Bachelor Thesis

Hydrogen as a power back-up

Course nr: ET-BA-U1

Martin Herløv Dorsch (425082) &
Alexander Lorentzen (426444)

Supervisor:

Lars Yde (lay@kbm.sdu.dk)
Abid Rabbani (abir@kbm.sdu.dk)

Character count (including spaces): 40,119

Faculty of Engineering
University of Southern Denmark

1st of June 2018

Can be published

Abstract

The move towards increased wind capacity in the Danish energy system will inevitably decrease the baseload production units and their economic feasibility. Furthermore, the security of supply will be compromised with this increase. This paper examines two options for hydrogen system integration as a power back-up in Jytland and Funen. The scenarios are built on a framework from the Danish Energy Agencys energy scenarios towards 2020, 2030 and 2050. Using EnergyPRO simulation tool it was shown that upgrading biogas was the cheapest solution with a system cost of 128.6 billion DKK. The cheapest solution used 1.61 PJ of biogas in total where most of the biogas used were to be upgraded to SNG. The sensitivity analyses showed that the cheapest solution could have a decrease in offshore wind capacity between 20 and 30 per cent if the capacity of photovoltaic were increased to the current estimation for 2040.

Contents

List of Tables

List of Figures

Acknowledgements

We would like to take this opportunity to thank our supervisors who have guided and help us throughout this project. Many thanks to Lars Yde, Abid Rabbani and our colleagues who provided valuable insights and critiques at the cluster meetings. A special thanks to Leif Holm Tarmbjerg for much needed support with our EnergyPRO model.

1 Introduction

In 2012 the then government and opposition agreed upon the future of the Danish energy system development. Now the government has proposed a new plan. In the 2012 plan, the amount of wind capacity that should be installed was about 1500 MW by 2020 while the new plan has only 800 MW wind capacity increase by 2030 [1, 2]. Their goal is to have 50 per cent of renewable energy in 2030. Moreover, the Danish Energy Agency, DEA, published in 2014 a report which presented four energy scenarios for the future Danish energy system, along with a reference scenario. Two of these scenarios has a significant increase in wind and solar capacity compared to 2014.
An increased amount of wind in the Danish energy system increases the spikes already seen in an electricity load profile. This can compromise the high level of supply security that Denmark has [3].
At the present moment, the excess electricity is sold to our neighbouring countries. By looking at Denmark as an isolated system the import and export of electricity is not possible. Therefore if the electricity production surpasses the consumption the electricity production is restricted and the wind turbines are stalled. The excess electricity produced at times with lower electricity consumption can be utilised in an electrolyser to produce hydrogen. Hydrogen, an energy carrier, can store the excess electricity for times with lower production and higher consumption. Another utilisation of hydrogen is to upgrade raw biogas by produce pure methane which can be stored on the national gas grid.
Utilising hydrogen, as either a back-up or as an upgrading agent, allows for the use of excess electricity when running in island mode. Especially with an increased wind capacity, a storage medium can maintain the security of supply.

1.1 Purpose

The purpose of this paper is to identify the socioeconomic system cost of hydrogen integration into the Danish energy system. This paper examines two applications of hydrogen.

1. The use of hydrogen for power back-up
2. The use of hydrogen for Hydrogenation of raw biogas in the Sabatier process

This paper evaluates, through a socioeconomic analysis, the usage of pure hydrogen or upgraded biogas as a back-up opportunity in an isolated Danish energy system.

1.2 Report Structure

The figure below shows the general work flow of this paper. Initially the problem was defined so that the data could be gathered.

Afterwards scenarios could be constructed in EnergyPRO which then could be used for socioeconomic- and sensitivity analyses. The scenarios construction were based on already made scenarios from the Danish Energy Agency, and simulated by EnergyPRO.

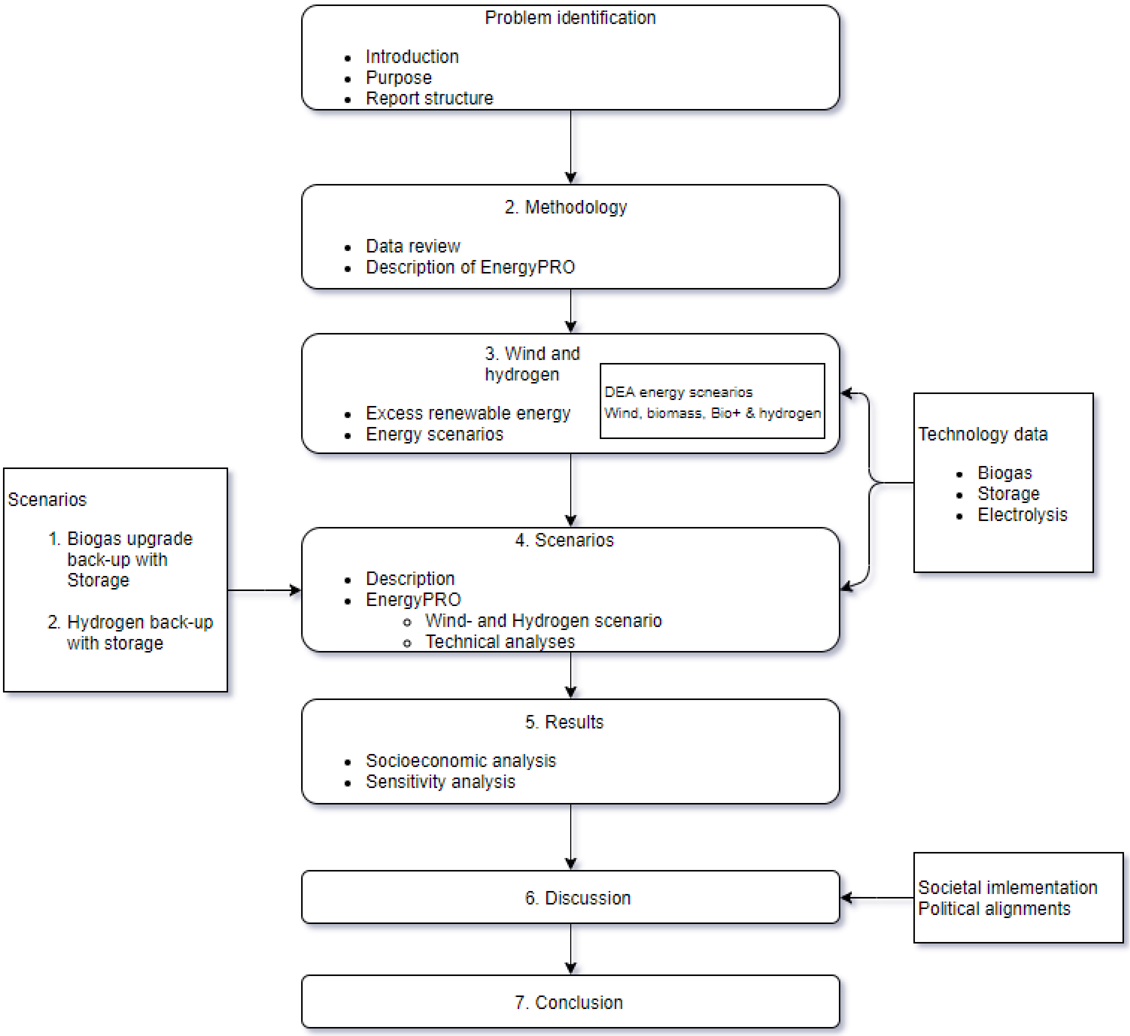

Figure 1: Flowdiagram of the structure of the paper

2 Framework

The scenarios of this project were based on the work of the DEA (*Energy scenarios towards 2020, 2035 and 2050*) [4]. Each scenario is briefly described in section 2.1. As more wind capacity is installed in the electricity system, the electricity production spikes from said turbines will increase. This increases the excess electricity produced which can then be used to produce hydrogen as either a power back-up or to hydrogenate raw biogas which can then be fed into the gas grid.

2.1 DEA Energy Scenarios

The five scenarios described in Energy scenarios are as followed wind, biomass, bio+, hydrogen and fossil. The fossil scenario have not been included because of the goals and incentives the Danish government have made for renewable solutions. As what goes for the last four scenario's it is difficult to say exactly where Denmark's energy system is headed but all the remaining DEA scenarios are challenged on the security of supply, in the wind -and hydrogen scenario it is because of the high usages of wind energy which has a high fluctuation of power productions. In the biomass -and bio+ scenario there is a much higher usages of biomass than the danish potential of 250 PJ, which means the rest of the biomass is imported. This makes the biomass and bio+ scenario impossible because of the simulation criteria. Because of those assessments the Wind -and Hydrogen scenarios were the focus in this paper. It is impotent to note that it is the development of the scenarios that were used, not the scenarios themselves [4]. Some production unit capacities of the wind and hydrogen scenario for 2035 can be seen in Appendix A.

3 Methodology

A part of the methodology was to isolate Denmark from the neighbouring countries, island mode, thus removing the electricity price dependency of the aforementioned countries and evaluate the system cost of a Danish energy system with power back-up.
The methodology used in this paper was conducted as a four step process:

1. Gather data on the energy production system as of 2014
2. Project the energy production for 2025, 2030, 2035 and 2040
3. Model the system in EnergyPRO
4. Perform sensitivity analysis

3.1 Data Input

The data used in this paper has been gathered from the DEA Wind -and Hydrogen scenarios and from the year the study was published, 2014. The data were then projected to estimate the capacities in 2025, 2030 and 2040 [4].

Data for photovoltaic cells, on- and offshore wind as well as other production units were estimated using data from Energinet.dk's analysis assumptions 2014 and the DEA's energy statistics 2014 as well as the capacities from the wind and hydrogen scenarios for 2035 and 2050 [5, 6].

The technologies were projected using Matlabs inbuilt curve fitting tool. Therefore, the projections were calculated using the following equations:

Exponential regression

$$Capacity = a \cdot e^{b \cdot Year} \text{ MW} \tag{1}$$

Linear regression

$$Capacity = a \cdot Year + b \text{ MW} \tag{2}$$

This allowed for the estimation of wind, solar and other production units in 2025, 2030 and 2040. The offshore wind- and the photovoltaic capacity followed an exponential curve from 2014 to 2050. The rest followed a linear regression, although those that did not follow a straight linear regression from 2014 to 2050 were spilt up into two parts, 2014 to 2035 and 2035 to 2050. This was done because there were no other trend line with an acceptable r^2 value.

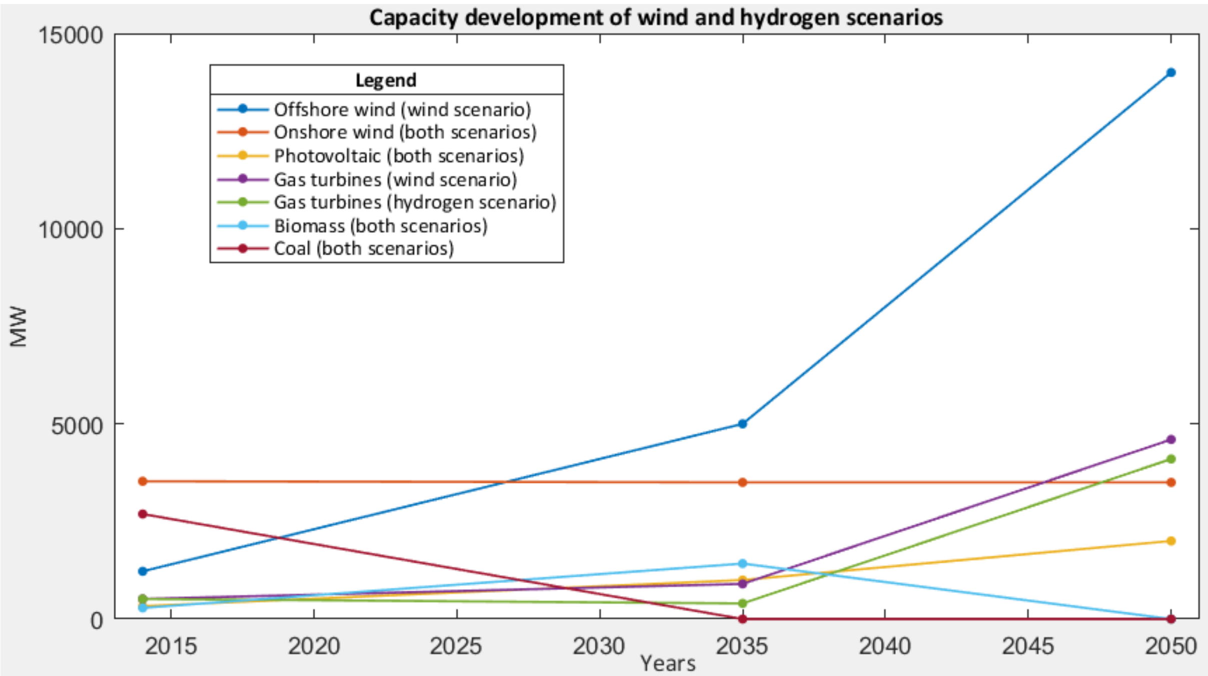

Figure 2: Projected development of electricity capacity

Figure 2 shows the capacity development of various production untis in the wind scenario from DEA, with the installed capacity of 2014 in DK1 [4].

Since this analysis only focus on the western part of Denmark, Jutland and Funen also designated DK1, all of the projected technology capacities for 2025, 2030, 2035 and 2040 needed to be approximated for DK1 only. According to analysis assumptions 2014 [5], Onshore and offshore wind capacities are divided approximately 70 and 30 % for DK1 and DK2 respectively. The same is true for photovoltaic panels. This was assumed for all years throughout all of the analysis. The wind capacity and solar capacity were therefore multiplied by a factor of 0.7. Using the same analysis assumptions from Energinet.dk, it was calculated that the total capacity for the other production units were split roughly 50/50 between DK1 and DK2. Therefore, production units such as biomass, natural gas, and coal were multiplied by a factor of 0.5. The calculated capacities for DK1 can be seen in Table 1.

	Wind				Hydrogen			
Technology ↓ year →	2025	2030	2035	2040	2025	2030	2035	2040
Offshore wind MW	1762	2480	3500	4915	2022	2879	4200	5950
Onshore wind MW	2459	2455	2450	2450	2459	2455	2450	2450
Photovoltaic MW	424	539	700	871	424	539	700	871
Gas turbine MW	354	400	450	1084	225	212	200	834
Biomass* MW	426	562	711	475	426	562	711	475
Coal CHP MW	649	329	0	0	649	329	0	0
Heat pumps MW_{heat}	163	237	325	166	166	245	325	1189
Biomass CHP MW_{heat}	836	953	1069	1760	836	953	1069	1760
Biomass CHP MW	669	762	855	1408	699	762	855	1408
Gas CHP MW_{heat}	1357	902	450	300	1285	790	300	200
Gas CHP MW	1086	751	360	240	1028	632	240	160
Solar heating km^2	1.25	1.60	19.44	19.44	1.25	1.60	19.44	19.44
Geothermal MW_{heat}	60	79.8	100	100	60	79.8	100	100

Table 1: Projected production capacities for 2025, 2030 2035 and 2040. * Biomass runs in condensation mode

The solar collector type was assumed to be HTHeatboost 35/10 [7]. Data for the solar collector can be seen in appendix B. The solar heating system uses relatively small amounts of electricity which was therefore excluded from this paper.

A heat storage has been used to increase the flexibility of the heating system. Although not all heat storages in DK1 has been included in this model, most of those in Funen and one in Jutland has been modelled [8, 9]. The heat storage was modelled as a steel storage tank with a 95% efficiency even though the heat loss is not modelled due the lack of information about the various storage tanks.

The electricity consumption of the years were estimated using the electricity consumption of 2017, gathered from ”Energi Data Service” [10]. Furthermore, the classical electricity consumption from the wind and hydrogen scenarios from 2035 and 2050 were used. From the data at ”Energi Data Service” it was deduced that the electricity split between DK1 and DK2 is roughly 65 and 35 percent respectively. Therefore, the classical electricity consumption from the DEA scenario were multiplied by a factor of 0.65. Figure 3 shows the load profile of 2025 hour by hour.

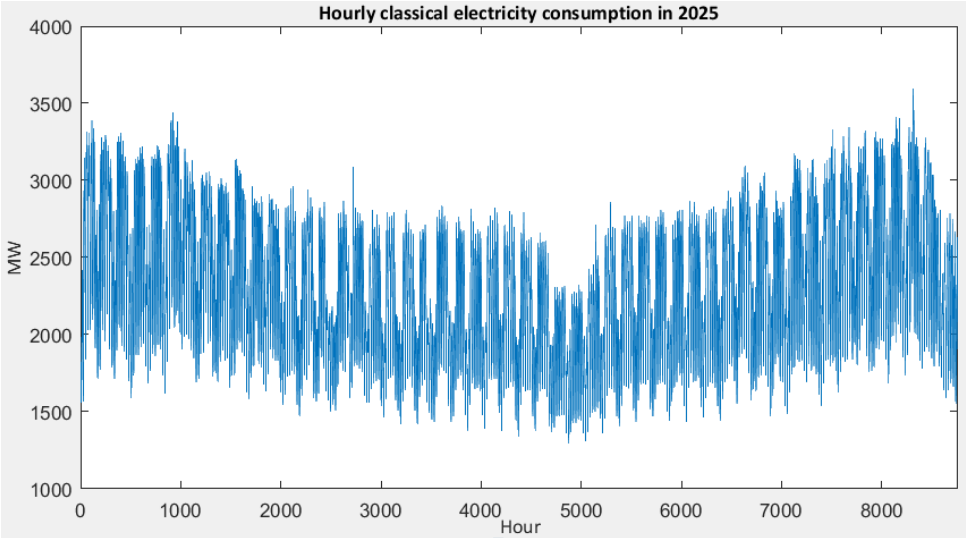

Figure 3: Yearly classical electricity consumption 2025

The classical electricity demand is the same for both the wind and the hydrogen scenario. Furthermore, the demand has the same shape for 2025, 2030, 2035 and 2040. Afterwards the electricity consumption of the electrolyser and sabatier process were added to ensure the correct electricity consumption.

The heat consumption for DK1 was found using the district heating consumption of the DEA scenarios and the heating consumption data from 2016 gathered from [11]. This provided the total consumption for the whole year. The whole consumption was the distributed using a general heat consumption curve for Odense.

$$\mathrm{HC}_{hour} = \mathrm{THC}_{future} \cdot \frac{\mathrm{HC}_{Odense,hour}}{\mathrm{THC}_{Odense,year}} \tag{3}$$

Here HC_{hour} is the hourly heat consumption of the future, THC_{future} is the total heat consumption of the future, $\mathrm{HC}_{Odense,hour}$ is the hourly heat consumption of Odense 2014 and $\mathrm{THC}_{Odense,year}$ is the total heat consumption of Odense in 2014.
As with the electricity consumption data, the heat consumption data were split between DK1 and DK2. The split was estimated to be 60 and 30 percent for DK1 and DK2 respectively. Figure 4 shows the load profile for heat consumption in 2025.

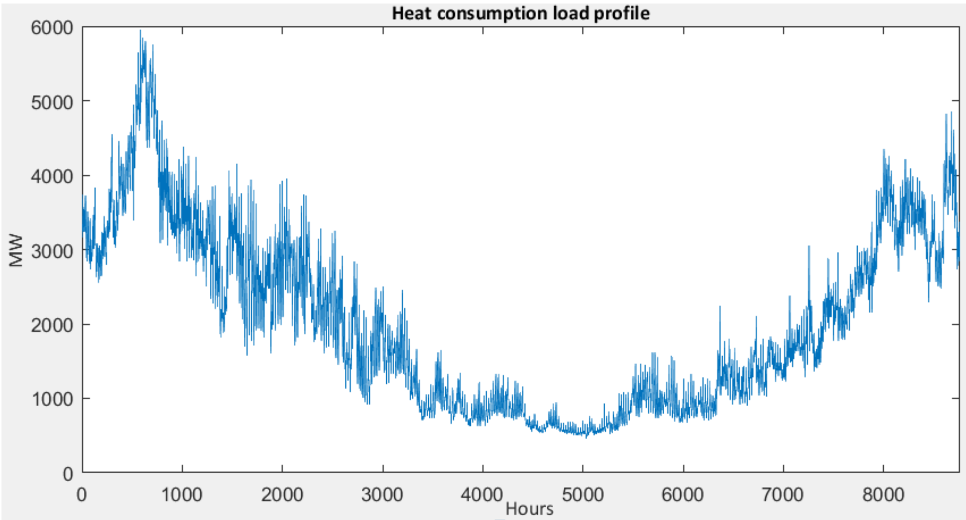

Figure 4: Heat load profile of DK1 in 2025

The individual heat production and the process heating are excluded from this paper. this was done because the heating of the system was not the main focus. It was only meant as supplementary to electricity production.

The upgraded biogas can be stored in the national gas grid. The cost of injecting the gas into the grid was estimated for three scenarios whereby the changes in gas production, pressure and the location from the injection site was varied [12]. The average cost of gas injection was 0.6 EUR_{2013} cents per kWh which was calculated to be 0.048 DKK per kWh.
The cost of storing hydrogen varies by storage method. In this paper the storage method used was gas tanks. The cost of storing hydrogen in tanks is about 550USD per kg. Multiplying with the dollar rate of 6.51 DKK per USD, the cost of hydrogen storage is 3,580.5 DKK per kg [13].

The investment cost and operation and maintenance cost, O&M, were found using the technology catalogues from DEA [14, 15, 16]. For the investment cost, operation and maintenance cost and the cost input of emission damages see Section 4.

It has been estimated that the Danish biogas potential is 48.6 PJ [17]. The amount of biogas used to produce the upgraded biogas was calculated as shown in equation 4:

$$\text{MWh biogas used} = \frac{\frac{(\text{kg SNG produced})\cdot 1.6}{4} \cdot 60\% \cdot 50\frac{\text{GJ}}{\text{ton}}}{40\% \cdot 3.6\frac{\text{GJ}}{\text{MWh}} \cdot 1000\frac{\text{kg}}{\text{ton}}} \tag{4}$$

Here 1.6 is the ratio of hydrogen input to methane output, 4 is the ratio of carbon dioxide to hydrogen in the input. 60 and 40 are the per centages of methane and carbon dioxide respectively.
The calculated biogas needed was added with the raw biogas used as fuel for biogas CHP to find the total amount of biogas used.

3.2 Power Back-up

As stated in 2.1 the wind and hydrogen scenario from the DEA study are both challenged on the security of supply. Therefore, investing in power back-up if Denmark were to move in either of these two directions would be a good idea. In the DEA study the excess electricity is exported to the neighbouring countries. One big recipient of this excess electricity would be Norway due to their large amount of water reservoirs.

3.2.1 Hydrogen as Power Back-up

Price of storage of hydrogen has been found using the roadmap from the European Association for Storage of Energy and European Energy Research Alliance ,EASE and EERA, [13]. They were given in Dollars pr kg, thus the price was multiplied with the dollar factor from ens.dk *samfundsøkonomiske analyseforudsætninger* [18].

Instead of selling of the excess electricity of wind and solar, as per usual, the utilisation of electrolysis could be beneficial to produce hydrogen which can be stored and used to produce electricity when the electricity production is low.
Hydrogen can be used as an energy carrier, which means that electricity is stored as chemical energy [13]. The hydrogen is produced by splitting water in an electrolyte, which will be further described in Section 3.2.1.1. In this paper the calorific value of hydrogen used is 120 MJ/kg [19].

When utilising hydrogen as a power backup, a great amount of storage is needed due to the low volume density. so in order to store the hydrogen it is often under a lot of pressure. Some storage options are gas tanks with a pressure of 350 and 700 bars. Other options include cryogenic storage and storage in solid state materials [13].

Figure 5 shows a system drawing of the utilisation of excess electricity production from wind turbines. Since the wind turbines are an intermittent production source, storing the excess produced electricity in an energy carrier, like hydrogen, instead of either stalling the turbine blades, making the turbines produce less electricity, or simply selling the electricity to the neighbouring countries whom all have their own electricity production.

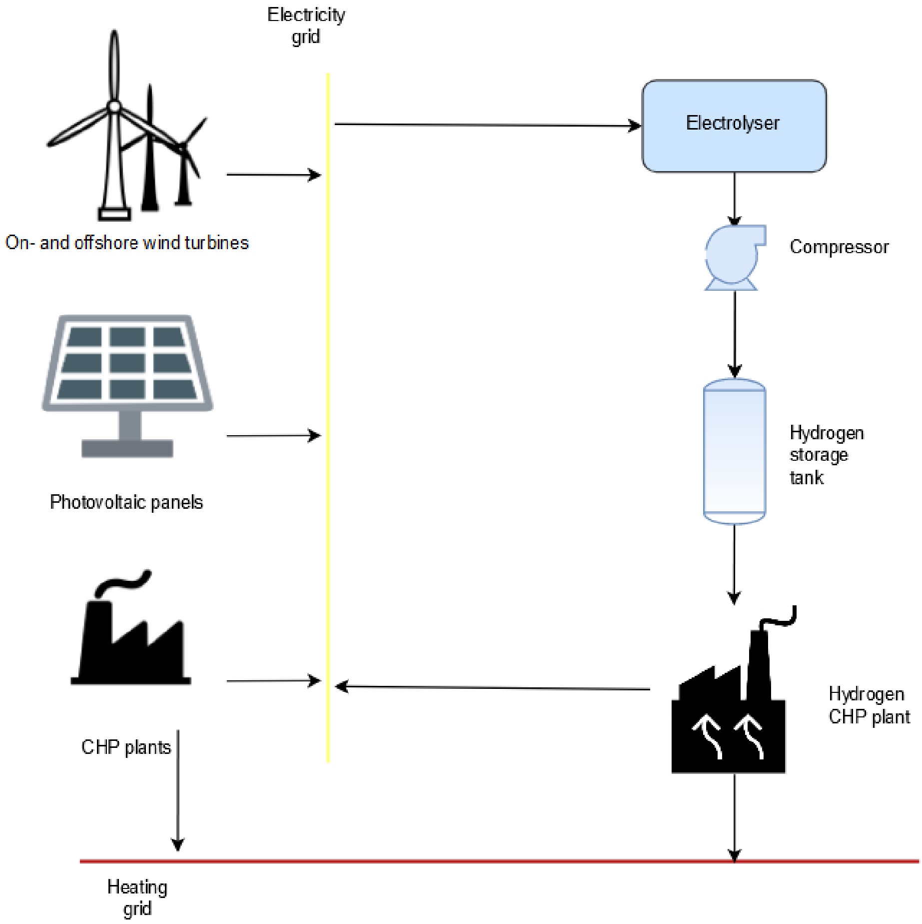

Figure 5: System drawing of hydrogen production and storage from excess electricity production

3.2.1.1 Electrolysis

As mentioned before, hydrogen is produced by splitting water using an electrolyser. By submerging an anode and a cathode in water thereafter a current is send through, the water is split into hydrogen and oxygen. Both partial and the full reaction can be seen below.

Cathode reaction:

$$2H^+_{(aq)} + 2e^- \rightleftharpoons H_{2(g)}$$

Anode reaction:

$$2H_2O \rightleftharpoons O_{2(g)} + 4H^+_{(aq)} + 4e^-$$

Full reaction:

$$2H_2O \rightleftharpoons 2H_2 + O_2$$

The current efficiency for an electrolyser is about 60 to 70 percent [13, 20]. Exothermic electrolysis could be more economically attractive since the heat produced could be fed into the heating grid. Electrolysis of water can be either a endothermic or exothermic reaction, it depends on the voltages used for the splitting [21].

3.2.2 Synthetic Natural Gas as Power Back-up

Another usage of hydrogen is to produce pure methane, which is called synthetic natural gas or substitute natural gas, SNG. This is done by adding the hydrogen to raw biogas, where the hydrogen reacts with the carbon dioxide in the biogas. This process is called methanation through hydrogenation. The produced SNG has a purity level of 98 per cent. Figure 6 shows a system drawing of hydrogen production and biogas upgrade using the produced hydrogen.

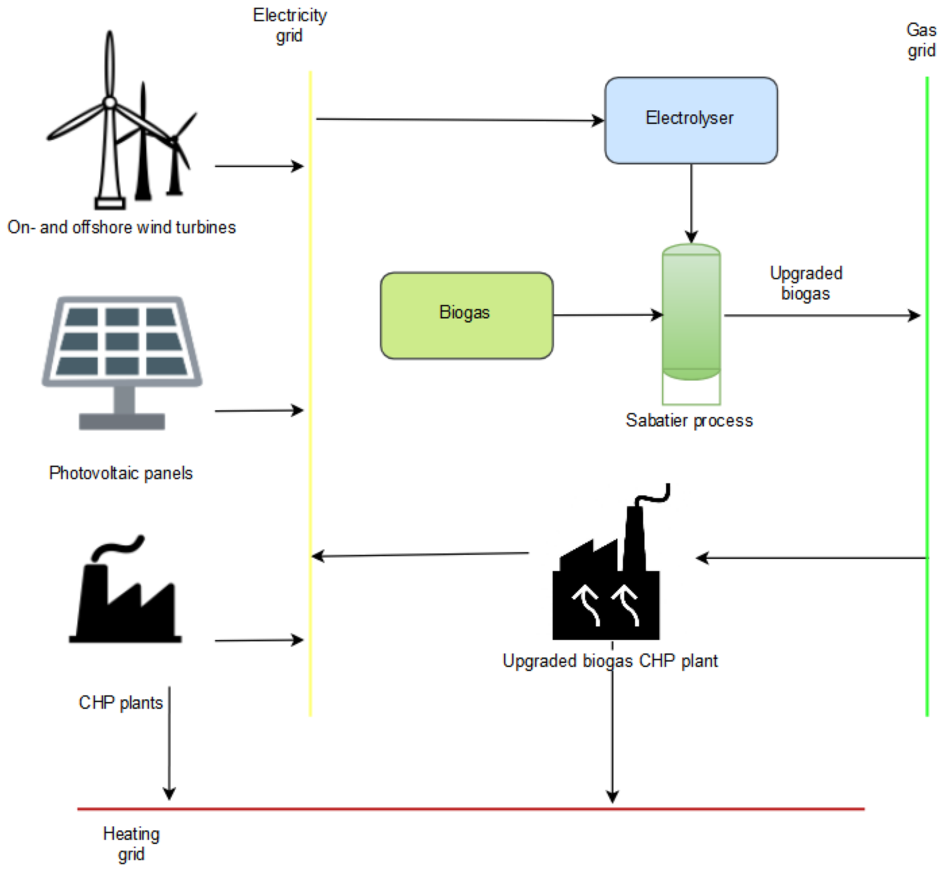

Figure 6: System drawing of biogas upgrade using hydrogen through sabatier process

By upgrading the biogas, it can be conveniently stored on the natural gas grid [22]. The raw biogas can be stored in the Danish natural gas grid for a few days, whereas upgraded biogas can be stored for a longer period; a few months [23]. This allows for greater flexibility for stored electrical energy.

3.2.2.1 The Sabatier process

The reduction of CO_2 with H_2 can be conducted chemically, based on Sabatier reaction. The Sabatier process combines hydrogen with carbon dioxide to produce methane with water as a bi-product. The reaction can be seen below [24].

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

It is a chemical hydrogenation process with various catalysts, where Nickel and Ruthenium are the most commonly used in industrial applications. Due to a high selectivity, complete conversions of CO_2 and H_2 could practically be achieved. One minor drawback is the high initial heat demand needed for the process which is only needed once because the Sabatier process is exothermic [25, 26].

3.3 EnergyPRO

To simulate the scenarios and the danish energy system, in island mode for the years in question, a simulation and modelling software has been used, EnergyPRO. EnergyPRO is a virtually modelling software for combined techno-economic optimisation and analysis of heat, CHP, process and cooling related energy projects. as mentioned in Section 2.1 the development of the Wind -and Hydrogen scenarios from DEA will be used to generate the simulations.
In the EnergyPRO scenarios, onshore and offshore wind farms, Photovoltiac cells, Coal -, Biomass -, and natural gas CHP plants, Biomass and natural gas units in condensation mode, Geothermal, Flat Plate Solar Collector and Compression Heat Pumps were added which is the base line of the operation units. This was the same for both back-up scenarios, the difference is how the produced hydrogen were used.

Throughout the scenarios some assumptions were made. The biomass CHP unit is a combination of all the biomass units of the DEA report to make a more simplified simulation, furthermore, waste incineration were modelled along side the biomass. The wind speeds of on- and offshore wind were assumed to be from Vejle and Anholt respectively. These wind speeds were the same for all the simulated years.

3.3.1 Hydrogen Storage and Back-up

The *Hydrogen Storage and Back-up* scenario used the excess electricity production from wind and solar to produce hydrogen that is stored in storage tanks, to be used later as back-up when the wind production is low and the electricity consumption was not met.

3.3.2 Upgraded Biogas Back-up

The *Upgraded Biogas Back-up* scenario used the excess electricity production from wind and solar to produce hydrogen that was used to produce methane which were stored in the gas grid for later use when the wind production is low and the electricity consumption was not met.

3.3.3 Operation strategy

The operation strategy determines how the simulation should be run, the lower the priority number the higher the priority the unit had. The on- and offshore wind turbines, Photovoltaic cells, Compression Heat pumps, geothermal and Flat Plate all have priority number 0 which makes the simulation run those production units first. The electrolyser and the Biogas CHP for burning the produced methane had the priority number 1 and

2 respectively, all other CHP plants had priority number 3, that goes for Coal, Biomass and Natural gas. The last priority number used is 9 and was used for Production units in condensation mode which is Biomass Con and Natural gas engine. A figure of the priority numbers can be seen in appendix D.

For units where a consumption is associated with it, a strategy for those units was made. The electrolysis, has a consumption associated with it which is electricity, that electricity came from the excess Wind- and solar power. In order to be certain the electricity used in the electrolysis is from the wind and solar its consumption priority number should be the same or below the operation priority numbers of wind turbines and photovoltaic cells, therefore the priority number for the consumption strategy is 0 for the electrolysis, compression heat pumps and geothermal plants, and 1 for the Biogas. A figure of the consumption strategy can be seen in appendix D.

4 Socioeconomic Analysis

The socioeconomic analysis was conducted in accordance with the guidelines provided by the DEA [27]. Therefore, the investment cost, O&M as well as the negative environmental effects were calculated for each technology using the technology catalogues and socioeconomic calculation prerequisites [14, 15, 16, 18]. The prices for investment and the O&M listed in the technology catalogues from the DEA, are listed in euros. Therefore, a conversion factor of 7.44 DKK/EUR was used. The fuel prices that were used when calculating the total system cost in EnergyPRO can be seen in Appendix E
Furthermore, all prices are calculated in 2018 prices using the assumed inflation rates from the socioeconomic calculation prerequisites [18].

4.1 Emissions

By burning these fuels, particles in the form of gases are emitted. These gases are damaging to the environment, animals and humans, therefore, the damages has to be rectified by economic penalties. In order to include the damage cost of said emissions, it is necessary to know how much is emitted. Equation 5 shows how the emissions of various fuels were calculated.

$$\text{Emission } \frac{\text{g}}{\text{kg of fuel}} = \text{emission factor } \frac{\text{g}}{\text{GJ of fuel}} \cdot \text{Calorific value } \frac{\text{GJ}}{\text{kg of fuel}} \tag{5}$$

Most calorific values for the fuels were given in socioeconomic calculation prerequisites and the heating value of biogas was found in and online database [18, 28]. The emissions from the various sources can be seen in Appendix E.

Table 2 shows the price of the damage particles emitted in DKK per kg emission. SO_2, NO_x and $PM_{2.5}$ where given in 2017 prices for larger incineration plants. They were projected to 2018 prices to a factor of 1.02. The CO_2 quota price was divided by 1000 in order to have the price in DKK per kg emitted CO_2. For the N_2O price, the price of CO_2

outside the quota system was divided by 1000 and multiplied by 298. Similarly the CH_4 was again the price outside the quota system, then divided by 1000 and multiplied by 25 [18]. Both the N_2O and the CH_4 were multiplied by 298 and 25 respectively in order to make the emissions CO_2 equivalent. This is due to N_2O and CH_4 being more potent.

Damage price DKK/kg	
SO_2	10.2
NO_x	7.14
$PM_{2.5}$	23.46
CH_4	1.071
N_2O	12.77
CO_2 (Quota)	0.042

Table 2: Damage prices of emissions in DKK per kg of emission

The damage prices and the emissions by the various sources were used to calculate the overall cost of the negative externalities by burning fuels.

4.2 Technologies

The technologies used in this paper represent the aggregated production technologies in DK1. Among the technologies used are: coal fired CHP, natural gas- and biogas simple cycle CHP as well as biomass. The calorific value of the biomass fuels is assumed to be wood chips, because of wood made up the most of the biofuels and the average calorific values was 11.98 GJ per ton. Here all the biomass fuels were modelled as wood chips. This was due to wood chip made up the most used biomass fuel the biomass also included waste incineration as a biomass as well [18].

Equation 6 shows the general method of calculating the investment cost of the production units used in the EnergyPRO simulations.

$$\text{Investment}\ \frac{\text{DKK}}{\text{MW}} = \text{Investment}\ \frac{\text{M EUR}}{\text{MW}} \cdot 7.44\ \frac{\text{DKK}}{\text{EUR}} \cdot \text{IR} \cdot 10^6 \tag{6}$$

Where IR in the inflation rate.
The O&M, of the technologies were calculated using equation 7.

$$\text{O\&M} = \left(\frac{\text{O\&M}_{fixed}\frac{\text{EUR}}{\text{MW}\cdot\text{Year}} \cdot 7.44\ \frac{\text{DKK}}{\text{EUR}}}{\text{full load hours}\frac{\text{h}}{\text{year}}} + \text{O\&M}_{variable}\frac{\text{EUR}}{\text{MWh}} \cdot 7.44\ \frac{\text{DKK}}{\text{EUR}}\right) \cdot \text{IR} \tag{7}$$

Where IR is the inflation rate, Full load hours are assumed to be about 4000 hours for most units and 6000 for some units in accordance with [14]. For on- and offshore wind, the full load hours used were 3150 and 4400 hours respectively. For photovoltaic panels the full load hours are assumed to be 1080 hours per year [15].

The investment and O&M costs of 2025 are shown in table 3.

Technology	Capital investment DKK/MWh	O&M DKK/MWh
Coal fired power plant	14,622,190	81.8
Natural gas turbine	6,649,985	88.9
Bio gas turibine	6,649,985	391.0
Biomass CHP	17,499,962	133.9
Biomass Condensation	17,499,962	133.9

Table 3: Capital investment- and O&M cost of used technologies in 2025

These investment and O&M costs does not change much over the years simulated. Therefore, only the costs of 2025 are shown here.

5 Results

5.1 Wind Scenario Development

Through the socioeconomic analysis the following results of the simulated back-up scenario for the years in question were obtained and can be seen in Figure 7.

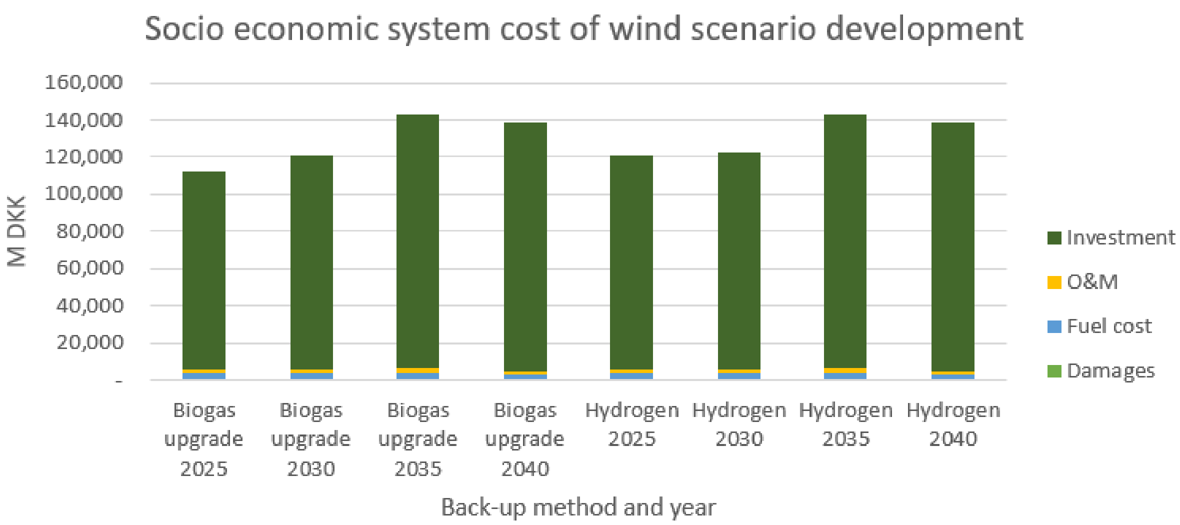

Figure 7: System cost of back-up methods with DEA's wind scenario development

As it can be seen, the system cost of biogas upgrade back-up system ranges from about 110 billion DKK to 140 billion DKK. The hydrogen back-up system is slightly more expensive with a range from almost 120 billion DKK to about 140 billion DKK. Furthermore, it can be seen that the investments constitute most of the system cost, while O&M-, fuel- and damage costs constitute only a fraction of the total system cost.

The average total system cost of the biogas upgrade back-up method is 128,656 million DKK, while the hydrogen back-up method is 131,237 million DKK.

The average damages of the biogas upgrade back-up was 311 million DKK, while the hydrogen back-up method had 248 million DKK in damages. The fuel cost of both back-up methods were roughly equal at 3,442 and 3,456 million DKK for biogas upgrade and hydrogen respectively. Furthermore, the O&M cost of both back-up methods were 1,883 and 2,032 million DKK for the biogas upgrade and hydrogen respectively. The exact cost of damages, fuel, O&M and investment can be seen in Appendix G.

The minimum SNG needed to be produced in the wind scenario development for the system, to have a full back-up, can be seen in Table 4

Back-up method and year	ton SNG needed	ton SNG produced
Biogas upgrade 2025	93,669	99,460
Biogas upgrade 2030	59,961	66,867
Biogas upgrade 2035	36,429	40,665
Biogas upgrade 2040	5,418	6,978

Table 4: SNG requirements of wind scenario development

The biogas used for upgrade and for direct use were on average 1.61 PJ of biogas ranging from 2.98 to 0.21 PJ in 2025 and 2040 respectively.

The amount of hydrogen needed and produced for the hydrogen back up can be seen in Appendix C.

In order to produce the hydrogen needed for the SNG production, from the biogas upgrade back-up method with the wind scenario development, the electrolysers capacity was 1200, 350, 150 and 20 MW in 2025, 2030, 2035 and 2040 respectively.

5.2 Hydrogen Scenario Development

Figure 8 shows the socioeconomic cost divided into investment-, fuel-, O&M- and damage cost by back-up method and year.

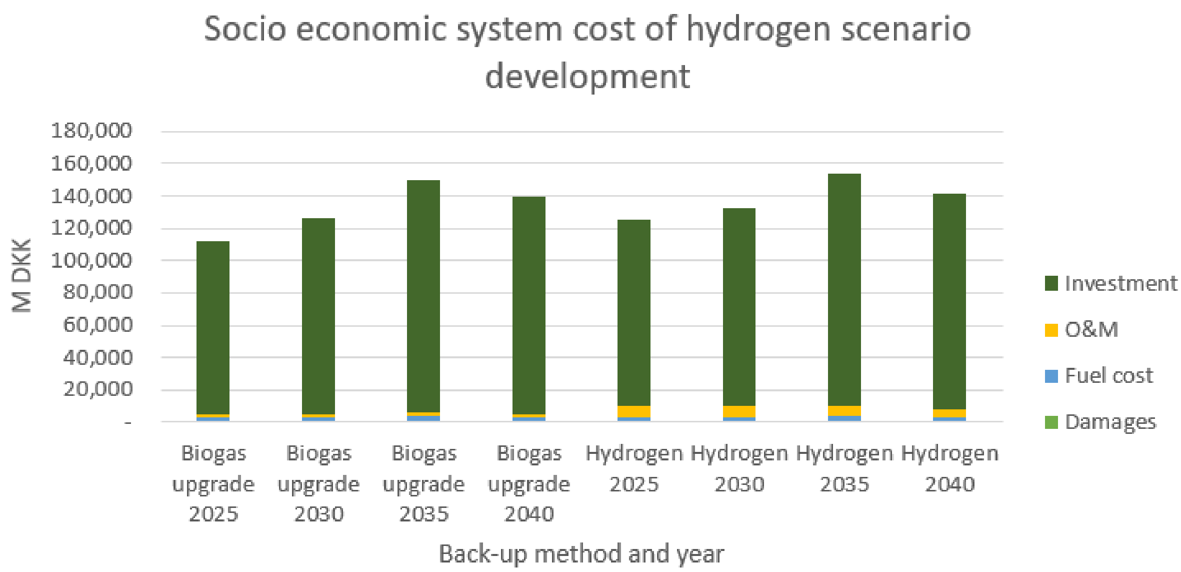

Figure 8: System cost of back-up methods with DEA's hydrogen scenario development

For the hydrogen scenario development, the ranges for biogas upgrade back-up is 110 billion DKK to almost 150 billion DKK. The hydrogen back-up ranges from 120 billion DKK to 150 billion DKK.

The average total system cost of the biogas upgrade back-up method is 131,784 million DKK, while the hydrogen back-up method is 138,466 million DKK.

The average damages of the hydrogen back-up method was 208 million DKK while the biogas upgrade back-up method had 206 million DKK in damages. The fuel cost of both back-up systems were closer than the fuel cost when the wind scenario development, of 3,014 and 3,018 million DKK of fuel cost. Operation and maintenance cost of 2,064 and 6,162 million DKK average for biogas upgrade and hydrogen respectively. The exact cost of damages, fuel, O&M and investment can be seen in Appendix G.

The hydrogen system development with biogas upgrade back-up method used on average 2.4 PJ of biogas ranging from 3.57 to 1.17 PJ in 2025 and 2040 respectively.

The amount of SNG and hydrogen needed and produced for the two back-up scenarios for all the years in question can be seen in Appendix C

The hydrogen back-up method for both wind and hydrogen system development was unable to produce enough hydrogen for back-up in 2025, but was able in all other years.

6 Sensitivity Analysis

There are numerous uncertainties associated with modelling the future energy system, like the price of production, reimbursements possibilities, fuel- and investment cost. In the DEA scenario report it is stated that:

"If the Photovoltaic cells becomes 30 per cent cheaper, the capacity of the photovoltaic cells can be increased, in the scenarioes, without any additional cost associated with it." [4]

— Danish Energy Agency

As mentioned in section 3.1 the DEA scenarios were conducted in 2014. In figure 9, can the average wind and Solar PV auction prices be seen.

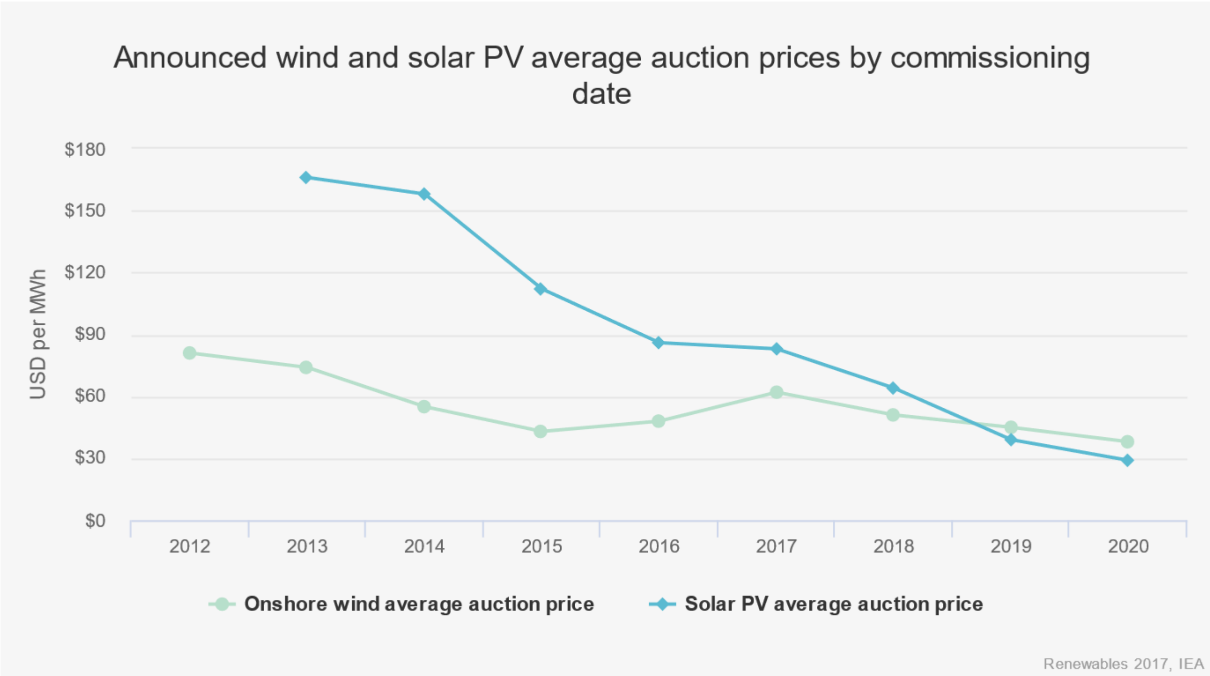

Figure 9: The average auction prices for Onshore wind and Solar PV by commissioning date

It can be seen that in 2014, when the scenarios were conducted, the average price per MWh solar PV is about 160 USD, and in 2020 it is down to 30 USD per MWh that is a decrease in price of 81,2 per cent which makes DEA's statement worth investigating and see how it affects the total system cost.

The sensitivity analysis was conducted by changing the production capacities of PV and on- and offshore wind. The PV capacity was increased to 6 GW in 2040 which is a estimate from Energinet.dks report but calculated for DK1 to be 4.2 GW [29]. In the two sensitivity scenarios, Sen-scenario, the on- and offshore wind capacities where decreased by 10 per cent to see the change in the total system cost.

The Sen-scenarios showed that the decrease of 10 per cent in offshore wind capacity was cheaper than onshore, therefore the offshore capacity was decreased again with 20 per cent. A comparison of the the cheapest scenario and 20 per cent less offshore wind capacity can be seen in the figure 10,

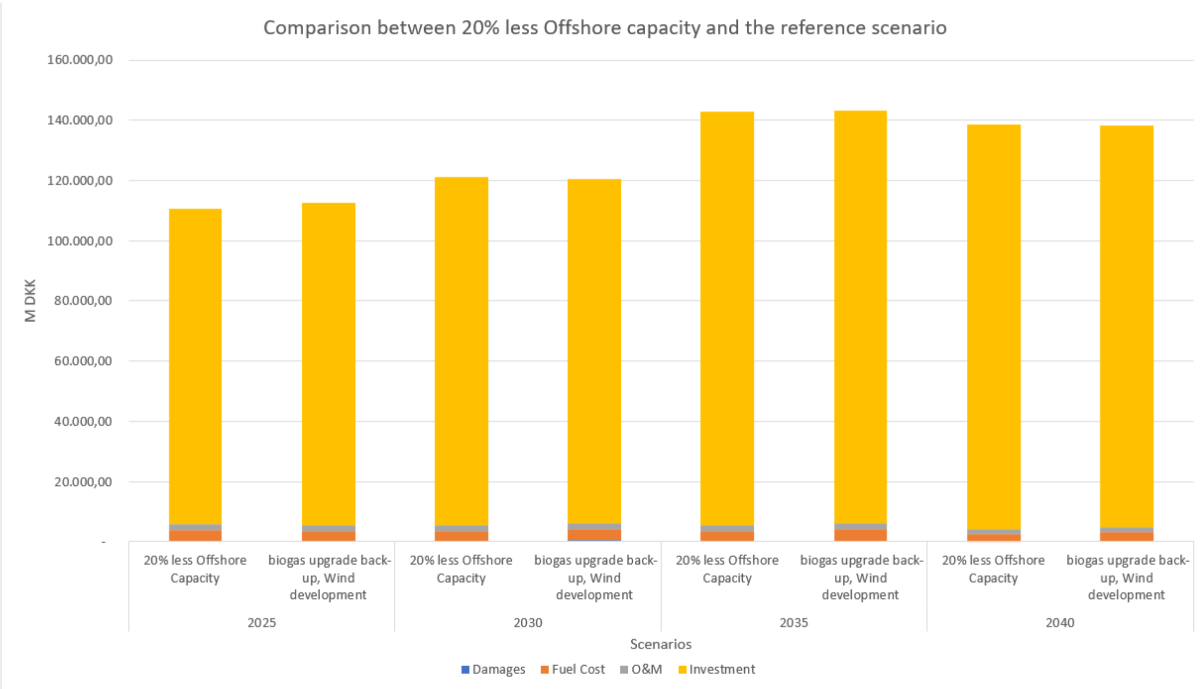

Figure 10: A comparison of the recommended scenario and the Sen-scenario with 20 per cent less offshore wind capacity

With the increase in PV to 4.2 GW in 2040, the offshore wind capacity can be decreased to be between 20 and 30 per cent before the SNG production would not be sufficient in 2025.

7 Discussion

It can be seen in section 5 that the wind scenario development with biogas upgrade method of power back-up is the cheapest solution while the second cheapest was the pure hydrogen back-up method for the same system development.

Although the overall damage costs are less with the hydrogen scenario system development, this is due to the higher share of offshore wind capacity in the system. As written in the DEA study the wind scenario has to increase the wind capacity with 400 MW per year while the hydrogen scenario has to increase that capacity even further.
Furthermore, due to this increase in offshore wind capacity for the hydrogen system development, the average fuel cost also decreases. However, both O&M- and investment cost increases.

The prices for PV's used in this paper are from the newest technology catalogue [15]. Therefore, the prices of PV system and the amount of PV installed in the regular scenarios possibly does not align. Hence, in section 6 the photovoltaic capacity was increased. With the increase in PV capacity, it was possible to decrease the amount of wind capacity in the system. It was cheaper to keep onshore wind and decrease the offshore wind, as expected. This is due to the higher investment cost of offshore wind turbines. Section 6 showed that a system with a decrease in offshore capacity by 20 per cent with the increased PV capacity was still able to provide power back-up. However, a decrease in offshore wind capacity by 30 per cent was not.

In section 5 it can be seen that the needed capacity of the electrolysis decrease as more and more renewable generation capacity is installed in the system. This happens because the renewable capacity is greater than the electricity consumption for an extended period of time.

Both hydrogen and upgraded biogas can be used for other technologies than power back-up. For example, it can be used in the transportation sector, which include cars, trucks, trains, ships and air planes. Although hydrogen is somewhat limited in the transportation sector compared to the upgraded biogas. The SNG can be used in forms of liquid natural gas and compressed natural gas.
It has been stated earlier that the Danish potential for biogas is 48.6 PJ and the biogas upgrade back-up methods used less than 2 PJ of biogas on average. This means that there are more than 46,8 PJ of biogas potential for the transport sector to utilise. It is stated by the Danish Gas Technology centre that the biogas production in Denmark is at 4 PJ per year in 2011 [30]. This number is for all of Denmark while the calculated biogas usage of the simulation only are for DK1. The biogas used directly for heat and power production were less than 0.004 PJ for all of the years calculated. It is doubt full that DK2 uses almost 4 PJ of biogas and therefore the biogas used in the simulation does not align with the use of biogas in Denmark. However, due to the small amount of biogas needed to produce enough for back-up for the system, there should still be plenty of biogas potential left.

Today, the transport sector alone is one fourth of the Danish greenhouse gas emissions and the Danish government climate goals for 2050 is to become 100 per cent renewable. But just in 2014 the *vejpersontransporten*, which only includes the cars and vans under 2 tonnes, emitted 7.2 M. tonnes of CO_2 which is almost half of the total emission of the transport sector [31]. If this goal should be met a drastic change needs to befall the transport sector. In which the implementaion of SNG would help with.

Hydrogen production from water also produces oxygen as a by-product. This poses a problem, economically, since there is no real market for oxygen [20]. If the hydrogen is used to upgrade biogas, the oxygen is no longer needed to react with the hydrogen to release the stored electricity. One obvious solution to the problem could be to let the oxygen out to the air. This will likely not have much of an effect since it will be such a small part of the oxygen already in the air.

Due to a lack of data the heat loss, for the storage units, was neglected. It was also not possible to include all the storage units in EnergyPRO, the main focus of this paper was the isolation of the Danish energy system, so we deemed it inconsequential.

As mentioned in Section 3 offshore wind and solar capacities followed an exponential curve. This was based on numbers from the DEA scenarios in which decommissioned wind farms have been taken into account. It should be kept in mind that the capacities of wind and solar in this paper are only estimations.

Biomass combined heat and power was assumed to be the aggregate of all biomass plants as well as the waste incineration plants which is mentioned in Section 3.3. This was done because the waste incineration plants uses waste in the form of discarded food among other waste. Furthermore, waste incineration plants usually receive money for burning the waste, which was not modelled in this paper.

The EnergyPRO simulations were not without problems. Even though there is enough back-up stored in the system and enough installed capacity, the simulation leaves out time periods were there is a shortage of electricity production. Therefore the needed hydrogen and upgraded biogas was calculated afterwards.

Wind speeds for onshore- and offshore wind production was assumed to be the same through all the simulated years and in two specific location, this assumption gave a misrepresented view of wind production in Denmark. When simulating wind productions, with more locations picked to calculate an average wind speed a lower level on uncertainty could be achieved and that way the data could achieve a higher level of confidence.

The full load hours for PV was assumed to be 1080 hours pr years as stated in Section 4.2. This is almost 200 hours more than the utilisation hour from the DEA study. However, the effects of this assumption is minimal compared to the total investment cost of the systems. Neither would it change which scenario would be the cheapest, since all the scenario has the same full load hours and the O&M cost are a DKK per MWh produced.

The capacity in Photovoltaic has increased more than the projected data since 2014 and Energinet.dk estimates that the installed PV capacity in 2040 will be 6 GW. The cause of this increase in the estimation is the price for installed MWh. The price is estimated to decrease by a factor of 2 every third year. If this trend continues, photovoltaic panels will then be cheaper in 2019 than onshore wind turbines.

Denmark is an electricity price taker which means the neighbouring countries, Norway, Sweden & Germany, are those that determine the electricity price. Denmark has a common price with one neighbouring country 90% of the time [32]. Therefore, Denmark is isolated in order to determine the socio economic aspects of the two back- up solutions for Denmark.
At the moment the electricity price is mainly effected by whether it is a dry or wet year as well as the coal price and the CO_2 quota price. It is unknown exactly how a power back-up system affects the energy system.

The Tesla mega battery in Australia has reduced the service cost of the electricity grid by 90%. A electricity storage system can provide stability to the system, decreasing the likely-hood for blackouts. Though it should be kept in mind that this is a lithium ion battery and, therefore, does not have the same limited efficiency of hydrogen production [33]. Australia had a high amount of renewable energy capacity in the region which caused instability [34]. It is unknown whether or not the same could or would occur in Denmark. Denmark has many interconnectors to the neighbouring countries, with two new interconnectors planned, Viking Link and COBRAcable. Viking Link is under construction and will connect to Great Britain and COBRAcable will connect with the Netherlands [35, 36]. These interconnectors perform almost in a similar fashion, e.g. through the Norwegian water reservoirs, by buying and selling electricity. However, since our neighbouring countries also move towards more renewable energy systems, their production becomes more intermittent as well. Therefore, having a storage solution within the Danish borders could prevent grid stability losses that could occur in the future.

In order to have a visual representation of the electricity and heat production as well as the hydrogen and SNG production depending of back-up method, sankey diagrams where created. These diagrams can be seen in Appendix F. From the diagrams it can be seen that it is only a small amount of electricity that is fed into the electrolyser. In the wind scenario development with a biogas upgrade back-up 4% of the electricity produced goes to electrolysis.

In this paper the capacities of production units were estimated using figures from 2014, yet the heat consumption data were from 2016 while the electricity consumption were from 2017. It was assumed that the electricity and heat consumption's have been relatively unchanged in their development since 2014.

EnergyPRO has the function to simulate in two different modes of operation strategy. One simulation mode is to simulate the production units according to the merit order. This means that the cheapest units are the first to produce. The other simulation mode is to simulate by a user defined strategy. Due to EnergyPRO's limitation on merit order simulation, meaning that fuel production cannot be included in this type of simulation, the simulations were run as user defined. This could make the production units deviate from the actual production order.

8 Conclusion

This paper examined the utilisation of hydrogen as power back-up in the Danish energy system. The focus was on the use of hydrogen directly or as a way to upgrade biogas. These uses of hydrogen were evaluated by socioeconomic analyses and sensitivity analyses on the technology composition.
The socioeconomic analyses were performed on four scenarios in order to determine the most cost efficient scenario that could be run in island mode.
The most cost efficient scenario were the biogas upgrade back-up method in the wind scenario development. The total system cost was 128,655.58 M DKK. Furthermore, the scenario showed that the SNG produced was only a fraction of the bio-SNG that is able to be produced. In addition, the scenario could provide further benefit to the transport sector by producing more hydrogen for SNG. The unused biogas potential for this scenario was 46.8 PJ meaning only 2 PJ were used.
The sensitivity analysis showed that with an increase in photovoltaic capacity and a decrease in offshore wind capacity by 20% has little effects on the total system cost.

It is therefore recommended that, if the Danish energy system were to utilise hydrogen as a means of power back-up, the hydrogen is used to upgrade biogas to SNG.

References

[1] "Danish Government". Energi forlig 2012. https://ens.dk/sites/ens.dk/files/EnergiKlimapolitik/aftale_22-03-2012_final_ren.doc.pdf, 22 March 2012.

[2] Energi forsynings-og klimaministeriet. Energi - til et grønt danmark. https://www.regeringen.dk/nyheder/energiudspil/, April 2018.

[3] "Danish Energy Ageny". Elforsyningssikkerhed i danmark. https://ens.dk/sites/ens.dk/files/energistyrelsen/Nyheder/2015/elforsyningssikkerhed_i_danmark_final_web.pdf, July 2015.

[4] Energistyrelsen. Energiscenarier frem mod 2020, 2035 og 2050. https://ens.dk/sites/ens.dk/files/Basisfremskrivning/energiscenarier_-_analyse_2014_web.pdf, 2014.

[5] Energinet.dk. Energinets tidligere analyseforudstninger. https://energinet.dk/Analyse-og-Forskning/Analyseforudsaetninger/Analyseforudsaetninger-2012-14, 2015. Accessed: 10-04-2018.

[6] Energistyrelsen. Energistatisk 2014. https://ens.dk/sites/ens.dk/files/Statistik/energistatistik_2014.pdf, 2015. Accessed: 10-04-2018.

[7] Acorn-Sunmark. Solar keymark certificate. [http://www.estif.org/solarkeymark/Links/Internal_links/SP/SC0841-14.pdf, 14-07-2016. Accessed: 15-04-2018.

[8] "EMD International A/S". Strategisk energiplan fyn den indledende kortlægning af fjernvarmenet og gasnet p fyn. http://www.energiplanfyn.dk/wp-content/uploads/2016/11/Indledende_kortl%C3%A6gning_infrastruktur.pdf, 29-10-2014.

[9] Sanne Wittrup. Her er verdens strste varmelager og solfanger. https://ing.dk/artikel/her-er-verdens-stoerste-varmelager-og-solfanger-171124, 26-07-2014.

[10] Energinet.dk. Energi data service. https://www.energidataservice.dk/, 07-03-2018.

[11] "Region Syddanmark" and "Danmarks statistik". Data2go.dk. http://data2go.dk.linux192.unoeuro-server.com/, 2018.

[12] Daniela Thrän, Eric Billig, Tobias Persson, Mattias Svensson, Jaqueline Daniel-Gromke, Jens Ponitka, Michael Seiffert, John Baldwin, Lukas Kranzl, Fabia Schipfer, Julian Matzenberger, Nathalie Devriendt, Mathieu Dumont, Jonas Dahl, and Günther Bochmann. *Biomethane: Status and Factors Affecting Market Development and Trade*. IEA Bioenergy, September 2014. pp.,.

[13] EASE and EERA. European energy storage technology development roadmap towards 2030: recommendations. https://www.betterworldsolutions.eu/wp-content/uploads/2016/11/EASE-EERA-ES-Tech-Dev-Roadmap-2030.x59522.pdf, March 2013.

[14] Eneristyrelsen. Technology data for energy plants. https://ens.dk/sites/ens.dk/files/Analyser/technologydata_for_energy_plants_-_may_2012_ver_mar2018.pdf, 2012. Accessed 28-03-2018. Updated: March 2018.

[15] Energistyrelsen. Technology data for energy plants for electricity and district heating generation. https://ens.dk/sites/ens.dk/files/Analyser/technology_data_catalogue_for_energy_plants_el_and_dh_-_aug_2016_update_march2018.pdf, 2016. Accessed 28-03-2018. Updated: March 2018.

[16] Energistyrelsen. Technology data for renewable fuels. https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_for_renewable_fuels_-_march_2018.pdf, 2017. Accessed: 28-03-2018. Updated: March 2018.

[17] Energistyrelsen. Biogas i danmark - status, barrierer og perspektiver. https://ens.dk/sites/ens.dk/files/Bioenergi/biogas_i_danmark_-_analyse_2014-final.pdf, February 2014.

[18] Energistyrelsen. Samfundsøkonomiske beregningsforudsætninger for energipriser of emissioner. https://ens.dk/sites/ens.dk/files/Analyser/samfundsoekonomiske_beregningsforudsaetninger_2017_ver_2.pdf, 2017. Accessed: 28-03-2018.

[19] Engineeringtoolbox. Fuel- higher and lower calorific value. https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html, 2003.

[20] Nancy E. Carpenter. *Chemistry of Sustainable Energy*. Taylor Francis Group, 6000 Broken Sound Parkway NW, Suite 300, Boca Raton, 2014. pp. 106.

[21] Marcelo Carmo Wiebke Lueke Martin Mueller Maximilian Schalenback, Geert Tjarks and Detlef Stolten. Acidic or alkaline? towards a new perspective on the efficiency of water electrolysis. http://jes.ecsdl.org/content/163/11/F3197.full.pdf+html, 31-08-2016. Accessed: 14-05-2018.

[22] D Matthew Ong, B. Robert Williams, and R. Stephen Kaffka. *Comparative Assessment of Technology Options for Biogas Clean-up*. California Biomasse Collaborative and University of California, Davis, 12 November 2014. pp. 28.

[23] Irini Angelidaki, Laura Treu, Panagiotis Tsapekos, Gang Luo, Stefano Campanaro, Henrik Wenzel, and Panagiotis G. Kougias. *Biotechnology Advances*, 36:452–466, 2018.

[24] Christian Dannesboe. Synergi mellem biogasopgradering og soec. http://pure.au.dk/portal/files/121739324/Presentation_Skive_Skandinaviens_Biogaskonference_2017.pdf, 7 November 2017.

[25] Panagiotis Tsapekos Gang Luo Stefano Campanaro Henrik Wenzel Panagiotis G. Kougias. Irini Angelidaki, Laura Treu. Biogas upgrading and utilization: Current status and perspectives. https://www.sciencedirect.com/science/article/pii/S0734975018300119, 11-01-2018. Accessed: 15-05-2018.

[26] Dennis Walsh Christian Junaedi, Kyle Hawley and Subir Roychoudhury. Compact and lightweight sabatier reactor for carbon dioxide reduction. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120016419.pdf, 17-06-2011. Accessed: 15-05-2018.

[27] Energistyrelsen. Vejledning i samfundskonomiske analyser p energiomrdet. https://ens.dk/sites/ens.dk/files/Analyser/vejledning_2005-rev2007.pdf, 2005. Accessed: 28-03-2018. Revised: 2007.

[28] New Zealand Digital Library. Engines for biogas: Energy content of biogas. http://www.nzdl.org/gsdlmod?e=d-00000-00---off-0envl--00-0----0-10-0---0---0direct-10---4-------0-1l--11-en-50---20-about---00-0-1-00-0--4----0-0-11-10-0utfZz-8-00&cl=CL2.9.1&d=HASH74f85bc0331b7141adcf66.7.2&gt=1, 1988.

[29] Energinet.dk. Solceller og batterier i danmark, version 2. https://energinet.dk/Analyse-og-Forskning/Analyser/RS-Analyse-Maj-2016-Solceller-og-batterier, May 1'st 2016. 28-05-2018.

[30] Torben Kvist. Status p biogas i danmark. https://www.dgc.dk/status-paa-biogas-i-danmark, June 2011.

[31] Klimarådet. Afgifter der forandrer. http://www.xn--klimardet-b3a.dk/da/rapporter/afgifter-der-forandrer, 06-2016. 31-05-2018.

[32] Energinet.dk. Hvad påvirker elprisen i Danmark? https://energinet.dk/Analyse-og-Forskning/Analyser/RS-Analyse-September-2016-Hvad-paavirker-elpriserne, 2016. Dok. 14/24552-14. Accessed: 15-04-2028.

[33] Fred Lambert. Tesla's giant battery in australia reduced grid service cost by 90%. https://electrek.co/2018/05/11/tesla-giant-battery-australia-reduced-grid-service-cost/, 11 May 2018. Accessed: 20-05-2018.

[34] Bjø rn Godske. Tesla færdiggør australsk megabatteri før tid. https://ing.dk/artikel/tesla-faerdiggoer-australsk-megabatteri-foer-tid-208801, 23-11-2017.

[35] "Energinet.dk". Viking link: Elforbindelse til storbritannien. https://energinet.dk/Anlaeg-og-projekter/Projektliste/Viking-Link, 2018.

[36] "Energinet.dk". Cobracable: Elforbindelse til holland. https://energinet.dk/Anlaeg-og-projekter/Projektliste/COBRAcable, 2018.

A DEA scenarios

2035		
	Wind	Hydrogen
Offshore wind	5000	6000
Onshore wind	3500	3500
Photovoltaic	1000	1000
Biomass	1421	1421
Gasturbines	900	400

Table 5: Electrical production capacitites unit in MW

B Solar collector data

HTHeatboost 35/10				
Incline	η_0	a1 [W/(m^2°C)]	a2 [W/(m^2°C)^2]	Kθ
38°	0.77	2.41	0.015	0.92

Table 6: Technical specifications for HTHeatboost 35/10

HTHeatboost specification used in EnergyPRO [7].

C Back-up production

Hydrogen scenario development with biogas upgrade back-up

Back-up method and year	ton SNG needed	ton SNG produced
Biogas upgrade 2025	114,306	119,014
Biogas upgrade 2030	85,062	86,546
Biogas upgrade 2035	70,429	74,974
Biogas upgrade 2040	33,296	38,877

Table 7: SNG requirements of Hydrogen scenario development

Hydrogen scenario development with hydrogen back-up

Back-up method and year	ton hydrogen needed	ton hydrogen produced
Hydrogen 2025	47,938	34,170
Hydrogen 2030	35,506	37,445
Hydrogen 2035	28,855	36,638
Hydrogen 2040	13,875	14,847

Table 8: Hydrogen requirements of hydrogen scenario development

Wind scenario development with hydrogen back-up

Back-up method and year	ton hydrogen needed	ton hydrogen produced
Hydrogen 2025	39,845	23,056
Hydrogen 2030	25,200	27,974
Hydrogen 2035	15,212	17,154
Hydrogen 2040	2,257	3,238

Table 9: Hydrogen requirements of wind scenario development

D EnergyPRO priorities

Tarif perioder	Prioritetsfunktioner
Offshore DK1	0
Onshore DK1_ G128 5MW	0
Photovoltaic Cells	0
Coal fired CHP	3
Biomass CHP	3
Natural Gas Turbine	3
Elektrolysis_Sabatier	1
Upgraded Biogas CHP	2
Biomass Con	9
Natural Gas engine	9
Compression Heat Pump	0
Geothermal	0
Flate Plate	0

Figure 11: Production Priority Numbers in EnergyPRO

E Fuel Price

Fuel prices 2018 [DKK/GJ]			
Year	Natural gas	Coal	Wood
2025	55.59	18.36	54.57
2030	68.65	19.58	56.61
2035	77.01	20.20	57.83
2040	80.58	20.50	59.06

Table 10: Fuel prices in 2018 prices

Emission [g/kg] by fuel	NO_x	$PM_{2.5}$	SO_2	CH_4	N_2O	CO_2
Woodchip	0.018	0.75	0.045	0.029	0.0074	0
Coal	0.24	0.70	0.051	0.022	0.020	2277.45
Natural gas	0.021	2.92	0.0053	0.053	0.053	3027.44
Biogas (raw)	0.32	3.32	0.0035	7.13	0.026	0

Table 11: Amount of NO_x, SO_2, $PM_{2.5}$ CH_4, NO_2 and N_2O emissions per kg fuel

F Sankey diagrams

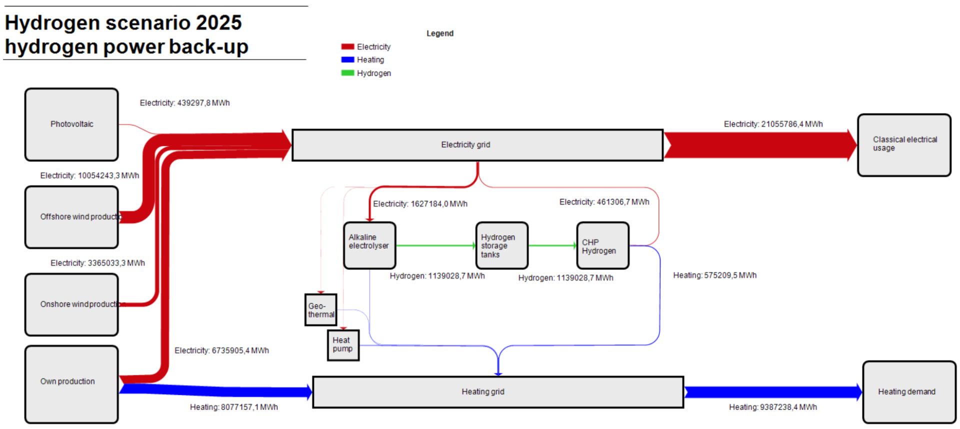

Figure 12: Sankey diagram showing the energy flow of hydrogen back-up method in hydrogen scenario development for 2025

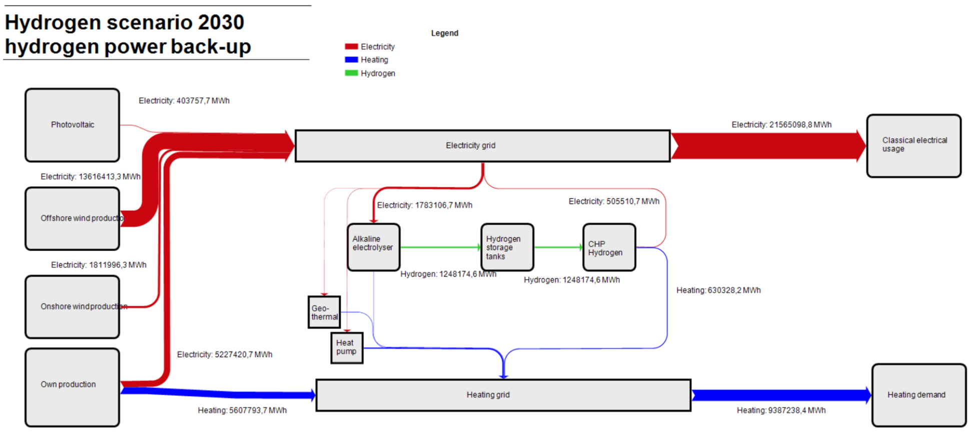

Figure 13: Sankey diagram showing the energy flow of hydrogen back-up method in hydrogen scenario development for 2030

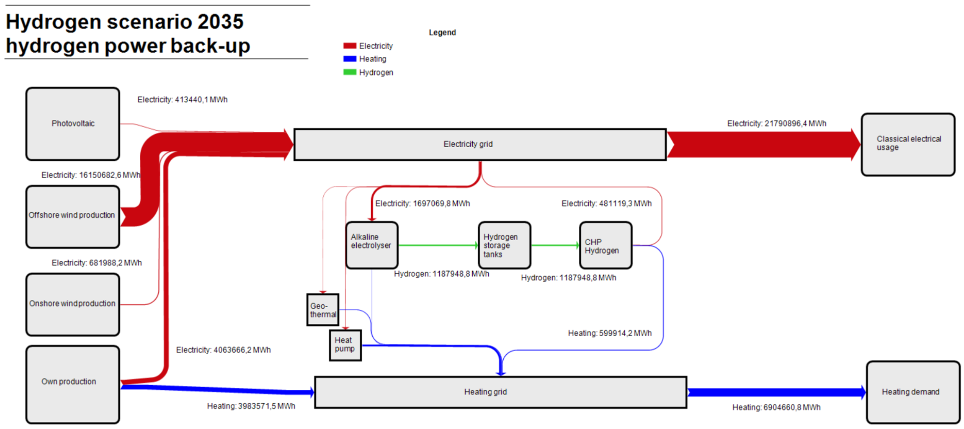

Figure 14: Sankey diagram showing the energy flow of hydrogen back-up method in hydrogen scenario development for 2035

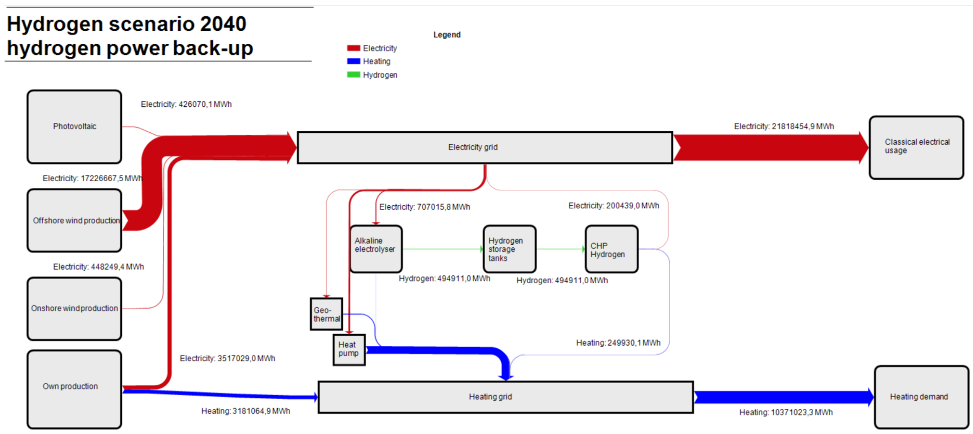

Figure 15: Sankey diagram showing the energy flow of hydrogen back-up method in hydrogen scenario development for 2040

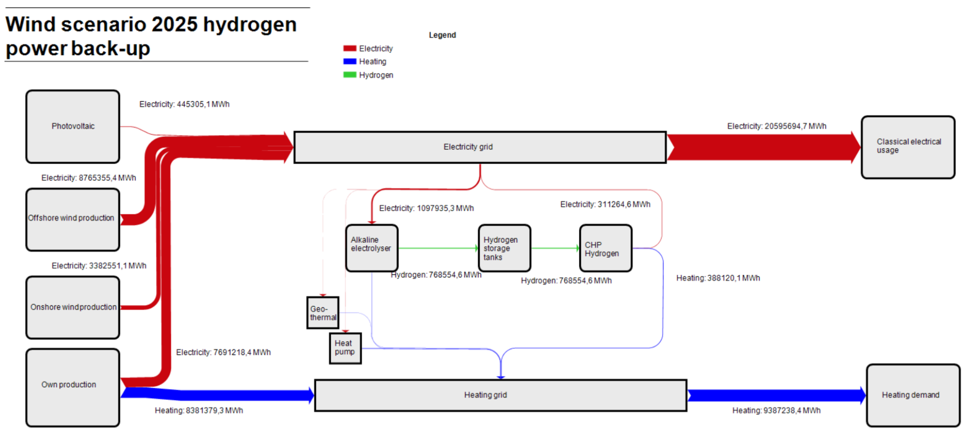

Figure 16: Sankey diagram showing the energy flow of hydrogen back-up method in wind scenario development for 2025

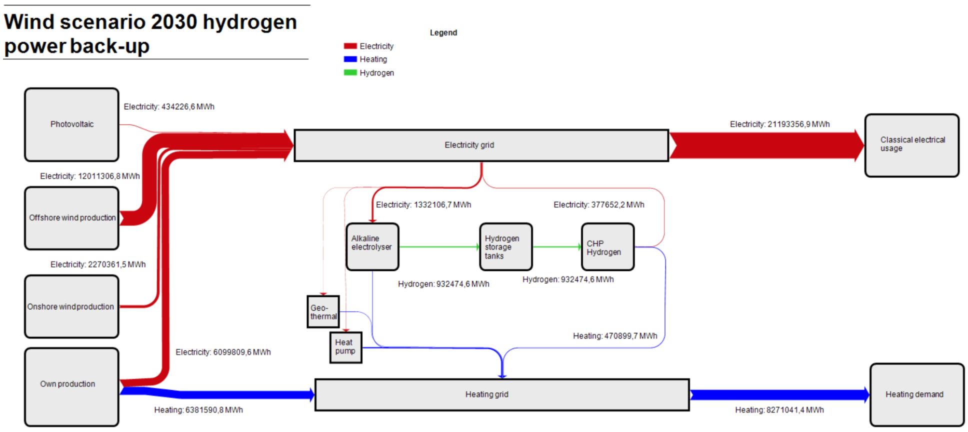

Figure 17: Sankey diagram showing the energy flow of hydrogen back-up method in wind scenario development for 2030

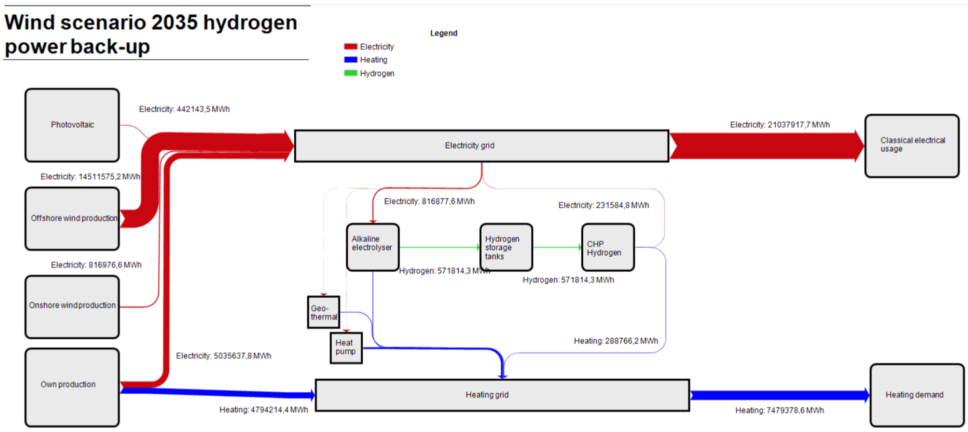

Figure 18: Sankey diagram showing the energy flow of hydrogen back-up method in wind scenario development for 2035

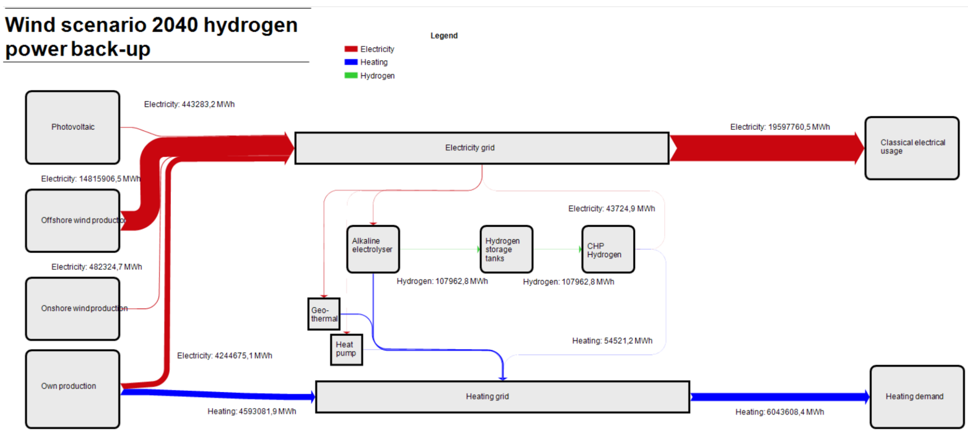

Figure 19: Sankey diagram showing the energy flow of hydrogen back-up method in wind scenario development for 2040

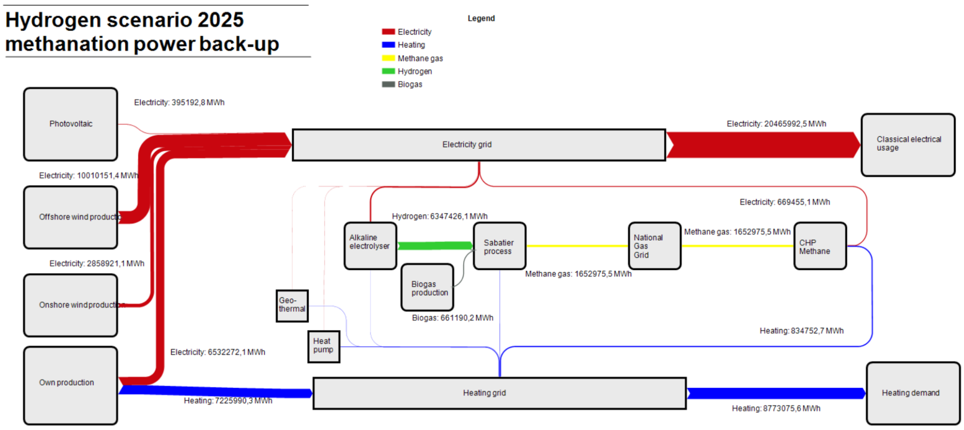

Figure 20: Sankey diagram showing the energy flow of biogas upgrade back-up method in hydrogen scenario development for 2025

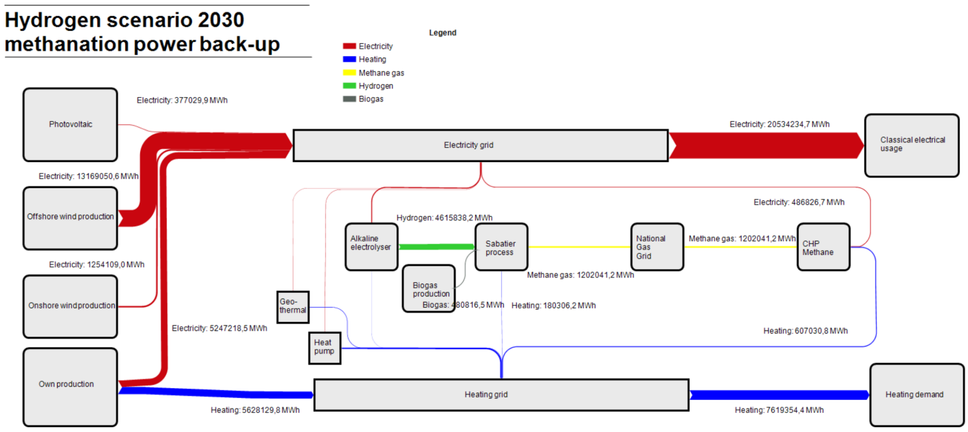

Figure 21: Sankey diagram showing the energy flow of biogas upgrade back-up method in hydrogen scenario development for 2030

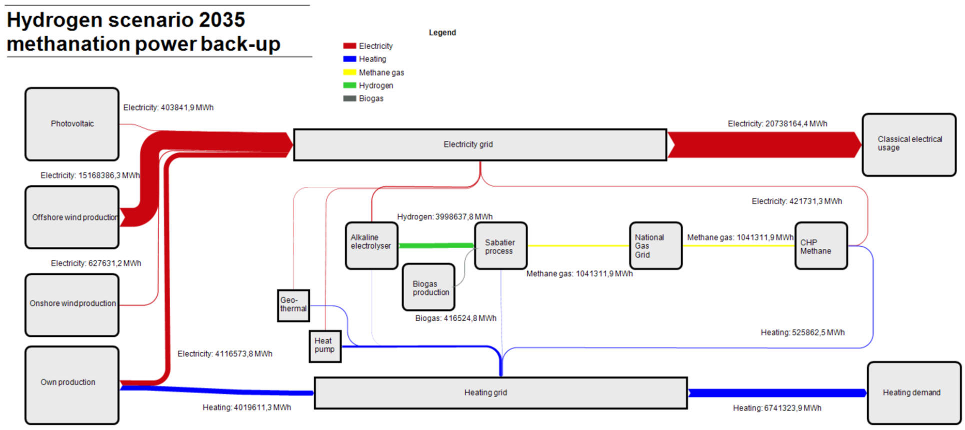

Figure 22: Sankey diagram showing the energy flow of biogas upgrade back-up method in hydrogen scenario development for 2035

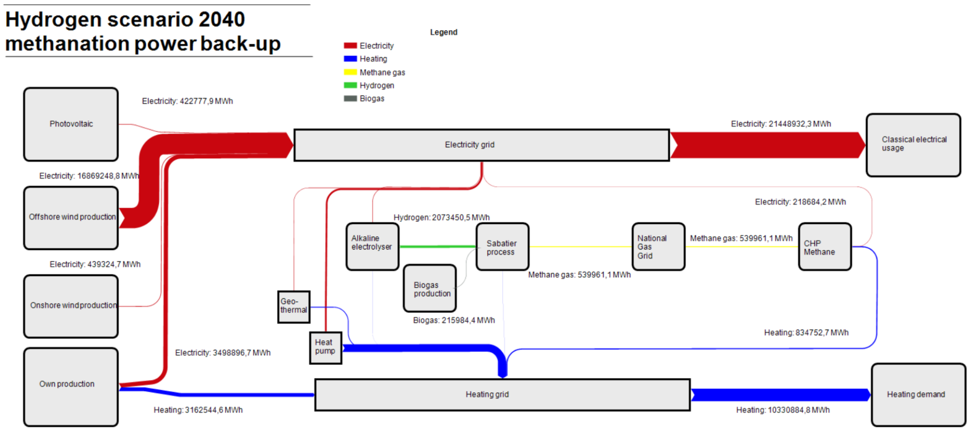

Figure 23: Sankey diagram showing the energy flow of biogas upgrade back-up method in hydrogen scenario development for 2040

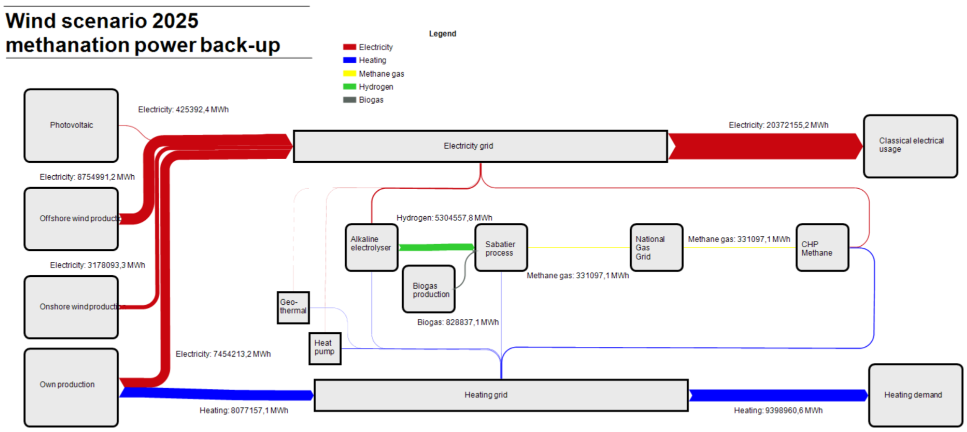

Figure 24: Sankey diagram showing the energy flow of biogas upgrade back-up method in wind scenario development for 2025

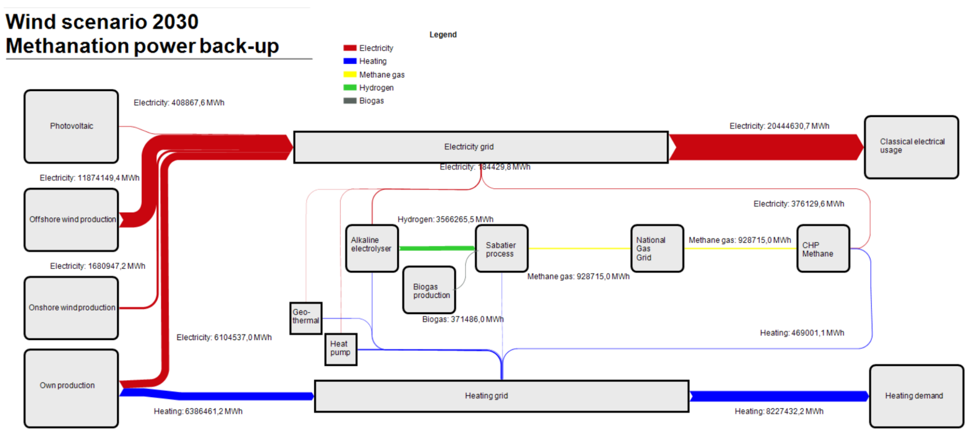

Figure 25: Sankey diagram showing the energy flow of biogas upgrade back-up method in wind scenario development for 2030

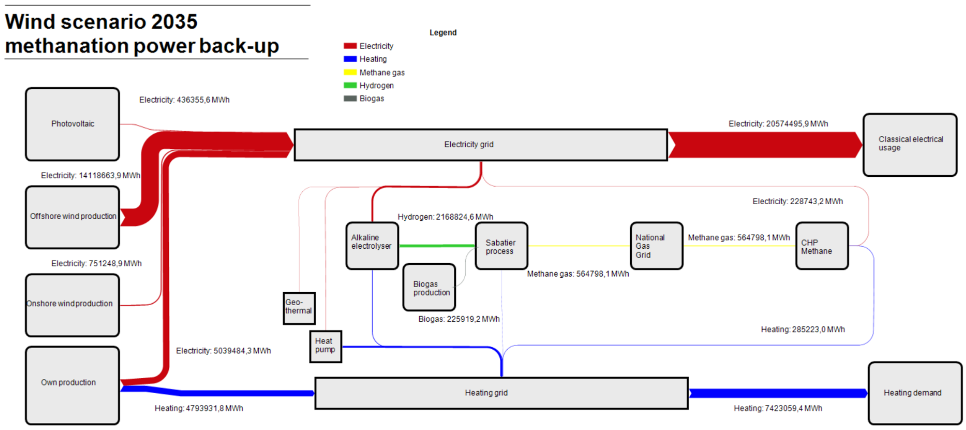

Figure 26: Sankey diagram showing the energy flow of biogas upgrade back-up method in wind scenario development for 2035

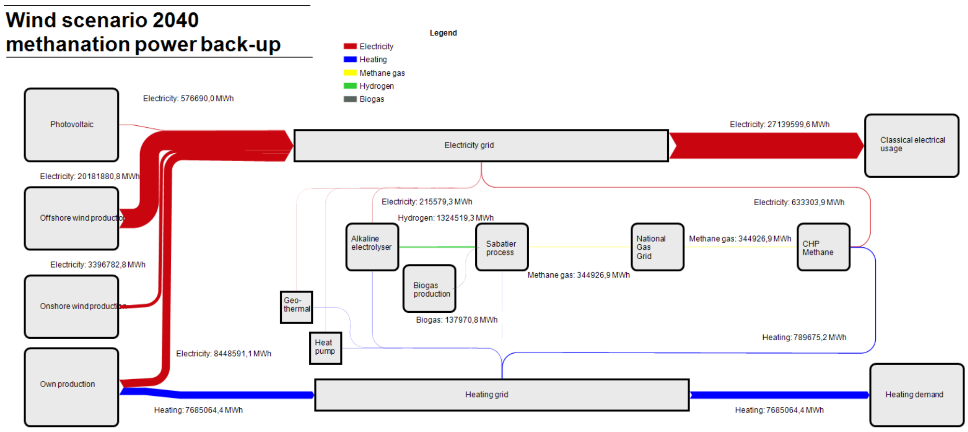

Figure 27: Sankey diagram showing the energy flow of biogas upgrade back-up method in wind scenario development for 2040

G Total system cost

Table 12: Hydrogen Scenario development

M DKK	Biogas Upgrade 2025	Biogas Upgrade 2030	Biogas Upgrade 2035	Biogas Upgrade 2040
Damages	327	239	156	101
Fuel cost	2,874	3,148	3,354	2,680
O&M	2,151	2,015	2,008	2,081
Investement cost	106,341	121,182	143,901	134,569
Total	111,694	126,587	149,421	139,433
M DKK	Hydrogen 2025	Hydrogen 2030	Hydrogen 2035	Hydrogen 2040
Damages	337	240	153	101
Fuel cost	2,941	3,132	3,304	2,692
O&M	6,297	6,654	6,542	5,153
Investement cost	115,665	122,681	144,153	133,812
Total	125,241	132,707	154,154	141,760

Table 13: Wind Scenario development

M DKK	Biogas Upgrade 2025	Biogas Upgrade 2030	Biogas Upgrade 2035	Biogas Upgrade 2040
Damages	377	545	200	122
Fuel cost	3,238	3,596	3,965	2,969
O&M	1,856	1,913	1,981	1,780
Investement cost	107,063	114,535	137,015	133,461
Total	112,536	120,5900	143,161	138,333
M DKK	Hydrogen 2025	Hydrogen 2030	Hydrogen 2035	Hydrogen 2040
Damages	388	273	199	129
Fuel cost	3,313	3,587	3,957	2,966
O&M	2,167	2,131	2,060	1,768
Investement cost	114,972	116,620	136,595	133,812
Total	120,842	122,613	142,813	138,677