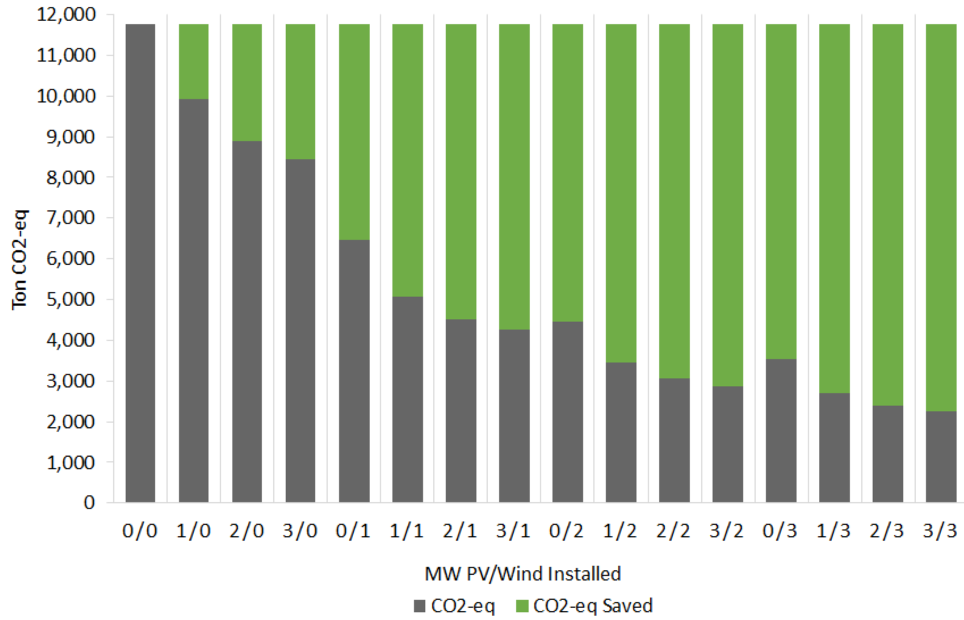


Figure 20: The emissions and savings from electricity consumption in the scenario over 20 years, in ton CO_2-equivalents.

From the figure it can be seen that the increase in photovoltaics and wind capacity has an effect on the overall emissions of the scenario. This is due to the decrease in use of electricity from the grid and an increase of self-produced renewable electricity.

The calculation for this was done by using the emission factors from the DEA guidelines shown in Figure 60 and 61, and the amount of electricity from the grid for the scenario. The electricity from the grid is shown in Table 9.

Electricity from the grid in [MW/year]					
	Photovoltaics				
Wind	MW	0	1	2	3
	0	8498	7179	6433	6106
	1	4679	3664	3260	3083
	2	3219	2488	2204	2082
	3	2560	1956	1727	1628

Table 9: Electricity purchased from the grid in the different sub-scenarios.

Table 10 shows the emitted ton CO_2-equivalents for the electricity from the grid. The emissions from the gas, from the natural gas grid, will be the same in all the configurations for this scenario and can be found in Table 8.

Emissions from electricity use in [ton CO_2-equivalents]					
	Photovoltaics				
Wind	MW	0	1	2	3
	0	11,756	9,931	8,899	8,447
	1	6,473	5,069	4,510	4,265
	2	4,453	3,442	3,049	2,880
	3	3,541	2,706	2,389	2,252

Table 10: Emissions from electricity from the grid in the different sub-scenarios.

From an emissions point of view, the scenario using 3 MW of wind power and 3 MW PV capacity would yield the highest decrease over the lifespan of the project. This is of course due to that sub-scenario being the one that uses the least amount of electricity from the grid.

Business Economics

The business economics will show the feasibility of different compositions of photovoltaics and wind capacities. The NPV and IRR has been calculated for each sub-scenario over the lifespan of 20 years. Furthermore, a breakdown of the expenses and revenues has been calculated. In Table 11 the NPV and IRR of the 15 different sub-scenarios and the reference scenario can be seen and in Figure 21 the numbers are presented visually.

MW PV/Wind Installed	0/0	1/0	2/0	3/0	0/1	1/1	2/1	3/1
NPV (20 years) [Million DKK]	-	-0.30	-1.05	-2.13	2.51	1.97	0.94	-0.24
IRR	-	9.09 %	8.42 %	7.46 %	14.50 %	12.20 %	10.77 %	9.84 %

MW PV/Wind Installed	0/2	1/2	2/2	3/2	0/3	1/3	2/3	3/3
NPV (20 years) [Million DKK]	3.16	2.40	1.29	0.05	3.19	2.33	1.18	-0.08
IRR	12.83 %	11.65 %	10.72 %	10.02 %	11.90 %	11.16 %	10.50 %	9.97 %

Table 11: The net present value and the internal rate of return of the 15 different sub-scenarios and the reference scenario.

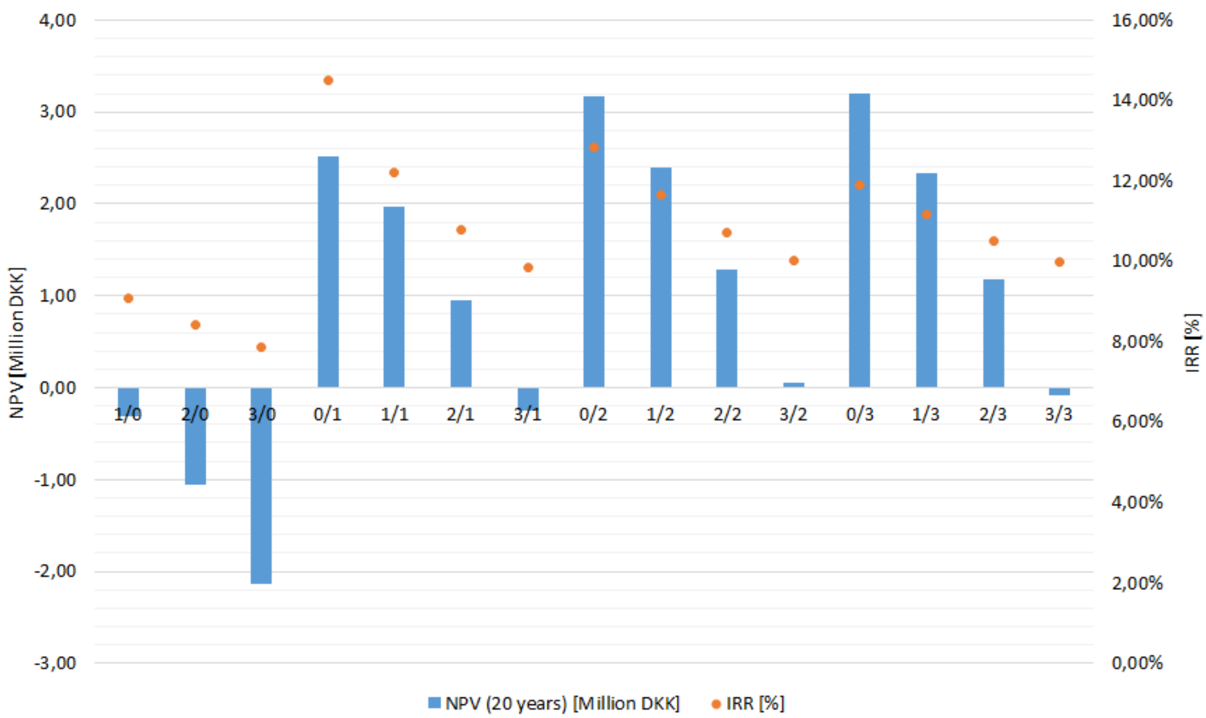
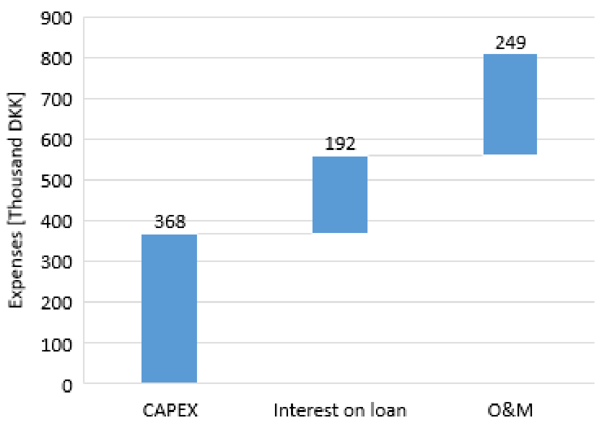


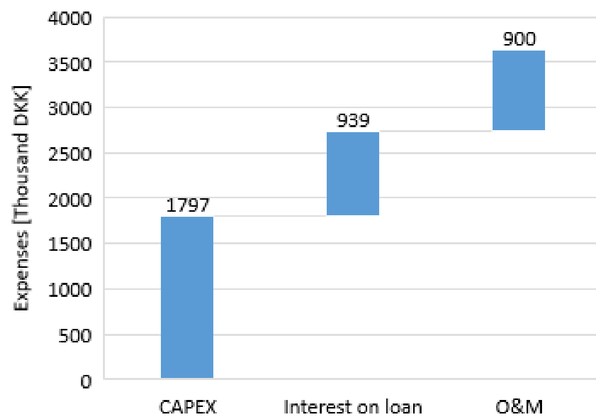
Figure 21: The NPV and IRR for the 15 sub-scenarios.

From Figure 21 it can be seen that the NPV is positive when the IRR is above 10 % and negative when it is below 10 %. That is because the interest used for the business economic calculations is set to 10 %.

From the figure, it can be concluded that the NPV increases as more wind power is installed and decreases as more photovoltaics are installed. Therefore, one might think that the best business case is to install as much wind power as possible. Looking at the values of the IRR it can however be seen that the scenario where only 1 MW of wind power is installed (sub-scenario 0/1) has the highest IRR. This is due to the fact that not all the electricity produced has the same value. When electricity is produced and consumed immediately the biogas plant saves both the spot price of electricity and the taxes and levies that are on electricity. The electricity that cannot be consumed by the biogas plant is sold on the spot market, and therefore, this amount does not gain the value of the taxes and levies. On the other hand, it is possible to sell guarantees of origin for electricity for the amount sold on the spot market. The value of the guarantees of origin is however not as large as the taxes and levies. In the figures below, a breakdown of the expenses and revenues of the two sub-scenarios 0/1 and 3/3 are shown.



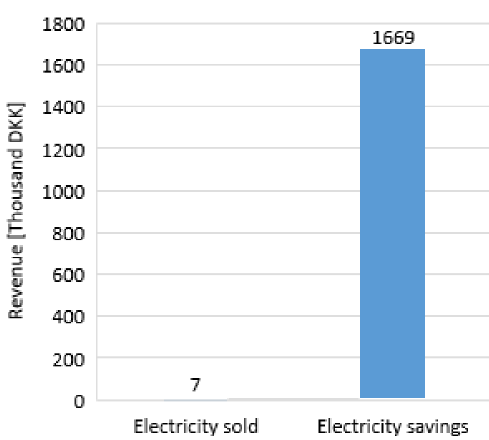
(a) Expenses the first year in the 0/1 sub-scenario.



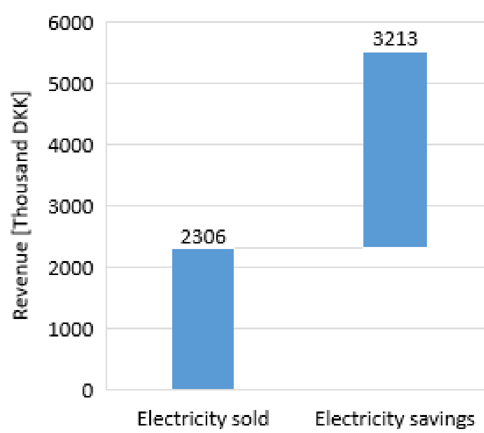
(b) Expenses the first year in the 3/3 sub-scenario.

Figure 22: Breakdown of the expenses in the first year of operation for two sub-scenarios.

Figure 22 shows the expenses in the two chosen sub-scenarios. The column CAPEX (capital expenses) is the investment costs of the photovoltaics and wind power divided with the lifetime of the project of 20 years and is constant over the project lifetime. The interest on the loan is calculated as if the entire investment costs is financed by a loan with a 2.75 % interest rate. The interest on the loan is largest in the first year of operation, since this is when the most money is left to be paid back. The interest on the loan decreases linearly towards zero throughout the lifetime of the project. The O&M is the operation and maintenance cost concerning the renewable electricity production and it is constant throughout the lifetime of the project.



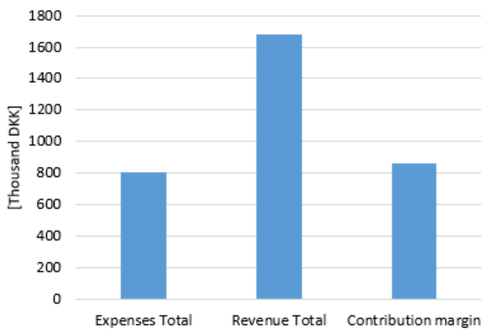
(a) Revenue the first year in the 0/1 sub-scenario.



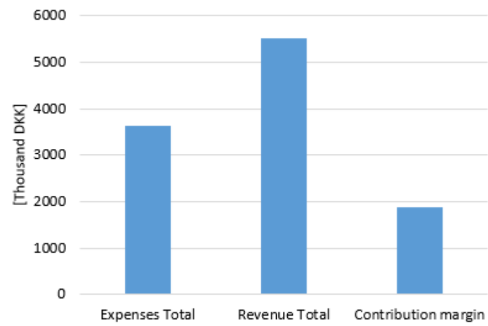
(b) Revenue the first year in the 3/3 sub-scenario.

Figure 23: Breakdown of the revenue in the first year of operation for the two sub-scenarios.

Figure 23 shows the revenue in the first year of the sub-scenarios 0/1 and 3/3. The revenue is made up of electricity sold and electricity savings. The column electricity sold includes the spot price of electricity and the value of the guarantees of origin for electricity. The column electricity savings include the spot price of electricity and the taxes and levies on electricity. Comparing Figure 23a and 23b it can be seen that a much larger part of the produced electricity is consumed by the biogas plant in the 0/1 sub-scenario. This is the reason why the IRR is the largest in this sub-scenario. In Figure 24 the difference between the expenses and revenue is shown as the contribution margin.



(a) The contribution margin the first year in the 0/1 sub-scenario.



(b) The contribution margin the first year in the 3/3 sub-scenario.

Figure 24: Breakdown of the monetary flows the first year of operation.

From Figure 24 it can be seen that the contribution margin is relatively larger in the sub-scenario 0/1. This is an important factor for a business that wants to invest since it shows that the investment is making money from the first year. Having a relatively larger contribution margin, compared to the expenses, also shows that the investment will pay back faster. In Figure 25 the expenses, revenue and contribution margin, over the lifetime of the project, can be seen for all the 15 different sub-scenarios.

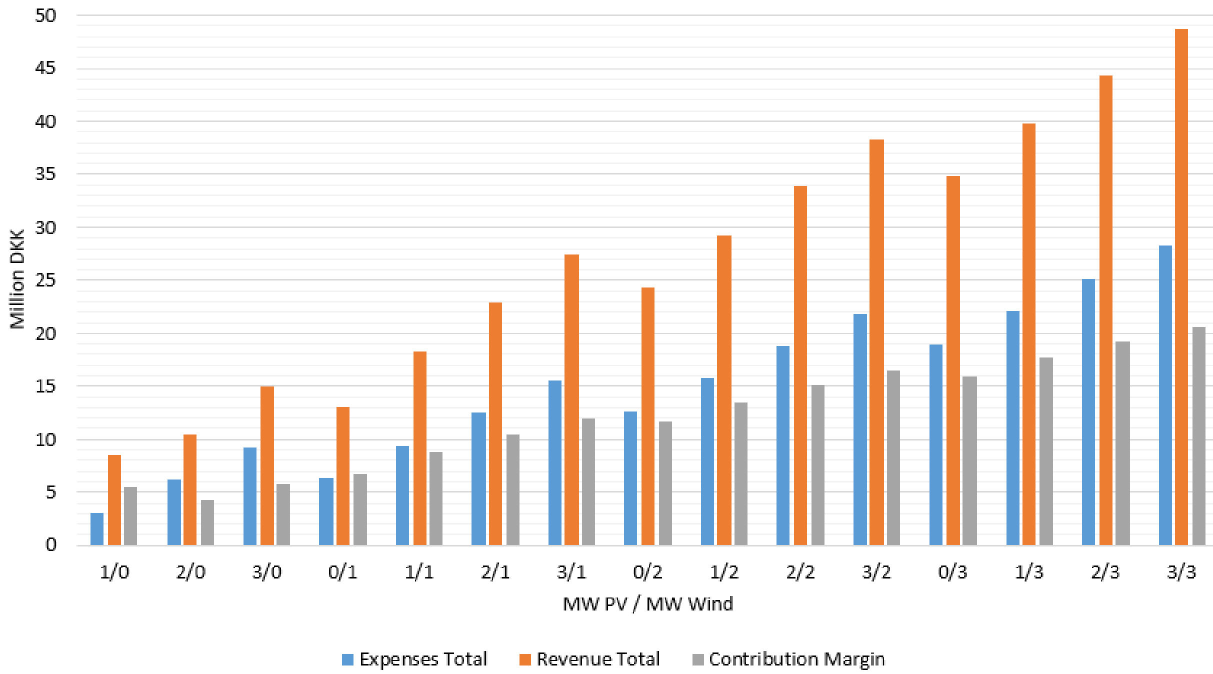


Figure 25: The expenses, revenue and contribution margin for the 15 sub-scenarios. Values are presented as net present values over the lifespan of the project.

From Figure 25 it can be seen that sub-scenario 0/1 has the largest revenue, compared to its expenses. This means that it has the highest IRR and the shortest payback time. It can therefore be concluded that the best investment is one that produces as much electricity as possible, while still being able to consume it immediately. Sub-scenario 0/1 is the scenario that does this the best.

It is interesting to determine how much the price of biomethane would have to increase for Nature Energy to be interested in the suggested solutions. That is, how much would they have to increase the price of the REDcert certificates. According to Nature Energy a project where they install renewable electricity production would need an IRR of 12 % to be considered as a business investment. The increase in price can be seen in Figure 26.

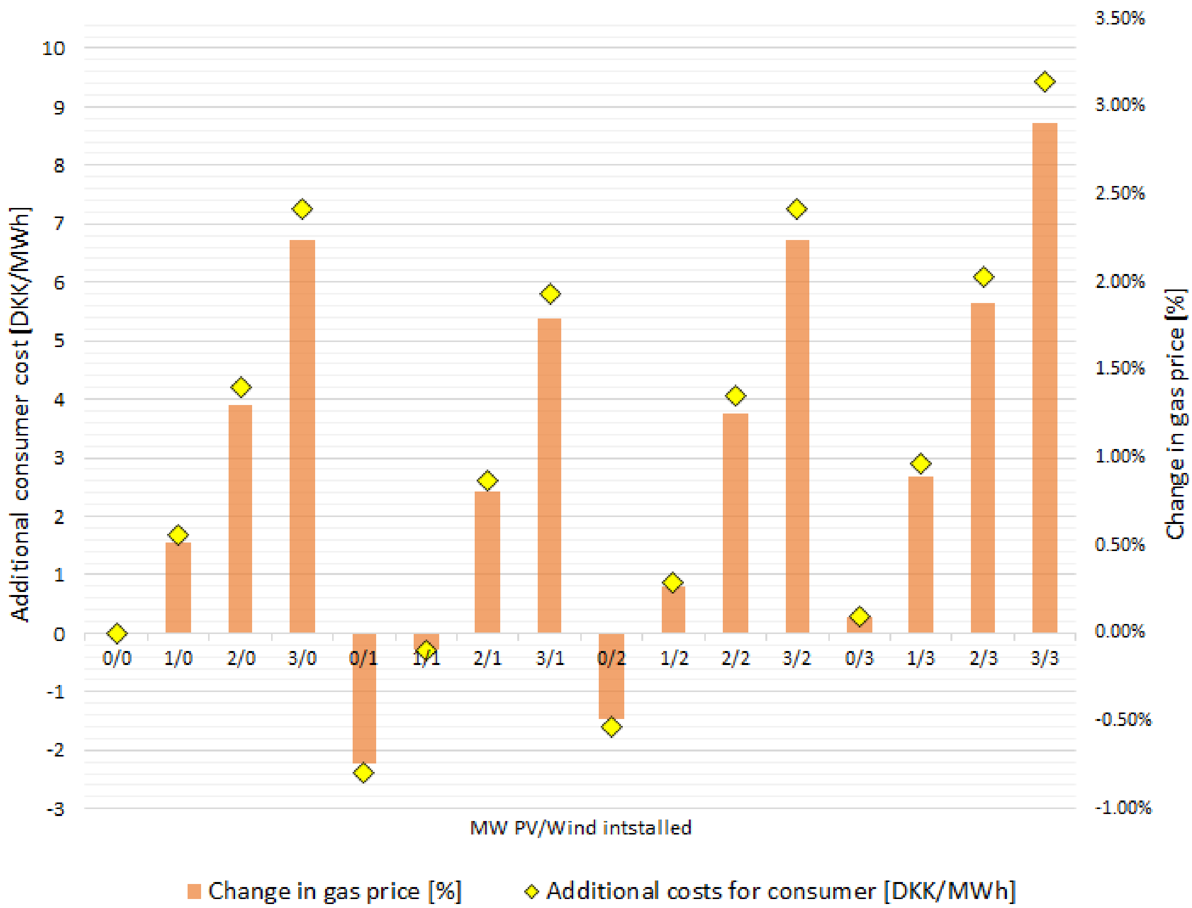


Figure 26: The additional consumer costs for each of the sub-scenarios.

Figure 26, shows the additional cost of the biomethane sold to the end consumer. The gas price used as a reference, to calculate the percentage change in consumer price, is 324 DKK/MWh [48], which is the price of natural gas plus the current price of a REDcert certificate. In order to evaluate the additional costs for the consumer, the net tax factor of 1.325 [35] is used to add taxes and levies. The figure shows that the change in REDcert certificate price would have to change within the range of -2.4 to 9.4 DKK/MWh. A negative price happens when the sub-scenario has an IRR of more than 12 % and indicates that Nature Energy could decrease the price of REDcert certificates, and still have an IRR of 12 %. The figure also shows that even in the sub-scenario that requires the highest increase, sub-scenario 3/3, the increase in price is still less than 3 % for the end consumer.

Socio-Economic Benefit

The socio-economic benefits for Scenario 1 will be highlighted in the following section. The benefits are determined in DKK/MWh produced biomethane, where DKK is the valuation of the increased or decreased emissions of the sub-scenarios. For this scenario the benefits are found using Equation (3).

$$\frac{\text{Change in emission cost from electricity [DKK]}}{\text{Total biomethane produced [MWh]}} \tag{3}$$

Figure 27 shows the renewable consumption share of the biogas plant, together with sold excess electricity.

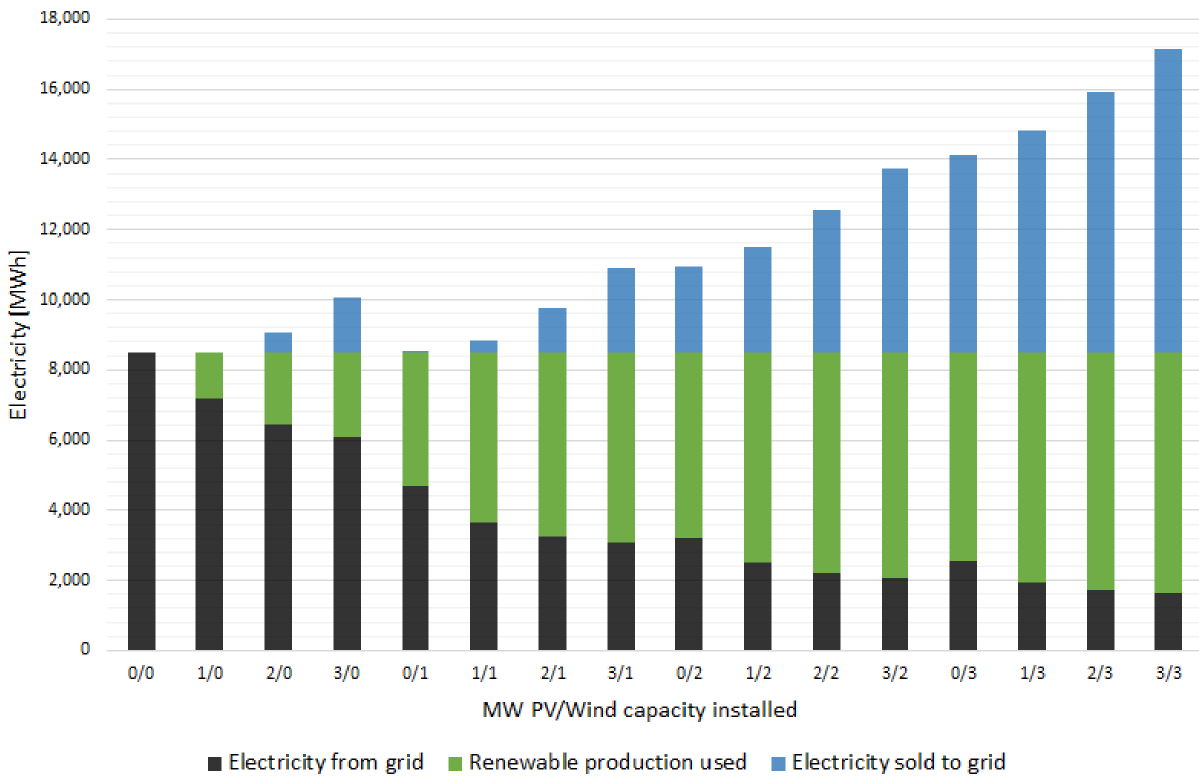


Figure 27: Electricity consumption, production and export for the different sub-scenarios.

From the figure, the total consumption of electricity is the same in each sub-scenario. The amount of renewable electricity used is increasing with more installed renewable capacity. And the excess electricity is sent back into the grid. Regarding reducing the emissions from the electricity consumption the most, it can be seen that installing more renewable capacity has a diminishing effect on the renewable share of electricity consumption.

Figure 28 shows the socio-economic benefit from reduced emissions in each of the sub-scenarios together with renewable production.

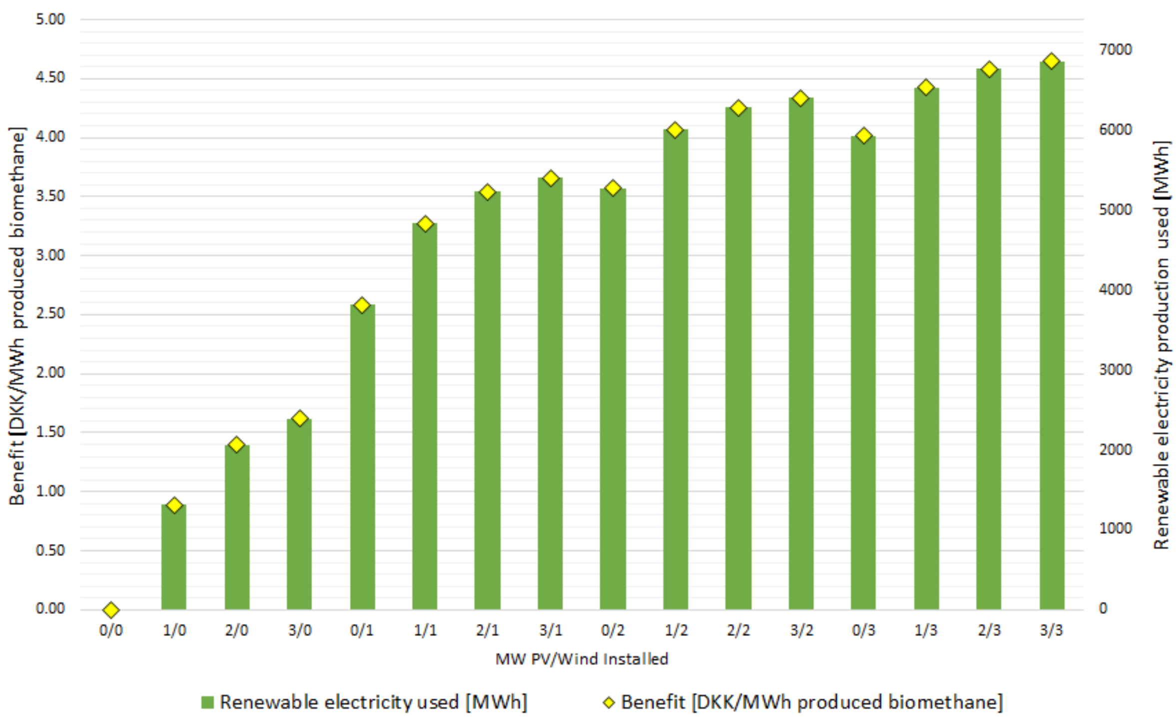


Figure 28: Renewable production and the benefits from this for the different sub-scenarios.

The yellow diamonds in Figure 28 indicate the size of the benefit in DKK/MWh produced biomethane and the green bars indicate the renewable electricity production in each sub-scenario. The general tendency is that more renewable production, gives a higher socio-economic benefit due to reduced marginal reduction costs and damage costs. From the business economics, Section 6.3 found that the most feasible solution would be to install just enough capacity to match the consumption of the plant and not anymore. From this, the realistic socio-economic benefit with the business economics in mind would be the case of 1 MW installed wind capacity at 2.58 DKK/MWh produced biomethane.

Conclusively, it can be said that the benefits of installing renewable electricity production at the biogas plant is a good idea, but it will in most cases add an additional cost to the gas purchased by the end user.

6.4 Scenario 2 - Biogas Replaces Natural Gas for Heating

For this scenario the biogas plant will chose to use its own produced biogas and not use natural gas from the grid for heating the biomass. When own produced biogas is used, this will result in less biomethane sold to the grid. How this will affect emissions, socio-economic benefits and business-economics is elaborated in this section.

Emissions

The emission results for this scenario is based on replacing natural gas usage which emits greenhouse gasses, with own produced biogas. The biogas used will be considered CO_2 neutral. The total reduction for this scenario is equal to the emissions from natural gas usage and is 18,258 ton CO_2-equivalents. This can also be found in Table 8. The reduction in emissions will have a socio-economic effect in regards to the emission reductions, this is described later in the socio-economic part of this section.

Business Economics

This section will present the feasibility of replacing the natural gas consumption at Nature Energy Midtfyn with its own biogas. The expenses in this scenario are: investment costs, interest on loan, fixed and variable O&M, losses in biomethane sales and the tax on burning biogas. The expenses in the first year can be seen in Figure 29.

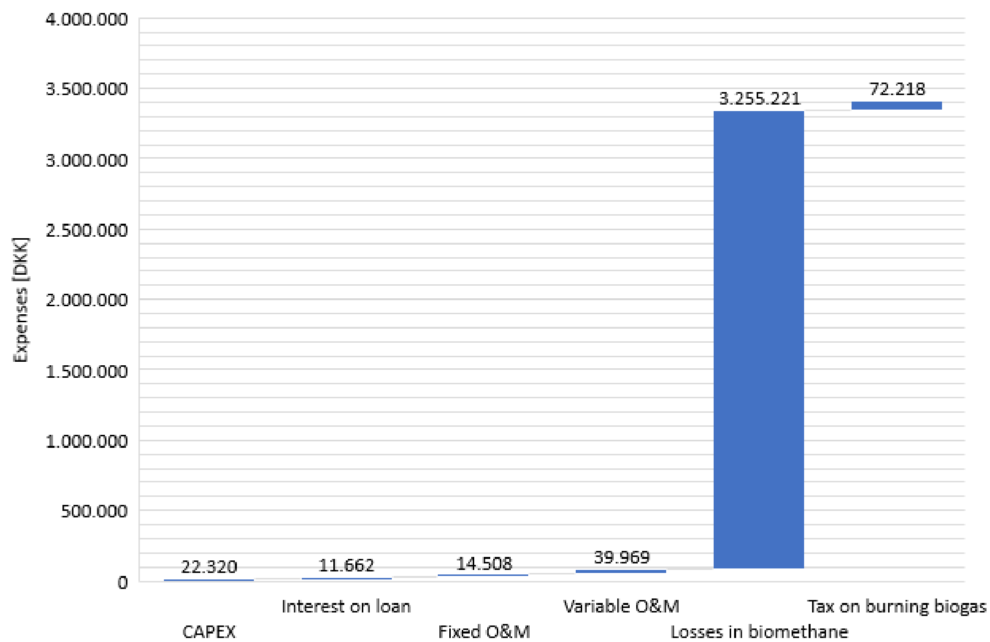
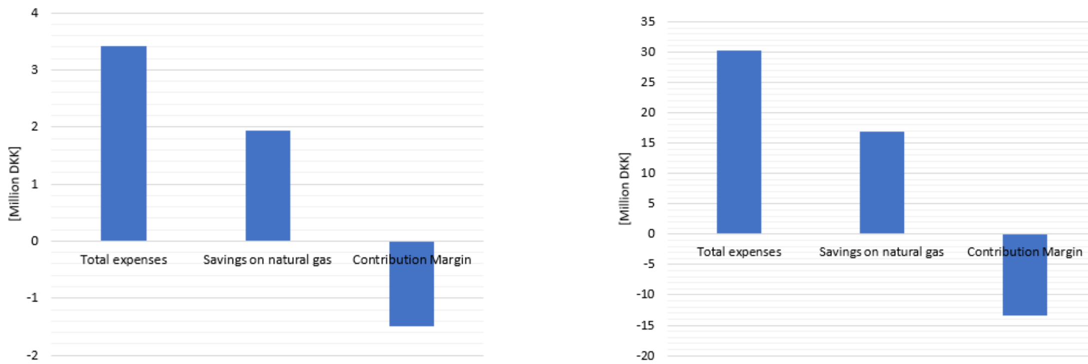


Figure 29: The expenses the first year for Scenario 2.

In Figure 29, CAPEX includes the investment of a biogas boiler, divided by the lifetime of the project of 20 years. The interest on the loan is calculated as if the entire investment costs is financed by a loan with a 2.75 % interest rate. The expense from a loss in biomethane sales include the price of natural gas, the biogas certificate and the subsidy for producing the biomethane. From the figure, it is clear that the losses in biomethane sales is by far the largest expense in this scenario. In Figure 30 the expenses, both for the first year and over the lifetime of the project, are compared to the revenue.



(a) The contribution margin the first year in the biogas scenario.

(b) The contribution margin over the lifetime of the project in the biogas scenario.

Figure 30: Breakdown of the monetary flows in the biogas scenario.

The revenue in Figure 30 is seen as the savings on natural gas, since this is the only revenue. The savings on natural gas include the price of natural gas and the taxes and levies on natural gas. It can be seen in the figure, that both in the first year, and over the lifetime of the project, the expenses are much larger than the revenue. Over the lifetime the NPV of the scenario is -13.4 million DKK.

Nature Energy could choose to cover this cost by increasing the price of their REDcert certificates. In order to get an NPV of zero, the price of the REDcert certificates would have to increase by 17.26 DKK/MWh.

The added consumer cost for this scenario will be 22.87 DKK/MWh. A reference price for gas bought as a consumer was used to find the percentage increase in gas price for the end consumer. The reference price is 324.6 DKK/MWh [48]. This will yield an end cost of 347 DKK/MWh and is an increase of 7 % compared to the reference price.

Socio-Economic Benefit

The benefits of using own biogas can be seen in Figure 31. The benefits will decrease over the lifetime of the project due to the decrease in emissions tied to natural gas from the grid. The benefits are calculated using Equation (4) which is the change in benefit divided by the total biomethane production.

$$\frac{\text{Benefit from reduction in natural gas usage [DKK]}}{\text{Total biomethane produced [MWh]}} \tag{4}$$

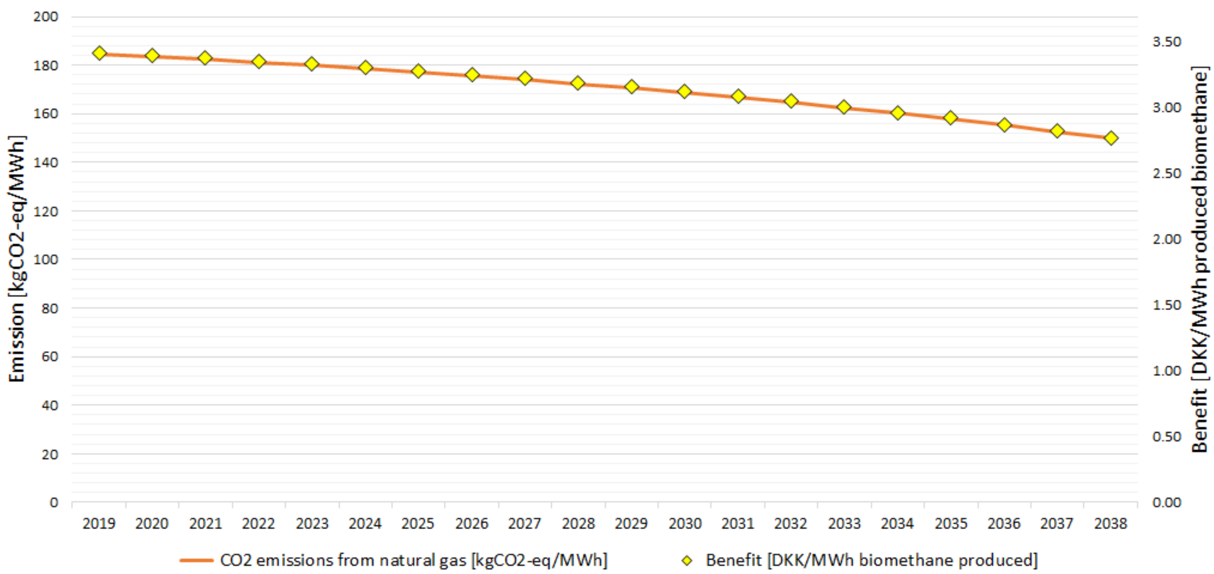


Figure 31: Socio-economic benefits of using own biogas instead of natural gas from the grid.

The primary y-axis indicates the benefits and the secondary y-axis the emissions in kg CO_2-equivalents per MWh natural gas consumed. The yellow dots therefore indicate the development, like Figure 62. The benefits might decrease over time but would still be benefits. As with Scenario 1, the benefits are given in DKK/MWh-produced biomethane. There is, as mentioned, a smaller amount produced, equal to the replaced natural gas usage of 5,372 MWh/year.

6.5 Scenario 3 - Hydrogenation

The hydrogenation results will highlight the feasibility, emissions and socio-economic benefits of installing a hydrogen production unit with methanation at the biogas plant. Results from Scenario 1 have had an effect on the decision making in this scenario in regard to which configuration of installed renewable electricity production would be the most feasible to add to the hydrogenation in order to create a better business case and increase benefits.

Emissions

The emissions of the different sub-scenarios can be seen in Table 12. The emissions are for the lifespan of the project, set to 20 years and follows the electricity consumption. To reduce the emissions and reduce the costs of purchasing electricity, 10 MW wind capacity is installed and yields the reductions in Table 13.
To get a better understanding of the results in the two tables, a more detailed description of how the results were calculated and how different factors have an effect on the results can be seen in Appendix D.
The two tables are divided into two each, where the first part show the results for the sub-scenarios "50" to "300" DKK/MWh and the second part shows the rest from "400" to "Always on".

Emissions from hydrogenation in the sub-scenarios over the lifetime of the project.

Cut-in price [DKK/MWh]	50	100	150	200	250	300
Additional electricity from grid [GWh]	5.06	34.3	109	234	358	504
Kiloton CO_2-eq	1.45	2.79	8.91	18.3	27.9	39.7
Extra biomethane produced [GWh]	4.93	19.3	55.9	117	178	250
CO_2-eq/biomethane [kg/MWh]	295	145	159	155	156	159

Cut-in price [DKK/MWh]	400	500	600	700	800	Always on
Additional electricity from grid [GWh]	1,207	1,626	1,775	1,838	1,852	1,853
Kiloton CO_2-eq	82.3	105	112	116	116	116
Extra biomethane produced [GWh]	511	1,456	1,605	1,668	1,682	1,683
CO_2-eq/biomethane [kg/MWh]	161	146	143	141	140	140

Table 12: Emissions and electricity usage over the lifetime of the project at different cut-in prices.

Emissions from hydrogenation with installed wind capacity of 10 MW over the lifetime of the project.

Cut-in price [DKK/MWh]	50	100	150	200	250	300
Additional electricity from grid [GWh]	1	5	38	82	133	200
Kiloton CO_2-eq	0.07	0.50	3.15	6.5	10.4	16.2
Extra biomethane produced [GWh]	381	382	398	420	445	478
CO_2-eq/biomethane [kg/MWh]	0.18	1	8	16	23	34

Cut-in price [DKK/MWh]	400	500	600	700	800	Always on
Additional electricity from grid [GWh]	468	723	846	900	911	912
Kiloton CO_2-eq	38.2	53.6	60.1	62.8	63.1	63.1
Extra biomethane produced [GWh]	468	723	846	900	911	912
CO_2-eq/biomethane [kg/MWh]	63	73	76	76	76	76

Table 13: Emissions and electricity usage over the lifetime of the project, with 10 MW of wind power installed, for each cut-in price.

From an emissions point of view, the integration of renewable electricity will have a large impact on the emissions tied to the scenario. This is of course because the renewable electricity production is CO_2 neutral. This emission reduction will however have an impact on the socio-economic benefits of the scenario. This is elaborated later in this section.

Business Economics

This section will present the feasibility of implementing hydrogenation as it is explained in Section 4.4. In all the sub-scenarios, electrolysis and methanation plants capable of using 50 % of the biogas is installed. The electrolysis and methanation is then activated when the average daily electricity price is below a certain cut-in price. In Figure 32 the NPV of the 12 different sub-scenarios can be seen.

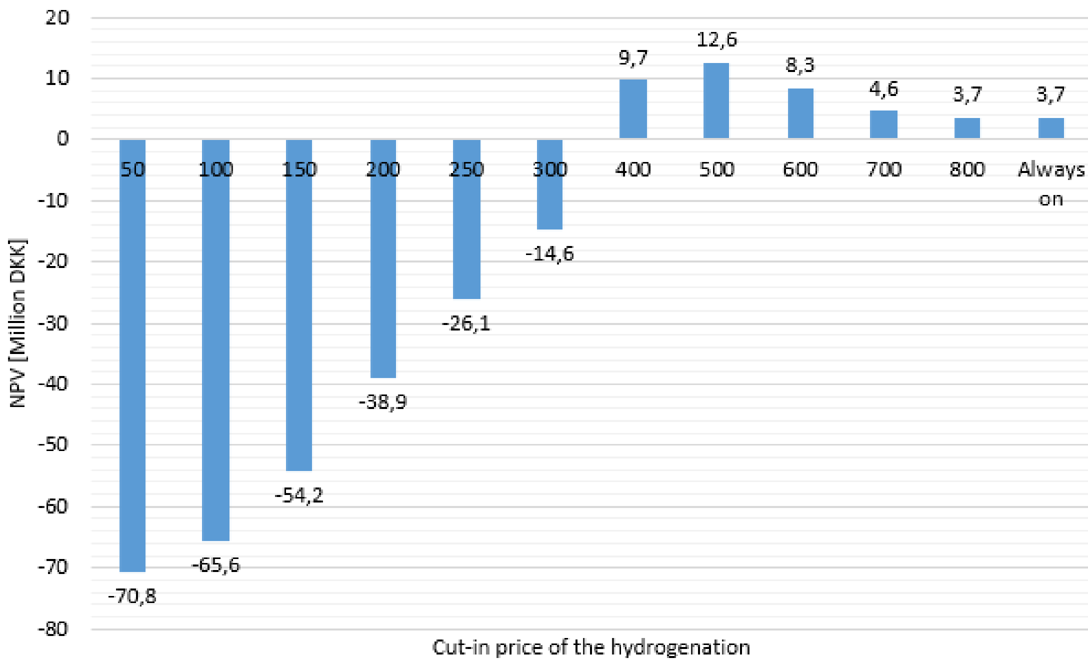
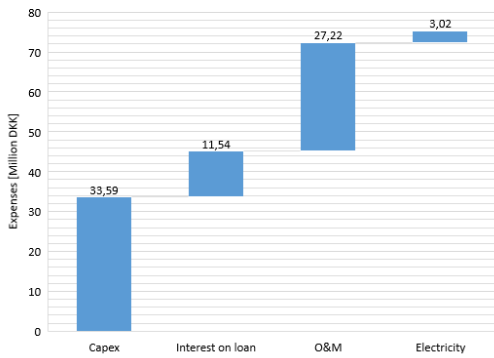
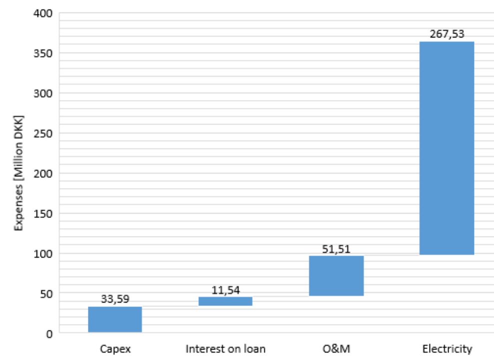


Figure 32: The NPV for the 12 sub-scenarios.

The cut-in price affects the economy of the sub-scenarios in different ways. A lower cut-in price would result in a lower cost of hydrogen production in the electrolysis plant. On the other hand, a very low cut-in price will result in few operating hours, and therefore very little additional biomethane production. Conversely, a higher cut-in price will allow a higher biomethane production from methanation. From Figure 32, a cut-in price of 500 DKK/MWh seems to be the best option. In order to understand why this is the case, the expenses and revenues of the two sub-scenarios with cut-in prices of 100 and 500 DKK/MWh are examined in Figure 33 and 34.



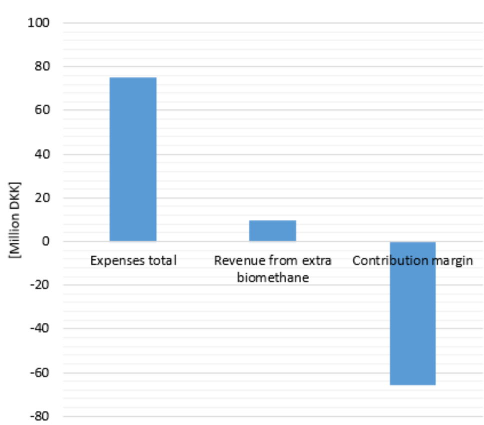
(a) The expenses over the lifetime in the sub-scenario with a cut-in price of 100 DKK/MWh.



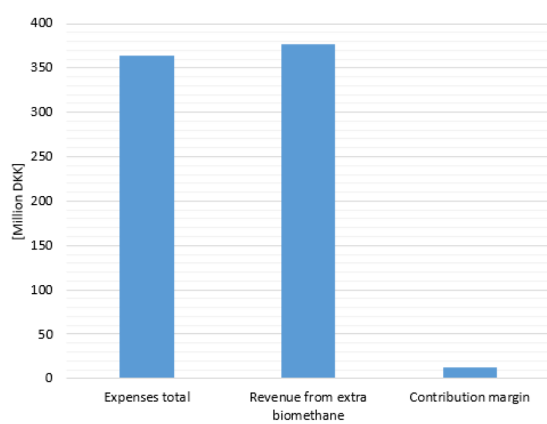
(b) The expenses over the lifetime in the sub-scenario with a cut-in price of 500 DKK/MWh.

Figure 33: A comparison of the expenses in the sub-scenarios with cut-in prices of 100 and 500 DKK/MWh.

Figure 33a and 33b show the expenses over the lifetime of the project for the sub-scenarios with cut-in prices of 100 and 500 DKK/MWh, respectively. From the figures, it can be seen that the CAPEX and the interest on the loan, are the same in each sub-scenario. This is a result of the fact that the same capacity of electrolysis and methanation is installed in all scenarios. The cost of O&M is higher in the sub-scenario with a cut-in price of 500 DKK/MWh, since it depends on the biomethane production, which is higher in this scenario. The cost of electricity is also much higher in this scenario, primarily because the electricity consumption is much higher, but also because the hydrogenation plant operates when the electricity price is higher. From Figure 33 one might conclude that the sub-scenario with a cut-in price of 100 DKK/MWh is the better option, because of the lower expenses, but in Figure 34 it can be seen that this is not the case.



(a) The expenses, revenue and contribution margin over the lifetime in the sub-scenario with a cut-in price of 100 DKK/MWh.



(b) The expenses, revenue and contribution margin over the lifetime in the sub-scenario with a cut-in price of 500 DKK/MWh.

Figure 34: A comparison of the expenses, revenue and contribution margin in the sub-scenarios with cut-in prices of 100 and 500 DKK/MWh.

Figure 34a and 34b show the expenses, revenue and contribution margin over the lifetime of the two sub-scenario with cut-in prices of 100 and 500 DKK/MWh. The expenses shown are the sum of the expenses in Figure 33. The revenue consists of the extra revenue gained from the added biomethane production, compared to the reference scenario. The added biomethane production consists both, of the extra biomethane created in the hydrogenation process and of the extra biomethane produced by the quick biomasses, which utilise the available capacity in the upgrading plant. The extra biomethane is approximately half from hydrogenation and half from fast biomasses. From Figure 34 it can be seen that the revenue from extra biomethane production is much larger in the sub-scenario with a cut-in price of 500 DKK/MWh. This is due to the fact that the hydrogenation in this sub-scenario has a lot more operating hours than the sub-scenario with a cut-in price of 100 DKK/MWh. In Figure 35, the expenses, revenue and contribution margin is shown for all of the 12 sub-scenarios.

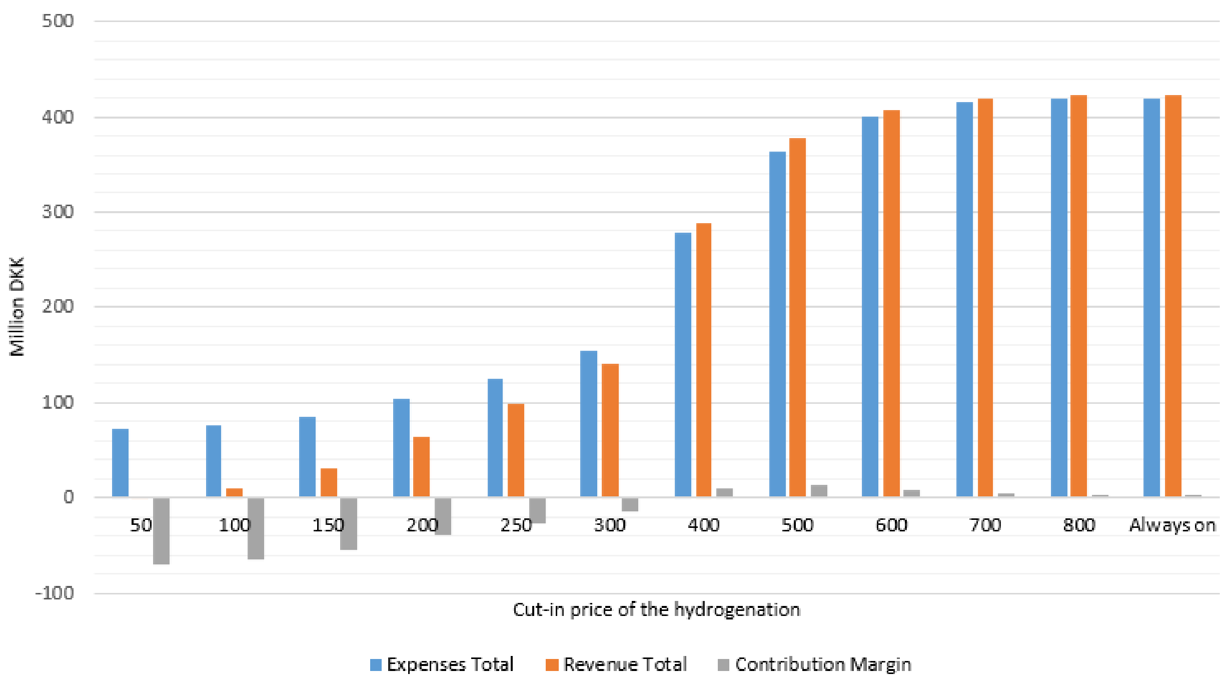


Figure 35: The expenses, revenue and contribution margin for the 12 sub-scenarios.

Figure 35, as well as Figure 32 show that the best sub-scenario is the one with a cut-in price of 500 DKK/MWh. From Figure 33b it could be seen that the cost of electricity constituted the largest part of the expenses. It is therefore interesting to investigate how this expenditure can be reduced. In Section 6.3 it was concluded that installing as much renewable electricity production as possible, without exceeding your own consumption capacity, was the most economically feasible. Therefore, the 12 sub-scenarios were run again in energyPRO, but this time with 10 MW of wind power installed. In these scenarios, the hydrogenation (electrolysis and methanation) is set to follow the electricity production of the wind production when the electricity price is above the cut-in price. When the average daily electricity price is below the cut-in price, the hydrogenation will run at full capacity, just like in the previous scenarios. This is expected to give a much larger up-time of the hydrogenation in the sub-scenarios with low cut-in prices and to reduce the cost of electricity in all the sub-scenarios. However, it will not be possible to use the freed-up capacity of the upgrading plant, since it would not be possible to reliably predict the electricity production of the wind turbines. The revenue from extra biomethane from fast biomasses has therefore been removed from these sub-scenarios. The results of the simulations of hydrogenation with 10 MW of wind power can be seen in Figure 36.

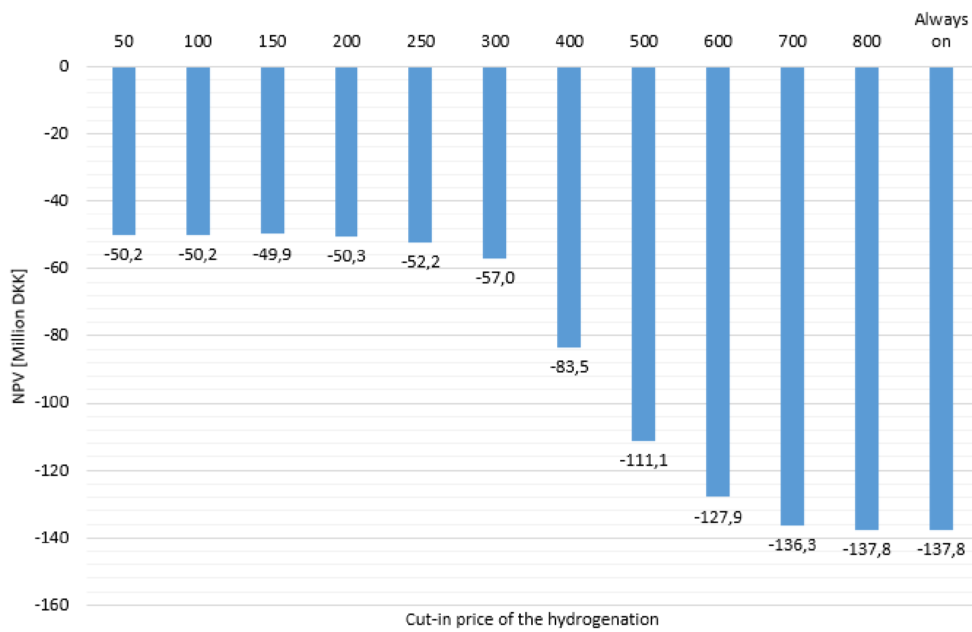
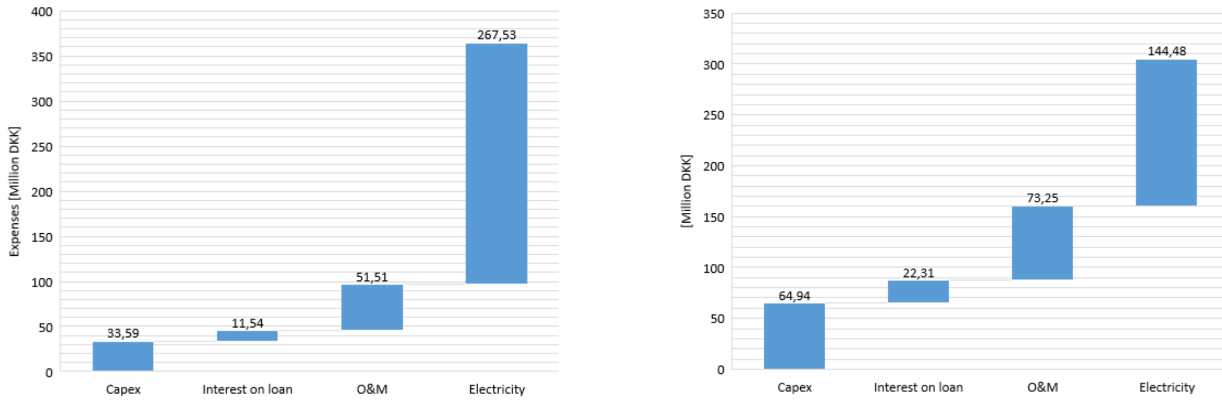


Figure 36: The NPV for the 12 sub-scenarios, when 10 MW of wind power is installed.

Comparing Figure 36 to Figure 32 it can be seen that the business case of the three sub-scenarios with the lowest cut-in prices has improved, while the rest of the sub-scenarios show worse results. Since it was expected, that the implementation of 10 MW of wind power would improve the business case, it is investigated why this is not the case. This is done in Figure 37 and 38.

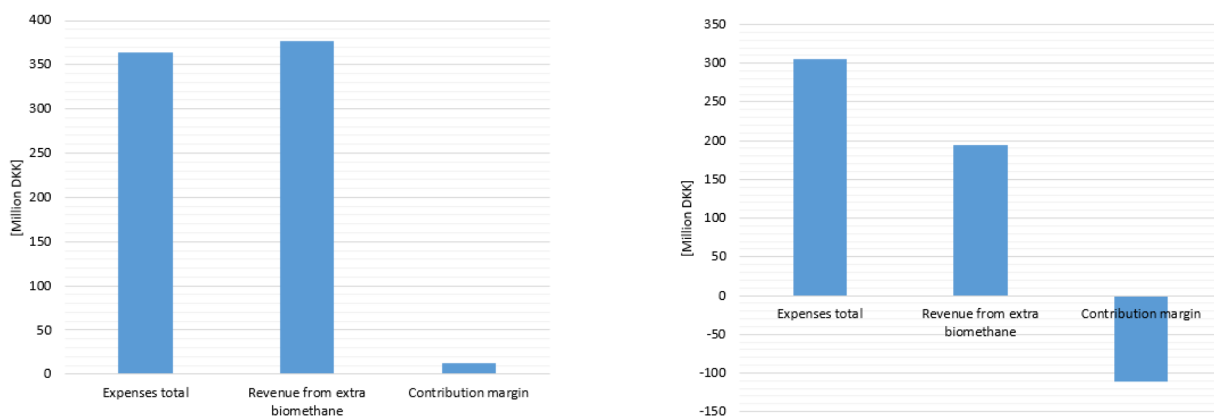


(a) The expenses over the lifetime with a cut-in price of 500 DKK/MWh.

(b) The expenses over the lifetime with a cut-in price of 500 DKK/MWh, when 10 MW of wind power is installed.

Figure 37: A comparison of the expenses in the sub-scenarios with cut-in prices of 500 DKK/MWh with and without 10 MW of wind power installed.

Figure 37a shows the expenses of the sub-scenario with a cut-in price of 500 DKK/MWh without wind power installed, just like Figure 33b, while Figure 37b shoes the expenses with 10 MW wind power installed. From the figures it can be seen that even though the CAPEX and interest on the loan is higher, due to the investment in wind power, the total expenses are still lower, because the cost of electricity has been reduced by such a large amount.



(a) The expenses, revenue and contribution margin over the lifetime in the sub-scenario with a cut-in price of 500 DKK/MWh.

(b) The expenses, revenue and contribution margin over the lifetime in the sub-scenario with a cut-in price of 500 DKK/MWh, when 10 MW of wind power is installed.

Figure 38: A comparison of the expenses, revenue and contribution margin in the sub-scenarios with cut-in prices of 500 DKK/MWh with and without 10 MW of wind power installed.

In Figure 38 the expenses are compared to the revenue in the sub-scenario with a cut-in price of 500 DKK/MWh without and with wind power installed. From the figure it can be seen that the drop in NPV from the sub-scenario without wind power the sub-scenario with wind power, is due to a decrease in revenue from extra biomethane. This decrease is caused by the fact that it is not possible to utilise the fast biomasses in the sub-scenarios with wind power installed. About half of the revenue in the sub-scenarios without wind power installed, originated from the extra biomethane from fast biomasses, and it is clear that the loss of this revenue is hurting the business case.

Additional Consumer Costs

This section will determine what the price of the biomethane would have to be in each sub-scenario in order to reach an IRR of 12 %. Figure 39 shows the needed additional consumer costs for the sub-scenarios where the hydrogenation starts at different cut-in prices, and no wind power is installed.

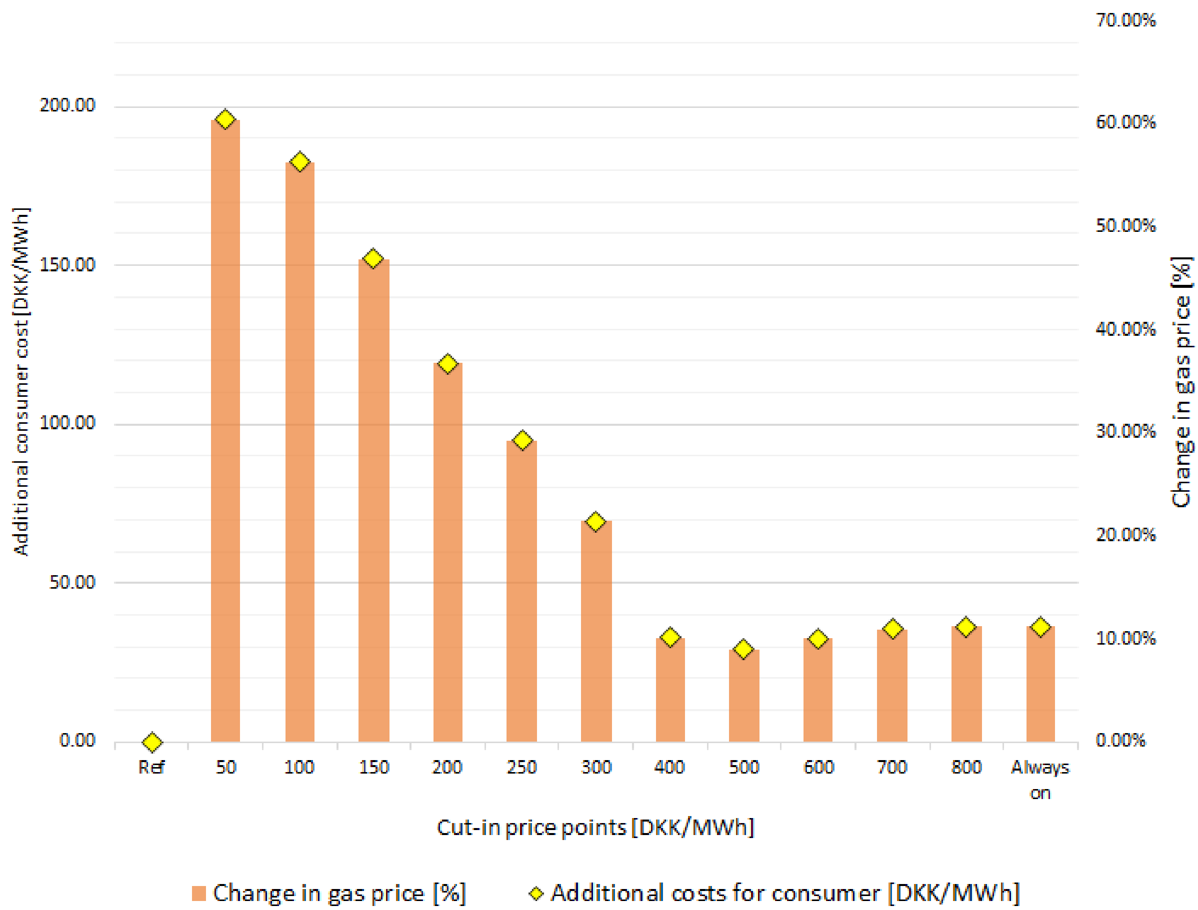


Figure 39: The additional consumer costs for each of the sub-scenarios.

Figure 39 shows that the needed increase in consumer costs are much larger in this scenario, than in Scenario 1 and 2. The best scenario, the sub-scenario with a cut-in price of 500 DKK/MWh, would require a price increase of around 30 DKK/MWh, which is around a 10 % increase.

Figure 40 shows the needed additional consumer costs for the sub-scenarios where the hydrogenation starts at different cut-in prices, and 10 MW of wind power is installed.

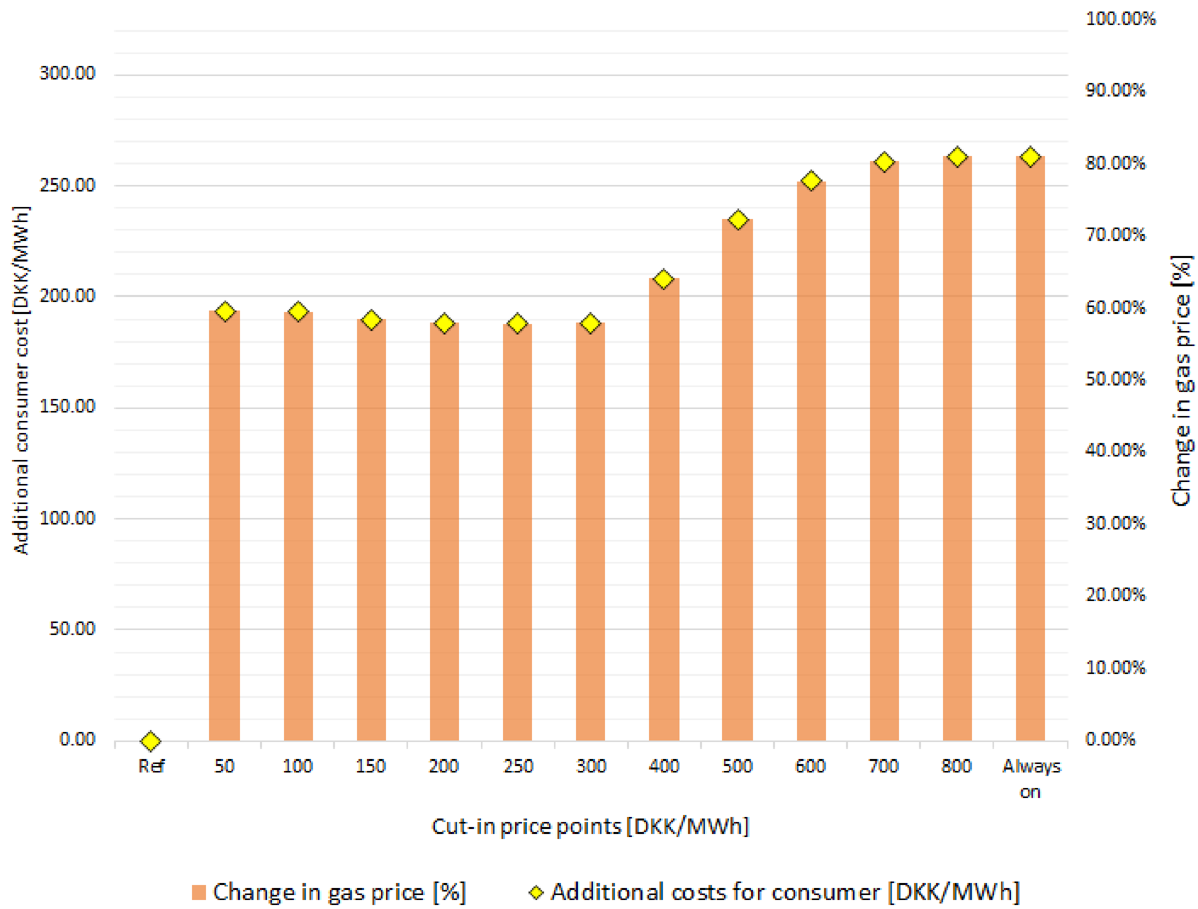


Figure 40: The additional consumer costs for each of the sub-scenarios with wind.

From Figure 40 it can be seen that the needed increase in gas price is larger than in the scenario where no wind power is installed. This is in line with the results of the scenario feasibility presented previously in this section, in Figure 36.

Socio-Economic Benefit

This section presents the socio-economic benefits of the scenario with and without added wind capacity of 10 MW. For this scenario, the additional biomethane produced from methanation is calculated as replaced natural gas production and thereby increasing the reduction of emissions and increasing the benefits.

The benefits for this scenario is found by subtracting the benefits of additional biomethane added to the grid, thereby replacing some natural gas production elsewhere, by the damage costs and marginal reduction costs of increased electricity usage and divided with the new total biomethane production. This is seen in Equation (5).

$$\frac{\text{Benefit from reduced natural gas use [DKK]} - \text{Change in emission cost from electricity [DKK]}}{\text{Total biomethane produced [MWh]}} \tag{5}$$

The results of this is that in the first years, there is a high socio-economic cost tied to the electricity and in the latter years, this cost from electricity usage have dropped to almost zero and thereby increasing the benefits.

Figure 41 shows the benefits each year for each of the sub-scenarios, the sub-scenarios being cut-in prices.

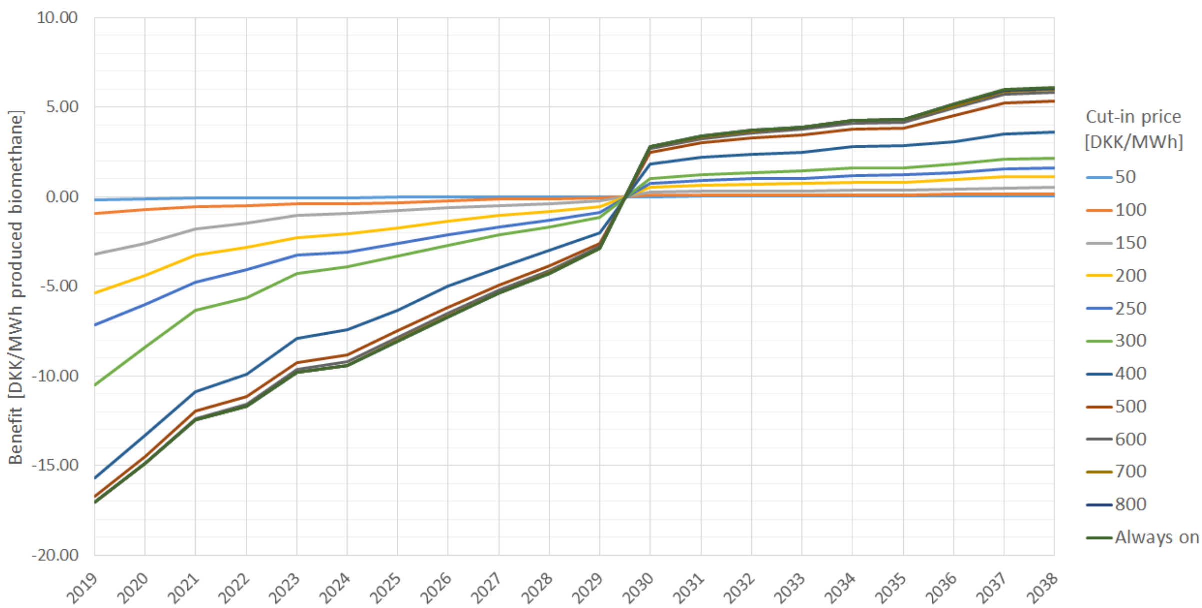


Figure 41: The socio-economic benefits at different cut-in prices.

From the figure it can be seen that a higher cut-in price, gives a higher negative benefit in the first years until the electricity in the grid will be CO_2 neutral. It is clear from the graph that the electricity becomes CO_2 neutral in 2030. Here the costs all become benefits. From this it can be said that it would be best to install or invest in hydrogenation from 2030 in order to yield socio-economic benefits from reduced emissions from the beginning of the project. There is however a way of having benefits earlier on in the project lifetime, this can be achieved by installing renewable electricity production alongside the hydrogenation. The effect of this is seen in Figure 43 and will be discussed later.

To show if any of the sub-scenarios of this scenario will yield a benefit over their lifetime Figure 42 was made.

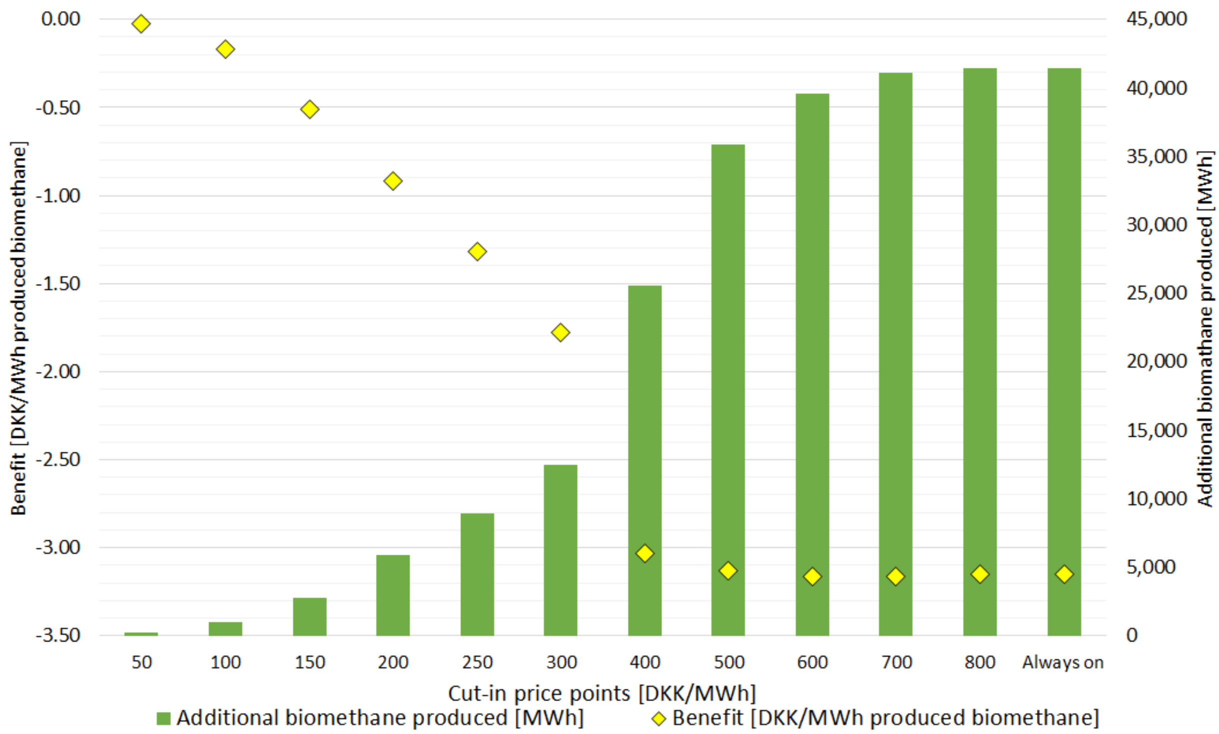


Figure 42: The average benefits and average biomethane production over the lifetime of the project at the different cut-in price points.

Here the benefits are the yellow diamonds and the green bars are the average extra biomethane production over the lifetime. It is clear that there would be no socio-economic benefits of introducing hydrogenation in the production as is.

Figure 43 shows the benefits of hydrogenation when renewable capacity of 10 MW wind is installed alongside the hydrogenation.

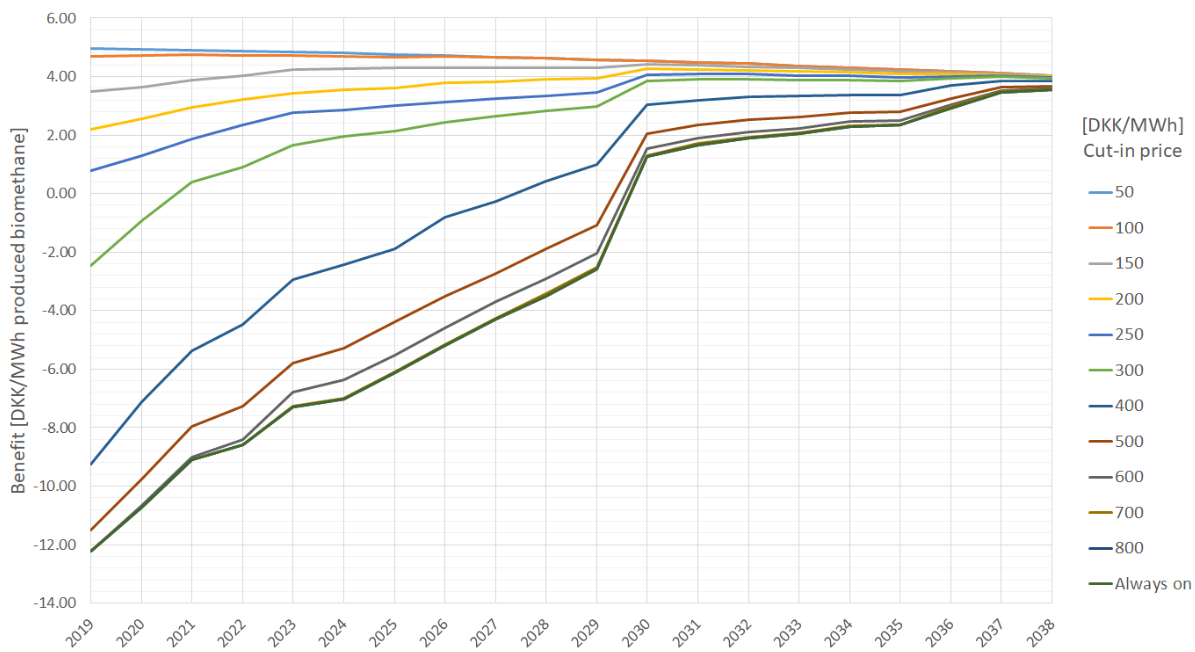


Figure 43: Benefits over the lifetime of the project with 10MW installed wind capacity.

From the figure it can be seen that the socio-economic benefit for the cut-in prices from "300" DKK/MWh to "Always on" will start at a less negative benefit than in the scenario without wind capacity, Figure 42. The cut-in price points of "150" to "250" will start off by having a socio-economic benefit, peak at around 2030 and then decline towards 2038. Lastly, price points "50" and "100" will decline from the beginning of the project to the end, but never be negative in the project period.

Something that applies to all of the price points for this scenario is that they end up having close to similar benefit by 2038. This can be explained by the emissions development in the electricity used from the grid. The electricity emissions go towards a CO_2 emission content of zero. Because of this the costs tied to electricity consumption from Equation (5) can almost be negated and the ratio of benefits from additional biomethane production divided by the total amount produced will end up being the same. To simplify, Equation (6) shows this.

$$\frac{\text{Benefit from reduced natural gas use [DKK]} - \cancel{\text{Change in emission cost from electricity [DKK]}}}{\text{Total biomethane produced [MWh]}} \tag{6}$$

From a socio-economic point of view the hydrogenation scenario itself shows that with the current allowance price it would be best to implement hydrogenation by 2030, when the electricity in the grid is close to CO_2 neutral. For the scenario with added wind capacity, the point where the costs become benefits are shifted further towards the beginning of the project periods, where the sub-scenario with low cut-in electricity prices will be beneficial from the beginning of the project period. This means that the higher the allowance price will go the earlier the project will become beneficial in relation to emission reduction.

6.6 Section Summary

Scenario 1 - Photovoltaics and Wind

Through the calculations of the simulation outputs it was found that in Scenario 1, the most feasible solution would be to install 1 MW wind capacity yielding an IRR of 14.50 %. This solution simultaneously yields a reduction of 15.5 % in CO_2 emissions compared to the Reference Scenario.
From an emission reduction point of view the best scenario would be to install as much renewable capacity as possible. This would unfortunately give a worse business case. It is concurrently found that the best sub-scenarios regarding net present value are the ones with only wind capacity installed. The sub-scenario with 1 MW wind proves to be the best for the consumers since there would be a consumer cost saved of 2.4 DKK/MWh biomethane. The socio-economic benefit is however greatest in the scenario with the most renewable capacity installed as is with the savings in emissions.

Scenario 2 - Biogas Replaces Natural Gas for Heating

For this scenario, it was found that using own biogas instead of using natural gas from the grid, the emission savings would be equal to the emissions tied to the natural gas. This amounted to 18,258 ton CO_2 equivalents over the lifetime of the project. The business would suffer great losses amounting to 13.4 million DKK in lost biomethane sales over the 20-year lifetime of the project. In order to make this scenario feasible for Nature Energy, the REDcert certificate price would need to be raised with 17.26 DKK/MWh. The added consumer cost due to the certificate increase was found to be 22.87 DKK/MWh. The socio-economic benefit of the scenario was found to be 3.42 DKK/MWh in the first year and decreasing to 2.77 DKK/MWh by the end of the lifetime. The steady decrease is explained by the increased amount of biomethane expected in the natural gas grid.

Scenario 3 - Hydrogenation

From the hydrogenation scenario it was found that the best case in terms of emission reduction would be to install wind capacity alongside hydrogenation. The maximum amount of emissions per produced biomethane was found to be 295 kg/MWh in the scenario without wind capacity and 76 kg/MWh in the scenario with wind capacity.
From a business standpoint, the scenario without wind capacity would have a positive NPV from cut-in prices 400 DKK/MWh electricity and above, where the scenario without wind would never yield a positive NPV. The reason for this is because the wind scenario cannot utilise fast biomasses to produce additional biomethane.
The additional consumer costs added to make the scenarios reach an IRR of 12 % was found be be at least 30 DKK/MWh in the scenario without wind and a at least 188 DKK/MWh in the scenario with wind capacity installed. It was found that the main expense of the hydrogenation scenario is purchasing electricity, hence the attempt of reducing the use of electricity from the grid by installing wind capacity.
It was found that at an allowance price of 200 DKK/t the hydrogenation scenario would yield socio-economic benefits from 2030. The average socio-economic benefit over the lifetime of the project was however found to be negative in all sub-scenarios.

7 Sensitivity Analysis

A sensitivity analysis of the different results is done in order to investigate how reactive the outcome of each scenario is. The analysis will help understand which parameters that can have an impact on results and thereby help in decision making regarding how volatile a project like the scenarios will be. The sensitivity analysis has been done on the electricity price, the natural gas price, the investment costs and the CO_2 allowance price.

7.1 Electricity Price

This section will look at the uncertainty of the electricity price, and how a change in electricity price affects the results of the scenarios.

For the sensitivity of the electricity price, the uncertainty from the future projections from The Danish Energy Agency has been extrapolated [49]. This uncertainty has been used on the electricity price used in the simulations to give a high and a low estimate of the future electricity price. This can be seen in Figure 44.

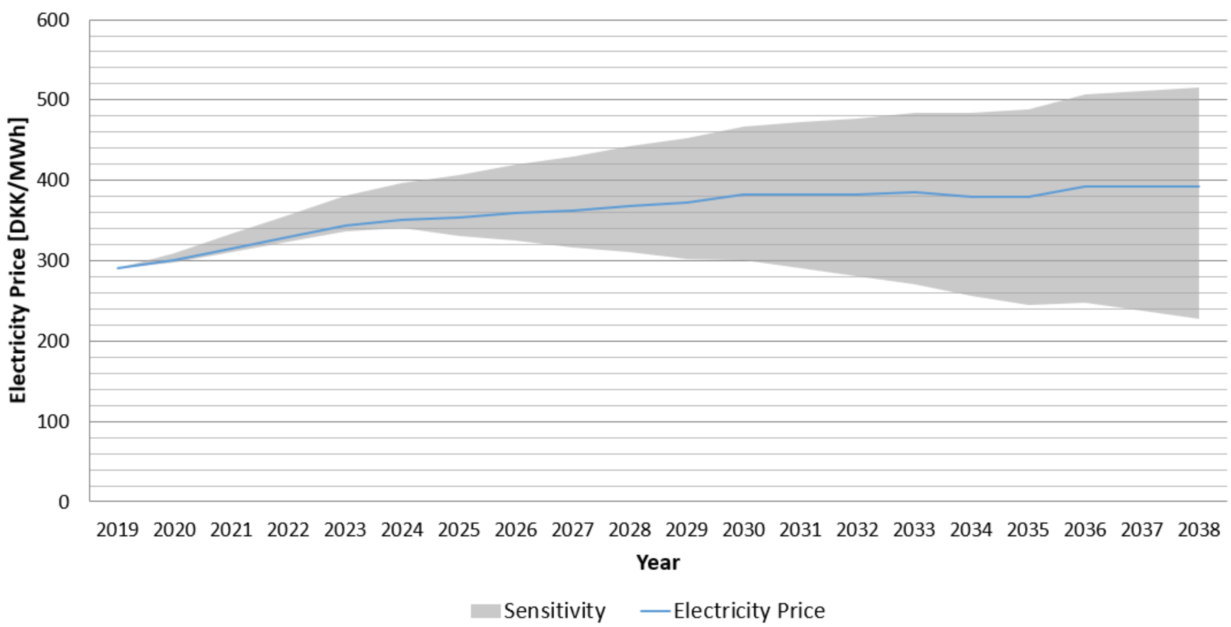


Figure 44: The uncertainty of the future electricity spot price.

From Figure 44, the lower boundary of the uncertainty will be used as the low electricity price and the upper boundary will be used as the high electricity price.

Sensitivity of Scenario 1 - Photovoltaics and Wind Power

In Figure 45 the simulations from Scenario 1, are run again, and the NPV is calculated.

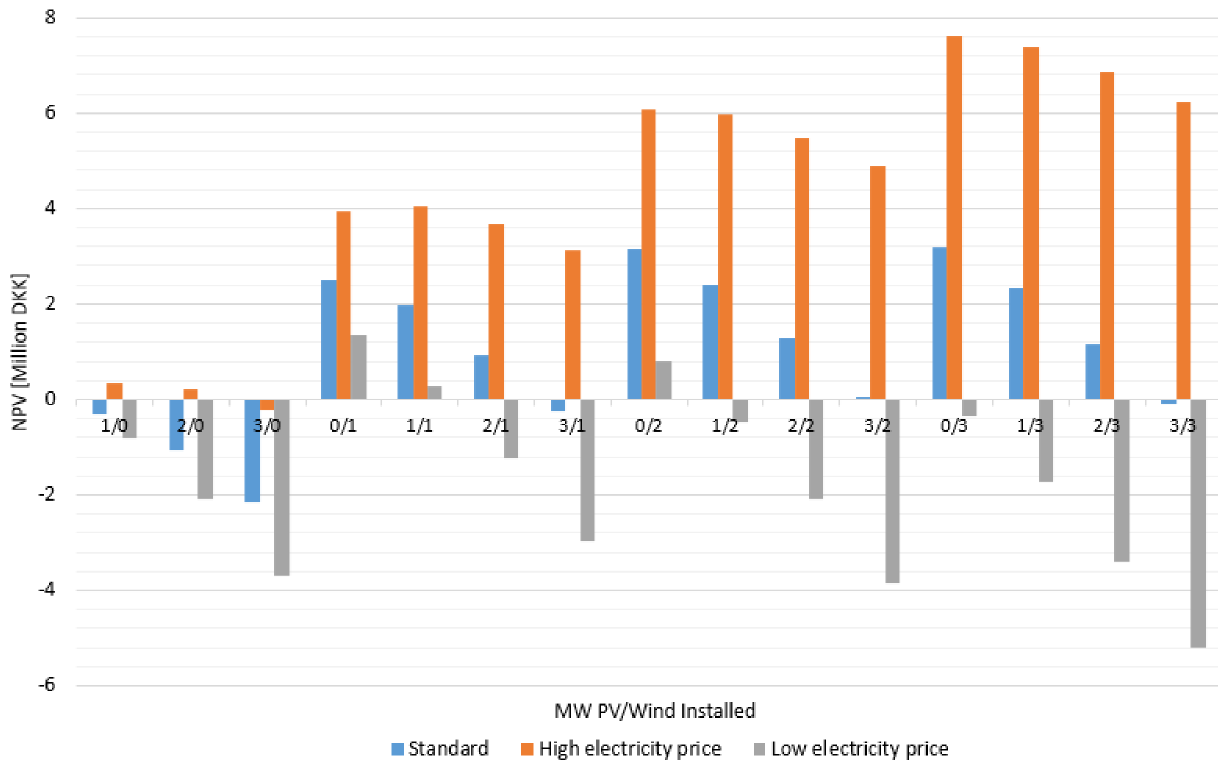


Figure 45: The NPV of the sub-scenarios with the high and low projections of the future electricity price.

From Figure 45, it can be seen that the price of electricity has a significant effect on the feasibility of the projects. In the scenarios with the high electricity prices, the NPV is higher than when the standard electricity price is used. Also, when using the high electricity prices, there is no significant difference if the electricity is not consumed immediately. This is because the spot price constitutes a larger percentage of the electricity price. When the low electricity price is used the NPV decreases, and only three sub-scenarios have a positive NPV. It can also be seen that its more important to only produce electricity when it can be consumed immediately. This is because the spot price constitutes a smaller percentage of the total electricity price. This is shown in Figure 46 where the difference between the high and low electricity prices in 2030 can be seen.

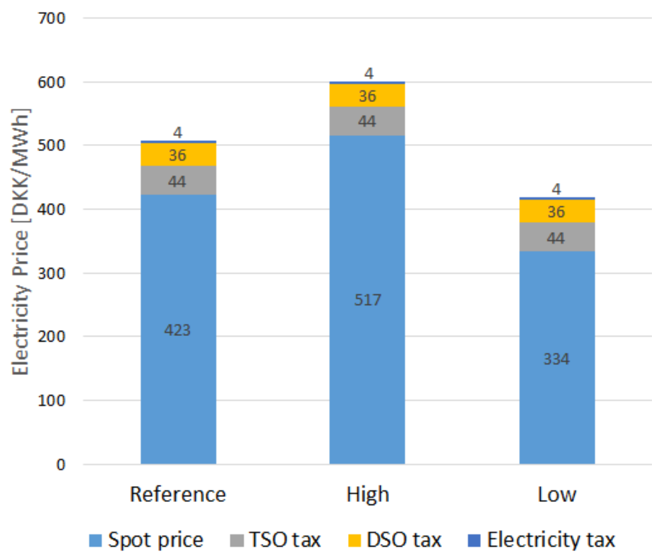


Figure 46: The breakdown of the cost of electricity in the high and low electricity price scenarios.

Sensitivity of Scenario 3 - Hydrogenation

In Figure 47 the results of the hydrogenation scenario with the upper and lower electricity price can be seen, compared to the original hydrogenation scenario, which is the blue bar in the figure.

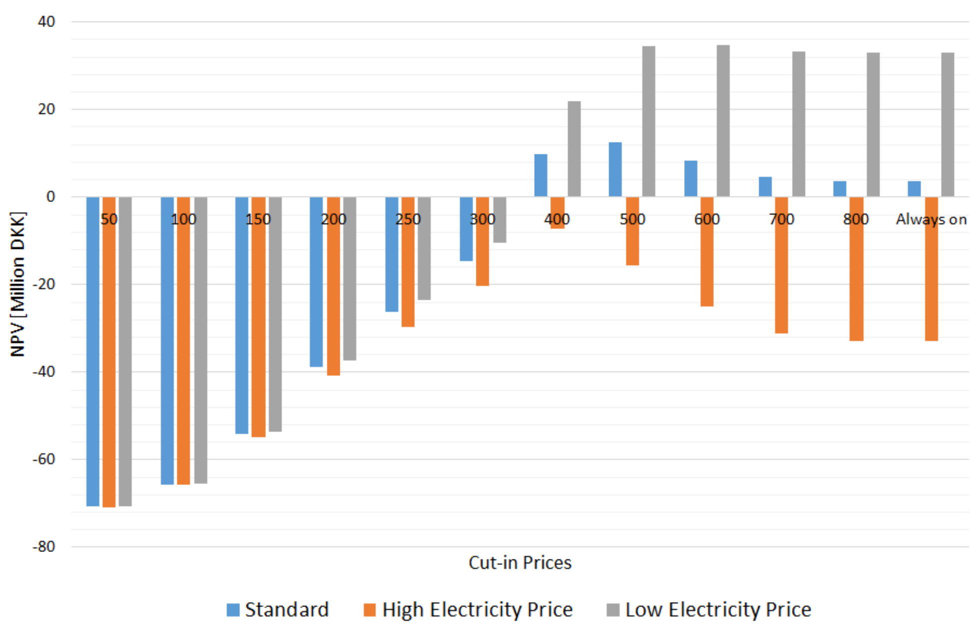


Figure 47: The NPV in the sub-scenarios at different cut-in prices at different electricity prices.

From Figure 47, it can be seen that the change in electricity price makes a small difference when the cut-in price is low and a big difference when the cut-in price is high. This is due to the fact that the electricity consumption is higher, when the cut-in price is high. In the simulation with the upper electricity price, none of the sub-scenarios have a positive NPV due to the increase in electricity costs. In the simulation with the low electricity price, the sub-scenarios have a positive NPV in the same sub-scenarios as with the original electricity price, the NPV is however significantly larger.

Sensitivity of Scenario 3.1 - Hydrogenation with Wind Capacity

Figure 48 shows the results of the simulations in the scenario with hydrogenation and wind power.

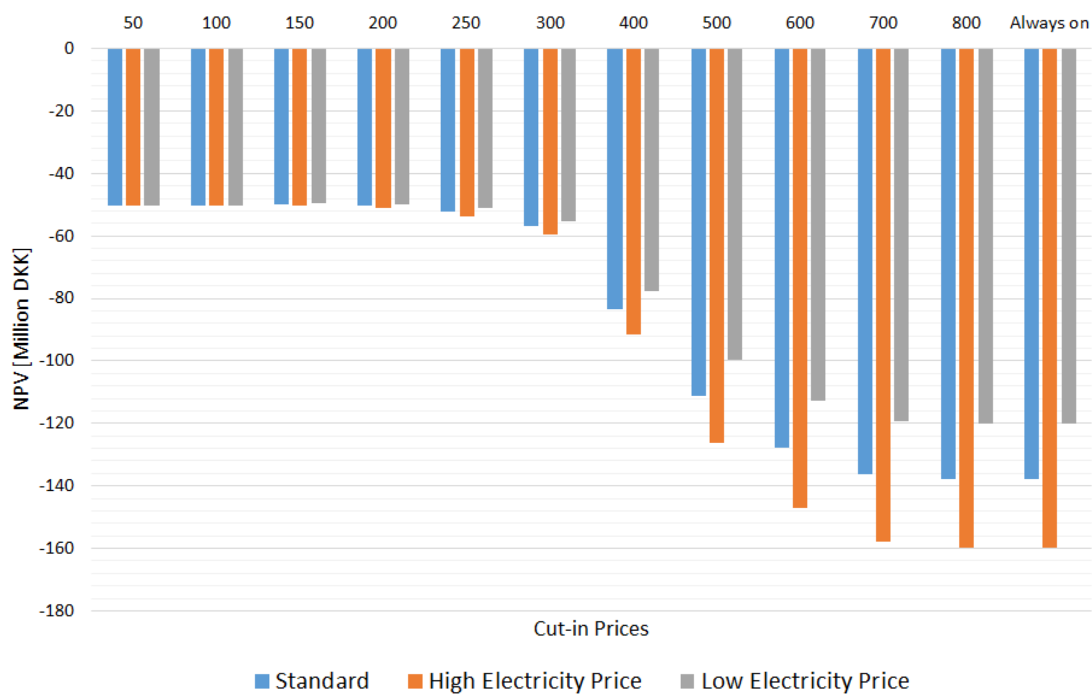


Figure 48: The NPV in the sub-scenarios with wind at different cut-in prices at different electricity prices.

The results in Figure 48 show that a change in electricity price does not have as big of an effect compared to the results in Figure 47. This is due to the fact that the electricity consumption is smaller in these sub-scenarios, since some of the consumption is produced by the wind power. All the sub-scenarios still have a negative NPV. The NPV decreases when the upper electricity price is used, due to an increase in electricity costs. Conversely, it increases when the lower electricity price us used, due to a decrease in electricity costs.

7.2 Natural Gas Price

In this section the uncertainty of the natural gas price will be investigated. It will also be investigated how a change in the natural gas price will change the outcome of the scenario where the natural gas consumption at the biogas plant will be replaced with biogas from own production.

Figure 49 shows the natural gas price used for the simulations, and its uncertainty. For the sensitivity of the natural gas price, the uncertainty from the future projections from The Danish Energy Agency has been extrapolated [49].

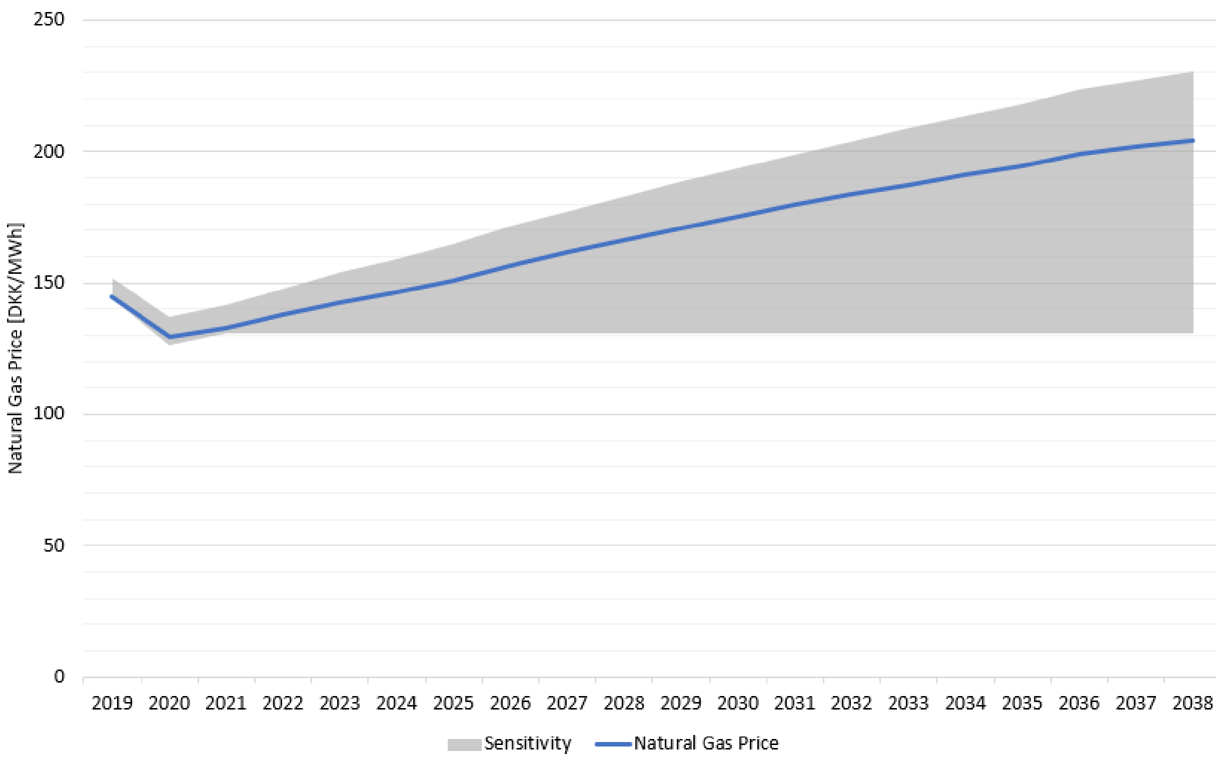


Figure 49: The uncertainty of the natural gas price.

Figure 49 shows that the lower estimate for the natural gas price is constant from 2021, while the higher estimate is consistently increasing slightly more than the standard prediction of the natural gas price.

Sensitivity of Scenario 2 - Biogas Replaces Natural Gas for Heating

Figure 50 shows the result of Scenario 2, with the standard, upper and lower natural gas price, where the standard price is the one used in the project.

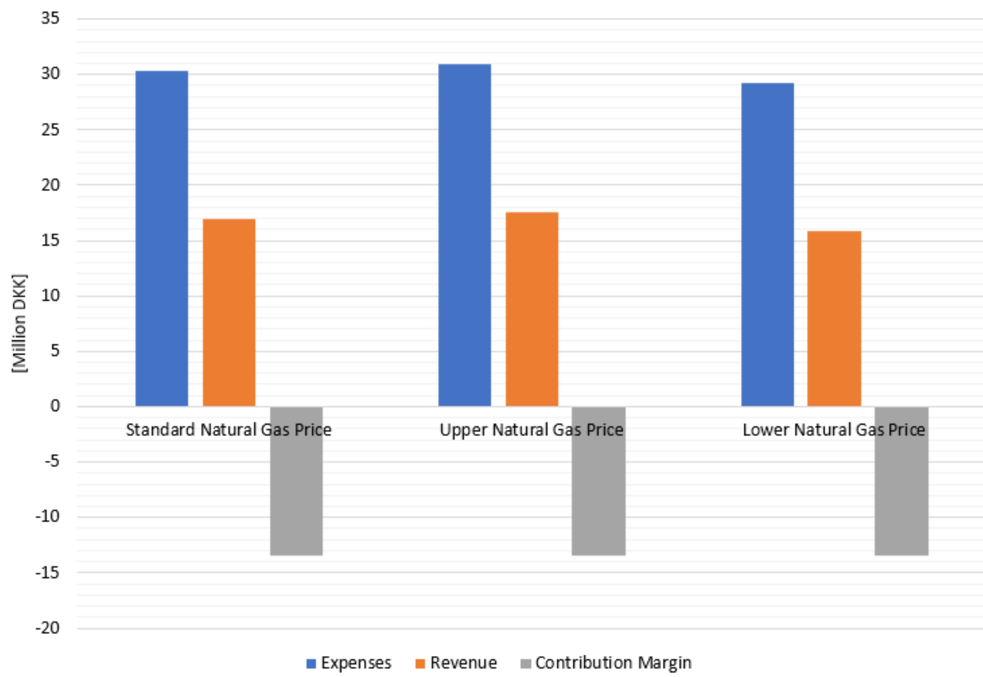


Figure 50: The expenses, revenue and contribution margin with the normal, upper and lower natural gas price over the lifetime of the project.

Figure 50 shows that the change in natural gas price only makes a slight change. The expenses and revenue are slightly higher and slightly lower when using the upper and lower natural gas prices, respectively. The contribution margin only differs around 400 DKK between the scenarios out of a total contribution margin of -13.4 million DKK. The reason for this is that when the natural gas price increases and more money is saved on natural gas, an equally large amount of money is lost on biomethane sales.

The future change of the natural gas price, and how it will affect the price of biomethane, will also be discussed in Section 8.3.

7.3 Investment Costs

The investment costs used in this project all stem from the technology data catalogues compiled by the DEA [26] [32]. The investment cost are shown in Table 14 along with the upper and lower boundaries of the uncertainty.

Data	Value	Lower	Upper
	Wind Power		
Investment Costs	7,365,600 DKK/MW	91 %	111 %
	Photovoltaics		
Investment Costs	4,612,800 DKK/MW	N/A	N/A
	Biogas Boiler		
Investment Costs	446,400 DKK/MW	58 %	416 %
	Hydrogenation		
Investment Costs	6,770,400 DKK/MW SNG	50 %	150 %

Table 14: The investment cost of energy conversion technologies used in the project, and their upper and lower uncertainties.

In Table 14 it can be seen that there is no uncertainty for the photovoltaics. In order to address this, the investment cost has been compared to an offer that Nature Energy received from Better Energy. The offer was 7 % larger pr. MW compared to the investment cost listed in the Technology Data Catalogues. The effect on a change in the investment costs would result in a change in the expenses for CAPEX and the interest on the investment. The change would have a larger impact in the scenarios where renewable electricity production and hydrogenation is installed, since investment costs are a relatively large portion of the expenses. In Scenario 2, a change in investment cost will only have a small impact, since the investment costs constitute a very small part of the expenses.

7.4 CO_2 Allowance Price

The CO_2 allowance prices are volatile, and the projections often miss their highest estimates by a substantial amount. The allowance price used in the project for the socio-economic benefit calculations is 200 DKK/t CO_2, which was the allowance price the 15th of April 2019 [37]. The allowance price projections from the DEA is shown in Figure 51.

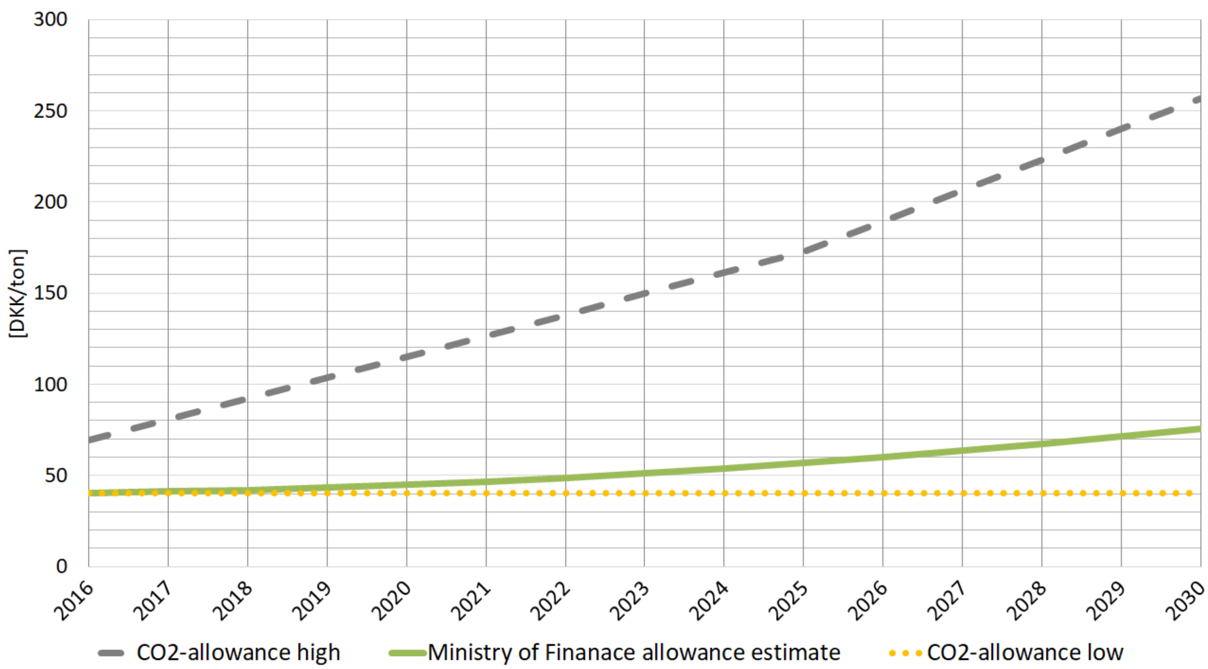


Figure 51: The allowance price projection in 2016 DKK/ton from the DEA from 2017 [49].

Following the DEAs projection, the allowance price would have hit 200 DKK/t by 2026. Because of the large uncertainties regarding the allowance price, the value in this sensitivity analysis have been halved (100 DKK/t) and doubled (400 DKK/t) to see the effects on the socio-economic benefits in the different scenarios. These effects can be seen in Figure 52 for Scenario 1, Figure 53 for Scenario 2 and Figures 54, 55 and 57, 58 for Scenario 3.

Scenario 1 - Photovoltaics and Wind Power

The sensitivity of the socio-economic benefits in Scenario 1, is created adjusting the CO_2-allowance prices. This is because the CO_2-allowance prices are the main contributor to the marginal cost reduction.

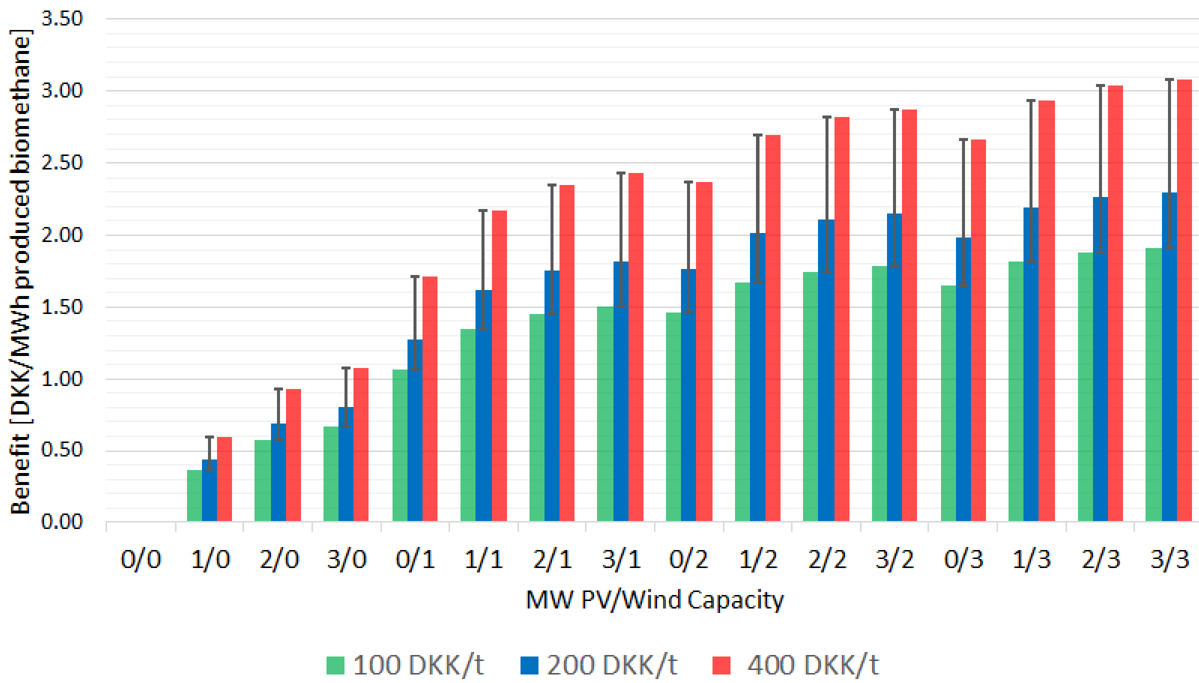


Figure 52: The sensitivity of the socio-economic benefits at different future CO_2 allowance prices.

The figure shows the difference between an allowance price of 100 to 400 DKK/t. The reference price of 200 DKK is the one used in the project and is the solid blue bar. The black line shows the span of which the benefit would change in relation to the CO_2 allowance price.

Scenario 2 - Biogas Replaces Natural Gas for Heating

The CO_2 allowance price is used as parameter to find the change in socio-economic benefits at different allowance prices and Figure 53 is the result.

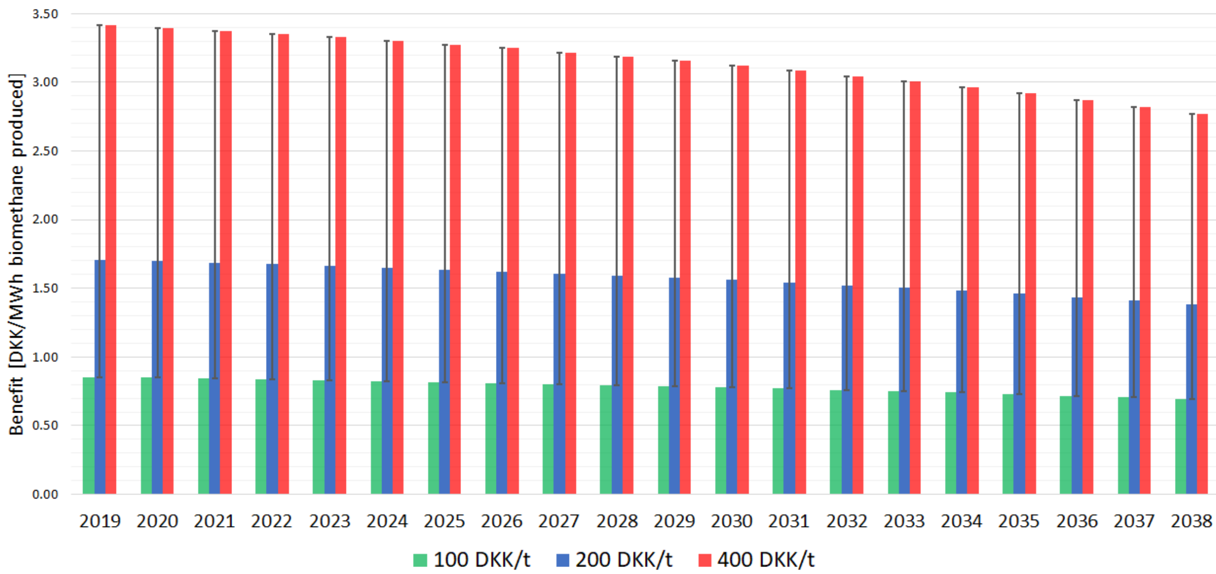


Figure 53: Sensitivity of benefits from using own biogas instead of natural gas.

From Figure 53 it can be seen that the benefits follow the emission reduction over the lifetime of the project. The black line indicates the span of which the socio-economic benefit change with the two allowance prices.

Scenario 3 - Hydrogenation

For Scenario 3, the allowance price changes will determine what year the additional produced biomethane would yield socio-economic benefits and of course how large the benefit can get, since a higher CO_2-allowance price would yield higher marginal reduction cost savings.

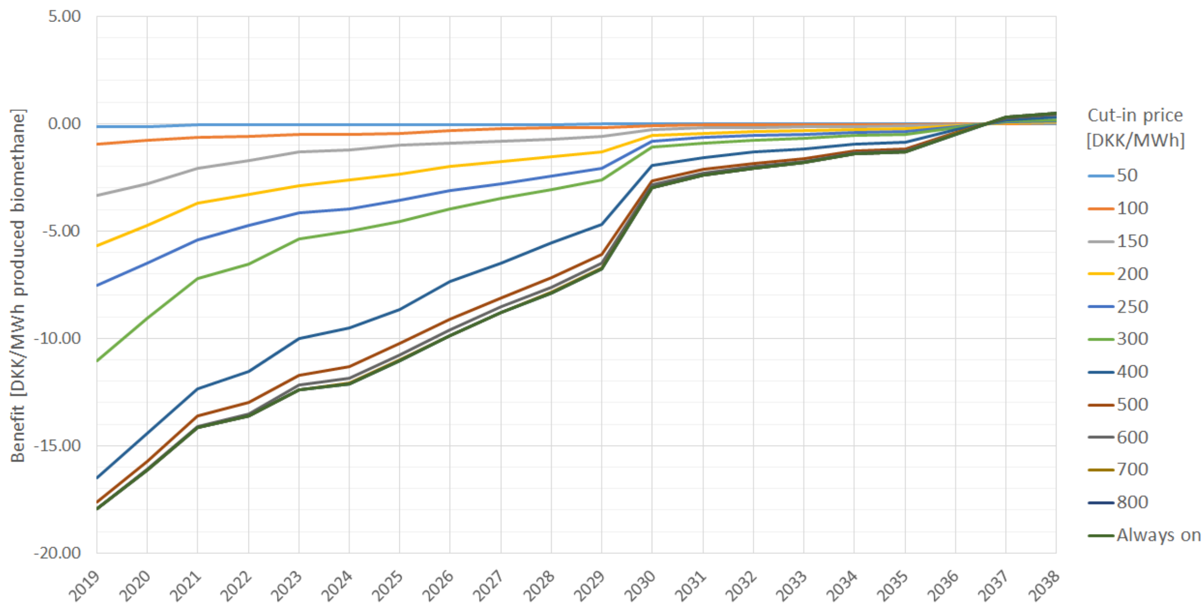


Figure 54: Hydrogenation benefits - allowance price of 100 DKK/t.

Figure 54 shows the benefits of the hydrogenation scenario if the allowance price would be 100 DKK/t. From the figure, there would not be beneficial until the latter years of the project period.

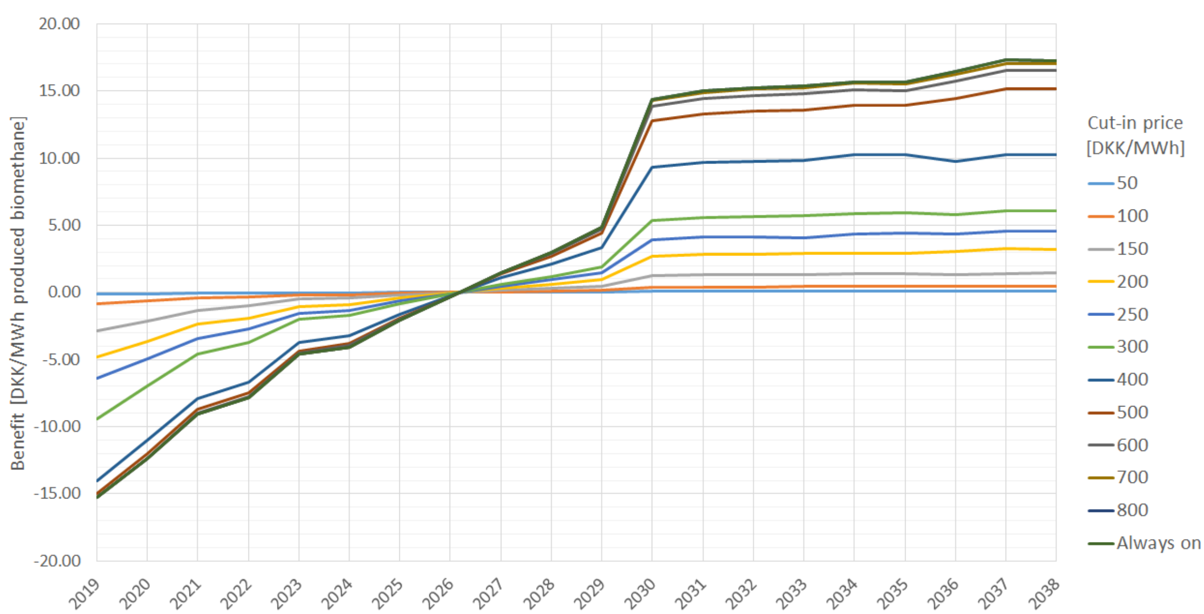


Figure 55: Hydrogenation benefits - allowance price of 400 DKK/t.

Figure 55, where the allowance price is set to be 400 DKK/t shows that there would be socio-economic benefits relatively early in the project lifetime and provide higher benefits towards the end of the lifetime.

To better show how sensitive, the benefits are to changes in the allowance prices, Figure 56 was made. This shows the sensitivity of the sub-scenario 300 DKK/MWh cut-in price.

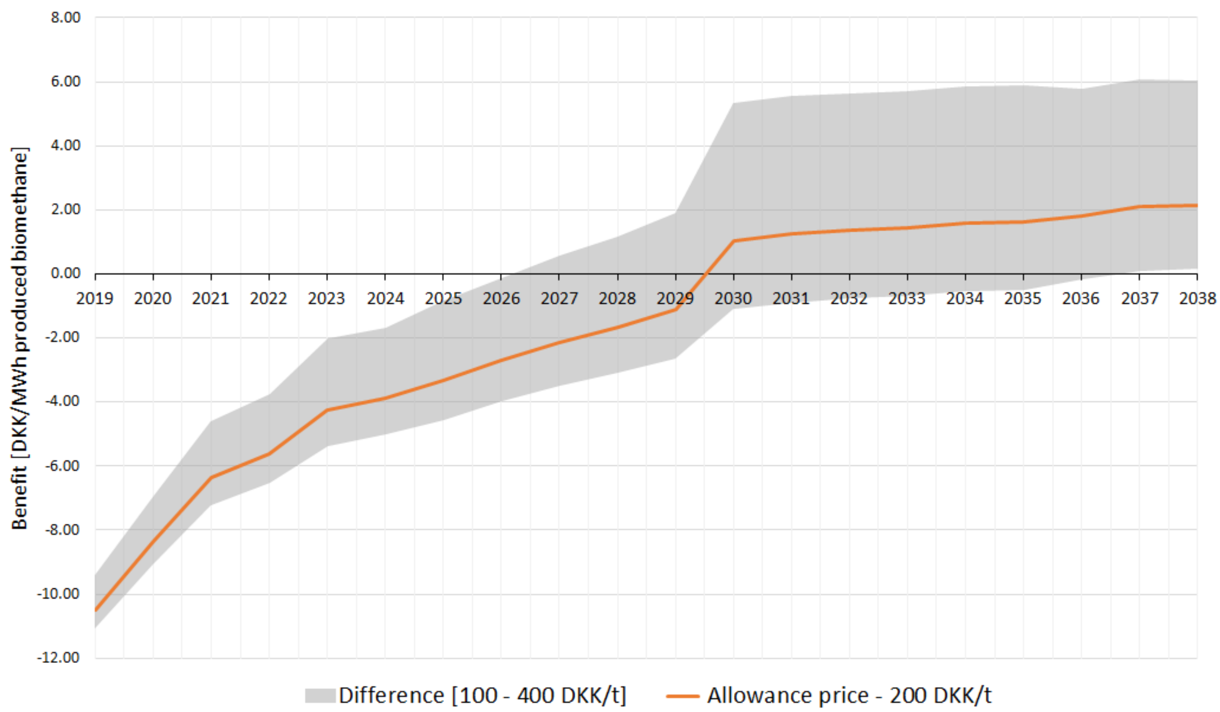


Figure 56: Sensitivity of sub-scenario 300 DKK/MWh cut-in price.

Scenario 3.1 - Hydrogenation with 10 MW Wind Capacity

The hydrogenation scenario with added wind capacity is not as susceptible to changes in allowance price as the scenario without wind capacity due to a large portion of the electricity being produced by the wind turbines themselves. Because of this, the highest benefit achievable in the 400 DKK/t scenario will be 10.58 DKK/MWh produced biomethane compared to 17.31 DKK/MWh produced biomethane in the scenario without wind capacity.

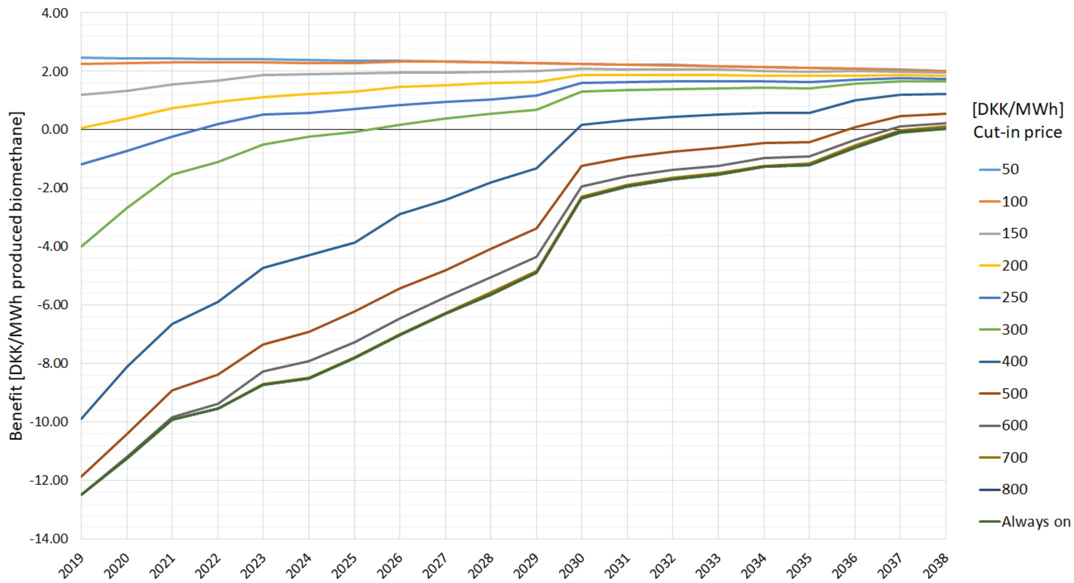


Figure 57: Hydrogenation benefits - allowance price of 100 DKK/t.

For Figure 57 the socio-economic benefits at an allowance price of 100 DKK/t would be able to still achieve socio-economic benefits for most of the price points half way through the lifetime whereas the scenario with no wind capacity installed would almost never yield a benefit as shown in Figure 54.

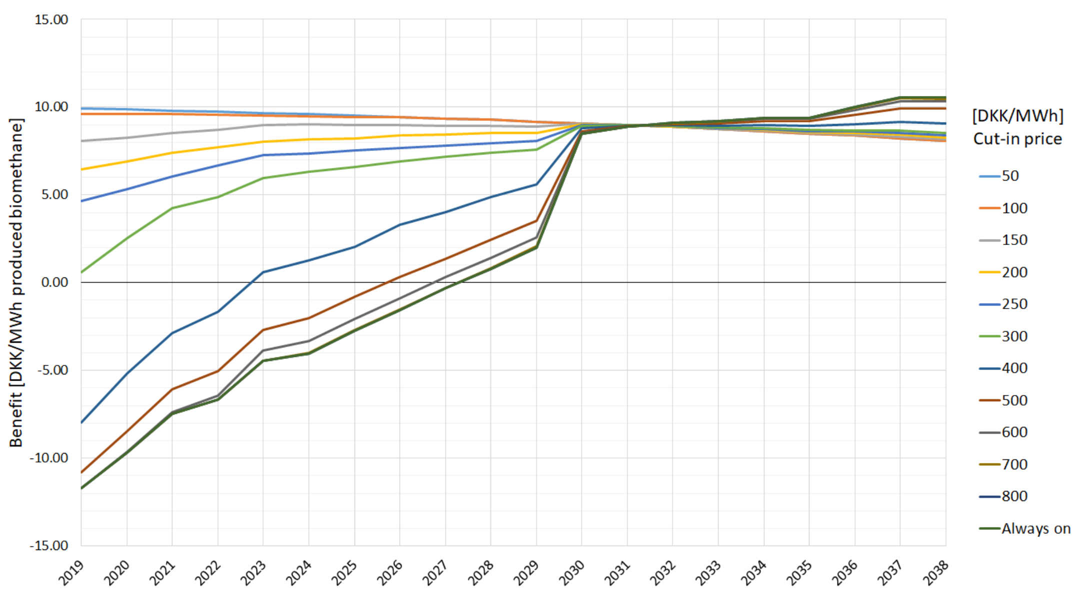


Figure 58: Hydrogenation benefits - allowance price of 400 DKK/t.

Figure 58 shows the socio-economic benefits if the allowance price is 400 DKK/t. Compared to the 100 DKK/t allowance price, the higher price would yield higher benefits in total and enable for a positive benefit earlier in the project lifetime. In order to better show how sensitive the benefits are to changes in the allowance price, Figure 59 was made.

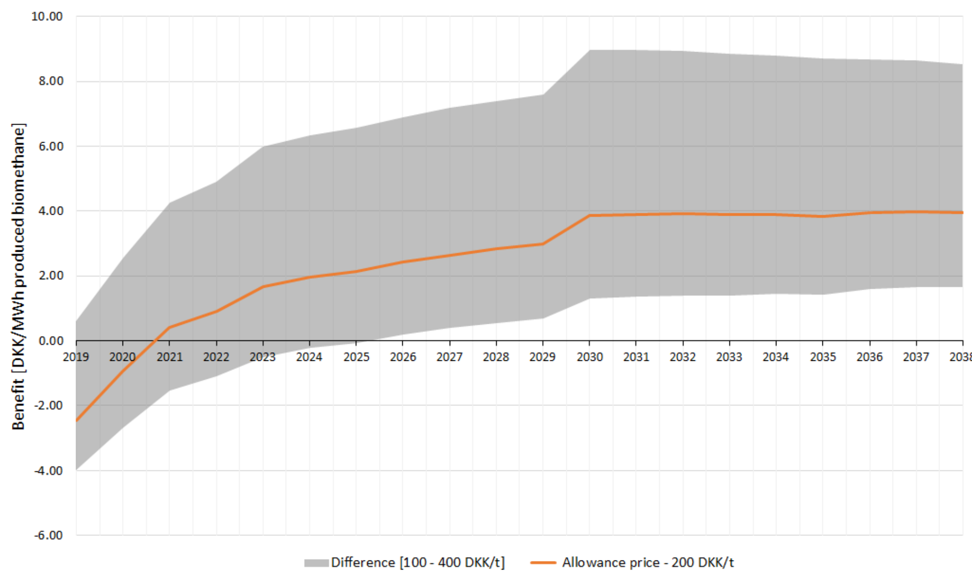


Figure 59: Sensitivity of sub-scenario 300 DKK/MWh with wind capacity cut-in price.

The figure shows the sensitivity of the sub-scenario with a cut-in price of 300 DKK/MWh.

7.5 Section Summary

Through the sensitivity analysis the sensitivity of the results and the different input parameters were investigated. The electricity price was found to have a great impact on whether Scenario 1 would yield a positive NPV and showed that using the high electricity price, all the sub-scenarios with wind installed would yield a positive NPV. The low price however only made three of the sub-scenarios have a positive NPV.

The electricity price change in the hydrogenation scenario was found to have little impact at a low cut-in price and a high impact at a high cut-in price. This is because the electricity consumption increases at higher cut-in prices. In the hydrogenation scenario with added wind capacity all the results still have a negative NPV.

The natural gas price was found to only have a slight change in the contribution margin by using own biogas rather than natural gas from the grid for heating of the biomass. It was found that the reason for this was due to the natural gas savings having an equal value to the lost biomethane sales.

The sensitivity of the investment costs was found to have a large impact in Scenario 1 and 3, since these account for a large part of the total expenses. Through the sensitivity of the socio-economic benefits in relation to the CO_2 allowance price, it was found that the high allowance price would yield benefits earlier in the scenarios and the low allowance price would yield benefits later in the scenarios.

8 Discussion

In this section the results and the limitations and applicability of these will be discussed. This section is divided into sub-sections that all discuss subjects or parameters that could have affected the results. The discussion includes the considerations regarding the simulations tool, the GHG calculations, the future price of biomethane, a better foundation for hydrogenation and the applicability of the findings.

8.1 energyPRO

energyPRO was used to simulate the three scenarios and provided the consumption, production and financial data needed to answer the problem statement for the project. In order to check the validity of the result output from energyPRO, the business case of Scenario 1 was compared with a business case tender from Better Energy and it was found that with the same assumptions the results was so similar that it is expected that the tool provides a reasonable and realistic result.
As a reference for the weather data and electricity prices 2015 was used in order to have a good representation of the correlation between renewable production and electricity prices. Unfortunately, energyPRO did not provide the availability to use a loop of more than one year of data, which would be able to create a better average for the weather conditions in the simulations. Whether this functionality could have provided better results is hard to say since the analysis of finding the best year to represent weather conditions found that 2015 should be able to provide a reasonable average year regarding weather conditions.

8.2 GHG Emission Calculations

When calculating the GHG emissions, the parameters and assumptions that are made, can have a large impact on the result of the calculations. Ideally all GHG emissions should be included, but this is in practice quite difficult and the approximations made are with great uncertainty. In the calculations in this project, the guideline from the REDcert scheme has been used, while emission coefficient from DEA's projections has been used.

Using the GHG calculation requirements from REDcert [21] means that different GHG emission savings cannot be included in the calculations. When manure is used for biogas production and the digested biomass is used as fertilizer instead of the manure, much less methane is emitted. This cannot be included in the calculations, yet, according to REDcert, but will be implemented when the new Renewable Energy Directive (RED II) [50] will take effect in 2021. According to RED II typical GHG emissions from biomethane produced by wet manure are -103 gCO_2-eq/MJ. This is a considerable decrease compared to the emissions from Nature Energy Midtfyn at 17.8 gCO_2-eq/MJ. This shows, that even though the GHG emission calculations following the REDcert scheme, might show that biomethane production is not completely CO_2-neutral, the GHG savings will be above 100 % when the entire picture is included.

Using different sources for the emissions from electricity can cause a large variance in the results of the GHG calculations. The REDcert scheme suggests a standard value for GHG emissions from electricity of 127.65 gCO_2-

eq/MJ [21], while the DEA suggests using 43.9 gCO_2-eq/MJ in 2019, decreasing to 2.9 gCO_2-eq/MJ. The standard value suggested by REDcert is an average of the EU mix and is therefore not a very good estimate for Denmark. Therefore, the suggested values from the DEA has been used for the calculations in this project, and that will give a more correct result than using the standard values from REDcert, since the scenarios are in Denmark.

Additional Emission Reduction

Two sources of emission were not attempted reduced in the scenarios set up, these are the emissions from methane leakage and the emissions from transportation of biomasses. In the calculations of this project the methane leakage is estimated to be 1 % of the produced biomethane. This value is based on the guarantee set by the producer of the water scrubber at Nature Energy Midtfyn [23]. Most of this emission can be removed by installing a biogas upgrading plant that has a better guarantee of methane leakage. This has been done at Nature Energy Korskro where an amine scrubber is used, and the producer has given a guarantee of maximum 0.05 % methane leakage [23]. This change alone can reduce the emissions from methane leakage by 95 %, which corresponds to a reduction of 20.4 % compared to the reference scenario.

The most realistic method for reducing the emissions from transportation of the biomasses, would be to use biomethane to fuel Nature Energy's own trucks, that are used for transporting wet manure. This solution is technically possible, but taxes and levies currently make is economically not feasible [51]. A lot of the biomasses are however not transported by Nature Energy's own trucks, and it is therefore not under the control of Nature Energy to completely remove this emission.

8.3 Future Price of Biomethane

The value of the biomethane, for Nature Energy, used in the simulations are the sum of the natural gas price, the price of the biogas certificate and the subsidy on biogas. These values will change in the future. The change in the natural gas price has been accounted for in the report by using the projections of the natural gas price by the DEA [31]. The fact that an increasingly larger percentage of the gas in the gas grid is becoming biomethane, might be included in the projections of the natural gas price. This would mean that the higher production costs of biogas are included in the price projections. The subsidy scheme is also bound to change in the future. New biogas plants will from 1st of January 2020 not receive any subsidies, but 240 million DKK/year has been put aside for an invitation to tender for biogas plants [12]. Despite these uncertainties, the value of biomethane for Nature Energy has to be fairly constant, in order to keep the business running. This means that a change in natural gas prices and subsidies will cause a change in the price of the certificates, in order to keep the value of the biomethane constant.

Once we get closer to 2050, where Denmark wants to be free of fossil fuels, all the gas in the grid will be carbon neutral. This will result in the value of the certificate diminishing to zero. In 2050 there will probably not be any subsidies left for biomethane production, considering that current biogas plants will stop receiving subsidies in 2032 [12]. This means that the entire value of the biomethane will be moved to the value of the gas price in 2050.

8.4 Optimisation of Hydrogenation

Other projects have shown better business cases for utilising hydrogenation with biogas production, than what is shown in this thesis. PlanEnergi has made an analysis of including electrolysis and methanation in biogas production [52], where methanation is the primary method for removing the CO_2 from the biogas, while different technologies are used as back-up. Their analysis shows that using amine upgrading as back-up is the best solution, and it gives a profit as long as the average electricity price is below 350 DKK/MWh. The average electricity price used in this project starts at 290 DKK/MWh in 2019 and ends at 392 DKK/MWh in 2038. Therefore, hydrogenation should be profitable at least in the first half of the project period.

The reason why the results in this project does not give better results, is that this thesis has tried implementing hydrogenation in an already existing biogas plant. This means that the income generated from implementing hydrogenation would only amount to the *extra* biomethane produced by utilising hydrogenation. Whereas, if a new biogas plant were built with hydrogenation as the primary way of removing the CO_2, the entire amount of biomethane is used to pay off the hydrogenation. When a biogas plant is built specifically for utilising hydrogenation, it is also easier to optimise the entire plant with this in mind. This is not the case when implementing it at an existing plant.

8.5 Recommendation

It was found that the best case for Nature Energy Midtfyn is to install just enough renewable capacity to meet the maximum electricity consumption of the plant, which is close to 1 MW. The value of selling the excess electricity was not high enough to justify the installation of more capacity than what is needed, even though this would provide a higher emission reduction. This knowledge was applied to the hydrogenation scenario were the expectation was that it would help the business case only to find that the revenue was too low to ever become a good business investment decision.

The data used to create the simulation and generate the results were directly from Nature Energy Midtfyn. Therefore, the results are directly applicable to Nature Energy Midtfyn, but can also be used on similar biogas plants of similar capacity.

General takeaways and recommendations that can be used for all biogas plants are:

- It is not recommended to install more renewable electricity capacity, than what can be consumed immediately, due to the levies and taxes tied to electricity consumption.
- The loss in biomethane sales are too high to justify using own biogas for heating biomasses.
- It is not feasible to implement hydrogenation at a biogas plant that already have means of upgrading the biogas.

- Projects that reduce the GHG emissions can become economically feasible by increasing the price of the biogas certificates, if there are customers that demand lower GHG emissions.

Specifically, for Nature Energy Midtfyn, the recommendation is to install 1 MW of wind power, since this is a good business investment decision. If Nature Energy Midtfyn wishes to reduce their GHG emissions further, they should use their own biogas for heating the biomasses or improve their upgrading unit to achieve a lower guarantee of methane leakage.

9 Conclusion

Through three different scenarios a best case is found for implementing renewable production at Nature Energy Midtfyn. Scenario 1 and 2 investigates what can be done right now to reduce the emissions in the biogas production, where scenario 3 has more of a future perspective in regard to increasing the utilisation of biomass in the production.

In Scenario 1, it was found that renewable production is best introduced as wind capacity with a capacity of no more than what is needed at the biogas plant due to the levies and taxes tied to electricity consumption. The sub-scenario that installed 1 MW of wind capacity had the best IRR of 14.5 %. This sub-scenario showed a decreased consumer cost of 2.4 DKK/MWh for gas and a socio-economic benefit of 2.58 DKK/MWh produced biomethane. The extra income from selling excess renewable electricity was found to be too low to justify installing more capacity.

For Scenario 2 the emission reduction was found to be 18,258 ton CO_2 equivalents over the project lifetime of 20 years. The reduction is equal to the amount of emissions tied to the replaced natural gas consumption. This reduction however causes a loss in sales from biomethane and will increase the end consumer price by 22.87 DKK/MWh but still have a socio-economic benefit of at least 2.77 DKK/MWh produced biomethane.

Hydrogenation would along with other technologies be able to increase the biogas potential in Denmark. In the case used in the project, the introduction of hydrogenation yielded an additional biomethane production of 67 %. In relation to introducing hydrogenation alongside the biogas production it was found to be too costly due to high capital investments and electricity costs.

The most realistic emission reduction found obtainable was combining the best case from Scenario 1 and Scenario 2. This yielded an overall reduction of 39.55 % in relation to the Reference Scenario and a socio-economic benefit of at least 5.35 DKK/MWh produced biomethane.

It was found that the results in Scenario 1 and 3 are highly sensitive to a change in electricity price and investment costs. Likewise, it was found that the socio-economic benefit highly depends on the CO_2 allowance price in all scenarios.

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Appendices

A Problem Proposal

Background

The production and use of biogas is considered CO_2 neutral. There is, however, greenhouse gas emissions from biogas production. These emissions stem from electricity consumption, natural gas consumption, methane leakage and transport of biomasses. It is relevant for Nature Energy to know what the cost of reducing these emissions would be. This reduction could be achieved by introducing renewable electricity production in the production of biogas or using biogas instead of natural gas. The decrease in greenhouse gasses would cause increased costs, and therefore would increase the price of biogas certificates. However, the biogas would be a better product, in relation to emissions, and this might have a value for the costumers.

Goal

The goal is to investigate how renewable energy sources best can be introduced in the biogas production. The investigation will include a system analysis of the current system and an analysis of how the levies and tax systems affects the introduction of renewable production. The analysis will mainly be done in energyPRO, a tool used for energy system analyses. How electricity from renewables can be used in biogas production, e.g. hydrogen from electrolysis for methanation, will also be included.

Partner

Nature Energy

B Overview of Attached Files

This appendix will provide an overview of the simulation and excel files used for the thesis.

B.1 energyPRO Simulations

A guide to help the reader understand the energyPRO simulations. In order to run the files, you will need a licence for energyPRO. The report outputs used from energyPRO are "cash flow, summary" and "energy conversion, summary". The cash flow summary includes all payments for all years of the project and the energy conversion summary shows the annual energy conversion basis of the following: Demands, productions, transmissions, losses, hours of operation, number of turn-on and fuel consumption.
The summaries can be seen in the excel files attached with the thesis.

B.1.1 Scenario 1 - Photovoltaics and Wind Power

The simulations of the different sub-scenarios for this scenario are separated into 16 different simulation files. Each file has its own configuration of wind and photovoltaics capacity ranging from 0 MW wind and 0 MW photovoltaics to 3 MW wind and 3 MW photovoltaics.
The file names are given as "Scenario 1 - 0PV 0W". Where the number indicates the capacity of installed renewable in MW, PV is photovoltaics and W is wind.

B.1.2 Scenario 3 - Hydrogenation

The simulations of the different sub-scenarios of this scenario are separated into 12 different simulation files. Each file has a different cut-in price of the hydrogenation unit ranging from 50 DKK/MWh to 800 DKK/MWh and with an additional simulation always having the hydrogenation unit running.
The file name is given as "0PV 0W El-grid 50 Dayily avg". Where the number indicates the capacity of installed renewable in MW, PV is photovoltaics and W is wind and "50" is the cut-in price in DKK/MWh.

B.1.3 Scenario 3.1 - Hydrogenation with Wind Capacity

The simulations of the sub-scenarios with added wind capacity will be the same as the sub-scenarios for the hydrogenation simulations with the exception of having 10 MW wind capacity added to the simulation.

B.2 Excel Calculations

A guide to help the reader understand the data sheets and calculations in excel.

B.2.1 Business Economic Results

The business economic calculations for the three scenarios has been done in the following Excel files:

- 1. Results - PV and Wind

- 2. Results - Biogas replaces natural gas
- 3. Results - Hydrogenation
- 3. Results - Hydrogenation and Wind

Each Excel file contains a sheet with an overview and sheets for each sub-scenario. In the sheets for each sub-scenario, the results from the energyPRO simulations are inserted, and the economic calculations are performed.

B.2.2 Socio-economic and Emission Results

The socio economic and emission results are found for each scenario in the following Excel files:

- Socio-eco 1 - PV and Wind
- Socio-eco 2 - Biogas replaces natural gas
- Socio-eco 3 - Hydrogenation
- Socio-eco 3 - Hydrogenation and Wind

The excel files contains a sheet with overview of all the calculation results and sensitivity results of the socio-economic benefits. Furthermore, the certificate increase and the additional consumer costs can be found in these excel files under the sheet "Socio-certificate".

B.2.3 Sensitivity Analysis

The calculations for the sensitivity analysis have been made in different Excel files explained here:

Electricity price: The sensitivity of the electricity price is calculated in the following Excel files:

- Sensitivity 1 - PV and Wind
- Sensitivity 3 - Hydrogenation
- Sensitivity 3 - Hydrogenation and Wind

Natural gas price: The sensitivity of the natural gas price has been calculated in the following Excel file:

- Sensitivity 2 - Biogas replaces natural gas

CO2 allowance price:
The sensitivity calculations concerning the CO_2 allowance price are calculated in the same excel files as socio-economic and emission results. In the files "Socio-eco 3 - Hydrogenation" and "Socio-eco 3 - Hydrogenation + Wind" the reader is able to quickly change the allowance price and see the difference from the reference price in sheet "Overview" cell "AF74" for the first file and "Socio-graph" cell "AB55" for the second file.
For scenario 2, the sensitivity of the allowance price is calculated as fixed examples in the file.

C Foundation for the socio-economic and the emission calculations

The following section will describe the foundation for the calculations in regard to emissions and socioeconomics for the different scenarios. All the data used for this section is primarily from the Danish Energy Agency and their guidelines on how to do socio-economic analyses for energy projects [35]. The data used for the calculations are the emission development for electricity and natural gas from the grid and damage cost coefficients for emissions in the energy sector.

The Figures 60 and 61 shows the development in electricity emissions and Figure 62 shows the expected development in emissions from the natural gas grid.

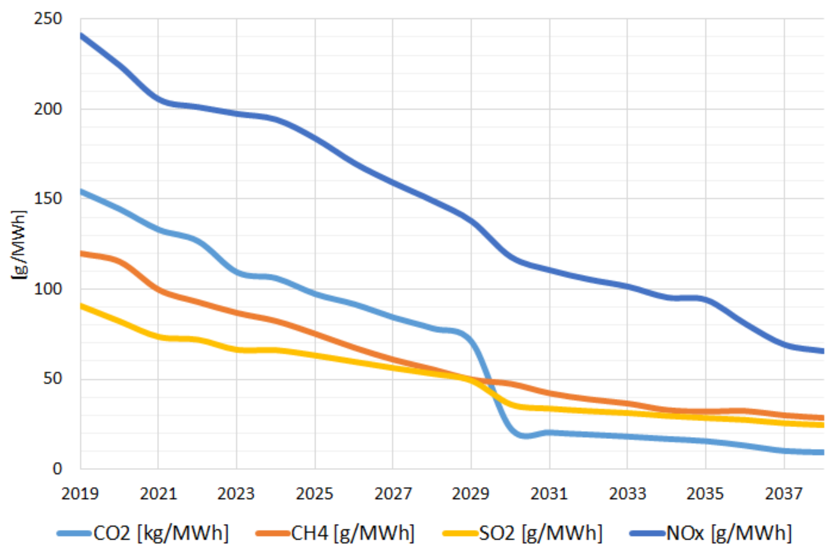

Figure 60: Emission development in Danish electricity grid - CO_2, CH_4, SO_2 and NO_x.

To elaborate further, Figure 60 shows the expected future emissions tied to 1 MWh of electricity consumption. There exists data for production and these can be found in the guidelines from the DEA [35]. It is important to note that the emissions from CO_2 is given in kg/MWh where the rest are in g/MWh. Furthermore, the CO_2 values are calculated by using an average recital, meaning the total emissions from all production units is divided evenly between the entire electricity consumption. In the figure, by 2030 there is a sudden dip in CO_2 emissions, this is because of the governmental goals of having 100 % of the Danish electricity renewable by 2030. This dip will have a significant impact on the socio-economic results tied to the hydrogenation scenario given the scenario has a high amount of electricity consumption.

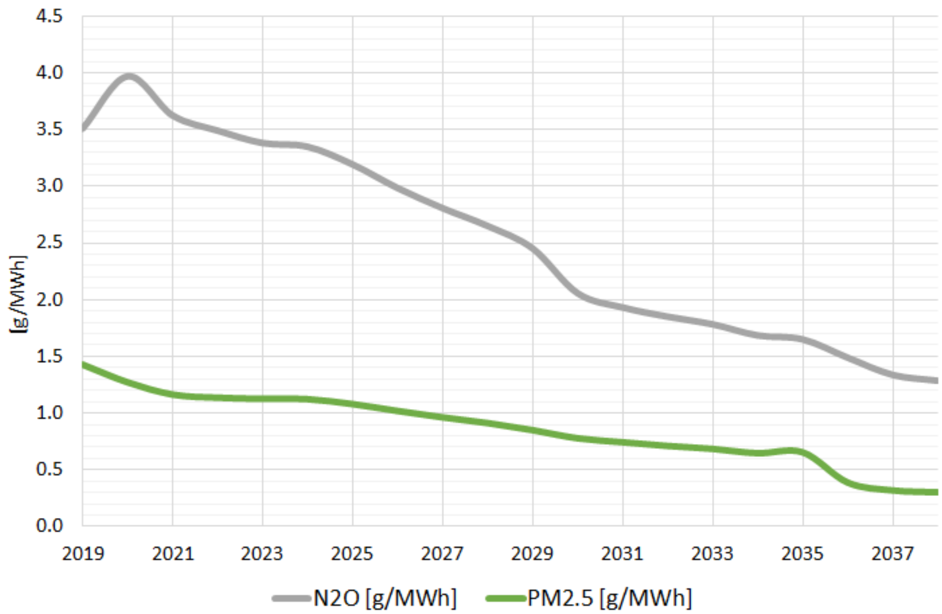

Figure 61: Emission development in Danish electricity grid - N_2O and $PPM_{2.5}$.

Figure 61 has the development of N_2O and $PPM_{2.5}$ over the lifetime of the project, 20 years. The figure is simply to give a better overview, since these numbers are considerably smaller than the other emissions.

Figure 62 shows the expected development in emissions in CO_2-equivalents from natural gas consumption from the grid over the lifetime of the project, 20 years.

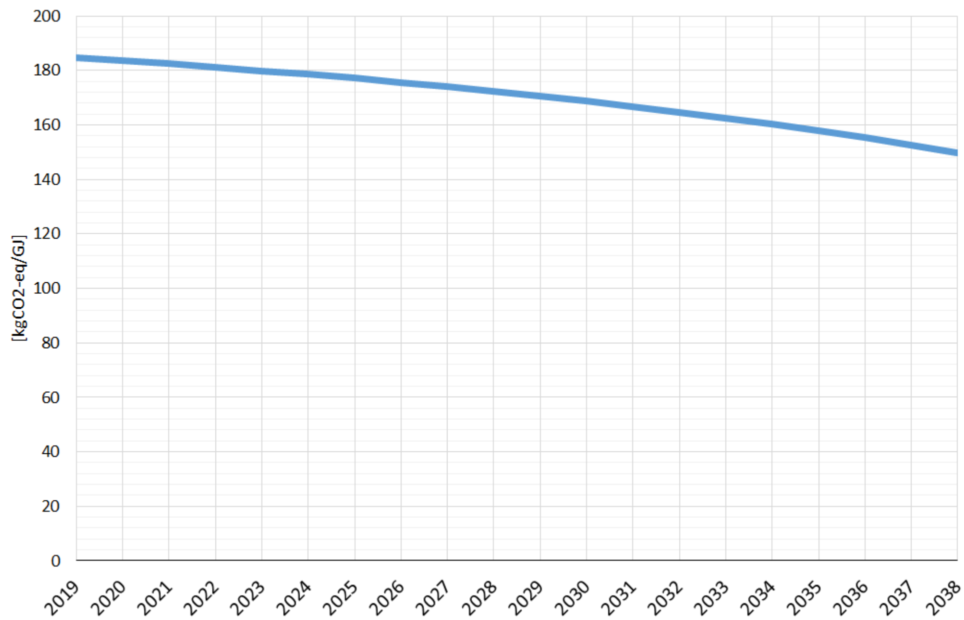

Figure 62: Emission development in the natural gas grid in CO_2 equivalents.

As can be seen in the figure, the expected reductions in emissions of the natural gas grid are decreasing at a noticeably slower rate than in the case for electricity. This will have an effect on the socio-economic benefits in the scenario where natural gas consumption is replaced with biogas consumption.

For calculating the damage costs, the values in Table 15 will be used in order to get the total damage costs. The damage costs from emissions are tied to diseases originating from exposure to the harmful emissions.

Emission	SO_x, SO_2, SO_4	NO_x, O_3, NO_2, NO_3	$PPM_{2.5}$
DKK/kg	134	137	265

Table 15: Damage cost values for SO_x, NO_x and $PPM_{2.5}$ [38].

For the marginal reduction costs, the CO_2-allowance price is used on the emissions that are not directly tied to damage costs. These are CO_2, CH_4 and N_2O. The allowance price was 200 DKK/t as 15th of April [37]. CH_4 and N_2O will be calculated in CO_2-equivalents with the conversion factors of 25 for CH_4 and 298 for N_2O [35].
With the development in emissions tied to gas and electricity usage from the grid, this can be used together with damage costs tied to the emissions and the marginal emission reduction costs to find the socio-economic benefits of the different scenarios.

D Description of Results Table in Scenario 3

Additional electricity used [GWh]

- The additional electricity used comes from the electricity consumption of the hydrogenation in the simulation. The run time of the hydrogenation is dependent on the day ahead electricity price. The scenario was calculated using an index from the DEA [27] of increasing electricity prices and this has an effect of how many turn-ons the hydrogenation will have over the lifetime of the project. The additional electricity is the total consumption over 20 years.
  The additional electricity consumption for the scenario with installed wind capacity is both dependant on the wind production and the electricity price development. The electricity use from the grid ends up being more than halved in all sub-scenarios compared to not having installed wind capacity.
  At times where the wind production is 0, the hydrogenation unit is primarily dependant on the electricity price.

Kiloton CO_2-eq

- The additional electricity purchased is the foundation of the emission calculations. From this, the emissions attached to electricity used from the grid is calculated. The emission values decrease over the lifetime of the project given the electricity from the grid will have less and less emission.
  The emissions follow the electricity consumption.

Extra biomethane produced [GWh]

- The additional biomethane produced in the scenario is increased with the increase in electricity use and will have an effect on the emission per additional biomethane produced ratio. As with the emissions, the biomethane production increased with electricity production.

CO_2-eq/biomethane [kg/MWh]

- The emission per MWh biomethane production is the cost in emission to produce 1 MWh of additional biomethane in the different sub-scenarios. Using this as a comparison parameter, the best solution emission-wise will be the one with the lowest emission per additional biomethane produced.
  For the scenario without wind production, the best scenario would be to have no max set price point and let the hydrogenation unit run all the time. This is because the emissions from the electricity from the grid reduce over time and therefore the emissions per produced biomethane decrease.

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Master's Thesis

University of Southern Denmark

Printed at Print & Sign, SDU
June 2019