Socio-economic evaluation of centralized and decentralized renewable jet fuel production on Funen.

University: University of Southern Denmark

Faculty: The Faculty of Engineering

Study: Energy Technology (ENTEK)

Project period: 1st of February-2nd of June 2020.

Supervisors: Lars Yde & Abid Rabbani

Character count: 119.507

2nd of June-2020

Delivery Date

Alexander Nielsen

Alexander Nielsen

Exam number: 84930228

Abstract

The world is facing a future where sustainability is in high focus. Denmark is no exception. Denmark is subject to the Paris agreement [1]. The overall mitigation for the Paris agreement is reducing the emission of greenhouse gases [1]. Denmark further has the goal to be a CO_2 neutral society by 2050 [2].
Denmark has already taken a leap towards reduced emission of greenhouse gases, by being the leading country of wind energy per capita [3].
Further replacement of fossil-fueled facilities is needed to meet the goal of the Paris agreement and the vision of being a CO_2 neutral society by 2050.
One sector which needs replacement is the transportation sector. The international transport sector in Denmark represents almost 50% of the total emission of greenhouse gases [4].

This paper investigates the socio-economic cost of renewable jet fuel on Funen, by only including the available biogas on Funen. The biogas potential of Funen is the initial condition, which is limiting the potential of jet fuel production.
The investigation includes two scenarios with two different pathways of producing renewable jet fuel.
The two scenarios are; A centralized scenario, where the LCOE of renewable jet fuel is evaluated with one centralized facility in Odense. The second scenario is a decentralized scenario, where the LCOE of renewable jet fuel is evaluated based on 8 decentralized small-scale FT facilities on Funen.
For each of the scenarios, two pathways are investigated. The differences in the pathways are the method of syngas production. One pathway is syngas production with partial oxidation and another pathway with steam methane reforming for syngas production.
Through calculations, the partial oxidation pathway produces more jet fuel than the steam methane reforming pathway.
Based on assumptions and calculations. It is found that the centralized scenario, with the partial oxidation pathway of jet fuel production on Funen, is the cheapest regarding socioeconomic LCOE.
Through investigation, integration of the facilities does not seems to be a problem, as no complications were found in the availability of the gas grid or delivery of the gas.

Table of contents.

Contents

List of figures

List of tables

List of equations

List of Abbreviations and Acronyms

AEC - Alkaline electrolysis cell

BBL – Barrel

BPD – Barrel per day

CAPEX – Capital cost

$C_{11}H_{24}$ – Undecane

$C_{23}H_{48}$ – Tricosane

CH_4 – Methane

CO – Carbon monoxide

$CO+2H_2$ – Syngas (Partial oxidation)

$CO+3H_2$ – Syngas (Steam methane reformer)

CO_2 – Carbon dioxide

FT – Fischer Tropsch

GHG – Greenhouse gases.

GJ – Giga joule

GTL – Gas to liquid

H_2 – Hydrogen

H_2S – Hydrogen sulfide

HH – High/High

HL – High/Low

HTFT – High-temperature Fischer Tropsch

HHV – Higher Heating value

JF – Jet fuel

kJ – Kilo joule

LCOE – Levelized cost of energy

LF – Liquid fuel

LH – Low/High

LHV – Lower heating value

LL – Low/Low

LNG – Liquefied Natural Gas

LTFT – Low-temperature Fischer Tropsch

M/R station – Meter and Regulator station

MJ – Megajoule

MW – Megawatt

MWh – Megawatt hour

NPV – Net Present Value

O&M – Operation and maintenance.

OP – Other products

PEM – Proton exchange membrane

PJ – Peta joule

POX – Partial oxidation

Renewable JF – Renewable jet fuel.

SMR – Steam methane reformer.

Exchange rates:

100 € = 746 DKK [5]

100 $ = 93 € [6]

Conversion rates:

1 PJ = 1.000.000 GJ [7]

1 GJ = 1000 MJ [7]

1 MJ = 1000 kJ [7]

1 Wh = 3600 J [7]

1 BBL = 4,2 GJ

1 BBL = 119,2 liter [8]

1. Introduction

Achievement of the Danish goal of 100% GHG (Green-house gases) neutral society by 2050 makes it imperative to focus on how to reduce these emissions [2]. Among the highest contributors to GHG emissions is the transportation sector. Derived from Figure 1, the international transport sector represents 46% of the total GHG emissions in Denmark [4].

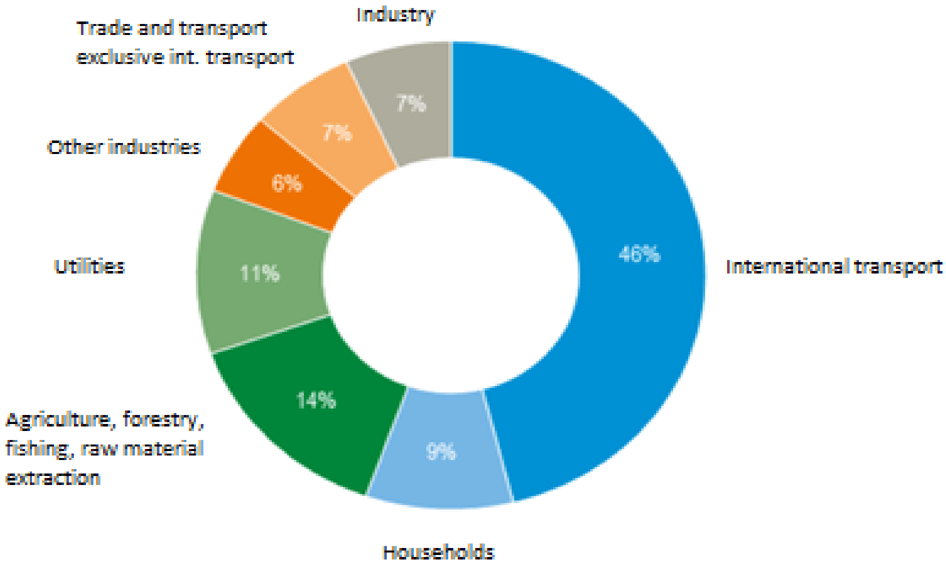


Figure 1: Percentage of GHG related to Danish economic activities

The massive GHG emission in the transportation sector is related to the carbon-content fuel used in international transport.
The CO_2 emission from the transportation sector is decreased by 15% from 2007 to 2018, and 0,5% from 2017 to 2018[9]. The prime reason for decreasing CO_2 emission is the increased range of cars and the introduction to electric vehicles. This development shows an increased focus on the CO_2 emission in the transportation sector, but with the goal of 100 % GHG neutral society by 2050, does it require further development and focus on decreasing the GHG emissions in the transportation sector.
One of the challenges to go towards an electrified transportation sector is the electrification of long-distance aviation, long-distance heavy road vehicles, and larger ships. These types of transportations require a tremendous amount of energy, which challenge the range [10]. Therefore, synthetic fuels are needed in the future.
The problem regarding carbon-content fuels is not that they emit CO_2 when combusted. The problem is that they are produced based on fossil fuels. Fossil-fuel-based production of fuel leaves an excess of CO_2. To achieve the Danish goal of 100% CO_2 neutral society by 2050, the replacement of fossil-fueled based production of fuel is needed.

Existing jet fuel is produced by fossil fuel, and are not environmentally friendly, and is not keeping up to the standards in the future with a CO_2 neutral society, the Paris agreement or UN's sustainable development goals; 7. (Affordable and clean energy), 12. (Responsible consumption and production) and 13. (Climate action)[11].
To move towards these goals makes it imperative to look at Renewable JF production.

1.1 What is jet fuel?

Jet fuel is a fuel used for the aviation industries and aircrafts powered by gas-turbines. The most used jet fuel is "Jet A" and "Jet A-1". These fuels are produced withing the standards of jet fuel international specifications [12].
The jet fuel consists of many different hydrocarbons, which is based on the source of petroleum. For that reason, it is almost impossible to define a ratio of hydrocarbons in jet fuel.
Therefore, jet fuel is considered as performance specifications rather than a chemical composition.
The hydrocarbon ratio is therefore defined, so that the jet fuel is within the international specifications, such as freezing point (-47 °C) and flashpoint (38 °C) [13].
Conventional jet fuel is mostly produced by crude oil, using fractional distillation in refineries. The jet fuel has a boiling point of 175 – 288 °C and defines as a middle distillate [12].
The jet fuel contains few light or heavy hydrocarbons and has a carbon number between 8 and 16. However, most of the hydrocarbon has a carbon length of 10-13 atoms. In these cases, jet fuel has a density of 0,747 – 0,84 g/cm, which is lower than diesel and higher than gasoline [12].
The specific energy of jet fuel is 43,1 MJ/kg and is, therefore, a little higher than gasoline and diesel [12].

1.2 Reading guide

The paper initiates with a problem statement, where the purpose of the project is described. Which is followed by “scope and delimitations.” The scope establishes research questions and hypotheses for the project, which are answered thorough investigation of the subject.
A methodology section follows up, where general assumptions and methods are described.
The report firstly identifies the initial conditions, which set the boundaries for the project, such as biogas potential, electricity prices, and technology identification.
The technology identification describes the technologies which are used in the different pathways of renewable JF production. The description is including a brief introduction to the technology, a process flow diagram, and technical specifications such as efficiencies. The cost regarding electro biomethane is identified in this section as well.

The establishment of the scenarios is hereafter done. It is divided into two sections; centralized and decentralized. It is a descriptive analysis of the placement for the facilities. This includes how and why the placements were chosen. Furthermore, this section identifies the total energy production and capacities for each scenario and the pathways.

The results are followed afterward. The results are identifying the LCOE of renewable JF, based on the assumptions, initial conditions, and the scenarios capacity. The results further contain sensitivity analysis, to identify which parameters and which pathways are most or least sensitive. Investigation of the scenarios' feasibility is also included in the result section. A risk assessment is further included to identify the risk associated with each scenario.

The report is concluded with a discussion where parameters which have not been investigated in the sensitivity analysis, is discussed, and which affect they might have. The complete report is summarized lastly in conclusion.

The report includes calculated elements, which are necessary for a better understanding. For certain calculated elements has the methods been described to get a better understanding. Calculated elements that have not been explained can be found in “Appendices.” In the report, appendices are referred.

All the results are calculated in Excel and are seen in the folder “Results.” The economic calculations include the CAPEX & OPEX for a biogas plant, electrolysis & methanation. This is done to achieve a dynamic electro biomethane cost, which is varying with the electricity prices.

2. Problem statement

The demand for JF is increasing over the years, as the mechanical work for aviation is expected to increase in the future. The demand for JF in Denmark is seen in Table 1 [12].
Denmark's JF demand is projected based on consumption in 2017. The demand is projected with an annual increase of 1,5%.

Year	**2014**		**2025**		**2050**	
Unit	*Million liters*	*Petajoule*	*Million liters*	*Petajoule*	*Million liters*	*Petajoule*
Denmark*	1,200	45	1,300	50	1,900	70
Sweden	1,000	38	1,300	45	1,200	45
Norway	1,200	44	1,500	55	1,400	50
Finland	900	34	1,100	40	1,100	40
Iceland	240	9	300	10	300	10
Total	**4,540**	**170**	**5,500***	**200***	**5,900***	**215***

Table 1: Projected jet fuel demand towards 2050

Derived from the table, Denmark is among the highest consumer of JF in the Nordics and the country with the highest consumption in 2050. If JF is continuously produced by fossil fuels, it is impossible for Denmark to reach the environmental goal of being CO_2 neutral by 2050 and the Paris agreement. This makes it imperative to focus on pathways of producing renewable JF.
To secure and show Denmark is going towards the right path of reducing GHG, it would make sense to investigate the socioeconomics, feasibility, and which pathway of renewable JF production in Denmark. Fjernvarme Fyn is obligated to replace their coal-fired unit by 2025[14]; this would make a convenient location for FT & refining facility. The facility could work as an alternative for the coal-fired unit, as the Fischer Tropsch produces heat. This scenario would be considered as the Centralized scenario. Furthermore, as the integration of a large-scale FT & refining facility could be difficult, a scenario is investigated where renewable JF production is distributed over Funen. This scenario is considered as the decentralized scenario. By this, the paper sets the boundary condition for the investigation to Funen.

2.1 Scope & delimitations

The scope of this paper is twofold:

1) Determining the socioeconomics of renewable JF production cost, for two scenarios on Funen: Centralized and decentralized renewable JF production. Each of the scenarios is investigated with two different pathways. The differences in the pathways are the production method of syngas production, which is either done via POX or SMR.

2) Investigate the integration for the decentralized and centralized scenario, on Funen, to determine if any complications of integration appear.

The socio-economic cost is exclusive externalities, as the pathway from biomass to JF is CO_2 neutral. Funen's biogas potential is fixed throughout the investigation period, which makes the energy flow static. Dynamic biogas potential would be more realistic since the yield of biomass varies with conditions such as weather. Information regarding specific biogas potential for Funen is limited; it has only been possible to find one report dealing with such information.

It has not been possible to gather specific data for Funen's heating or gas grid. Rough assumptions regarding the pipe sizes and lengths are used for the cost of grid connection and investigation of possible integration of the facilities

Economics of scale calculations for SMR and POX are based on three existing facilities. It has not been possible to find more than three existing facilities for each technology.

For FT facilities, plenty of existing facilities with data are available. Information on economics for existing small-scale FT facilities is limited since this technology is relatively new. One existing pilot-project in Japan is known, but the economy has not been able to be found [15].

The calculation of LCOE for renewable JF is based on static capacities for the facilities and yearly average electricity prices. Price optimization has, therefore, not been done regarding the cost of electro biomethane. Theoretically, the electro biomethane could be lower than the estimated price in this report.

2.2 Research questions and hypotheses

For this project will three primary research questions be investigated.

1. Is jet fuel production using larger-scale technologies for jet fuel production more effective than smaller-scale technologies to achieve better economics of jet fuel production?

2. Will the integration of small-scale technologies for jet fuel production be more effective than the integration of larger-scale technologies for jet fuel production?

3. Will integrating of jet fuel production using smaller-scale technologies be more effective than using larger-scale technologies to achieve better heat utilization?

Furthermore, are following hypothesis established:

1. If the economics of scale is related to lower economics, then the centralized scenario has better economics than the decentralized scenario.

2. If better economics is related to choose of the pathway, then the cheapest pathway is chosen.

3. If economics is related to better integration of a facility, then the facility, which is the best integrated, is the cheapest one.

3. Methodology

This chapter describes the methodology applied to the paper. Firstly, the structure-approach of the paper is defined. Secondly, the general assumptions are defined, and lastly, the general methodology regarding calculations of energy flows, and economics are described.

3.1 Report structure

The report's structure is based on the IMR(a)D-structure. The approach for such a structure is depicted in Figure 2[16].

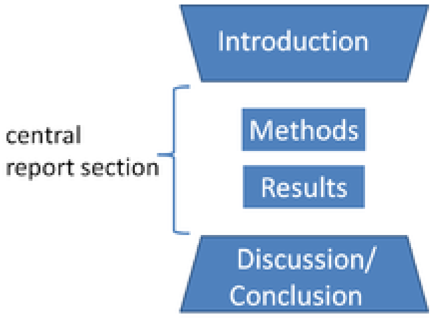


Figure 2: Structure of the report. IMR(A)D

The report is starting comprehensive, to establish a general knowledge about the Danish climate goals, the barrier, and solutions. It further narrows down, to establish a specific problem identification and investigation area.
The general knowledge and description from "Introduction" are further narrowed in "methods." This contains analysis work to establish specific initial conditions, framework, and data foundation. This is used in the "results" to depict the LCOE and integration feasibility of this study.
The paper starts to get wider, as "discussion/conclusion" occurs. This sets the methodology and results in perspective, and answer if different assumptions and approaches were used. The conclusion is summarizing the report's points and relate back to the problem statement in the beginning.

The primary approach for the report has been based on meta-analyses of existing reports, papers, and statements. The meta-analysis approach is the foundation for the initial conditions and collected data.
In a few occasions, it has been necessary to expand the data, for example, further projections of the electricity prices. The meta-analyses are conducted based on the newest existing reports, as this minimizes the uncertainties related to validating data and the results.

3.2 Assumptions

In this section, the general assumptions are described. The general assumptions are predefined assumptions, which are used for determining the initial conditions. More specific assumptions are described in the specific sections.
Economically assumptions and calculations are found further in the report.

3.2.1 General assumptions

The investigation period for the paper is set to 2025-2050. This is done to incorporate the problem statement of Fjernvarme Fyn's obligation of replacing their coal-fired unit by 2025[14]. An alternative is required, which makes it interesting to investigate a FT & refining facility as an alternative. The same investigation period is applying for the decentralized cases, as this would make the base on the same assumptions and, more comfortable, to compare regarding the LCOE of renewable JF.
Regarding the biogas potential for Funen, it is assumed that the full potential of biogas is available, even though there is not enough installed capacity of biogas plants on Funen yet. In 2018 was the biogas production between 0,7 – 2,1 PJ on Funen [17].
Furthermore, it is assumed that the whole biogas potential is utilized for JF production. This has been done to investigate the maximum capacity of JF production on Funen, by only including Funen's biogas resources.
As this paper's investigation period is 2025 – 2050, the technically and economically specifications for the facilities are assumed to be in line with the "Technology catalog" for 2020 [18], [19], [20]. The economics are found in appendix A.
For identified technologies that are not found in the Technology catalog, the economic and technical specifications are found through literature reviews. The economically and technically specifications from literature reviews are in line with the year the paper or statement was published.
It Is assumed that the location of the required facilities for the pathway for renewable JF production, such as biogas plants, methanation plants, electrolysis, syngas unit, and FT & refining, is not restricted by any regulations. Specific placements for the facilities have not been considered due to a lack of information on the areas and future. Therefore, the cost of land is neither identified.
The facilities' production is assumed to be constant over the period of investigation, with a utilization rate of 93%, to account for downtimes related to maintenance and holidays.

3.3 Methodology and approach for energy flows and economic numbers

The method of calculation is performed in Excel. Firstly, energy production is determined. This is based on the identified potential of biogas on Funen and the identified technologies' efficiencies used for the pathway of going from biomass to renewable JF. The energy production is calculated step-by-step in processes and is seen in the attached Excel appendix [Capacity sheets].

In Figure 3, shows a process chart of determining the energy production of JF. The chart is without excess heat and losses.

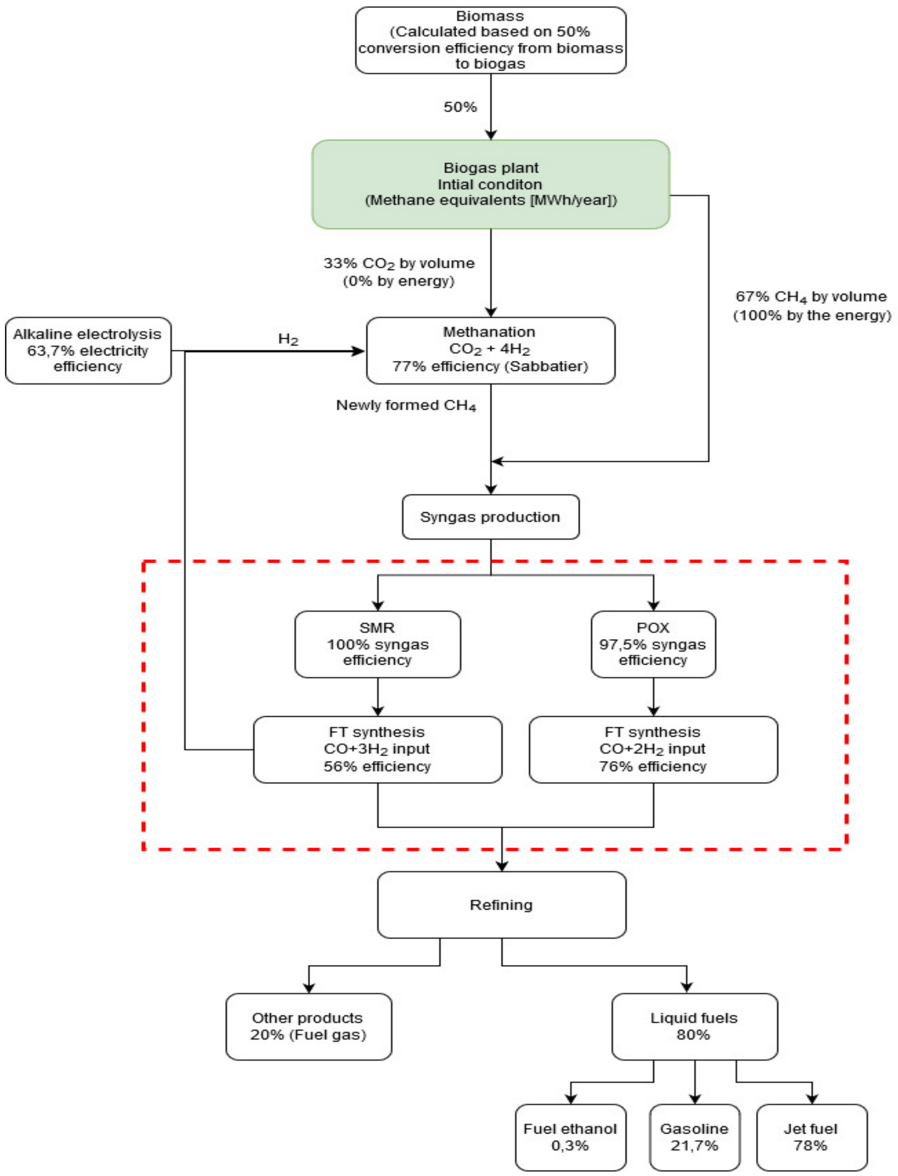


Figure 3: Methodology for energy production

The amount of biomass in energy terms has been assumed to be approximately double the amount of biogas in energy terms, as a 48% conversion efficiency is assumed [21].

For the economic calculations, the economic assumptions described is used. The assumed and found economics were assigned to the specific pathway's and case's capacities, such as investments and o&m. The income is calculated based on each pathway's excess heat, side product, and gasoline production multiplied by its selling price.

As the report investigates, the socio-economic LCOE of JF, Energistyrelsen's guidelines for socio-economics are used. This indicates that neither taxes nor inflation is considered in economics [22].
For discounting the money over time, Net present value (NPV) for all cases is calculated. The calculations are performed over 25 years, from 2025 to 2050. NPV is a method of discounting the value of money over time, by a defined discount rate [23]. This makes it easier to compare different projects/investments, which occur in different years. Additionally, NPV can be used as a guide to determine whether a project or investment is profitable.
The NPV is given by Eq. 1 [23].

$$NPV = \sum_{t=1}^{n} \frac{R_T}{(1+i)^t}$$

Eq. 1

$R_t = Net\ cash\ inflow - outflows\ during\ a\ singe\ period\ of\ t$
$i = The\ dicsount\ rate\ or\ rate\ that\ alternative\ investments\ could\ earn.$
$t = Number\ of\ periods\ (years)$

A discount rate of 4% is recommended by The Danish Ministry of Finance, with projects of a lifetime from 0-35 years [24].
The balance of the cash-flow is negative without including the income of JF. The price of JF is identified by solving eq.1 where the NPV equals to zero in the last year. The price of JF, which equals the NPV calculations to hit the break-even point in the last year, is called "LCOE" [25].
General is the LCOE given by Eq. 2

$$Levelized\ cost = \frac{Expenditures - income}{GJ_{jet\ fuel}}$$

Eq. 2

The LCOE calculations are done with a solver in Excel. The solver uses iterative steps by changing a defined parameter, in this case, the price of JF, to balance the income and expenditures, with a discount rate of 4%, which equals to a break-even point in 2050.

4. Initial conditions

The initial conditions are the foundation of the report. Therefore, are these clarified to get a better understanding of the underlying assumptions. The initial conditions include biogas potential, electricity prices, and technical identification for the two different pathways of renewable JF production. Any change in the initial condition is changing the outcome of the report.

4.1 Biogas potential

The framework for the investigation is Funen, therefore is the biogas potential on Funen identified. Funen's biogas potential, furthermore, limits the maximum potential of renewable JF production on Funen, as biogas is essential in producing electro biomethane.
Funen's biogas is shown in Figure 4. The biogas potential is calculated based on the assumption that each communes' total amount of biomass (manure, straw, waste, and natural areas) is utilized for biogas production.

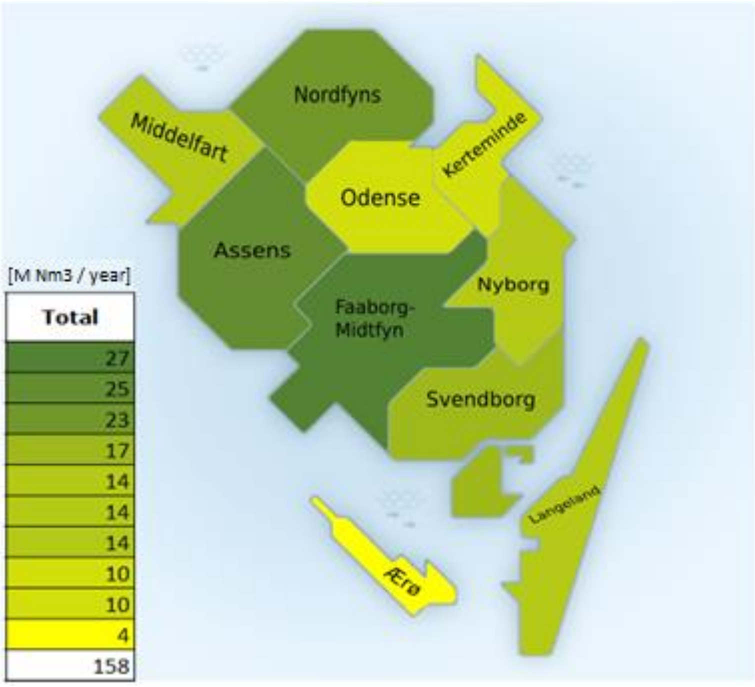


Figure 4: Biogas potential in methane equivalents of communes on Funen.

Derived from Figure 4, the yearly potential of biogas, in methane equivalents, is 158 million Nm^3 [26]. Based on an HHV for methane of 39,8 MJ/m^3 [27], it equivalents to 6,32 PJ each year.
In methane equivalents, straw is representing about 63% of the biogas potential on Funen, and manure only 23% [26]. If the biomass is considered in dry matter, manure is representing 23% and straw 51%. The total amount of dry matter each year for Funen is 841.000 tons distributed over 10 communes [26].
The complete list of each commune's biomass & biogas potential is represented in appendix B.

4.2 Electricity prices

Electricity prices are used for determining the cost of electro biomethane, as hydrogen is needed for this process.

Future electricity prices are identified to achieve a future and dynamic hydrogen cost. "Energinet" has projected the electricity prices from 2020 to 2040 [28]. The prices are projected further from 2040-2050, with an annual increase of 0,8 €/MWh. The constant annual increase after 2040 is assumed based on the average annual increase from 2035-2040.

The projected electricity prices from "Energinet" are made on intern analysis foundations and are results of model work. The model work is based on assumptions about future capacities, electricity consumption, and fuel prices. All these assumptions have uncertainties related to them. The electricity prices seen in Figure 5 are proposed future electricity prices, rather than a determined electricity price.

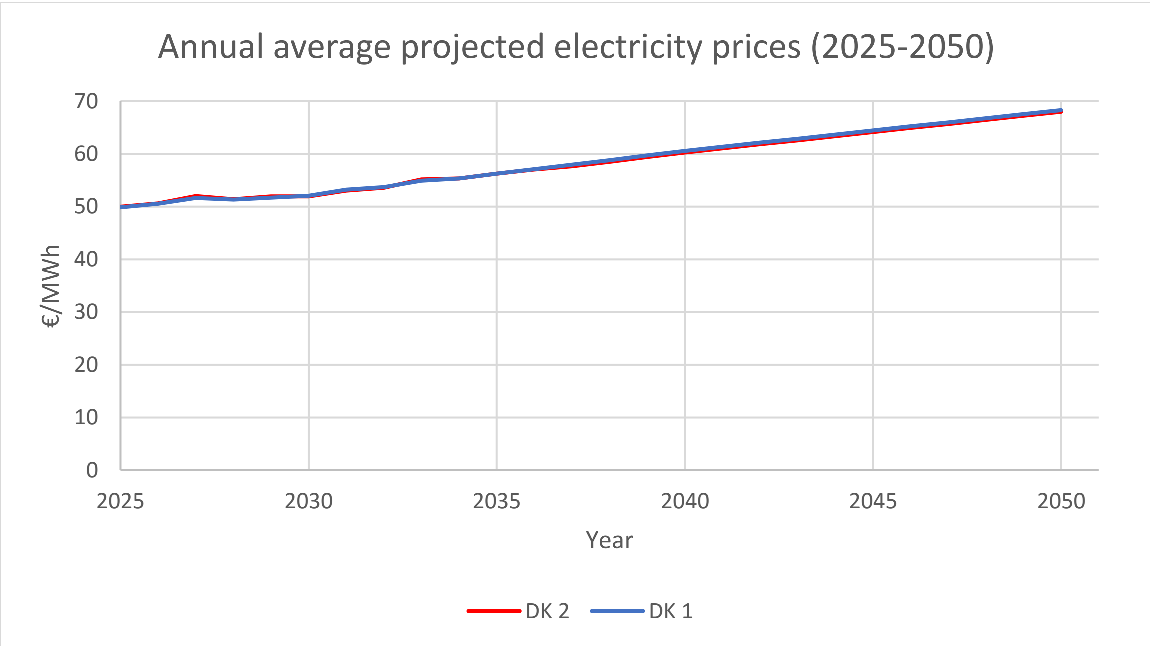


Figure 5: Annual average electricity prices

DK1 electricity prices are used in this paper, as the report investigates the cost of renewable JF production on Funen. The annual average electricity between DK1 & DK2 differs, even though it does not seem to. DK1 is around 0,3 $€/MWh_{electricity}$ higher than DK2 in 2050. The specific electricity prices are seen in appendix C.

5. Pathway identification

Two pathways of renewable JF production are investigated, as described in the introduction. The differences in the pathways are the production of syngas, which is either produced by POX or SMR. This section will describe the differences in the pathways.

5.1 POX

The POX pathway is depicted in Figure 6. The dotted lines indicate the centralization of the facilities. For the POX pathway does it indicate, that the production of electro biomethane, which include electrolysis, biogas plant, and methanation plant are centralized, as one unit, called **Electro biomethane "facility."** The production of JF, which includes partial oxidation, Fischer Tropsch synthesis, and refining, is centralized as another unit, called **"FT & refining facility."** The electro biomethane produced from the "Electro biomethane facility" is transported to the "FT & refining facility" via the gas grid.

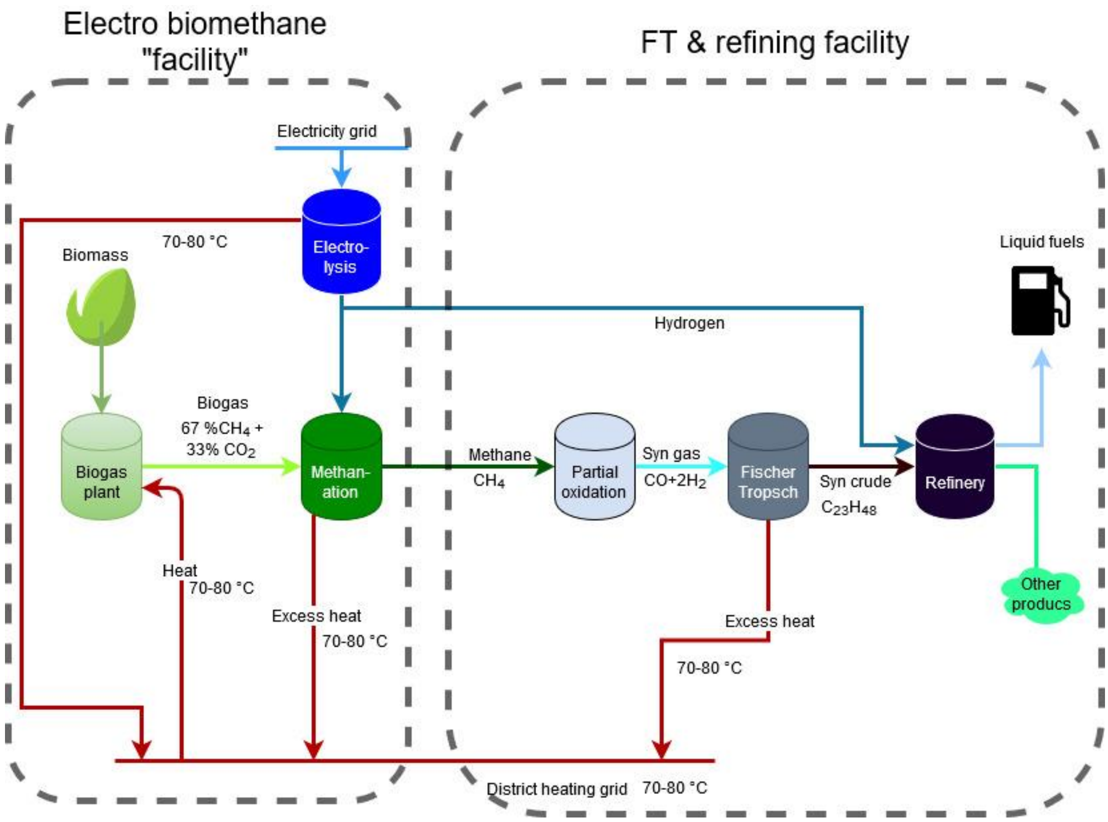


Figure 6: Overview of POX pathway for renewable JF.

The POX pathway requires extra hydrogen production from electrolysis, due to hydrogen use in the refining process.

5.2 SMR

The pathway for renewable JF by SMR is depicted in Figure 7. Like the POX-pathway, the dotted lines indicate the centralization of the production units. The transportation of electro biomethane to the “FT & refining facility” is also via the gas grid.

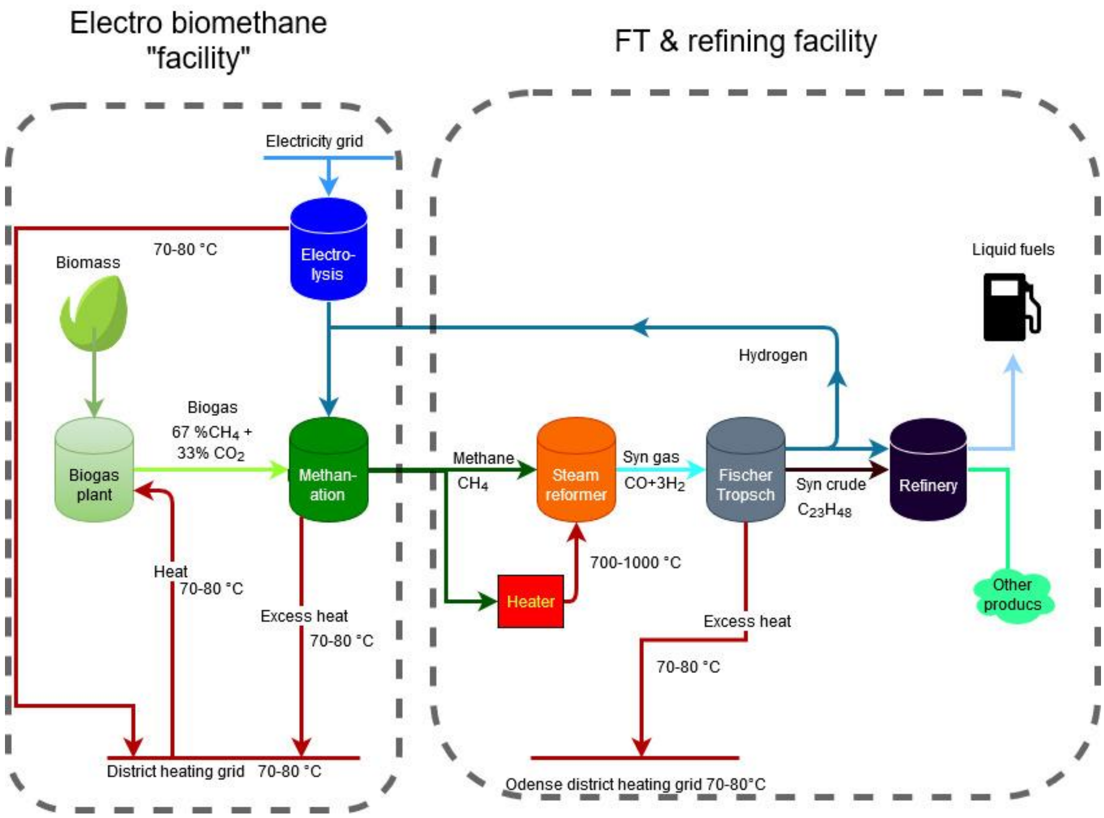


Figure 7: Overview of SMR pathway for renewable JF.

In the SMR pathway, extra hydrogen production by the electrolysis is not necessary due to the excess hydrogen from the steam reforming process.
A description of the technologies is followed next.

5.3 Technology description

This section identifies the technologies needed for a biomass-to-renewable JF pathway, with either SMR or POX. It includes a small overall description of the technologies, followed by a process flow diagram and technical specifications. It is chosen to upgrade the biogas to electro biomethane, with CO methanation, for a higher CH_4 potential. Common for both pathways is the production method, amount, and cost of electro biomethane. Therefore, the cost related to electro biomethane is evaluated in this section as well. These calculations are seen in the attached Excel file *"Prices for gasses"*.

The calculation of electro biomethane is done with a utilization rate of 93% for the facilities.

The stoichiometric calculations are seen in appendix D.

5.3.1 Biogas production

Biogas production is the first step of the pathway to renewable JF.

Biogas is a biofuel produced by the decomposition of organic matter on a biogas plant. When organic matter is under anaerobic conditions, different gasses are released, mainly CH_4 and CO_2 [29].

The process flow diagram of biogas production in a biogas plant is depicted in Figure 8.

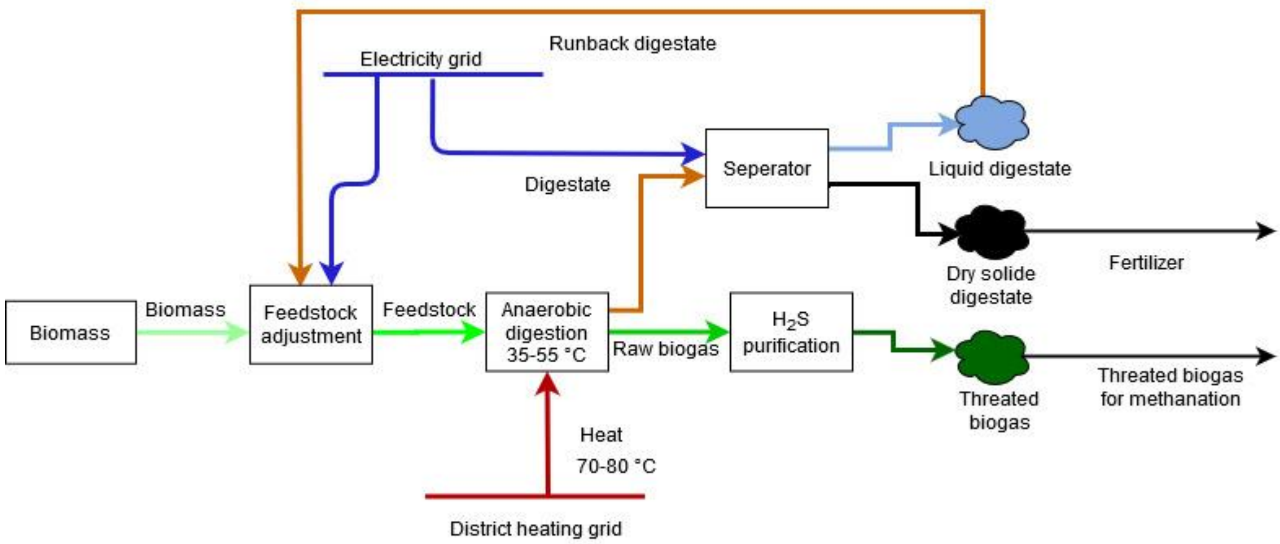


Figure 8: Process diagram of a biogas plant with a biogas cleaning system.

The biomass is first fed into a feedstock adjuster, to ensure that the feedstock has the right conditions for anaerobic digestion, such as size for straw. Straw is, by dry matter, the primary source of biomass for biogas on Funen. The straw requires watery content since they consist of small air-filled pores [30]. The straw is therefore blended with either manure or runback digestate.

The next step is anaerobic digestion. The adjusted feedstock is fed into the tank, where the anaerobic digestion begins.

In this case, the biogas is not CO_2 purified, since CO_2 for methanation is used. However, the biogas is purified from H_2S.

After these stages, left-over digestate is still present. The left-over digestate is fed into the separator, which separates the left-over digestate into fertilizer and liquid digestate. The liquid digestate is fed back to the feedstock adjustment for a better utilization degree.

The energy efficiency of the biogas plant is assumed to be 48% [21]. The biogas content after purification has been assumed to 67% CH_4 and 33% CO_2, which is in line with general biogas compositions [31]. All other impurities are removed in the purification stage of the biogas plant. The technical specifications of the assumed biogas plant are seen in table 2 [18].

Technology	**Biogas plant + purification**
Efficiency [%]	48
Inlet	Biomass
Outlet	Biogas [67%] CH_4 + CO_2[33%]
Electricity use [% of inlet]	3,80%
Heating use [% of inlet]	8,90%
Operating temperature [°C]	35-55
Technical lifetime [Years]	25

Table 2: General technical specifications for biogas plants.

The biogas cleaning of H_2S is important as H_2S results in corrosion during combustion. Furthermore, the removal of H2S increases the biogas' purity of CO_2 and CH_4 [32]. It is assumed that BiogasClean provides the biogas cleaning system. Their biogas cleaning system is 100% biological, and the operation costs are 70-80% lower than chemical gas cleaning systems [32]. The cost of such a cleaning facility is estimated based on data provided by BiogasClean. The costs related to biogas cleaning is based on investment and o&m for a 9 MW plant, with an assumed lifetime of 25 years. Based on the provided data and assumptions, the cost of biogas cleaning is 0,49 €/GJ_{biogas}. For further explanation of the cost related to biogas cleaning, the Excel sheet *"BiogasClean price"* is referred to.
The total production cost of biogas is described in Table 3.
The economic calculation is based on a total biogas plant capacity of 214 MW [18]. The capacity is equivalent to the total needed capacity of a biogas plant for producing the total potential biogas on Funen.

Biogas plant	Total [M €]	€/GJ_{biogas}
OM	972,04	6,18
Investment	458,65	2,92
Heat	39,19	0,25
Electricity	95,71	0,61
Gas cleaning	77,09	0,49
Biomass transportation	1153,98	7,33
Biogas total	2796,66	17,78
Fuel price:	€/GJ_{biogas}	
	17,78	

Table 3: Economics of biogas production.

The transportation cost for biomass is calculated based on the transportation cost of the available biomass in Odense. The transportation cost is calculated to 27 €/$_{\text{ton biomass}}$, which in methane equivalents is 7,33 €/$GJ_{methane}$. The total transportation cost is seen in appendix E.

The biogas cost is increasing with increasing electricity prices, as a small amount of electricity is needed. The biogas cost in 5-year intervals is shown in Table 4

Year	2025	2030	2035	2040	2045	2050
Average electricity price [€/MWh]	49,6	51,8	55,9	60,2	63,8	66,9
Biogas cost [€/GJ_{biogas}]	17,68	17,70	17,75	17,83	17,83	17,86

Table 4: 5-year intervals of biogas costs towards 2050.

5.3.2 Electrolysis

Alkaline electrolysis is the chosen technology to produce hydrogen in both pathways. The hydrogen is mainly used to produce electro biomethane by methanation of biogas.
Alkaline was chosen based on the combination of relatively low operating temperatures and high hydrogen effectivity when compared to other electrolysis technologies. PEM (Proton Exchange Membrane) has similar technical specifications but has a lower hydrogen effectivity (58%) [18].

The alkaline electrolysis bases on the principle of separating hydrogen and oxygen in water when a direct current is applied. The process flow diagram is depicted in Figure 9 [33] [34].

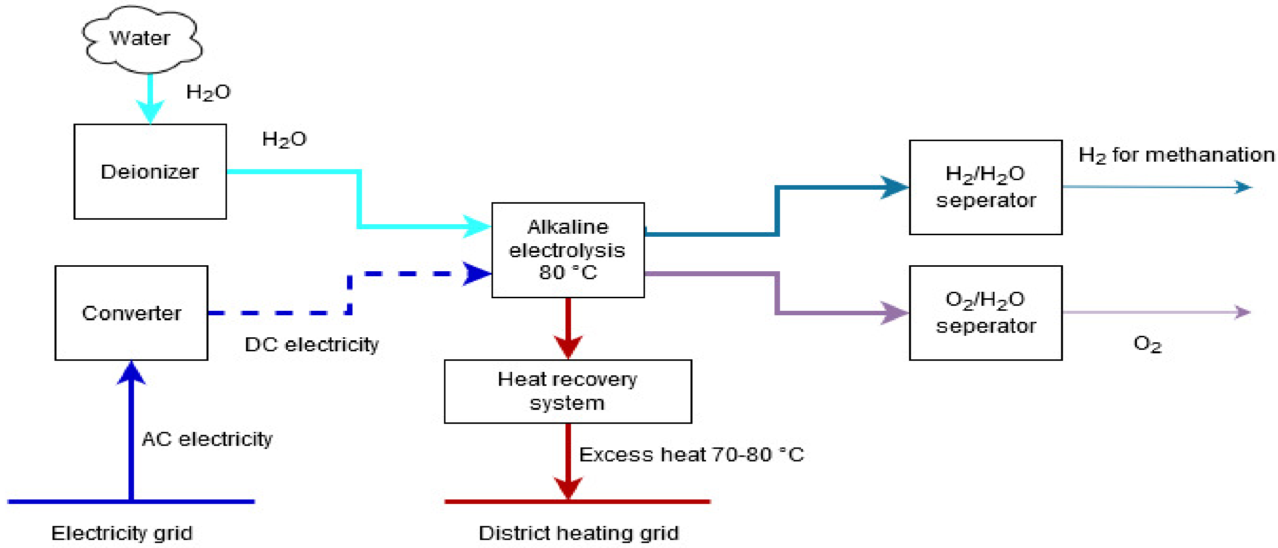


Figure 9: Process flow diagram of alkaline electrolysis.

The transmitted electricity from the power transmission grid is AC (Alternating current) electricity. As described, the electrolysis needs DC (Direct current) electricity. It is, therefore, necessary to convert the AC electricity to DC electricity [34].

The process is described by Eq. 3 [34].

$$\begin{aligned} &Cathode: 2H_2O + 2e- \rightarrow H_2 + 2OH \\ &Anode: 2OH- \rightarrow 12O_{12} + H_2O + 2e - \\ &Total: 2H_2O \rightarrow\ O_2 + 2H_2 \end{aligned} \qquad \textit{Eq. 3}$$

The technical specifications for the Alkaline electrolysis is seen in Table 5 [18].

Technology	Alkaline electrolysis
Efficiency [% hydrogen]	63,6
Inlet	Electricity & water
Outlet [% total size]	Hydrogen (63,6%) & heat (14%)
Electricity use [% of total size]	100
Heating use [% of inlet]	-
Operating temperature [°C]	80
Technical lifetime [Years]	25

Table 5: General technical specification for alkaline electrolysis in 2025

The production cost of hydrogen produced by alkaline electrolysis is calculated throughout the investigation period and are seen in Table 6. The calculation is performed to achieve a yearly dynamic cost of hydrogen and the electro biomethane. The calculations are based on the described electricity prices, technical & economic specifications for the alkaline electrolysis [18]. The cost of hydrogen bases on a total alkaline electrolysis capacity of 135 MWe. This capacity is equivalent to the total capacity of alkaline electrolysis, which is needed to deliver enough hydrogen for upgrading Funen's biogas potential to electro biomethane.
The total cost is divided by the total of hydrogen produced to achieve a €/$GJ_{hydrogen}$.

Alkaline electrolysis	Total [M €]	€/$GJ_{hydrogen}$
Electricity	2525,30	25,24
Investment	128,73	1,29
Fixed OM	160,91	1,61
Electrolysis total	2814,94	28,14
	€/$GJ_{hydrogen}$	
Fuel price	28,14	

Table 6: Economics of hydrogen production via alkaline electrolysis 2025.

Derived from Figure 5, the projected electricity prices increase — the increase in electricity prices results in higher expenditures for the electrolysis. In Table 7, the hydrogen prices are shown in a 5-year interval.

Year	2025	2030	2035	2040	2045	2050
Average electricity price [€/MWh]	49,6	51,8	55,9	60,2	63,8	66,9
Hydrogen cost [€/$GJ_{Hydrogen}$]	24,6	25,5	27,3	29,3	30,7	32,1

Table 7: LCOE for hydrogen produced by alkaline electrolysis towards 2050.

5.3.3 Description of methanation

To achieve higher methane content of the available biogas on Funen is CO methanation introduced in the pathway of renewable JF production.
It is assumed that all of Funen's biogas potential is upgraded into electro biomethane by CO methanation. The overall process of the CO methanation is shown in Figure 10.

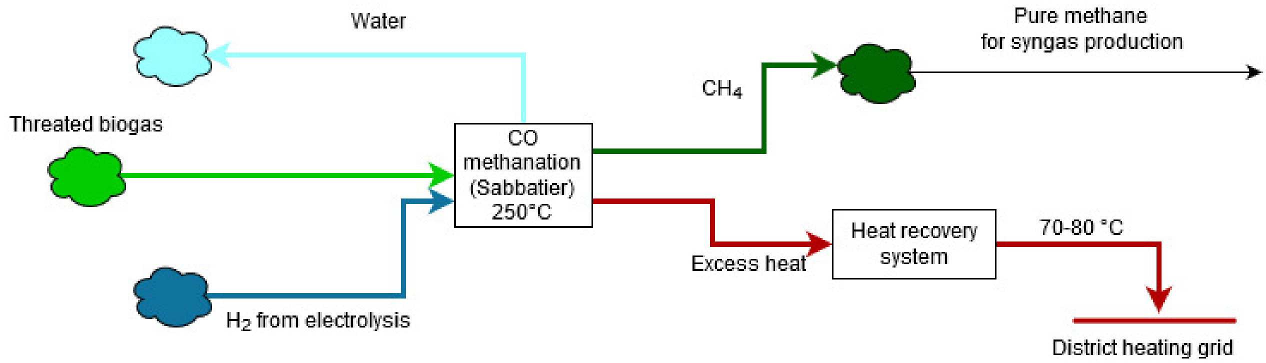


Figure 10: General process diagram of methanation plant 2025

The treated biogas, from the biogas plant, and the hydrogen, produced by the alkaline electrolysis, is fed into the CO methanation tank. The tank has an operational temperature of about 250 °C [35].
CO_2 and H_2 are converted into electro biomethane, water, and excess heat, which is utilized for district heating, in the CO methanation tank.
The chemical reaction between CO_2 and H_2 is described with Sabatier formula seen in Eq. 4 [36].

$$CO2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad \Delta H = -255\ kJ/mol \qquad \textit{Eq. 4}$$

The technical specifications for the CO methanation plant are seen in Table 8.

Technology	CO methanation (Sabatier)
Efficiency [%]	77
Inlet	Biogas + H_2
Outlet [% Total size]	CH_4 [77%] + Heat [23%]
Electricity use [% of total size]	-
Heating use [% of inlet]	-
Operating temperature [°C]	250-500
Technical lifetime [Years]	25

Table 8: General technical specifications of methanation plants in 2025.

The biogas is assumed to be 67% CH_4 and 33% CO_2 after the H_2S cleaning. This means that 33% of the total biogas by volume is methanated. By adding the existing energy in the biogas (CH_4) and the methaneted biogas will the potentially CH_4 increase by about 50%.

The production cost of electro biomethane with CO methanation is seen in Table 9 [37]. The cost of electro biomethane is calculated based on the previously calculated hydrogen and the biogas costs.
The estimated cost of electro biomethane bases on calculations for a methanation plant with a capacity of 298,2 MW. The capacity is equivalent to the total capacity of methanation, needed for upgrading the whole biogas potential of Funen.

CO Methanation (Sabatier)	Total [M €]	€/GJ$_{Electro\ biomethane}$
Investment	382,62	1,63
Fixed OM	478,28	2,03
Variable OM	188,68	0,80
Methanation plant total	1049,58	4,46
Biogas expenses	2796,66	11,90
Hydrogen expenses	2814,94	11,97
Total electro biomethane expenses	6661,19	28,34
	€/GJ$_{Electro\ biomethane}$	
Average electro biomethane cost	28,34	

Table 9: Average LCOE of electro biomethane.

Since the hydrogen production cost increase with an increase in electricity prices, the cost of electro biomethane is increasing as well. The electro biomethane production prices are seen in Table 10 with a 5-year interval.

Year	2025	2030	2035	2040	2045	2050
Average electricity price [€/MWh]	49,6	51,8	55,9	60,2	63,8	66,9
Biogas cost [€/GJ$_{biogas}$]	17,68	17,70	17,75	17,83	17,83	17,86
Hydrogen cost [€/GJ$_{hydrogen}$]	24,6	25,5	27,3	29,3	30,7	32,1
Electro biomethane cost [€/GJ$_{Electro\ biomethane}$]	26,64	27,09	27,95	28,89	29,57	30,22

Table 10: Electro biomethane cost to 2050

5.3.4 Syngas production

Two pathways of renewable JF are investigated; the difference in these are the production methods of syngas. For the syngas production is two technologies chosen; SMR and POX.
The main differences between the technologies' production of syngas are the H_2:CO ratio output and whether they are endothermic or exothermic processes.

5.3.4.1 Steam methane reforming

SMR utilizes electro biomethane, heat, and steam to produce syngas. To achieve higher purity of CH_4 is desulphurization, the first step in the process.
The SMR process is highly endothermic, and heating is therefore required. The operational temperature is ranging between 700-1000 °C [38]. A boiler produces the heat; in this case, it is assumed that the boiler is fueled with electro biomethane. Utilization of electro biomethane for heating, lower the input of electro biomethane in the reformer.
To minimize the use of heat to produce steam, is a heat recovery system implemented.
A process diagram for syngas production with SMR is shown in Figure 11 [39].

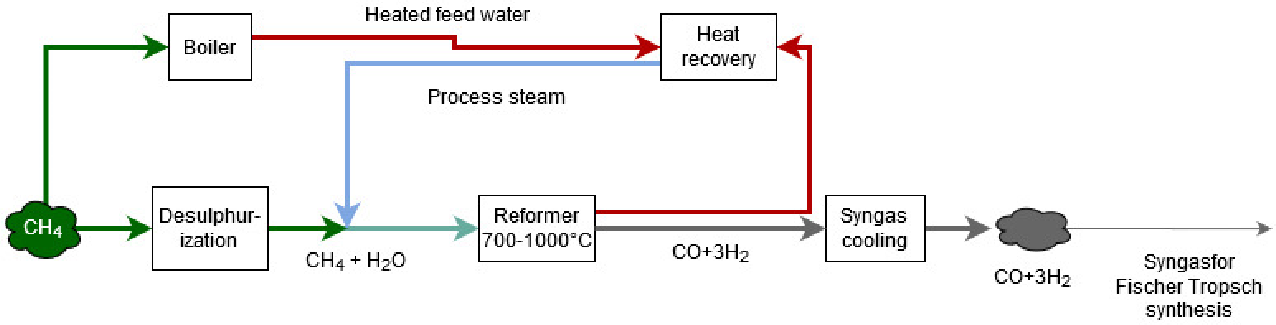


Figure 11: General process diagram of SMR.

The process reaction of production syngas by SMR is represented in Eq. 5 [38].

$$CH_4 + H_2O \rightarrow 3H_2 + CO \qquad \Delta H = 251{,}94\ kJ/mol \qquad \text{Eq. 5}$$

Stoichiometric calculations show a hydrogen effectivity of 75% and a syngas effectivity of 100% for the SMR process. Seen from eq. 5 the H2:CO ratio of the syngas produced by SMR is 3:1.
The operational specifications are seen in Table 11. As seen from the Table 11, SMR requires about 20% heat of the total energy inlet; This indicates 20% of the total electro methane produced by the methanation is used for heating.

Technology	**Steam methane reforming**
Efficiency [% Syngas]	100
Inlet	CH_4 [80%] + heat [20%]
Outlet [% total size]	Syngas [100%]
Electricity use [% of total size]	-
Heating use [% of inlet]	20
Operating temperature [°C]	1100-1300
Technical lifetime [Years]	20

Table 11: Technical specifications for SMR.

5.3.4.2 Partial oxidation

The other pathway to produce renewable JF is by producing syngas with POX. POX-technology uses electro biomethane and oxygen to produce syngas. The oxygen is produced by an oxygen separator, which separates oxygen from the air, as air only contains 20% of oxygen [40].
The POX process is an exothermic process [38], which permits utilization of excess heat for district heating. The utilization of excess heat increases the income and lowers the cost of syngas, which further affects the LCOE of renewable JF.
In Figure 12, the process flow-diagram of syngas is represented.

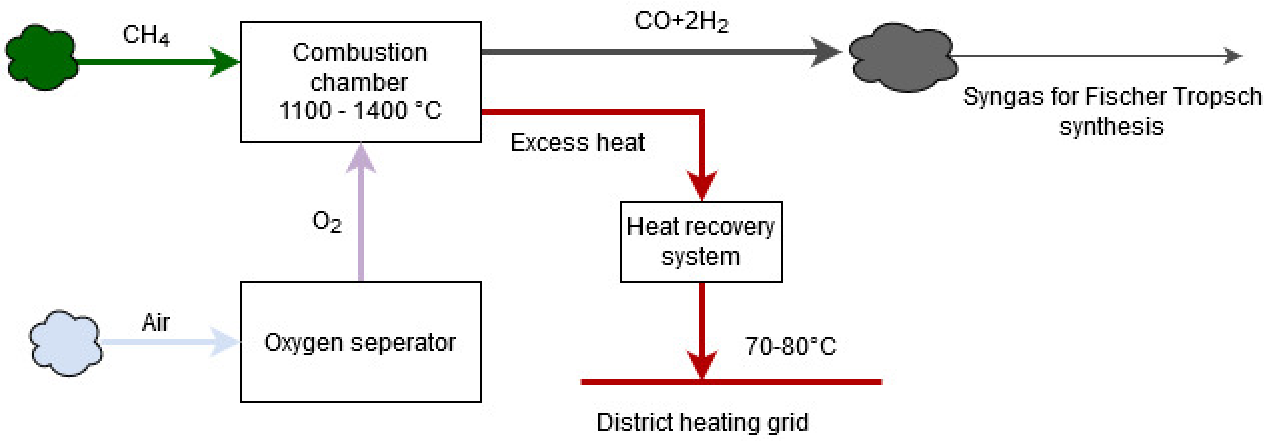


Figure 12: General process flow diagram of POX.

The process reaction of syngas production with POX is described by Eq. 6 [38].

$$CH_4 + 0{,}5O_2 \rightarrow CO + 2H_2 \qquad \Delta H = -34{,}54\ kJ/mol \qquad \textit{Eq. 6}$$

As seen in eq. 6, the H2:CO ratio of syngas produced by POX is 2:1, which is lower an H_2 ratio than SMR. By stoichiometric calculations, the POX has a hydrogen effectivity of 66% and a syngas effectivity of 96,3%. Compared to SMR, POX has a lower hydrogen efficiency than SMR.
The technical specifications for syngas production with POX are seen in Table 12.
Derived from the table, POX syngas efficiency is slightly lower than SMR's due to an exothermic process rather than an endothermic process as SMR.

Technology	**Partial oxidation**
Efficiency [% hydrogen]	96,30%
Inlet	CH_4
Outlet [% total size]	Syngas [96,3%] + heat [3,7%]
Electricity use [% of total size]	-
Heating use [% of inlet]	-
Operating temperature [°C]	1100-1300
Technical lifetime [Years]	20

Table 12: General technical specifications for POX.

5.3.5 Description of Fischer-Tropsch & refining

5.3.5.1 Syncrude production

The production of syncrude (synthetic crude oil) is done through Fischer-Tropsch synthesis [13]. The Fischer Tropsch synthesis uses syngas, which were produced either with SMR or POX.
The needed H_2:CO ratio of syngas for Fischer Tropsch synthesis is about 2:1[41].
A syncrude production with syngas from SMR would lead to an excess of hydrogen, as the H_2:CO ratio of syngas produced by SMR is 3:1. A fraction of the excess hydrogen is used for refining. The rest of it is used in the methanation process. Utilization of excess hydrogen lowers the production of hydrogen by the electrolysis and, by that, lower the required capacity and investments.
The H2:CO ratio of syngas produced by POX is 2:1, which is a better match for the Fischer Tropsch synthesis. On the other side, further hydrogen for the refining process is required.

In Figure 13, the process flow-diagram of FT synthesis is depicted.

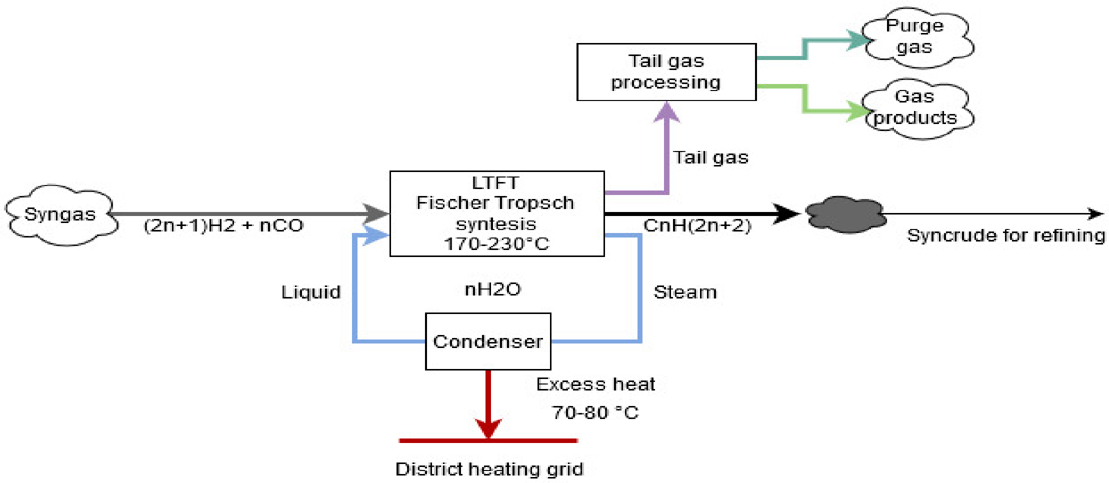


Figure 13: General process flow diagram for LTFT.

The Fischer Tropsch synthesis is either HTFT (High-temperature Fischer Tropsch) or LTFT (Low-temperature Fischer Tropsch) [13]. This paper has chosen a pathway with LTFT, which has an operational temperature of about 200 °C [12]. Such a choice is due to the refining of the syncrude, which further is explained in the refining section. The FT synthesis is exothermic, and excess heat is available for utilization for district heating. The tail gas could potentially be used for syngas production but is not evaluated in this paper.

The overall process of syngas to Syncrude in the FT synthesis is described by Eq. 7 [41]:

$$(2n+1)H_2 + nCO \rightarrow CnH(2n+2) + nH2O + heat \qquad \text{Eq. 7}$$
$$11H_2 + 23CO \rightarrow C_{23}H_{48} + 11H_2O \qquad \Delta H = -4208{,}83\ kJ/mol$$

The syncrude efficiency of FT depends on the syngas inlet. Based on stoichiometric calculations is the syncrude efficiency of 78% for POX-syngas and 59% for SMR-syngas. The excess hydrogen is calculated to be 24% for FT synthesis with syngas produced by SMR.

It is assumed that the produced syncrude from FT synthesis is a long chain hydrocarbon of $C_{23}H_{48}$. The technical specifications for the FT synthesis are seen in Table 13.

Technology	**Fischer-Tropsch synthesis - POX**	**Fischer-Tropsch synthesis - SMR**
Efficiency [% Syncrude]	78% (POX)	59% (SMR)
Inlet	$CO+2H_2$	$CO+3H_2$
Outlet [% total size]	Syncrude [78%] + heat [22%]	Syncrude [59%] +H_2 [24%] + heat [17%]
Syncrude chemical formula	$C_{23}H_{48}$	
Electricity use [% of total size]	-	
Heating use [% of inlet]	-	
Operating temperature [°C]	170 - 230	
Technical lifetime [Years]	25	

Table 13: Technical specifications for LTFT using syngas production with either POX or SMR [12] [42].

5.3.5.2 Refining

Different types of refineries exist, with numerous configurations [13].
There are mainly three types of refinery designs for crude and syncrude oil; these are *energy*, *petrochemicals*, and *lubricants [13]*. This paper evaluates an energy refinery.
The refinery's primary purpose is to refine the long length hydrocarbons to lower length carbons, to obtain useful fuels. The refining of syncrude categorizes into two subcategories: *liquid fuel*s and *other products*. Liquid fuels relate to the primary product, which is gasoline, diesel, JF, and fuel ethanol. Other products relate to uncovered organics and fuel gas [13].
Refineries are either defined as JF, gasoline, or diesel refineries [13]. The configurations of the refinery define the primary liquid fuel and its effectivity.

In Table 14 are two different configurations of JF refineries; an HTFT (300-350 °C) refinery and an LTFT (200-240 °C) refinery [43].

Product	**Refinery production**							
	HTFT				**LTFT**			
	Kg/h	**M3/h**	**bpd**	**Vol%**	**Kg/h**	**M3/h**	**bpd**	**Vol%**
Liquid fuels								
Motor-gasoline	98880	131	19742	22,4	101328	137	20641	23
Excess fuel ethanol	17624	22	3351	3,8	2272	3	432	0,5
Jet fuel	302863	389	58650	66,5	355912	455	68720	76,5
Diesel fuel	0	0	0	0	0	0	0	0
LPG	23563	42	6410	7,3	0	0	0	0
Other Products								
Fuel gas	32612				26781			
Unrecovered organics	14894				15634			
Hydrogen	281				-3243			
Water	9277				1315			
Sum	500000	584	88152	100	500000	595	89793	100

Table 14: Example of output distribution of products for HTFT & LTFT refinery [13].

This paper focuses on maximizing the JF output, firstly to lower LCOE and secondly to cover as much of the demand as possible described in Table 1. The LTFT refinery seen in Table 14, therefore, is chosen. This refinery configuration has a liquid fuel effectivity of 92% by mass, equaling to 93% in energy. JF represents 76,5% by volume, equivalent to 78% by the energy of the total liquid fuels. This configuration allows the highest theoretically JF output. An LTFT refinery further requires hydrogen as input; based on the total mass, is this equal to 0.6%, and in energy equivalent around 2% of the total energy output[1].

[1] This calculation is based on an assumed HHV for excess fuel ethanol, gasoline, fuel gas, and jet fuel. The calculations are seen in appendix F.

The JF, which is produced, has been assumed to be $C_{11}H_{24}$. The specifications for $C_{11}H_{24}$ are seen in appendix G. The technical specifications for the assumed LTFT refinery are seen in Table 15.

	LTFT jet fuel refinery (200-240 °C)		
	Mass %	Energy [%]	HHV [MJ/kg]
Other products	8	7%	52,8
Liquid fuels	92%	93%	
Total	100%	100%	
	Mass % of LF	**Energy % of JF**	
Liquid fuel	**100%**	**100%**	
Jet fuel	76,5%	78,0%	47,63
Gasoline	23%	21,7%	46,4
Diesel	0%	0%	
Excess fuel ethanol	0,5%	0,3%	29,7
Total	100%	100%	

Table 15: Product distribution of LTFT refinery.

6. Energy flows for SMR and POX pathway

The below-shown energy flows are the maximum energy flows, due to a limitation of biogas, which was described in the section "Biogas potential for Funen."
If the two overall pathways are evaluated, it seems that the thermal efficiencies are almost equal. The thermal efficiency for SMR is a little lower, due to a heat loss in the internal electro biomethane heater. The major difference is the carbon efficiency. The difference is about 14% points. The reason should be found in the syngas production, as the carbon/hydrogen ratio output is higher for POX (1:2) than SMR (1:3). The overall JF conversion is nearly the same, due to the utilization of the excess hydrogen in the pathway for SMR. If the excess hydrogen is not included, the JF conversion for SMR is 20,5% instead of 24,5%. Therefore, the utilization of excess hydrogen in the SMR pathway is necessary to make it competitive with the POX pathway in terms of JF conversion efficiency.

The efficiencies are calculated based on the below-seen equations [44], [45].

$$\text{JF conversion efficiency} = \frac{\text{Output}_{\text{JF}}}{(\text{Input}_{Biomass} + \text{input}_{\text{electricity}} + \text{input}_{\text{heat}})} \quad \text{Eq. 8}$$

$$\text{Thermal efficiency} = \text{Output}_{\text{Usefull energy}} / \text{Input}_{\text{Energy}} \quad \text{Eq. 9}$$

$$\text{Carbon efficiency} = \text{Carbon}_{\text{in}} / \text{Carbon}_{\text{out}} \quad \text{Eq. 10}$$

6.1 POX pathway

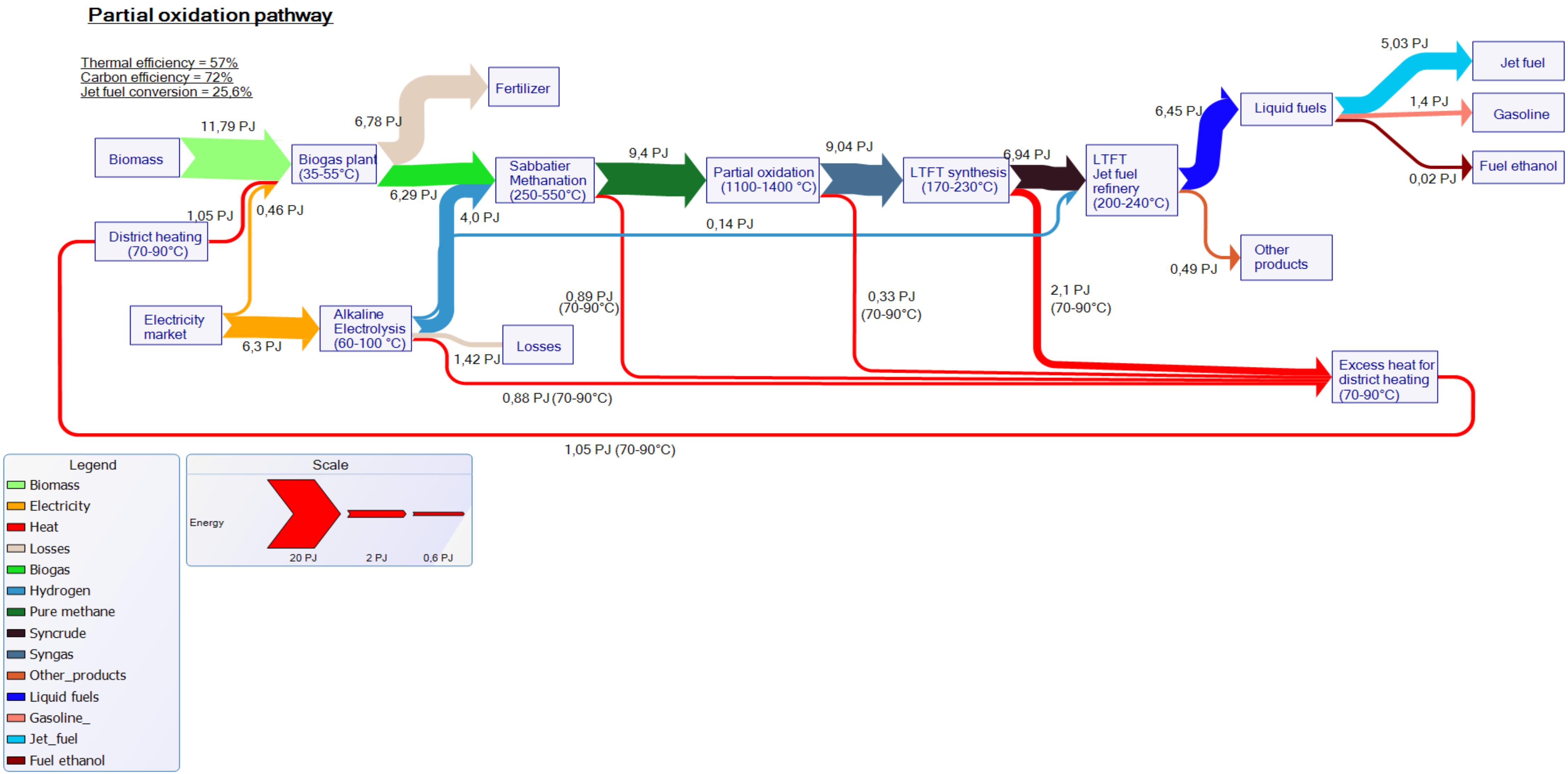


Figure 14: E-Sankey diagram for POX pathway

6.2 SMR pathway

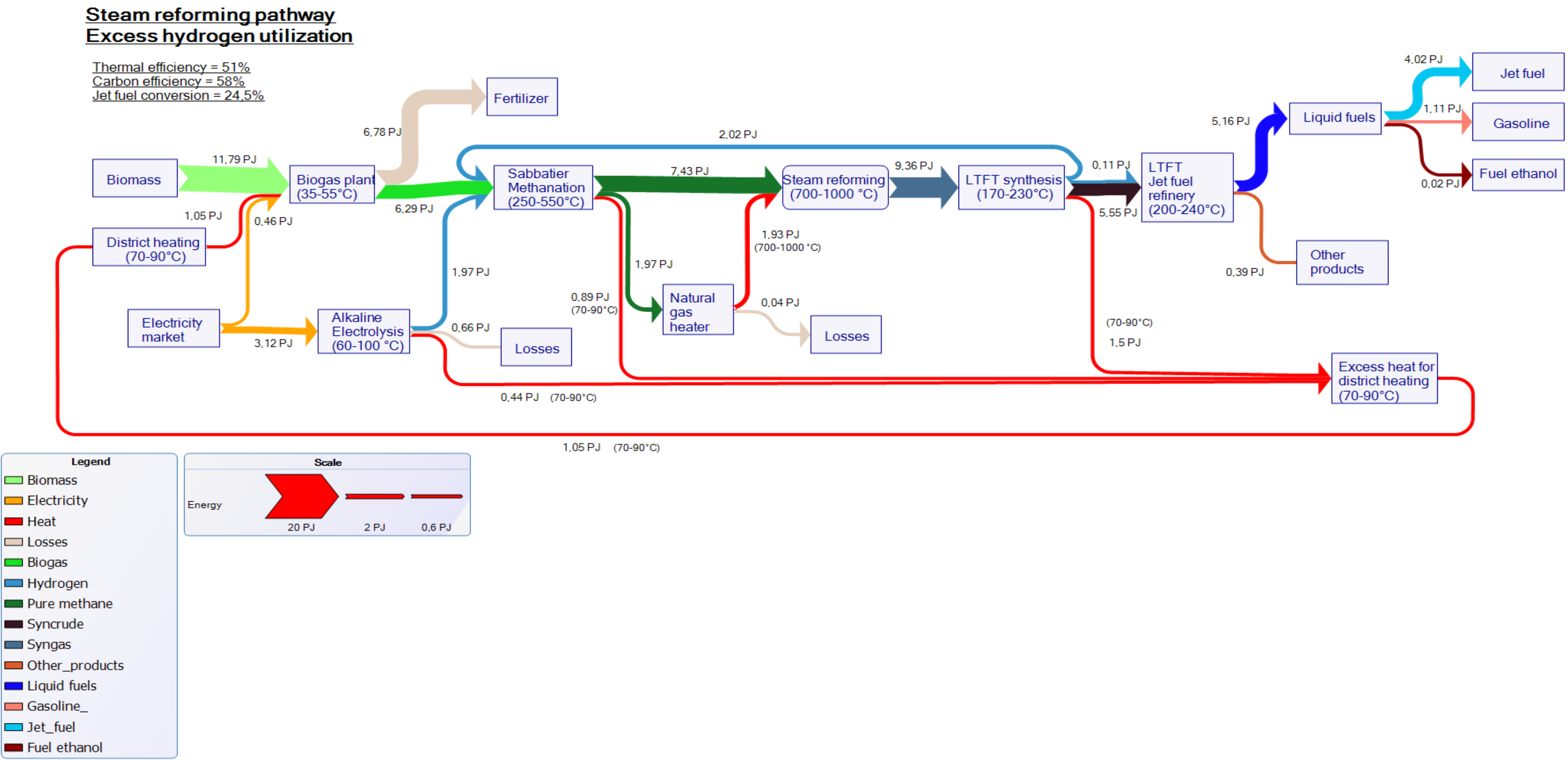


Figure 15: E-Sankey diagram for SMR pathway

7. Location and description of the centralized and decentralized scenarios

This section analysis convenient locations for the centralized scenario and the decentralized scenario. The analysis is performed firstly for the centralized and afterward for the decentralized scenario. The assigned locations for the facilities are the same for both pathways.
The analysis is based on specific criteria, which are identified necessary for the integration of renewable JF production on Funen. These criteria are to be described further.
The locations' availability of utilizing excess heat is in specific focus, as the production of renewable JF produces a decent amount of excess heat.
The location for FT facilities is dependent on the below-mentioned criteria:

- District heating infrastructure
- Nearby gas grid
- Heating demand in the given area.
- Access to biogas – Local biogas availability

Data based on literature reviews, approximations, and calculations are examined to justify the criteria.
It should be noted that the criteria are more relevant for the decentralized scenario, as the location for centralized production is nearly already given.

A description of the scenarios is also included. This description includes capacities, JF production, heat production, and needed assumptions.

7.1 Centralized JF production

The company Fjernvarme Fyn, which is producing and delivering about 99% of the heat for the municipality of the same name [46], is obligated to out-phase their coal-fired unit to non-production by 2025 [14]. This makes it convenient to place a FT facility, as an alternative for the coal-fired unit, for delivering heat. Integration of the FT facility would make it easier and cheaper, as already existing pipes for district heating and gas is available.

7.1.1 Odense heating demand[2]

The production of JF produces excess heat, which is utilized. Therefore, the heating demand for Odense is identified; This is done to evaluate the integration of such a plant later. The demand Fjernvarme Fyn covers is seen in Figure 16, and further described by Table 16.

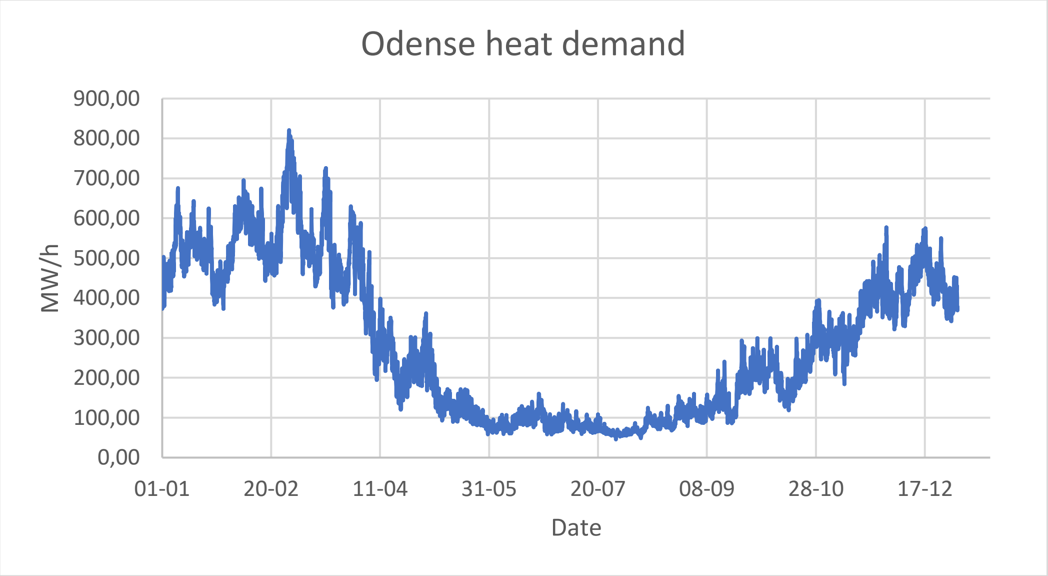


Figure 16: Odense heating demand

City	Population	Total heat demand [GWh]	Max [MWh]	Min [MWh]	Avg. Heating demand [MWh]
Odense	204.895	2494,49	820,82	45,52	284,76

Table 16: Heating demand specifications for Odense

For the base cases, it is assumed that the heat can be stored. This is based on the existing storages on Fjernvarme Fyn. The capacity of these is not defined [48]. This implies that the base case has excess heat utilization of 100%.

[2] Data of Odense total heat consumption is forwarded by Fjernvarme and can be seen in attached Excel document (Fjernvarme Fyn data) [47] F. F.-O. Mindorf. *Fjernvarme Fyn data*. .

7.1.2 Specific assumption for the centralized scenario

The scenario for a larger scale FT plant suggests that the plant is placed in Odense to replace the existing coal-fired unit. This further gives complications for the rest of the technologies in the pathway, as they would not fit into the same location as the FT facility due to space requirements and transportation difficulties of the enormous amount of needed biomass.

This would imply that only the FT facility (with syngas and refining processes included) is placed central in Odense, and the technologies as biogas plants, electrolysis, and methanation, is placed outside the city, where space and transportation of biomass are more accessible.

This solution would work, as shown in Figure 17.

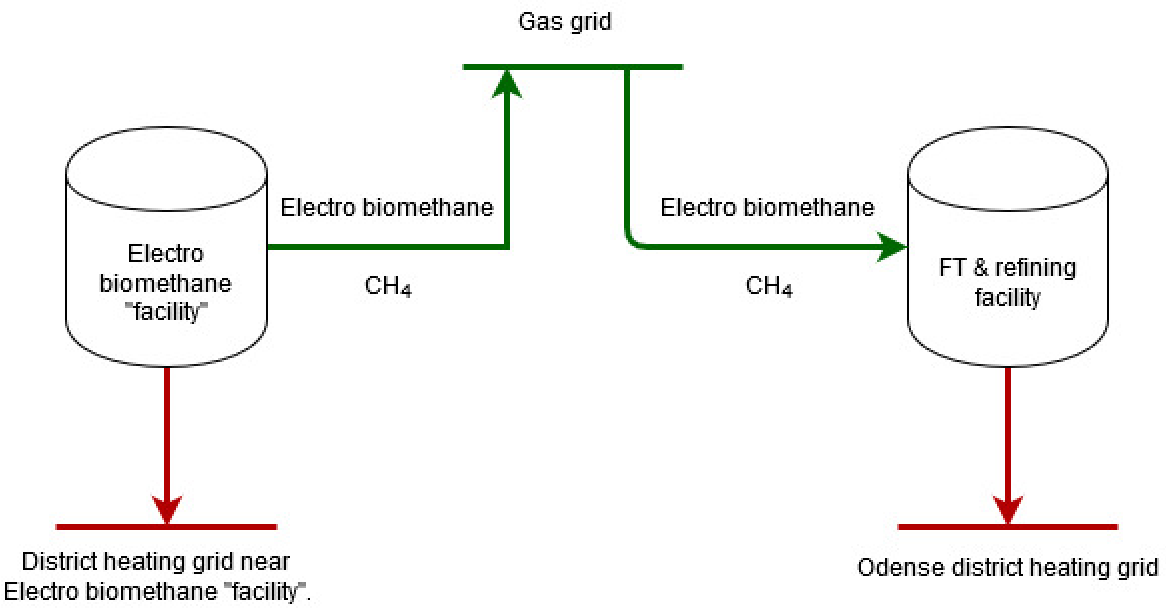


Figure 17: Picture of where the excess heat is utilized - Centralized scenario

The biomass is converted to biogas in the biogas plant and further purified. Nearby, hydrogen is produced via alkaline electrolysis. Hydrogen and treated biogas are fed into a methanation plant to produce electro biomethane, which is in a convenient location from the biogas plant and electrolysis. The number of such facilities is not determined. The methane is fed into the nearby gas grid and delivered to Fjernvarme Fyn's FT & refining facility.

The heat, from electrolysis and methanation, is utilized by the biogas plant and the nearby cities with district heating. The excess heat from the FT & refining facility is delivering to the district heating grid of Odense.

This is assumed for a more realistic case, as electro biomethane production is decentralized, and should be nearby biogas plants. There is no existence of future planned biogas plants nearby Fjernvarme Fyn's facility. All the excess heat from electro biomethane production is assumed to be utilized and sold for a price of 10,07 €/GJ_{heat} [12].

7.1.3 Capacity and demands

The required demand for biogas, hydrogen production, and electro biomethane production for both pathways in the centralized scenario, is seen in Table 17, together with the required capacity of syngas and FT & refining.

Yearly biogas demand [PJ]		
	POX pathway	SMR pathway
Biogas	6,29	6,29
Yearly production of hydrogen [PJ]		
Hydrogen (Alkaline electrolysis)	4	1,87
Yearly electro biomethane production [PJ]		
Electro biomethane (CO methanation)	9,4	9,4
Capacity sizes of syngas and FT & refining facility [MW]		
Syngas capacity	286,6	296,9
Fischer Tropsch & refining	220	175,9
Yearly mainly products [PJ]		
Jet fuel	5,03	4,02
Total excess heat	4,23	2,98
Total excess hydrogen	-	2,02
FT capacity [BPD JF]		
Fischer Tropsch	3544	2835
Label	Small scale	Small scale

Table 17: Yearly demands and capacities for the centralized scenario. The "labels" are determined by the capacity of the FT facility [49].

Both pathways for the centralized scenario is demanding the same amount of biogas and electro biomethane.
The differences in the pathways are mainly the JF output, due to a lower syncrude production in the SMR pathway.
As POX produces 2:1 and SMR produces 3:1 of H_2:CO ratio, is the syngas produced with SMR with a higher H_2:CO ratio that FT synthesis needs (About 2:1). This leaves an excess of hydrogen. Only a small fraction of the excess hydrogen is used for the LTFT refinery. The rest of it is sent back to the methanation plant.
The energy flows for the two pathways are identical to the shown E-Sankey diagrams in figure 14 and figure 15, as the centralized scenario evaluates the pathways with all Funen's biogas potential utilized at one centralized facility.

7.2 Decentralized JF production

The placement of decentralized FT facilities is not already given and evident as the case for the centralized scenario. Therefore, the before-mentioned criteria are investigated further to find suitable locations for better integration.

7.2.1 Potentially locations

7.2.1.1 District heating connectivity and gas grid availability

The identification of potential locations is firstly determined based on the two first criteria (district heating connectivity and gas availability). The data used for such analysis is a grid map of the district heating & natural gas grid. This map is shown in Figure 18 [50].

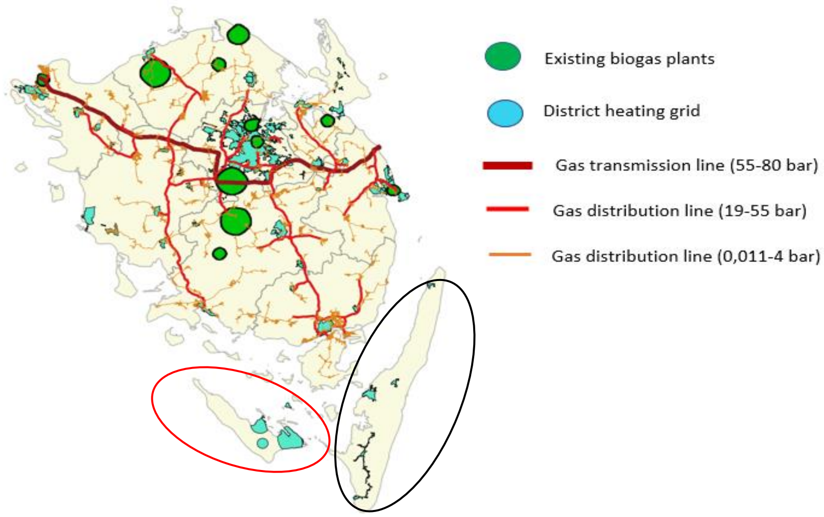


Figure 18: Map of Funen with existing biogas plants, district heating grid, gas transmission, and distribution lines.

A correlation between the gas grid and district heating grids, except for Ærø (marked with a red circle) and Langeland (marked with a black circle), is derived from the map. Due to a lack of gas availability, Ærø, and Langeland do not comply with the criteria. Based on the map does at least 11 cities comply with the criteria of having both district heating and gas availability. These 11 cities are:

1. Assens
2. Bogense
3. Kerteminde
4. Middelfart
5. Munkebo
6. Nyborg
7. Nørre-Aaby
8. Odense
9. Otterup
10. Ringe
11. Svendborg

7.2.1.2 Heating demand for the potential locations

To identify whether the city's heating demand is suitable for utilizing excess heat produced by the facilities, each city's heating demand is identified.

It is assumed that the 11 listed cities, has a heating demand profile, which is similar in pattern as Odense city, and the citizens of Odense represent a normal population with average heating consumption/person[3]. Based on an hourly heating demand and population of Odense, is Odense's hourly demand/person calculated by Eq. 11.

$$\frac{Hourly\ heatdemand}{Person} = \frac{Houlty\ Heat\ demand\ Odense\ [MW/h]}{Population\ of\ Odense} \qquad \textit{Eq. 11}$$

The heat demand generates an hourly heating demand profile per person. This is depicted in Figure 19.

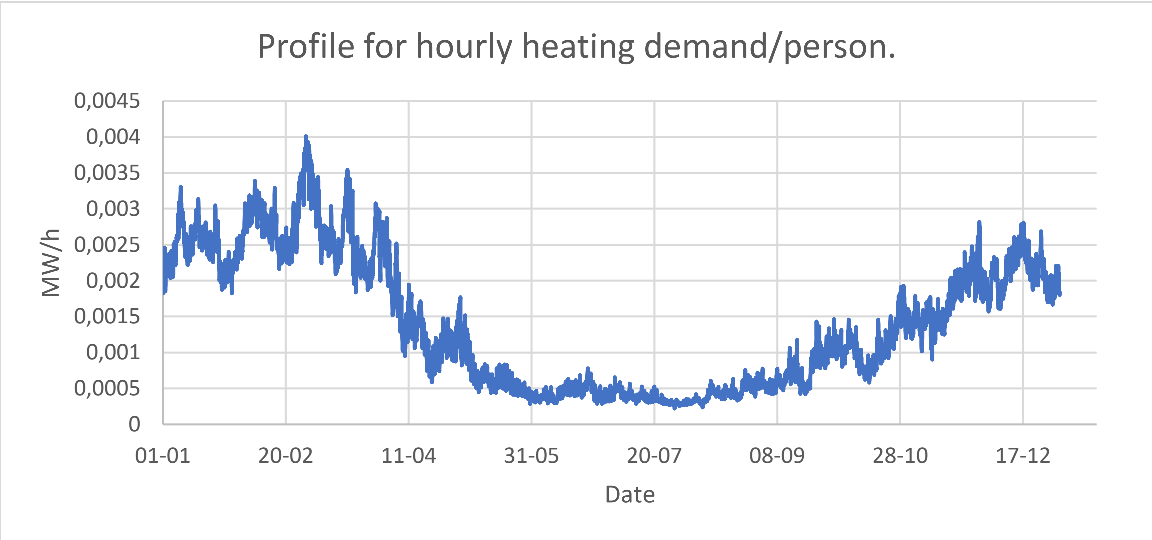


Figure 19: Hourly heating demand/person profile. The profile is based on a total heating demand for Odense city in 2025.

To identify each of 11 listed cities' heating demands, the hourly heating demand/person profile is multiplied by each of the cities' population; This results in a total yearly heating demand with a similar demand pattern as depicted in Figure 19.

[3] Data of Odense total heat consumption is forwarded by Fjernvarme and can be seen in attached Excel document (Fjernvarme Fyn data) or in Figure 16. The provided data is based on heat consumption in 2025 [47] ibid..

Based on the hourly heat demand profile, the total heat demand is calculated for the 11 cities.
The heat demand for each of the cities is seen in Table 18.

City	Population	Total yearly heating demand [GWh]	Average heating demand [MWh]	Max [MWh]	Min [MWh]
Assens by	6155	74,93	8,55	24,66	1,37
Bogense	3949	48,08	5,49	15,82	0,88
Kerteminde	5898	71,81	8,20	23,63	1,31
Middelfart	15540	189,19	21,60	62,25	3,45
Munkebo	5576	67,88	7,75	22,34	1,24
Nyborg	17175	209,1	23,87	68,8	3,82
Nørre-Aaby	2964	36,09	4,12	11,87	0,66
Odense	204895	2494,49	284,76	820,82	45,52
Otterup	5218	63,53	7,25	20,9	1,16
Ringe	6110	74,39	8,49	24,48	1,36
Svendborg	27210	331,27	37,82	109	6,05

Table 18: Total district heating demand for the 11 chosen cities [51].

The two next criteria are investigated, as the heating demand is identified: Total heating demand and biogas availability.
It is assumed that only locations with an annual heating demand above 45000 MW are considered. In such a case, the heating demand for Nørre-Aaby is too low and not considered as a potential location for a FT facility. Further investigation of the potential locations reveals Nyborg has an existing refinery facility, which provides excess heat for the citizens of Nyborg. The refinery covers 96% of the city's yearly heating demand [52]. An FT facility at Nyborg would lead to a tremendous amount of unutilized heat, which would make it a dangerous case for the FT facility.
Many of the heating demands shown in Table 18 are similar. Therefore, it is decided to choose "only" the below listed 8 locations:

1. Assens
2. Bogense
3. Kerteminde
4. Middelfart
5. Odense
6. Otterup
7. Ringe
8. Svendborg

Bogense is chosen over Munkebo, despite the fact Munkebo's heating demand is higher than Bogense's. Bogense is chosen due to a broader distribution of plants and due to an already existing nearby biogas plant, Nature Energy Nordfyn. The biogas plant has a capacity of 300.000 tons biomass each year, equivalent to 10 million Nm^3 of upgraded biogas [53].
The 8 listed cities' heating demand profile is seen in appendix H.

The locations for the facilities are depicted in Figure 20 [50].

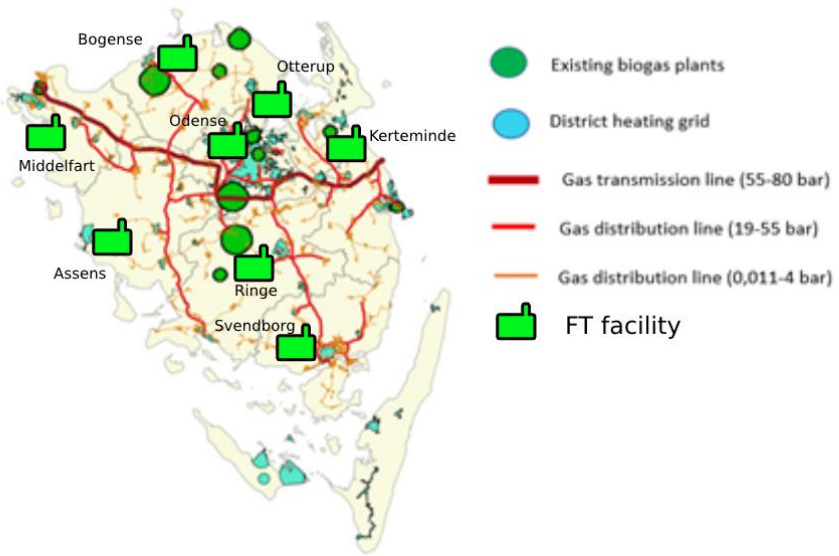


Figure 20: Map of Funen with plots of chosen cities.

For most of the cases, the JF & refining facility is placed nearby a biogas plant and the gas grid. In cases where no biogas plants are nearby, new biogas plants should be built.

7.2.2 Specific assumptions for decentralized scenario

8 potential locations for decentralized JF production, have been identified. The next step is to determine each city's amount of required electro biomethane and capacities for syngas production and FT & refining facility. This is done for both pathways (SMR and POX).

It is assumed that for the decentralized cases, that the required biogas plant, electrolysis, and methanation plant is operating in the same area as the syngas and FT & refining facility; This furthermore, indicates that all the produced excess heat is utilized in the same area. The concept is depicted in Figure 21.

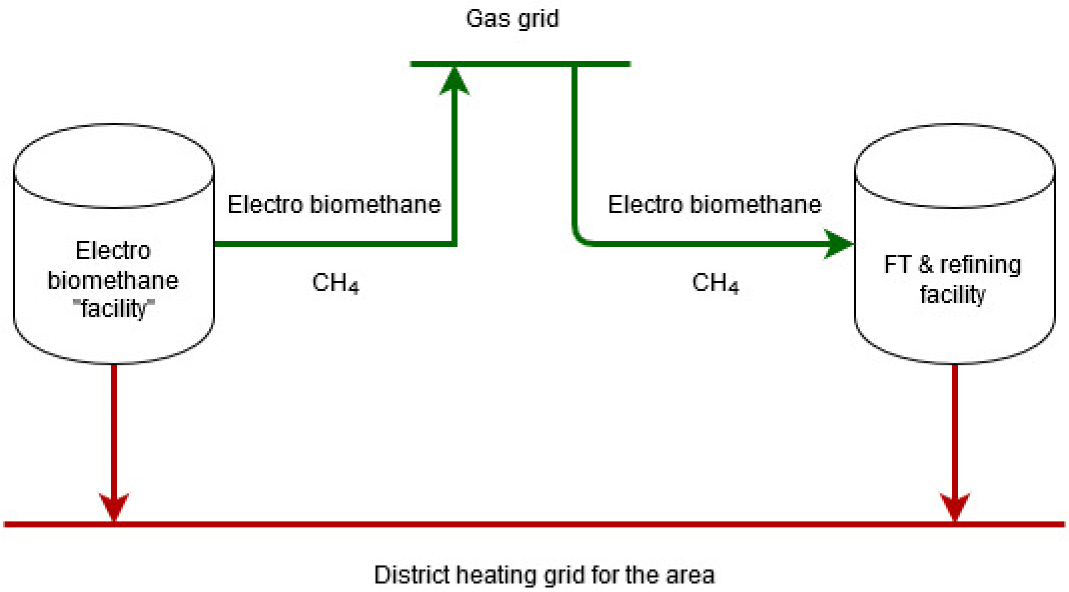


Figure 21: Picture of where the excess heat is utilized - Decentralized scenario

The capacity of the FT & refining, the required syngas production, and the demand for electro biomethane, in each area, is determined based on the heating demand for the same area. It is done to avoid over-scaling of the facilities, as this would lead to unutilized excess heat, which would result in lower income from selling of heat. For most of the cases, the capacities are scaled, so the total production of excess heat covers 65% of the total heating demand for the given city. Exceptions are made for Bogense, Otterup, and Odense, where a lower heating coverage fraction is used (20% for Bogense and 30% for Otterup). For Bogense and Otterup, it is done to get a variety of capacities. For Odense, the capacities are scaled based on the available left-over biomass, which is not utilized by the 7 other facilities.

The limitation of 65% is used, as a 100% replacement of the existing heat production facilities within 5 years may not seem realistic.

It implies that the total production of excess heat is the same for both pathways (SMR and POX) in the areas of Bogense, Otterup, Kerteminde, Ringe, Assens, Middelfart, and Svendborg, as the capacities are scaled based on the amount excess heat produced.

The total excess heat production for the POX pathway is higher than the SMR pathway for the case in Odense since the POX pathway includes the exothermic process of syngas production. This further implies that the total excess heat is higher for the POX pathway than for the SMR pathway.

Described under the assumption, the heat a 100% utilization of excess is assumed. This further suggests heating storages are needed, as the production of excess heat exceeds the heat demand in the summer periods.
The minimum needed storage capacities are calculated based on each of 8 locations overproduction of excess heat. The minimum storage capacity and types are shown in Table 19 [19].

<table>
<tr><td></td><td colspan="2">Storage capacity [MWh]</td><td>Storage type</td></tr>
<tr><td>Bogense</td><td colspan="2">0,6</td><td>Small scale hot water tank</td></tr>
<tr><td>Otterup</td><td colspan="2">353</td><td>Large hot water tank</td></tr>
<tr><td>Kerteminde</td><td colspan="2">8595</td><td>PTES seasonal</td></tr>
<tr><td>Ringe</td><td colspan="2">8904</td><td>PTES seasonal</td></tr>
<tr><td>Assens</td><td colspan="2">8969</td><td>PTES seasonal</td></tr>
<tr><td>Middelfart</td><td colspan="2">22645</td><td>PTES seasonal</td></tr>
<tr><td>Svendborg</td><td colspan="2">39651</td><td>PTES seasonal</td></tr>
<tr><td></td><td>SMR [MWh]</td><td>POX [MWh]</td><td rowspan="2">PTES seasonal</td></tr>
<tr><td>Odense</td><td>0</td><td>5742</td></tr>
</table>

Table 19: Minimum storage capacities for the 8 chosen cities.

The calculations are based on the maximum accumulated excess heat, with no other heating sources producing heat. If other sources of heating were included, the proposal for minimum heating storage would increase. The 8 listed cities' minimum storage capacity is seen in appendix H.

7.2.3 Capacities

Each of the 8 locations' demand of biogas, hydrogen, and electro biomethane are presented further, together with the syngas and FT & refining facility's capacity.

In Table 20, the specific demand for biogas and the production of JF for each location are seen for the POX pathway. The table is categorized smallest to highest of biogas demand.

Yearly biogas demand [PJ]								
	Bogense	Otterup	Kerteminde	Ringe	Assens	Middelfart	Svendborg	Odense
Biogas	0,05	0,1	0,25	0,26	0,26	0,66	1,16	3,54
Yearly production hydrogen [PJ]								
Electrolysis	0,03	0,06	0,16	0,16	0,17	0,42	0,73	2,25
Yearly electro biomethane production [PJ]								
Methanation	0,08	0,15	0,37	0,39	0,39	0,99	1,73	5,28
Capacity sizes of syngas and FT & refining facility [MW]								
POX capacity	2,36	4,7	11,5	11,9	12	30,2	52,9	161,2
Fischer Tropsch & refining	1,8	3,6	8,8	9,1	9,2	23,2	40,6	123,7
Yearly mainly products [PJ]								
Jet fuel	0,04	0,08	0,2	0,21	0,21	0,53	0,92	2,83
Total excess heat	0,03	0,07	0,17	0,18	0,18	0,44	0,77	2,36
FT capacity [BPD JF]								
Fischer Tropsch	29	58	141	147	148	373	653	1993
Label	Micro	Micro	Mini	Mini	Mini	Mini	Mini	Small scale

Table 20: Yearly biogas demand and production for the 8 decentralized facilities – POX pathway.

From the table, it is seen that 2 FT facilities are labeled as Micro, 5 as mini, and 1 as small scale. The label is depending on the amount BPD for the FT facility [49].

In Table 21, each city's specific demand for biogas and the production of JF is seen for the SMR pathway. The table has been categorized smallest to highest of biogas demand.

Yearly biogas demand [PJ]								
	Bogense	Otterup	Kerteminde	Ringe	Assens	Middelfart	Svendborg	Odense
Biogas	0,07	0,14	0,35	0,37	0,37	0,93	1,64	2,41
Yearly production hydrogen [PJ]								
Electrolysis	0,02	0,04	0,11	0,11	0,11	0,28	0,49	0,72
Yearly electro biomethane production [PJ]								
Methanation	0,09	0,17	0,42	0,43	0,44	1,1	1,93	2,85
Capacity sizes of syngas and FT & refining facility [MW]								
SMR capacity	3,4	6,8	16,7	17,3	17,5	44,1	77,2	113,9
Fischer Tropsch & refining	2	4	9,9	10,3	10,3	26,1	45,7	67,5
Yearly mainly products [PJ]								
Jet fuel	0,05	0,09	0,23	0,23	0,24	0,6	1,05	1,54
Total excess heat	0,03	0,07	0,17	0,17	0,18	0,44	0,78	1,14
Total excess hydrogen	0,02	0,05	0,11	0,12	0,12	0,3	0,53	0,78
FT capacity [BPD JF]								
Fischer Tropsch	33	65	160	165	166	421	736	1086
Label	Micro	Micro	Mini	Mini	Mini	Mini	Mini	Small scale

Table 21: Yearly biogas demand and production for the 8 decentralized facilities – SMR pathway

Even though the capacities are higher for the 7 first locations, it does not change the labels. The labels are the same as for the POX pathway.

The total utilization of biogas is the same for both pathways. The difference in the POX and SMR are specific cases. Since the capacities are scaled on the heat demand for a given city and POX pathway produces more excess heat than the SMR pathway, the capacities of POX are smaller in all the cases except Odense.
This furthermore, gives a lower JF production for the POX pathway, compared to the same location in the SMR pathway. On the other hand, the facility in Odense is higher for POX than SMR, due to more left-over biogas.
E-Sankey diagrams for all the decentralized locations are seen in appendix I.

8. Economic assumptions

Before the results are presented, the economic assumptions are described, which are the foundation for the economic evaluation.
The economic assumptions are based on literature reviews, approximations, calculations, and intern conversations.
In this section, the economic assumptions are described and how they were gathered, such as “economy of scale” for the syngas facilities and the FT & refining facilities.

8.1 General economic assumptions

For all the facilities, a utilization rate of 93% is assumed, which equals to 8147 hours each year. Leap years are not considered.

The price for excess heat is assumed to be 10,07 €/GJ_{heat}. This estimate is based on the willingness for district heating companies to pay for heat facilities they have not financed them-selves [12].
The price of self-financed facilities would most likely be lower but has higher risks associated.

The selling price of gasoline has a higher selling price of 17,34 €/$GJ_{gasoline}$ and a lower of 13,3 €/$GJ_{gasoline}$.
These are calculated based on Denmark’s market price [54]. The specific calculations are seen in appendix J.
Side-products selling price for the base case is assumed to be 37,99 €/$GJ_{side\text{-}product}$, which is the same price as 2. generation bioethanol [55]. Side-products has a lower selling price of 20,08 €/GJ, which is the same price as bio-LNG [56].

Technologies with a lifetime lower or higher than 25 years are calculated to match 25 years. This means that the investment cost is divided by the lifetime and multiplied with 25. The investment cost has furthermore been assumed to all happen in year 0.

8.2 Economy of scale

8.2.1 Syngas production facilities

The economy of scale is calculated for syngas production. It is done by evaluating existing facilities' capacities and specific investment and calculate their tendency of investments in €/MW.
For both, POX and SMR, are three examples used to calculate the economics of scale.
These can be seen in appendix K.

The economy of scale is described by the graph represented in Figure 22. The graph is expanded by inserting further capacities (1-2000 MW. Market with circles) to get a smoother graph. The triangles represent the three examples for each technology.

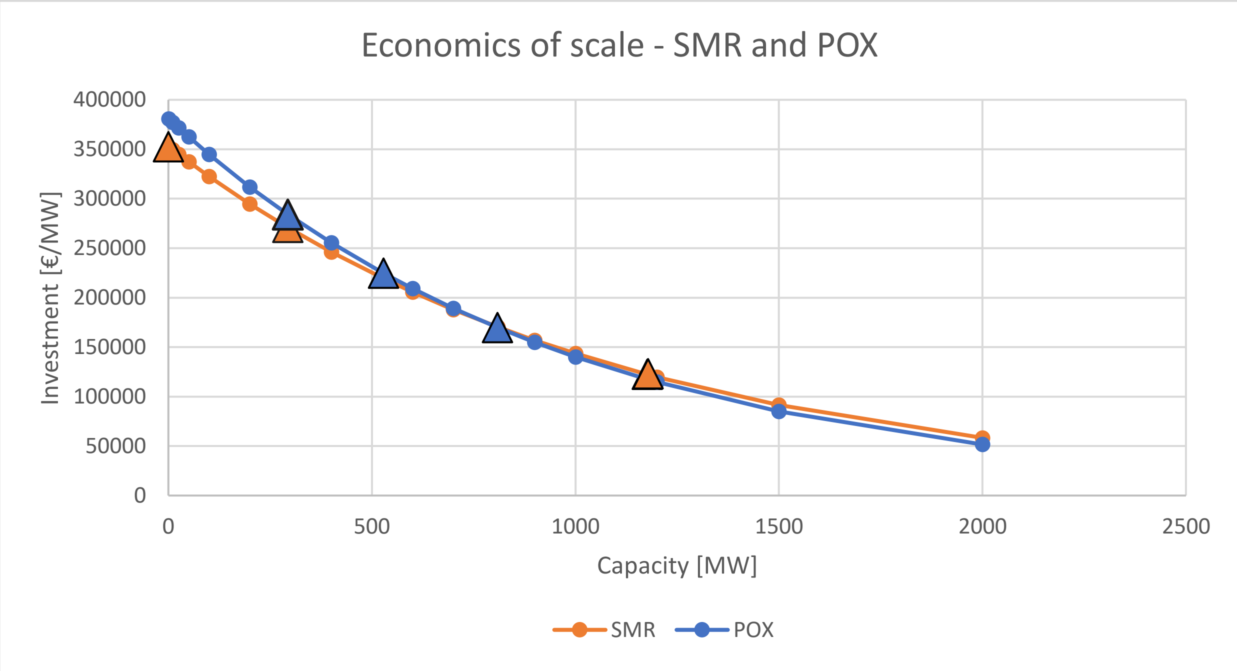


Figure 22: Calculated economics of scale for SMR and POX.

The graph is plotted based on the trendline each technology generates, seen in Figure 22. The investment is, therefore, scalable with the capacity of the facility.
The investment covers the entire facility, which includes the heater for SMR and oxygen separator for POX.

The specific economics for syngas production with either POX or SMR is seen in Table 22.

	SMR	POX
Specific investment. (X=capacity in MW)	"353090*$e^{-9E-04x}$"	"381021*$e^{-0,001x}$"
Fixed O&M/year	5% of capital cost	5% of capital cost
Variable O&M	2 €/MWh	2,25 €/MWh
Utilization rate	93%	93%

Table 22: Economically specifications of syngas production.

8.2.2 Fischer Tropsch economics

Economics of scale is also calculated for the FT facility. The capital cost of the Fischer Tropsch and the refining is calculated in one. The economy of scale is calculated based on two existing world-scale FT facilities, and three assumed lower-scale FT facilities.
The plants and their economics are seen in Table 23.

Plant	**Capacity (BPD)**	**CAPEX [M $]**	**$/BPD (GTL facility)**	**€/BPD (GTL facility)**	**€/BPD (FT & refining)**	**Reference**
Assumed plants						
Micro scale	10	1,7	170.000	158.100	79.050	[49]
Mini scale	100	13	130.000	120.900	60.450	[49]
Small scale	1.000	100	100.000	93.000	46.500	[49]
Existing plants						
Shell, Bintulu, Malaysia	14.700	1.500	68.000	63.240	31.620	[57] [58]
Sasol / Chevron, Oryx, Qatar	32.400	4.500	35.000	32.550	16.275	[58] [12]

Table 23: Existing and assumed CAPEX for FT facilities.

The found investments are for GTL (Gas-to-liquid) facilities, which includes the syngas production. A capital cost break-down for such facilities is shown in Figure 23 [59].

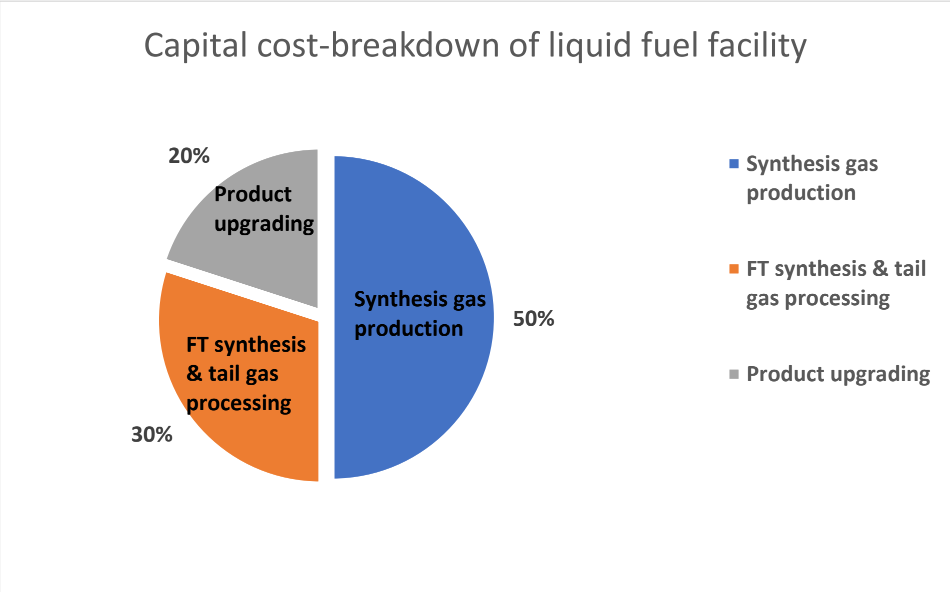


Figure 23: Example of Capital Cost break-down of FT facilities.

The diagram proposes that the capital cost of Fischer Tropsch and refining facility is 50% of the total investment for a GTL facility (which includes the syngas unit).
Therefore, the found and assumed economics for the FT facility should be divided by 2 to get the investment for Fischer Tropsch synthesis & refining alone.

Based on the five plants' capacity and investments [€/BPD], a trendline is calculated. The five plants are depicted in Figure 24. The triangles represent the existing facilities, and the squares represent the assumed facilities.

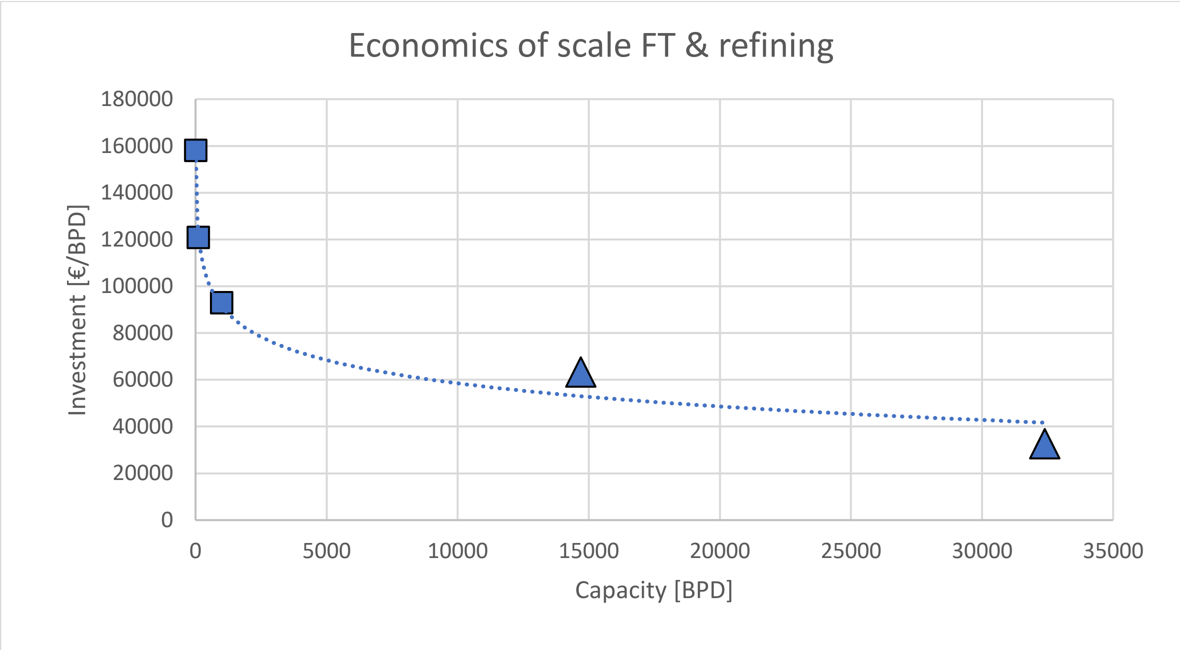


Figure 24: Economics of scale for FT facility.

The calculated trendline is representing the general investment cost in €/BPD. The specific investment is found by multiplying the general investment [€/BPD] with the specific capacity.
The general economics for Fischer Tropsch synthesis and refining is defined in Table 24.

Investment [€/BPD]	"14301*ln (BPD) + 190225"
Fixed O&M	5% of capital cost
Variable O&M	4,5 €/BBL
Utilization rate	93%

Table 24: Economically specifications for the FT facility [12].

9. Results

The results of the investigated scenarios and pathways are presented further. The results are divided into economic evaluation and integration availability.

The economic evaluation for the base cases is divided into 3 sub-categories: *"Centralized"*, *"Decentralized"*, and *"Comparison".* In *"Centralized"* and *"Decentralized"* are the LCOE's presented and compared between the pathways; POX and SMR. In *"Comparison"* are the results of the centralized scenario compared to the decentralized scenario.
The economic numbers are valid based on the identified assumptions and initial conditions. Any change in these would change the LCOE.
For the decentralized scenario, an average LCOE of the 8 facilities is calculated, for a better comparison of the LCOE between the decentralized scenario and the centralized scenario.
The economic evaluation further calculates a proposal cost of grid connection for district heating and gas. Sensitivity analysis is performed lastly to determine which scenario and pathway, is most sensitive to a change in the assumed data.

The results for the integration include the heating contribution to Odense's district heating grid of excess heat from the centralized scenarios. Furthermore, it is evaluated if the gas grid capacity is high enough for the facilities' demand of electro biomethane; this is done for both the centralized and decentralized scenario.

9.1 Economic evaluation

The following section identifies the LCOE of renewable JF. Firstly, the LCOE of renewable JF using the POX pathway and SMR pathway for the centralized scenario is investigated. Afterward, the LCOE of renewable JF using the POX pathway and SMR pathway for the decentralized scenario is investigated.
The results are presented as column graphs. For each graph, three columns are seen; *"Expenditures/income"*, *"Cost break-down by processes"* and *"Cost break-down by product"*.
The total expenditures and income are found by multiplying the total amount of produced JF, as the graphs are represented as €/$GJ_{jet\ fuel}$.
The investments are based on the economics of scale defined in the *"Economic of scale"*.
The specific cash-flows are seen in "Results".

9.1.1 Centralized scenario

9.1.1.1 LCOE and cost break-down

Figure 25 depicts the LCOE and cost break-down for the POX pathway.
The total expenditures are 59,64 €/$GJ_{jet\ fuel}$. The majority relates to auxiliaries, which include electricity for the electrolysis and heating for the biogas plant.
The total income from heating, side-products, and gasoline is 17,02 €/$GJ_{jet\ fuel}$. Most of the income is excess heat, which represents 8,41 €/$GJ_{jet\ fuel}$.

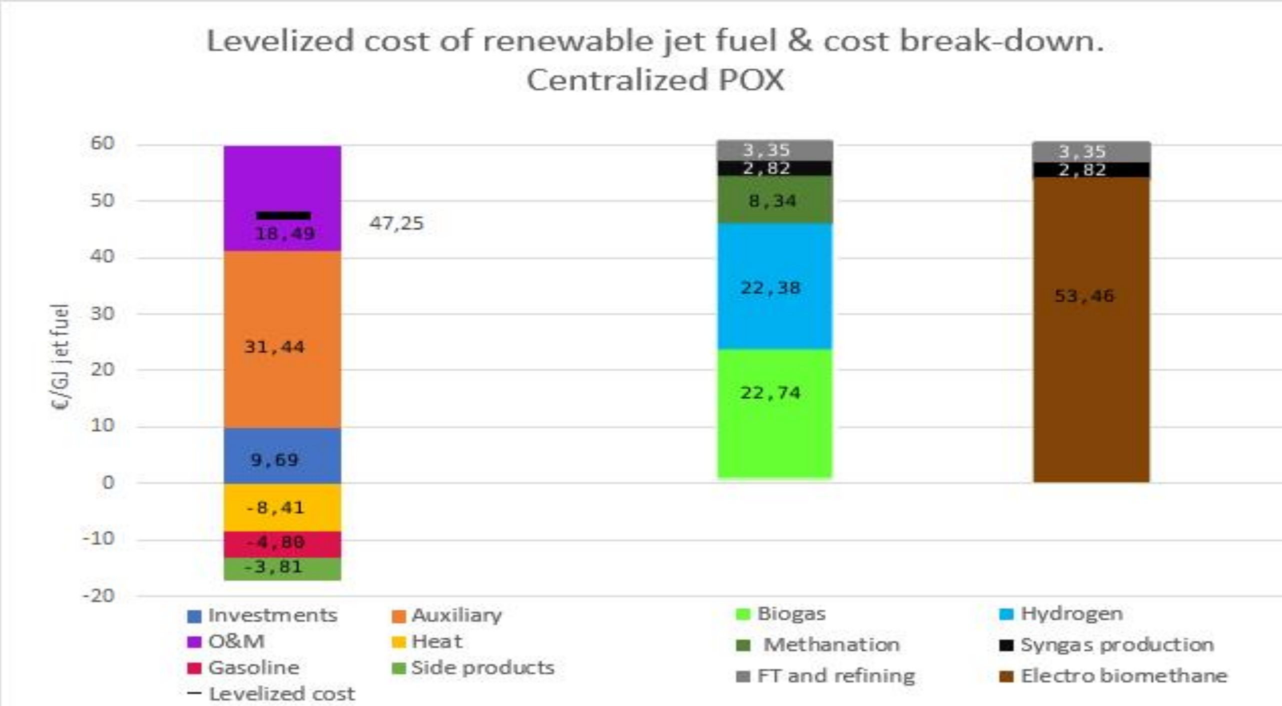


Figure 25: Levelized cost and cost break-down of renewable jet fuel for the centralized case – POX pathway. All the expenditures for the first column are inclusive the total investments, auxiliary, and o&m for electro biomethane production.

The cost break-downs are shown as the contribution of the expenditures related to a giving fuel/facility in terms of €/$GJ_{jet\ fuel}$.
The highest contributor is the production of biogas and hydrogen. The total expenditures related to the production of electro biomethane represent almost 90% of the total expenditures related to renewable JF production.

The cost break-down of renewable JF production with the SMR pathway is seen in Figure 26. The first column relates to the general cost break-down by economic expenditures and income. The second and third bar depicts the cost break-down by product and processes.
The total expenditures related to the production of renewable JF is 58,75 €/$GJ_{jet\ fuel}$. The total income is 16,07 €/$GJ_{jet\ fuel}$, where the majority is related to excess heat as for the POX pathway. In this case, sales of excess heat represent 7,46 €/$GJ_{jet\ fuel}$, which is 0,95 €/GJ_{jet} lower than for the POX pathway.

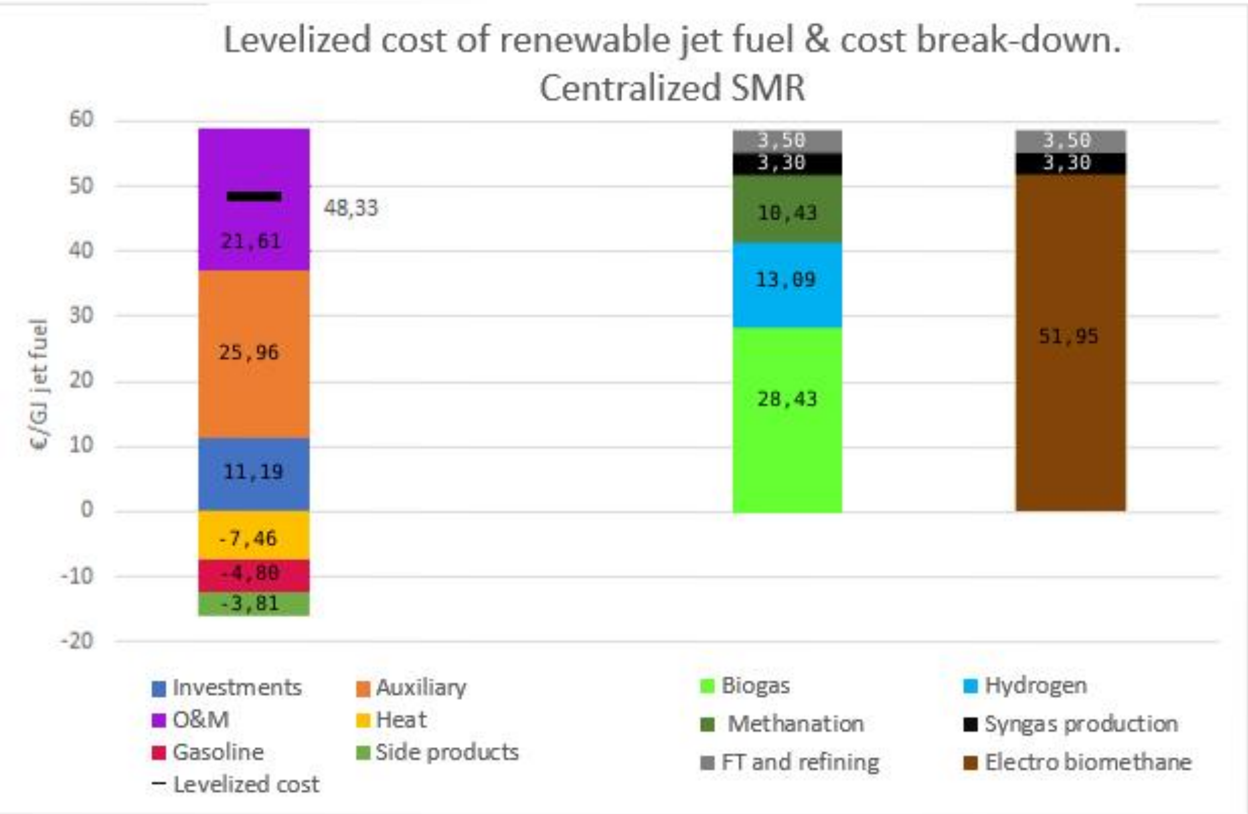


Figure 26: Levelized cost and cost break-down of renewable jet fuel for the centralized case – SMR pathway. All the expenditures for the first box are inclusive the total investments, auxiliary and o&m for electro biomethane production

The cost of biogas is the highest contributor related to expenditures in the SMR case. The cost of biogas/$GJ_{jet\ fuel}$ is a little higher for SMR than for POX, due to the lower output of JF.
The pathway for SMR produces an excess of hydrogen, which is utilized in the methanation stage. For this reason, the expenditures related to hydrogen are lower than the hydrogen expenditures for the POX pathway. Lower expenditures related to hydrogen production could imply that the SMR pathway is less sensitive to a change in electricity prices.
The electro biomethane represents almost 90% of the total expenditures related to renewable JF production, as the case of the POX pathway.
A comparison between the two pathways in the centralized scenario shows a remarkable phenomenon. Expenditures for JF production using the SMR pathway is slightly lower than the POX pathway (Around 1 €/$GJ_{jet\ fuel}$) but has higher LCOE (1,08 €/$GJ_{jet\ fuel}$ higher). The reason for lower expenditures is found in the auxiliaries. The excess hydrogen from SMR is used in the methanation process, which lowers the expenditures related to hydrogen production.

The reason for a higher LCOE of JF, even with a lower net production cost, is due to the lower income of the pathway with SMR. The SMR pathway produces 32% lower heat in terms of energy, with the same amount of electro biomethane available.
The differences in income are more significant than the differences in expenditures, which make the POX pathway most economically viable in the centralized scenario.

9.1.1.2 Cash-flow - Centralized

The accumulated cash-flow for the two pathways is depicted in Figure 27.
The difference between the yearly accumulated cash-flows is equal to the yearly cash-flow. If the accumulated cash-flow is lower than the previous year, the yearly cash-flow is positive. If the accumulated cash-flow is higher than the previous year, it indicates that the yearly cash-flow is negative.
The accumulated cash-flows for both pathways is further described by the polynomial equation seen in Figure 27. The polynomial curve flattens out, because of the discount rate of 4%.
The total expenditures for year 0 are 1131 M€ for POX and 1049 M€ for SMR, which further indicates the lower expenditures of renewable JF production related to the SMR pathway.

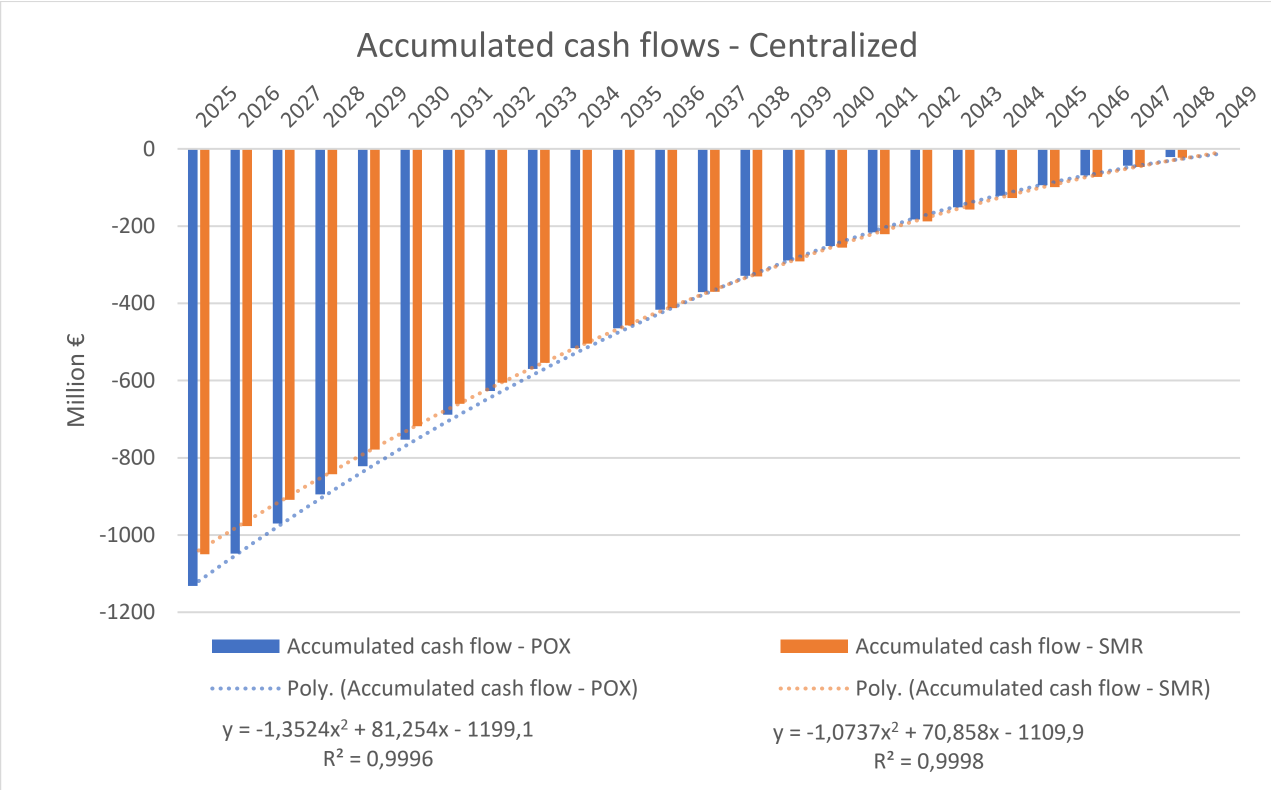


Figure 27: Accumulated cash-flow (Shown in M €) for centralized cases. The cash-flow is inclusive all expenditures related to electro biomethane production.

The polynomial equations describe the yearly accumulated cash-flow. Seen from the graph and the two equations, the accumulated cash-flow is more aggressively decreasing for POX. This implies that the positive cash-flow is higher for the POX pathway, which is a result of higher income. The accumulated cash-flow for POX starts to be lower than the accumulated cash-flow for SMR after 14 years, in the year 2038.

9.1.2 Decentralized cases

For the decentralized scenario, the 8 cities' average LCOE of renewable JF is presented. The LCOE of the decentralized scenario varies between 48,6-53 €/$GJ_{jet\ fuel}$ for the POX pathway and 50,4-54 €/$GJ_{jet\ fuel}$ for the SMR pathway. The specific LCOE for each city is shown in the attached Excel document "*Results*".

9.1.2.1 LCOE and cost break-down

Figure 28 depicts the column graph for the average LCOE of renewable JF with a pathway of using POX as syngas production. The total expenditures are 62,57 €/$GJ_{jet\ fuel}$. The majority is related to auxiliaries, which include mainly electricity costs. The reason for the difference between centralized and decentralized cases is the economics of scaling. The investment cost and O&M are about 10% higher/$GJ_{jet\ fuel}$ for the decentralized case than for the centralized case.

The income is the same as for the POX pathway in the centralized scenario (17,05 €/$GJ_{jet\ fuel}$), as the total JF production is the same, and the income is defined in €/$GJ_{jet\ fuel}$.

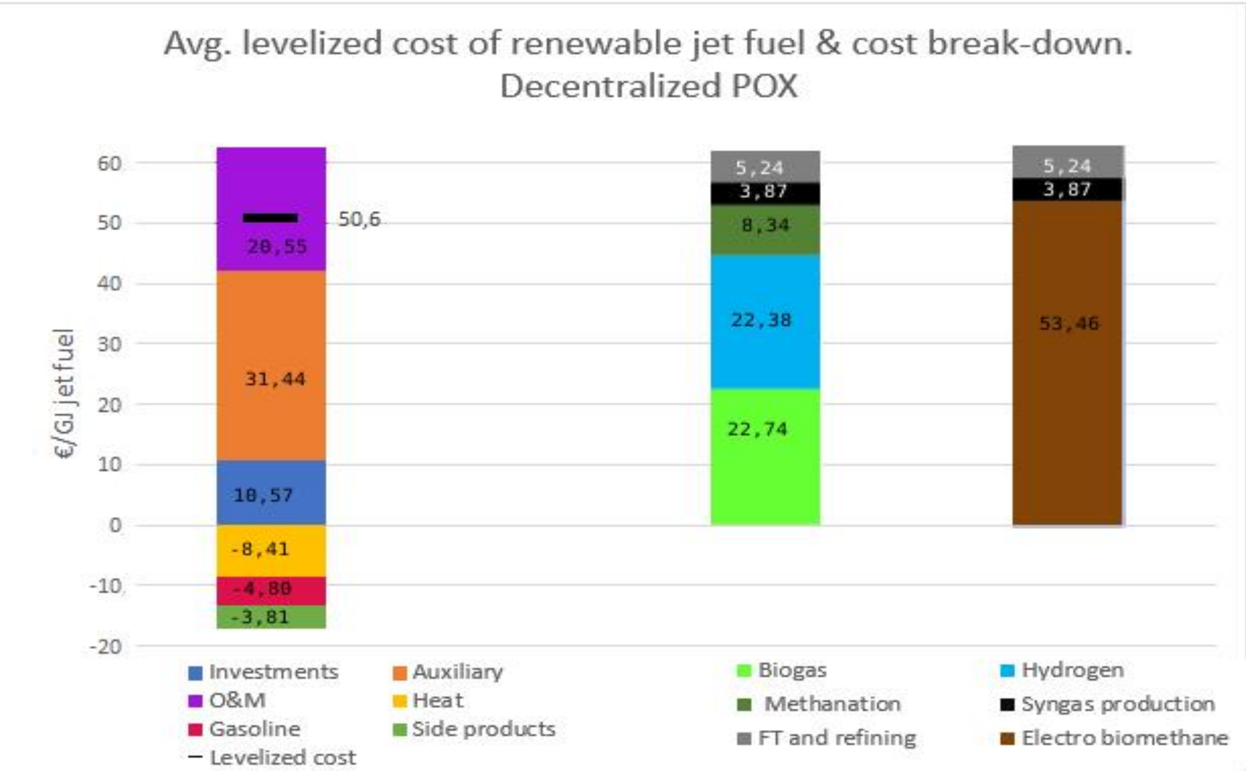


Figure 28: Levelized cost and cost break-down of renewable JF for decentralized case – POX pathway. All the expenditures for the first column are inclusive the total investments, auxiliary, and o&m for electro biomethane production.

The cost break-down is based on the contribution of the expenditures related to a giving fuel/facility in terms of €/$GJ_{jet\ fuel}$.

The cost break-down shows the same tendency as for the centralized scenario. The electro biomethane represents the same amount (53,46 €/$GJ_{Jetfuel}$) as for the centralized scenario, due to the cost of electro biomethane is fixed, and not depending on the economics of scale, at least not in this paper.

The difference between the centralized and decentralized scenario is the expenditures related to syngas production and FT & refining, as these are based on the defined economies of scale.

The total expenditures related to the production of electro biomethane are nearly 90% of the total expenditures in the decentralized scenario, as the case for the centralized scenario.

Figure 29 depicts the column graphs for the average LCOE of renewable JF with a pathway of using SMR as syngas production. The total expenditures are 61,54 €/$GJ_{jet\ fuel}$. The majority is related to auxiliaries, which include electricity, heating, and biogas expenditures. The reason for the difference between centralized and decentralized cases is the economics of scaling. The investment cost and O&M are about 10% higher for the decentralized case than for the centralized case.
The income from heat and side-products is the same as for the SMR pathway in the centralized scenario (16,08 €/$GJ_{jet\ fuel}$), as the total JF production is the same, and the income is defined in €/$GJ_{jet\ fuel}$.

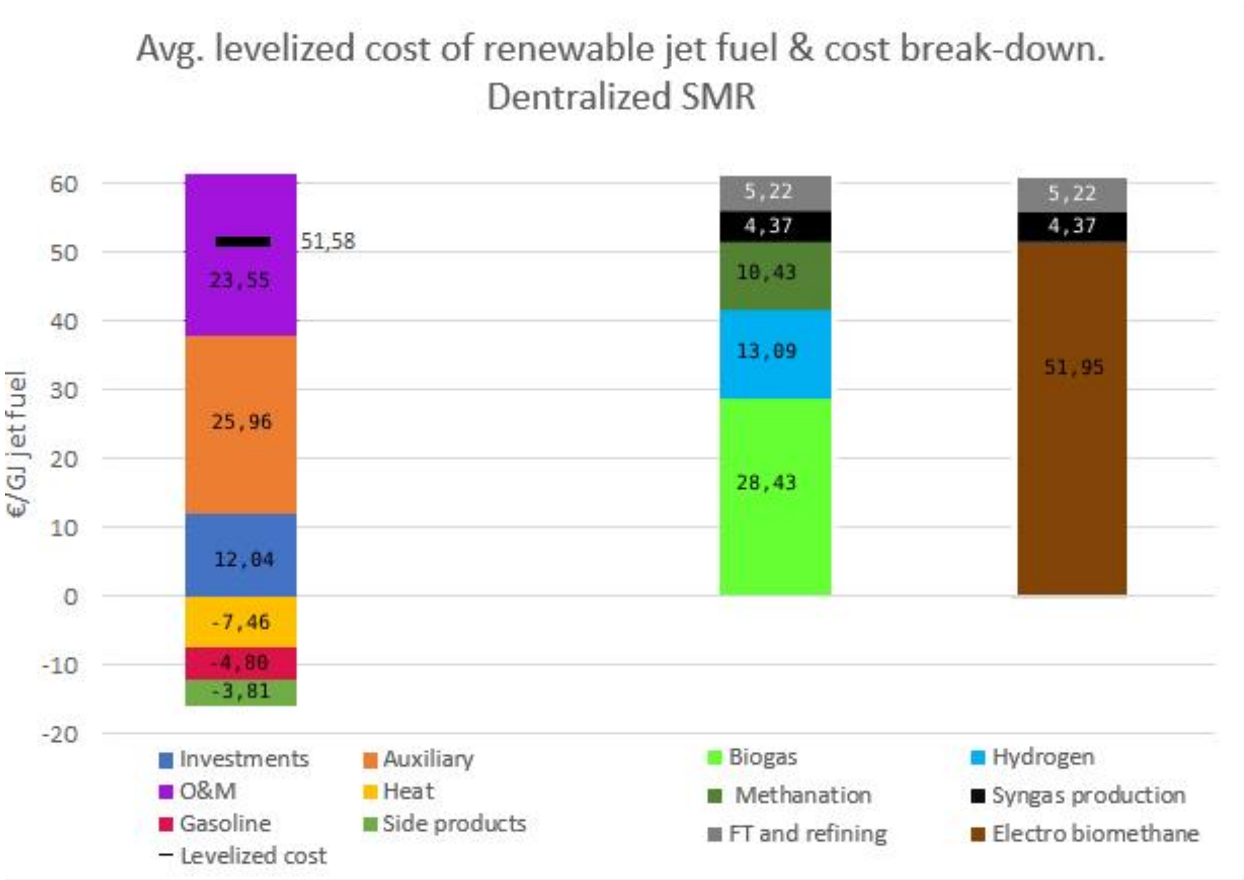


Figure 29: LCOE and cost break-down of renewable jet fuel for the centralized case – POX pathway. All the expenditures for the first box are inclusive the total investments, auxiliary, and o&m for electro biomethane production.

The relation between LCOE, income, and expenditures are the same as for the centralized case.
The pathway with POX has higher expenditures and income than the pathway with SMR, which results in a lower LCOE for renewable JF.

9.1.2.2 Cash-flow - Decentralized

The total accumulated cash-flow is depicted in Figure 30. The accumulated cash-flow for each of the 8 cases is added up to find the total accumulated cash-flow for the decentralized scenario.
The total expenditures for year 0 are 1187 M€ for POX and 1105 M€ for SMR, as the investments are made in year 0, which is a little higher than for the centralized scenario.

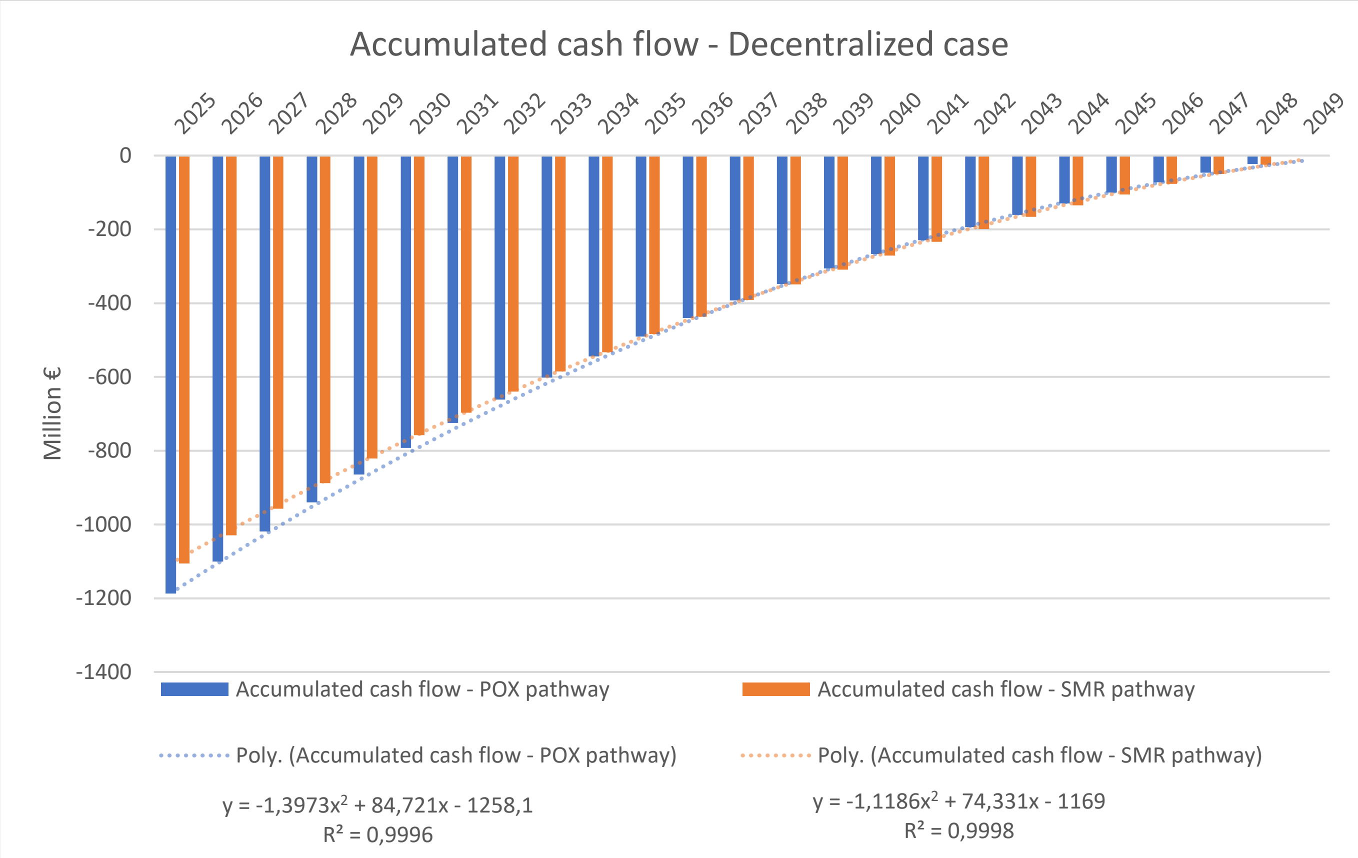


Figure 30: Accumulated cash-flow for the decentralized scenario. The cash-flow is inclusive all expenditures related to electro biomethane production.

The polynomial equations describe the accumulated cash-flow each year. Derived from the graph and the two equations, the same tendency as for the centralized scenario is seen; that the accumulated cash-flow is more aggressively decreasing for POX. This further confirms that the positive cash-flow is higher for the pathway POX than for the SMR pathway. The accumulated cash-flow for POX starts to be lower than the accumulated cash-flow for SMR after 14 years, in the year 2038. The same year as for the centralized scenario.
If the equations and graphs for the accumulated cash-flows of the decentralized scenario and the centralized scenario are compared, it is seen that the polynomial curve is steeper for the decentralized scenario. The reason for this is due to the higher expenditures related to the decentralized scenario, which is caused by the economics of scale.

9.1.3 Comparison

This section compares the expenditures, income, and LCOE of centralized and the average decentralized scenario. In Figure 31 are the LCOE's represented for both scenarios and pathways.

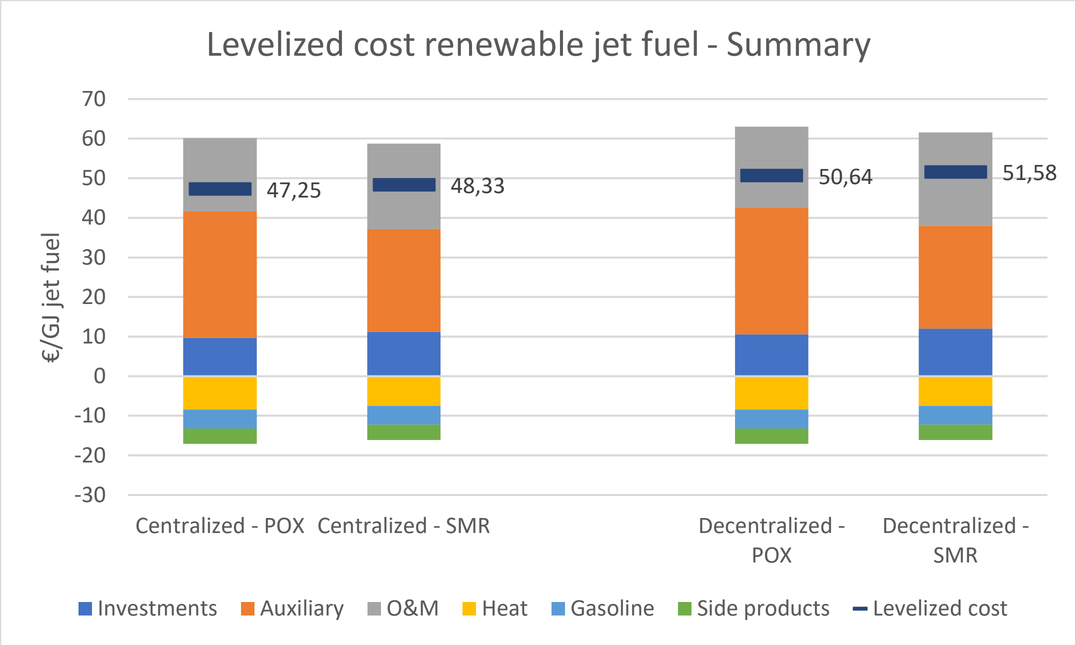


Figure 31: Comparison and summary of LCOE and cost breakdown for centralized and decentralized cases, using POX and SMR pathway.

Derived from Figure 31, the LCOE of renewable JF is lower for the centralized scenario than the decentralized scenario. The difference in LCOE between the centralized scenario and the decentralized scenario in the POX pathway is 3,39 €/GJ. The difference in LCOE between the centralized scenario and the decentralized scenario, using the SMR pathway, is 3,25 €/GJ.
The reason for this is found in the economics of scale, as the smaller facilities have higher CAPEX/MW, as described under *"Economically assumptions"*.

Even though the SMR pathway has lower expenditures related to JF production, the LCOE for the SMR pathway is 1,08 €/$GJ_{jet\ fuel}$ higher than the POX pathway in the centralized scenario. The reason is due to a higher income of heat for the POX pathway.
For the centralized scenario are the expenditures for SMR pathway 0,89 €/$GJ_{jet\ fuel}$ lower than the POX pathway (58,75 €/GJ for SMR vs. 59,64 €/GJ for POX). However, the income for the POX pathway is 0,97 €/$GJ_{jet\ fuel}$, higher than the SMR pathway (17,05 €/GJ for POX pathway and 16,08 €/GJ for SMR pathway). This makes the POX pathway a total of 0,08 €/$GJ_{jet\ fuel}$ lower than SMR. When NPV calculations have applied, the differences in LCOE raise to 1,08 €/GJ.

The cost break-down between POX centralized & decentralized scenario and SMR centralized & decentralized scenario shows the same tendency. The differences between the decentralized and centralized cost break-down are their magnitude, as economies of scale are applied for syngas production and FT & refining.

The LCOEs of renewable JF production for the centralized and centralized scenario, with both pathways, are depicted in Figure 32.
The LCOE follows the concept of economy of scale; an increase of FT jet fuel capacity decreases LCOE.
The differences in the LCOE's of renewable JF for the pathways are not much. It is not unthinkable that a change in the assumptions results in lower LCOE for the SMR pathway than for the POX pathway.

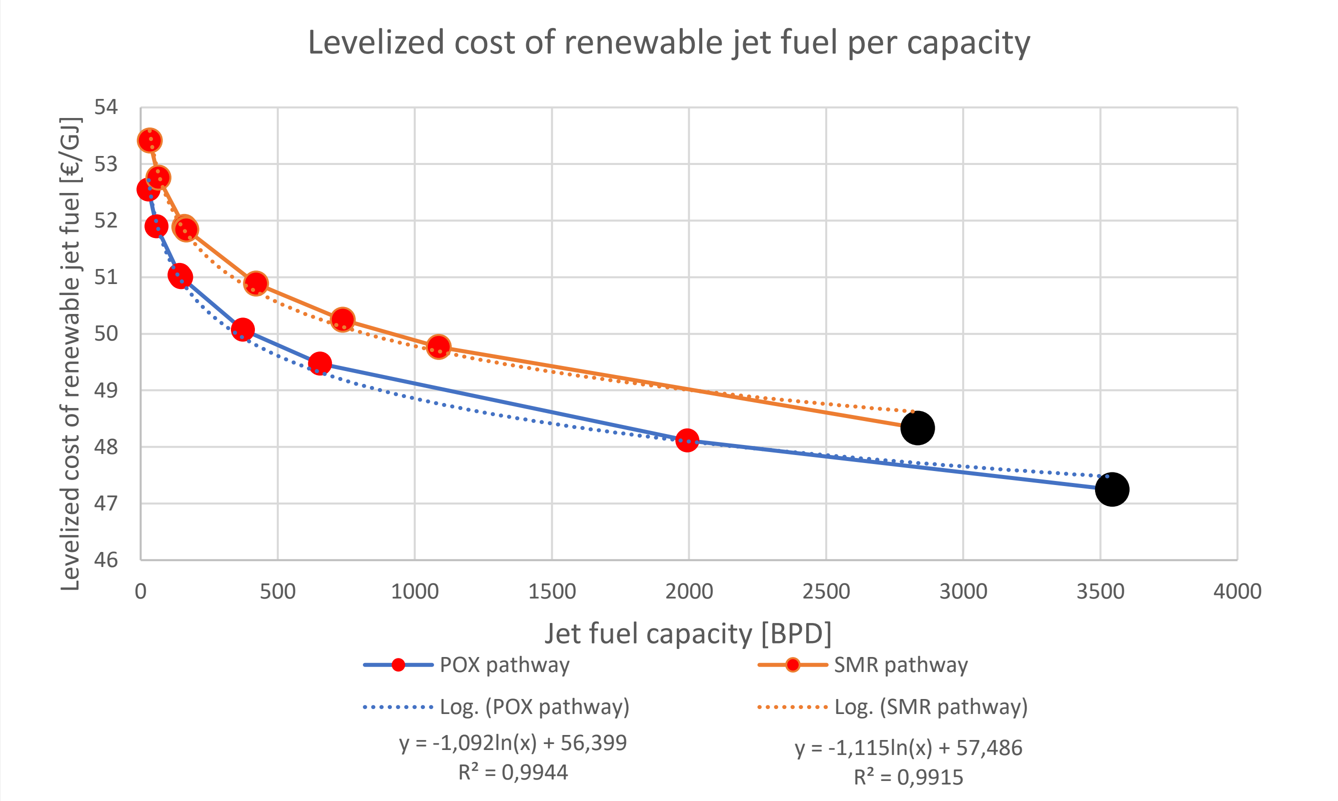


Figure 32: LCOE of renewable jet fuel by capacity and pathway. The red dots represent the decentralized cases, and the more prominent black dots represent the centralized cases

The polynomial equations for the LCOE of renewable JF production, which is shown in the graph, implies that higher capacity equals to lower LCOE. The difference of LCOE between pathways is eventually equalizing, as higher capacities of FT & refining are used.
The costs are exclusive the cost of grid connection; this is done better to compare the decentralized scenario versus the centralized scenario. Furthermore, has it not been identified whether the areas for the decentralized scenario have existing pipe installation, which would make it cheaper to connect to the natural gas and district heating grid. Overall, the uncertainties related to grid connection are assumed too high and risky to include in the LCOE. However, a proposal for grid connection costs is described further.

9.1.4 Price for grid connection

The cost for grid connection is only evaluated for the decentralized scenario, as an already convenient location at Fjernvarme Fyn, where the grid connection is already available, is determined for the centralized scenario. Furthermore, as the decentralized scenario also includes one facility at Odense, would the grid connection only be evaluated for the 7 other locations.

The identification of pipe sizes and costs are based on the maximum capacity of heat and gas, which is either needed (heat for biogas plant) or produced (excess heat from processes).
Furthermore, the location of the pipe installation affects the cost, whether it is done in the city or suburban areas. It is assumed that all the cities in the decentralized scenario are in suburban areas.
For all the areas, it is assumed that both the gas pipe and the central district heating pipe have a length of 500 meters. Furthermore, it is assumed that the pipe length from each facility to the central pipe is 20 meters.
The total pipe length of methanation plant to biogas plant and electrolysis to biogas plant is assumed to be a total of 500 meters. Necessary pump stations are included in the calculations, which are based on Energistyrelsen's technology catalog.
In Figure 33, the pipe set-up is shown for both pathways. The dotted line from "POX/SMR" indicates that only POX is delivering heat.

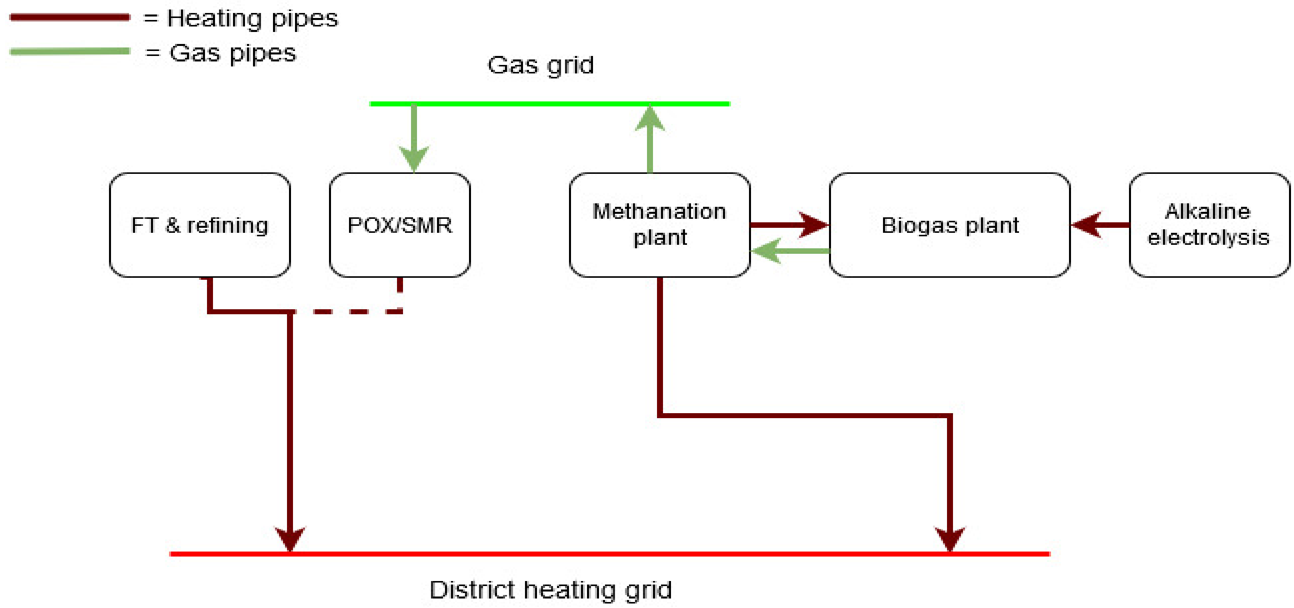


Figure 33: Description of pipe installations.

The picture suggests, the total excess heat for the facilities are added and delivered to the central transmission pipe.

The grid installation costs, shown in Figure 34, are calculated in €/$GJ_{jet\ fuel}$. This implies that the installation cost could be added to the LCOE of renewable JF. As seen in Figure 34, the grid cost is not following a clear tendency. The reason for this is due to the costs of pipes and pump stations are divided into intervals, determined by the transmission capacity of heat or gas. For example, Kerteminde POX has a higher grid connection cost than Otterup POX, even though Kerteminde's JF capacity is higher. This is due the excess heat capacity has exceeded a limit where a new pump station and larger pipes are needed.

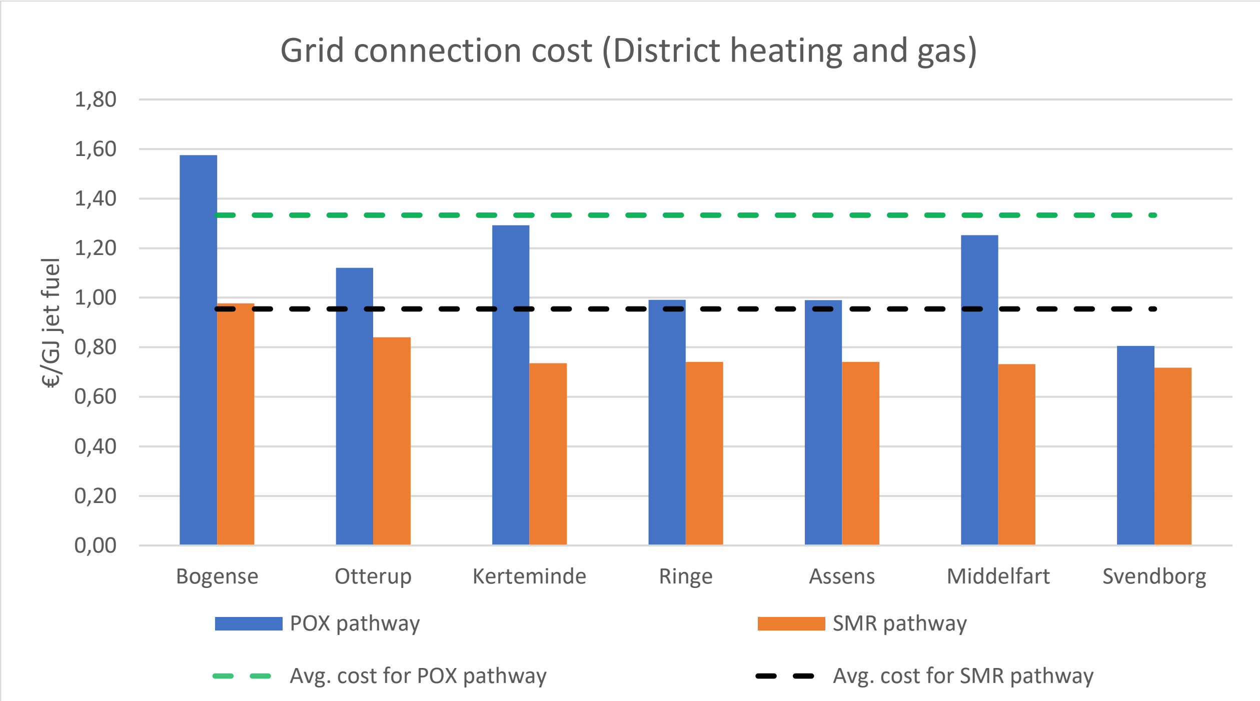


Figure 34: Grid connection cost for decentralized cases.

Derived from Figure 34, the price for grid connection is ranging between 1,83-0,94 €/$GJ_{jet\ fuel}$ for the POX pathway and between 1,18-0,88 €/$GJ_{Jet\ fuel}$ for the SMR pathway. The average cost for grid connection in the POX pathway is 1,33 €/ $GJ_{Jet\ fuel}$ and 0,95 €/ $GJ_{Jet\ fuel}$ for the SMR pathway. SMR has a lower grid connection cost due to lower total production of excess heat and a facility less to connect (the syngas unit).
If the cost of grid connection is added to the LCOE, it increases the LCOE of renewable JF production by a small amount. Since the grid connection cost for the SMR pathway is lower than the POX pathway, it decreases the gap between the LCOE of POX and SMR but not change the fact that the POX pathway is cheaper than the SMR pathway. If the average grid connection cost is added to the LCOE for both pathways, is the LCOE with grid connection costs for the POX pathway 51,97 €/$GJ_{jet\ fuel}$ and 52,52 €/$GJ_{jet\ fuel}$ for the SMR pathway for the decentralized scenario. This decreases the gap from 0,94 €/GJ in the base case to 0,55 €/GJ in LCOE with a grid connection cost.
The specific calculations for grid connection cost are seen in the Excel sheet *"Grid connection costs".*

10. Sensitivity analysis

The calculations are based on certain assumptions, projections, and approximations for the input values; these are based on literature reviews, but still with uncertainties related to them. Therefore, several sensitivities analyses are performed to evaluate the results from a different perspective.
The sensitivity analysis is performed with a change of the future projected electricity prices; three different projections of future electricity prices are evaluated.
Furthermore, a change in parameters related to income is evaluated. More specifically; A change in the selling price of side-products, gasoline, and excess heat.
Lastly, the assumption regarding the availability of storage of excess heating is changed to no available heating storage.
The results from the sensitivity analysis are presented with percental differences between the reference case and the sensitive result.

The sensitive analysis is only performed for the centralized scenarios, as the LCOE's for the decentralized scenario shows the same tendency as the centralized scenario in the base case. One exception is made; The results regarding changing the assumption about available heating storage also include the decentralized scenario, as the assumption affects the scenarios differently.
In the attached folder, under "*Sensitivity analysis"* the sensitivity results are presented for the decentralized cases.
The sensitive parameters are presented further, with evidence of why they are chosen, and how much they are changed from the reference case.

10.1 Electricity prices

In this section, the effect of a change in electricity prices is evaluated.
Three different projections of the electricity prices are gathered through literature reviews. The three electricity prices are projected from 2020-2035 by Elpris Outlook in 2019 [60], with the use of electricity prices model Balmorel. The prices are further projected from 2035-2050, with an annual increase of 0,39% for black, 1,3% for blue, and 1,0% for green.
Each of the three projections builds on certain assumptions, which are further described below:

- Black
    - The Danish politicians do not push for a greener and more renewable energy production in the future.
      Three main assumptions are used: No CO_2 quote price, the opportunity for storing electricity is not available, and the electricity consumption is constant.
- Blue
    - The blue case is based on assumptions that Denmark does business as usual. This price model should be the closest to the reference case's electricity prices.
      Three main assumptions are used: A CO_2 quote price of 30 €/ton, storing technologies as batteries are available, and the electricity consumption is increasing 0,5% p.a.

- Green
    - The green case is based on assumptions that Denmark pushes harder to reach the Paris agreement. 4 main assumptions are used; A high CO2 quote price (60 €/ton in 2030, double of the blue case), electricity storage technologies are available and mature (both batteries and long-term storing), an increase of electricity consumption of 2% p.a (due to a massive increase of electrified vehicles) and investments of new transmission lines if they are economically feasible.

The electricity prices for the three scenarios are seen in Table 25.
The shown electricity prices in Table 25 are defined as the average price from 2025 to 2050. For a specific yearly price, Figure 35 or appendix L should be seen.

Electricity price	Average [DKK/MWh]	Average [€/MWh]	Change from reference [%]
Reference	422,21	56,60	0
Black	402,83	54,00	-5
Blue	429,33	57,55	2
Green	457,10	61,27	8

Table 25: Average electricity prices for sensitivity analysis.

The variation of the investigated electricity prices varies between -5% – 8% in differences from the reference electricity price.
The yearly average electricity prices are seen in Figure 35.

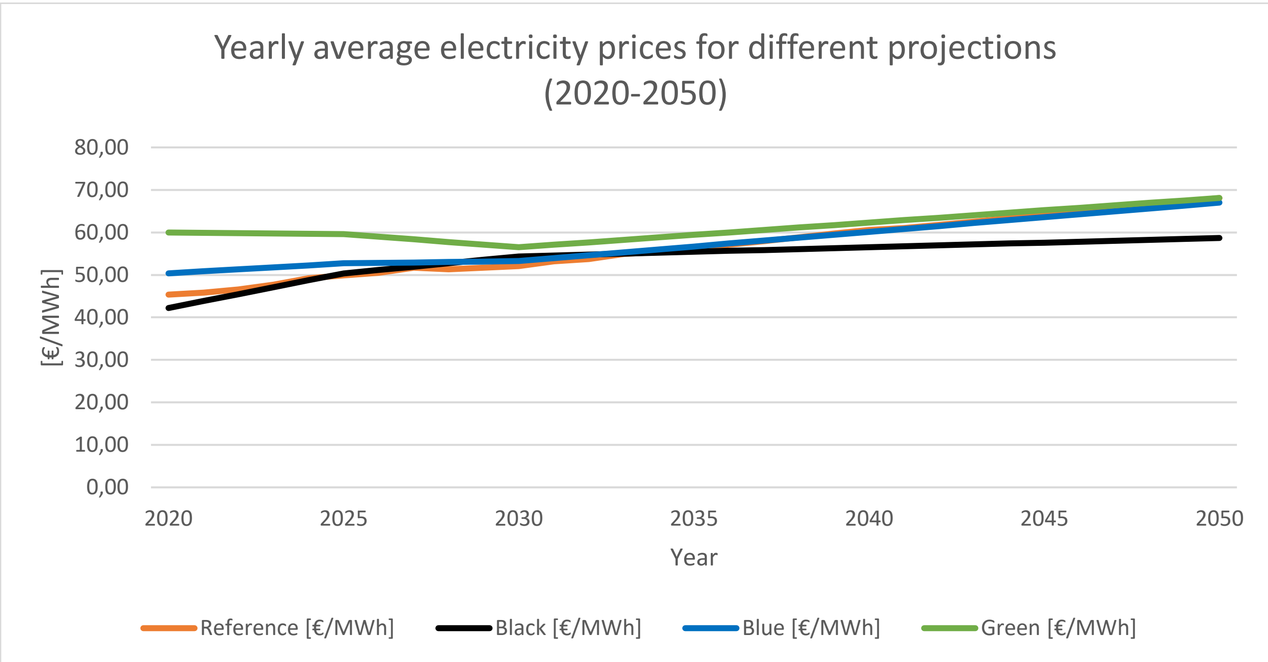


Figure 35: Yearly average electricity prices for sensitivity analysis. Replicated from "El Outlook 2019" report [60].

From the graph, it is seen that the main difference between the three electricity prices is in 2020-2025. From 2025, are 3 of the 4 electricity prices similar towards 2050.

The change of the LCOE to a change in electricity price is depicted in Figure 36. The results are depicted as a percental difference in the LCOE of renewable JF from the reference case. For example, a 2,84% change in the POX pathway from the POX reference case, corresponds to an LCOE of 48,59 €/$GJ_{jet\ fuel}$.

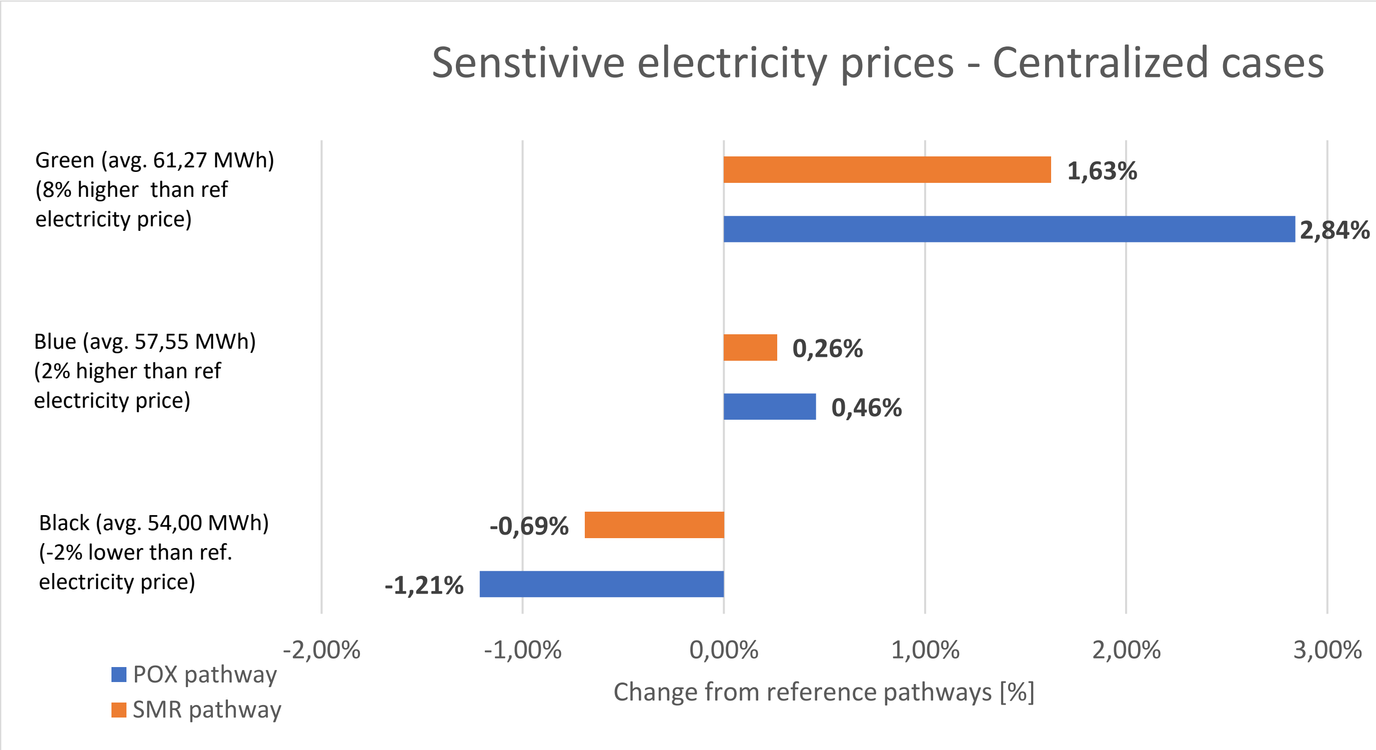


Figure 36: Results for sensitivity analysis using different projected electricity prices.

The change in electricity prices is influencing the cost of electro biomethane, as the operational expenditures for the electrolysis are either increasing or decreasing. Since electro biomethane is the primary fuel for syngas production, the LCOE of jet fuel is changing.
The "green" electricity price has the highest impact, as this also has the highest deviation from the reference electricity price. The LCOE's of JF by using "blue" electricity prices are close to the reference case, as they have similar assumptions and numeric values for the average electricity prices.

The percental deviation of the three electricity prices from the reference electricity is not corresponding to an equal deviation in the LCOE's, as the production of renewable JF is affected by the cost of syngas and FT & refining, which is not influenced by the electricity prices. However, there is a correlation between the deviation in the electricity price from reference electricity price and the deviation of LCOE's from the reference case.

10.2 The income of side-products

The LCOE of JF is highly dependent on the income, as well as the expenditures. A change in income would unbalance the income/expenditures and change the LCOE.
A change of side-products' and gasoline's selling price is therefore evaluated further.
Three cases are evaluated; These are represented as; HL, LH, and LL. The "H" stands for "High price," and "L" stands for "Low price" of the given product.
The cost of side-products and gasoline is changed one by one, to evaluate the specific effect on the LCOE.
In

Table 26, the three different scenarios for gasoline and side-product selling prices are seen.

	Side-product [€/GJ]	Gasoline [€/GJ]	Change from reference	
			Side product	Gasoline
HH = High/High (Reference)	37,99	17,34	0%	0%
HL = High/Low	37,99	13,3	0%	-23%
LH = Low/High	20,08	17,34	-47%	0%
LL = Low/Low	20,08	13,3	-47%	-23%

Table 26: Different assumed selling price for side-products and gasoline for sensitivity analysis.

Side-products' prices are assumed to be equal to either LNG (the low price) [55] or 2. generation bioethanol (the high price) [56]. The prices for gasoline are calculated based on the highest and lowest market price without taxes in the year 2020 in Denmark.

The results for a change in the selling prices of side-product and gasoline are depicted in Figure 37. The y-axis of Figure 37 represents the scenarios, and the x-axis represents the percental change from the reference pathway.

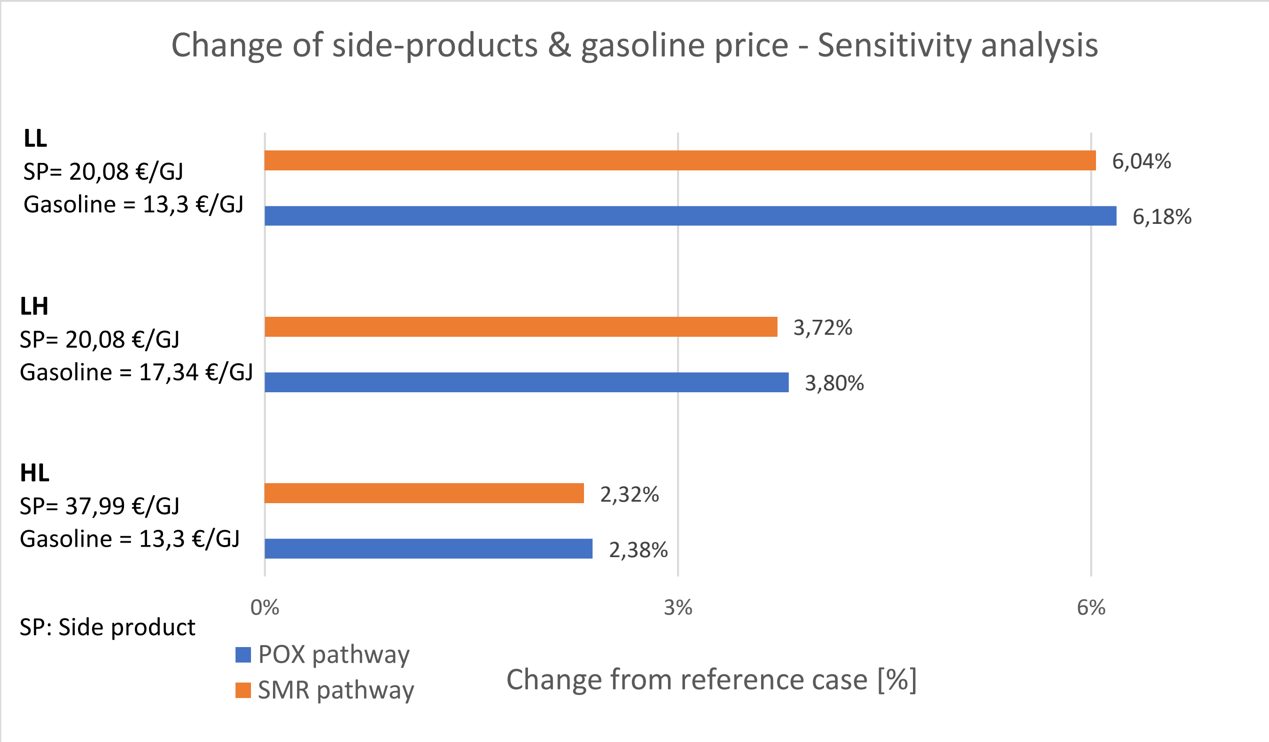


Figure 37: Results of sensitivity analysis with changed selling prices of side-products and gasoline.

The LL-scenario has the most significant impact of the LCOEs, as this is lowering the income the most. The total income from side-products and gasoline is decreasing by 40% for both pathways.
A change in selling price for side-products has a higher impact than the change of gasoline; this is due to the decrease in side-products' selling price is 47% versus 23% for gasoline.

10.3 Adjusted heating utilization & heat price

The base case assumes that existing district heating companies have storage available, and therefore are heat utilization 100% for scenarios and locations.
If the assumption is changed to no available heating storage, then all excess heat, which exceeds the hourly demand, is wasted.
In such a case, the heating utilization should be adjusted, so that the excess heat never exceeds the heating demand; This lowers the total utilized heat, which is further affecting the income, as less heat is sold.
It is assumed that the centralized scenario only delivers excess heat produced by the Fischer Tropsch synthesis (and the syngas facility for the POX pathway), as the electro biomethane is produced around on Funen and delivered via the gas grid.

The adjusted heating utilization is seen in Table 27.

Decentralized	Heat utilization reference [%]	Adjusted utilization [%]		Change from reference [%]	
Bogense	100%	100%		>1%	
Otterup	100%	97%		3%	
Kerteminde	100%	81%		19%	
Ringe	100%	81%		19%	
Assens	100%	81%		19%	
Middelfart	100%	81%		19%	
Svendborg	100%	81%		19%	
		POX pathway	SMR pathway	POX pathway	SMR pathway
Odense	100%	100%	100%	0%	0%
Centralized					
Odense	100%	98%	100%	2%	>1%

Table 27: Reference and adjusted heat utilization.

The heating utilization decreases mostly for facilities at Kerteminde, Ringe, Assens, Middelfart, and Svendborg; this is due to the production capacities are scaled based on an excess heat coverage of 65% of the total heating demand. For these locations, it would result in a yearly overproduction 41% of the time, which equals a reduction of 19% in utilized heat.
For Bogense and Otterup, the capacities are scaled on a lower percental coverage (20% & 30%). This results in an overproduction of excess heat of <1% and 15% of the time, equating to a reduction of <1% and 3% in utilized heat.
The facility at Odense for the decentralized cases is not affected by a change in the assumptions, because of Odense's high heating demand. Odense, in the decentralized scenario, produces 43 MW/h of excess heat with the POX pathway, and 36 MW/h of excess heat with the SMR pathway. The lowest hourly heating demand for Odense is 45 MW.

In the centralized scenario, the heating utilization is reduced by 2% in the pathway using POX, as overproduction occurs 11% of the time. For the SMR, the heating utilization is decreasing by less than 1%, as overproduction only occurs 7 hours each year.
The adjusted heating utilizations are seen in appendix M.

A change in the heating's selling price is also evaluated.
The assumed heating selling price for the reference cases is 10,07 €/GJ_{heat}. This price is a constant yearly price, which was assumed based on a district heating company's willingness to pay for renewable excess heat.
A seasonal dependent price for excess heat is provided by Fjernvarme Fyn [61]. The excess heat selling price is depending on the season it is delivered; Winter= 12,28 €/GJ_{heat}, Autumn/Spring= 7,07 €/GJ_{heat} and in the summer period 3,35 €/GJ_{heat}, which equals to an average of 7,45 €/GJ_{heat}. An average price is used, as the excess heat production is constant; The average heating selling price is a reduction of 26% of the selling price from the reference case.

The results for adjusted heat and the changed heating price is depicted in Figure 38.
The change of the excess heat selling price has the highest impact among the two investigated parameters for both centralized and decentralized scenarios, as the heating price is reduced by 26%. The change in heating utilization is only reducing the LCOE by 0,3% for the POX path and 0,1% for the SMR pathway from the reference cases in the centralized scenario. For the decentralized scenario is the heat utilization changed from 100% to an average of 87,5%. A reduction of heating utilization changes the LCOE by respectively 1,8% (For SMR pathway) and 2,0% (For POX pathway). The change is more significant than for the adjusted heating utilization in the centralized scenario since the change in heat utilization is higher.

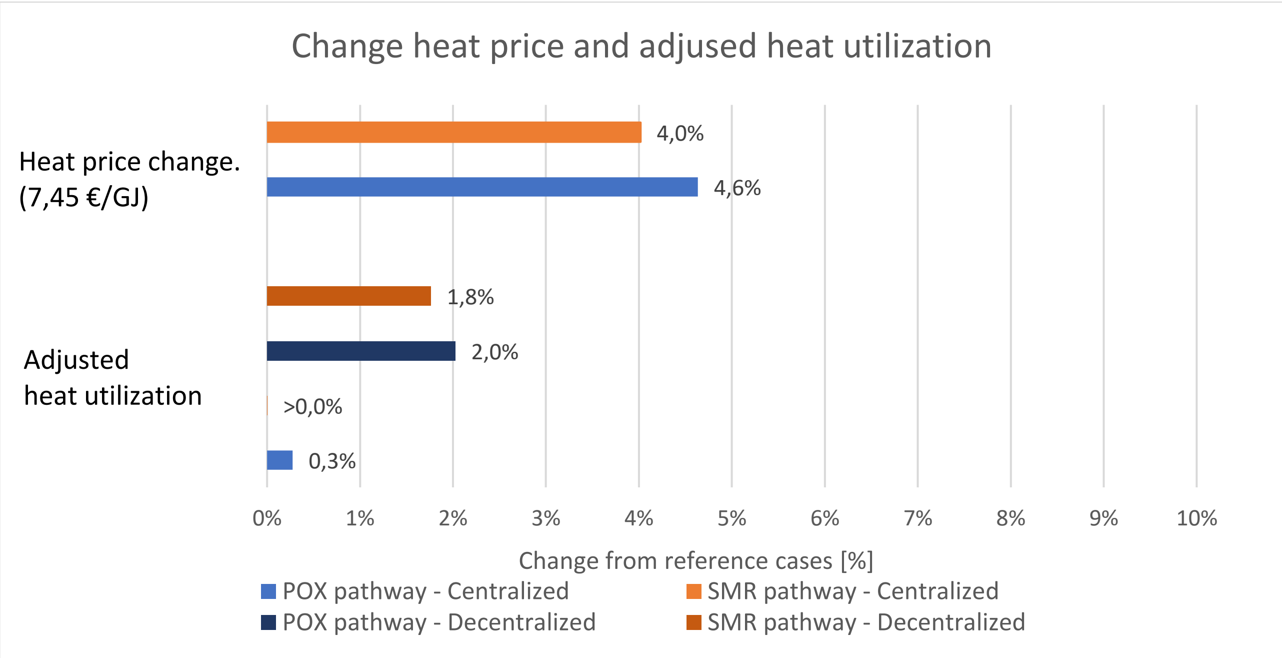


Figure 38: Results for sensitivity analysis with adjusted heat utilization and reduced selling price of heating.

Seen in Table 27, the adjusted heat utilization is not much lower than the base case for centralized cases. The reason for this is due to that the excess heat from Fischer Tropsch synthesis, and POX (For POX pathway) are only considered. The excess heat from these facilities in the POX pathway represents 58% of the total heat for the whole pathway, from biomass to JF. For the SMR pathway is Fischer Tropsch synthesis representing 56%. This makes the total excess heat fraction lower for the centralized scenario than for the decentralized scenario since the decentralized scenario utilizes the heat from the whole pathway (electrolysis and methanation).

10.4 Worst-case scenario

For the worst-case scenario, the previous parameters which had the highest impact of the LCOE on POX and SMR pathway are used.
The Worst case scenario uses the green electricity price, LL scenario for side-product and gasoline prices (20,08 €/$GJ_{side\text{-}product}$ and 13,3 €/$GJ_{gasoline}$), and an excess heat price of 7,45 €/GJ.

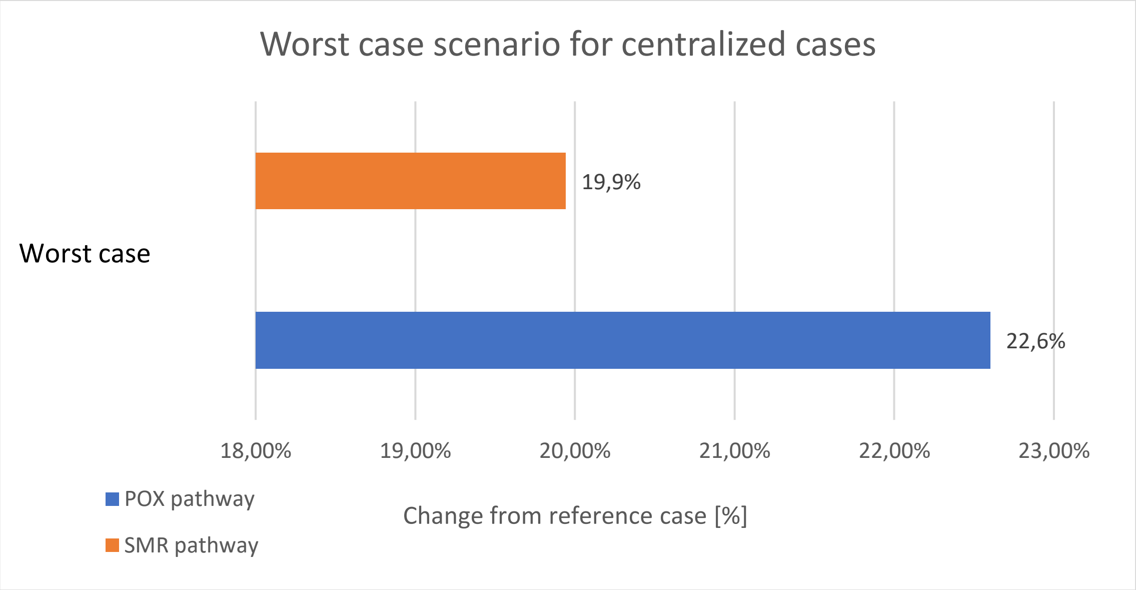


Figure 39: Results for sensitivity analysis using the worst-case scenario.

From Figure 39, it is seen that the LCOE of JF increases significantly if worst-case scenario parameters are used. Worst is it for the POX pathway, as the LCOE increases almost 23%, which is about 3% point higher than for the SMR pathway (20%). The LCOE for the POX pathway increases from 47,25 €/$GJ_{jet\ fuel}$ to 57,64 €/$GJ_{jet\ fuel}$, for SMR pathway it increases from 48,33 €/GJ to 57,94 €/$GJ_{jet\ fuel}$. The worst-case scenario reduces the gap between LCOE of JF for POX and SMR, from 0,94 €/$GJ_{jet\ fuel}$ to 0,30 €/$GJ_{jet\ fuel}$.
The increase of 23% for POX versus 20% for SMR, evidences that the POX pathway is more sensitive to a change in the data.

The highest impact of the sensitivity analysis is related to the income, as a 48% reduction of side-product & a 23 % reduction of gasoline, increase the LCOE by 6,18% (POX), and 6,04% (SMR).
Furthermore, a 27% reduction of the excess heat selling price increases the LCOE of renewable JF by 4,6% (POX) and 4,0% (SMR).
The lowest impact of sensitive parameters is related to a change in the assumption of storage availability as the LCOE only increase 0,3% (POX) and 0,01% (SMR).
All the investigated sensitive parameters show that the POX pathway is more sensitive than the SMR pathway; This implies that with the right assumptions, the LCOE of renewable JF could be lower for the SMR pathway, than for the POX pathway.

11. Integration

11.1 Heat contribution – Case in Odense[4]

As both pathways utilize the excess heat, existing production facilities at Fjernvarme Fyn can lower their production or even shut down.

The excess heat from the POX pathway is equal to a 77 MW facility, and the case for the SMR pathway is equal to a 53 MW facility. This makes it imperative to look at the existing facilities at Fjernvarme Fyn, to investigate production facilities, which could lower their production of heat.

The production of the coal-fired unit (Blok 7) on Fjernvarme Fyn is represented in Figure 40. The facilities take the heat demand for 2025 into account.

The coal-fired unit is shown in Figure 40, to evaluated whether the amount of excess heat can replace the coal-fired unit.

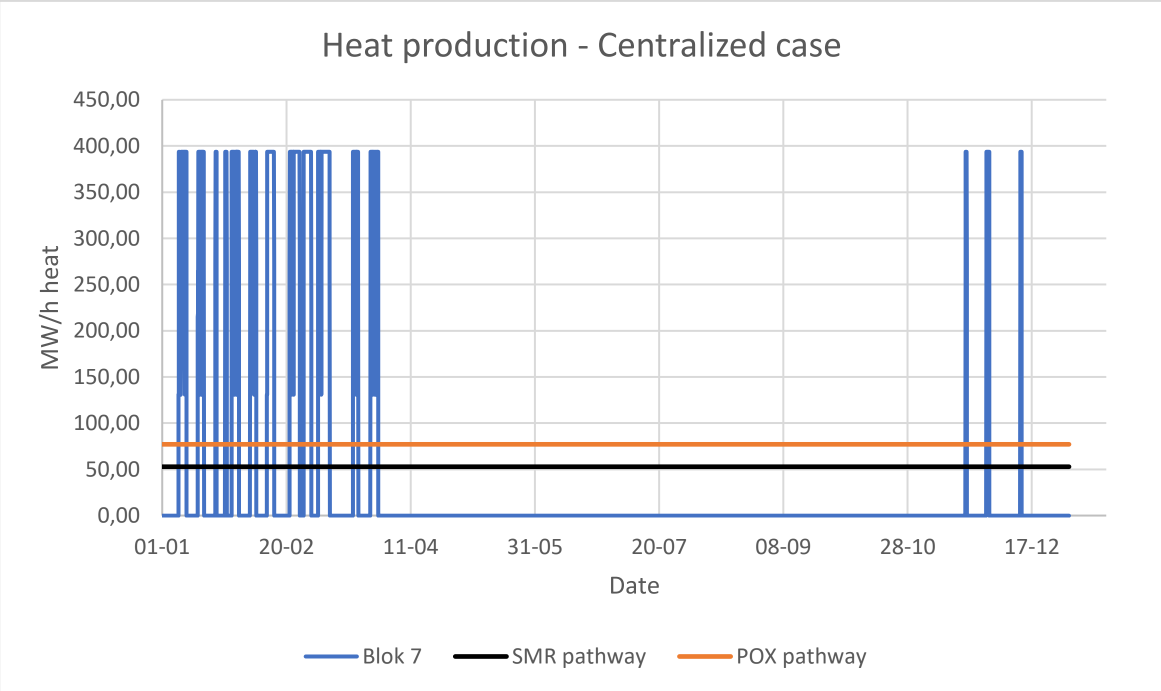


Figure 40: Heat production for Blok 7 at Fjernvarme Fyn and excess heat from the POX & SMR pathway - Centralized scenario

Seen in Figure 40, the coal-fired unit's peak production is 393 MWh. This is higher than the peak production for both pathways' excess heat production. Therefore, the excess heat cannot fully replace the coal-fired unit, since the peak production is too high.

The total produced heat from the coal-fired unit is lower (1,06 PJ/year) than the total amount of excess heat for both pathways (2,4 PJ/year for POX pathway and 1,67 PJ/year for SMR pathway). It enables the possibility to replace the coal-fired unit if heating storage is available.

[4] The data is provided by Fjernvarme Fyn. See attached Excel sheet:" Fjernvarme Fyn data" for specific numbers [47] ibid.

Among the production facilities at Fjernvarme Fyn are two facilities fired by biomass: Blok 8 (straw) & the Wood chip boiler. The peak production for these facilities, seen in Figure 41, is higher than the peak production of excess heat (It is constant). A direct replacement with excess heat is therefore not possible. However, the yearly amount excess heat from the POX pathway (2,4 PJ/year) is higher than the total heat production of Blok 8 (1,7 PJ/year), and the Wood chip boiler (1,9 PJ/year). If storage, with enough capacity, is implemented, the excess heat from the POX pathway, can replace one of these units. The SMR pathway only produces 1,67 PJ/year, which is not enough to replace any of the facilities.

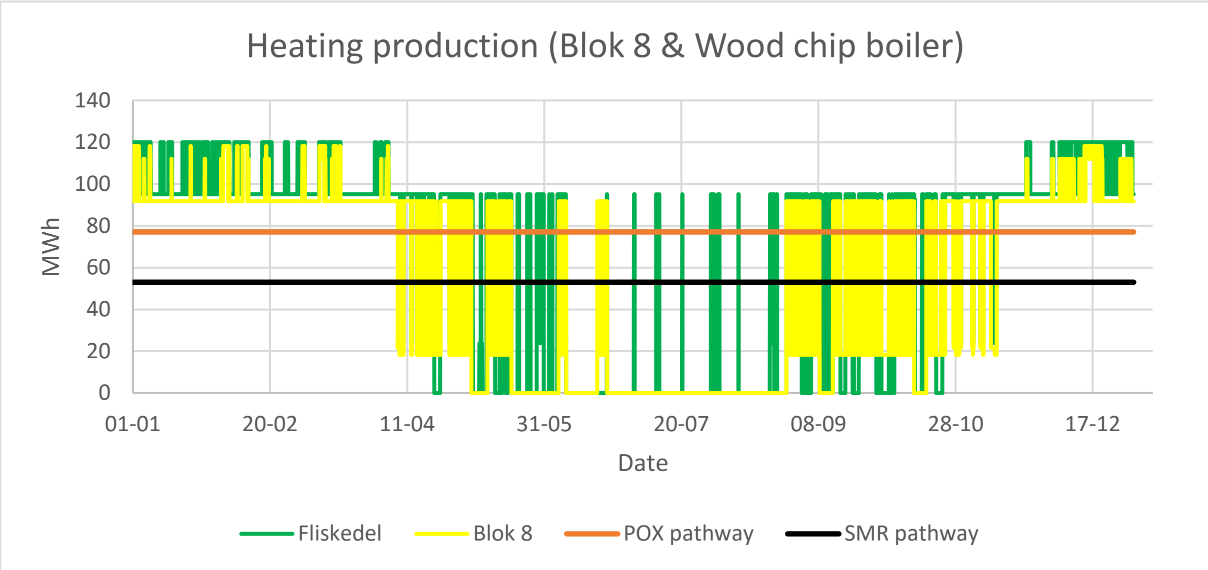


Figure 41: Heat production for Blok 8 & Wood chip boiler at Fjernvarme Fyn and excess heat from the POX & SMR pathway - Centralized scenario

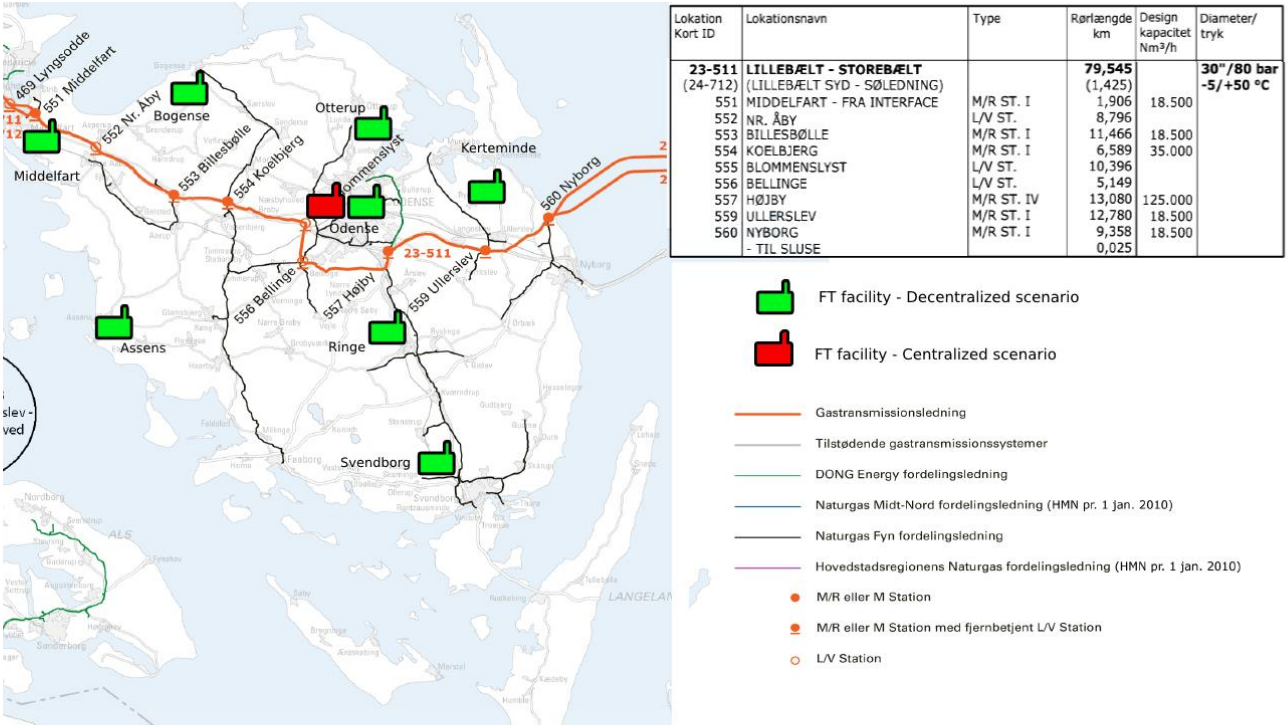
The heat produced by biomasses on Fjernvarme Fyn represents about 40% of the total production each year. It is unknown where the straw and wood chips are delivered from, but if some of the biomass is taken from Funen, it reduces Funen's biogas potential for JF production.

This would leave a paradox, as the biomass which should be converted to biogas and utilized for JF production is instead used for heating. It is, therefore, necessary to investigate if any of the biomass-fueled facilities can be replaced, to uphold the same utilization degree of biogas to JF production. Otherwise, an import of biomass should be considered.

11.2 Gas integration

The integration of the FT facilities is a huge part of whether it is possible to realize renewable JF production. The primary fuel for the syngas production is electro biomethane. The electro biomethane needs transportation from the electro biomethane facility to the syngas facility. It is, therefore, investigated if the demanded electro biomethane for each facility is withing the transmission capacity of the gas grid. It is assumed that all the areas are connected to the distribution grid. The gas is delivered from the transmission grid to the distribution grid via M/R stations. M/R stations regulate the pressure and temperature of the gas [62]. Therefore, the maximum capacity of a given distribution line is limited by its M/R station.

The placement of the facilities (note the differences in colors of the facilities) and the gas grid of Funen is depicted in Figure 42.



Lokation Kort ID	Lokationsnavn	Type	Rørlængde km	Design kapacitet Nm³/h	Diameter/ tryk
23-511	**LILLEBÆLT - STOREBÆLT**		**79,545**		**30"/80 bar -5/+50 °C**
(24-712)	(LILLEBÆLT SYD - SØLEDNING)		(1,425)		
551	MIDDELFART - FRA INTERFACE	M/R ST. I	1,906	18.500	
552	NR. ÅBY	L/V ST.	8,796		
553	BILLESBØLLE	M/R ST. I	11,466	18.500	
554	KOELBJERG	M/R ST. I	6,589	35.000	
555	BLOMMENSLYST	L/V ST.	10,396		
556	BELLINGE	L/V ST.	5,149		
557	HØJBY	M/R ST. IV	13,080	125.000	
559	ULLERSLEV	M/R ST. I	12,780	18.500	
560	NYBORG	M/R ST. I	9,358	18.500	
	- TIL SLUSE		0,025		

Figure 42: Map of gas grid and location for facilities on Funen [63].

Each M/R stations' design capacity, in energy equivalents, are seen in appendix N.

11.2.1 Centralized

Fjernvarme Fyn is connected to the distribution grid. It is therefore determined what the maximum capacity of gas that can be delivered to the facility in the centralized scenario.
The centralized facility at Fjernvarme Fyn is connected to the distribution grid, which is fed with gas from Højby M/R station. The gas demands for each pathway and the design capacity for the M/R station in Højby are seen in Table 28.

Area of facility	Gas demand (SMR pathway) [MW/h]	Gas demand (POX pathway) [MW/h]	M/R station for distribution grid	Design capacity [MW/h]
Odense (Centralized)	199,60	199,60	Højby	1409,72

Table 28: Gas demands for the two pathways and design capacity for Højby M/R station – Centralized scenario [63].

From Table 28, it is seen that the electro biomethane demand is not exceeding the design capacity for Højby M/R station. In such a case, the integration of the FT facility in the centralized scenario seems realistic.

11.2.2 Decentralized.

To evaluate the degree of integration of the decentralized facilities is the hourly electro biomethane demand for each facility used. Furthermore, it is identified which distribution grid they are connected to, and which M/R stations the distribution grid is connected to. This is seen in Table 29.

Area of facility	Gas demand (SMR pathway) [MW/h]	Gas demand (POX pathway) [MW/h]	M/R station for distribution grid
Bogense	2,32	1,64	Koelbjerg
Otterup	4,59	3,26	Højby
Kerteminde	11,24	7,98	Ullerslev
Ringe	11,65	8,26	Højby
Assens	11,73	8,33	Koelbjerg
Middelfart	29,63	21,02	Middelfart
Svendborg	51,87	36,80	Højby
Odense	76,52	112,26	Højby

Table 29: Gas demands for decentralized facilities with identified M/R station.

Some of the facilities are demanding gas from the same distribution line and, therefore, also from the same M/R station. The total demand for each distribution line is calculated to ensure the demand is not exceeding the distribution line's capacity. This is seen in Table 30.

M/R station	Gas demand (SMR pathway) [MW/h]	Gas demand (POX pathway) [MW/h]	Design capacity [MW/h]
Middelfart	29,63	21,02	208,64
Billesbølle	0,00	0,00	208,64
Koelbjerg	14,05	9,97	394,72
Højby	144,63	160,59	1409,72
Ullerslev	11,24	7,98	208,64
Nyborg	0,00	0,00	208,64

Table 30: Gas demands for decentralized facilities and design capacity for identified M/R station [63].

From the table, it is seen that the total capacity for each distribution line is not exceeding its M/R station's design capacity. This implies that no complications of integrating the facilities occur, for the decentralized scenario. At least not regarding the transportation of the electro biomethane.

12. Risk analysis

The papers investigate two scenarios of renewable JF on Funen; Centralized and decentralized. The risks associated with these scenarios are, therefore, evaluated.
The risk assessment is used to get a further understanding of the pros and cons of each scenario. The risk assessment determines the probability and impact of a specific event. These will be labeled as either “low”, “medium” or “high” and inserted in the risk matrix lastly.
3 main events related to risks are identified: Placement, Production, and Security of supply.

12.1 Location risk

The placement risk is associated with the risk of not finding a proper location for the facilities, which is not thoroughly evaluated in this paper.
The likelihood of not finding a proper location for the centralized scenario is considered low, since the FT & refining facility already has a prospect for a convenient location at Fjernvarme Fyn in 2025, as the coal-fired unit needs replacement [14].
On the other hand, if the location at Fjernvarme Fyn is not suitable, it would have a significant impact for the centralized scenario, as a new suitable location has to be found within the district heating grid of Odense, to fully utilize the excess heat and upholding a low LCOE of JF. If such a location is not found and the total capacity of JF should be upheld, the decentralized scenario should be considered. Otherwise, the facility needs to decrease its capacity to match the location at Odense.
The likelihood of not finding proper locations for all facilities in the decentralized scenarios is considered medium, because of several inclusive municipalities.
The impact of not finding a proper location of one facility is considered medium; It seems realistic that another appropriate location can be found, as the decentralized facilities have individually lower capacities and lower space requirements.

12.2 Production risk.

Production risks are associated with a change in the production of JF, as a different biomass outcome or biogas utilization would cause a change in available biogas for JF production.
The capacities and the LCOE’s are evaluated based on 100% utilization of Funen’s biogas potential. A change in biogas utilization or biomass outcome would change the economics.
The likelihood of a change in the biogas potential and utilization is considered high, as biogas potential on Funen is mainly produced by straw [26]. A farmer might change the crops in the future to sunflowers, which have a lower biogas potential than straw [64].
Both centralized and decentralized scenarios are the likelihood of a change in production assumed to be high.
The impact of such an event is found in economics and LCOE. The decentralized scenario has a more negative impact on the LCOE, as the total investment is higher, due to economics of scale. Therefore, would the LCOE’s increase more for the decentralized scenario than for the centralized scenario, which the same percental change in production.

12.3 Security of supply

This risk is related to uphold a constant supply of renewable JF. The centralized scenario has one large facility, and the decentralized scenario has 8 facilities with lower capacities.
If technical faults occur at the facility, the supply of renewable JF stops. The faults could potentially keep the production down for a while. It depends on the complexity of the fault.
The likelihood of such an event happening over 25 years is assumed to be medium. The likelihood of such an event happens in the centralized scenario is equal to the likelihood that it happens for one of the facilities in the decentralized scenario.
The impact of such an event is different, whether it happens in the centralized scenario or decentralized scenario.
If such an event happens in the centralized scenario, it's causing a high impact. For the centralized scenario, is all the JF supplied from one facility; This means, if something happens at the facility that causes the entire production to stop, then no JF is produced in that period.
If the same fault occurs at one of the decentralized facilities, the production only stops for that specific facility. The supply of jet fuel is not stopping completely but only decreases. The impact of such an event is considered low for the decentralized scenario.

12.4 Risk matrix

The risk matrix contains all the risks just analyzed.
The risks are divided into three groups; Red (high risk) – Yellow (medium risk) – Green (low risk) [65].
High risk means that an event is more likely to happen and has a huge impact. A plan "b" should be made beforehand, including how to deal with and overcome such an event.
Medium risks mean that the likelihood of risks is considered normal, with relatively high impact, or events that frequently appear, but has low impact. In such cases should a plan on how to either reduce the likelihood or impact be performed.
Low risks indicate that events are rarely appearing, with low impacts, or appears more frequently without any impacts. In such cases should a plan on how to reduce the likelihood be performed.
The matrix has the axis "likelihood" at the y-axis and "impact" on the x-axis. For each axis, the identified event is inserted based on assigned numbers from 1-5. The higher the number, the greater the impact or likelihood of the event. The higher in the top right corner, the higher risk is associated with an event.
The matrix is depicted in Figure 43.

Risk matrix						
Likely hood	L5. Very likely			Production change (C & DC)		
	L4. Likely					
	L3. Possible			Placement (DC)		
	L2 Unlikely		Security of supply (DC)			Security of supply (C)
	L1. Highly unlikely				Placement (C)	
		I1 No impact	I2 Minor impact	I3 Medium impact	I4 Major impact	I5 Extensive impact
		Impact				

	Low risk
	Medium risk
	High risk

(C) = Centralized scenario
(DC) = Decentralized scenario

Figure 43: Risk matrix for centralized cases

The total risk score for centralized cases is 29 points, and 28 points for decentralized cases; This implies risks associated with the decentralized is a little lower than for the centralized scenario. Other risks, which are not included in this risk assessment, might appear. If so, these should be included in the risk matrix. This would generate a new total risk score, which might show a higher difference between the two scenarios' total risk score.
The risk scores are calculated in appendix O.

13. Discussion

This discussion attempts to investigate the assumptions, approximations, and delimitations that have affected the results, and what consequences differences would cause.
Furthermore, it is discussed whether renewable JF production is economically competitive with existing fossil fuel produced JF. Due to the many points of discussion, each discussion point is divided into subsections, *Configuration of Fischer Tropsch refinery*, *syngas production with electric heating*, *modeling, assumptions*, *realization* & *competitiveness*.

13.1 Configuration of Fischer Tropsch refinery

The refining of syncrude produced by the Fischer Tropsch comes in many configurations [13]. As mentioned, does a change in the configuration change the liquid fuel output and the ratio between JF, gasoline, and diesel.
A JF refining facility has a liquid fuel output of 45 – 76,5% JF, 20-24% gasoline, and 0-10% diesel [13]. This paper evaluates the LCOE of renewable JF based on a refining facility with 76,5% JF output, which is done to cover as much of the JF demand described in

.

If the entire transportation sector in Denmark was evaluated and investigated, which configuration of FT refining is most preferable and practical, an all-around facility could be used. For example, HTFT diesel refinery facility with 29,1% JF, 13,4% gasoline, 13,6% excess fuel ethanol and 43,6% of diesel [13].
This facility would deliver fuels for the heavy road transportation sector, and gasoline fueled vehicles. This would make an excellent baseline of renewable fuels for transportation.

13.2 Syngas production with electric heat

The pathway from biomass to JF is, for one of the cases, with syngas production by SMR. For the SMR pathways, it is assumed that electro biomethane is used for internal heating, which is done to secure renewability and increased carbon efficiency.

In the future, the biomass could be much valuable, and using it for internal heating would be a waste [66]. In such a case, it would require another supplier of heating the SMR. An electric heater could be used as an alternative. This would increase the syngas production, as more electro biomethane is fed into the reformer and not used for heating. The process flow-diagram for SMR using the electric boiler is shown in Figure 44.

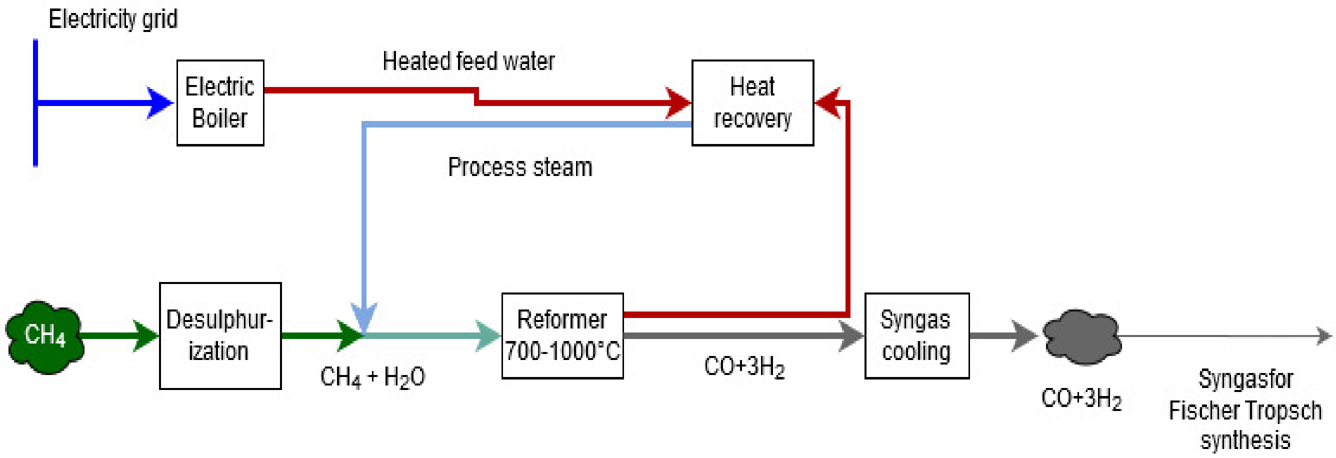


Figure 44: Syngas production with SMR - Electric heater instead of methane heater.

If the syngas production by using an electric heater is compared to using electro biomethane as heating in the reference scenario (seen in equation x), syngas production is, by using the same amount of electro biomethane, 2,5 PJ higher for using electric heating. This is seen in Eq. 12 and Eq. 13.

Calculations with electro biomethane heater

$$CH_4\ (80\%\ electro\ biomethane) + heat(20\%\ electro\ biomethane) \rightarrow CO + 3H_2 \quad \text{Eq. 12}$$
$$7{,}43PJ(Electro\ biomethane) + 1{,}97PJ(Heat\ from\ electro\ biomehtane) \rightarrow 9{,}4PJ\ (syngas)$$

Calculations with electric heater

$$CH_4\ (100\%\ electro\ biomethane) + heat\ (100\%\ electric) \rightarrow CO + 3H_2 \quad \text{Eq. 13}$$
$$9{,}4\ PJ\ (Electro\ biomethane) + 2{,}5\ PJ\ (heat) \rightarrow 11{,}9\ PJ\ (syngas)$$

Increasing in syngas production is further increasing the production of JF, as more syncrude is produced. The yearly amount of JF for the SMR pathway would be higher than for the POX pathway, as the SMR process has syngas effectivity of 100%.

The cost of heating for both heating methods is calculated and shown in Table 31. It should be noted that the calculations do not include investments or operations costs for the heaters.

	Input energy	Yearly energy input [PJ]	Yearly heat output [PJ]	Avg. energy price [€/GJ]	€/GJ_{heat}
Electric boiler	Electricity	2,53	2,5	16,1	16,89
Electro biomethane boiler	Electro biomethane	2,01	1,97	28,12	29,24

Table 31: Syngas cost for SMR with electric heater and methane heater [28].

The cost of heat by using electricity is significantly lower than using electro biomethane for heating. A problem regarding using an electric heater is the uncertainties relating to the production source of electricity. It could be via fossil fuels, which would further increase the socioeconomics related to fossil-based electricity production.

13.4 Modeling

All the facilities are assumed to produce constantly throughout the investigation period. With this assumption, it has only been necessary to determine the yearly average electricity prices over the investigation period. The LCOE's of renewable JF are calculated based on this assumption in this paper. If dynamic production were applied, the LCOE's could be optimized with the objective of reducing expenditures relating to the electricity prices. Dynamic electricity prices would mostly affect the production of electro biomethane. If Elspot prices (dynamic electricity prices) were applied, the hydrogen production could optimize the production cost by only produce in periods where the electricity prices are under the average. The production of hydrogen would further need higher capacity and storage, to compensate for periods where it is not producing, due to electricity prices higher than average. The lower cost of hydrogen affects the electro biomethane cost, which further affects the LCOE of renewable JF.

13.5 Assumptions

The electrolysis technology makes the foundation for all the cases. The used electrolysis in this paper is the Alkaline technology. It is assumed that the alkaline technology from 2015 to 2020, develop a heat recovery system, to utilize the heat and have better energy efficiency [18]. A heat utilization of the alkaline electrolysis is helping to decrease the cost of hydrogen and electro biomethane. Estimate for hydrogen efficiency in 2050 suggests a hydrogen efficiency for alkaline electrolysis to be nearly 70% in 2050 [18]. This is an increase of 7% points. The increase in hydrogen efficiency decreases the available heating to 8%. However, as hydrogen is the primary fuel in the electrolysis, it is preferable to have a higher hydrogen efficiency. The hydrogen prices might get cheaper than described in this paper.

The investigated pathways suggest a syngas production with electro biomethane. In the future, the pathway to JF may consist of different technologies to produce syngas. The pathway could include DAC (Direct-Air-Capture) technologies and CO-electrolysis for syngas production. This would spare the biomass and biogas, and let it be used for other things, such as district heating or industrial process heating.

For the decentralized scenario, smaller-scale FT facilities are used. Small-scale FT facilities are relatively new, with only a few pilot projects [67] [15]. No existing economics can be found for smaller-scale FT facilities. It has therefore been necessary to collect estimated economics for these facilities [49]. However, based on statements from Velocys, small-scale FT facilities can be economically competitive with large scale FT facilities [67].

Described under *competitiveness* of JF, business economic investigation suggests, that the LCOE of JF with electro biomethane, has the same LCOE as JF produced with natural gas. This does only apply if the subsidies rules are kept as they are now.

The rules and criteria to be permitted subsidies are in a changing phase. The new criteria imply that the amount of biomethane, which is subsided, for a specific upgrading plant, is yearly fixed. The yearly fixed amount of biomethane that can be subsided throughout the upgrading plant's lifetime is calculated based on the total production of biomethane in the first 12 months of the plant's lifetime [68]. In the following years, all yearly produced biomethane, which exceeds the first year's total production of biomethane, is not subsided. In such a case, it suggests that the biogas plants should be operating with maximum capacity the first year to ensure subsidies in the future.

It was mentioned that the socio-economic LCOE of renewable JF is calculated without externalities since the CO_2 emission in the pathways is neutral. Externalities related to construction and connection of the facilities are also excluded. To find the exact socio-economic cost of renewable JF with the established scenarios and pathways, one should find a way to quantitative these externalities.

13.6 Realization

In this part of the discussion, is the realization of renewable JF production on Funen, with 100% utilization of the biogas potential of Funen, discussed.
This paper bases on the assumption that 100% of biogas potential is used for JF production, but does this seem realistic?

The usage of natural gas for internal heating is out-phasing to 2050 [69], due to Denmark's goal of a fossil-free society by 2050; This leaves a gap in the internal heating sector, where district heating is not reachable. Natural gas for internal heating represents 21% of the total energy use of natural gas in 2018 [70]. To fill this gap different strategies can be used. One is to expand the district heating grid enormously and let the unreachable users have heating pumps or electric heaters. Another way to fill the gap is by using the purified biogas or electro biomethane as a substitute for natural gas.

The gas consumption for Funen is depicted together with the found biogas & electro biomethane potential in Figure 45 [71].

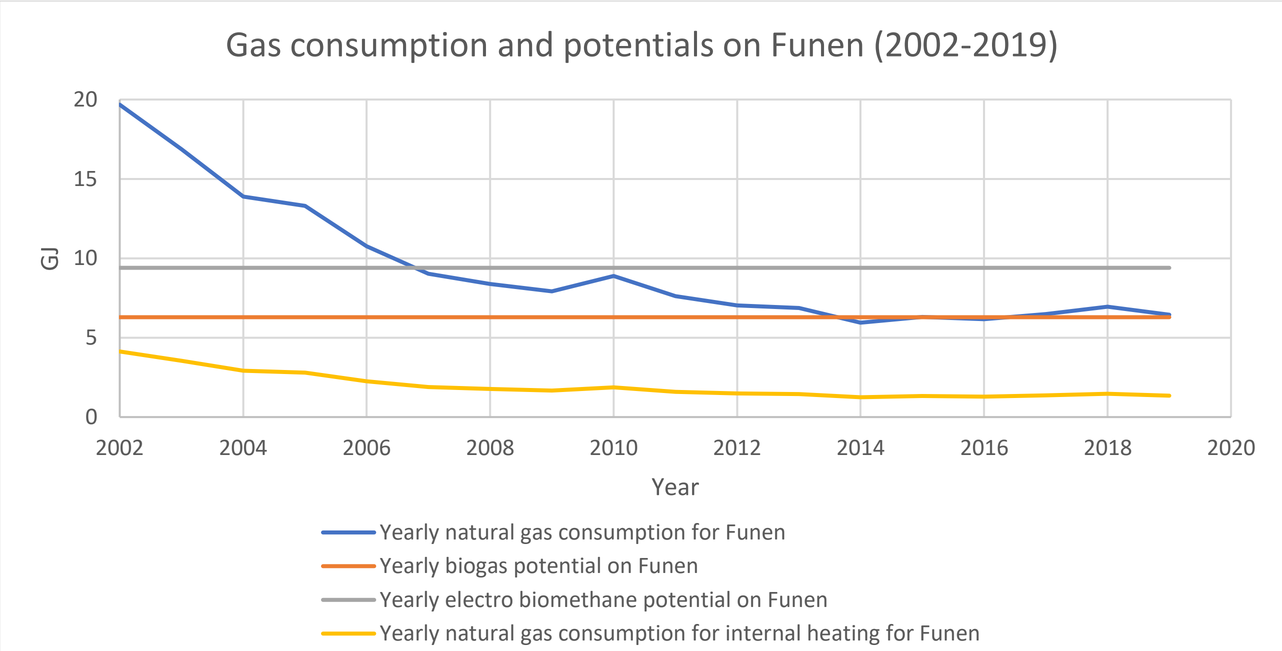


Figure 45: Funen's natural gas consumption & potential biogas and electro biomethane.

The consumption of natural gas for internal heating on Funen was 1,35 PJ in 2019. If the biogas or electro biomethane potential was used for substitution of natural gas for internal heating, it would lower the potential utilization of biogas (-22%) or electro biomethane (-15%) for JF production. A lower biogas potential for JF production, would lower the total amount of produced JF and increase the LCOE of JF, due to the concept of "economy of scale".
In case of reduced utilization of the biogas potential for renewable JF production, it would most likely be a centralized scenario instead of a decentralized scenario, as the decentralized facilities would have deficient capacities.

From an economics perspective, 100% biogas utilization would most likely not be the cheapest; This is due to transportation costs of biomass from the rural areas as Langeland and Ærø. Together do they only represent about 8% [26] of the total biogas potential of Funen. As no existing or planning biogas plants or gas grid are placed in these areas, it would require transporting the biomass to adjacent biogas plants. Transportation of the available biomass on Ærø and Langeland would be expensive due to long transportation distance, as the closets biogas plant is in Midtfyn [72].
The biomass for these rural areas would most likely be burned and used for electricity and heating.

A realization of 100% utilization of the biogas potential on Funen for JF production does not seem reasonable since the biomass and biogas are highly valuable in the future. The usages of biogas will most likely split across fuel production, heating, and industrial process.
Furthermore, evaluation of the transportation cost for biomass should be performed, as the cost for transportation of rural biomass could be increasing the LCOE rather than decreasing it.

13.7 Competitiveness

The price for renewable JF is evaluated to around 47,2-48,3 €/$GJ_{jet\ fuel}$ for the centralized scenario and 50,6-51,6 €/$GJ_{jet\ fuel}$ for the decentralized scenario.
As the investigated pathways include only renewable sources, it is possible to get subsidies. The production of electro biomethane is justified to get subsidies by the government, as the production of electro biomethane is considered renewable [73]. The production of electro biomethane rather than pumping natural gas from the North Sea helps Denmark reaching the Paris agreement.
The subsidies for electro biomethane are yearly regulated based on the yearly average price of natural gas [74]. The subsidies are equal to the differences between the cost of electro biomethane and the price of natural gas. This regulates the price of electro biomethane to equal natural gas prices.

Based on studies from Energistyrelsen, the natural gas price is increasing in the future. This would lower the subsidies if the subsidies still apply.
In Table 32, the natural gas price, potential subsidies, and subsidized electro biomethane cost are shown in 5-year intervals.

Year	2025	2030	2035	2040	2045	2050
Natural gas price	5,8	6,6	7,3	7,8	8,7	9,3
Subsidies	21,4	21,1	21,2	21,6	21,5	19,5
Biomethane price	5,8	6,6	7,3	7,8	8,7	9,3

Table 32: Future natural gas prices and subsidies for electro biomethane

As a result of electro biomethane prices equal to natural gas, the LCOE of renewable JF produced via electro biomethane is equal to the LCOE of JF produced with natural gas. This would potentially make the cost in the range of 10-21 €/$GJ_{jet\ fuel}$, which is the same as fossil fuel based JF [12].

Another way of making renewable JF more competitive is by using "green certificates". The competitiveness advantage is not in the price but in advertising.
It is impossible to distinguish between natural gas and upgraded biogas in the gas grid, as the molecules are blended. To solve this problem, "green certificates" were introduced. Green certificates are documentation, which can be bought by gas shippers, to document that the amount of gas they deliver is equivalent to a specific amount of biomethane from a biogas upgrading plant [75].
The buyers of the green certificates get advantages in their competitive market, as they can prove and advertise that they are buying biomethane.
This could, for example, be SAS. Well known that the renewable JF gets a little higher, due to the cost green certificate, they are still willing to buy it, as they can document that they support a CO_2 neutral society in the future; This might increase their customer base.

14. Conclusion

The goal of this paper was to investigate the LCOE's of renewable JF for two scenarios; Centralized and decentralized, with two different pathways; POX or SMR for syngas production. For both pathways and scenarios, the focus was Funen. Funen was chosen, due to the opportunity of replacing the coal-fired unit 7, at Fjernvarme Fyn in Odense, as Fjernvarme Fyn is obligated to replace their coal-fired unit by 2025. A renewable FT & refinery facility could work as an alternative to produce heat, as the FT & refinery facility produces a significant amount of usable excess heat.

The pathway to JF is considered renewable to reach the goal of the Paris agreement in 2030 and a CO_2 neutral society by 2050. With such a pathway, it was chosen to focus on a pathway with biomass as the first step on the pathway. The biomass's conversion pathway to renewable JF includes biogas plants, alkaline electrolysis, methanation plants, syngas facilities, and FT & refining facilities.

To set the framework, boundaries, and initial conditions for the investigation, the yearly biogas potential for Funen was identified to be 6,29 GJ in CH_4 equivalents [26]. A biogas potential of 6,29 GJ, will theoretically be converted to 9,4 GJ electro biomethane, with CO methanation.

The differences in the two investigated pathways are their method of producing syngas. The POX pathway includes syngas production with partial oxidation, and SMR produces syngas with steam methane reforming. The differences in these production methods are mainly their CO:H_2 ratio. POX produces syngas with 2:1 H_2:CO ratio and SMR produces syngas with a 3:1 H_2:CO ratio.

It can be concluded that the total amount of JF produced is higher with a pathway using POX. The total produced amount of JF for POX is 5,03 PJ, and 4,02 PJ for the SMR pathway. A difference of about 20%. The reason for this is due to the above-mentioned H_2:CO ratio.

The introduction of this paper included several research questions and hypotheses, which were in specific focus when investigation the scenarios and pathways of renewable JF on Funen.
Based on the first research question*: "Is jet fuel production using larger-scale technologies for jet fuel production* ***more effective than*** *smaller-scale technologies* ***to achieve*** *better economics of jet fuel production?",* it can be concluded that the cost for the centralized scenarios, which included higher capacity of syngas production and FT & refining facilities, are cheaper than the average LCOE for the decentralized scenarios, as seen in Figure 46. It is concluded that the differences in the costs lay within the amount of produced excess heat, as the POX pathway produces more excess heat than the SMR pathway.

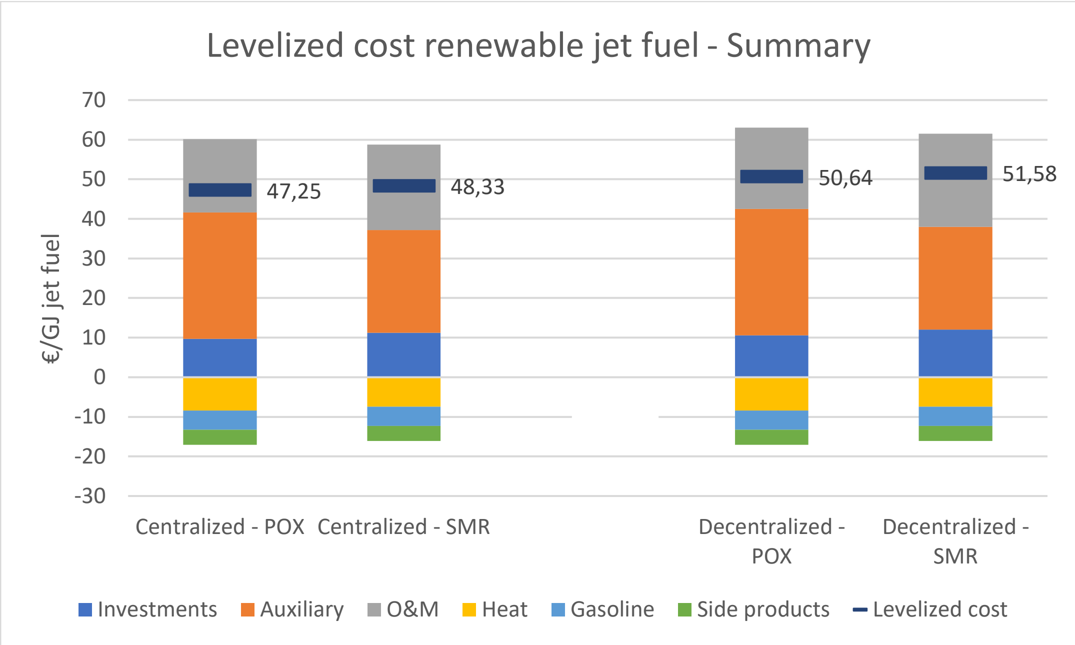


Figure 46: LCOE of renewable JF

The cost relating to decentralized scenarios are about 3,3 €/$GJ_{\text{jet fuel}}$ higher than the centralized cases. Which would suggest that the first and second hypothesis is confirmed: "*If the economies of scale are related to lower economics, then the centralized scenario has better economics than decentralized scenario"* and *"If economics is related to better integration of a facility, then the facility which has best integrated is the cheapest one".*

Furthermore, is the second hypothesis plausible*: "If better economics is related to suggest of the pathway, then the cheapest pathway is the suggested",* as the investigation determines the LCOE's integration possibilities and risk for each pathway, rather than suggestion one above another. The suggested pathway should be identified individually.
From the sensitivity analysis, it is concluded that the most sensitive parameter is the change in the selling price of side-products and gasoline, as these will change about 6% for both pathways.
The POX pathway is more sensitive than the SMR pathway for all the investigated parameters, which indicates that with the right assumptions, SMR could be a cheaper pathway than POX.

Regarding how well the scenario is integration, does the centralized scenarios, seems to have better heating utilization if storages are not available. This is due to that the centralized scenarios are placed in the highest demanding district heating grid on Funen. The production of excess heat rarely exceeds the hourly demand for heat. Furthermore, as the FT & refining facility is an alternate for blok 7, is grid

connection of heat and gas easily accessible, which makes the centralized case easier to integrate. The answer to research question 2 & 3. 2) "*Will integration of small-scale technologies for jet fuel production be more effective than the integration of larger-scale technologies for jet fuel production?"* & 3) *"Will integrating of jet fuel production using smaller-scale technologies be more effective than using larger-scale technologies to achieve better heat utilization?"* would be no, based on the results of integration.
Overall it is concluded that the production of renewable JF is economically competitive with fossil-fueled based JF if subsidies apply, as this would decrease the price for electro biomethane significant.

15. References

[1] *Paris Agreement*, E. Commission, 2015. [Online]. Available: https://ec.europa.eu/clima/policies/international/negotiations/paris_en

[2] *Klimapolitisk redegørelse 2019*, e.-o. f. Klima-, 2019.

[3] S. o. Green. "Denmark: The Most Wind Energy Producing Country Per Capita." https://stateofgreen.com/en/partners/state-of-green/news/denmark-the-most-wind-energy-producing-country-per-capita/ (accessed 17/5, 2020).

[4] H. M. Wanscher. "Fakta om Danmarks udledning af drivhusgasser samt energiforbrug." https://www.dst.dk/da/Statistik/bagtal/2018/2018-12-06-fakta-om-danmarks-udledning-af-drivhusgasser-samt-energiforbrug (accessed 2/2, 2020).

[5] ValutaKurser. "DKNBEUR." https://www.valutakurser.dk/forex/details.aspx?id=233058 (accessed 17/4, 2020).

[6] ExchangeRates. "Live Dollar to Euro Exchange Rate." https://www.exchangerates.org.uk/Dollars-to-Euros-currency-conversion-page.html (accessed 23/4, 2020).

[7] Conversion-measurement-units. "Conversion-calculator for measurement units." https://www.convert-measurement-units.com/conversion-calculator.php?type=energy (accessed 24/5, 2020).

[8] Wikipedia. "Barrel (unit)." https://en.wikipedia.org/wiki/Barrel_(unit) (accessed 25/4, 2020).

[9] *CO2-udledning fra transportsektoren*, M. M. Jensen. [Online]. Available: https://www.drivkraftdanmark.dk/viden/danmarks-samlede-udledning/

[10] *Electrification in aviation: Identifying opportunities and challenges*, E. Justin G. Fisch, Dustin C. Elliott, Esq., and William F. Tarantino, Esq., Morrison and Foerster, 2019.

[11] U. Nations. "Sustainable Development Goals." https://sustainabledevelopment.un.org/?menu=1300 (accessed 2/3, 2020).

[12] H. W. Anders Winther Mortensen, Kasper Dalgas Rasmussen, Stine Sandermann Justesen, Erik Wormslev and Martin Porsgaard, "Nordic GTL – a pre-feasibility study on sustainable aviation fuel

from biogas, hydrogen and CO2," 24/10 2019.

[13] *Fischer-Tropsch Refining*, A. d. Klerk, 27/3-2020 2008. [Online]. Available: https://repository.up.ac.za/bitstream/handle/2263/26754/Complete.pdf?sequence=10

[14] F. Fyn. "Velkommen til Fjernvarme Fyn." https://www.fjernvarmefyn.dk/media/1042/rundvisning_folder_2019.pdf (accessed 2/3, 2020).

[15] Velocys. "Velocys secures order for biorefinery licence in Japan." https://www.velocys.com/2019/09/19/velocys-secures-order-for-biorefinery-licence-in-japan/ (accessed.

[16] Wikipedia. "IMRAD." Wikipedia. https://en.wikipedia.org/wiki/IMRAD (accessed 20/4, 2020).

[17] *Biogasproduktion pr kommune*, Energistyrelsen, 1/12 2015. [Online]. Available: https://ens.dk/sites/ens.dk/files/Statistik/biogas_kommune_2015.pdf

[18] Energistyrelsen. "Teknologikatalog for fornybare brændstoffer." Energistyrelsen. https://ens.dk/service/fremskrivninger-analyser-modeller/teknologikataloger/teknologikatalog-fornybare (accessed 4/3, 2020).

[19] T. M. Ø. Filip Gamborg, Thøger Kiørboe, Jacob Hjerrild Zeuthen and Christoph Wolter. "Teknologikatalog for energilagring." Energistyrelsen. https://ens.dk/service/fremskrivninger-analyser-modeller/teknologikataloger/teknologikatalog-energilagring (accessed 4/3, 2020).

[20] Energistyrelsen. "Teknologikatalog for distribution og transmission af el, gas og fjernvarme." Energistyrelsen. https://ens.dk/service/fremskrivninger-analyser-modeller/teknologikataloger/teknologikatalog-distribution-og (accessed 4/3, 2020).

[21] Y. Zhang, "Anaerobic digestion system: Energy balance," 2013.

[22] *Samfundsøkonomiske beregningsforudsætninger for energipriser og emissioner*, Energistyrelsen, 2017.
[23] W. Kenton. "Net Present Value (NPV)." https://www.investopedia.com/terms/n/npv.asp (accessed 19/4, 2020).
[24] *Vejledning i samfundsøkonomiske konsekvensvurderinger*, Finansministeriet, 2019.
[25] *Levelized Cost of Energy (LCOE)*, D. O. O. I. ENERGY, 2015. [Online]. Available: https://www.energy.gov/sites/prod/files/2015/08/f25/LCOE.pdf
[26] K. H.-G. Torkild Birkmose, Jørgen Hinge, Rita Hørfarter, "Kortlægning af hensigtsmæssig lokalisering af nye biogasanlæg i Danmark - Udpegning af områder med særlige muligheder for biogasanlæg," Biogasrejseholdet, Erhvervsstyrelsen, Landbrugsinfo, 2015. Accessed: 10/3. [Online]. Available: https://www.landbrugsinfo.dk/Oekologi/biogas/Sider/Rapport_om_hensigtsmaessig_placering_af_biogasanlaeg_i_Danmark_pl_16_2793_b1.pdf
[27] T. E. ToolBox. "Fuels - Higher and Lower Calorific Values " https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html (accessed 20/3, 2020).
[28] Energinet, "Analyseforudsætninger 2019," 2019.
[29] Gasum. "How is biogas produced?" https://www.gasum.com/en/About-gas/biogas/Biogas/how-is-biogas-produced/ (accessed 29/3, 2020).
[30] *STRAW FOR BIOGAS AT INDUSTRIAL QUANTITIES IS A TECHNICAL CHALLENGE - WHICH HAS BEEN SOLVED!*, K. biofuel, 2018.
[31] B. R. Energy. "Biogas composition." https://www.biogas-renewable-energy.info/biogas_composition.html (accessed 15/3, 2020).
[32] B. A/S, "Biogasclean has the optimal solution for your biogas plant." [Online]. Available: https://www.biogasclean.com/.
[33] A. P. a. P. Nikolaidis, "A comparative overview of hydrogen production processes," 2017.
[34] M. Ali Keçebaş, MutlucanBayat, "Electrochemical hydrogen generation," in *Solar Hydrogen Production*, M. D. D. A. Francesco Calise, Massimo Santarelli, Andrea Lanzini, Domenico Ferrero Ed. Sciencedirect: Academic Press, 2019, ch. 9, pp. 299-317.
[35] *Compact and Lightweight Sabatier Reactor for Carbon Dioxide Reduction*, K. H. Christian Junaedi, Dennis Walsh, Subir Roychoudhury, Morgan B. Abney and Jay L. Perry, 2011.
[36] L. O. E. Monitor. "Sabatier process." https://learn.openenergymonitor.org/sustainable-energy/energy/sabatier-process (accessed 1/3, 2020).
[37] I. R. N. Skov, Steffen; Nørholm, Malte Skovgaard; Vestergaard, JohannPálmason, "Screening of biogas methanation in Denmark," Aalborg Universitet, 2019. [Online]. Available: https://vbn.aau.dk/ws/portalfiles/portal/313424727/Screening_of_biogas_methanation_in_Denmark_20191030.pdf
[38] E. E. R. Energy. "Hydrogen Production: Natural Gas Reforming." https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming (accessed 5/4, 2020).
[39] *Technology handbook*, A. Liquide, 2018.
[40] F. T. a. J. A. M. Mackenzie. "Gaseous composition of dry air." https://eesc.columbia.edu/courses/ees/slides/climate/table_1.html (accessed 18/4, 2020).
[41] J. Dodaro. "Fischer-Tropsch Process." http://large.stanford.edu/courses/2015/ph240/dodaro1/ (accessed.
[42] A. S. Jingzheng Ren, Alessandro Manzardo and Hanwei Liang "Determination of NPV for Fischer-Tropsch case (FT case)," in *Biofuels for a More Sustainable Future: Life Cycle Sustainability Assessment and Multi-Criteria Decision Making. 1st Edition*, 2020, ch. 4, p. 105.
[43] J. G. Speight, "Production of syngas, synfuel, bio-oils, and biogas from coal, biomass, and opportunity fuels," in *Fuel Flexible Energy Generation - Solid, Liquid and Gaseous Fuels*: Woodhead Publishing, 2016, ch. 6, pp. 145-174.

[44] TOPPR. "Efficiency Formula." https://www.toppr.com/guides/physics-formulas/efficiency-formula/ (accessed 10/4, 2020).
[45] D. S. Pisupati. "Efficiency of Energy Conversion Devices." https://www.e-education.psu.edu/egee102/node/1938 (accessed.
[46] F. Fyn. "Fjernvarme Fyn er Danmarks 3. største fjernvarmeselskab." https://www.fjernvarmefyn.dk/om-os/overblik (accessed 20/4, 2020).
[47] F. F.-O. Mindorf. *Fjernvarme Fyn data*.
[48] *Strategisk energiplan Fyn - Den indledende kortlægningaf fjernvarmenet og gasnetpåFyn*, E. I. A/S, 2014.
[49] T. F. a. M. Howells, "Mini-GTL technology bulletin, volume 5," 2018. [Online]. Available: http://documents.worldbank.org/curated/en/696261537801358802/pdf/Mini-GTL-Technology-Bulletin.pdf.
[50] *Fyn map*, U. o. S. Denmark, 2020.
[51] *BY3: Folketal 1. januar efter byområder, landdistrikter og folketal, areal og befolkningstæthed*, D. Statistik, Statistikbanken, 2019. [Online]. Available: https://www.statistikbanken.dk/10021
[52] M. B. B. Pedersen. "Nyborg Forsyning runder de 96 procent på overskudsvarmen." https://www.energy-supply.dk/article/view/496708/nyborg_forsyning_runder_de_96_procent_pa_overskudsvarmen (accessed 27/4, 2020).
[53] N. Energy. "Nature Energy Nordfyn." https://natureenergy.dk/biogasanlaeg-danmark/nature-energy-nordfyn (accessed 18/4, 2020).
[54] G. P. Prices. "Copenhagen Gasoline prices, liter." https://www.globalpetrolprices.com/Denmark/Copenhagen/gasoline_prices/ (accessed 7/4, 2020).
[55] E. Energianalyse, "Biogas og andre VE brændstoffer til tung transport - Analyse af muligheder og udfordringer ved udfasning," 2016.
[56] Greenea. "Our view on the waste based biodiesel." https://www.greenea.com/en/market-analysis/ (accessed 26/3, 2020).
[57] R. Rapier. "Inside Shell's Bintulu GTL Plant." http://www.energytrendsinsider.com/2010/11/14/inside-shells-bintulu-gtl-plant/ (accessed 24/3, 2020).
[58] Enerdata. "The future of Gas-To-Liquid (GTL) industry." https://www.enerdata.net/publications/executive-briefing/future-gas-liquid-gtl-industry.html (accessed.
[59] A. S. a. M. Dry, "Commercial FT Process Applications," in *Fischer-Tropsch Technology*, vol. 152: Elsevier Science, 2004, ch. 5, p. 442.
[60] *Elpris Outlook - Perspektiver for det nordvesteuropæiske elmarked frem mod2035*, D. Energi, 2019. [Online]. Available: https://www.danskenergi.dk/sites/danskenergi.dk/files/media/dokumenter/2019-06/Elpris_Outlook_2019.pdf
[61] *Overskudsvarme pris*, F. Fyn, 2020.
[62] *Analyse af forsyningssikkerheden i gassektoren*, E.-f. o. klimaministeriet, 2016.
[63] Energinet, "Gasinfrastruktur," ed, 2017.
[64] R. B. Jerry Murphy, Peter Weiland, Arthur Wellinger, "Biogas from Crop Digestion," 2011.
[65] R. Clouzeau, "Including Risk Management in Construction Projects," 2018. [Online]. Available: http://wiki.doing-projects.org/index.php/Including_Risk_Management_in_Construction_Projects.
[66] *Energiscenarier frem mod 2020, 2035 og 2050*, Energistyrelsen, 2014.
[67] P. Stratmann, "Roll-out of smaller scale gas-to-liquids: current commercialisationand future approach," 2017.
[68] *Implementering af Energiaftalen – stop for nye anlæg på de eksisterende støtteordninger til anvendelse af biogas*, F.-o. k. Energi-, 2019.

[69] *Gassystemets fremtid og udfasning af naturgas*, D. Energi, 2015.
[70] *Energistatistik 2018*, Energistyrelsen, 2018.
[71] Energistyrelsen. "Månedlig og årlig energistatistik." https://ens.dk/service/statistik-data-noegletal-og-kort/maanedlig-og-aarlig-energistatistik (accessed 9/5, 2020).
[72] *Biogasproducenter i Danmark*, Energistyrelsen, 2018.
[73] Energistyrelsen. "Støtte til anvendelse af biogas." https://ens.dk/ansvarsomraader/stoette-til-vedvarende-energi/biogas/stoette-til-anvendelse-af-biogas (accessed 2/5, 2020).
[74] *Bekendtgørelse af lov om fremme af vedvarende energi*, F.-o. K. Energi-, 2015.
[75] EnergiNet. "Certifikater på biogas fra gasnettet." https://energinet.dk/Gas/Biogas/Gascertifikater (accessed 17/5, 2020).
[76] A. D. Ayhan Demirbaş, Namık Ak, Avni Aslan, Nejdet Sen, "Calculation of higher heating values of hydrocarbon compounds and fatty acids," 2018.
[77] *Benzin og dieselprisens sammensætning*, D. Danmark, 2019. [Online]. Available: https://www.drivkraftdanmark.dk/viden/benzin-og-dieselprisens-sammensaetning/
[78] D. G. Center. *Kompressibilitet_densitet*. [Online]. Available: https://www.dgc.dk/kompressibilitetsfaktor
[79] *Review of Synthesis Gas Processes*, F. P. F. v. B. a. G. M. C. M.A. Korobitsyn, 2000.
[80] J. E. a. M. Melaina, "Hydrogen Energy Storage and Power-to-Gas - Establishing Criteria for Successful Business Cases " 2015.

16. Appendices

Appendix A – Economics for the facilities.

Technology	Efficiency	Inlet	Outlet	Investment	Variable O&M	Fixed O&M	Technical lifetime
Biogas plant [21] [18]	48%	Biomass	Biogas	1,71 (mio €/MW output)	3,8% electricity 8,9% heat	194715,02 (€/MW/year)	20 years
BiogasClean	-	Biogas	Treated biogas	0,1 (mio €/MW output)	0,8 €/MWh	0,4 €/MWh	20 years
Electrolyzes (Alkaline) [18]	63,60%	Electricity	Hydrogen + heat (14%)	0,6 (mio €/ MWe)	Electricity price	30000 (€/ MWe)	25 years
Methanation [37]	79%	Biogas + H2	Methane + heat (21%)	0,91(mio €/ MW/h Gas)	0,12 (€/GJ upgraded biogas)	0,12 (€/GJ methane)	25 years
Steam reformer	100% syngas	Heat + Methane	Syngas	"353090e$^{-9E-04x}$"	2 €/GJ	5% of capital	20 years
Partial oxidation	96,5% syngas	O2 + methane	syngas	"381021e$^{-0,001x}$"	2,25 €/GJ	5% of capital	20 years
FT synthesis & refinery	56-78%	Syngas + hydrogen	Syncrude + Heat (20%) + (hydrogen)	33.000 BPD	4,5 €/BBL	5% of capital	20 years

Appendix B - Funen's biogas potential

Source: [26]

Methane production	[Mio. Nm^3/year]	[Mio. Nm^3/year]	[Mio. Nm^3/year]	[Mio. Nm^3/year]	[Mio. Nm^3/year]
Commune	**Manure**	**Waste**	**Nature areas**	**Excess hay**	**Total**
Faaborg-Midtfyn	8	1	0	17	27
Assens	9	1	0	15	25
Nordfyns	6	0	0	16	23
Svendborg	5	0	0	12	17
Langeland	3	0	0	11	14
Middelfart	7	0	0	6	14
Nyborg	4	1	0	9	14
Kerteminde	2	0	0	8	10
Odense	2	3	0	5	10
Ærø	1	0	0	2	4
Total	47	6	0	101	158

Appendix C – Reference electricity prices

Source: [28]

		2025	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**
DK1	**Euro/Mwh**	49,9	50,5	51,7	51,3	51,7	52,1	53,2	53,7	54,9	55,4	56,2	57,1	57,9
DK2	**Euro/Mwh**	50,0	50,6	52,0	51,4	52,0	51,9	53,1	53,6	55,1	55,3	56,2	57,0	57,6

		2038	**2039**	**2040**	**2041**	**2042**	**2043**	**2044**	**2045**	**2046**	**2047**	**2048**	**2049**	**2050**
DK1	**Euro/Mwh**	58,8	59,7	60,6	61,4	62,1	62,9	63,7	64,4	65,2	66,0	66,8	67,5	68,3
DK2	**Euro/Mwh**	58,5	59,4	60,2	61,0	61,8	62,6	63,4	64,1	64,9	65,7	66,4	67,2	68,0

Appendix D - Stoichiometric calculations

D.1 - Properties of gases

Source: [27]

	CH4	H2	CO	O2		C23H49
HHV [MJ/m3]	39,83	12,75	12,63	-	**HHV [MJ/kg]**	46,68
HHV [KJ/mol]	890,42	286,48	282,90	-	**HHV [KJ/mol]**	15761,45
LHV [MJ/m3]	35,89	10,79	12,63	-	**LHV [MJ/kg]**	-
LHV [KJ/mol]	802,34	242,44	282,90	-	**LHV [KJ/mol]**	-
Molar weight [g/mol]	16,04	2,02	28,01	32,00	**Molar weight [g/mol]**	337,65
Density [kg/m3]	0,72	0,09	1,25	1,42	**Density [kg/m3]**	-
kJ->kWh [multiplier]	0,000277778					

D.2 - Methanation

CO2			4H2			CH4			Heat	
KJ	kWh	+	KJ	kWh	"->"	KJ	kWh	+	KJ	kWh
0	0		1144	0,32		889	0,25		255	0,07

Eff methane	78%
Heat fraction	22%

D.3 - Syngas production – SMR

HHV calculations

Heat		+	CH4		"->"	3H2		+	CO	
KJ	kWh		KJ	kWh		KJ	kWh		KJ	kWh
251,94	0,07		890,42	0,25		859,45	0,24		282,90	0,08

Heat fraction needed of income CH4	H2 Efficiency	Syngas efficiency
22,1%	**75,2%**	**100%**

D.4 Syngas production – POX

HHV													
CH4		+	0,5 O2		"->"	CO		+	2H2		+	Heat	
MJ	kWh		MJ	kWh		MJ	kWh		MJ	kWh		MJ	kWh
890,416	0,247		-	-		282,900	0,079		572,970	0,159		34,546	0,010

H2 efficiency	Syngas efficiency
64,3%	**96,1%**

D.5 - Fischer Tropsch synthesis

D.5.1 - Syncrude production with 2:1 ratio syngas from POX

23CO			46H2			23CH48			23H2O			Heat	
KJ	kWh	+	KJ	kWh	"->"	KJ	kWh	+	KJ	kWh	+	KJ	kWh
6506,70	1,81		13464,79	3,74		15762,66	4,38		0,00	0,00		4208,83	1,17

Syncrude efficiency	79%
Heat	21%

D.5.2 - Syncrude production with 3:1 ratio syngas from SMR

23CO			69H2			23CH48			23H2O			H2			Heat	
KJ	kWh	+	KJ	kWh	"->"	KJ	kWh	+	KJ	kWh	+	KJ	kWh	+	KJ	kWh
6506,70	1,81		19767,46	5,49		15762,66	4,38		0,00	0,00		6302,67	1,75		4208,83	1,17

Syncrude efficiency	60%
Heat	16%
H2	24%

Appendix E – Biomass transportation costs

[18]

Transportation price [€/ton]	Manure	Straw	Natural areas	Waste	Reference		
	6,71	67,4	27,9	18,9			
Commune	**Manure [1000€]**	**Straw [1000€]**	**Natural areas [1000€]**	**Waste [1000€]**	**Total [1000€]**	**Total Energy [GJ]**	**[€]/GJ**
Assens	281,9	4379,9	25,5	417,3	5104,6	995000,0	5,1
Faaborg-Midtfyn	281,9	4918,9	24,5	303,6	5528,9	1074600,0	5,1
Kerteminde	53,7	2291,0	11,9	112,0	2468,7	398000,0	6,2
Langeland	100,7	3099,6	22,3	97,6	3320,2	557200,0	6,0
Middelfart	234,9	1819,3	12,2	261,2	2327,7	557200,0	4,2
Nordfyns	208,1	4582,0	22,0	152,2	4964,3	915400,0	5,4
Nyborg	134,2	2695,3	14,1	259,9	3103,5	557200,0	5,6
Odense	60,4	1549,8	15,0	1295,8	2921,0	398000,0	7,3
Svendborg	194,6	3369,1	13,9	86,6	3664,3	676600,0	5,4
Ærø	53,7	606,4	8,2	49,1	717,4	159200,0	4,5
Avg.	160,40	2931,14	16,97	303,55	3412,06	628840,00	5,4

Appendix F – Refinery calculations

Liquid fuels								
	Kg/h	MJ/kg	MJ/h	Mass %	Energy %		Mass % of LF	Energy % of LF
Gasoline	101328	46,4	4701619,2	20%	19%		22%	21,6%
Ethanol	2272	29,7	67478,4	0%	0%		0,5%	0,3%
JF	355912	47,6342	16953584,3	71%	75%		77%	78,0%
Total	459512	-	21722681,9	92%	93%		100%	100,0%
Other products								
Fuel gas	26781	52,82709	1414762,23	5%	7%			
Uncovered organics	15634	0		3%	-			
Water	1315	0	0	0,3%	-			
H2	-3243	142	-460506	-0,65%	-2%			
Total	40487		954256,226	8%				
Total	499999	-	22676938,1	100%	100%			

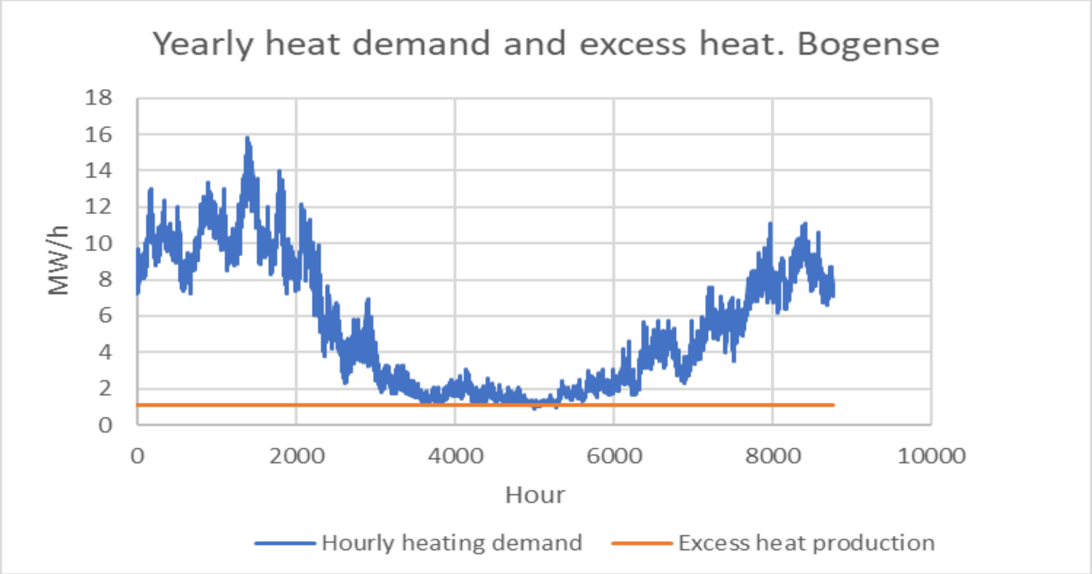
Appendix G – Specifications of jet fuel

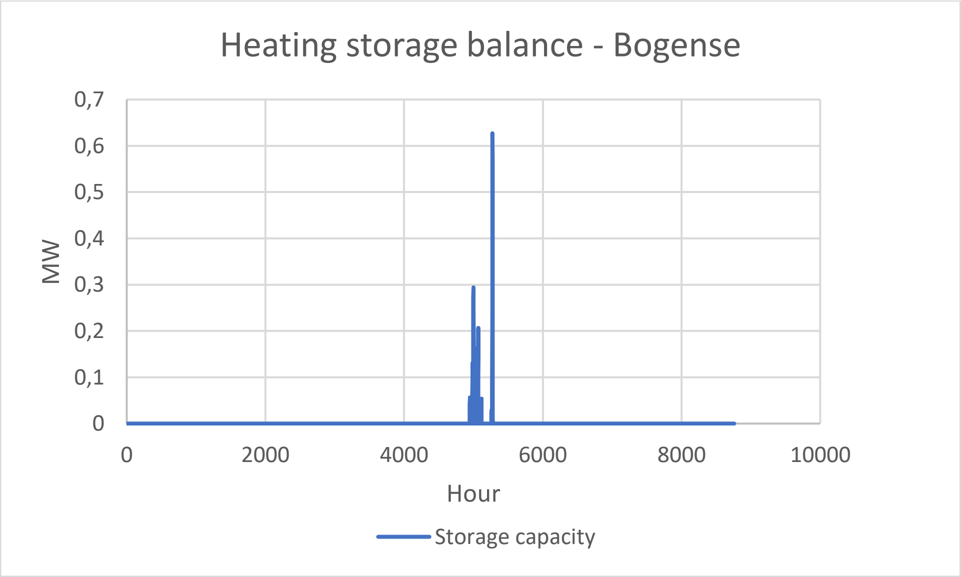
Source: [76]

Undecane	$C_{11}H_{24}$
HHV [MJ/kg]	47,63
HHV [KJ/mol]	7445,69
LHV [MJ/kg]	-
LHV [KJ/mol]	-
Molar weight [g/mol]	156,31
Density [kg/m3]	740
GJ/BBL	4,20

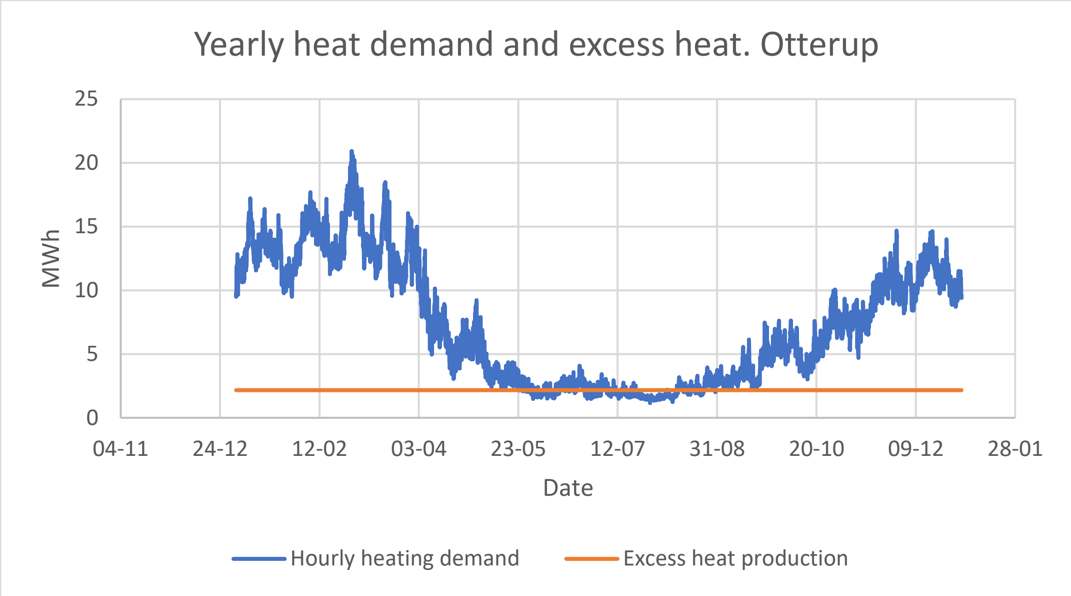
Appendix G – Demand and minimum storage for the 8 locations.

G.1 Bogense

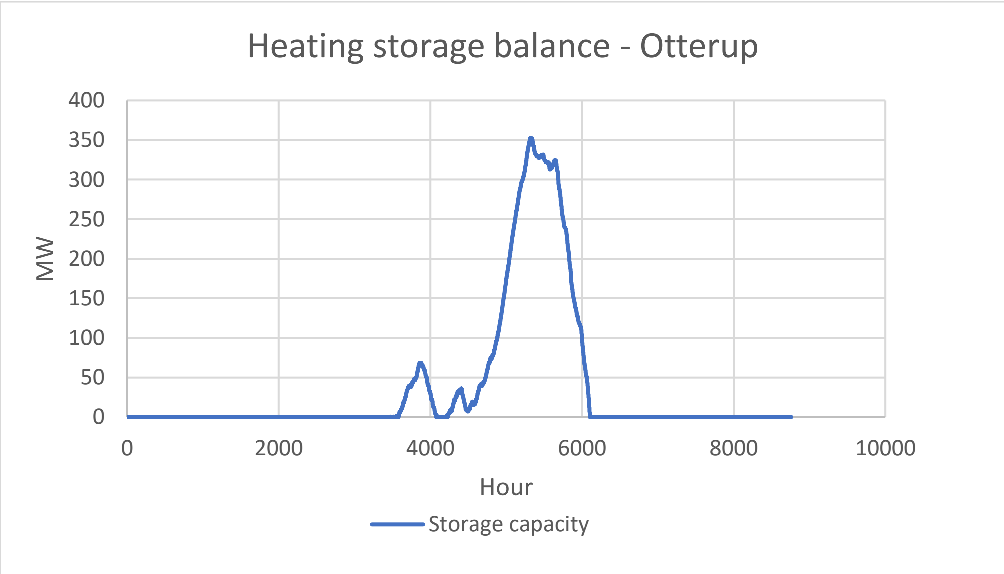




G.2 Otterup

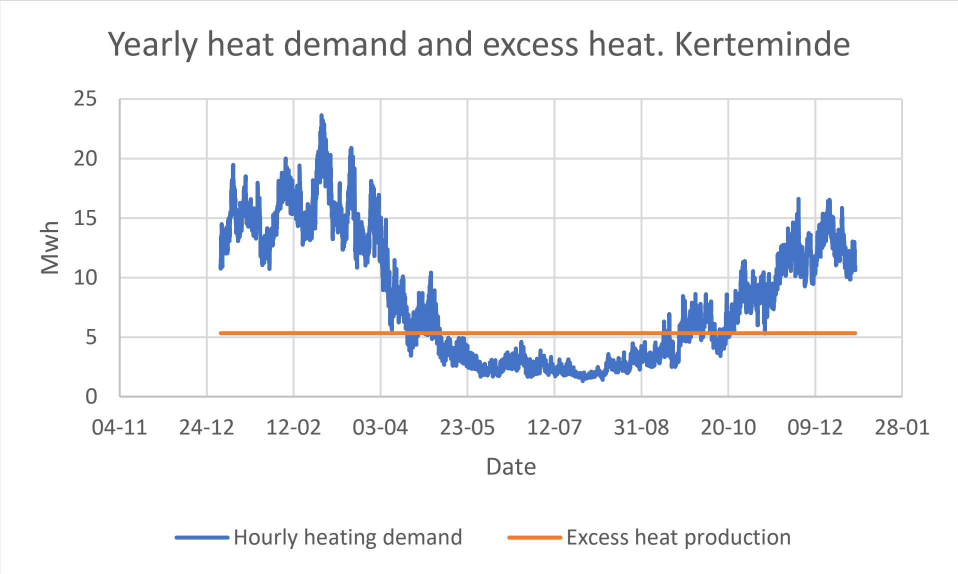


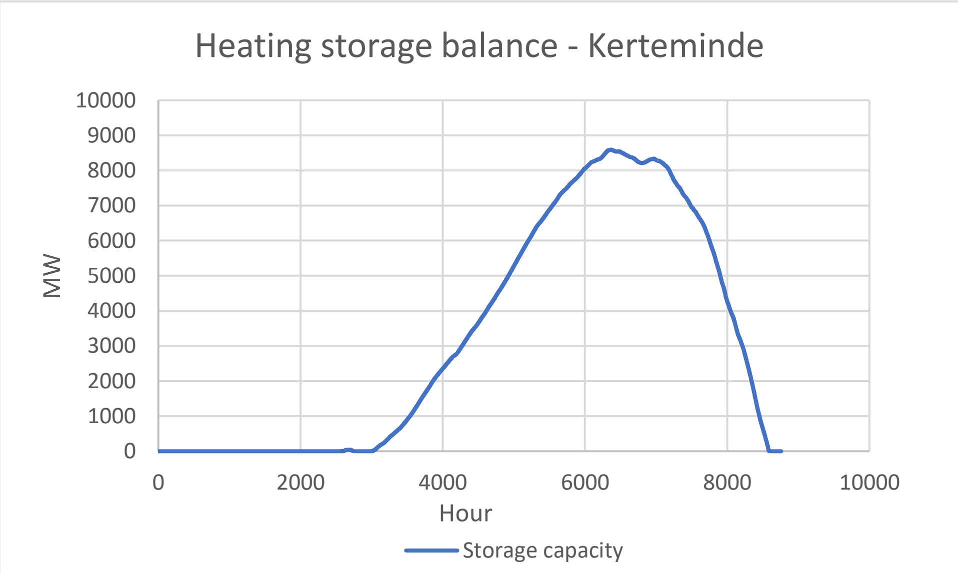
Yearly heat demand and excess heat. Otterup
MWh
25
20
15
10
5
0
04-11
24-12
12-02
03-04
23-05
12-07
31-08
20-10
09-12
28-01
Date
Hourly heating demand
Excess heat production



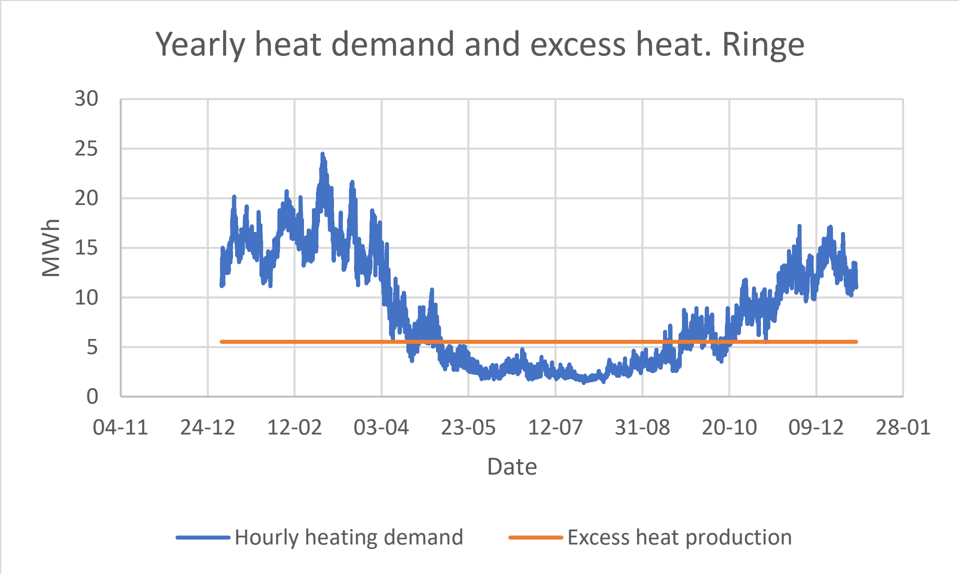
Heating storage balance - Otterup
MW
400
350
300
250
200
150
100
50
0
0
2000
4000
6000
8000
10000
Hour
Storage capacity

G.3 Kerteminde

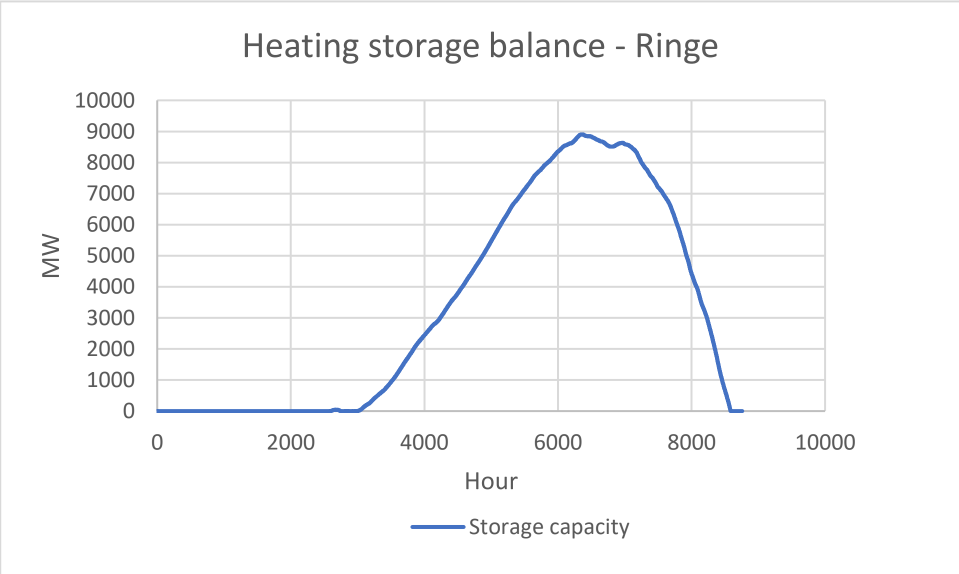




G.4 Ringe

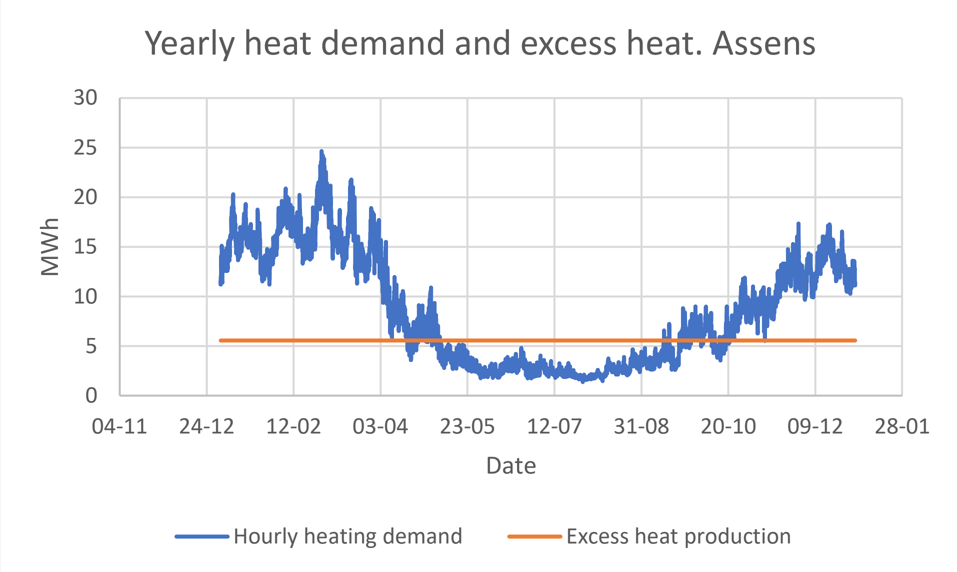


Yearly heat demand and excess heat. Ringe
30
25
20
15
10
5
0
MWh
04-11
24-12
12-02
03-04
23-05
12-07
31-08
20-10
09-12
28-01
Date
Hourly heating demand
Excess heat production

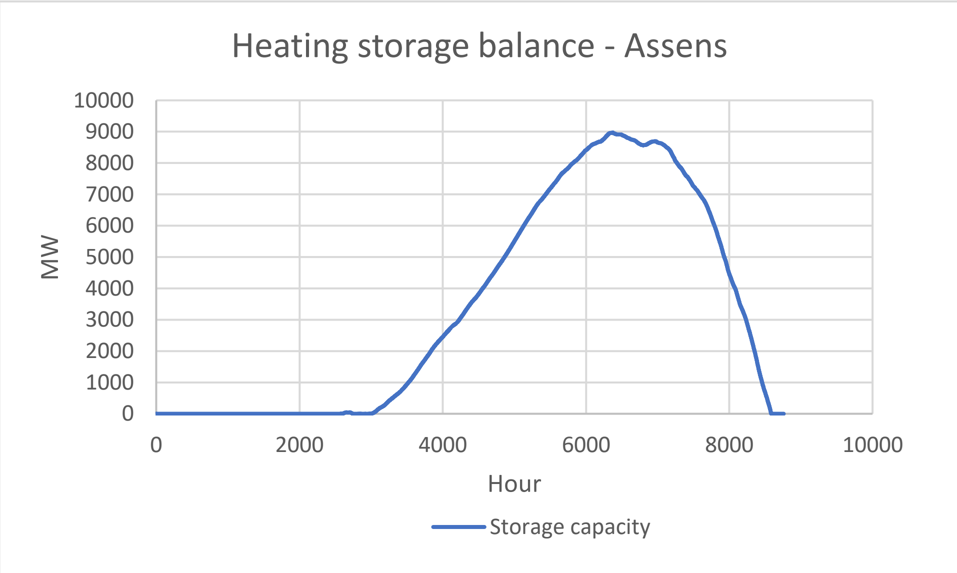


Heating storage balance - Ringe
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
MW
0
2000
4000
6000
8000
10000
Hour
Storage capacity

G.5 Assens

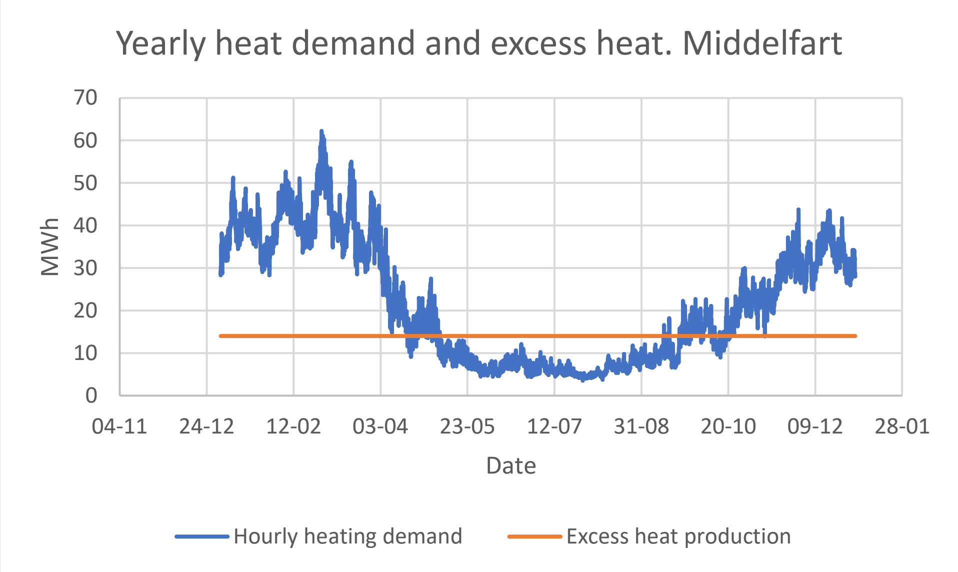


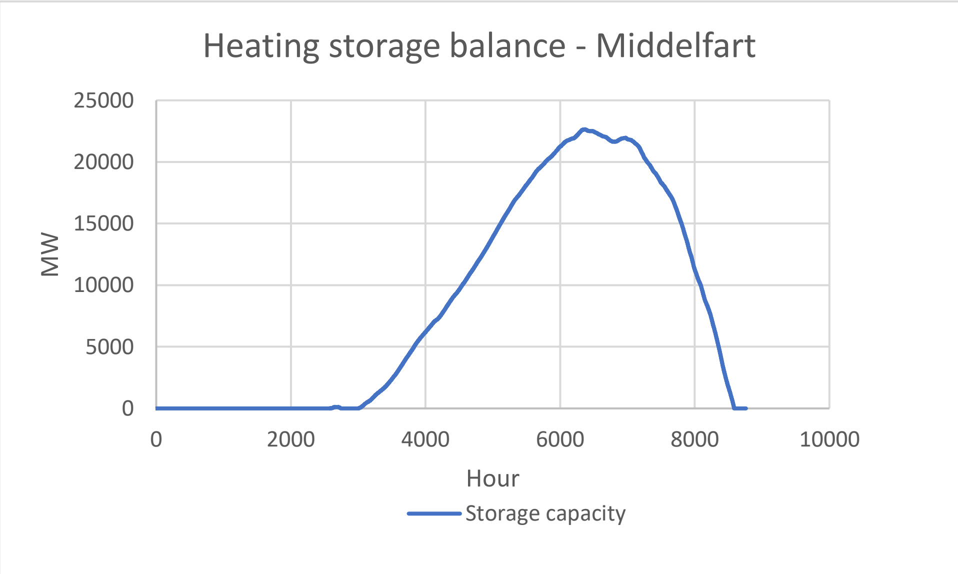
Yearly heat demand and excess heat. Assens
30
25
20
15
10
5
0
MWh
04-11
24-12
12-02
03-04
23-05
12-07
31-08
20-10
09-12
28-01
Date
Hourly heating demand
Excess heat production



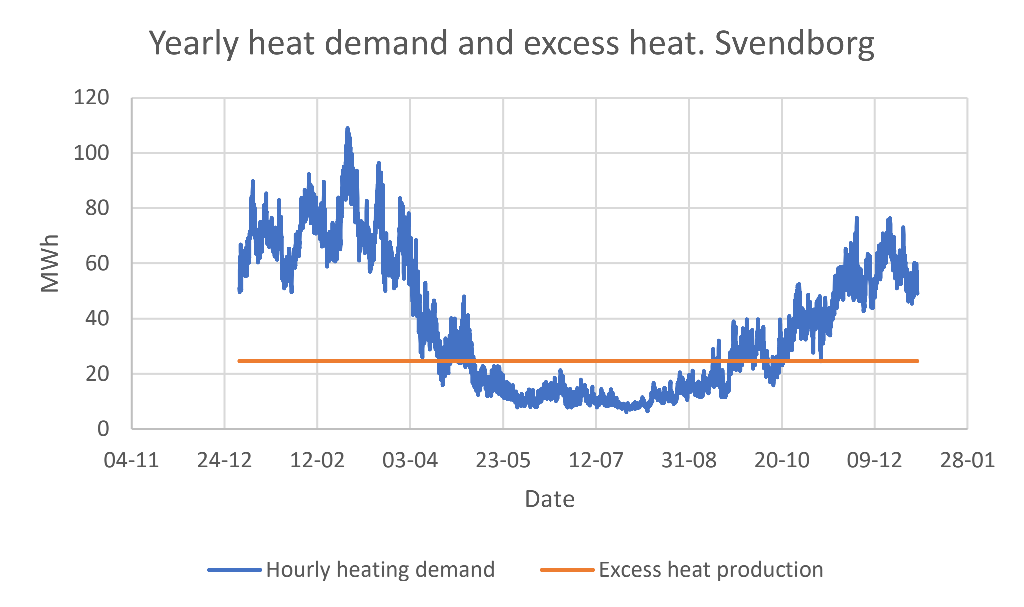
Heating storage balance - Assens
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
MW
0
2000
4000
6000
8000
10000
Hour
Storage capacity

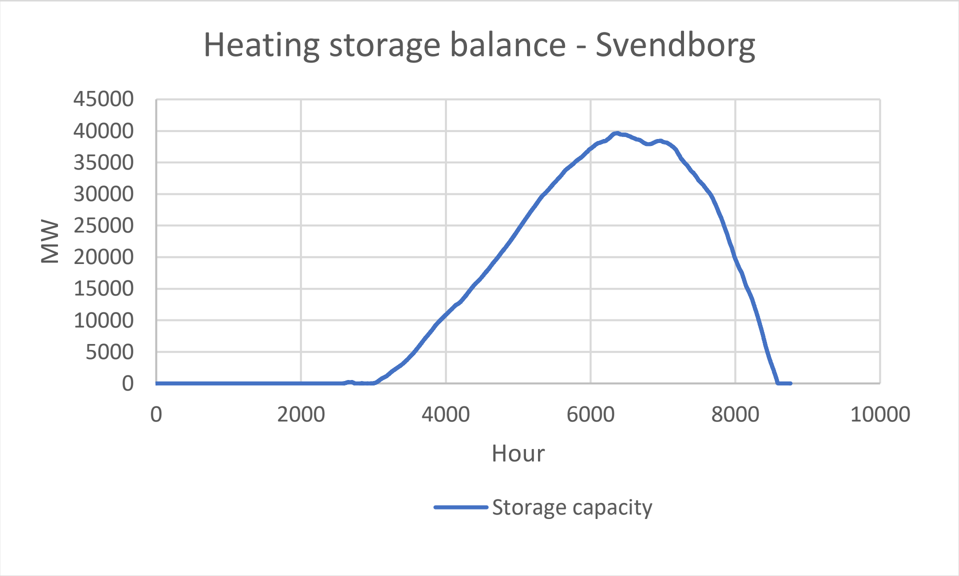
G.6 Middelfart





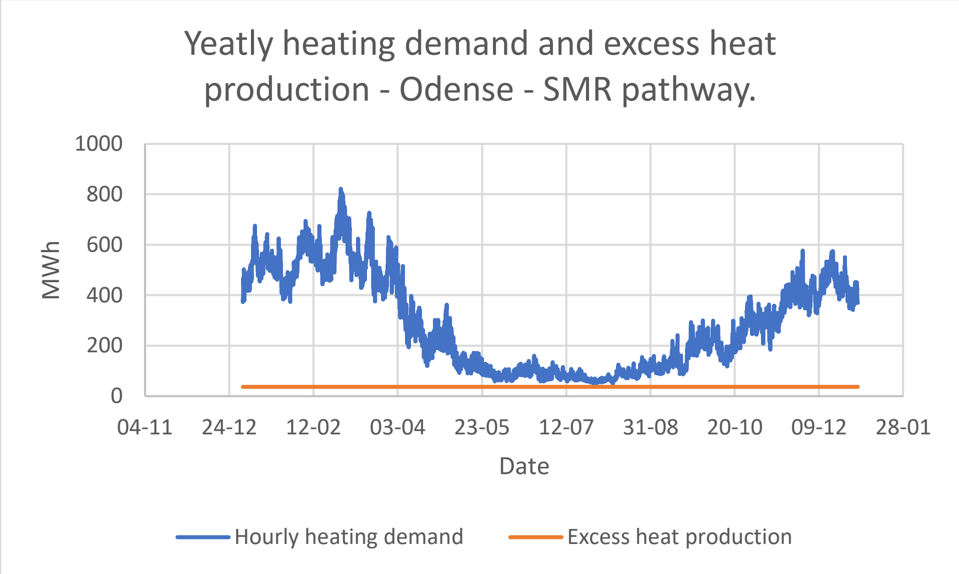
G.7 Svendborg



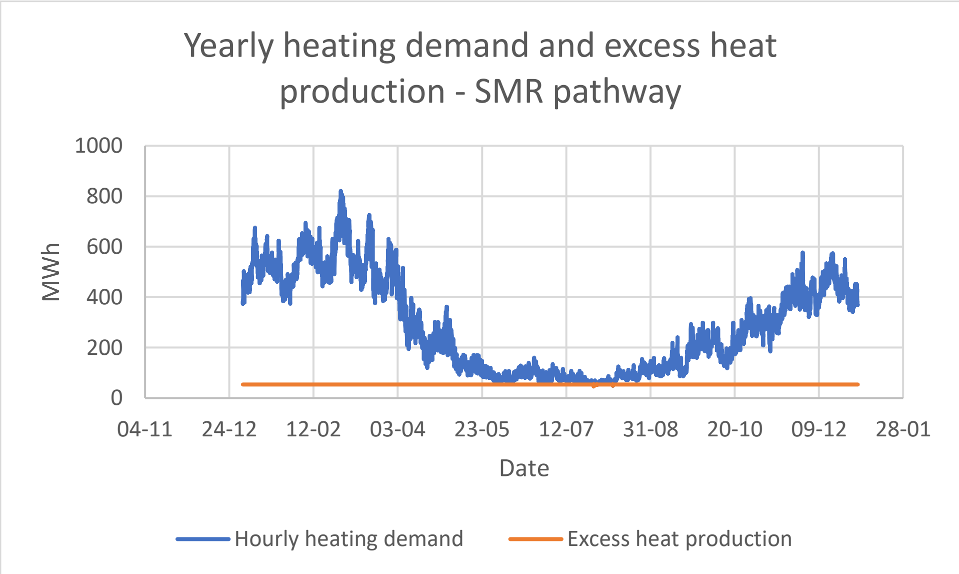


G.8 Odense SMR

G.8.1 Decentralized scenario

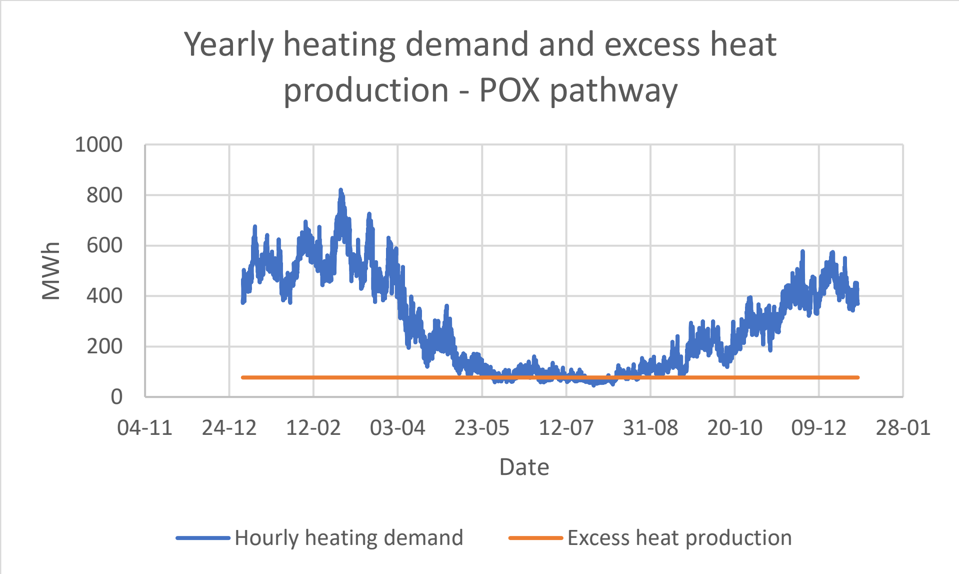


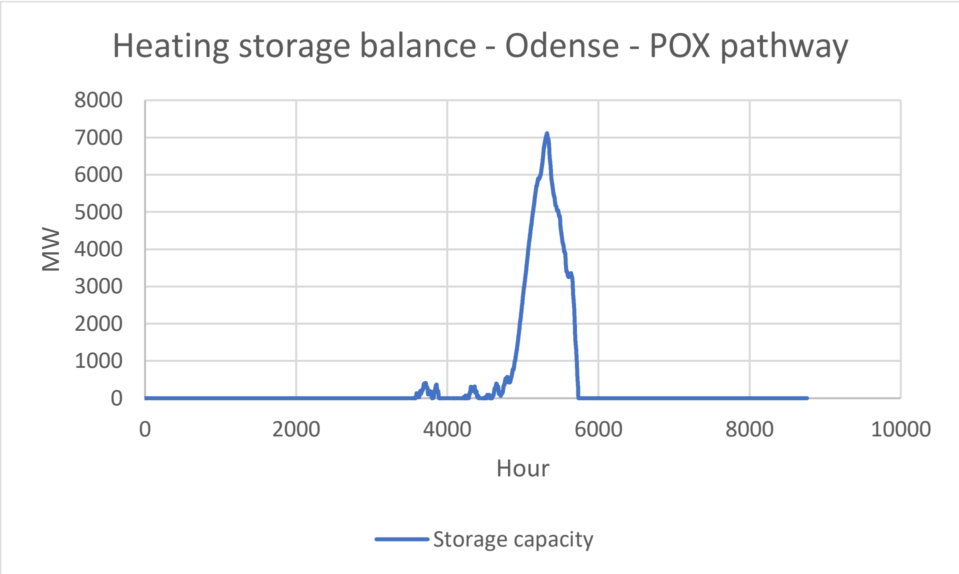
G.8.2 Centralized scenario



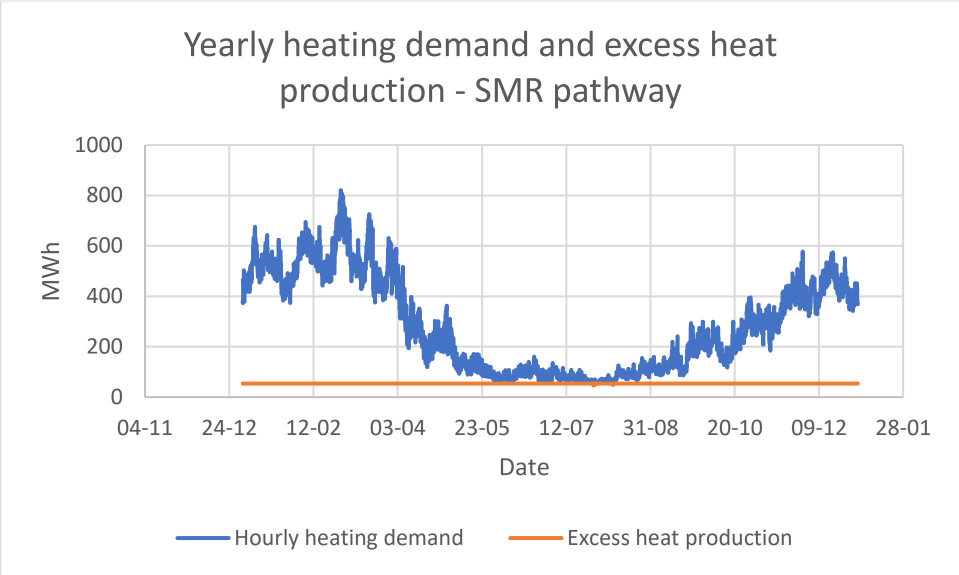
G.9 Odense POX

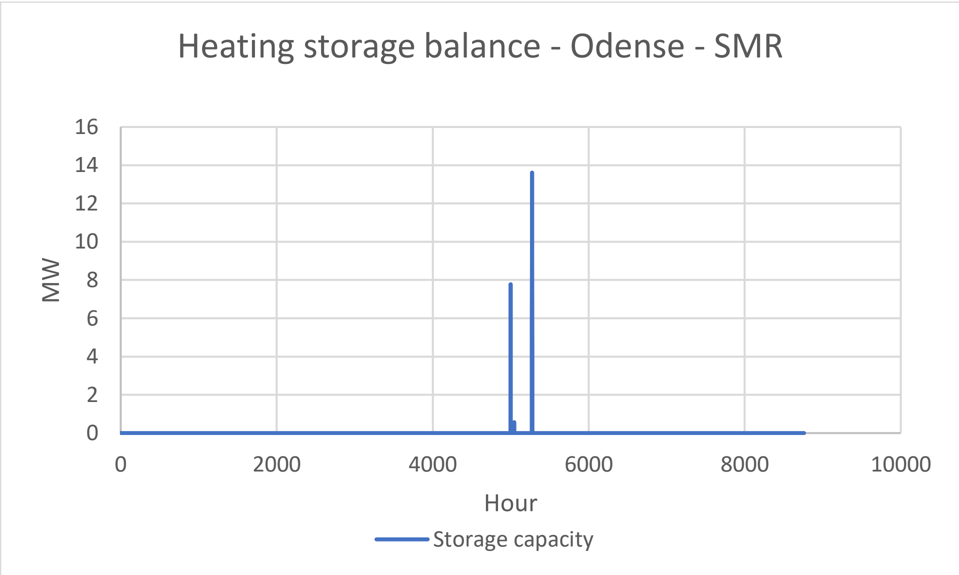
G.9.1 Centralized scenario





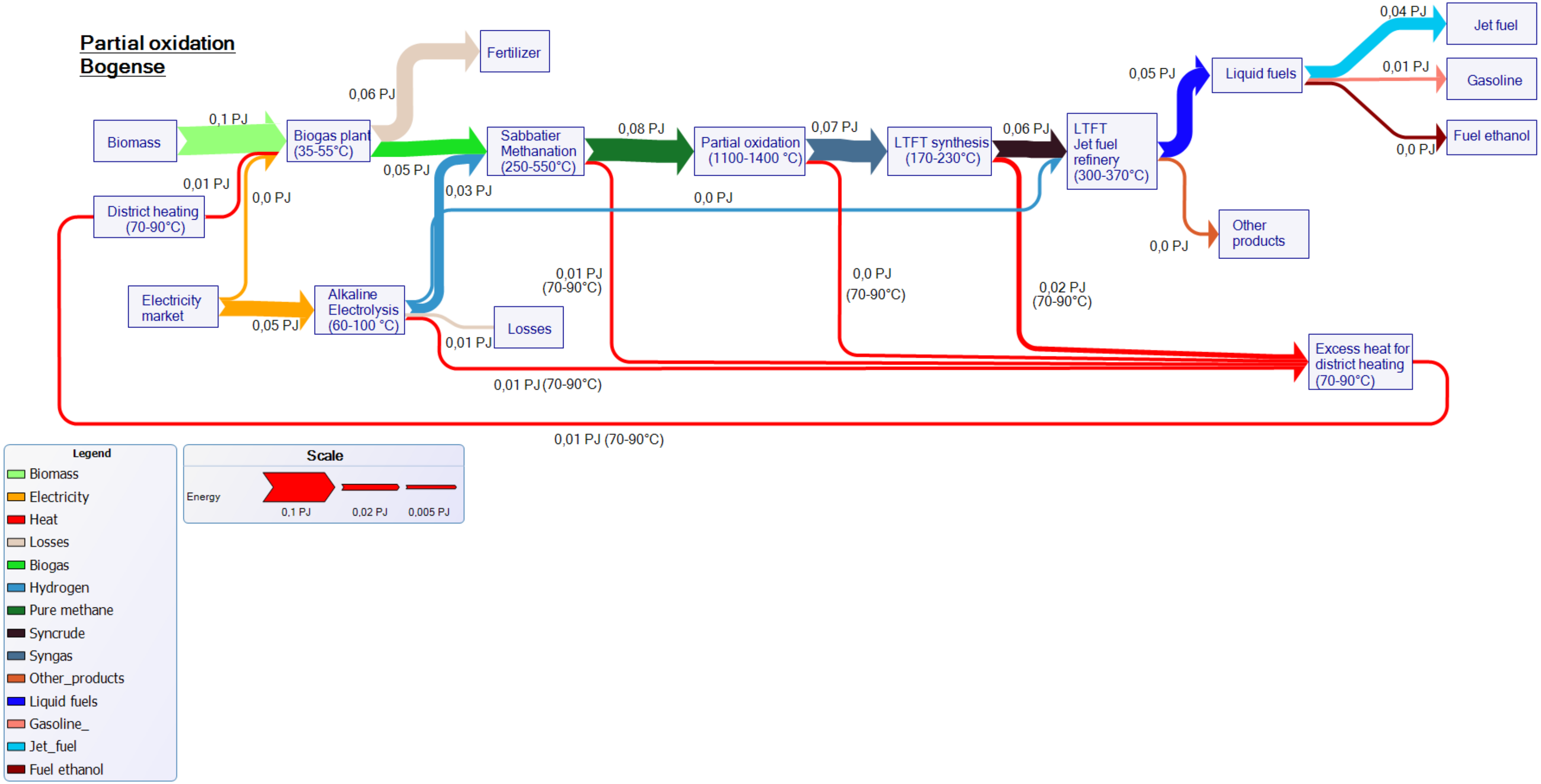
G.9.2 Decentralized scenario

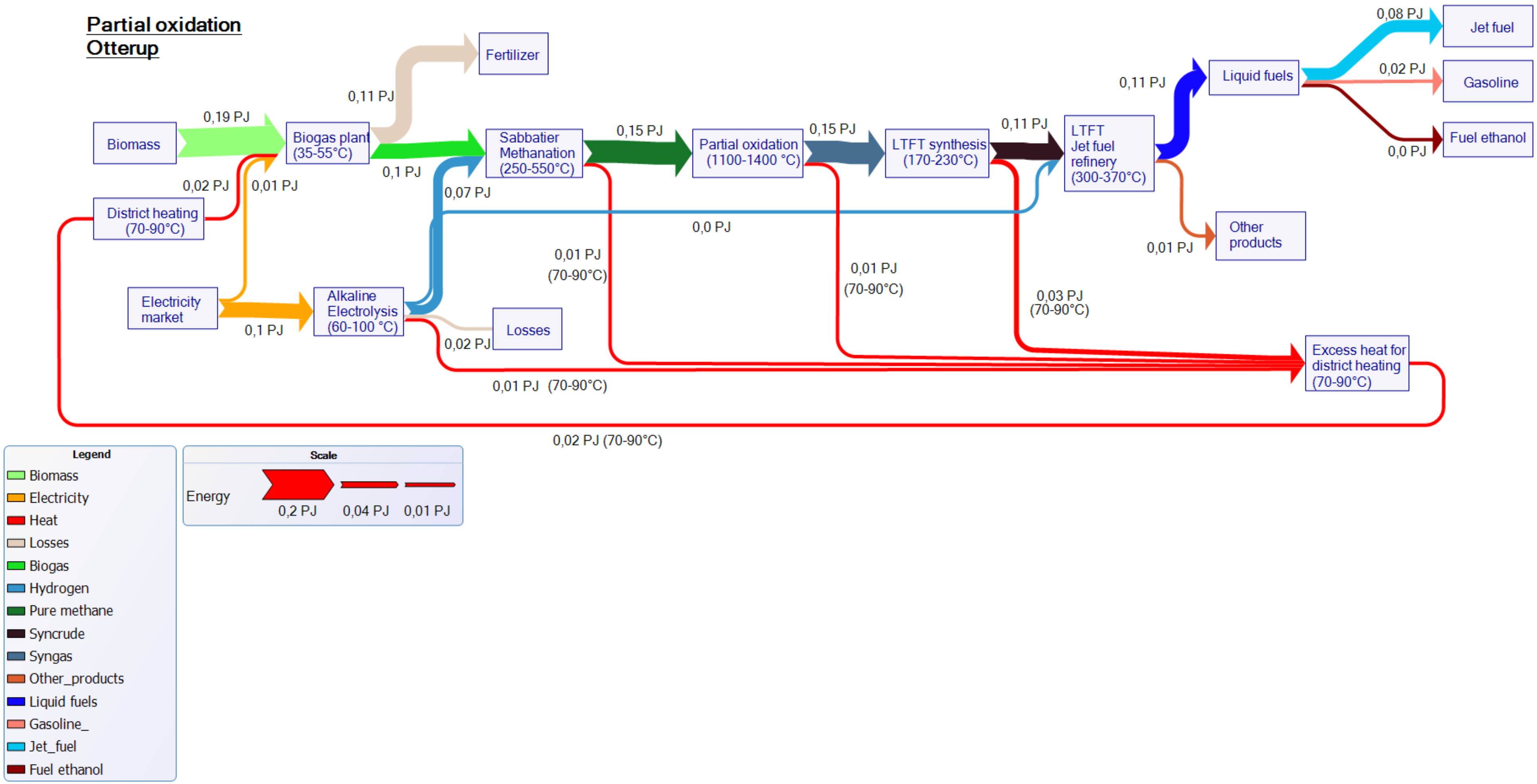




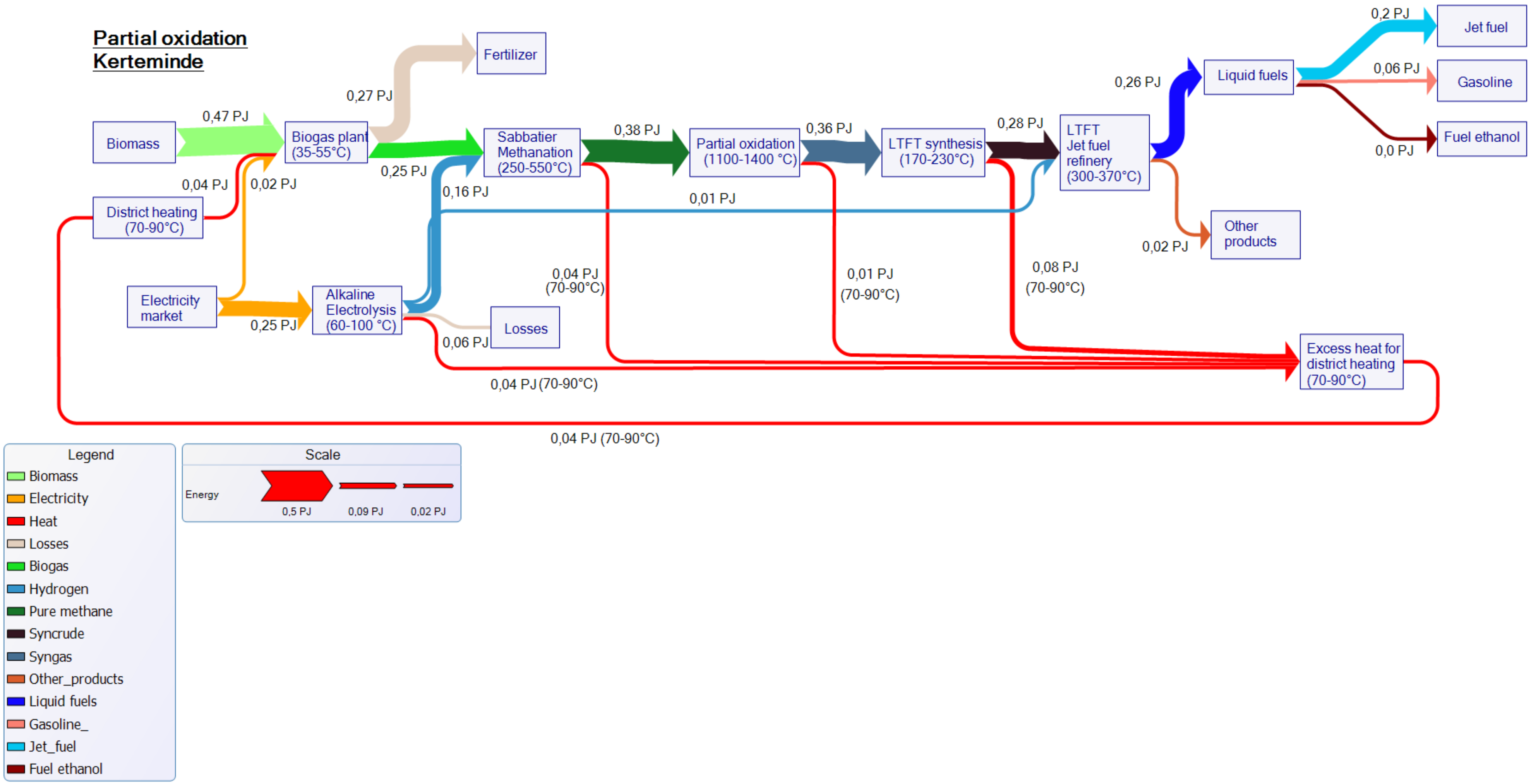
Appendix I – E-Sankey diagrams for the decentralized scenario.

I.1 POX pathway

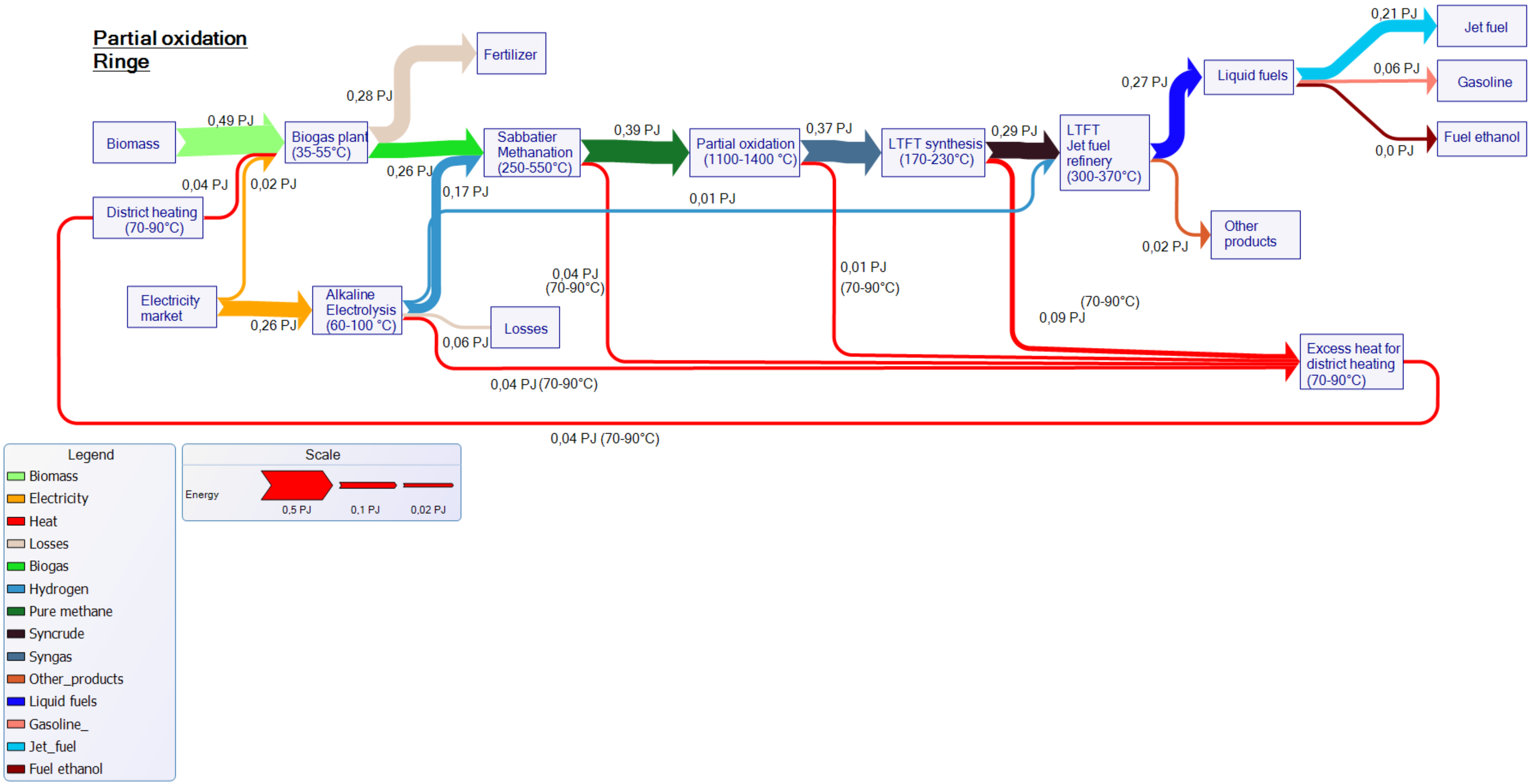


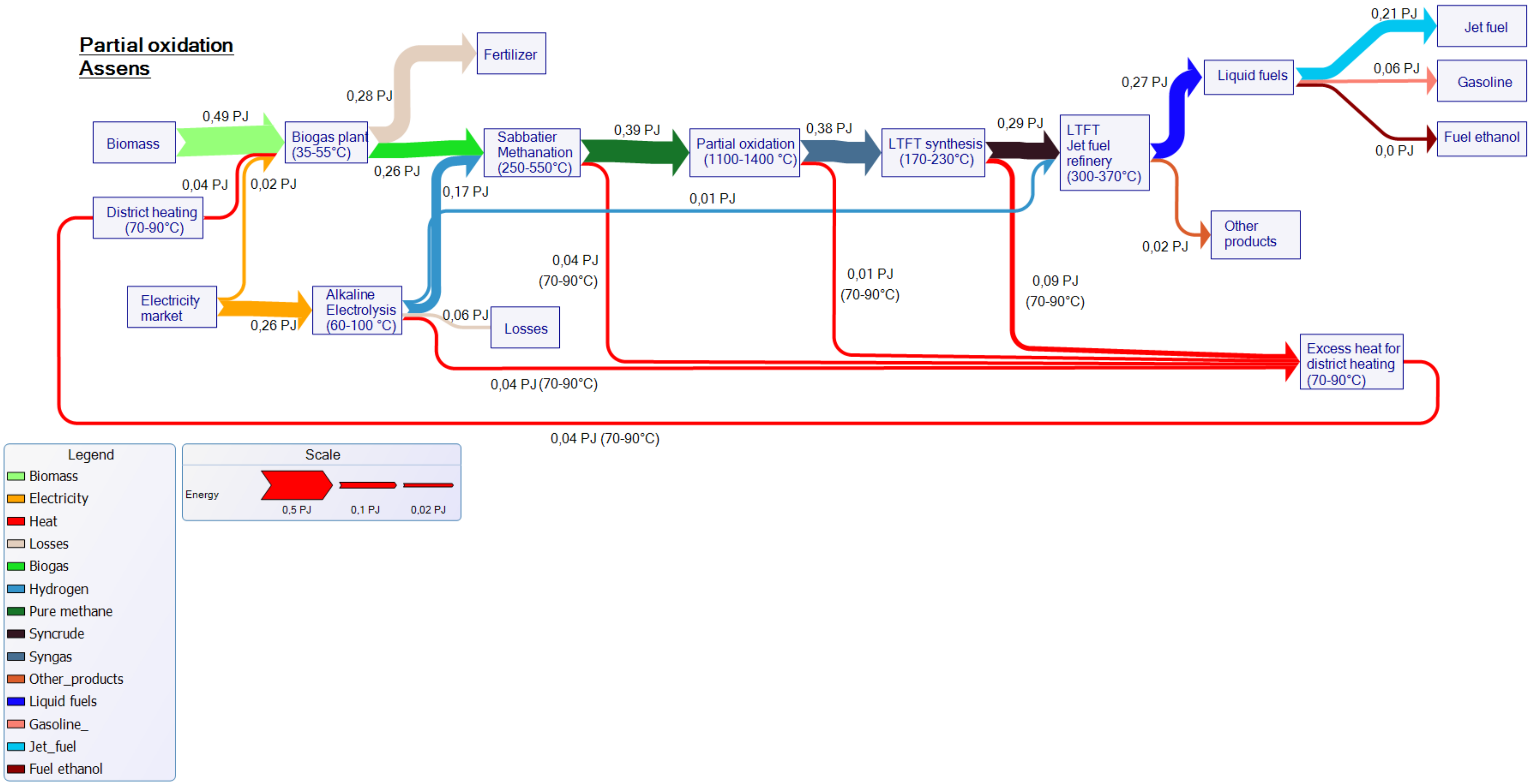


Partial oxidation
Otterup
Biomass
0,19 PJ
Biogas plant
(35-55°C)
0,11 PJ
Fertilizer
0,1 PJ
Sabbatier
Methanation
(250-550°C)
0,15 PJ
Partial oxidation
(1100-1400 °C)
0,15 PJ
LTFT synthesis
(170-230°C)
0,11 PJ
LTFT
Jet fuel
refinery
(300-370°C)
0,11 PJ
Liquid fuels
0,08 PJ
Jet fuel
0,02 PJ
Gasoline
0,0 PJ
Fuel ethanol
0,01 PJ
Other
products
0,02 PJ
0,01 PJ
District heating
(70-90°C)
0,07 PJ
0,0 PJ
Electricity
market
0,1 PJ
Alkaline
Electrolysis
(60-100 °C)
Losses
0,02 PJ
0,01 PJ
(70-90°C)
0,01 PJ
(70-90°C)
0,03 PJ
(70-90°C)
Excess heat for
district heating
(70-90°C)
0,01 PJ (70-90°C)
0,02 PJ (70-90°C)
Legend
Biomass
Electricity
Heat
Losses
Biogas
Hydrogen
Pure methane
Syncrude
Syngas
Other_products
Liquid fuels
Gasoline_
Jet_fuel
Fuel ethanol
Scale
Energy
0,2 PJ
0,04 PJ
0,01 PJ

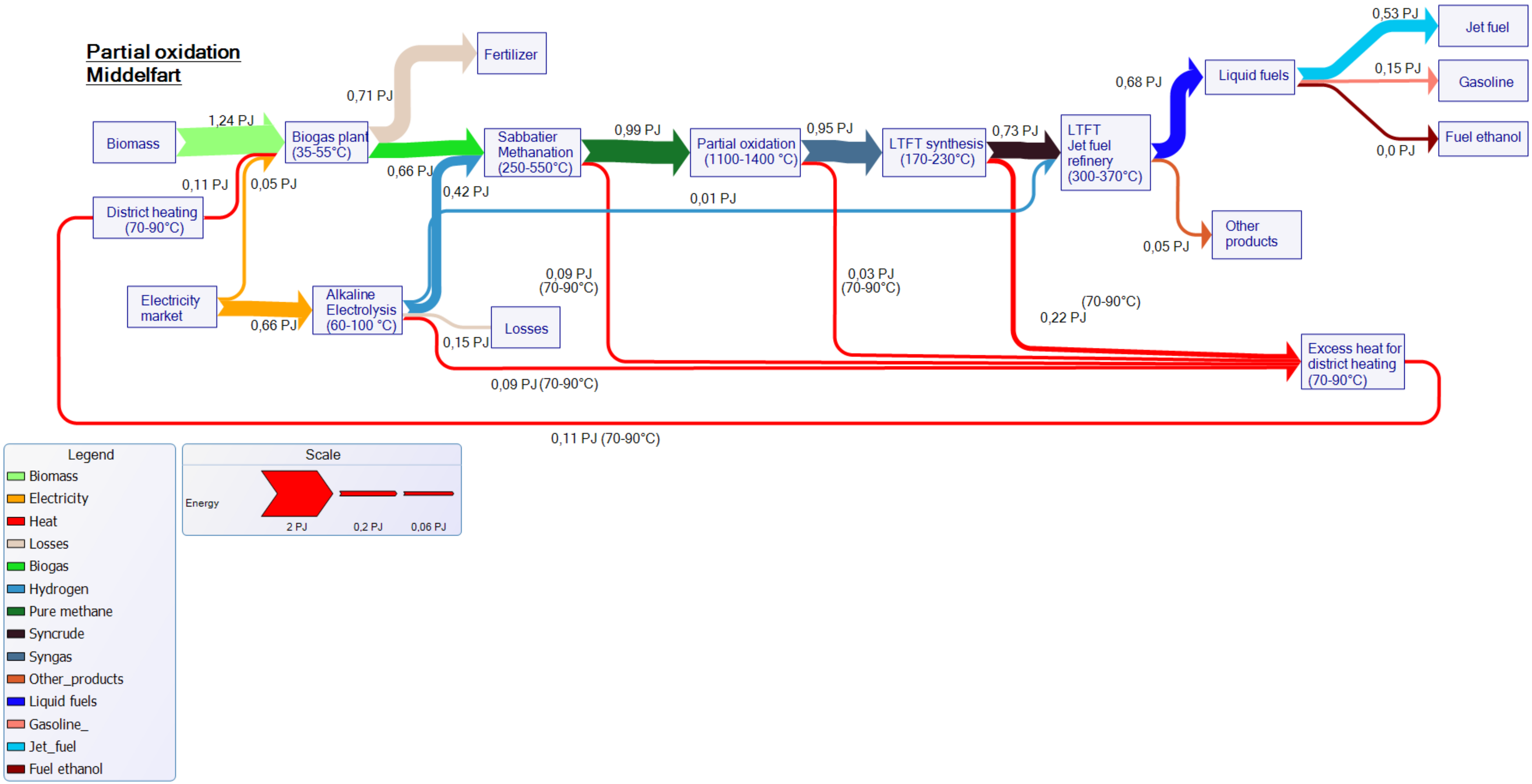


Partial oxidation
Kerteminde
Biomass
0,47 PJ
Biogas plant (35-55°C)
0,27 PJ
Fertilizer
0,25 PJ
Sabbatier Methanation (250-550°C)
0,38 PJ
Partial oxidation (1100-1400 °C)
0,36 PJ
LTFT synthesis (170-230°C)
0,28 PJ
LTFT Jet fuel refinery (300-370°C)
0,26 PJ
Liquid fuels
0,2 PJ
Jet fuel
0,06 PJ
Gasoline
0,0 PJ
Fuel ethanol
0,02 PJ
Other products
0,04 PJ
0,02 PJ
District heating (70-90°C)
Electricity market
0,25 PJ
Alkaline Electrolysis (60-100 °C)
0,16 PJ
0,01 PJ
Losses
0,06 PJ
0,04 PJ (70-90°C)
0,01 PJ (70-90°C)
0,08 PJ (70-90°C)
Excess heat for district heating (70-90°C)
0,04 PJ (70-90°C)
0,04 PJ (70-90°C)
Legend
Biomass
Electricity
Heat
Losses
Biogas
Hydrogen
Pure methane
Syncrude
Syngas
Other_products
Liquid fuels
Gasoline_
Jet_fuel
Fuel ethanol
Scale
Energy
0,5 PJ
0,09 PJ
0,02 PJ

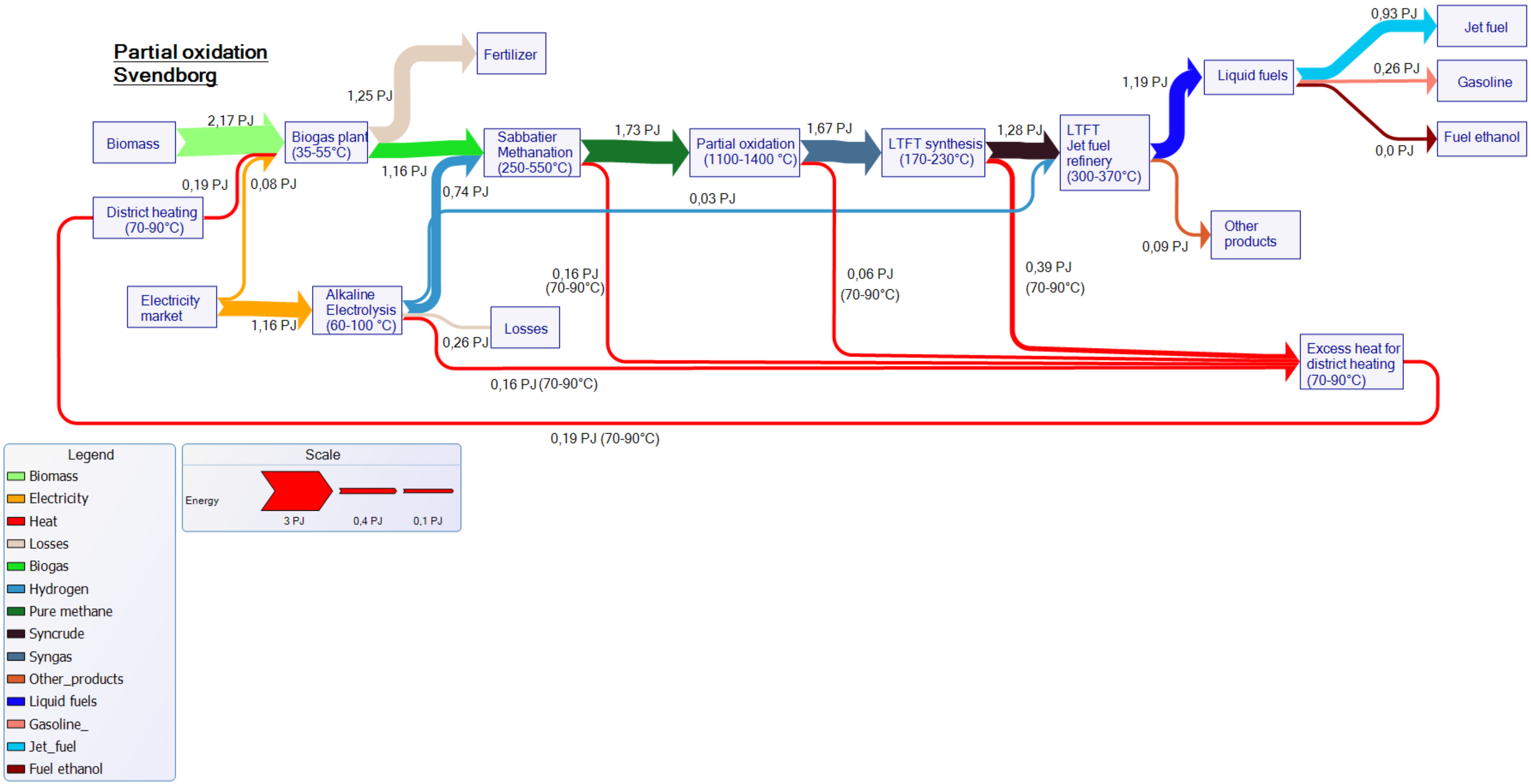

Partial oxidation
Ringe
Biomass
0,49 PJ
Biogas plant (35-55°C)
0,28 PJ
Fertilizer
0,26 PJ
Sabbatier Methanation (250-550°C)
0,39 PJ
Partial oxidation (1100-1400 °C)
0,37 PJ
LTFT synthesis (170-230°C)
0,29 PJ
LTFT Jet fuel refinery (300-370°C)
0,27 PJ
Liquid fuels
0,21 PJ
Jet fuel
0,06 PJ
Gasoline
0,0 PJ
Fuel ethanol
0,02 PJ
Other products
District heating (70-90°C)
0,04 PJ
0,02 PJ
Electricity market
0,26 PJ
Alkaline Electrolysis (60-100 °C)
0,17 PJ
0,01 PJ
Losses
0,06 PJ
0,04 PJ (70-90°C)
0,01 PJ (70-90°C)
(70-90°C) 0,09 PJ
Excess heat for district heating (70-90°C)
0,04 PJ (70-90°C)
0,04 PJ (70-90°C)
Legend
Biomass
Electricity
Heat
Losses
Biogas
Hydrogen
Pure methane
Syncrude
Syngas
Other_products
Liquid fuels
Gasoline_
Jet_fuel
Fuel ethanol
Scale
Energy
0,5 PJ
0,1 PJ
0,02 PJ

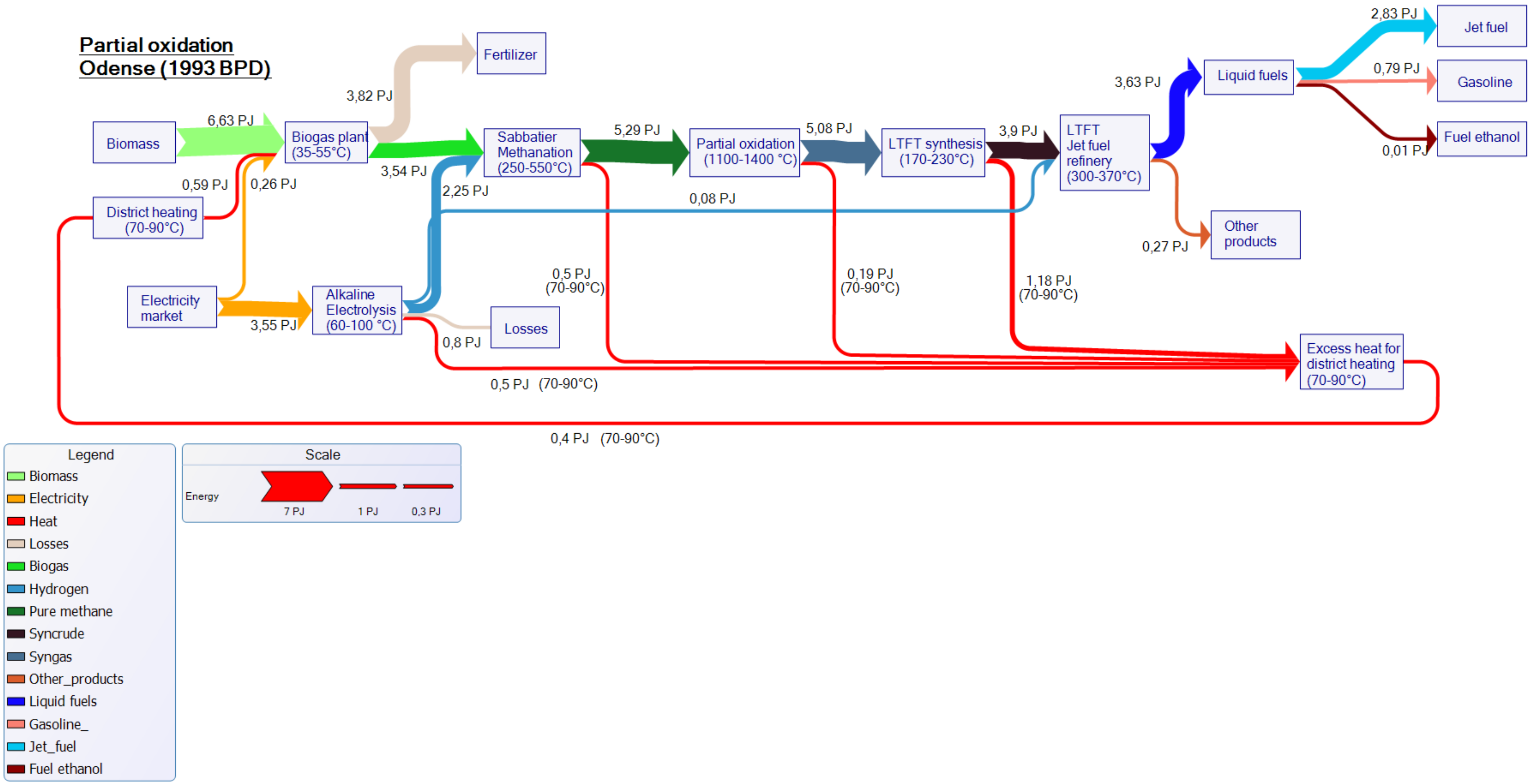


Partial oxidation
Assens
Biomass
0,49 PJ
Biogas plant
(35-55°C)
0,28 PJ
Fertilizer
0,26 PJ
Sabbatier
Methanation
(250-550°C)
0,39 PJ
Partial oxidation
(1100-1400 °C)
0,38 PJ
LTFT synthesis
(170-230°C)
0,29 PJ
LTFT
Jet fuel
refinery
(300-370°C)
0,27 PJ
Liquid fuels
0,21 PJ
Jet fuel
0,06 PJ
Gasoline
0,0 PJ
Fuel ethanol
0,02 PJ
Other
products
0,04 PJ
0,02 PJ
District heating
(70-90°C)
0,17 PJ
0,01 PJ
0,04 PJ
(70-90°C)
0,01 PJ
(70-90°C)
0,09 PJ
(70-90°C)
Electricity
market
0,26 PJ
Alkaline
Electrolysis
(60-100 °C)
0,06 PJ
Losses
Excess heat for
district heating
(70-90°C)
0,04 PJ (70-90°C)
0,04 PJ (70-90°C)
Legend
Biomass
Electricity
Heat
Losses
Biogas
Hydrogen
Pure methane
Syncrude
Syngas
Other_products
Liquid fuels
Gasoline_
Jet_fuel
Fuel ethanol
Scale
Energy
0,5 PJ
0,1 PJ
0,02 PJ



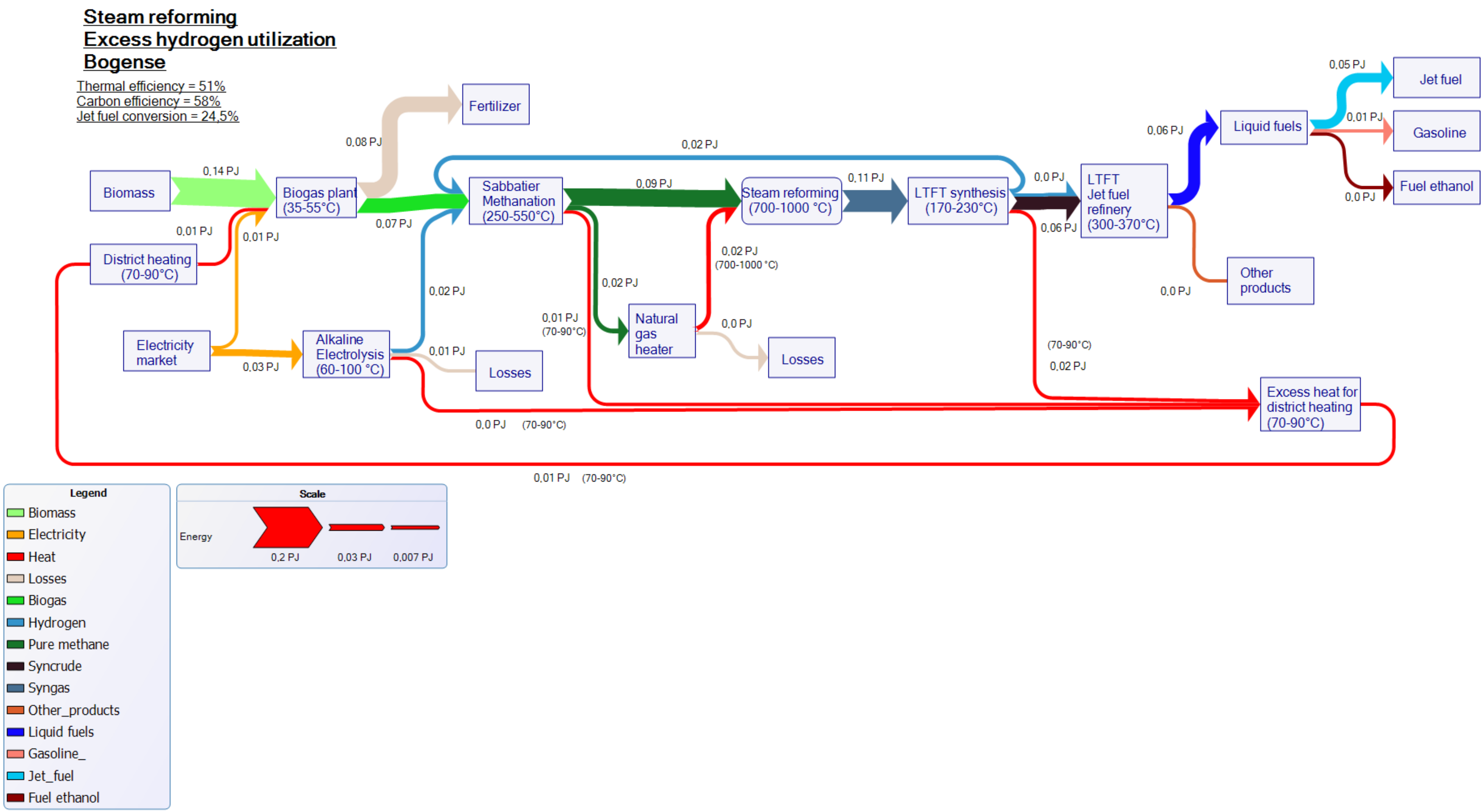
Partial oxidation Middelfart
Biomass
1,24 PJ
Biogas plant (35-55°C)
0,71 PJ
Fertilizer
0,66 PJ
Sabbatier Methanation (250-550°C)
0,99 PJ
Partial oxidation (1100-1400 °C)
0,95 PJ
LTFT synthesis (170-230°C)
0,73 PJ
LTFT Jet fuel refinery (300-370°C)
0,68 PJ
Liquid fuels
0,53 PJ
Jet fuel
0,15 PJ
Gasoline
0,0 PJ
Fuel ethanol
0,05 PJ
Other products
0,11 PJ
0,05 PJ
District heating (70-90°C)
Electricity market
0,66 PJ
Alkaline Electrolysis (60-100 °C)
0,42 PJ
0,01 PJ
0,15 PJ
Losses
0,09 PJ (70-90°C)
0,03 PJ (70-90°C)
0,22 PJ (70-90°C)
0,09 PJ (70-90°C)
Excess heat for district heating (70-90°C)
0,11 PJ (70-90°C)
Legend
Biomass
Electricity
Heat
Losses
Biogas
Hydrogen
Pure methane
Syncrude
Syngas
Other_products
Liquid fuels
Gasoline_
Jet_fuel
Fuel ethanol
Scale
Energy
2 PJ
0,2 PJ
0,06 PJ

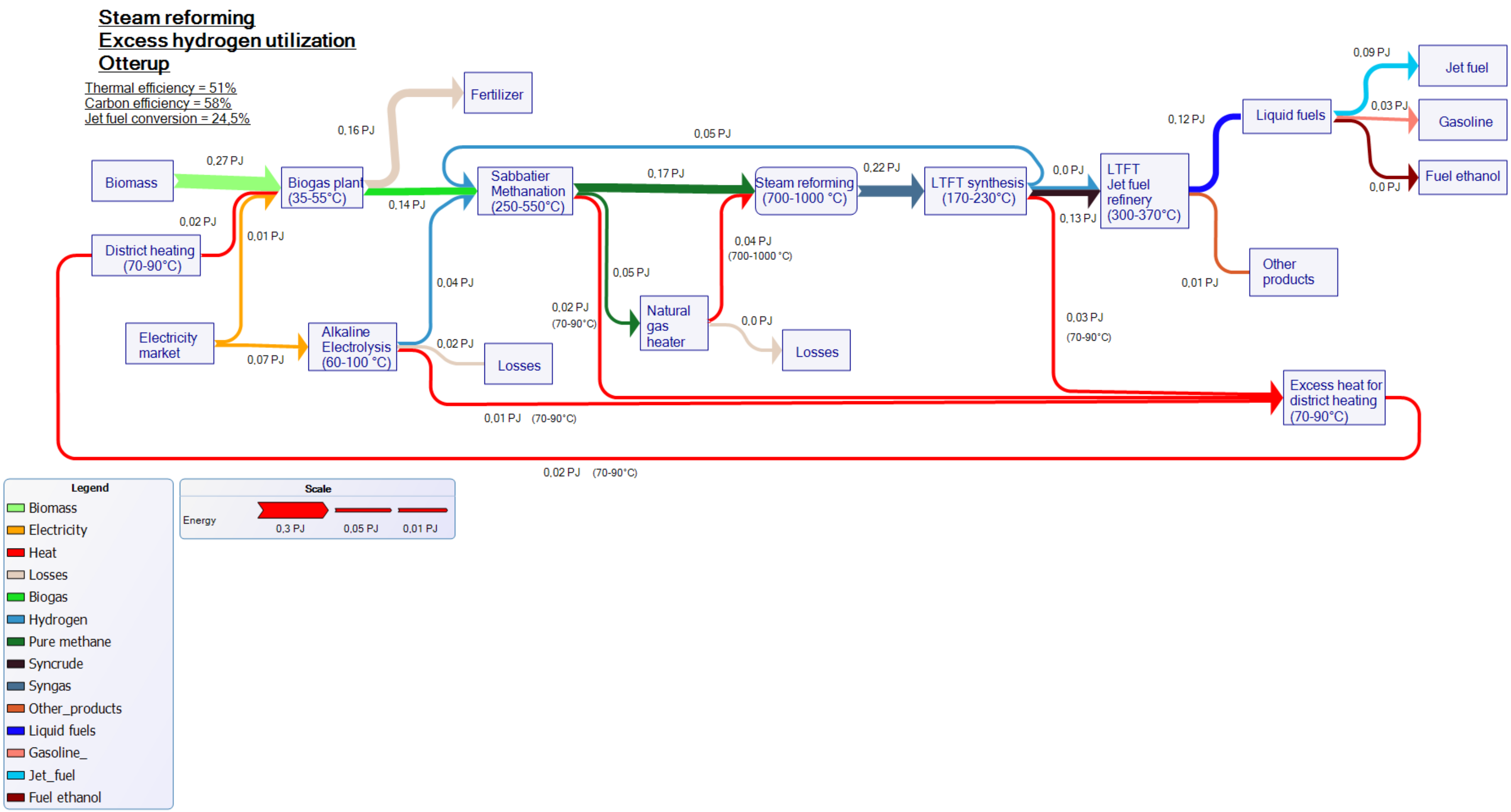

Partial oxidation
Svendborg
Biomass
2,17 PJ
Biogas plant (35-55°C)
1,25 PJ
Fertilizer
1,16 PJ
Sabbatier Methanation (250-550°C)
1,73 PJ
Partial oxidation (1100-1400 °C)
1,67 PJ
LTFT synthesis (170-230°C)
1,28 PJ
LTFT Jet fuel refinery (300-370°C)
1,19 PJ
Liquid fuels
0,93 PJ
Jet fuel
0,26 PJ
Gasoline
0,0 PJ
Fuel ethanol
0,09 PJ
Other products
0,19 PJ
0,08 PJ
District heating (70-90°C)
0,74 PJ
0,03 PJ
Electricity market
1,16 PJ
Alkaline Electrolysis (60-100 °C)
0,26 PJ
Losses
0,16 PJ (70-90°C)
0,06 PJ (70-90°C)
0,39 PJ (70-90°C)
Excess heat for district heating (70-90°C)
0,16 PJ (70-90°C)
0,19 PJ (70-90°C)
Legend
Biomass
Electricity
Heat
Losses
Biogas
Hydrogen
Pure methane
Syncrude
Syngas
Other_products
Liquid fuels
Gasoline_
Jet_fuel
Fuel ethanol
Scale
Energy
3 PJ
0,4 PJ
0,1 PJ



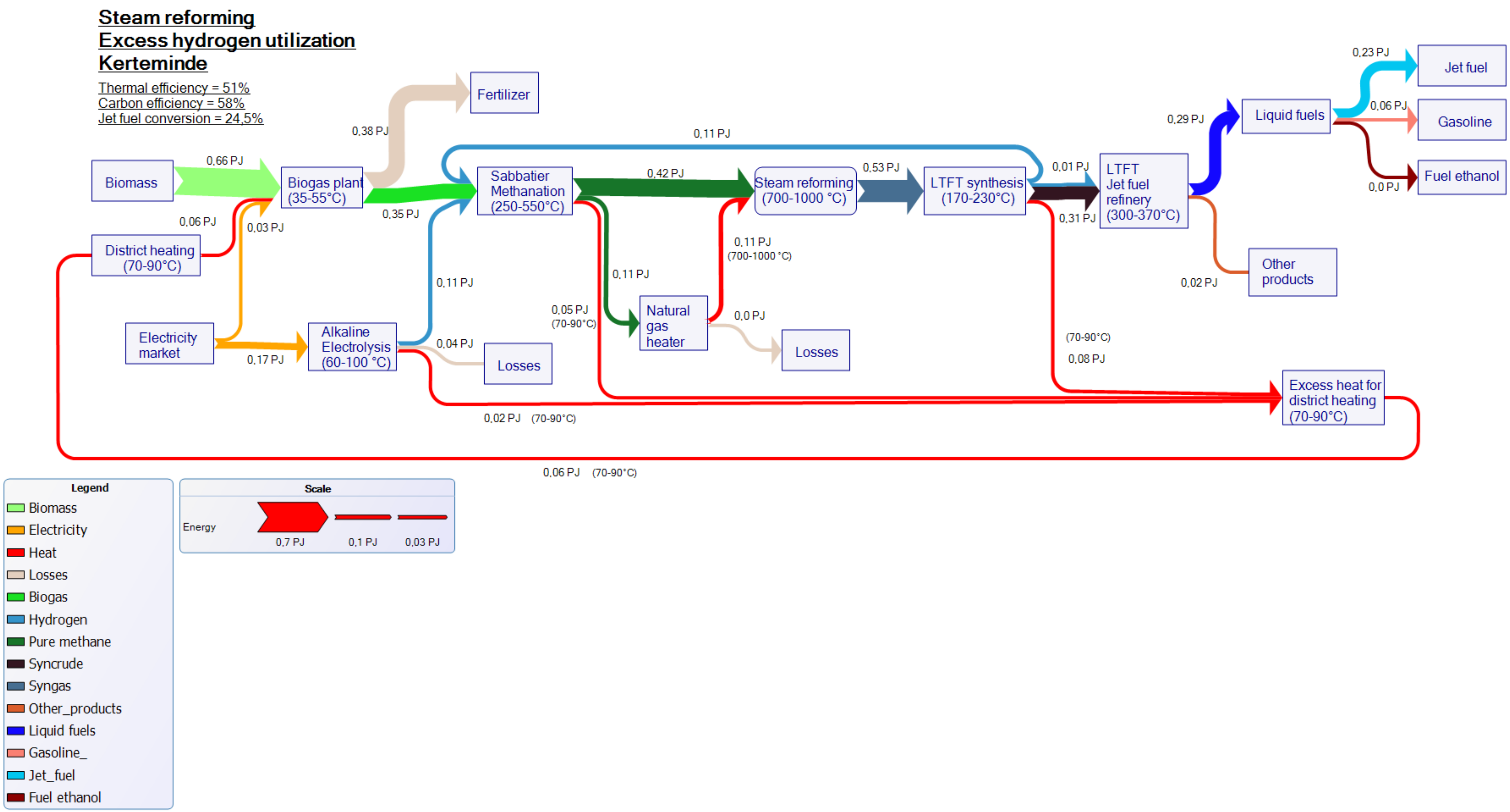
Partial oxidation
Odense (1993 BPD)
Biomass
6,63 PJ
Biogas plant (35-55°C)
3,82 PJ
Fertilizer
3,54 PJ
Sabbatier Methanation (250-550°C)
5,29 PJ
Partial oxidation (1100-1400 °C)
5,08 PJ
LTFT synthesis (170-230°C)
3,9 PJ
LTFT Jet fuel refinery (300-370°C)
3,63 PJ
Liquid fuels
2,83 PJ
Jet fuel
0,79 PJ
Gasoline
0,01 PJ
Fuel ethanol
0,27 PJ
Other products
0,59 PJ
0,26 PJ
District heating (70-90°C)
Electricity market
3,55 PJ
Alkaline Electrolysis (60-100 °C)
2,25 PJ
0,08 PJ
0,8 PJ
Losses
0,5 PJ (70-90°C)
0,19 PJ (70-90°C)
1,18 PJ (70-90°C)
Excess heat for district heating (70-90°C)
0,5 PJ (70-90°C)
0,4 PJ (70-90°C)
Legend
Biomass
Electricity
Heat
Losses
Biogas
Hydrogen
Pure methane
Syncrude
Syngas
Other_products
Liquid fuels
Gasoline_
Jet_fuel
Fuel ethanol
Scale
Energy
7 PJ
1 PJ
0,3 PJ

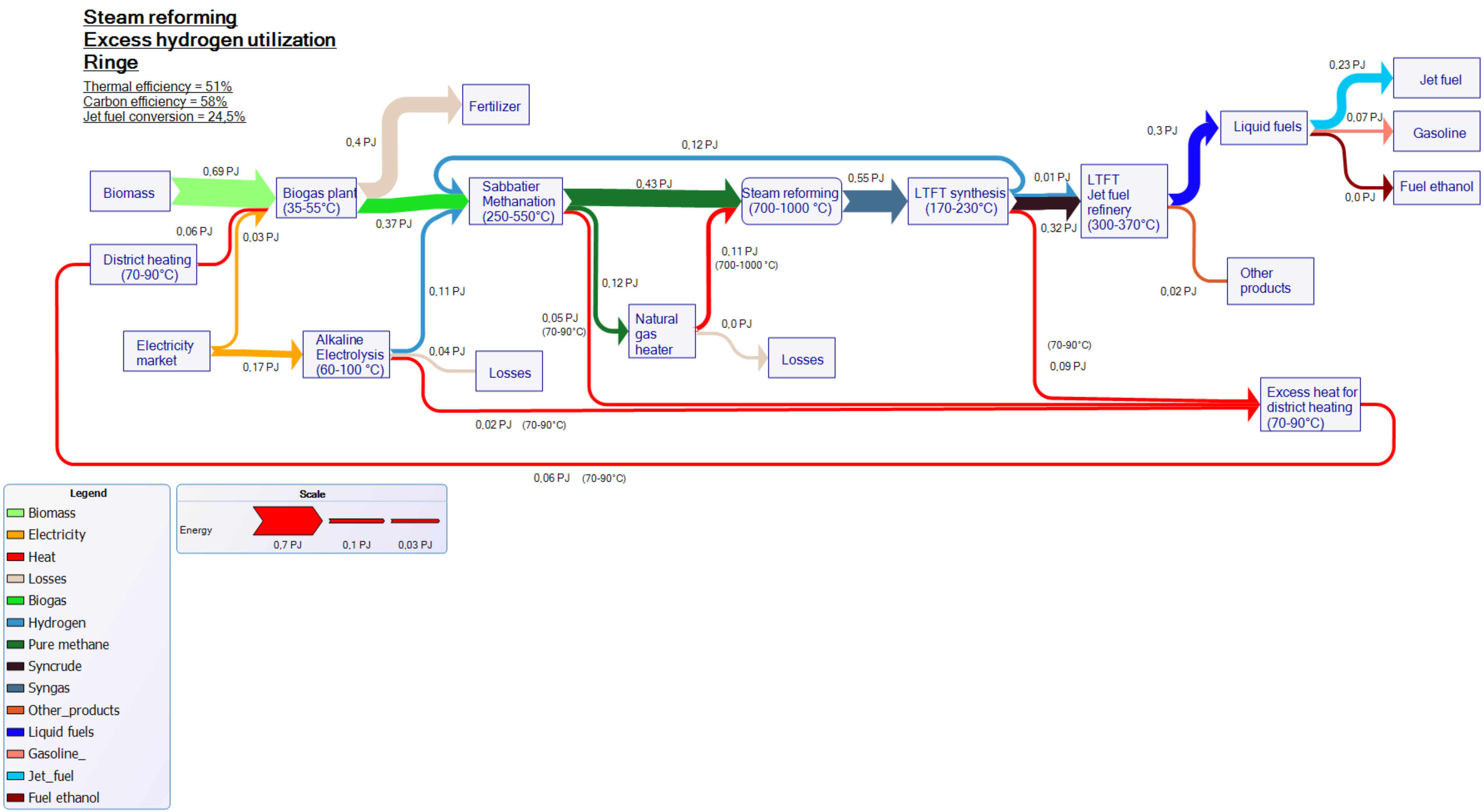
I.2 SMR pathway

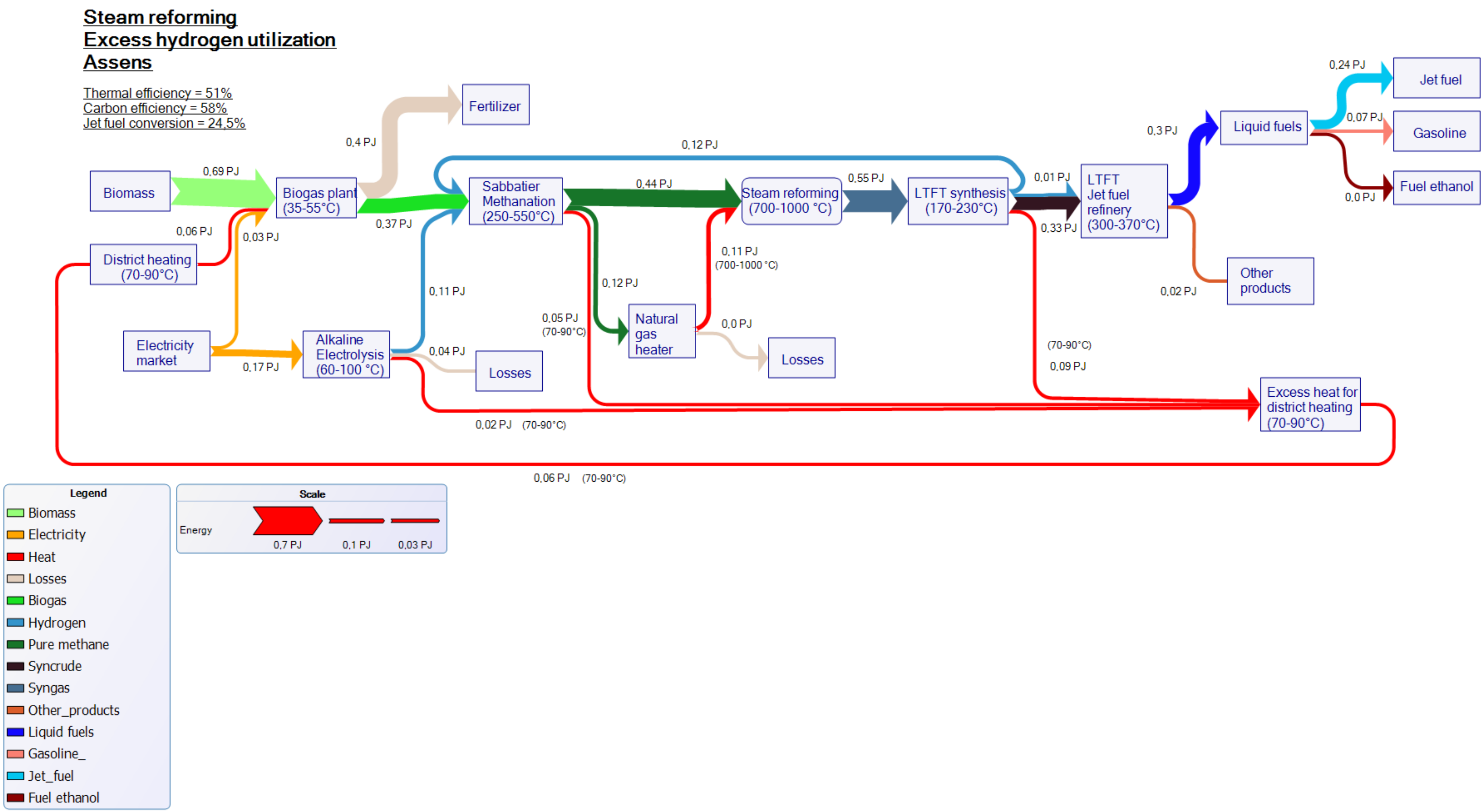


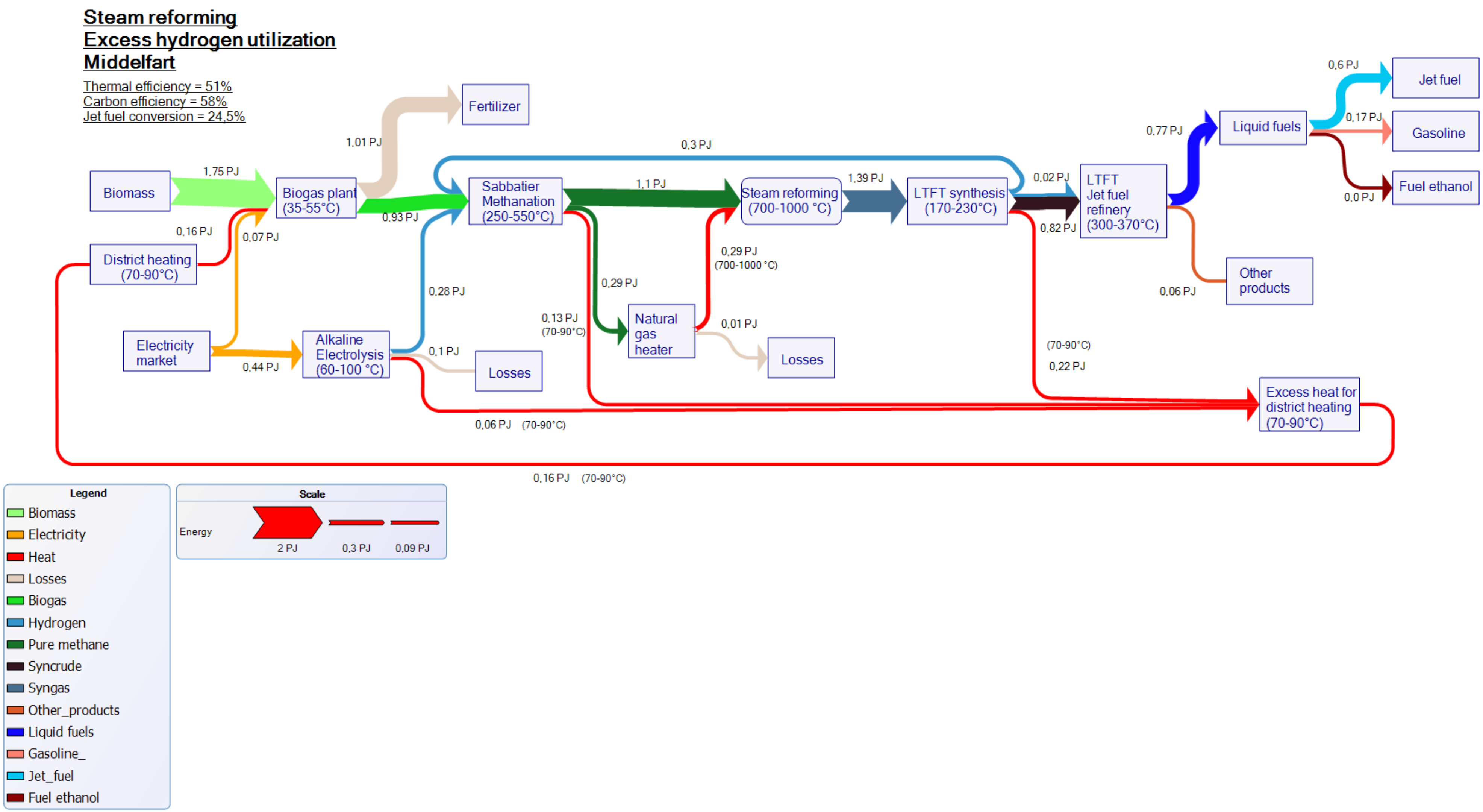


Steam reforming
Excess hydrogen utilization
Otterup
Thermal efficiency = 51%
Carbon efficiency = 58%
Jet fuel conversion = 24,5%
Biomass
0,27 PJ
Biogas plant (35-55°C)
0,16 PJ
Fertilizer
0,14 PJ
0,02 PJ
0,01 PJ
District heating (70-90°C)
Electricity market
0,07 PJ
Alkaline Electrolysis (60-100 °C)
0,04 PJ
0,02 PJ
Losses
Sabbatier Methanation (250-550°C)
0,05 PJ
0,17 PJ
Steam reforming (700-1000 °C)
0,22 PJ
LTFT synthesis (170-230°C)
0,0 PJ
LTFT Jet fuel refinery (300-370°C)
0,13 PJ
0,12 PJ
Liquid fuels
0,09 PJ
Jet fuel
0,03 PJ
Gasoline
0,0 PJ
Fuel ethanol
0,01 PJ
Other products
0,02 PJ (70-90°C)
0,05 PJ
Natural gas heater
0,04 PJ (700-1000 °C)
0,0 PJ
Losses
0,03 PJ (70-90°C)
Excess heat for district heating (70-90°C)
0,01 PJ (70-90°C)
0,02 PJ (70-90°C)
Legend
Biomass
Electricity
Heat
Losses
Biogas
Hydrogen
Pure methane
Syncrude
Syngas
Other_products
Liquid fuels
Gasoline_
Jet_fuel
Fuel ethanol
Scale
Energy
0,3 PJ
0,05 PJ
0,01 PJ


Steam reforming
Excess hydrogen utilization
Kerteminde
Thermal efficiency = 51%
Carbon efficiency = 58%
Jet fuel conversion = 24,5%
Biomass
0,66 PJ
Biogas plant (35-55°C)
0,38 PJ
Fertilizer
0,35 PJ
Sabbatier Methanation (250-550°C)
0,11 PJ
0,42 PJ
Steam reforming (700-1000 °C)
0,53 PJ
LTFT synthesis (170-230°C)
0,01 PJ
0,31 PJ
LTFT Jet fuel refinery (300-370°C)
0,29 PJ
Liquid fuels
0,23 PJ
Jet fuel
0,06 PJ
Gasoline
0,0 PJ
Fuel ethanol
0,02 PJ
Other products
District heating (70-90°C)
0,06 PJ
0,03 PJ
Electricity market
0,17 PJ
Alkaline Electrolysis (60-100 °C)
0,11 PJ
0,04 PJ
Losses
0,05 PJ (70-90°C)
0,11 PJ
Natural gas heater
0,11 PJ (700-1000 °C)
0,0 PJ
Losses
(70-90°C)
0,08 PJ
Excess heat for district heating (70-90°C)
0,02 PJ (70-90°C)
0,06 PJ (70-90°C)
Legend
Biomass
Electricity
Heat
Losses
Biogas
Hydrogen
Pure methane
Syncrude
Syngas
Other_products
Liquid fuels
Gasoline_
Jet_fuel
Fuel ethanol
Scale
Energy
0,7 PJ
0,1 PJ
0,03 PJ

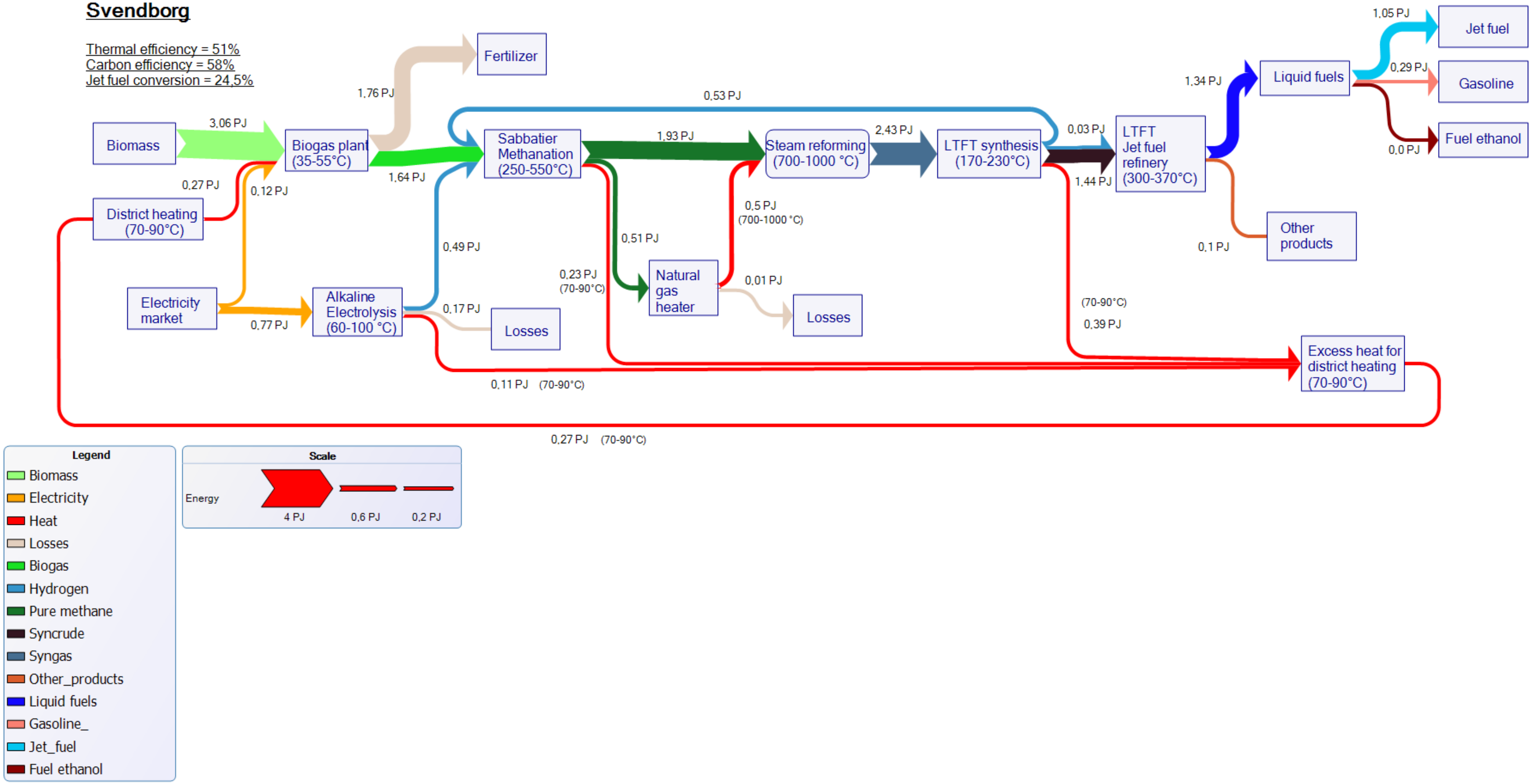

Steam reforming
Excess hydrogen utilization
Ringe
Thermal efficiency = 51%
Carbon efficiency = 58%
Jet fuel conversion = 24,5%
Biomass
0,69 PJ
Biogas plant (35-55°C)
0,4 PJ
Fertilizer
0,37 PJ
Sabbatier Methanation (250-550°C)
0,12 PJ
0,43 PJ
Steam reforming (700-1000 °C)
0,55 PJ
LTFT synthesis (170-230°C)
0,01 PJ
0,32 PJ
LTFT Jet fuel refinery (300-370°C)
0,3 PJ
Liquid fuels
0,23 PJ
Jet fuel
0,07 PJ
Gasoline
0,0 PJ
Fuel ethanol
0,02 PJ
Other products
0,06 PJ
District heating (70-90°C)
0,03 PJ
Electricity market
0,17 PJ
Alkaline Electrolysis (60-100 °C)
0,11 PJ
0,04 PJ
Losses
0,05 PJ (70-90°C)
0,12 PJ
Natural gas heater
0,11 PJ (700-1000 °C)
0,0 PJ
Losses
(70-90°C)
0,09 PJ
Excess heat for district heating (70-90°C)
0,02 PJ (70-90°C)
0,06 PJ (70-90°C)
Legend
Biomass
Electricity
Heat
Losses
Biogas
Hydrogen
Pure methane
Syncrude
Syngas
Other_products
Liquid fuels
Gasoline_
Jet_fuel
Fuel ethanol
Scale
Energy
0,7 PJ
0,1 PJ
0,03 PJ


Steam reforming
Excess hydrogen utilization
Assens
Thermal efficiency = 51%
Carbon efficiency = 58%
Jet fuel conversion = 24,5%
Biomass
0,69 PJ
Biogas plant (35-55°C)
0,4 PJ
Fertilizer
0,37 PJ
Sabbatier Methanation (250-550°C)
0,12 PJ
0,44 PJ
Steam reforming (700-1000 °C)
0,55 PJ
LTFT synthesis (170-230°C)
0,01 PJ
0,33 PJ
LTFT Jet fuel refinery (300-370°C)
0,3 PJ
Liquid fuels
0,24 PJ
Jet fuel
0,07 PJ
Gasoline
0,0 PJ
Fuel ethanol
0,02 PJ
Other products
0,06 PJ
District heating (70-90°C)
0,03 PJ
Electricity market
0,17 PJ
Alkaline Electrolysis (60-100 °C)
0,11 PJ
0,04 PJ
Losses
0,05 PJ (70-90°C)
0,12 PJ
Natural gas heater
0,11 PJ (700-1000 °C)
0,0 PJ
Losses
(70-90°C) 0,09 PJ
Excess heat for district heating (70-90°C)
0,02 PJ (70-90°C)
0,06 PJ (70-90°C)
Legend
Biomass
Electricity
Heat
Losses
Biogas
Hydrogen
Pure methane
Syncrude
Syngas
Other_products
Liquid fuels
Gasoline_
Jet_fuel
Fuel ethanol
Scale
Energy
0,7 PJ
0,1 PJ
0,03 PJ


Steam reforming
Excess hydrogen utilization
Middelfart
Thermal efficiency = 51%
Carbon efficiency = 58%
Jet fuel conversion = 24,5%
Biomass
1,75 PJ
Biogas plant (35-55°C)
1,01 PJ
Fertilizer
0,93 PJ
Sabbatier Methanation (250-550°C)
0,3 PJ
1,1 PJ
Steam reforming (700-1000 °C)
1,39 PJ
LTFT synthesis (170-230°C)
0,02 PJ
0,82 PJ
LTFT Jet fuel refinery (300-370°C)
0,77 PJ
Liquid fuels
0,6 PJ
Jet fuel
0,17 PJ
Gasoline
0,0 PJ
Fuel ethanol
0,06 PJ
Other products
District heating (70-90°C)
0,16 PJ
0,07 PJ
Electricity market
0,44 PJ
Alkaline Electrolysis (60-100 °C)
0,28 PJ
0,1 PJ
Losses
0,13 PJ
(70-90°C)
0,29 PJ
Natural gas heater
0,29 PJ
(700-1000 °C)
0,01 PJ
Losses
(70-90°C)
0,22 PJ
Excess heat for district heating (70-90°C)
0,06 PJ (70-90°C)
0,16 PJ (70-90°C)
Legend
Biomass
Electricity
Heat
Losses
Biogas
Hydrogen
Pure methane
Syncrude
Syngas
Other_products
Liquid fuels
Gasoline_
Jet_fuel
Fuel ethanol
Scale
Energy
2 PJ
0,3 PJ
0,09 PJ

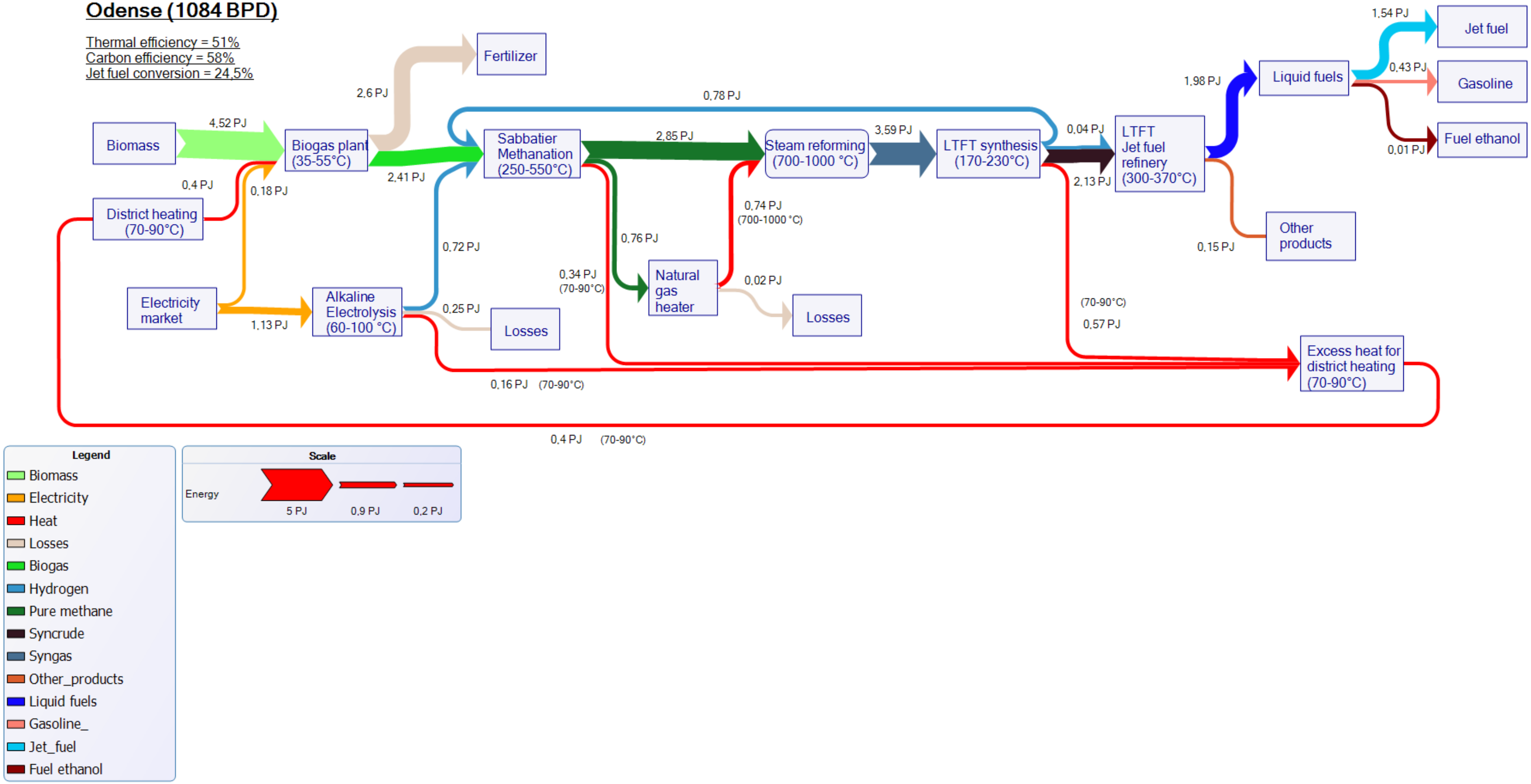
Steam reforming
Excess hydrogen utilization
Svendborg

Thermal efficiency = 51%
Carbon efficiency = 58%
Jet fuel conversion = 24,5%



Steam reforming
Excess hydrogen utilization
Odense (1084 BPD)

Thermal efficiency = 51%
Carbon efficiency = 58%
Jet fuel conversion = 24,5%



Appendix J – Gasoline selling price.

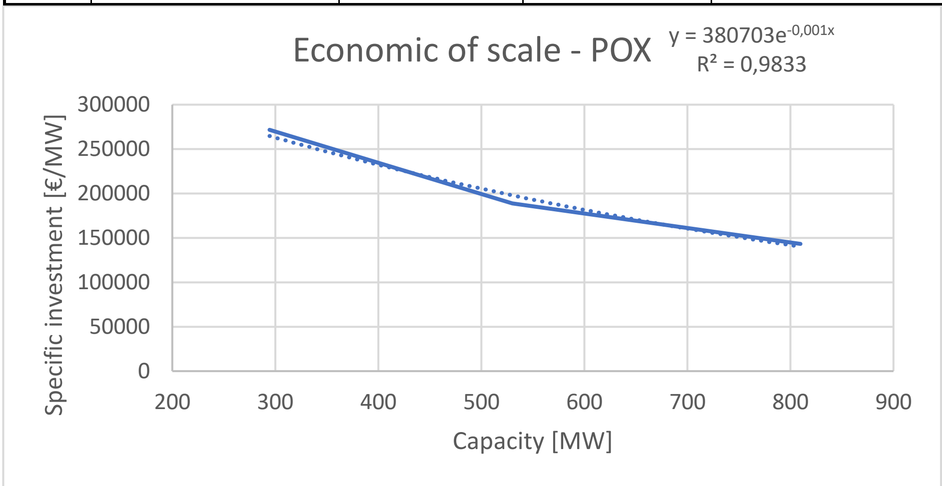
	With taxes				Without taxes			
LHV [MJ/l] [27]	Euro/liter [54]		Euro/GJ		Euro/liter		Euro/GJ	
32	Low	High	Low	High	Low	High	Low	High
-	1,15	1,5	35,94	46,88	0,4255	0,56	13,3	17,34

Gasoline breakdown [77]	
Energy agreements	40%
CO2-tax	3%
Moms	20%
Gasoline	37%

Appendix K – Economic of scale for syngas facilities

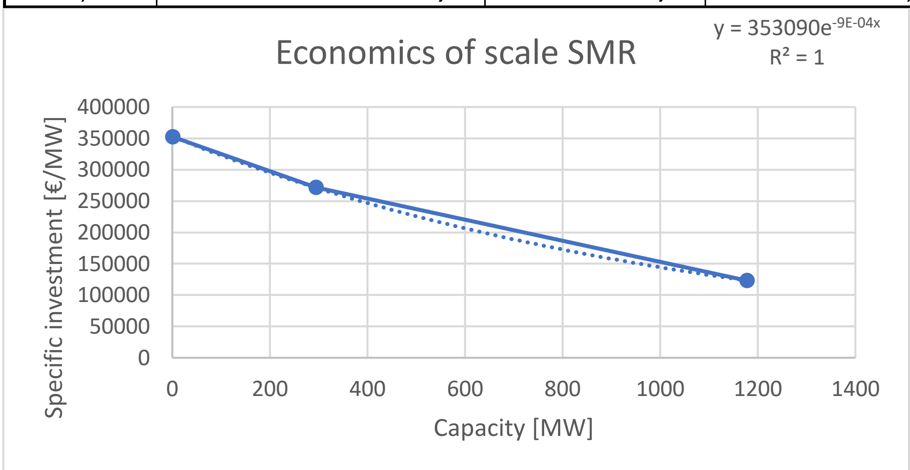
K.1 POX

POX syngas output = CO+3H2				HHV=12,71 MJ/nm^3 [78]		
POX	MM NM/day	Capacity (MW)	Investment [Million]	Investment/Nm3/day	Investment/MWh	References
	5,5	809,7	116	21,09	143259,0051	[79]
	3,6	530,0	100	27,78	188679,2453	[39]
	2	294,4	80	40,00	271698,1132	[79]



K.2 SMR

SMR syngas output = CO+3H2		HHV=12,72 MJ/nm^3 [78]			
NM/day	Capacity [MW]	Investment [M €]	Investment [€/Nm3/day]	Investment [€/MWh]	References
8	1177,78	**145,00**	18,13	123113,21	[79]
2	294,44	**80,00**	40,00	271698,11	[79]
0,0055	**0,81**	**0,29**	51,82	**352492,03**	[80]



Appendix L – Electricity prices for sensitivity analysis

Source: [60]

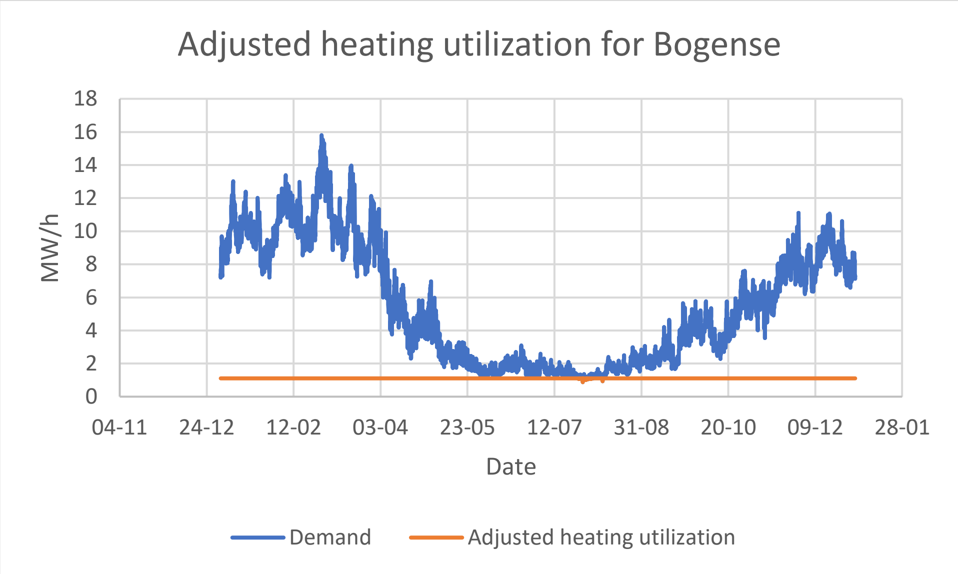
	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Reference [€/MWh]	45,36	45,80	46,54	47,67	49,20	49,86	50,53	51,66	51,33	51,66	52,08
Black [€/MWh]	42,21	43,84	45,47	47,10	48,73	50,36	51,16	51,95	52,75	53,55	54,34
Blue [€/MWh]	50,36	50,83	51,30	51,77	52,24	52,71	52,82	52,93	53,04	53,15	53,26
Green [€/MWh]	59,96	59,89	59,81	59,74	59,67	59,60	58,98	58,36	57,75	57,13	56,52

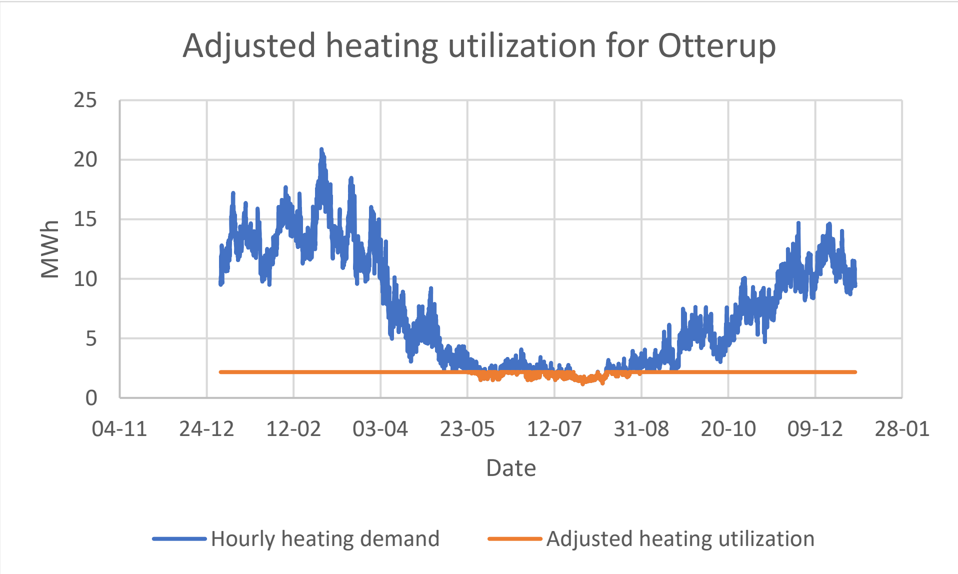
	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Reference [€/MWh]	53,23	53,70	54,94	55,36	56,24	57,10	57,94	58,82	59,72	60,55
Black [€/MWh]	54,56	54,78	55,00	55,21	55,43	55,65	55,86	56,08	56,30	56,52
Blue [€/MWh]	53,95	54,63	55,32	56,01	56,70	57,39	58,07	58,76	59,45	60,14
Green [€/MWh]	57,10	57,68	58,26	58,84	59,42	60,00	60,57	61,15	61,73	62,31

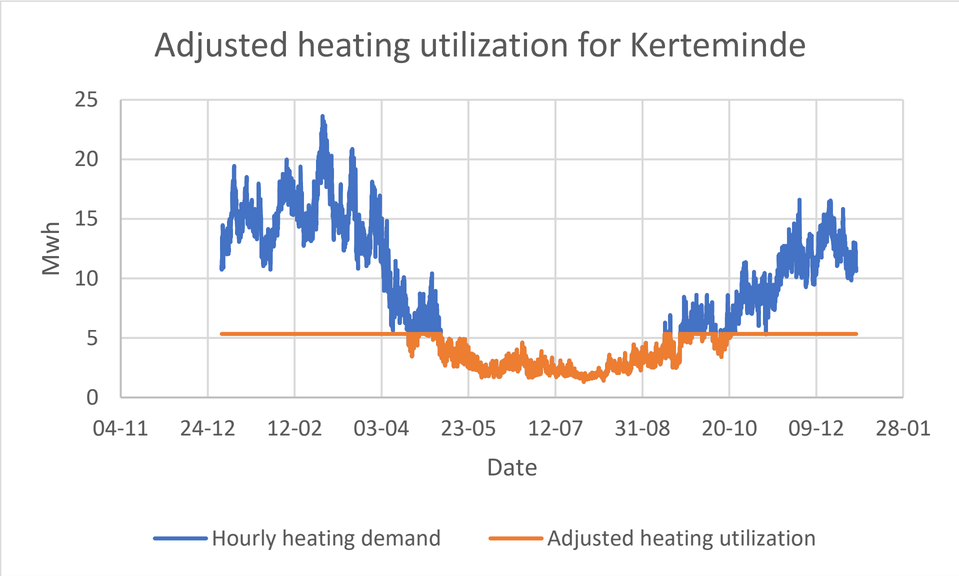
	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Reference [€/MWh]	61,01	61,78	62,55	63,33	64,11	64,90	65,69	66,48	67,28	68,08
Black [€/MWh]	56,73	56,95	57,17	57,38	57,60	57,82	58,04	58,25	58,47	58,69
Blue [€/MWh]	60,83	61,52	62,20	62,89	63,58	64,27	64,96	65,65	66,33	67,02
Green [€/MWh]	62,89	63,47	64,05	64,63	65,21	65,79	66,37	66,95	67,53	68,11

Appendix M – Adjusted heating utilization

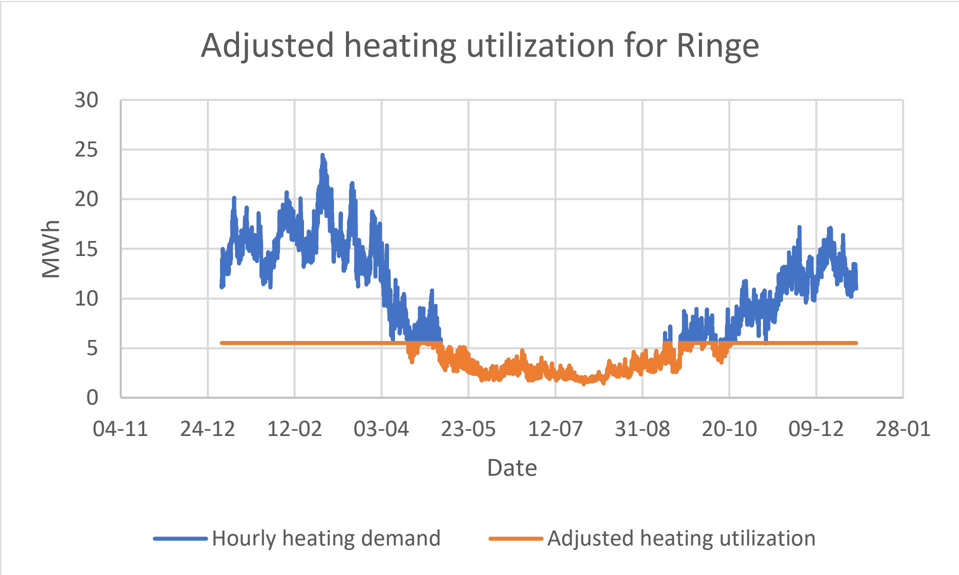
M.1 For decentralized scenario



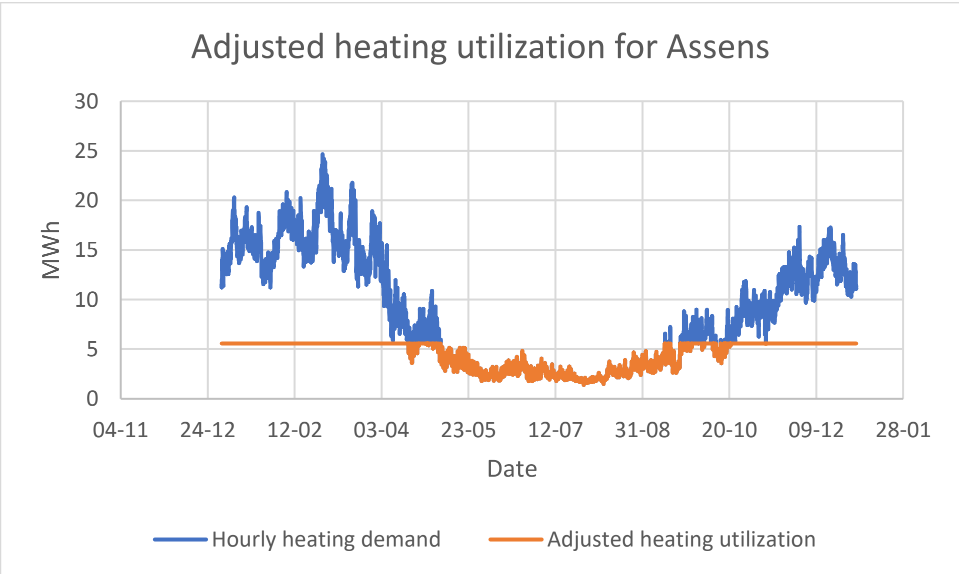




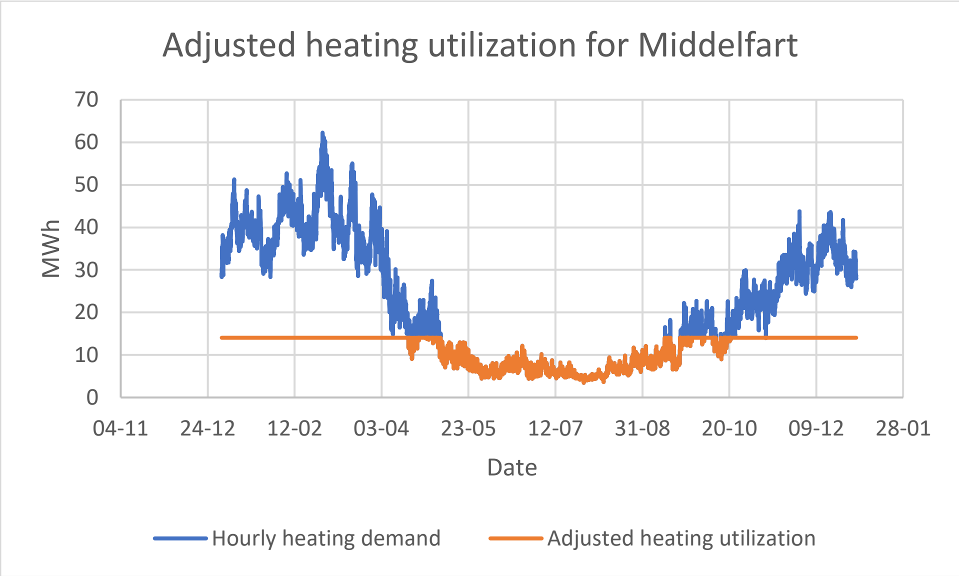
Adjusted heating utilization for Kerteminde
25
20
15
10
5
0
Mwh
04-11
24-12
12-02
03-04
23-05
12-07
31-08
20-10
09-12
28-01
Date
Hourly heating demand
Adjusted heating utilization



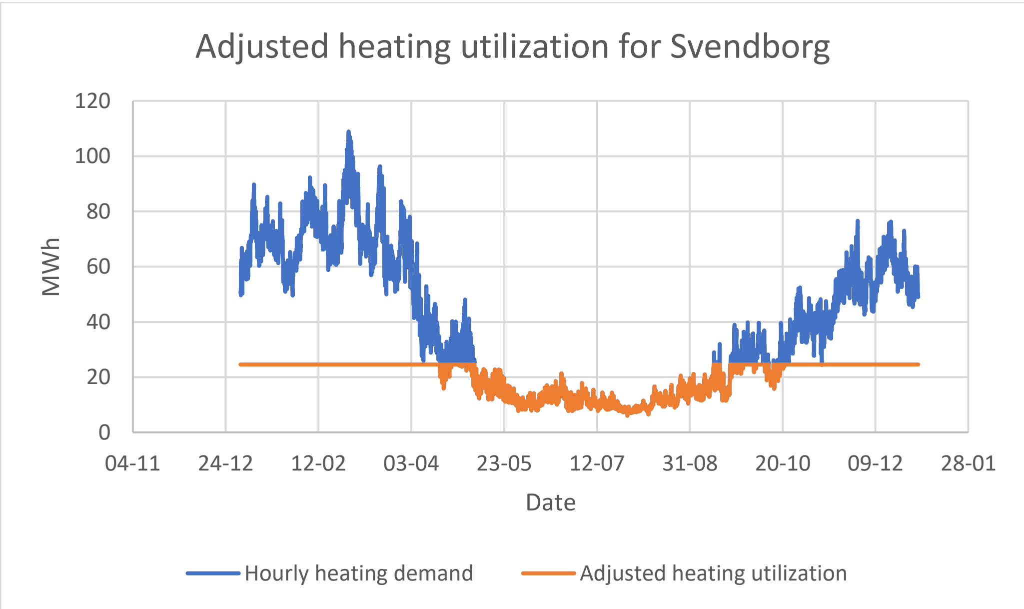
Adjusted heating utilization for Ringe
30
25
20
15
10
5
0
MWh
04-11
24-12
12-02
03-04
23-05
12-07
31-08
20-10
09-12
28-01
Date
Hourly heating demand
Adjusted heating utilization



Adjusted heating utilization for Assens
30
25
20
15
10
5
0
MWh
04-11
24-12
12-02
03-04
23-05
12-07
31-08
20-10
09-12
28-01
Date
Hourly heating demand
Adjusted heating utilization

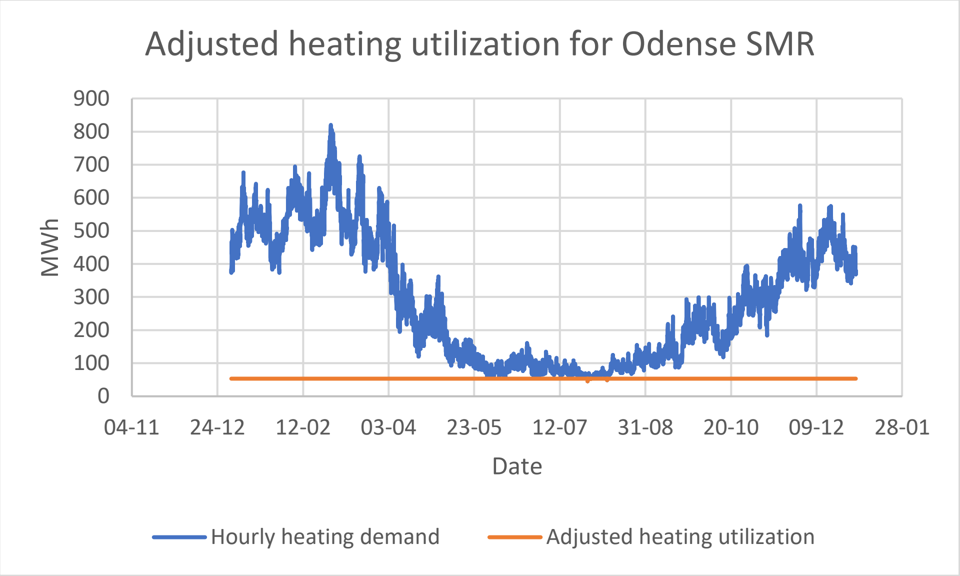


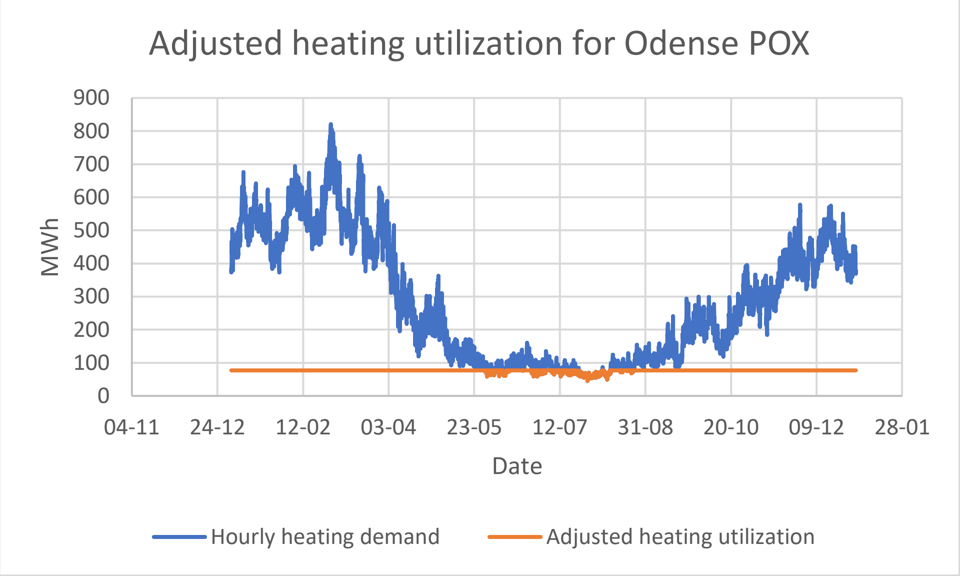
Adjusted heating utilization for Middelfart
MWh
0
10
20
30
40
50
60
70
04-11
24-12
12-02
03-04
23-05
12-07
31-08
20-10
09-12
28-01
Date
Hourly heating demand
Adjusted heating utilization



Adjusted heating utilization for Svendborg
MWh
0
20
40
60
80
100
120
04-11
24-12
12-02
03-04
23-05
12-07
31-08
20-10
09-12
28-01
Date
Hourly heating demand
Adjusted heating utilization

M.2 Centralized scenario





Appendix N – M/R stations design capacity in energy equivalents

Source: [63]

	Pressure	Pipe size	Natural gas HHV [MJ/Nm3]
Data for M/R stations on Funen	80 bars	30"	40,6

	Design capacity [Nm3/h]	MJ/h	MW/h
Middelfart	18.500	751100	208,64
Billesbølle	18.500	751100	208,64
Koelbjerg	35.000	1421000	394,72
Højby	125.000	5075000	1409,72
Ullerslev	18.500	751100	208,64
Nyborg	18.500	751100	208,64

Appendix O – Calculations of risk matrix scores.

O.1 Centralized scenario

The risk score for each is calculated by multiplying the score by the likelihood score.

$$Risk\ score = Impact\ score * Likelyhood\ score$$
$$Placement = 4 * 1 = 4$$
$$Production\ change = 3 * 5 = 15$$
$$Security\ of\ supply = 5 * 2 = 10$$

The total risk matric score is obtained by adding the individual risks' scores

$$Total\ score = 4 + 15 + 10 = 29$$

The total risk score for the centralized scenario is 29.

O.2 Decentralized scenario

The risk score for each is calculated by multiplying the score by the likelihood score.

$$Risk\ score = Impact\ score * Likelyhood\ score$$
$$Placement = 3 * 3 = 9$$
$$Production\ change = 3 * 5 = 15$$
$$Security\ of\ supply = 2 * 2 = 4$$

The total risk matric score is obtained by adding the individual risks' scores

$$Total\ score = 4 + 15 + 10 = 28$$

The total risk score for the decentralized scenario is 28.