Strategic Energy Planning of Funen, Denmark - System Perspectives for 2035 & 2050

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Energy Technology

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We hereby declare that the presented bachelor thesis '*Strategic Energy Planning of Funen, Denmark - System Perspectives for 2035 & 2050*' is written independently and without any other sources and aids than stated. Furthermore, we declare that we have cited each analogous applied passage.

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Abstract

This study investigates the prospects of adapting national energy system perspectives to the energy system Funen in 2035 and 2050, for the purpose of recommending an economically feasible roadmap towards a fossil free energy system.

In this report, models of the energy systems of 2016, 2035 and 2050 has been developed in EnergyPLAN and Excel, and these models are used to calculate the socioeconomic system costs.

The scenarios for the future energy systems are based on the Global Climate Action scenario from Energinet's *Systemperspektiv 2035*.

In this study, the system costs are used to compare the economic feasibility of each scenario in 2050. For the energy system of 2050, three scenarios have been investigated, to give a differentiated analysis of the system perspectives and all energy system balances has been presented in sankey diagrams.

The report focusses on the utilisation of excess heat from data centers, industrial processes and synfuel producing processes on Funen.

The framework for developing the scenarios is the question on whether or not there is going to be a production of synfuels on Funen, and if there were, should it be through biomass-to-liquid or biogas-to-liquid.

The results of this study show that the most economically feasible energy system in 2050 is based on biogas-to-liquid in order to produce 12.6 PJ of synfuels corresponding to 25% the demand in Denmark. This scenario results in a system cost of 7,491 MDKK per year. This is 2,120 MDKK per year lower than the system costs of the energy system in 2016, which has been calculated to 9,611 MDKK per year.

Finally, a sensitivity analysis will be carried out in order to investigate the robustness of the most feasible scenario in 2050.

Key words: Energy, System, Strategic, Perspective, Renewable, Synfuel, Excess heat, Data center, socioeconomic, system cost, 2035, 2050

Preface

This report was written by Asger Vestergaard Laursen and Jeppe Bay Pedersen for a combined 30 ECTS bachelor thesis at the Department of Chemical Engineering, Biotechnology and Environmental Technology (KBM), University of Southern Denmark, running from February 2018 to June 2018. The main supervisor of the project was Lars Yde, external lecturer at the Department of Chemical Engineering, Biotechnology and Environmental Technology and business developer for Energiplan Fyn. Furthermore, this thesis was co-supervised by Abid Rabbani, postdoc at the same department.

This study has been carried out in collaboration with Energiplan Fyn with the purpose of bringing the energy planning of Funen up to date with the newest global trends and projections.

We would like to express our thanks to Anders W. Mortensen, PhD-student at the aforementioned department, for providing us with the required data and assistance for modelling the future energy systems of Funen. We would like to thank our supervisors, Lars Yde and Abid Rabbani, for guiding us through this project, and providing both methods and data to perform the required calculations and modelling.
An additional gratitude goes out to everybody who has provided us with data and helped us by guiding us towards the right methodology and mindset.

Table of content

List of tables

List of figures

Abbreviations

MDKK	Million Danish Kroner
BDKK	Billion Danish Kroner
CAPEX	Capital Expenditures
O&M	Operation and Maintenance
VAT	Value Added Tax
PV	Photovoltaics
DEA	Danish Energy Agency
DH	District Heating
CEESA	Coherent Energy and Environmental System Analysis
DS	Danish Statistics
EV	Electric Vehicle
CHP	Combined Heat and Power
GNP	Gross National Product
TSO	Transmission System Operator
GCA	Global Climate Action
DG	Distributed Generation
ST	Sustainable Transition
EU	European Union
SDU	University of Southern Denmark
FVF	Fjernvarme Fyn
DAC	Direct Air Capture

Introduction

Transitioning to an energy system that is based entirely on renewable energy has been a topic of discussion for many years. The need to phase out fossil fuels has never been more relevant than it is today. Nations regularly meet to debate how this transition can be carried out both technically and economically. In 2015, 195 members, including the European Union, signed the Paris Agreement, which aims to keep the temperature-rise to below two degrees Celsius above pre-industrial levels while pursuing to limit it further [1].
To be able to reach the European Union's goal of cutting greenhouse gas emissions to 80% below 1990-levels by 2050, long-term planning is a necessity, and Denmark has a history of being up-front when it comes to pushing for replacing fossil fuels with new and efficient renewable energy sources.

It is essential to the energy planning that the recommendation of the transition towards 2050 remains cost-efficient, and local players on the market of energy need political goals as these are the foundation of long-term investment decisions.
In 2012, a new Energy Agreement was reached which targeted Denmark to becoming 100% renewable in the energy and transport sector [2]. The following year, Energiplan Fyn, which consists of nine Funish municipalities and some of the largest utility companies on Funen, developed a plan for how this long-term transition could be carried out on Funen.

In 2017, Facebook announced that their eighth data center will be located in Odense, which necessitates a new, updated version of the energy planning of Funen.
This study aims to present a more interacting energy system, which revolves around the utilization of excess heat produced by data centers and industrial processes, while integrating the electricity system with the production of fuels for transportation.
Furthermore, to help local players on the energy market of Funen to decide on investments, this project includes a projection of the energy system of 2035, which acts as a roadmap towards the energy system of 2050.

In this study a model resembling the current energy system on Funen will be developed using the software EnergyPLAN. This model will be used to simulate the socioeconomic system cost, which will serve as a reference for the future scenarios.

Three future scenarios of the energy system of Funen in 2050 will be designed and modelled in Microsoft Excel. The first two scenarios will incorporate production of synfuels on Funen, by using biomass-to-liquid and biogas-to-liquid respectively, while utilizing all potential heat from Facebook's data center and industrial processes. The third scenario will include no production of synfuel but incorporate an increased utilization of excess heat from a data center with a larger heat capacity.

Microsoft Excel will also be used to develop the model of 2035 resembling the roadmap towards the most socioeconomically feasible scenario in 2050.

Finally, a sensitivity analysis will be carried out in order to investigate the robustness of the most feasible scenario in 2050.

1 Methodology

When analysing future energy systems, an essential aspect is to compare to the existing system. This is done to underline the coming challenges of having an energy system that is heavily reliant on fossil fuels, and to illuminate both technical and economic opportunities of future technologies.
This section will serve as a description of the methodology used to analyse the energy system of 2035 and 2050 and comparing them to the reference system of 2016. For an in-depth description of the techno-economic aspects of the scenarios, go to Section 2 and Section 3.
All costs, prices, capacities and emission coefficients that are not explicitly mentioned in the report can be found in tables in the appendix.

1.1 System analysis

As mentioned in the introduction to this section, the energy system of 2016 will act as a reference to the energy systems of 2035 and 2050, where the system of 2050 will be the primary focus, since this is the goal for the Danish energy system to be based entirely on renewable energy [3]. The system of 2035 will then act as a roadmap between the fossil-based and the renewable energy systems.
Since, in the context of energy planning, 2050 is far in the future, three scenarios[1] have been chosen as technical feasible solutions, to account for uncertainty.
The idea behind the system scenarios has been to utilize the excess heat that is generated in industrial processes and services to phase out the heat production by fossil fuels such as gas boilers and coal fired extraction plants and replace with excess energy. Then, as the technical part of the analyses has been conducted, the economics of these systems has been analysed, which aims to calculate the total annual system costs which is the primary factor on which the scenarios will be compared.
Since the energy statistics for Denmark are not, in detail, performed specifically for Funen, when recorded data have not been available, the consumption of production on a national level have been scaled down by 10% to represent Funen. The inhabitants, electricity consumption and district heating consumption of Funen make up around 9%, but 10% have been chosen for simplicity, and by the logic of Funen, and Odense in particular, being in growth compared to other large cities in Denmark [4]. The particular aspect that are subject to scaling by the general factor of 10% will be pointed out in the report.

[1] Read: System designs

1.2 Modelling

Two different softwares have been used to model the energy systems of 2016, 2035 and 2050. EnergyPLAN has been used to model the reference energy system of 2016, while Microsoft Excel have been used to model the future scenarios of 2035 and 2050. The reason for this is that the data for the energy system of 2016 is quite detailed while being composed of mature energy technologies, which can easily be modelled in EnergyPLAN. Furthermore, EnergyPLAN optimizes by the merit order, if the Market Economic Simulation option is chosen, which reflects how energy is actually being produced today.

While encompassing many useful tools, EnergyPLAN lacks flexibility in modelling fuel production by different methods which is essential for the future energy systems of Funen. Therefore, Excel has been chosen as the modelling tool for both the technical analysis, that is the energy balance, and also the socioeconomic analysis.

1.3 Socioeconomic analysis

As mentioned in Section 1.1 the main comparison between the energy systems is based upon an economic analysis, which is a socioeconomic analysis since it is desired to investigate the socioeconomic feasibility of the systems. Since the desired parameter of comparison is the annual system cost, the analysis mainly focuses on the costs of the system and not the revenues. Before going in to detail with the different costs, it should be mentioned that EnergyPLAN calculates most of these costs by itself from the raw data and prices inserted in the software, which is why the methods described in the following sections is mainly methods for calculating the systems costs of the future scenarios in Excel. These methods are, however, indifferent from the ones that EnergyPLAN uses.

Every price which has not been given in 2018-price, has been projected using an average inflation rate of 2%.

1.3.1 Capital costs

One of the costs included is investment in production and storage units from which the capital expenditures (CAPEX) are used as a measure for the annualized cost of investing in a given unit including discounting of the investment. This method has been used since the system costs are only calculated for the given years 2016 and 2050, which means that if the CAPEX were not used as a measure for investment, the entire investment would fall in the given year resulting in a miscalculated annual cost of the system. The CAPEX of the different units has been calculated by the following Equation (1.1):

$$CAPEX = \frac{inital\ investment \cdot discount\ rate}{1 - (1 + discount\ rate)^{-number\ of\ periods}} \tag{1.1}$$

The number of periods refers to the lifetime of the given unit, which has been assumed to be an average of 20 years for all units. Furthermore, a discount rate of 4% has generally been used throughout the project, including the CAPEX, since this rate is recommended by the Danish Ministry of Finance [5].

1.3.2 Operation and maintenance costs

The costs for operation and maintenance (O&M) of these production units have also been accounted for, which includes both the fixed and variable O&M, where the fixed O&M is calculated in a price per installed capacity and the variable O&M is price per produced energy.

1.3.3 Fuel costs

The cost of consuming primary energy resources such as woody biomasses have also been accounted for by an annual fuel price given in a price per energy consumed. Furthermore, the cost of consumption of electricity, which have not been produced on Funen, has been accounted for by the difference between the import and export of electricity on Funen and a yearly price of electricity. These costs of consumption have been combined into one fuel cost.
Fuels that are being produced on Funen and exported will be accounted for as a revenue offsetting the total fuel cost.

1.3.4 Environmental damages

The socioeconomic analysis will also include damage costs from emission of damaging gasses and particles since the environmental damage results in a cost to the society. Emission of CO_2, CH_4, N_2O, SO_2, NO_x and $PM_{2.5}$ will be included in the analysis of both 2016, 2035 and 2050. For SO_2, NO_x and $PM_{2.5}$ the cost is a marginal damage cost, which is the result of a quantification of the damage it inflicts upon the environment and therefore society [6]. For CO_2 the socioeconomic cost depends on where the emission comes from. CO_2 emission from production units that are included in the CO_2 quota scheme, which is production units with a fired capacity of more than 20 MW, is priced by an estimate of the CO_2 quota price. In EnergyPLAN it has not been possible to differentiate between emission from production units within and outside the CO_2 quota scheme, but since emissions from production units that are not included in the CO_2 quota scheme are also priced by an estimate of the

CO_2 quota price up to and including 2020, it does not affect the resulting damage cost of the current energy system of Funen. For 2035 and 2050 it is assumed that all CO_2 emission comes from production units that are not included in the CO_2 quota scheme. CH_4 and N_2O emission have the same impact on the environment as CO_2, which is increasing the greenhouse effect. Therefore, damages from those emissions are priced by converting to CO_2 equivalents by multiplying the price of CO_2 with 25 and 298 for CH_4 and N_2O respectively.

1.3.5 Net tax factor

The purpose of the socioeconomic analysis is to weigh different alternatives against each other in order to obtain a result that is the most economically feasible alternative. This is accomplished by comparing the costs for the alternatives against each other. In order to do this, all costs have to be given in the same price level so that they are comparable.

Costs and revenues associated with the consumer are generally given in market prices, which means that they are including value added tax (VAT) and other taxes. However, costs and revenues associated with the state are given in the direct prices, which is called factor prices. In the socioeconomic analysis all prices are converted to market prices. This method reflects that the inputs (resources, working capacity etc.) associated with a given project could alternatively have been used differently where the consumer would value them at market prices.

Converting from factor prices to market prices is done by multiplying all factor prices with the net tax factor, which is given to 1.325. Prices that have been converted from factor prices to market prices includes prices for investments, O&M, fuels, electricity, CO_2 quotas and damage costs for CH_4 and N_2O since these are calculated from the price of CO_2. The only prices that have not been converted to market prices are the damage costs for SO_2, NO_x and $PM_{2.5}$, since these are already given in market prices.

2 Energy system of Funen in 2016

Analysing and using a reference system to compare to future energy systems provide key insight to where the policy-makers should put their focus. Having analysed the issues and advantages of the reference of 2016 helps design the future systems of 2035 and 2050. The year 2016 has been chosen since this is the most recent year in which a model, based on recorded data, could be developed.
This section provides detailed insight into the methodology of constructing the model of the Funish energy system of 2016, and the technical results will be presented as a sankey diagram, while the economic results will be based on the system cost.

2.1 Methodology

The energy system of Funen consists of over 100 different energy conversion units, each having individual properties. This means that the making of the model is subject to a series of assumptions, which will be discussed in detail. The sankey diagram in the results section shows the conversion from primary energy source to electricity, heating and for example means of transportation.

2.1.1 Electricity and district heat from power plants and boilers

For the energy consumption and production of conversion units on Funen, excluding wind turbines and photovoltaics (PV), the Danish Energy Agency's (DEA) *Energiproducenttælling 2016* has been used which is an account for primary energy used to produce district heating (DH) and electricity. Furthermore, the account contains detailed figures on production and capacity of the different production units. For simplicity, straw, wood chips, wood waste and wood pellets have been combined as biomass while gas oil, fuel oil and LPG has been combined as oil. Heat and power production from combustion of primary energy have been combined into *Heat & Power*, which uses coal, oil, bio-oil, biomass, waste, natural gas and biogas. The distribution of fuels can be seen in Figure 1.

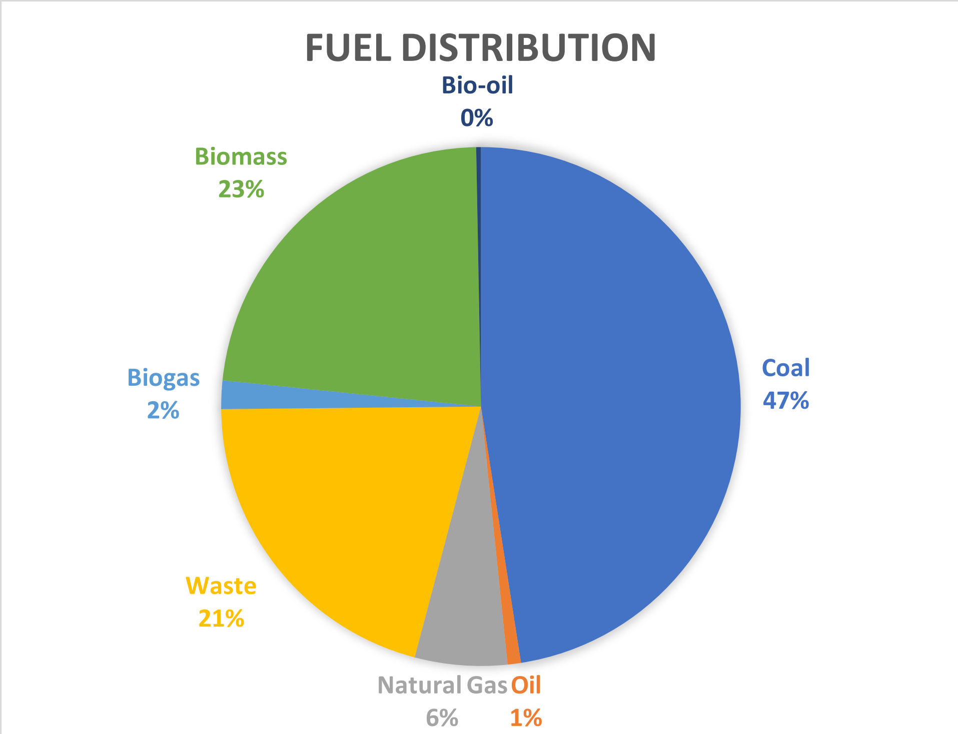

Figure 1: Pie-diagram showing the distribution of primary energy used for producing heat and power in power plants and boilers.

2.1.2 Electricity production from wind turbines and photovoltaics

DEA has statistics of the installed wind turbines and PVs and their respective production of electricity for every year since 1979, and the data for 2016 has been used as the production. In 2016, there was a total of 330 wind turbines on Funen, all of whom are onshore.

Data for installed PV capacity were found from DEA's account for Danish PVs, and through correspondence with Michael Madsen from DEA, Funish PVs are assumed to make up 6.5% of the total Danish capacity [Appendix A.8]. This percentage has been used to scale down the national electricity production from PVs, since the solar insolation has been assumed to be constant for all of Denmark.

2.1.3 Consumption of energy on Funen

Both the electricity and DH consumption are recorded by the Region of Southern Denmark through their data portal *Data2Go* [7]. In the statistics from Data2Go, the consumption of electricity and district heat is divided into different categories, and the categories that are combined to be *Industry,* *Commercial* and *Households* in which *Industry* covers: Agriculture, forestry, fishery, extractive industry, industry and utility companies[2].

The category *Commercial* covers: Construction, commerce, information and communication, finance and insurance and similar businesses.

The consumption of energies such as coal, biomass, natural gas and oil have been scaled down from the national consumption within the commercial and industrial sectors. Furthermore, some industries use heat at such a high temperature, that the excess heat could be utilized as district heating. The *Danish District Heating Association* provides an annual report of key figures from the Danish district heating networks, including the amount of industrial excess heat that has been utilized, and these numbers from 2017 have been used as the excess heat from industries, since it was the number closest to 2016 [8].

The energy consumption of households is, too, gathered from Data2Go for electricity and district heating while other energies are scaled down from the national consumption of primary energy in households.

2.1.4 Transport

The transport sector is an interesting sector for energy planning since it has proven to be economically infeasible to phase out fossil fuel in the same amount as the rest of the energy system. This is also the reason why the transport sector has been only lightly required to change to renewable energy, while the rest of the system has been changing rapidly. Energy for transport has to be energy dense so that trucks and cars can travel long distances while still being light and compact. This means that the energy used for transport in 2016 is mainly fossil fuels, namely oil. The transport sector has been split into light, medium and heavy transport and sea, rail, aviation and other transport. Light transport covers cars and small vans, medium covers mainly busses and heavy covers large vans and trucks.

This has been done to further investigate the road map for changing to a renewable sector, and to underline which transport technologies require which economic incentives. Furthermore, by splitting the transport sector, a more nuanced analysis of the total energy system of Funen can be conducted.

The division of the categories within the transport sector has been based on the *Coherent Energy and Environmental System Analysis* (CEESA) study. Each category's proportion of the total energy consumption has been calculated and the resulting distribution can be seen in Table 1.

[2] Excluding energy conversion companies

Table 1: Distribution of energy consumption in percent given by the CEESA study.

Energy consumption/category	**2016**	
	Total	Proportion of total
	PJ	%
Light	7.219	41%
Medium	3.960	22%
Heavy	3.138	18%
Rail	0.314	2%
Sea	0.471	3%
Aviation	0.288	2%
Other	2.264	13%
Total	17.654	100%

The total energy consumption of the transport sector has been calculated by the amount of fuels used in all of Denmark, and then scaling it down by the proportion of vehicles, ship berthings and flights from Funen in 2016. The proportion of vehicles and ship berthings are calculated by numbers from the *Danish Statistics* (DS), which are given specifically for Funen, resulting in 8.5% of vehicles, 7.62% ship berthings. The number of flights from Funen at the HCA Airport[3] has been given on the airport's website as 7,134 [9], which contributes to 1.49% of the total flights in Denmark.

These 17.654 PJ have then been corrected for electricity and bio-fuels mixed in the gasoline and diesel. Danish legislation states that at least 5.75% of the energy in the fuels must be from bio-fuels [10].

Furthermore, the DS does not account for electric vehicles (EV), which totalled 9,266 in Denmark in 2016 [Appendix A.9]. This corresponds to 0.3% of all cars being electric. This proportion has been assumed to be the same for Funen, resulting in 812 EV's on Funen. Furthermore, it has been assumed that EVs are three times as efficient as combustion engines.

Since the municipality of Odense has bought 38 hybrid busses gradually being instated towards 2020, starting with 18 in 2014, it has been assumed that there are 30 hybrid busses in 2016. Assuming that hybrid busses consumes 25% less energy than regular busses, this results in 0.00186 PJ of electricity used by hybrid busses. The corrected energy consumption by transportation on Funen can be seen in Table 2.

[3] Hans Christian Andersen Airport

Table 2: Corrected energy consumption of the transport sector, based on distributions from the CEESA study.

Energy consumption/category	2016			
	PJ			
	Oil	Bio-fuel	Electricity	Total
Light	6.795	0.415	0.009	7.219
Medium	3.733	0.225	0.001	3.960
Heavy	2.960	0.180	0	3.138
Rail	0.314	0	0	0.314
Sea	0.471	0	0	0.471
Aviation	0.288	0	0	0.288
Other	2.134	0.130	0	2.264
Total	16.692	0.950	0.011	17.654

2.1.5 Economic data input

As mentioned earlier, to compare the reference system of 2016 to the future scenarios, the system costs have been calculated. To do that, an array of different economic inputs have been obtained. This section will provide a description the different data inputs, to help get an overview of which parameters contribute to the system cost.

2.1.5.1 Investments

Since the system cost has been calculated using EnergyPLAN, some inputs have been subject to conversions and combinations of different technologies. EnergyPLAN uses *small-scale combined heat and power (CHP), large-scale CHP, waste incinceration, boilers, wind power, solar power, solar thermal, individual boilers* and *heat storage at CHP*. Since production units on Funen have widely different capacities and production patterns, it has been assumed that the only large-scale CHP is *Block 7* at *Fynsværket*. This means that every other CHP is assumed to be small-scale. Investment costs from DEA's *Technology Catalogue* has been used unless stated otherwise. Only investments for small-scale CHPs, boilers and individual boilers have been subject to conversion, and these are the only technologies discussed in detail. The remaining investments are taken directly from the catalogue.

Energiproducenttælling 2016 shows that far most of the fuels used for small-scale CHPs are biomass, and therefore, the investment costs for small-scale CHPs are assumed to be an average of small and medium biomass fired CHPs from the *Technology Catalogue* [11]. This results in an investment cost of:

$$
\begin{aligned}
&Investment_{small,CHP} \\
&= \frac{6.7\frac{M€}{MW} + 3.7\frac{M€}{MW} + 6.3\frac{M€}{MW} + 3.2\frac{M€}{MW} + 7.0\frac{M€}{MW} + 3.7\frac{M€}{MW}}{6} \\
&= 5.1\frac{EUR}{MW}
\end{aligned} \tag{2.1}
$$

Which, in DKK, is 53.5 MDKK/MW for small-scale CHPs.

The investment for DH boilers have been calculated in a similar way. 40% of the fuel used for boilers is natural gas, while the remaining 60% is mainly biomass. Therefore, the investment for boilers have been calculated as the average of biomass boilers with a combined weightage of 0.6 added to the investment for a natural gas boiler with a weightage of 0.4 [12]:

$$
\begin{aligned}
Investment_{boilers} &= \frac{0.7\frac{M€}{MW} + 0.74\frac{M€}{MW} + 0.91\frac{M€}{MW}}{3} \cdot 0.6 + 0.06\frac{M€}{MW} \cdot 0.4 \\
&= 0.9\frac{M€}{MW}
\end{aligned} \tag{2.2}
$$

Which, in DKK, is 5.2 MDKK/MW for DH boilers. For the investment costs of biomass fired boilers in the industry, the price is calculated as the average between the cost of wood chip, wood pellet and straw fired boiler. Investment costs of coal and oil fired industry boilers are assumed to follow the price of a natural gas fired boiler. The same assumptions follow in the O&M costs of the industry boilers.

This approach has, too, been used to calculate the investment cost of individual boilers. The distribution of fuels has been calculated by the amount of primary energy consumed in households in all of Denmark, retrieved from the DS. The fuels used for individual heating are; 56% biomass, 33% natural gas and 11% oil resulting in an investment for individual boilers of [13]:

$$
\begin{aligned}
Investment_{indv,boiler} &= 7.0\frac{M€}{MW} \cdot 0.56 + 3.2\frac{M€}{MW} \cdot 0.33 + 6\frac{M€}{MW} \cdot 0.11 \\
&= 5.64\frac{M€}{MW}
\end{aligned} \tag{2.3}
$$

Which, in DKK, is 57.9 MDKK/MW for individual heating.

An overview of all investment costs can be seen in Table 3.

Table 3: Overview of investment costs as input to EnergyPLAN.

Technology	Unit	Investment
Small-scale CHP	MDKK/MW-e	53.4
Large-scale CHP	MDKK/MW-e	20.2
Heat storage at CHP	MDKK/GWh	34.0
Waste CHP	MDKK/TWh/year	3370.4
DH boilers	MDKK/MW-th	5.2
Process boilers - Biomass	MDKK/MW-th	8.0
Process boilers - Gas, oil and coal	MDKK/MW-th	0.6
Biogas plant	MDKK/TWh/year	711.8
Wind power	MDKK/MW-e	11.2
Solar power	MDKK/MW-e	16.7
Solar thermal	MDKK/TWh/year	4829.2
Individual boilers	MDKK/1000-units	57.9

These investments have been used in EnergyPLAN to calculate the CAPEX.

2.1.5.2 Operation and maintenance

EnergyPLAN operates mainly with fixed O&M, with only a variable O&M for DH boilers, CHPs and individual boilers. This means that variable O&M for wind turbines have been incorporated in the fixed O&M by converting the variable O&M into a fixed value based on the number of full-load hours:

$$O\&M_{wind,variable} = 2.8 \frac{€}{MWh} \cdot 3100\ hours = 86{,}800 \frac{€}{MW} \tag{2.4}$$

This, combined with the given value for fixed O&M, results in fixed O&M for wind of 0.359 MDKK/MW. The fixed O&M is then converted into a percentage of the investment to be put into the EnergyPLAN model. An overview of all fixed O&M can be seen in Table 4.

Table 4: Overview of fixed O&M for production units of Funen in 2016 combined with each O&M's proportion in relation to investment costs.

Technology	Unit	O&M	Proportion of investment
Small-scale CHP	MDKK/MW-e	2.218	4.37%
Large-scale CHP	MDKK/MW-e	0.330	1.63%
Heat storage at CHP	MDKK/GWh	0.000	0.00%
Waste CHP	MDKK/TWh/year	108.977	3.23%
DH boilers	MDKK/MW-th	0.259	5.01%

Process boilers - Biomass	MDKK/MW-th	0.410	5.09%
Process boilers - Gas, oil and coal	MDKK/MW-th	0.021	3.33%
Biogas plant	MDKK/TWh/year	82.733	11.62%
Wind power	MDKK/MW-e	0.359	3.20%
Solar power	MDKK/MW-e	0.167	1.00%
Solar thermal	MDKK/TWh/year	6.463	0.13%

Lastly, the variable O&M for DH boilers, CHP's and individual boilers have, too, been calculated according to the weightage of the fuel used for production. The variable O&M for DH boilers has been calculated as the average of O&M for each biomass-fired boiler with a combined weightage of 0.6 added to the O&M of natural gas-fired boilers with a weightage of 0.4, resulting in a variable O&M of 9.0 DKK/MWh$_{thermal}$. The variable O&M for CHPs has been calculated as the combined O&M of small-scale and large-scale, with a weightage of 0.4 and 0.6, respectively according to their proportion of the total energy production.

The variable O&M for the biomass fired industry boilers is again calculated as an average of the different types of biomass to 7.2 DKK/MWh$_{thermal}$, while the variable O&M for gas, coal and oil fired industry boilers is calculated to 11.3 DKK/MWh$_{thermal}$.

2.1.5.3 Fuel prices, electricity prices and damage costs

Most of the economic figures regarding fuel prices and damage costs have been obtained from DEA [14]. Since the biomasses are combined into one group in EnergyPLAN, the fuel price has been calculated as an average of the individual prices.

Since waste incineration charges a fee in order to receive the waste, the fuel price of waste is negative. The price of waste in 2016 has been calculated by extrapolating prices between 2007-2015 [15].

The electricity prices for DK1[4] in 2016 has been extracted hour by hour from Energinet [16].

The damage costs have been obtained from DEA and the total damage cost for the system has then been calculated from the costs and the emission coefficients by the methodology described in Section 1.3.4 [17]. It should be mentioned, that the damage costs are dependent on the source of the emission, which is accounted for in the model.

The emission coefficients have also been obtained from DEA, except for the emissions from mobile sources, that is passenger cars, airplanes, etc. [18]. These have been obtained from research made by Aarhus University [19].

[4] Western Danish electricity market including Jutland, Funen and smaller islands.

2.2 Results

Since this analysis is purposed with updating and improving Energiplan Fyn's original *Rammeplan* from 2013 [20], this section will introduce the results of the analysis of the energy system of 2016, while underlining the key differences between the original report and this study.

2.2.1 Technical results

In Figure 2, the energy flow diagram, or sankey diagram, shows the conversion of primary energy to electricity and heat and the consumption of other energies such as oil. These flows are a graphic representation of the results that are described in this section. It can be seen that that the largest conversion of primary to secondary energy happens in CHP's and boilers, which has been combined into *Heat & Power* for simplicity. These units combined consumes 25.1 PJ of primary energy to produce 13.4 PJ and 5.8 PJ of heat and power, respectively. The energy balance of Funen, from *Rammeplan* can be seen in Figure 3. One key difference between the two flow diagrams is the amount of detail. The original 2014 energy balance is based on simplistic calculations and therefore, yields some imprecise results, while the information and analysis behind this project's energy balance being more comprehensive. As for the differences between the energy flows, especially the flow of two energies change drastically, namely oil and coal. In 2014, the amount of coal and oil used for both heat and power and for transport amount to 32.7 PJ, in which 22.7 PJ are used to produce heat and power. From the analysis performed in this project however, this amount is only 12.3 PJ, while the amount of oil used for transport is 70% higher. The overall value of oil and coal in both analyses are similar, which could suggest that the calculations from 2014 have made a skewed division of oil and coal. The amount of electricity produced from wind, solar, etc. from 2014 can be seen to be somewhat optimistic, since the actual production in 2016 is almost 50% lower which would mean a large recession of renewable energy, which has not been the case. Furthermore, the original energy system shows an electricity export of 5.9 PJ, which is primarily because of a much higher production of electricity from CHP's. According to data from *Energiproducenttælling 2013* the true production of electricity in 2013 was 8.1 PJ. This suggests that the value from the 2014 analysis is based on either the assumption that the electricity price was higher than it really was or that the efficiencies of the CHPs were too high, which would make them competitive in more hours than was actually the case in 2013. Using the real production would result in an export of around 3 PJ instead of 5.9 PJ. The difference of the real production of 8.1 PJ and the production in 2016 could be a result of the decreasing electricity prices, or the increase of alternative capacity to produce heat, which could enable some units to only produce heat, and not any electricity in hours where this would be economically infeasible but necessary due to the DH demand.

In this project, the export and import has been combined as a net import/export and has been calculated as the difference between production and consumption on Funen. The true exchange of electricity might vary from this project's value of 0.9 PJ, but data for the real exchange were not available.

It should be mentioned, that the consumption of electricity in individual heat pumps is included in the household electricity consumption.

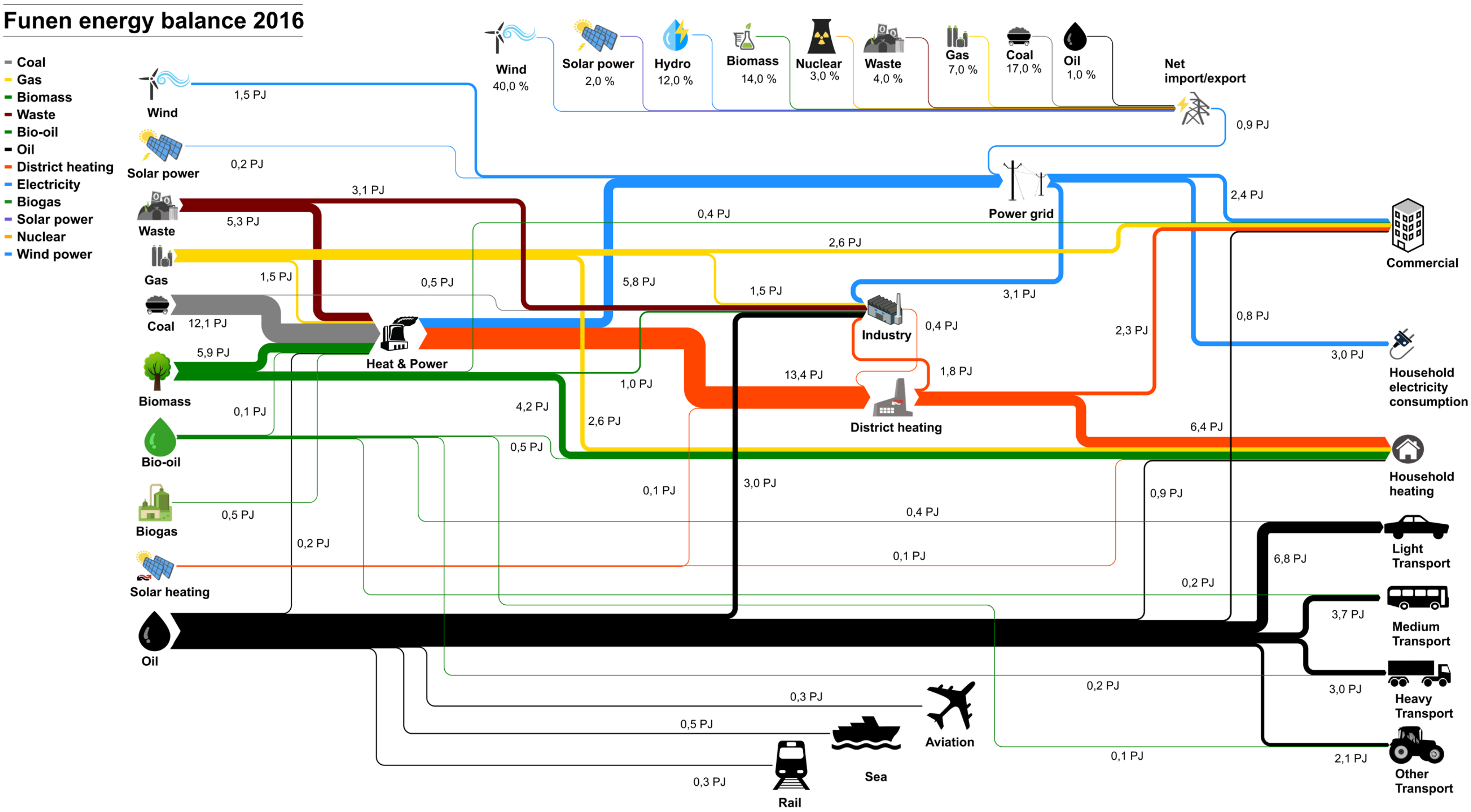

Figure 2: Sankey diagram showing the conversion from primary energy to utilizable electricity, heat and other energies for the energy system of 2016.

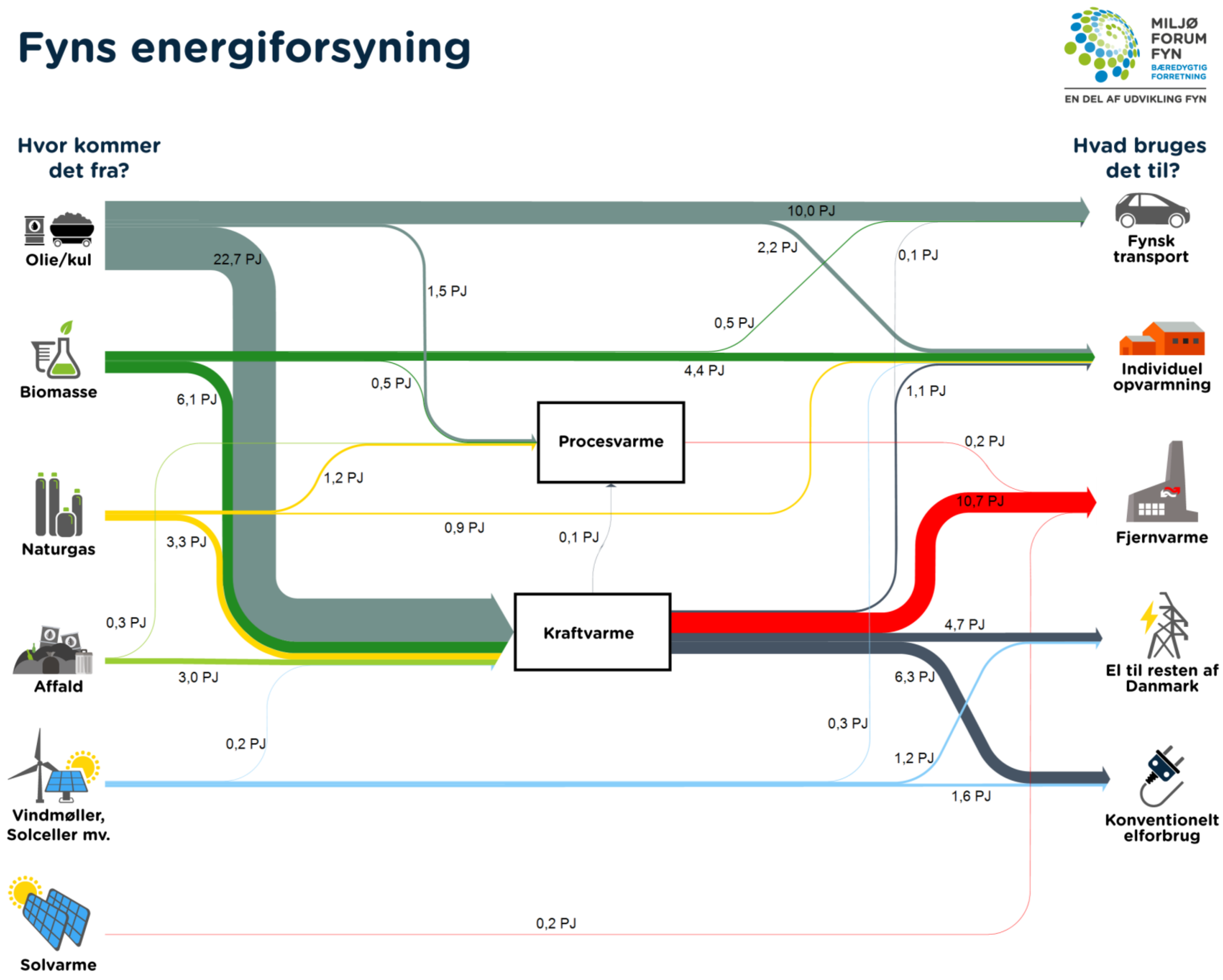

Figure 3: Sankey diagram of the energy system in 2014 from Energiplan Fyn's Rammeplan [21].

2.2.2 Economic results

While it was not possible to compare the socioeconomics of the analyses performed in 2014 and 2016, the system costs for the system in 2016 has been calculated with the main purpose of comparing it to the projected energy systems of 2050. The system costs have been divided into five categories; CAPEX, fixed and variable O&M, fuel and environmental damages. As can be seen in Figure 4, the largest contributor to the system costs is the purchase of fuels, which include coal, oil, biomass, etc. Almost 70% of the fuel cost comes from the purchase of petrol and diesel for transport.

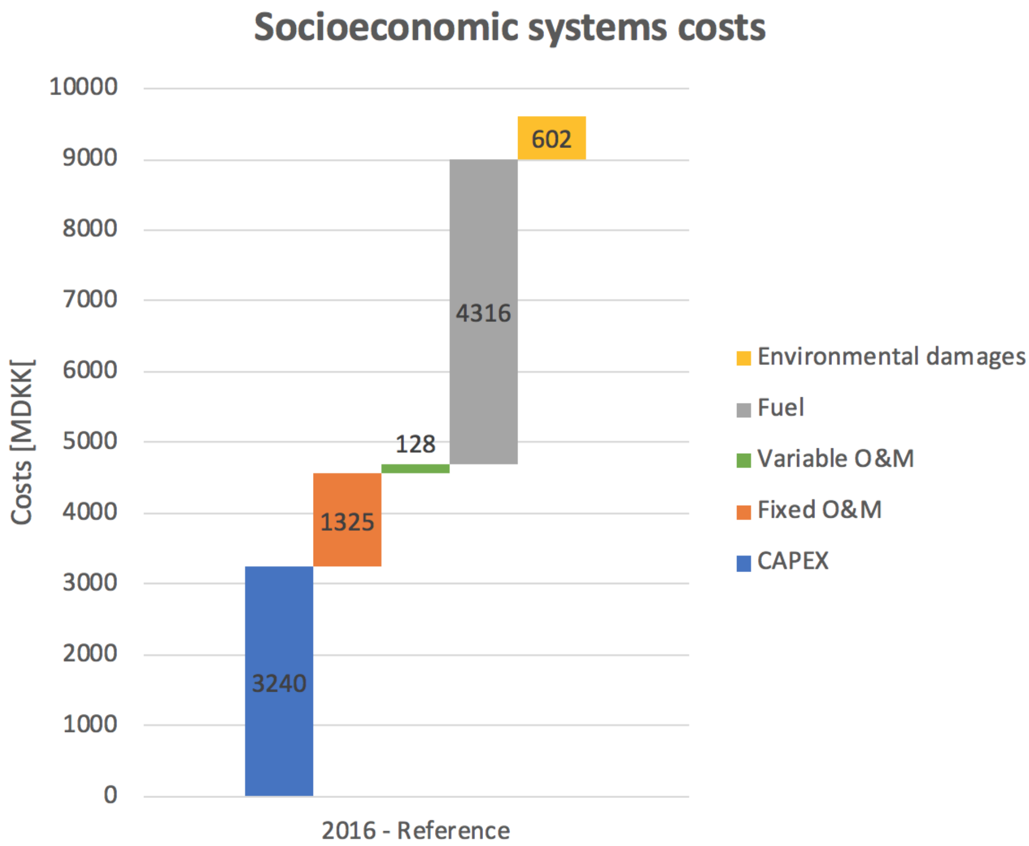

Figure 4: Breakdown of elements of the socioeconomic system costs for the energy system of 2016.

The total system costs of the energy system in 2016 has been calculated to be 9,611 MDKK. In 2016, the Danish Gross National Product (GNP) was 2,149,427 MDKK, which means that the energy system of Fyn made up 0.43% of the Danish GNP in 2016, while making up 6.72% of the Funish GNP of 142,967 MDKK [21].

In Europe, to estimate the efficiency of the energy system, *energy intensity* is calculated. This is a measure of how much energy is used to generate GNP, given in GJ/MDKK GNP.

In 2016, the energy intensity of the Danish energy system was 323 GJ/MDKK GNP [22].

As can be seen in Figure 2, by adding all streams, the sum of energy consumption on Funen in 2016 was 42.6 PJ. Given that the Funish GNP, in 2016, was 142,967 MDKK, the energy density on Funen was 310 GJ/MDKK GNP, which suggests that the energy system on Funen is slightly more efficient that for the rest of Denmark. Furthermore, this value further proves the validity of this socioeconomic analysis.

3 Energy system of Funen in 2050

The following sections contain a description of the methodology behind modelling the future energy system scenarios of Funen in 2050. This introduction will however be followed by a section regarding the Global Climate Action scenario, presented by Energinet[5], which will be used as a base for defining the specific scenarios for 2050.

3.1 Energinet's Global Climate Action scenario

Visioning and planning of the Danish energy system is something that many companies and organisations are concerned about. Because of this, different reports exist containing energy system perspectives for 2035 and 2050. The latest of them all is Energinet's *Systemperspektiv 2035*. This report has taken the three main scenarios for the future European energy system and created three scenarios from a Danish perspective.

One of them is the Global Climate Control (GCA) scenario, which is characterized by collaborating internationally to meet the climate goals set by the European Union (EU). In this scenario the EU is on track with the climate goals. The second scenario Distributed Generation (DG), is a scenario which is more nationally and locally orientated, with less international collaboration. The EU is also on track with the climate goals in this scenario. The last scenario Sustainable Transition (ST) is a scenario with a less aggressive green policy, where the EU is almost on track with the climate goals.

The GCA scenario suggests a high penetration of power production from both onshore and offshore wind power and PV in Germany, the Netherlands, the United Kingdom and Denmark. The penetration is so high that in 2040 the production from these technologies is estimated to exceed the demand of electricity in roughly 2000 hours during the year, or 4000 hours when accounting for the impossibility of decreasing production from base load CHP, resulting in negative electricity prices [23]. This is illustrated in Figure 5, where the electricity demand has been subtracted from the electricity production from wind power and PV, and the yellow and blue curves illustrate the number of hours with overproduction with and without "must-run" production from CHP's respectively.

[5] The Danish transmission system operator (TSO)

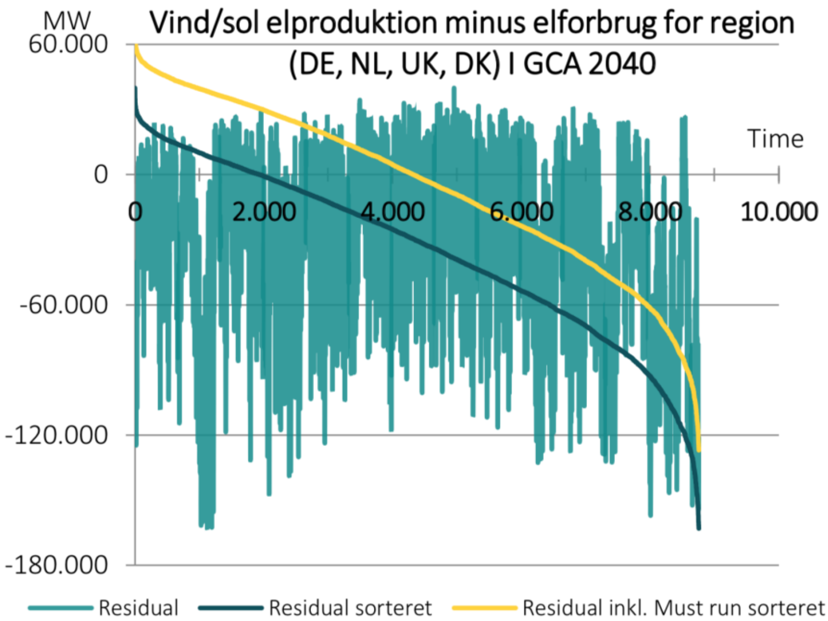

Figure 5: Wind and solar electricity production minus the electricity demand for Germany, Netherlands, United Kingdom and Denmark in the GCA scenario for 2040.

This excess production of electricity requires other methods of utilizing the electricity. Energinet suggests that the excess electricity should be utilized at fuel factories by producing hydrogen through electrolysis, which together with synthetic gas (syngas) can be used to produce synthetic fuel (synfuel) through Fischer-Tropsch process. Furthermore, most of the processes used to produce synfuel are exothermic, which means that the excess heat generated can be utilized as district heating. The GCA scenario of 2050 has been chosen as a base for defining the specific scenarios concerning the future energy system of Funen. This is due to the fact, that the GCA scenario generally focuses on electrification of sectors and how to utilize excess electricity from wind and solar power in a smart way, which results in a lower consumption of biomass. This is important since biomass, which CO_2 neutrality could be discussed, might very well become a scarce resource if the entire energy system depended upon it.

Energinet has made suggestions on rough locations for these fuel factories. According to Energinet a fuel factory could be placed on Funen in the city of Odense, which is why the three scenarios defined in this project focus on investigating the question on whether or not to place a fuel factory in Odense, and if a fuel factory were to be located there, how should the syngas for the Fischer-Tropsch process be produced?

3.2 General methodology for modelling of the future scenarios

Prior to describing the individual scenarios in-depth Section 3.2 will serve as a description of the general methodology behind all scenarios to minimize repetition.

3.2.1 Base model for the scenarios

Since the GCA scenario is a national scenario, the initial part of modelling the future scenarios has been scaling the system down to Funen by using the general factor of 10%, which results in a model serving as a base for the three scenarios. This was done by scaling down every demand to 10% except for the demand of bio jet fuel which was scaled down to 5%. Recalling from Section 2.1.4 the current jet fuel demand on Funen is estimated to only 1.49% of the Danish jet fuel demand, due to larger airports in Denmark being located outside of Funen. HCA Airport, which is relatively small, has been assumed to grow with the general growth of Funen, resulting in a Funish bio jet fuel demand of 2 PJ corresponding to 5% of the combined Danish demand.

3.2.2 Wind power potential

DEA has mapped potential locations for new wind farms, as seen in Figure 6, where the yellow dots indicate the locations [24]. It can be seen that there are no designated areas for offshore wind farms around Funen, which is why the future scenarios will not include any electricity production from offshore wind power. In the scaled GCA scenario there is a large penetration of offshore wind power, as mentioned in Section 3.1, resulting in an electricity production of 18.2 PJ. This electricity

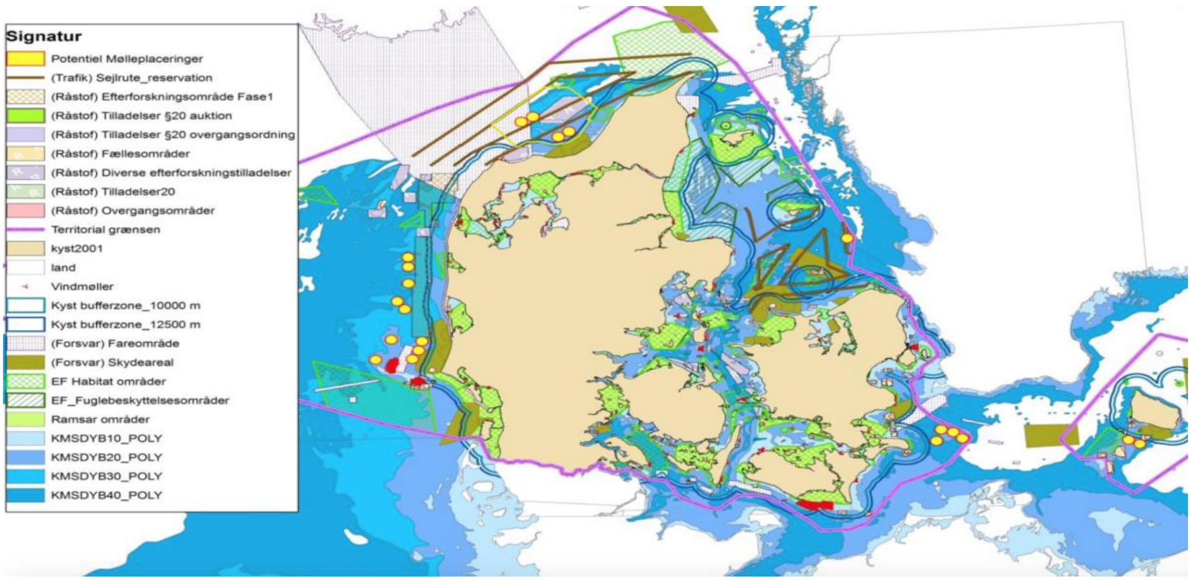

Figure 6: Map of potential wind farm locations in Denmark (yellow dots).

production has been added to the import of electricity instead, while the production of 5.2 PJ from onshore wind power remains the same.

3.2.3 Biogas potential

In 2015, *AgroTech* mapped the potential for utilizing straw and manure to produce biogas on Funen in the report *Potentialet for nye biogasanlæg på Fyn, Langeland og Ærø* [25]. The potential was estimated under the assumption that all excess straw from agriculture is utilized and mixed with the manure. Normally the straw and manure are mixed until a dry matter percentage of 14% is reached, but in the future scenarios it is assumed that the straw is forehandedly treated so that all potential excess straw can be utilized. This results in a biogas potential of 4.9 PJ, which has been used as the production of biogas in all three scenarios. Of this potential 3.69 PJ comes from straw and 1.22 PJ comes from manure.
The anaerobic digester used to produce the biogas has an efficiency of 71%, resulting in an input of straw and manure of 5.2 PJ and 1.72 PJ respectively.

3.2.4 Excess heat from industry

The total Danish potential of excess heat from industry in 2035 and 2050 has been mapped in 2018 in a report from the University of Southern Denmark (SDU) called *Utilizing commercial and industrial excess heat for district heating in Denmark - Business and socioeconomic assessment of taxation* [26]. This report estimates the total Danish potential, without including the excess heat generated at data centers, to 37.26 PJ in 2035 and 26.6 PJ in 2050. This decrease from 2035 to 2050 is caused by the industry becoming more efficient by integrating the streams of excess heat. This results in smaller fuel input to the industry, from 2035 to 2050, in order to produce the demand of process heat, and a smaller output of excess heat.
The Danish potential of excess heat has been scaled down to Funen by the general factor of 10% resulting in a potential of 2,66 PJ, which will be the actual input of heat to district heating since it is assumed that a 100% of the potential is being utilized in 2050.
It is assumed that half of the excess heat from industry is being utilized in the district heating network in Odense, operated by Fjernvarme Fyn (FVF), and the other half is being utilized evenly in the remaining district heating networks on Funen.
The utilization of excess heat from data centers will be discussed individually in the scenarios since this is dependent on the scenario in question.

3.2.5 Thermal energy storage

Thermal energy storages for heat production units such as solar thermal, CHPs and DH boilers located decentralized, which means that they are connected to any other DH network than the DH network in Odense, are assumed to have a combined storage capacity of 25 GWh.

3.2.6 Investment and O&M costs

The costs for investment, fixed and variable O&M have generally been obtained from Energinets *Systemperspektiv 2035* [27]. Generally, the costs associated with mature technologies, such as CHPs, boilers, wind power, PV and heat pumps, that Energinet has used in their scenarios, are equivalent to the costs given in the Technology Catalogues by DEA.

The amount of data for fuel factories is insufficient to some degree, which is why data for the available technologies in the Technology Catalogue for Renewable Fuel Technologies has been used to complement the data from Energinet. These technologies include a biogas plant, with an additional input of straw and thermal gasification of biomass. The rest of the fuel factory units, except from Fischer-Tropsch and steam reforming, have been taken from the economic data in *Systemperspektiv 2035*. These technologies include methanation by hydrogenation, water-gas shift reactor and an electrolyzer.

Systemperspektiv 2035 does not contain data for Fischer-Tropsch and steam reforming. Therefore, investment and O&M costs for the Fischer-Tropsch unit have been assumed to be the same as the costs of methanol synthesis. This is an investment cost of 0.177 M€/MW fuel output and Fixed O&M of 5308 €/MW [27].

The investment cost for a regional/central steam reforming plant is given to be 13.8 M$, and the O&M is estimated to be 4% of the investment [28].

3.2.7 Fuel prices

The fuel prices used to estimate the fuel cost in the future scenarios have generally been obtained from DEA [29]. DEA, however, does not publish the projected prices beyond 2040, which is why the prices in 2020 and 2035 have been used to calculate extrapolated prices in 2050, under the assumption of a linear change in price. The fuels in question are woody biomasses and straw.

Today, the fuel price of waste is negative, but this is assumed to change in the future with increasing demand of waste for waste incineration which would likely balance the demand and supply. Therefore, the price for waste is assumed to be 0 DKK/GJ in the future scenarios. The same assumption goes for manure from agriculture used to produce biogas.

Prices for fuels such as natural gas (methane), gasoline and jet fuel has also been projected by DEA, but these prices relate to the fossil based fuels. Therefore, the prices for renewable natural gas (biomethane) and renewable gasoline (biogasoline) has been obtained elsewhere [30] [31]. The fuel price of bio jet fuel is assumed to be the same as for biogasoline.

The future fuel price of hydrogen is assumed to reflect the cost of production by electrolysis [32]. All fuel prices can be seen in Table 5.

Table 5: Future fuel prices for 2050.

Future fuel prices [DKK/GJ]	
Wood chips	84.1
Wood pellets	171.4
Straw	67.4
Waste	0
Manure	0
Biomethane	205.7
Biogasoline	371.0
Bio jet fuel	371.0
Hydrogen	125.1

3.2.8 Electricity price

The electricity price has been projected to 2040 by DEA and the price of 2050 is extrapolated by the same method as with the fuel prices. The average electricity price in 2050 is estimated to be 196.9 DKK/GJ [33].

3.2.9 Damage costs

Like the damage costs for 2016 the damage costs for 2050 have been obtained from DEA and the total damage cost for the system has then been calculated from the costs and the emission coefficients by the methodology described in Section 1.3.4. It should be mentioned, that since the emission coefficients for combustion of natural gas at CHPs, DH boilers, industry boilers and individual boilers are only given for the fossil based natural gas, the emission coefficient of CO_2 for the combustion of renewable natural gas has been set to 0 kg/GJ.

The emission coefficients for mobile sources running on synfuels has been obtained from the research made by Aarhus University [19].

3.3 Modelling of Scenario 1: Biomass-to-liquid + 130 MW data center

The methodology behind Scenario 1 (Biomass-to-liquid + 130 MW data center) has been sizing the fuel factory by the excess heat generated in the components of the factory. From a socioeconomic point of view, producing fuels in areas where the excess heat cannot be utilized is infeasible as heat produced from other production units could have been avoided and replaced by excess heat that is produced either way.

3.3.1 Data center and thermal energy storage

Locating large data centers in Denmark is a growing trend amongst big corporations such as Apple and Facebook. Since Facebook's new data center located just outside of Odense is currently under construction it is also included in the future scenarios. Data centers consume a large amount of electricity in order to power the servers, and this electricity is converted into heat in the processors and released into the environment. By capturing this excess heat and boosting the temperature in a heat pump, it is possible to utilize the heat in a district heating network.

Facebooks electricity load is estimated to be 130 MW [34]. By assuming that 100% of the electricity used in the servers in 2050 is converted to heat, that the data center operates the whole year around and that the buildings are subject to a heat loss of 100 kWh/m^2 per year, the heat generated in the data center is calculated to [35]:

$$\begin{aligned}(0{,}130\ GW \cdot 8760\ hours) - \left(0.0001\frac{GWh}{m^2} \cdot 184{,}000\ m^2\right) &= 1120.4\ GWh \\ &= 4.0334\ PJ\end{aligned} \tag{3.1}$$

By accounting for the losses in the building, the heat capacity of the data center is 128 MW.

Since the constant heat production from the data center surpasses the heat demand in Odense's DH network in some of the summer months, a pit thermal energy storage is needed in order to utilize all excess heat. The size of the storage is calculated from the sum of the excess heat from every hour of 2014, in which the excess heat exceeds the heat demand. Since the heat demand will increase in the future but the efficiency of heat consuming units, such as houses, will increase, the district heating load profile of 2050 is assumed to be the same as the one in 2014. This results in a storage capacity of 66.4 GWh for the data center.

The costs associated with the data center will be expressed in the investment and O&M of the heat pumps, needed to boost the temperature of the excess heat from the data center, and the pit thermal energy storage.

3.3.2 Biomass-to-liquid

The central approach to sizing the fuel factory in the Scenario 1 has been to size it by the excess heat that could be utilized in the DH network of Odense. The DH network of Odense is subject to a large input of excess heat from the industry and Facebook's data center. Therefore, the capacity of the fuel factory is limited due to its potential of delivering excess heat to the DH network. The fuel factory is the limited production unit since the Facebook data center is already under construction and it would be infeasible not to utilize the full potential of excess heat from both the data center and industry. Furthermore, some heat producing capacity is reserved for waste incineration, since this is an effective way of handling waste, and heat pumps since this technology is used to balance the heat during peak demand. The theory behind the production of synfuels has been based on the same theory from Energinet's Systemperspektiv 2035 since the same method for producing the synfuels is used. This method can be seen in the schematic in Figure 7.

As seen in the block diagram woody biomass in the form of woodchips is used in thermal gasification to produce syngas. 9.6 PJ of wood chips is used to produce 7.16 PJ of syngas while the excess heat from the processes, including gasification and cleaning of the gas, accounts for 2.29 PJ. The thermal gasification is an endothermic reaction, but because heat is recovered in the cleaning processes combined with cooling of the syngas, the overall heat balance results in an output of heat [36].

The syngas leaving the thermal gasification does not have the most optimal ratio of H_2 to CO for use in the Fischer-Tropsch unit where synfuels are produced. In order to balance the content of H_2 and CO in the syngas, the Fischer-Tropsch unit is combined with water-gas shift, where the H_2 content is boosted [37]. The resulting outputs from the Fischer-Tropsch unit are 5.02 PJ bio jet fuel, 1.87 PJ biogasoline while excess heat accounts for 1.93 PJ.

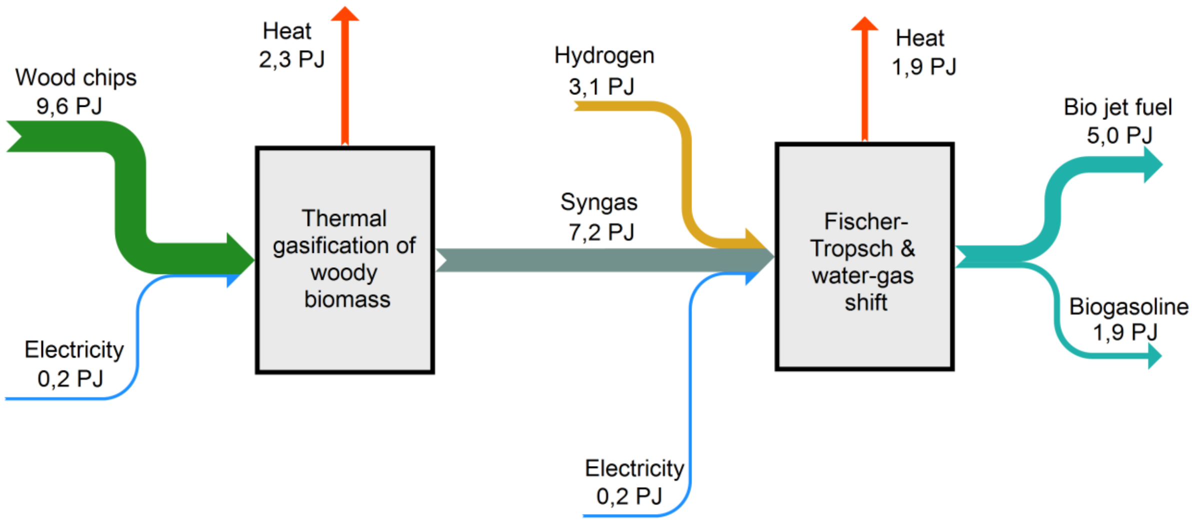

Figure 7: Schematic of the conversion from biomass to synfuels in the biomass-to-liquid scenario, with Fischer-Tropsch and water-gas shift combined into one unit.

3.4 Modelling of Scenario 2: Biogas-to-liquid + 130 MW data center

Since the production of synfuels is such a central aspect of the future energy systems, Scenario 2 (Biogas-to-liquid + 130 MW data center), too, focuses on the production of these. However, the general approach to designing the biogas-to-liquid differs somewhat from Scenario 1, since the production using biogas does not raise the issue of restriction of excess heat.

3.4.1 Data center and heat storage

As in Scenario 1 the heat capacity of the data center has been assumed to be 128 MW, which provides 4.03 PJ of heat, including a heat storage of 66.4 GWh for excess heat from the data center.

3.4.2 Biogas-to-liquid

Since the components that produced the most heat in Scenario 1, the thermal gasification and gas cleaning, are not needed in this scenario, the restriction of heat is not an issue, since the excess heat from biogas-to-liquid is relatively small. Therefore, the sizing of the fuel factory has been done with the purpose of producing 25% of the national demand of synfuels, which is 12.55 PJ. The inputs and outputs of the specific components have been calculated based on *Fuel Factories: Renewable Energy* *for the Heavy Transport* [38]. A schematic of the theoretical inputs and outputs can be seen in schematic of the theoretical inputs and outputs can be seen in Figure 8.

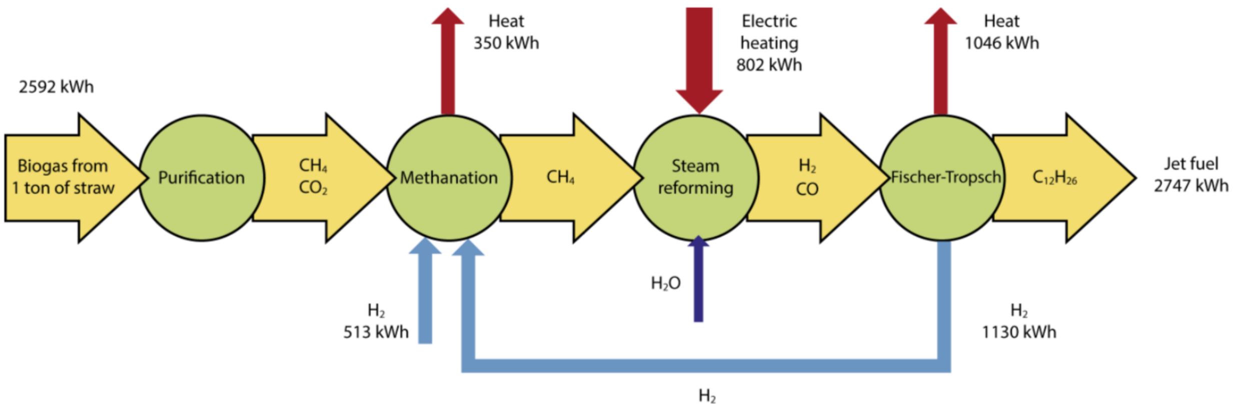

Figure 8: Schematic of the conversion from biogas to synfuels. Fuel Factories: Renewable Energy for the Heavy Transport [38] .

As mentioned in Section 3.2.3, the biogas potential of Funen is 4.9 PJ and this entire biogas is used to produce synfuels. Figure 9 shows the schematics of the conversion from biogas to bio jet fuel when using biogas. It is assumed that the biogas input in the fuel factory has been purified beforehand. To upgrade the biogas to biomethane, the biogas is methanated by hydrogenation, in which hydrogen is added to bond with the CO_2 in biogas in order to produce CH_4, and the output of this component is pure biomethane and heat in the form of oxygen. This biomethane is then used as input in the steam reforming unit in which the biomethane is used to produce syngas, which is ultimately used in the Fischer-Tropsch unit to produce synfuels. In this process, synfuels covers biogasoline and bio jet fuel with a distribution of approximately 25% and 75% respectively.

As can be seen in the figure, it is assumed that the excess heat from the Fischer-Tropsch unit has been utilized in the steam reformer to supply the required heat to produce steam, while the remaining

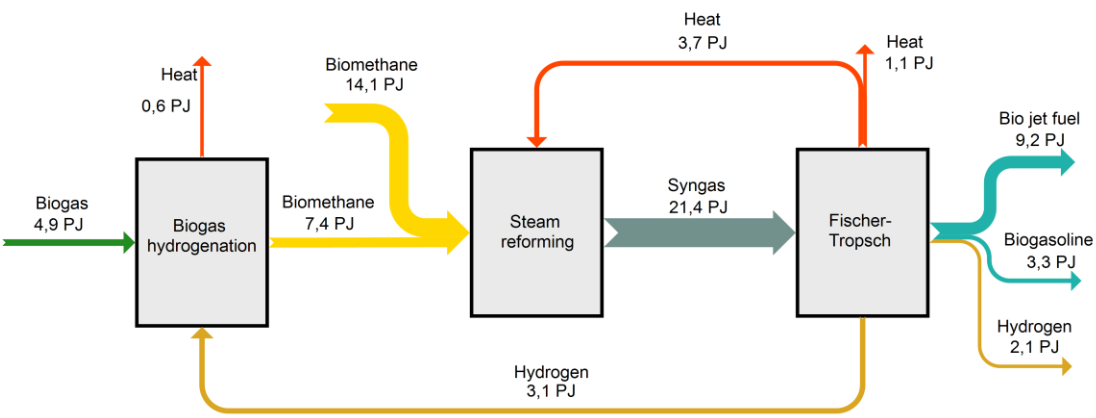

Figure 9: Schematic of the conversion from biogas to synfuels in biogas-to-liquid scenario, with looping of heat and hydrogen from Fischer-Tropsch.

excess heat is used for DH. Furthermore, the hydrogen that is produced in the Fischer-Tropsch unit is used to supply the methanation unit. Since biomethane is imported to produce more synfuels the amount of excess hydrogen exceeds the demand for hydrogenation, and this excess hydrogen is assumed to be sold on the market and exported.

3.5 Modelling of Scenario 3: No fuel factory + 254 MW data center

Since this project has included two future scenarios in which there is production of synfuels on Funen this third scenario has the purpose of investigating the system if there were no synfuel production and the entire DH network of Odense would be supplied by excess heat from the industry and data centers. Since there is no excess heat from either gasification or Fischer-Tropsch, the network lacks heat. In this scenario, this lack of heat will be used to analyse how much data center capacity can fit the system, when it is only complemented by industrial excess heat.

3.5.1 Data centers and thermal heat storage

The excess heat from the fuel factory in Scenario 1 constitutes 4.22 PJ of the entire supply, in which 2.29 PJ comes from thermal gasification and the remaining 1.93 PJ comes from the Fischer-Tropsch unit. In Scenario 1, the heat pumps produce 0.425 PJ, which is assumed to be the minimum heat that can be produced from heat pumps in the DH network of Odense and will remain the same. It is assumed that the data centers provide heat at its full capacity for all 8760 hours during the year. However, it should be mentioned that the electrolysis unit in Scenario 1 consumes 0.51 PJ of heat, which is 0.25 PJ higher than in Scenario 3. This results in a possible increased excess heat utilization from data centres of 3.97 PJ. Converting this to MWh and dividing by the number of hours, in equation (3.2), yields the new allowed capacity of data centres in Odense.

$$\frac{1{,}102{,}777.8}{8760\ hours} = 125.9\ MW \tag{3.2}$$

Adding this to the existing 128 MW yields a maximum of 253.9 MW, which is ultimately used for this scenario. Then the excess heat from data centres has increased to 8.01 PJ.

The size of the thermal heat storage has been calculated by the same method as in Scenario 1 and 2. Since the heat capacity of data centers in this scenario is larger, the resulting heat storage has been calculated to 524 GWh, equal to 1.89 PJ.

4 Results of future scenarios

The results of the technical energy system analyses and socioeconomic analysis of the system costs of the future scenarios of 2050 will be presented in the following sections and compared with each other and the reference system of 2016.

4.1 Energy system analysis

This section will provide insight to the different technical results of the scenarios.
Similar to the analysis of the energy system of 2016, the three scenarios, that have been analysed for 2050, is represented in sankey diagrams.
Since all three scenarios are based on many of the same assumptions, as discussed in Section 3.2, the systems are quite similar in many ways. The most notable difference is the amount of synfuels in the systems, and if they are either produced locally, imported or a combination. As described in Section 1.1, the fundamental idea of the system analyses has been to utilize the excess heat as first priority. This is the reason why the excess heat from the industry is the same for all scenarios, since it is both economically and technically feasible to utilize heat that is already produced instead of using additional energy to produce more heat. Comparing the sankey diagrams in Figure 10, Figure 11 and Figure 12, it can be seen that Scenario 1 and 3 are the most similar, with the only notable differences being that only scenario 1 has locally produced synfuels, while there is an increased 125.9 MW data centre capacity in Scenario 3. The synfuel production in Scenario 1 amounts to a total of 6.89 PJ in which 5.02 PJ is bio jet fuel and 1.87 PJ is biogasoline, which results in a synfuel export of 4.13 PJ. In Scenario 3, all 3.2 PJ of synfuels are imported. In scenario 3, the output heat from the data centers has increased by almost 100%, which results in a heat output of 8.01 PJ. In 2016, Fynsværket produced 2,641 GWh, or 9.5 PJ, heat for the DH network of Odense, and since the additional capacity would likely be located in Odense, excess heat from the data centers would cover approximately 85% of the total heat demand of Odense. Only Scenario 1 and Scenario 3 have an export of biomethane, both of which is 1.2 PJ.
Scenario 2, presented in Figure 11, stands out in the amount of synfuels and biomethane in the system. Since the excess heat is considerably lower in biogas-to-liquid, it is possible to produce more synfuel, while not producing too much heat for the DH network. This results in a total synfuel production of 12.55 PJ, which, as described in the methodology in section 3.4.2, covers 25% of the total Danish demand of synfuel. It is also worth noticing that Scenario 2 does not require additional hydrogen production through electrolysis, since hydrogen produced in the Fischer-Tropsch process is utilized

for hydrogenation of biogas. Due to this hydrogen utilization the amount of exported electricity in Scenario 2 is significantly higher than both Scenario 1 and 3, with an increased export of 6.4 PJ.

It is, however, clear that electricity plays a significantly larger role in the future energy system of 2050, than in 2016 - independently of the scenario.

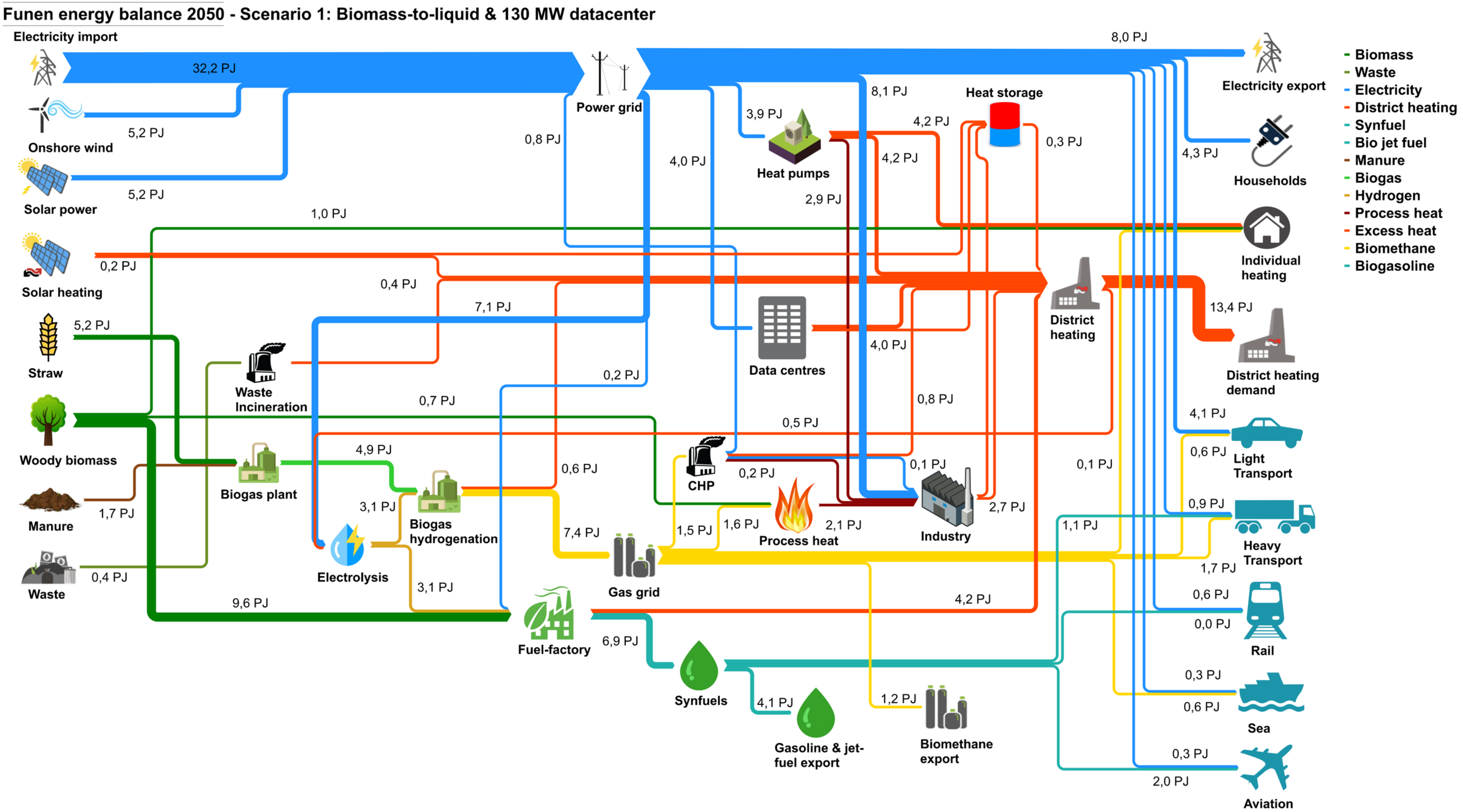

Figure 10: Sankey diagram of the biomass-to-liquid scenario in 2050.

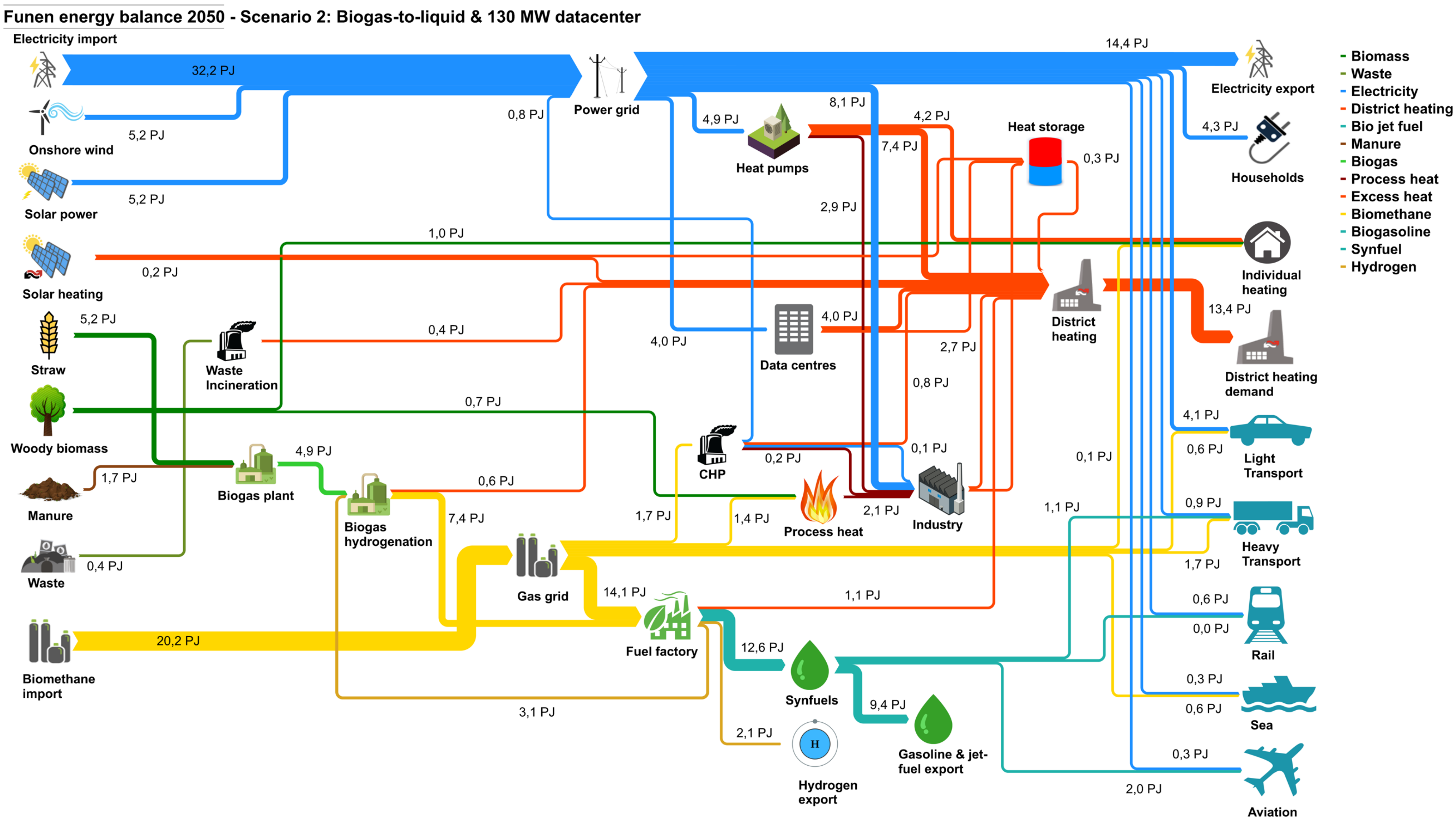

Figure 11: Sankey diagram of the biogas-to-liquid scenario in 2050.

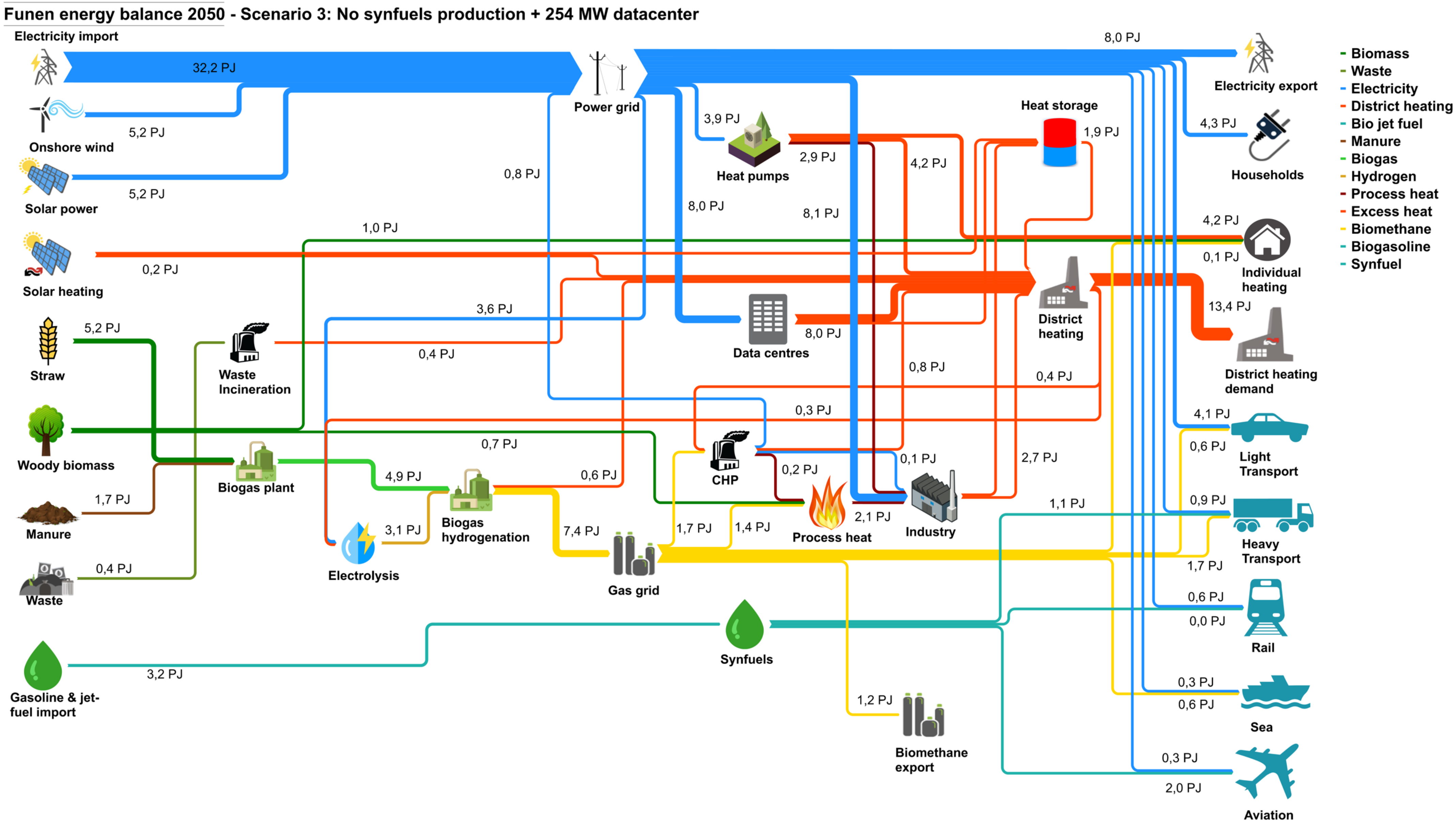

Figure 12: Sankey diagram of the no synfuel production scenario in 2050.

4.2 Socioeconomic analysis

As described in Section 1.3 the five elements that have been included in the socioeconomic analysis of the system cost is the CAPEX, fixed and variable O&M, fuel costs and damage costs due to environmental damages. A visual representation of the breakdown of these different costs can be seen in Figure 13. It can be seen that Scenario 2 (Biogas-to-liquid + 130 MW data center) results in being the most economically feasible future scenario with the lowest system cost of 7491 MDKK per year.

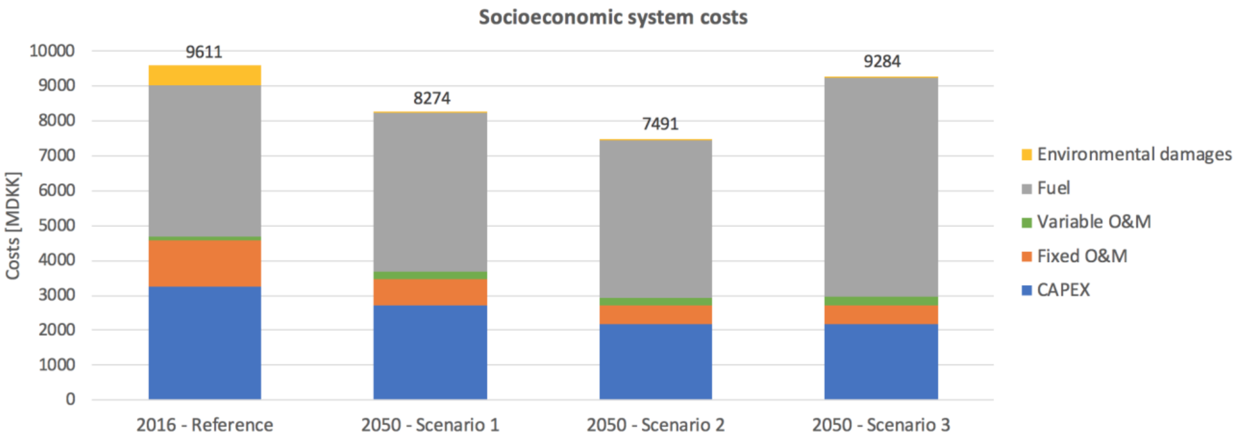

Figure 13: Visual breakdown of elements of the socioeconomic system costs for the energy system of 2016 and the three future scenarios.

Scenario 1 (Biomass-to-liquid + 130 MW data center) has the second to lowest system cost with 8274 MDKK per year, while scenario 3 (No fuel factory + 254 MW data center) is the most expensive scenario with a system cost of 9284 MDKK per year.

The largest deviation between the future scenarios originates from differences in the resulting fuel costs, CAPEX and O&M cost.

As seen in Table 6 the largest difference in costs between producing synfuels from biomass-to-liquid and biogas-to-liquid comes from the difference in CAPEX and O&M while the fuel costs does not differ significantly between scenario 1 and 2. The difference in CAPEX is almost 550 MDKK while the difference in O&M is almost 190 MDKK, even though the production of synfuels is higher in Scenario 2 than Scenario 1.

The difference in Fischer-Tropsch capacity of 315 MW between Scenario 1 and 2 does result in Scenario 2 having a higher CAPEX of the Fischer-Tropsch unit in the amount of 41 MDKK. However, Scenario 1 still has a higher total CAPEX since the thermal gasification unit has a significantly higher investment cost, resulting in a CAPEX of 583 MDKK, and the steam reforming unit has a relatively low investment cost.

Table 6: Economic breakdown of elements of the socioeconomic system costs for the energy system of 2016 and the three future scenarios.

	System cost			
	2016 - Reference	2050 - Scenario 1	2050 - Scenario 2	2050 - Scenario 3
	MDKK	MDKK	MDKK	MDKK
CAPEX	3240	2712	2164	2178
Fixed O&M	1325	756	545	551
Variable O&M	128	206	228	237
Fuel	4316	4551	4505	6269
Environmental damages	602	49	49	49
Total	**9611**	**8274**	**7491**	**9284**

The largest difference in system costs between Scenario 3 and the two other scenarios is associated with the fuel cost. Since there is no production of synfuels in Scenario 3, the costs of importing the synfuels at a high fuel price results in a much higher fuel cost. Neither the absence of investment and O&M costs of a fuel factory nor the saved investment and O&M costs, from not having to produce the heat which the increased heat capacity of the data center provides, compensates for the increased fuel costs.

Compared to the reference system, the future scenarios are generally less expensive. A large difference is expressed in the CAPEX and fixed O&M, since a lot of heat and power is produced at CHPs in the current energy system resulting in a high amount of CHP capacity of especially small-scale CHPs. Since the investment cost and O&M of small-scale CHPs are relatively high, their resulting CAPEX and fixed O&M are 990 MDKK and 588 MDKK per year respectively. For large-scale CHP the CAPEX and fixed O&M are 602 MDKK and 133 MDKK per year respectively, meaning that CHP's account for 51% of the total CAPEX.

Furthermore, the environmental damage cost is experiencing a significant percentage decrease of 92%, which is a result of transitioning from fossil to renewable fuels, both for energy producing units and in the transport sector. There is still a damage cost of 49 MDKK for every scenario, even though they are fossil free. This environmental damage is mainly caused by the transport sector which accounts for 34.4 MDKK (70%). The synfuels are considered CO_2 neutral and therefore CO_2 does not contribute to the damage costs, but since other harmful gasses are still released into the environment, combustion of synfuels inflict a damage upon the environment, with the worst emission from synfuels being NO_x. However, they will not contribute to the greenhouse effect.

Comparing the systems costs of the future scenarios by the GNP of Denmark and Funen, it can be seen from Table 7, that the system costs are generally around 0.3% of the Danish GNP and between

4.3-5.4% of the Funish GNP. The GNP of Funen in 2050 has been calculated by the same percentage increase as the one between the Danish GNP in 2016 and the estimate of the Danish GNP in 2050 by DEA in *Energiscenarier frem mod 2020, 2035 og 2050*, which is 21.1% [39]. Compared to 2016, the future scenarios are roughly 1.4-2.4% lower in regard to system cost as a percentage of the Funish GNP.

Table 7: Comparison between resulting system costs of the reference system and the future scenarios as a percentage of Danish and Funish GNP.

	2016 Reference	2050 Scenario 1	2050 Scenario 2	2050 Scenario 3
System cost [% Danish GNP]	0,43%	0,31%	0,28%	0,34%
System cost [% Funish GNP]	6,72%	4,78%	4,33%	5,36%

5 Energy system of Funen in 2035 - Roadmap towards 2050

While the purpose of this project is to analyse how the energy system should be in 2050, over 30 years is a very long prospect for energy planning and therefore subject to a wide range of changes. Most companies will not be able to act on prospects for an energy system in 2050, and therefore, a roadmap towards the system of 2050 have been made to better enable decision makers and companies on Funen to shape their development plans. This roadmap will be done by showing the energy system of 2035, which will act as a milestone towards the system of 2050, since 2035 is a more comprehensible future for politicians and other decision makers.

As has been analysed in Section 4 the system that has proved to be both the most economically and technically feasible scenario for 2050, is the biogas-to-liquid scenario. This means that this analysis will focus on how to reach that destination by planning towards 2035. It should be mentioned that aspects that are not subject to changes between 2035 and 2050 will not be discussed in this section.

5.1 Methodology

5.1.1 Electricity supply

Even though there are many large projects regarding renewable generation of electricity in development, it would be unrealistic and economically infeasible to produce the same amount of electricity from especially PVs and wind turbines. Therefore, to account for the gradually increasing production capacity of these technologies, the production has been multiplied by a factor of 0.6 and 0.5 for wind turbines and PVs, respectively. Since the electricity production of most other technologies are the same as in 2050, the lower production from wind turbines and PVs results in a lower export of electricity.

5.1.2 Heating supply

CHPs will be mostly phased out by 2035, with a total output of only 19% compared to the output in 2016. While being only 19% of 2016, CHPs still play a larger role in 2035 than in 2050. Since there is significantly less utilizable heat as a product of only producing 1 PJ synfuels, CHPs still has almost four times as high an output in 2035 as in 2050. This suggests that the decommissioning of CHPs happens exponentially declining towards 2050, since the heat produced from CHPs in 2050 is still 0.8 PJ. While the CHPs in 2016 were mainly using coal, waste and biomass as fuel, the CHPs in 2035 will be gas CHPs using methane and biogas. Furthermore, 2.7 PJ of woody biomass will be used to produce heat in biomass boilers.

Since large-scale heat pumps are still a relatively new technology, it is assumed that the heat output in 2035 will be 60% of the output in 2050. The same goes for heat pumps used to produce process heat. The heat for individual heating that, in 2050, is produced by heat pumps will, in 2035, be produced by an increased amount of wood pellets and a small amount of methane.
In the industry, the heat that is produced by heat pumps in 2050, is, in 2035, produced by electric boilers, and gas boilers. In total, heat pumps produce 7.1 PJ heat in which 1.8 PJ is process heat, 2.5 PJ is individual heating and the remaining 2.8 PJ is central and decentral district heating.

5.1.3 Data centers and heat storage

Since Facebook announced that the first excess heat from the data center in Odense would be utilized in 2020, it is fair to assume that the data center will reach its full capacity by 2035. This means that the excess heat from data centers will be the same in 2035 as it will be in 2050, namely 4.03 PJ, which, too, requires a heat storage of 66.7 GWh. Combined with the heat storage capacity in other DH networks on Funen, this results in a total heat storage capacity of 91.4 GWh.

5.1.4 Transport

The transport sector has, historically, been subject to more concessional requirements when it comes to using renewable energy due to the technical difficulties associated with this. Therefore, the most significant difference between the energy system of 2035 and 2050 will be the energy used for transportation. While there will still be used renewable energy and electricity, the amount will be considerably less. It is assumed that the maturing of the electric vehicle technology develops as an s-curve, and that this s-curve reaches 50% of the amount used in 2050 by 2035. Since there are different efficiencies associated with different engines, it is necessary to calculate the energy consumption be the demand of mechanical energy. Therefore, the mechanical energy, that will be supplied be electricity in 2050, has been multiplied by a factor of 0.5. For some means of transportation, there is a consumption of methane. Since vehicles with gas motors is a technology that is proven and ready to be implemented it is assumed that the methane used for transportation will stay the same from 2035 to 2050 [40]. Since synfuels will play a larger role in the transport sector in 2050, it is assumed that there will be a production of 1 PJ synfuels in 2035, distributed in 0.73 PJ of bio jet fuel and 0.27 PJ of biogasoline. These synfuels are distributed between the means of transportation relative to their individual demand of mechanical energy, i.e. the transportation demanding the largest amount of mechanical energy, uses the largest amount of the produced synfuels. When these three energy forms have been supplied to the transport sector, there is still a lack of energy. This energy will be supplied by oil in the form of fossil-based gasoline, similar to the system of 2016. Since the efficiency of a gasoline engine is assumed to be 30%, which is significantly lower than an electric motor, the total amount of energy consumed in the transport sector will be corresponding to this difference in efficiency. The transport sector consumes a total of 16.4 PJ of energy, and the distribution of fuels can be seen in Figure 14. The energy consumption of the transport sector is almost identical to the consumption in 2016, even though there are more electric vehicles, which have a significantly more efficient motor. But the increase in fuel consumption, in especially aviation, balances the decrease in road transport.

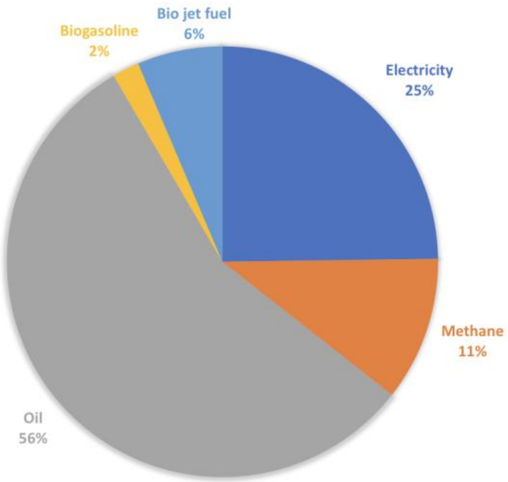

Figure 14: Fuel distribution in the transport sector in 2035.

5.1.5 Biogas

In 2050, the potential for production of biogas from manure and straw has been estimated to be 4.9 PJ, as presented in Section 3.2.3, and in 2035 it is assumed that this potential is the same since biogas production is a relatively mature technology, that is likely to reach its full potential on Funen by 2035. In 2050, the entire production of biogas is used to produce synfuels, but this will not be the case in 2035. In 2035, it is assumed that half of the biogas is used in CHPs to produce heat and electricity, while the other half is used to produce the 1 PJ of synfuels and 3.7 PJ of biomethane by hydrogenation.

5.2 Resulting energy system of 2035

As described above, the energy system of 2035 will represent a transition towards 2050. This means that the number of energy streams will be significantly higher, since there are many small streams from many different energy sources. The energy system of 2035 is presented in Figure 15. Especially the transport sector is in a transition between fossil fuels and renewable fuels, which is illustrated by several parts of the transport sector having up to four different energy inputs.

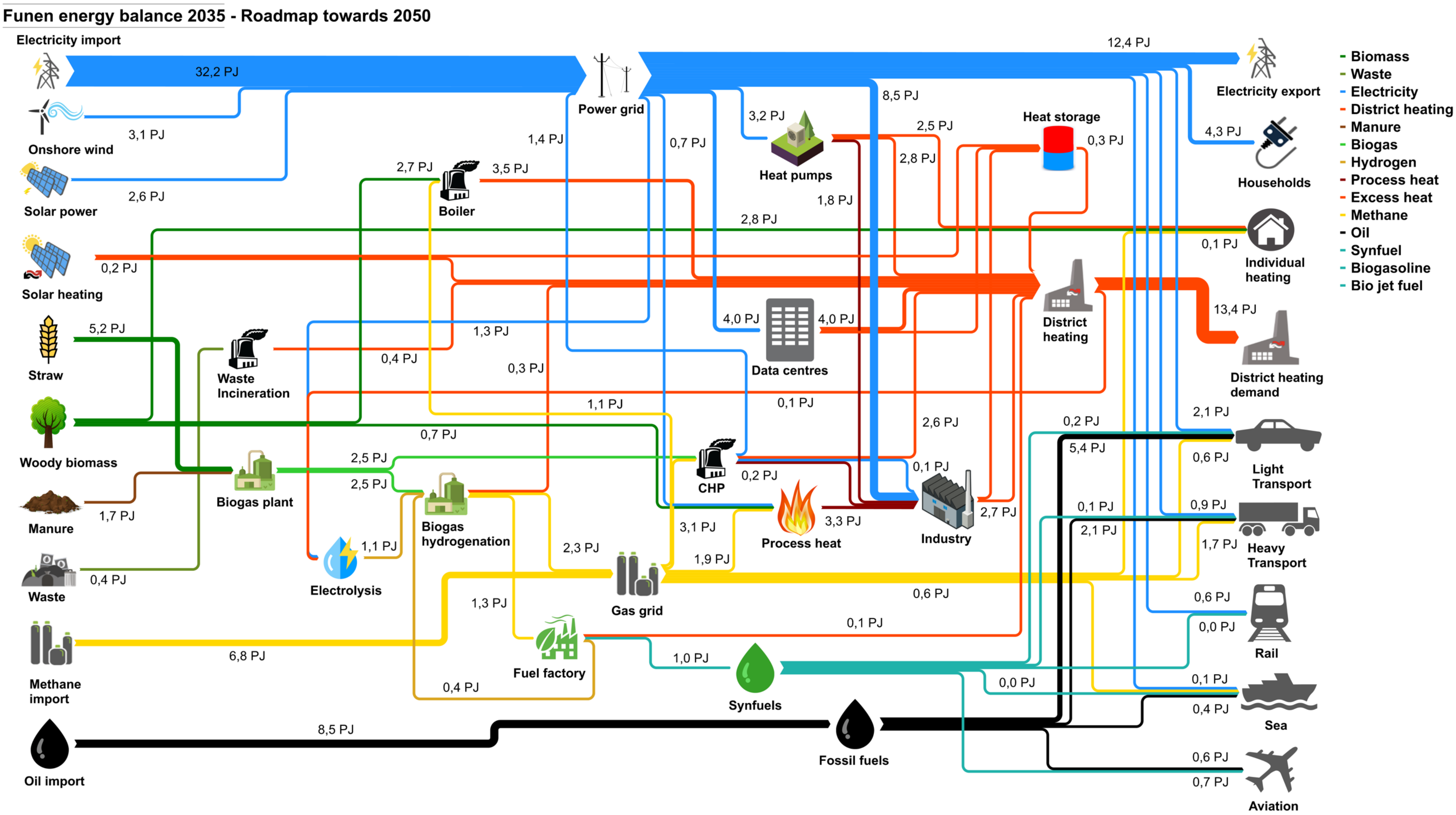

Figure 15: Energy flow from primary energy to consumption of the energy system of 2035. Compared to the energy system of 2050, the number of streams is significantly higher due to the state of being "in-between" to energy systems. Streams that are noted with 0,0 PJ are smaller than 0,05 but is included to help the reader understand the concepts of the energy flow. While the output from synfuels seems to be higher than the input, this is due to a minimum thickness of the streams, and the same goes for the power and gas grid.

5.3 Socioeconomic system cost of 2035

Most of the same methodology used for calculating the socioeconomic system costs of the future scenarios goes behind calculating the system cost in 2035. The changes that exist are mainly related to the sub-sections before this one.

Since investment and O&M costs generally decrease with maturity in technologies, the costs used for 2035 are different from the ones used in 2050. All the economic figures from the models of 2050, which was provided by the Technology Catalogues, are also given for 2030 and assumed to be the same as for 2035. Economic figures from the models of 2050, which was provided by Energinet's *Systemperspektiv 2035*, has also been given for 2035.

The energy system of 2035 consists of a combination between fossil fuels and renewable fuels, of which prices are very different, and this will be accounted for by using the projected prices in 2035 of fossil fuels by DEA, and assuming that the price levels for renewable fuels are the same in 2035 as for 2050.

An exception to the differentiation between fossil fuels and renewable fuels is the import price methane. Since it is very difficult to estimate the percentage of biomethane in the gas grid in 2035, it has been assumed that the import price of methane follows the fossil based.

Another result of the combination between the fossil fuels and renewable fuels are the different emission coefficients. This has also been accounted for by differentiating between combustion of the different kinds of fuels. However, as with the fuel price of methane, it is difficult to differentiate between combustion of the fossil and renewable based since it is mixed in the gas grid, which is why it is assumed that all emission coefficients related to the combustion of methane follows the fossil based.

5.3.1 Results

The resulting socioeconomic system cost of the future energy system in 2035 amounts to 9147 MDKK, and in Figure 16, a breakdown of the different elements is visualized.

Even though CHPs play a larger role in 2035 than in 2050, a lot has been phased out from 2016 and together with the absence of a large-scale fuel factory, but only a small-scale with a capacity of 55.6 MW fuel output, the CAPEX and O&M costs are relatively low. Also heat pumps, which generally have a large impact on the CAPEX and O&M due to high costs of investment and O&M, plays a smaller role in 2035 than 2050 which contributes to the low CAPEX and O&M.

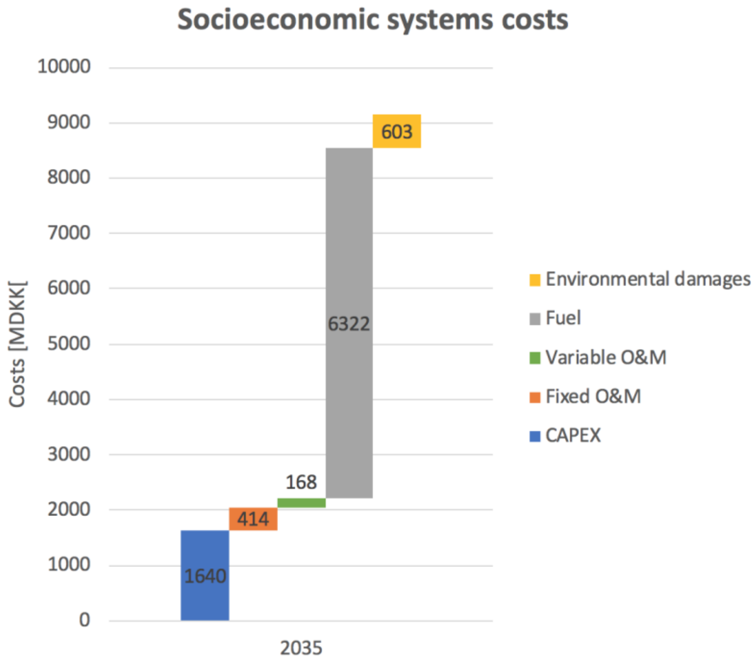

Figure 16: Breakdown of elements of the socioeconomic system costs for the future energy system of 2035.

As seen in the figure, fuels costs are relatively high compared to Scenario 1 and 2 but resembles the fuel cost in Scenario 3. This is explained by the lack of local fuel production on Funen, which results in a large import, and together with the increased fuel input from an increased capacity of CHP the fuel costs amount to 6322 MDKK.

The environmental damages amount to a cost of 603 MDKK, which compared to the damage cost in 2016 of 602 MDKK, is relatively high. This can be explained by the fact that a large part of the transport sector is still fuelled by fossil fuels in 2035. It can also be explained by the assumption that all combustion of methane is related to the fossil based. If part of the methane would be biomethane the total damage cost would be lower due to CO_2 not contributing to the damage cost from combustion of biomethane. This would however increase the fuel costs, since biofuels are more expensive than fossil fuels.

6 Sensitivity analysis

When calculating certain costs many years into the future, the uncertainty of the result increases since prices are bound to change from the ones used in the socioeconomic analysis. Therefore, a sensitivity analysis has been conducted in order to investigate the robustness of the system cost of Scenario 2 (Biogas-to-liquid + 130 MW data center).

The analysis consists of two parts. One where key parameters are changed by specific percentages, and another where it is investigated how Scenario 2 compares against Scenario 1 (Biomass-to-liquid + 130 MW data center) with varying prices in biomethane and synfuel.

6.1 Part 1: Varying key parameters by a fixed percentage

The first part of the sensitivity analysis focuses on varying key parameters by a fixed percentage, in order to investigate how changes in the parameters shifts the total system cost of Scenario 2.

Table 8 shows the parameters that have been varied in the first part of the sensitivity analysis, and by what percentage the individual parameter has been varied.

Table 8: Parameters of interest for the first part of the sensitivity analysis, including specific changes and codenames. The first of the codenames for each parameter refers to the decrease in the parameter i.e. SA1.1 refers to a decrease of 25% in the costs of investment and O&M.

Parameters of interest		
Parameter	Change	Codename
Investment and O&M costs	∓ 25%	SA1.1 and SA1.2
Electricity price	∓ 10%	SA2.1 and SA2.2
Fuel prices	∓ 10%	SA3.1 and SA3.2
Discount rate	∓ 2%	SA4.1 and SA4.2

These parameters have been chosen due to their high uncertainty and influence on the future scenarios.

The investment and O&M costs are linked together and are highly uncertain since developments in technologies could have a large effect on the specific costs. These costs will be varied by ∓ 25%.

Fuel prices and the electricity price are also quite uncertain when analysing 32 years into the future. Especially prices of renewable fuels, including synfuels, biomethane etc., are very likely to change since these fuels are relatively immature and not properly implemented in current energy systems.

The discount rate often varies between different projects and a relatively small percentage change can have a large effect on the costs.

6.1.1 Results

The results of the first part of the sensitivity analysis can be seen in Figure 17, where it is visualized of specific changes in certain parameters shifts the system cost of Scenario 2 up or down.

As seen from the figure, varying the investment and O&M costs by ∓ 25% has the largest influence

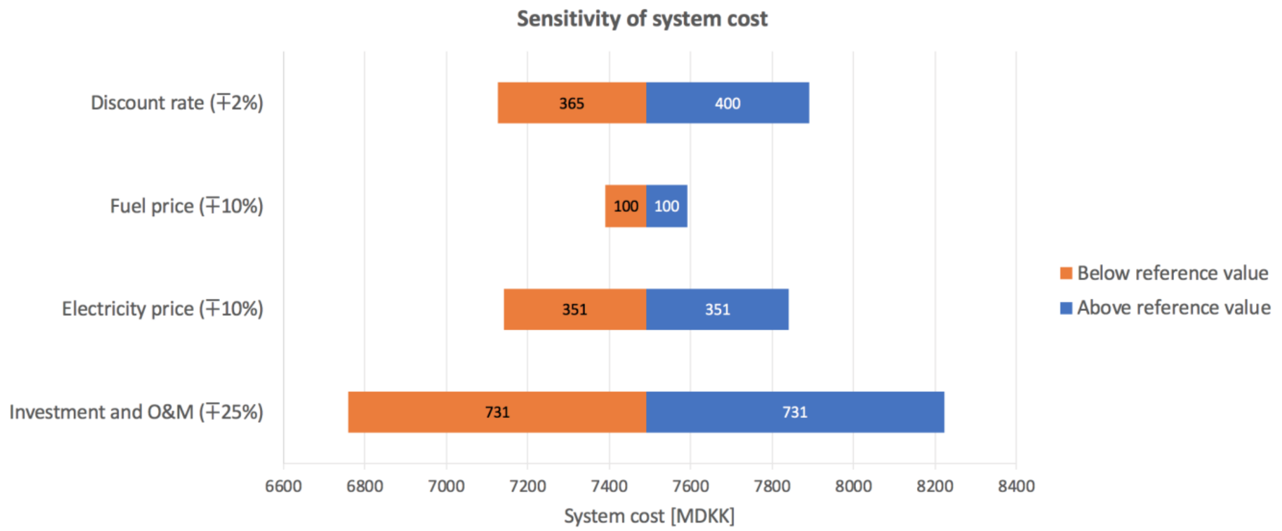

Figure 17: Visualization of shifts in the system cost of Scenario 2 (Biogas-to-liquid + 130 MW data center) when varying key parameters.

on the system cost by shifting it ∓ 731 MDKK. The model is subject to a high number of economic figures for the different technologies that are all influenced by this change.

Comparing the shifts in system cost between an equal percentage change in fuel prices and the electricity price, it is seen that the model is more robust to a change in the fuel prices. The system cost will only experience a shift of ∓ 100 MDKK by varying the fuel prices, while the shift will be ∓ 351 MDKK when varying the electricity price.

This can be explained by the fact that a lot of electricity is imported and only half the amount of the import is being exported at the same price. While the import of biomethane is higher than the export of synfuel, the same percentage change in the fuel prices as the electricity price results in a smaller shift due to the fuel price of synfuels being much higher than the fuel price of biomethane.

Varying the discount rate shifts the system cost by - 365 MDKK and + 400 MDKK, and it is seen how a relatively small change can cause large shifts in the system cost.

All the resulting system costs from the first part of the sensitivity analysis of Scenario 2 can be seen in Figure 18.

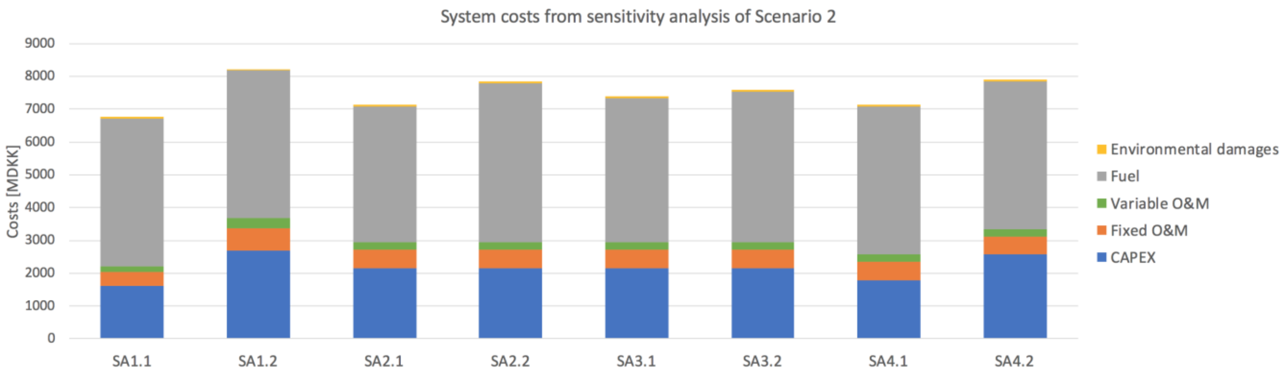

Figure 18: Resulting system costs from the first part of the sensitivity analysis of Scenario 2 (Biogas-to-liquid + 130 MW data center).

6.2 Part 2: Comparing Scenario 2 against Scenario 1 by varying the price of biomethane and synfuels

The second part includes an analysis of how changes in the price of biomethane and synfuels can shift the most economically feasible scenario from Scenario 2 to Scenario 1. Biomethane and synfuels have a large influence on Scenario 2 since large amounts are being imported and exported. In order to produce 25% of the total demand of synfuels in Denmark, and supply biomethane for transport, CHP's and boilers Funen needs to import 20.2 PJ of biomethane at a price of 205.7 DKK/GJ. A large amount of this biomethane is used to produce synfuels at the fuel factory and since the production surpasses the local demand on Funen, 9.4 PJ is exported at a price of 371.0 DKK/GJ.

Changes in these fuel prices can have a large effect on the resulting fuel costs when such large amounts are being imported and exported. Therefore, it has been analysed how an increase in the price of biomethane and a decrease in the price of synfuels will affect the system cost of Scenario 2.

6.2.1 Results

The results of the second part of the sensitivity analysis can be seen in Figure 19, where the blue line shows the constant system cost of Scenario 1, the yellow line shows the system cost of Scenario 2 when increasing the price of biomethane and the green line shows the system cost of Scenario 2 when decreasing the price of synfuels.

As presented in the results of the socioeconomic analysis, the system costs of Scenario 1 and 2 have a difference of 783 MDKK, however when increasing the price of biomethane by 17.8% the price of the two scenarios equal each other. Furthermore, it can be seen that Scenario 2 is more robust to changes in the price of synfuels since a decrease of 33.1% is required in order for the two scenarios to equal each other.

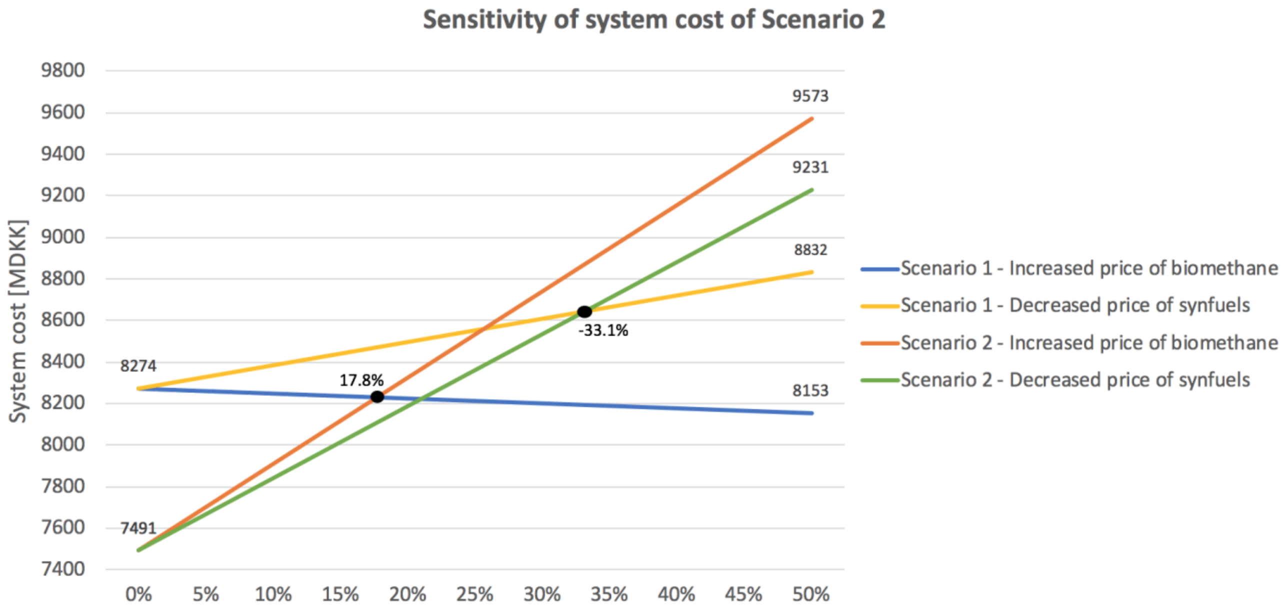

Figure 19: Visualization of increases in the system cost of Scenario 2 (Biogas-to-liquid + 130 MW data center), when increasing the price of biomethane and decreasing the price of synfuel.

As seen from the figure, Scenario 2 is generally more sensitive to changes in the two fuel prices since the gradient of the curves are steeper than the ones for Scenario 1.

It should be noted that an increase in the price of biomethane would actually decrease the system cost of Scenario 1, since 1.2 PJ of biomethane is exported while nothing is being imported.

Discussion

Recalling the initial problem statement in the introduction, Facebook announced that their eighth data center will be located just outside Odense, which necessitates an update of the recommendations for the development of the future Funish energy system. Furthermore, since the energy sector is in constant evolution, it would be relevant to update the recommendations from Energiplan Fyn's *Rammeplan* either way.

This project was purposed with analysing the impact of having a large data center located in Odense, and how the energy flow would be affected by this. Furthermore, it was stated that the energy system was to be based on the utilisation of excess heat and should aim to be more interactive between electricity production and the production of fuels, and this has been the fundamental approach throughout the project, which is also transparent in both the methodologies and the result sections in this report.

When analysing such a comprehensive system, the modelling is bound to be based on assumptions. Some of these assumptions will be discussed in this section, as well as the reasoning behind some of the ideas that have come up during the project. Furthermore, this section will be used to discuss other opportunities such as using Direct Air Capture to decrease the need for importing biomethane in Scenario 2.

Scenario 3 (No fuel factory + 254 MW data center)

As discussed in Section 3, the three scenarios that has been modelled for the future energy system, were based on system perspectives from an international analysis of the energy system. Fitting these perspectives to the energy system of Funen requires "an engineer's guess"[6], since it is extremely difficult to accurately predict such a detailed framework, 32 years in the future. Scenario 1 and 2 are designed by perspectives that are deemed more realistic, while Scenario 3 is added mainly as a comparison to the economics of producing synfuels, while it is not regarded as the most realistic of the scenarios. Furthermore, there are some aspects of the socioeconomic analysis, that would prove Scenario 3 to be even less feasible, which will be discussed along with the assumptions regarding the socioeconomic method later in this section.

[6] Qualified guess based on technical understanding and experience

Scenario 2 (Biogas-to-liquid + 130 MW data center)

At this point, Scenario 2 has been calculated as the most socioeconomically feasible scenario for the energy system of 2050. While the synfuel production in Scenario 2 has been chosen as 25% of the national demand, the system actually allows for even more production if heat produced from gas CHPs and heat pumps were reduced to a bare minimum. From the energy balances in Section 3.4.1, it can be seen, that to produce 1 PJ of synfuels, the Fischer-Tropsch only produce 0.09 PJ of excess heat, when utilisation in the steam reformer has been accounted for. This means that by only reducing heat pumps to their minimum, which was discussed in Section 3.5.1, it would be possible to produce an additional 28.8 PJ of synfuels, which is a production of 82% of the national demand. While this would yield a more economically feasible energy system, provided the fuel prices do not develop in a negative way, it might be too risky an investment as discussed later. However, this should be seen as an opportunity for Funen to be first-movers when it comes to the production of synfuels, since it might very well prove a profitable business case.

Socioeconomic analysis

The overall comparison of the energy systems in 2016, 2035 and 2050 are based mainly on the calculation of the socioeconomic system costs. While this is the widely used methodology of analysing energy systems, the framework for the development in the energy sector is partially based on political decisions and legislation, a true socioeconomic analysis, incorporating politics, has been outside the scope of this project. Furthermore, other elements of a full socioeconomic analysis have been left out due to complexity of the parameters. These parameters include job creation, growth of economy, decline in housing prices in relation to building large production units nearby, and growth in population. This is also the reason why Scenario 3 might be even less competitive, due to the loss of jobs from having less production units on Funen.

System costs in relation to Danish gross national product

In Section 4.2, the system costs of the scenarios for the future energy system were calculated and described. In that section, it was found that the system costs make up between 4.33% and 5.36% of the Funish GNP. In DEAs *Energiscenarier for 2020, 2035 og 2050*, it is stated that the energy system contributes to 5-7% of the national GNP. By that fact, the system costs in this project are a little low. However, recalling the discussion of the elements of the socioeconomic analysis that has been left out of this project. These parameters might just be the additional costs, that could bring the system costs up in between the 5-7%. Even though the system costs that has been calculated in this project are a little low, it still underlines the validity of this project.

Uncertainty related to projections of fuels prices and costs

Since this project deals with many new, and some untested technologies, the economic calculations are associated with some uncertainty since costs of operations and maintenance and investments decreases as a technology matures. For example, since 1990, the levelized cost of electricity for wind turbines, has decreases from approximately 0.23 USD/kWh to only 0.05 USD/kWh in 2016, corresponding to a decrease from 1.48 DKK/kWh to 0.32 DKK/kWh [42]. Therefore, all economic figures in this report are subject to changes, even though they are projected to future costs.

In the sensitivity analysis, it was found that a change of 17.8% and -33.1% for biomethane and synfuels respectively, would equal the system cost of Scenario 1 and 2. This means that Scenario 2 is very dependent on the future prices of biomethane and synfuels. Even though the large fuel production on Funen contributes to making Scenario 2 the most economically feasible scenario, it might not be considered favourable to build an entire energy system around a production that is relatively sensitive to changes in the fuel prices. Imagine the price of biomethane increasing by 50% of to the projected price. This would increase the system cost of Scenario 2 by almost 2.1 BDKK, justifying why it might be too risky to further increase the production on Funen from 25% of the national demand even though it is technical feasible to produce 82% of the national demand.

However, it should be mentioned that the fuel prices could also change in a direction that would further underline Scenario 2 being the most economically feasible scenario.

Using different methods for 2016 and the future scenarios

While the system costs of 2016, 2035 and 2050 are all within a margin that allows for comparison, it should be mentioned that these costs could be skewed, since the system costs of 2016 have been calculated using EnergyPLAN, which uses an hour-by-hour optimization analysis, which could offset the costs, since the system costs for 2035 and 2050 are all calculated manually, using Excel and by annual resulting energy flows. In 2016, some production units have been combined for simplicity, which could also offset the costs in either direction.

Full-load hours

As discussed earlier, since the project uses many new technologies, some only tested as pilot projects, the number of full-load hours, that are used to estimate the capacities, are based on “an engineer’s guess”. These full-load hours can influence the CAPEX and O&M costs considerably and to further investigate the robustness of the model, a sensitivity analysis of the full-load hours might be relevant.

Direct Air Capture

In Scenario 2, it would be interesting to investigate the feasibility of adding Direct Air Capture (DAC) to the production of synfuels by filtering CO_2 from the air. This would mean that more biomethane could be produced locally through methanation of CO_2, and the need to import biomethane would decrease. The captured CO_2 is then used in a Sabatier reactor which produces biomethane and water from CO_2 and hydrogen. The size of the DAC and Sabatier is based on the exported excess hydrogen from the Fischer-Tropsch process. Therefore, the energy of the exported hydrogen, of 2.1 PJ, dictates the size of the DAC and Sabatier by energy balances.
The reaction is described by Equation (D.1) [43]:

$$CO_2 + H_2 \rightarrow CH_4 + H_2O \tag{D.1}$$

However, this reaction is not balanced, after which it can be described as Equation (D.2):

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \tag{D.2}$$

Using the relative mass of the molecules of each component of the reaction by their molecular masses:

$$(44.009\ g)\ CO_2 + (8.064\ g)\ 4H_2 \rightarrow (16.043\ g)\ CH_4 + (36.03\ g)\ H_2O \tag{D.3}$$

Hydrogen has an energy density of 3.3 kWh/kg and biomethane an energy density of 15.4 kWh/kg. This means that for every reaction, the energy input of hydrogen is:

$$8.064\ g \cdot 33.3 \frac{kWh}{kg} = 0.269\ kWh \tag{D.4}$$

And the output energy of biomethane is:

$$16.043\ g \cdot 15.4 \frac{kWh}{kg} = 0.247\ kWh \tag{D.5}$$

While the rest of the energy is lost as heat, but this will not be included in this discussion.
Since we have 2.1 PJ of hydrogen, that means that the Sabatier reactor can perform a total of:

$$\frac{569{,}910{,}000\ kWh}{0.269\ kWh} = 2{,}118{,}624{,}535.3\ reactions \tag{D.6}$$

Going back to the relative mass of CO_2 for each reaction, it was given as 44.009 g. This yields a CO2 mass input of:

$$44.009\ g \cdot 2{,}118{,}624{,}535.3 = 93{,}238{,}547{,}174\ g \approx 93{,}238.5\ ton \tag{D.7}$$

Climeworks, whom develops DAC units estimates that the price of capturing CO_2 will decrease to \$100/ton CO_2 [44]. This would mean that the cost of acquiring these 93,238.5 ton of CO_2 would cost:

$$93{,}238.5\ t \cdot 100\ \$/t \cdot 6.3\ DKK/USD = 58{,}740{,}255\ DKK \tag{D.8}$$

This input in the Sabatier reactor would produce an additional biomethane of:

$$0.247\ kWh \cdot 2{,}118{,}624{,}535.3 = 523{,}300{,}260.2\ kWh \approx 1.884\ PJ \tag{D.9}$$

The fuel price of biomethane is 205.7 DKK/GJ, which means that using DAC to produce biomethane saves 388 MDKK, compared to the relatively low production cost of 58.7 MDKK. Including the added Investment and O&M for the Sabatier process, which prices are assumed to be the same as for CO_2 hydrogenation, the change in overall system costs would then be the savings from importing less biomethane minus the costs for DAC and lost export of hydrogen:

$$\begin{aligned} 1{,}884{,}000{,}000\ GJ \cdot 205{,}7\frac{DKK}{GJ} - 58{,}700{,}000\ DKK - 15{,}800{,}000\ DKK \\ - 2{,}100{,}000{,}000\ GJ \cdot 125.1\ DKK/GJ = 50{,}328{,}800\ DKK \end{aligned} \tag{D.10}$$

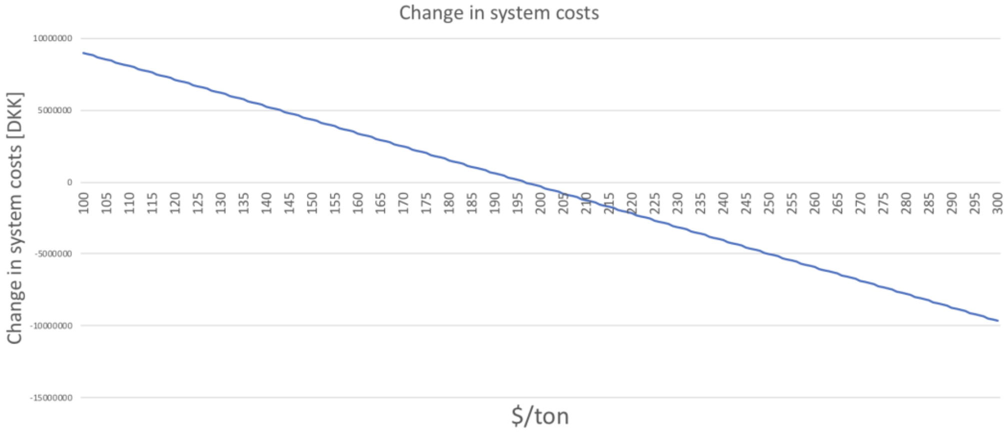

Figure 20: Graph showing the breakeven point of the price of DAC in relation to the change in system costs of Scenario 2. Here, the price of DAC of which results in no change in system cost is $196.5/t, or 1,338.75 DKK/t.

For the addition of DAC to result in no change in system costs, the price per ton can be as high as $196.5/ton, which is illustrated in Figure 20. DAC could also be used to reduce the consumption of biomass since, as mentioned briefly in Section 3.1, biomass could very well be a scarce resource. A schematic of DAC implemented in Scenario 2 can be seen in Figure 21.

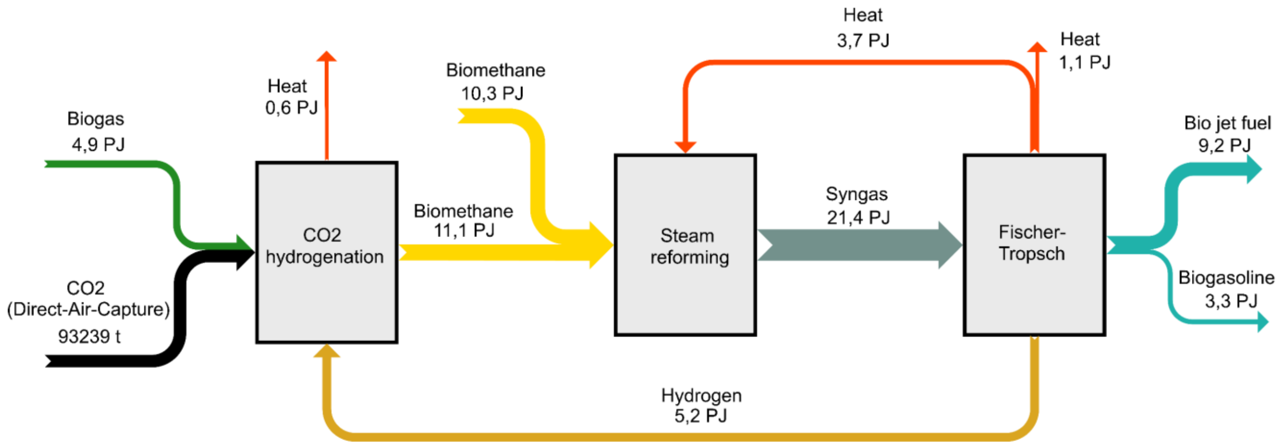

Figure 21: Schematic of biogas-to-liquid when additional CO_2 is added through Direct Air Capture to increase the output of biomethane for hydrogenation and decrease the need to import.

It would be interesting to investigate the prospects of becoming self-sufficient on account of biomethane as well. Installing additional DAC capacity to be able to produce the previously imported 14.1 PJ combined with 6.3 PJ for gas turbines, CHP's and transport in Scenario 2, would require DAC to capture approximately 990,000 ton of CO_2. Given the same cost of $100/ton the system cost of being self-sufficient would increase to 10.1 BDKK. This increase would result in not only Scenario 1 being more economically feasible but also Scenario 2 having a higher system cost than the system of 2016. This increase in system costs is largely due to the large capacity of electrolysis, high import of electricity and a large investment cost of DAC.

The most feasible size of the DAC system remains as sized by the excess hydrogen from the Fischer-Tropsch unit in Scenario 2.

Interconnecting district heating networks on Funen

The main issue with the fuel production of Scenario 1 is, as described earlier, the restriction in excess heat from thermal gasification and Fischer-Tropsch. However, a report from SDU, *Feasibility Study of Interconnections between District Heating Networks on Funen,* investigates the feasibility of interconnecting the district heating networks on Funen [45]. In this report, it is concluded, that optimizing for the production and exchange of heat, when Odense is connected to both Nyborg and Ringe, yields that it would be feasible to export approximately 0.7 PJ of heat combined to Nyborg and Ringe [Appendix A.10]. If this heat were produced as excess heat from the fuel factory, the production of synfuels could be increased by 1.1 PJ of synfuels which alone would contribute with a revenue of 259 MDKK.

In Scenario 3, the interconnection would mean that an additional 22 MW of data center capacity could be installed in Odense, increasing the heat capacity from 253.9 MW to 273.9 MW, and providing 8.64 PJ of heat.

Conclusion

The current energy system of Funen, located in Denmark, has been analysed in detail and modelled in EnergyPLAN. Furthermore, it has been analysed from three scenarios, how the energy system of Funen should be constructed in 2050, in order to comply with the national climate goal of becoming independent from fossil fuels in 2050.

As seen from Figure 22, it can be concluded that the most economically feasible way of designing the future energy system of 2050, is by producing synfuels on Funen using biogas-to-liquid technologies (Scenario 2). This is done by producing biomethane from the local potential of straw and manure, as well as importing biomethane, and using this biomethane to produce syngas in a steam reformer, which is the input of the Fischer-Tropsch process where synfuels are produced.

As can be seen from the figure this results in the lowest annual system cost of 7491 MDKK.

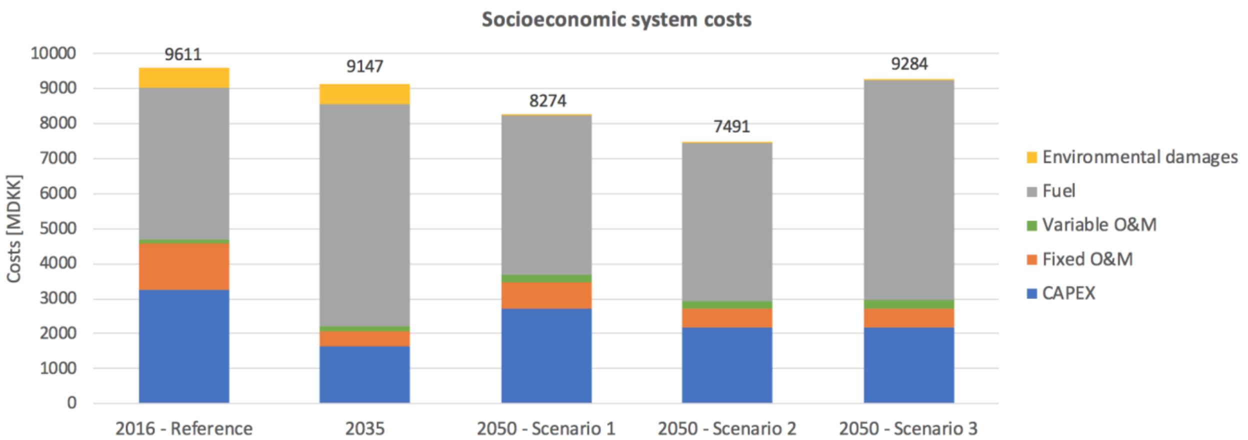

Figure 22: Breakdown of resulting socioeconomic system costs for the reference system of 2016, the roadmap system of 2035 and the three future scenarios of 2050.

In Scenario 2, the fuel factory has a capacity of approximately 700 MW meaning that it is able to produce around 25% of the national demand of synfuels. It is possible to increase the production to 40% of the national synfuel demand by lowering the heat production from other units connected to the district heating network of Odense. However, a sensitivity analysis of the model for Scenario 2 showed, that the system cost is relatively sensitive to changes in the price of biomethane and synfuels since such large amounts are being imported and exported. An increase in the price of biomethane of 17.8% or a decrease in the price of synfuels of 33.1% would shift the most economically feasible scenario from Scenario 2 to 1. It was also found, that by increasing the price of biomethane by 50% the system cost of Scenario 2 would increase by 2.1 BDKK, which is why it might not be feasible to

further increase the production of synfuels from 25% to 40%, since the energy system, including the supply of excess heat from the fuel factory, would be quite dependent on the production of synfuels. Comparing Scenario 2 for the future Funish energy system of 2050 with the reference energy system of 2016, it can be concluded that by phasing out fossil fuels, producing synfuels and utilizing the excess heat generated in Facebook's data center, industrial process and the fuel factory, the savings are in the total amount of 2.12 BDKK.
From the analysis of the future energy system of 2035, which serves as a roadmap towards the energy system of 2050, it can be concluded that major changes in the energy system between 2016 and 2035 should focus on:

- Phasing out fossil fuels used in heat and power production.
- Integrating more excess heat in the district heating networks, both in Odense and in the remaining district heating networks on Funen.
- Utilizing the potential of local resources of straw and manure on Funen to produce biogas and upgrading the biogas to biomethane using methanation by CO_2 hydrogenation. The hydrogen used in the methanation process should be produced from electrolysis utilizing the excess electricity produced from wind and solar power.
- Install a pilot project of a fuel factory using biogas-to-liquid technologies (steam reforming and Fischer-Tropsch) in order to discover eventual challenges and pitfalls related to producing synfuels on Funen.

In 2035 the transport sector is still expected to be mainly based on fossil fuels, expect for the small amount being produced at the pilot fuel factory. The largest transition from fossil to synthetic fuels in the transport sector will happen between 2035 and 2050 when a large-scale fuel factory has been constructed.

Furthermore, the opportunity of implementing Direct Air Capture in Scenario 2 has been investigated. It can be concluded that by using a Sabatier process to produce biomethane from CO_2 and the excess hydrogen from the Fischer-Tropsch process, the total savings in system costs amounts to 50.3 MDKK.
Finally, the feasibility of interconnecting the district heating network of Odense with the networks in Nyborg and Ringe was investigated. It was found, that by exporting excess heat from the fuel factory in Scenario 1, it is possible to increase the capacity of the fuel factory, making Funen self-sufficient in synfuel consumption, while being able to export excess synfuel to a value of 259 MDKK.

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Appendix

A.1 Capacities

	Capacities				
	2016	2035	2050 - Scenario 1	2050 - Scenario 2	2050 - Scenario 3
	MW	MW	MW	MW	MW
Onshore wind power	228	264,1	440,1	440,1	440,1
Photovoltaics - Large	58	482,6	965,2	965,2	965,2
Solar thermal district heating	45	32,6	32,6	32,6	32,6
Boiler - Waste	204	29,2	29,2	29,2	29,2
Boiler - Gas - Process	360	174,7	132,9	132,9	132,9
Boiler - Gas - DH	419	0,0	0,0	0,0	0,0
Boiler - Biomass - DH	629	71,5	0,0	0,0	0,0
Boiler - Biomass - Process	127	60,3	60,3	60,3	60,3
Boiler - Electric - Process	0	66,7	0,0	0,0	0,0
Boiler - Coal - Process	43	0,0	0,0	0,0	0,0
Boiler - Oil - Process	353	0,0	0,0	0,0	0,0
CHP - Gas - Central	0	86,8	30,8	30,8	30,8
CHP - Large scale	405	0,0	0,0	0,0	0,0
CHP - Gas - Decentral	0	32,7	32,7	32,7	32,7
CHP - Small scale	252	0,0	0,0	0,0	0,0
CHP - Gas - Process	0	7,6	7,6	7,6	7,6
Heat pump - DH	0	393,5	577,0	1022,4	577,0
Heat pump - Data center	0	128,1	128,1	128,1	253,9
Heat pump - Process	0	162,8	271,3	271,3	271,3
Biogas plant	21	227,3	227,3	227,3	227,3
Methanation - CO2 Hydrogenation	0	170,4	340,7	340,7	340,7
Thermal gasification	0	0,0	397,8	0,0	0,0
Water-Gas Shift	0	0,0	99,4	0,0	0,0
Steam reforming	0	74,1	0,0	1190,0	0,0
Fischer-Tropsch	0	55,6	382,5	697,4	0,0
Electrolysis	0	72,6	392,4	0,0	197,6
Individual boilers - Gas	440	11,8	11,8	11,8	11,8
Individual heat pumps	-	464,5	774,1	774,1	774,1
Individual boilers - Biomass	553	466,7	157,9	157,9	157,9
Individual boilers - Oil	127	0,0	0,0	0,0	0,0
Pit Thermal Energy Storage [GWh]	5	91,4	91,4	91,4	524,0

A.2 Investment costs

A.2.1 2035

	Investment SP35/TC unit	Investment (TC/SP35)
Onshore wind	M€/MW	0,89
Photovoltaics - Large	M€/MW	0,66
Solar thermal district heating	M€/MW	0,46
Boiler - Waste	M€/MW	1,86
Boiler - Gas - Process	M€/MW	0,09
Boiler - Biomass - DH	M€/MW	0,8
Boiler - Biomass - Process	M€/MW	0,8
Boiler - Electric - Process	M€/MW	0,14
CHP - Gas - Central	M€/MW	0,82
CHP - Gas - Decentral	M€/MW	0,89
CHP - Gas - Process	M€/MW	0,89
Heat pump - DH	M€/MW	0,58
Heat pump - Data center	M€/MW	0,58
Heat pump - Process	M€/MW	0,56
Biogas plant	M€/MW	0,395
Methanation	M€/MW	0,177
Steam reforming	M$	13,844
Fischer Tropsch	M€/MW	0,177
Electrolysis	M€/MW	0,949
Individual boilers - Gas	M€/MW	0,4
Individual heat pumps	M€/MW	0,98
Individual boilers - Biomass	M€/MW	0,6
Pit Thermal Energy Storage	€/m3	35

A.2.2 2050: Scenario 1 – Biomass-to-liquid + 130 MW data center

	Investment	
	SP35/TC unit	Investment (TC/SP35)
Onshore wind	M€/MW	0,83
Photovoltaics - Large	M€/MW	0,56
Solar thermal district heating	M€/MW	0,46
Boiler - Waste	M€/MW	1,74
Boiler - Gas - Process	M€/MW	0,09
Boiler - Biomass - Process	M€/MW	0,8
CHP - Gas - Central	M€/MW	0,8
CHP - Gas - Decentral	M€/MW	0,85
CHP - Gas - Process	M€/MW	0,85
Heat pump - DH	M€/MW	0,53
Heat pump - Data center	M€/MW	0,53
Heat pump - Process	M€/MW	0,525
Biogas plant	M€/MW	0,395
Methanation	M€/MW	0,177
Gasification	M€/MW	2,016
Water-Gas Shift	M€/MW	0,072
Fischer Tropsch	M€/MW	0,177
Electrolysis	M€/MW	0,633
Individual boilers - Gas	M€/MW	0,4
Individual heat pumps	M€/MW	0,9
Individual boilers - Biomass	M€/MW	0,6
Pit Thermal Energy Storage	€/m3	35

A.2.3 2050: Scenario 2 – Biogas-to-liquid + 130 MW data center

	Investment	
	SP35/TC unit	Investment (TC/SP35)
Onshore wind	M€/MW	0,83
Photovoltaics - Large	M€/MW	0,56
Solar thermal district heating	M€/MW	0,46
Boiler - Waste	M€/MW	1,74
Boiler - Gas - Process	M€/MW	0,09
Boiler - Biomass - Process	M€/MW	0,8
CHP - Gas - Central	M€/MW	0,8
CHP - Gas - Decentral	M€/MW	0,85
CHP - Gas - Process	M€/MW	0,85
Heat pump - DH	M€/MW	0,53
Heat pump - Data center	M€/MW	0,53
Heat pump - Process	M€/MW	0,525
Biogas plant	M€/MW	0,395
Methanation	M€/MW	0,177
Steam reforming	M$	13,844
Fischer Tropsch	M€/MW	0,177
Electrolysis	M€/MW	0,633
Individual boilers - Gas	M€/MW	0,4
Individual heat pumps	M€/MW	0,9
Individual boilers - Biomass	M€/MW	0,6
Pit Thermal Energy Storage	€/m3	35

A.2.4 2050: Scenario 3 – No fuel factory + 254 MW data center

	Investment	
	SP35/TC unit	Investment (TC/SP35)
Onshore wind	M€/MW	0,83
Photovoltaics - Large	M€/MW	0,56
Solar thermal district heating	M€/MW	0,46
Boiler - Waste	M€/MW	1,74
Boiler - Gas - Process	M€/MW	0,09
Boiler - Biomass - Process	M€/MW	0,8
CHP - Gas - Central	M€/MW	0,8
CHP - Gas - Decentral	M€/MW	0,85
CHP - Gas - Process	M€/MW	0,85
Heat pump - DH	M€/MW	0,53
Heat pump - Data center	M€/MW	0,53
Heat pump - Process	M€/MW	0,525
Biogas plant	M€/MW	0,395
Methanation	M€/MW	0,177
Electrolysis	M€/MW	0,531
Individual boilers - Gas	M€/MW	0,4
Individual heat pumps	M€/MW	0,9
Individual boilers - Biomass	M€/MW	0,6
Pit Thermal Energy Storage	€/m3	35

A.3 Fixed O&M costs

A.3.1 2035

	Fixed O&M SP35/TC unit	Fixed O&M (TC/SP35)
Onshore wind	€/MW	22025
Photovoltaics	€/MW	8450
Solar thermal district heating	€/MW	0
Boiler - Waste	€/MW	77000
Boiler - Gas - Process	€/MW	3500
Boiler - Biomass - DH	€/MW	0
Boiler - Biomass - Process	€/MW	0
Boiler - Electric - Process	€/MW	1020
CHP - Gas - Central	€/MW	27350
CHP - Gas - Decentral	€/MW	9100
CHP - Gas - Process	€/MW	9100
Heat pump - DH	€/MW	2000
Heat pump - Data center	€/MW	2000
Heat pump - Process	€/MW	3650
Biogas plant	€/MW	55930
Methanation	€/MW	5308
Steam reforming	€	4424499,9
Fischer Tropsch	€/MW	5308
Electrolysis	€/MW	33228
Individual boilers - Gas	€/MW	4000
Individual heat pumps	€/MW	15000
Individual boilers - Biomass	€/MW	1600
Pit Thermal Energy Storage	€/m3	-

A.3.2 2050: Scenario 1 – Biomass-to-liquid + 130 MW data center

	Fixed O&M	
	SP35/TC unit	Fixed O&M (TC/SP35)
Onshore wind	€/MW	21200
Photovoltaics	€/MW	7400
Solar thermal district heating	€/MW	0
Boiler - Waste	€/MW	73011
Boiler - Gas	€/MW	3500
Boiler - Biomass - Process	€/MW	0
CHP - Gas - Central	€/MW	26000
CHP - Gas - Decentral	€/MW	8500
CHP - Gas - Process	€/MW	8500
Heat pump - DH	€/MW	2000
Heat pump - Data center	€/MW	2000
Heat pump - Process	€/MW	3650
Biogas plant	€/MW	60162
Methanation	€/MW	5308
Gasification	€/MW	41599
Water-Gas Shift	€/MW	3512
Fischer Tropsch	€/MW	5308
Electrolysis	€/MW	18987
Individual boilers - Gas	€/MW	4000
Individual heat pumps	€/MW	15000
Individual boilers - Biomass	€/MW	1600
Pit Thermal Energy Storage	€/m3	-

A.3.3 2050: Scenario 2 – Biogas-to-liquid + 130 MW data center

	Fixed O&M	
	SP35/TC unit	Fixed O&M (TC/SP35)
Onshore wind	€/MW	21200
Photovoltaics	€/MW	7400
Solar thermal district heating	€/MW	0
Boiler - Waste	€/MW	73011
Boiler - Gas	€/MW	3500
Boiler - Biomass - Process	€/MW	0
CHP - Gas - Central	€/MW	26000
CHP - Gas - Decentral	€/MW	8500
CHP - Gas - Process	€/MW	8500
Heat pump - DH	€/MW	2000
Heat pump - Data center	€/MW	2000
Heat pump - Process	€/MW	3650
Biogas plant	€/MW	60162
Methanation	€/MW	5308
Steam reforming	€	4424499,9
Fischer Tropsch	€/MW	5308
Electrolysis	€/MW	18987
Individual boilers - Gas	€/MW	4000
Individual heat pumps	€/MW	15000
Individual boilers - Biomass	€/MW	1600
Pit Thermal Energy Storage	€/m3	-

A.3.4 2050: Scenario 3 – No fuel factory + 254 MW data center

	Fixed O&M	
	SP35/TC unit	Fixed O&M (TC/SP35)
Onshore wind	€/MW	21200
Photovoltaics	€/MW	7400
Solar thermal district heating	€/MW	0
Boiler - Waste	€/MW	73011,1104
Boiler - Gas	€/MW	3500
Boiler - Biomass - Process	€/MW	0
CHP - Gas - Central	€/MW	26000
CHP - Gas - Decentral	€/MW	8500
CHP - Gas - Process	€/MW	8500
Heat pump - DH	€/MW	2000
Heat pump - Data center	€/MW	2000
Heat pump - Process	€/MW	3650
Biogas plant	€/MW	60162
Methanation	€/MW	5308
Electrolysis	€/MW	26530,2
Individual boilers - Gas	€/MW	4000
Individual heat pumps	€/MW	15000
Individual boilers - Biomass	€/MW	1600
Pit Thermal Energy Storage	€/m3	-

A.4 Variable O&M costs

A.4.1 2035

	Variable O&M SP35/TC unit	Variable O&M (TC/SP35)
Onshore wind	€/MWh	2,3
Photovoltaics	€/MWh	0
Solar thermal district heating	€/MWh	0,57
Boiler - Waste	€/MWh input	8,4
Boiler - Gas - Process	€/MWh	1
Boiler - Biomass - DH	€/MWh	3,4
Boiler - Biomass - Process	€/MWh	3,4
Boiler - Electric - Process	€/MWh	1
CHP - Gas - Central	€/MWh	4,2
CHP - Gas - Decentral	€/MWh	5,1
CHP - Gas - Process	€/MWh	5,1
Heat pump - DH	€/MWh	3,7
Heat pump - Data center	€/MWh	3,7
Heat pump - Process	€/MWh	3,7
Biogas plant	€/MWh	0
Methanation	€/MWh	0
Steam reforming	€/MWh	0
Fischer Tropsch	€/MWh	0
Electrolysis	€/MWh	0
Individual boilers - Gas	€/MWh	0
Individual heat pumps	€/MWh	0
Individual boilers - Biomass	€/MWh	0
Pit Thermal Energy Storage	€/MWh	0

A.4.2 2050: Scenario 1 – Biomass-to-liquid + 130 MW data center

	Variable O&M	
	SP35/TC unit	Variable O&M (TC/SP35)
Onshore wind	€/MWh	2,1
Photovoltaics	€/MWh	0
Solar thermal district heating	€/MWh	0,57
Boiler - Waste	€/MWh input	8,7
Boiler - Gas	€/MWh	1
Boiler - Biomass - Process	€/MWh	3,7
CHP - Gas - Central	€/MWh	4
CHP - Gas - Decentral	€/MWh	4,6
CHP - Gas - Process	€/MWh	4,6
Heat pump - DH	€/MWh	3,9
Heat pump - Data center	€/MWh	3,9
Heat pump - Process	€/MWh	3,9
Biogas plant	€/MWh	0
Methanation	€/MWh	0
Gasification	€/MWh	0,7
Water-Gas Shift	€/MWh	0
Fischer Tropsch	€/MWh	0
Electrolysis	€/MWh	0
Individual boilers - Gas	€/MWh	0
Individual heat pumps	€/MWh	0
Individual boilers - Biomass	€/MWh	0
Pit Thermal Energy Storage	€/MWh	0

A.4.3 2050: Scenario 2 – Biogas-to-liquid + 130 MW data center

	Variable O&M	
	SP35/TC unit	Variable O&M (TC/SP35)
Onshore wind	€/MWh	2,1
Photovoltaics	€/MWh	0
Solar thermal district heating	€/MWh	0,57
Boiler - Waste	€/MWh input	8,7
Boiler - Gas	€/MWh	1
Boiler - Biomass - Process	€/MWh	3,7
CHP - Gas - Central	€/MWh	4
CHP - Gas - Decentral	€/MWh	4,6
CHP - Gas - Process	€/MWh	4,6
Heat pump - DH	€/MWh	3,9
Heat pump - Data center	€/MWh	3,9
Heat pump - Process	€/MWh	3,9
Biogas plant	€/MWh	0
Methanation	€/MWh	0
Steam reforming	€/MWh	0
Fischer Tropsch	€/MWh	0
Electrolysis	€/MWh	0
Individual boilers - Gas	€/MWh	0
Individual heat pumps	€/MWh	0
Individual boilers - Biomass	€/MWh	0
Pit Thermal Energy Storage	€/MWh	0

A.4.4 2050: Scenario 3 – No fuel factory + 254 MW data center

	Variable O&M	
	SP35/TC unit	Variable O&M (TC/SP35)
Onshore wind	€/MWh	2,1
Photovoltaics	€/MWh	0
Solar thermal district heating	€/MWh	0,57
Boiler - Waste	€/MWh input	8,7
Boiler - Gas	€/MWh	1
Boiler - Biomass - Process	€/MWh	3,7
CHP - Gas - Central	€/MWh	4
CHP - Gas - Decentral	€/MWh	4,6
CHP - Gas - Process	€/MWh	4,6
Heat pump - DH	€/MWh	3,9
Heat pump - Data center	€/MWh	3,9
Heat pump - Process	€/MWh	3,9
Biogas plant	€/MWh	0
Methanation	€/MWh	0
Electrolysis	€/MWh	0
Individual boilers - Gas	€/MWh	0
Individual heat pumps	€/MWh	0
Individual boilers - Biomass	€/MWh	0
Pit Thermal Energy Storage	€/MWh	0

A.5 Fuel prices

Fuel prices													
DKK/GJ	Fossil/renewable	Coal CHP	Oil CHP	Methane CHP	Hydrogen	Biomass CHP	Wood Chips CHP/Fuel factory	Wood pellets Consumer	Straw Plant	Diesel (6.5% biodiesel) Consumer	Gasoline (4.6% bioethanol) Consumer	Jet Fuel Consumer	Waste CHP
2016	Fossil	17,8	68,4	53,2	-	72,0	67,6	120,8	55,6	153,0	164,2	105,2	54,0
2020	Fossil	24,4	92,5	54,7	-	74,5	69,2	139,2	56,9	181,4	181,1	131,2	0,0
2035	Fossil	33,6	149,2	103,9	-	85,0	76,6	155,3	62,2	224,1	223,8	173,8	0,0
2050	Renewable	36,2	200,2	205,7	125,1	93,5	84,1	171,4	67,4	371,0	371,0	371,0	0,0

A.6 Environmental damage costs

	Damage costs								
	CO2 - 2016	CO2 - 2035 & 2050	CH4* - 2016	CH4* - 2035 & 2050	N2O* - 2016	N2O* - 2035 & 2050	SO2	NOx	PM2.5
	DKK/kg	DKK/kg	DKK/g	DKK/g	DKK/g	DKK/g	DKK/g	DKK/g	DKK/g
SNAP 1: Large plants incl. waste incineration	0,059	0,438	0,001	0,011	0,018	0,130	0,010	0,007	0,022
SNAP 2: Household plants	0,059	0,438	0,001	0,011	0,018	0,130	0,030	0,018	0,085
SNAP 3: Industrial combustion plants	0,059	0,438	0,001	0,011	0,018	0,130	0,014	0,009	0,028
SNAP-All: Average of all sectors within DK	0,059	0,438	0,001	0,011	0,018	0,130	0,029	0,016	0,093

A.7 Emission coefficients

	Emission coefficients					
	CO2	CH4	N2O	SO2	NOx	PM2.5
	kg/GJ	g/GJ	g/GJ	g/GJ	g/GJ	g/GJ
Natural gas - Cen./Decen. CHP avg.	57,1	1,4	1,0	0,4	51,5	0,1
Coal	94,5	0,9	0,8	10,0	29,0	2,1
Fuelolie	79,2	0,8	0,3	100,0	138,0	2,5
Biomass	0,0	1,5	1,0	30,2	107,4	2,6
Waste	37,0	0,3	1,2	8,3	102,0	0,3
Wood chips - Boiler	0,0	11,0	4,0	11,0	90,0	10,0
Wood pellets - Individual	0,0	3,0	4,0	11,0	80,0	29,0
Natural gas - Central CHP	0,0	1,0	1,0	0,4	55,0	0,1
Biogas - Central CHP	0,0	1,0	1,0	0,4	55,0	0,1
Natural gas - Decentral CHP	0,0	1,7	1,0	0,4	48,0	0,1
Natural gas - Boiler (present)	57,1	1,0	1,0	0,4	33,0	0,1
Natural gas - Boiler (future)	0,0	1,0	1,0	0,4	33,0	0,1
Natural gas - Individual (present)	57,1	1,0	1,0	0,4	24,3	0,1
Natural gas - Individual (future)	0,0	1,0	1,0	0,4	24,3	0,1
Methane - Passenger cars (present)	56,8	2,3	0,4	0,0	10,2	0,4
Gasoline - Passenger cars (present)	73,0	4,8	0,9	0,5	79,5	0,6
Gasoline - Passenger cars (future)	0,0	4,8	0,9	0,0	79,5	0,6
Diesel - International sea traffic (present)	74,0	1,8	1,9	46,8	1590,1	22,6
Methane - National sea traffic (present)	56,8	263,1	0,0	0,0	161,6	8,4
Methane - Heavy duty vehicles (present)	56,8	0,1	3,6	0,0	49,4	0,6
Methane - Passenger cars (future)	0,0	2,3	0,4	0,0	10,2	0,4
Methane - National sea traffic (future)	0,0	263,1	0,0	0,0	161,6	8,4
Methane - Heavy duty vehicles (future)	0,0	0,1	3,6	0,0	49,4	0,6
Gasoline - Heavy duty vehicles (present)	73,0	16,0	0,9	0,5	671,4	0,0
Gasoline - Heavy duty vehicles (future)	0,0	16,0	0,9	0,0	671,4	0,0
Jetfuel/kerosene - Air traffic, Int. > 3000 ft. (present)	72,0	0,0	2,3	23,0	315,0	4,4
Jetfuel/kerosene - Air traffic, Int. > 3000 ft. (future)	0,0	0,0	2,3	23,0	315,0	4,4
Gasoil - Individual	74,0	0,7	0,7	23,0	52,0	5,0
Firewood - Individual	0,0	140,0	4,0	11,0	75,0	501,0
Diesel - Passenger cars/Heavy duty vehicles avg.	74,0	0,7	3,6	0,5	271,1	5,7

A.8 E-mail correspondance with Klaus Bernhof Jakobson, DBI IT A/S

På følgende link (https://ens.dk/sites/ens.dk/files/Statistik/estat2016.pdf)(side 12) kan du finde nedenstående tabel.

Elproduktion fordelt efter anvendt brændsel

Direkte energiindhold [TJ]	1994	2000	2005	2010	2014	2015	2016	Ændring '94 - '16
Elproduktion i alt (brutto)	**144 707**	**129 776**	**130 469**	**139 906**	**115 857**	**104 205**	**109 877**	**-24,1%**
Olie	9 547	15 964	4 933	2 783	1 137	1 122	1 159	-87,9%
- heraf orimulsion	-	13 467	-	-	-	-	-	•
Naturgas	8 206	31 589	31 606	28 464	7 518	6 499	7 798	-5,0%
Kul	119 844	60 022	55 666	61 222	39 828	25 596	31 915	-73,4%
Overskudsvarme	-	139	-	-	-	-	-	•
Affald, ikke-bionedbrydeligt	836	2 002	2 938	2 689	2 607	2 706	2 542	204%
Vedvarende energi	**6 275**	**20 060**	**35 326**	**44 749**	**64 768**	**68 283**	**66 464**	**959%**
Solenergi	-	4	8	22	2 144	2 175	2 678	•
Vindkraft	4 093	15 268	23 810	28 114	47 083	50 879	46 014	1024%
Vandkraft	117	109	81	74	54	65	69	-40,9%
Biomasse	1 743	3 928	10 410	15 253	13 837	13 396	15 639	797%
- Halm	293	654	3 088	3 968	2 293	2 080	2 294	684%
- Træ	429	828	3 730	7 998	8 358	7 987	10 228	2281%
- Bioolie	-	0	1	1	-	22	10	•
- Affald, bionedbrydeligt	1 021	2 447	3 591	3 286	3 186	3 307	3 107	204%
Biogas	321	751	1 017	1 285	1 649	1 768	2 063	543%

Output'et viser den aggregerede elproduktion fordelt på brændsler i hele DK.
Ca. 6,5% af nettilsluttede MW solcelleanlæg er placeret på Fyn (sortering for postnumrene 5000-5999).
Hvis det antages, at alle solcelleanlæg producerer lige meget, kan denne procentsats anvendes som fordelingsnøgle for solcelleproduktion på Fyn.

På følgende link (https://ens.dk/sites/ens.dk/files/Statistik/estat2016.pdf)(side 17) kan du finde nedenstående tabel.

Fjernvarmeproduktion fordelt efter anvendt brændsel

Direkte energiindhold [TJ]	1994	2000	2005	2010	2014	2015	2016	Ændring '94 - '16
Produktion i alt (brutto)	**113 103**	**119 702**	**128 382**	**150 393**	**122 944**	**129 948**	**135 687**	**20,0%**
Olie	6 335	4 433	6 103	4 627	1 155	1 405	1 383	-78,2%
- heraf orimulsion	-	1 291	-	-	-	-	-	
Naturgas	25 370	41 620	39 377	44 844	23 363	23 649	25 291	-0,3%
Kul	55 748	38 873	34 189	36 337	24 648	26 050	24 917	-55,3%
Overskudsvarme	2 838	3 676	3 174	2 518	2 921	3 131	3 448	21,5%
El, ekskl. varmepumper	-	-	-	110	388	1 036	697	•
El, varmepumper	12	1	-	0	14	29	32	177%
Affald, ikke-bionedbrydeligt	6 084	8 651	10 713	10 627	11 396	12 251	12 583	107%
Vedvarende energi	**16 715**	**22 448**	**34 826**	**51 331**	**59 058**	**62 398**	**67 336**	**303%**
Solenergi	6	24	53	139	735	956	1 482	25689%
Geotermi	21	29	86	106	83	70	112	430%
Biomasse	16 304	21 462	33 509	49 912	56 317	59 106	62 982	286%
- Halm	4 318	5 696	7 681	11 507	9 860	11 295	11 059	156%
- Træ	4 327	5 153	12 086	23 731	31 851	32 329	36 305	739%
- Bioolie	223	39	650	1 685	678	508	239	7,1%
- Affald, bionedbrydeligt	7 436	10 574	13 093	12 989	13 928	14 974	15 380	107%
Biogas	348	903	1 169	1 173	1 874	2 184	2 659	665%
Varmepumper	36	29	9	0	49	82	100	176%

Output'et viser den aggregerede fjernvarmeproduktion fordelt på brændsler i hele DK.
Et forslag til omregning kunne være at anvende den fynske andel af fjernvarmekunder i DK som fordelingsnøgle.
Dette vil selvfølgelig blot være en grov estimation af det reelle produktionstal for solvarme på Fyn.

A.9 E-mail correspondance with Michael Madsen, Danish Energy Agency

Hej Klaus

Det er korrekt.
Jeg, og min makker, er lige nu i gang med at lave vores bachelorprojekt, som går ud på at kortlægge energi systemet på Fyn i 2016, og komme med nogle forudsigelser om, hvordan det system vil se ud i 2035 og 2050.

Til vores analyse af energisystem i 2016, var vi inde og hente statistik for bestanden af elbiler i 2016. Det link, som vi havde gemt prøvede jeg at gå ind på i dag, da vi er gået i gang med at dokumentere vores arbejde, hvortil jeg kunne se, at det ikke findes mere - og det var derfor jeg kontaktede jer.
Det eneste tal jeg egentligt leder efter er antallet af registrerede elbiler i 2016. Jeg har selv noteret 9266, hvilket jeg håber stadig er tilfældet.

Venlig hilsen / Best regards

Jeppe Bay Pedersen

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Drewsensvej 10, 5000 Odense C

See More from Klaus Bernhof Jakobsen

Klaus Bernhof Jakobsen 18 May 2018 at 14.08
SV: Forespørgsel vedr. abonnement på bilstatistik.dk Details
To: Jeppe Bay Pedersen, Cc: Asger Vestergaard Laursen KJ

Hej Jeppe

Jeg beklager min sene tilbagemelding.

Tallet er helt korrekt og dækker over alle person- og varebiler indregistreret i Danmark, opgjort pr. 31/12-2016.

Venlig hilsen

Klaus Bernhof Jakobsen
Uddannelsesansvarlig

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A.10 Results from Feasibility Study of Interconnections between District Heating Networks on Funen

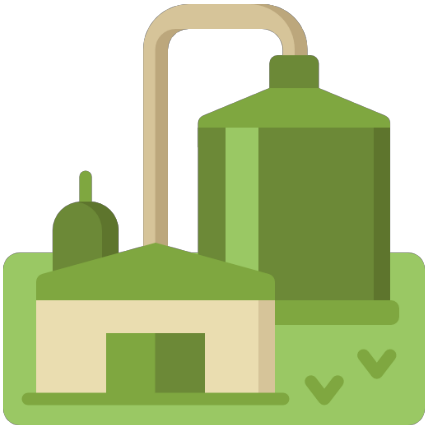
energyPRO 4.5.179

27-05-2018 22:26

Energiomsætning, Årlig

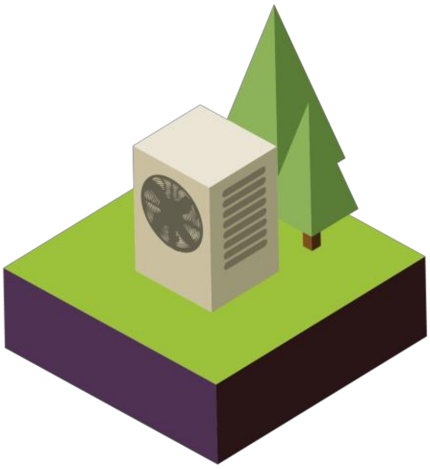
Beregnet periode:	01-2016 - 12-2016		
Odense			
Varmebehov:			
	Varmebehov Odense	2.557.225,20MWh	
	Max varmebehov	800,9MW	
Varmeproduktioner:			
	NYBlok7	500.075,30MWh/år	
	BLOK8	413.168,70MWh/år	
	FFA	835.200,00MWh/år	
	VPFacebook	1.004.687,60MWh/år	
	Sendt til Nyborg	-148.836,30MWh/år	
	Sendt fra, Nyborg	6,00MWh/år	
	Transmissionstab fra Nyborg	-878,40MWh/år	
	Sendt til Ringe	-50.617,70MWh/år	
	Sendt fra, Ringe	6.396,20MWh/år	
	Transmissionstab fra Ringe	-1.976,40MWh/år	
	Total	2.557.225,20MWh/år	100,00%
Ringe			
Varmebehov:			
	Varmebehov Ringe	72.491,00MWh	
	Max varmebehov	20,30MW	
Varmeproduktioner:			
	TræpilleKedel	3,70MWh/år	
	NaturgasMotor	21,40MWh/år	
	NaturGasKedelRinge	0MWh/år	
	Solfanger	13.368,50MWh/år	
	Træfliskedel	16.852,30MWh/år	
	Sendt til Odense	-6.396,20MWh/år	
	Sendt fra, Odense	50.617,70MWh/år	
	Transmissionstab fra Odense	-1.976,40MWh/år	
	Total	72.491,00MWh/år	100,00%

A.11 Icons used for sankey diagrams



Icon made by [Freepik](#) from www.flaticon.com

Icon made by [Freepik](#) from www.flaticon.com



Icon made by https://flixboroughecotechnologies.co.uk/service/air-source-heat-pumps/