APPENDIX TO SYSTEMPERSPECTIVE 2035

MODELLING OF ENERGY PLANTS

Dok. 17/01970-19

Indhold

1. Introduction

This document describes modeling of a combined energy plant in 2030/2035.. This type of energy plant is a part of Energinet's "System Perspective 2035" analysis. In this analysis two integrated "Energy Plants" is analysed.

Centralized energy plant (type 3) and Decentralized energy plant (type 2) as shown below.

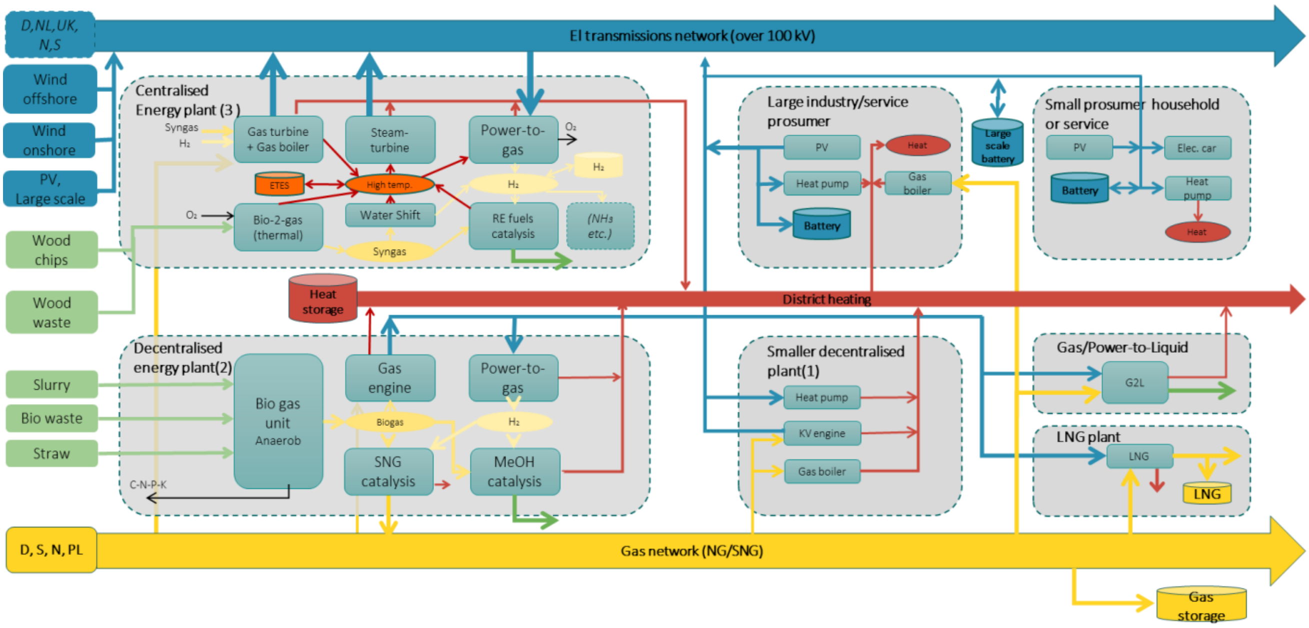

Figure 1: Integration of power, gas and heat. In this appendix the type 3 plant (upper left) is documented in more details.

The energy plant is seen as a potential rebuilding/replacement of a central power plant. One of the constraining parameters for the plant is therefore to supply district heating to the city where the power plant is located.

The combined energy plant produces: District heating/process heat, methanol for transportation use and potential peak electricity. Furthermore the energy plant should be able to fit into an electricity market with large amount of wind energy.

The energy plant will be modeled in Energinet's modeling tool, Sifre. This enable hour to hour operational optimization based on forecasted hour-to-hour electricity prices.

Sifre's ADAPT module for investment optimization is used in second step to optimize the sizes of the individual process units based on one year of operation.

Energy plant type III model:

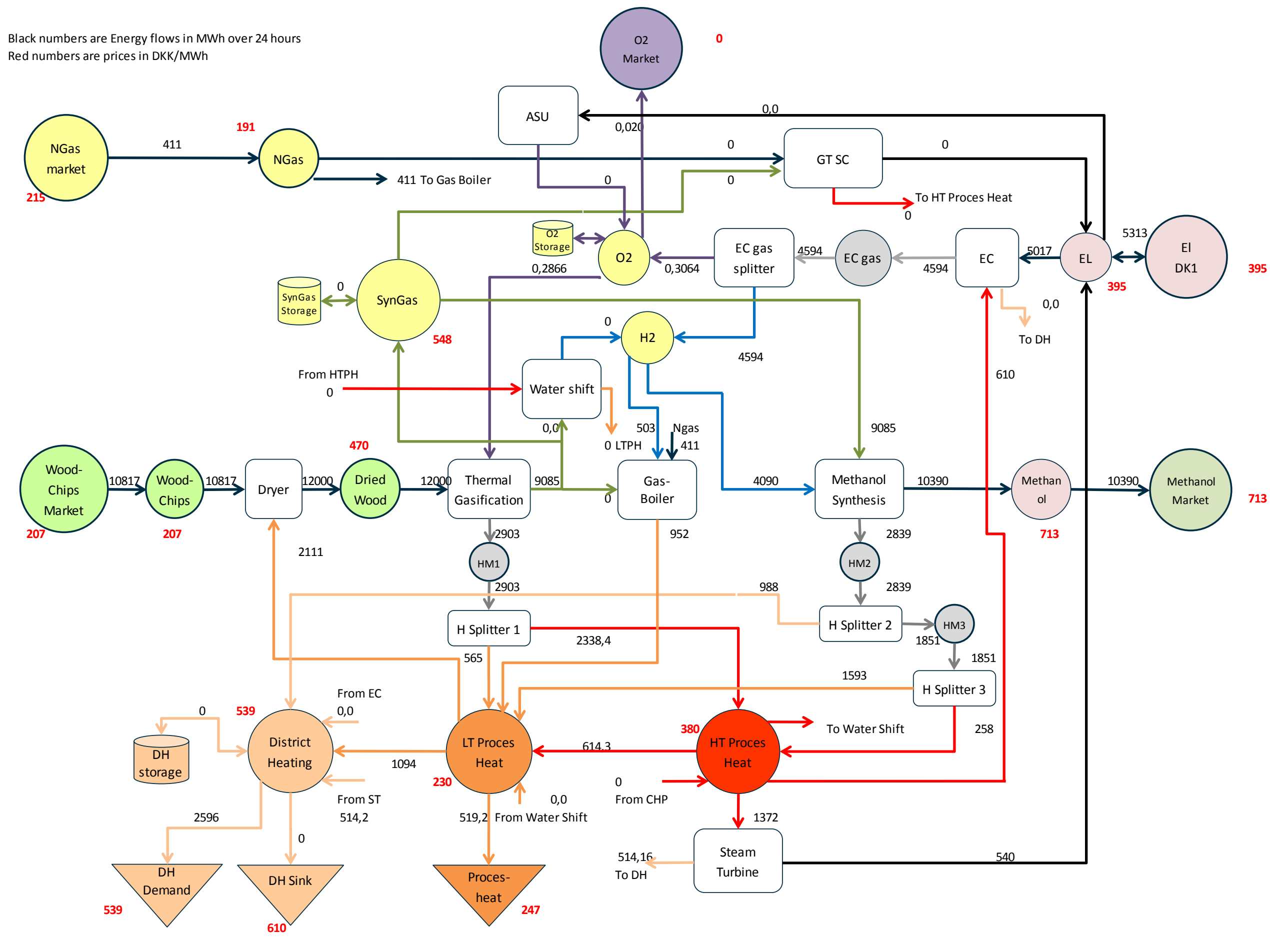

Figure 2: Sifre detailed model of Energy Plant Type III

This model is partly based on technologies under development. It is assumed, that especially the Thermal Gasification and Gas Cleaning will be developed to a commercial level with the today expected investment costs. EA Energianalyse summarise in the report: Grøn Roadmap 2030. Scenarier og virkemidler til omstilling af transportsektorens energiforbrug, November 2015.

"De tekniske udfordringer ved forgasningsteknologierne har vist sig at være betydelige, når biomasse er råvaren. Et egentligt kommercielt gennembrud kræver derfor en målrettet og lang-sigtet udviklingsindsats som bedst løftes i internationalt samarbejde. Det synes særdeles usik-kert, om der kan opnås en betydelig kommerciel produktion inden 2030." [15]

2. Heat Areas

As Sifre doesn't work with mass flows and temperature and pressure levels but only energy flows it has been chosen to operate with three different heat areas:

- District Heating area for energy streams at 50-110°C (DH)
- Low Temperature Process Heat for energy streams at 110-300°C (LTPH)
- High temperature Process Heat for energy streams at 300-1000°C (HTPH)

The general idea of the splitting in three heat areas is, that the HTPH is capable of generating steam for at steam turbine and supplying HT heat for a SOEC electrolysis. The LTPH is used for drying and purification processes and can be sold as process heat for industrial use. The DH will be supplying District Heating for the DH network or can be cooled away if in excess. Energy can freely flow from high temperature areas to lower temperature areas. Thereby the process is limited by the production of Process Heat, but surplus process heat can be led to the DH sink.

In the following description the DH, LTPH and HTPH will be used for heat streams and Areas.

3. Production units

3.1 Dryer Unit

In the dryer unit, the incoming wood chips, with 50% water content, is dried down to 15% and grinded. This is necessary to be able to feed the wood into a pressurized gasifier.

Dryer data is found in in the "Polygeneration" report [1], where supplier data for a Metso belt-drier is chosen.

3.1.1 Assumptions

Wood Chips is supplied at 50% water content and a LHV at: 8.4 MJ/kg

Wood chips are dried down to 15% water content and a LHV at: 15.9 MJ/kg [1]

The process is driven by 2 bar steam, witch in the Sifre model correspond to LTPH (Low Temperature Process Heat). The air and condensate outlet is not implemented in the Sifre simulation.

3.1.2 Mass and energy balance:

Mass Balance:

100 wet wood chips becomes 58.8 dried wood fuel

Energy balance:

100 wet wood chips becomes 111 dried wood fuel

Energy consumption:

Metso bet drier: 3.975 MJ/kg water evaporated [1]

1 MWh wet wood chips = 429 kg wet wood chips. Water to be evaporated is 429*0.412 = 177 kg

Process heat demand: 177*3.975/3600 = 0.195 MWh

3.1.3 Power consumption

In the Polygeneration report [1] a power consumption of 0.01 MWh per 1 MWh wet wood chips input is used. Same number is used here. NOTE: There are no data on the power consumption for grinding of the dried wood chips. Has to be found when we know the level of grinding necessary.

The total energy balance of the drying unit will then be:

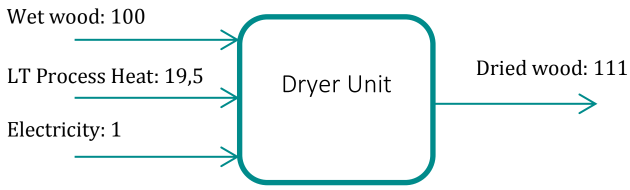

Figure 3: Energy balance for Dryer Unit

And in Sifre, the fuel input and efficiency will be like shown in figure 4.

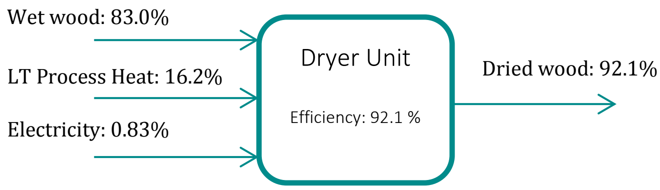

Figure 4: Sifre energy balance for Dryer Unit

Sifre input:

- Type: Condensation
- Production efficiency: B: 3.91
- Fuel Consumption: Dried wood: 83%, LTPH: 16.2%, El: 0.83%
- ADAPT: Investment cost: 0.36 MDKK/MW [2]
- ADAPT: O&M cost: 14,400 DKK/MW/y [6]
- ADAPT: Life time: 20 y [G]
- Maintenance: 2 Weeks/y [G]
- Outage Probability: 2% [G]
- Operating Cost:
- Ramping up/down: 20%/min [G]
- Min production: 15% [G]

3.2 Gasification and methanol production

The gasification and methanol production process includes many different production processes. In this Sifre model, the processes are grouped in three Production Units:

- Thermal Gasification and Gas Cleaning
- Water Shift Reactor
- Methanol Synthesis and purification

Each unit includes several processes and the input- and output streams for each unit is calculated as the net input/output for all the processes in the unit. Figure 5 shows the full process diagram for the biomass to methanol conversion and how the split-up in production units is chosen.

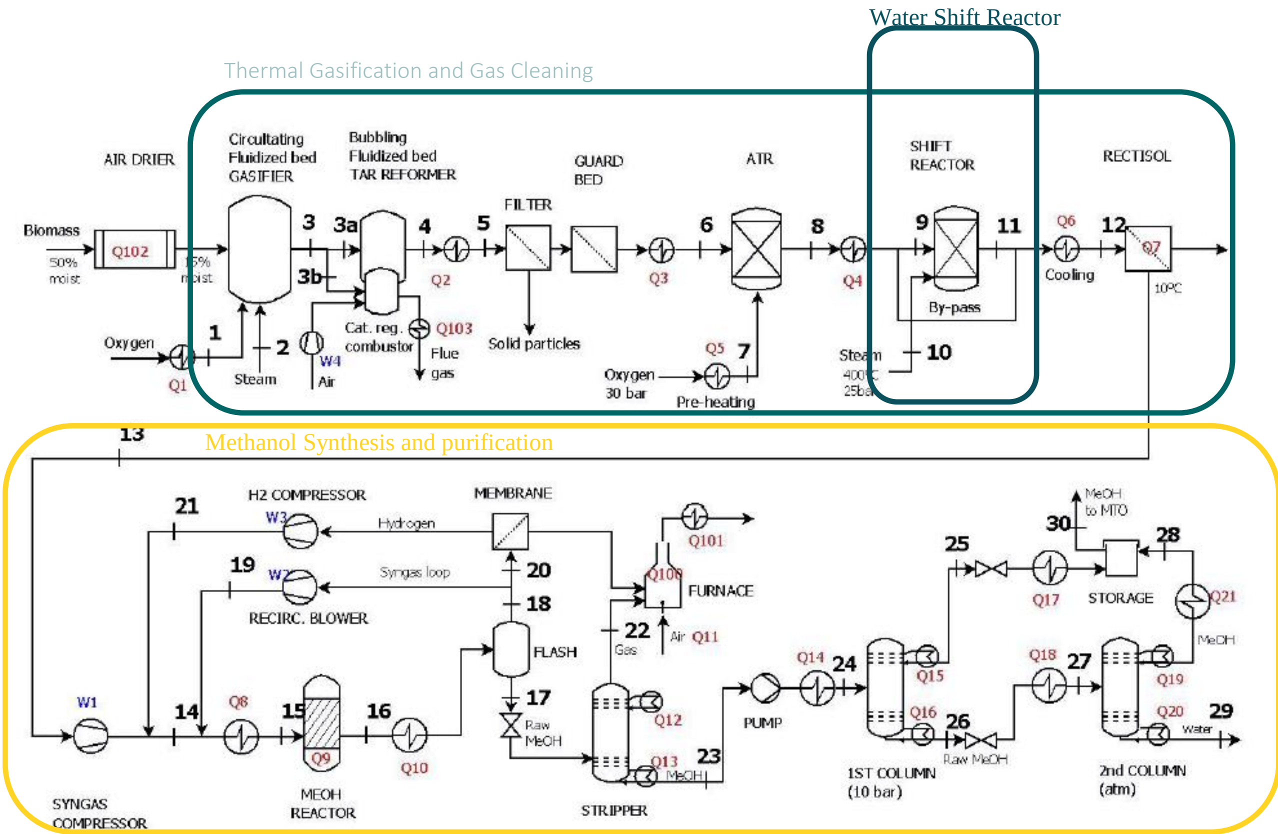

Figure 5: Process diagram for biomass to methanol process, Methanol via biomass gasification [3].

3.3 Thermal Gasification and Gas Cleaning Unit

As shown in Figure 5, the Thermal Gasification and Gas Cleaning Unit includes following processes:

- Biomass infeeder
- Thermal gasification reactor
- Tar Reformer
- Dust filter
- Guard bed (H_2S cleaning)
- ATR - catalytic autothermal reformer
- Rectisol CO_2 removal

The Water Shift reactor is excluded in this unit because it doesn't operate with the same load variations as the rest of the processes. This is due to the Electrolyser Units production of hydrogen. This hydrogen makes it possible to partly or fully bypass the Water Shift Reactor especially at low power prices.

3.3.1 Description of processes

In the following description, the energy in- and outputs are set based on an Aspen+ simulation model of the process shown. Figures are related to a biomass feed in to the gasification at 100 MW LHV.

3.3.2 Biomass Infeeder

Type: Piston infeeder.

Key figures [1]

- P: 440 kW

3.3.3 Thermal gasification reactor

Type: The biomass is gasified in pressurized conditions (at 25 bar) and in presence of oxygen and steam. Pressurization of the whole gas production process through a pressurized biomass feeding system introduces significant savings in the subsequent gas compression required to achieve the optimal synthesis pressures both in terms of capital and operating costs. However, since combustion and gasification occur in the same reactor, to avoid large amount of inert nitrogen the direct gasification concepts necessitates a pure oxygen stream. Gasification occurs also in presence of steam which is required as a reforming agent. These latter endothermic reactions require energy to be provided by combustion and therefore the consumption of oxygen increases with the steam input. The optimal ratio between oxygen and steam for a temperature around 886°C and for a pressure of around 25 bar is around 1:1 [4].

Mass balance of the TG process:

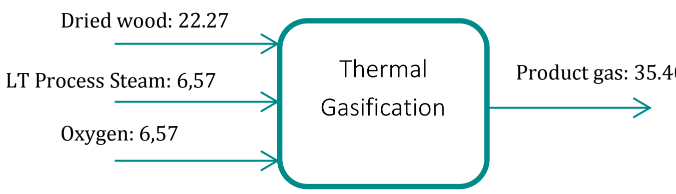

Figure 6: Mass balance for Thermal Gasification [3]

Both Process Steam and oxygen is supplied at 25 bar pressure and around 230°C. In this temperature area LTPH can be utilized.

3.3.3.1 Energy Balance

The energy balance is the one that controls the simulations in Sifre. Therefore every significant stream must be assigned with energy. O_2 does have a LHV at 0 MJ/kg. If this is used it will not be possible to track the O_2 production and consumption. The O_2 stream from Electrolyser to Gasification is vital and to be able to track the O_2 production and consumption, it is necessary to assign the O_2 an LHV. It is chosen to set an arbitrary LHV value for O_2 to: 0.001 MJ/kg. Low enough not to corrupt the general energy balance but high enough to be calculated correctly.

In Sifre it has to be assigned as a percentage of energy input. 1 MJ of wood (0.063 kg) will require 0.0184 kg of O_2. As the LHV of O_2, is set to 0.001 MJ/kg, 1 MJ of wood will require 0.0000184 MJ of O_2 in Sifre.

Now the energy balance for Sifre can be concluded, taking into account 0.33 MW LTPH for Oxygen preheating (Not with SOEC):

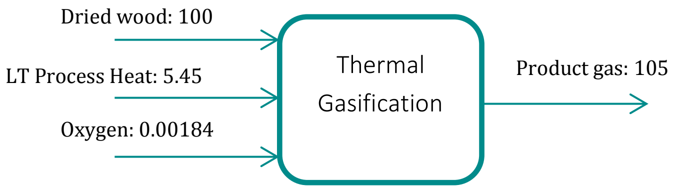

Figure 7: Energy balance for Thermal Gasification

The estimated composition of the product gas is shown in Figure 8:

Component	***Mol. Frac. (%)***
H_2	20.1
CO	15.8
CO_2	21.9
H_2O	34.1
CH_4	5.4
N_2	0.027
O_2	-
Acetylene	0.035
Ethylene	1.476
Ethane	0.377
Propane	0.017
Benzene	0.328
Naphthalene	0.364
Ammonia	0.050
H_2S	0.003
HCl	0.005

Figure 8: Estimated composition of product gas [3]

3.3.4 The Product gas cleaning processes

The mass and energy balances for the individual steps of the product gas cleaning process will not be outlined fully here. Only the sum-up of the processes will be presented. But as the technology choices for these steps are important for the energy balance the, the technology is briefly described and key figures presented.

3.3.5 Tar reformer

The Tar reformer is an isothermal (890°C) catalytic bubbling fluidized bed in which the tar compounds are reformed in presence of the abundant steam content of the product gas. Data about such a reformer were obtained from publications by the US NREL (Spath, Aden et al. 2005) [5]. Tar compounds such as Naphthalene, light hydrocarbons such as propane and ethane as well as ethylene and acetylene are found in the product gas from the gasifier and are largely reformed into H2 and CO by catalytic cracking. Methane is also partially cracked although about half of that still remains in the gas at the reformer outlet. The heat for reforming is provided by circulating the bed and the catalyst from a side combustor which is fuelled by a certain quantity of product gas (about 10% of the total product gas) that is by-passed prior the reformer and therefore does not contribute to methanol production [3].

Key figures [3]:

- Energy efficiency (product gas to syngas): 90%
- Heat recovery: 4.6 MW HTPH
- Power consumption: 1.74 MW (for air compressor)

3.3.6 Dust filter

At the outlet of the tar reformer, particulate matter, alkali materials, and sulphur compounds are still present in the gas and must be removed prior to the gas upgrading and synthesis reactions. This is done by hot gas cleaning technologies and in particular by candle filters. The syn gas has to be cooled prior to the filter

Key figures [3]:

- Energy efficiency: 100%
- Heat recovery: 9.92 MW HTPH (cooling prior to filter)

3.3.7 Guard bed (H_2S cleaning)

The sulphur, assumed here completely in the form of H2S, is removed through a guard bed based on metal oxides.

3.3.8 ATR - catalytic reformer

In order to finally convert the remaining hydrocarbons that would otherwise remain as inert in the methanol synthesis process, a catalytic reformer is used. Steam injection is not required as the steam to carbon ratio is already higher than 1. Oxygen is added for the cracking. The reformer operates at temperatures higher than the dust filter, so syn gas heating is required. After the reforming the temperature has to be lowered before the Water Shift Reactor.

Key figures [3]:

- Oxygen addition: 1.98 t/h
- Oxygen heating (not with SOEC electrolysis): 0.09 MW LTPH
- Syn gas heating: 6.62 MW HTPH
- Syn gas cooling: 11.56 MW HTPH

3.3.9 Rectisol CO_2 removal

The gas is cooled to ambient temperature and most of the CO_2 is removed by a Rectisol process where methanol is used as a physical absorbent. A final CO_2 concentration of 3% in the dry syngas is obtained as it is the optimal concentration for subsequent methanol synthesis [3].

Key figures [3]:

- Syn gas cooling: 10.12 MW LTPH
- Heat added to process: 0.2 MW LTPH
- Power: 0.76 MW

This cooling is correct if no gas passes the Water Shift Reactor. The extra cooling needed, if some gas passes the Water Shift Reactor is allocated to the Water Shift Reactor Unit.

Adding all the gas cleaning process steps up results in this energy balance:

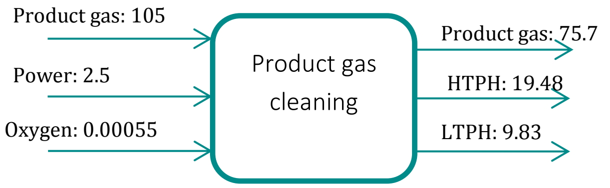

Figure 9: Sum-up energy balance for gas cleaning

In total the Thermal Gasification and Gas Cleaning Unit looks like this:

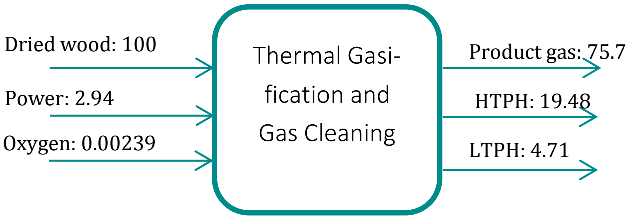

Figure 10: Total energy balance for Thermal Gasification and gas Cleaning.

As Sifre only can handle two output streams from a Production Unit, is has been necessary to group the heat outputs in HeatMix1 and split them in a subsequent Heat Splitter1.

Sifre input (Thermal Gasification and Gas Cleaning Unit):

- Type: Backpressure (Syn gas and HeatMix1)
- Cb: 3.129
- Production efficiency: B: 4.895
- Fuel Consumption: Dried wood: 97.14168%, Oxygen: 0.00232%, El: 2.856%
- ADAPT: Investment cost: 4.70 MDKK/MW [2]
- ADAPT: O&M cost: 188,000 DKK/MW/y [6]
- ADAPT: Life time: 20 y [2]
- Maintenance: 2 Weeks/y [G]
- Outage Probability: 2% [G]
- Operating Cost: 17.9 DKK/MWh [8] (only for gasification unit)(modeled in Sifre as a tax)
- Ramping up/down: 50%/min [6]
- Min production: 15% [6][G]
- Emissions: Has to be estimated

Sifre input (HeatSplitter1):

- Type: Backpressure (HTPH and LTPH)
- Cb: 4.136
- Production efficiency: B: 4.47
- Fuel Consumption: HeatMix1: 100%
- All other inputs are 0, as this component isn't a physical component

3.4 Methanol Synthesis and Purification

The total process of methanol synthesis and purification is shown in Figure 5. All processes included will be handled as one Production Unit in Sifre. This is a fair simplification as all the processes energy consumptions and performances are directly related to the inflow of syngas and its composition. The composition is kept fixed by adjusting the Hydrogen inflow to an optimal mixture in all operation points.

3.4.1 Technical description

Methanol synthesis occurs in a fixed bed reactor at 90 bar [3] where steam is produced by reactor cooling. The reaction products are subsequently cooled leaving a two-phase stream. The crude methanol is obtained at the bottom of the flash drum and is then sent to distillation after the pressure has been released to atmospheric values. A stripper is used to evaporate the remaining gases entrained in the raw methanol. The methanol rich liquid still present a large quantity of water which is removed in a two column system.

3.4.2 Recirculation and purge gas

A certain amount of hydrogen is recovered from a purge stream after the methanol synthesis which is mixed to the fresh syngas feed to reach the final synthesis ratio of around 2.05 with a 3% CO_2 molar fraction [3]. The syngas is then mixed with the synthesis loop gas obtained at the top of the flash drum right after the reactor. Here the synthesis loop is assumed to be 3:1 in volume with respect to the fresh syngas. The purge gases are burnt thus producing additional heat that can be used for steam production.

3.4.3 Syn gas composition

The methanol synthesis operates with highest efficiency, if the M ratio is 2.05 [3]. Furthermore, the CO_2/CO ratio should be low [2]. The M ratio is calculated as shown in Figure 11:

$$M = \frac{H_2 - CO_2}{CO + CO_2}$$

Figure 11: M-ratio calculation by mole fraction

The H_2/CO ratio of the raw syngas is: 20.1/15.8 = 1.27

Though the H_2 level has to be raised. As described some hydrogen is recirculated from the purge gas. This recirculation raises the M-ratio 0.13. So the M- ratio before the hydrogen is added has to be: 1.92.

As the CO_2 content is 3% after the CO_2 scrubber, the H_2 content can be calculated:

1.92 = (x-3)/(97-x+3)

x = 66.8

The mole fraction of hydrogen has to be 66.8% at the inlet to the methanol synthesis and purification unit. Without Water Shift Reaction the mole fraction of H_2 is: 51.2% and the mole fraction of CO is: 45.9%. To raise the level to 66.8% further 45.6 mole of H_2 has to be added per 100 mole raw syn gas.

Approximately one Mole of H_2 has to be added for each mole CO in the syngas.

This has to be converted to energy terms to be used in Sifre. As CO represents approximately 46% of the syngas after CO_2 and H_2O removal, approximately 0.46 Mole of H_2 has to be added to 1 Mole of cleaned syngas.

LHV:

CO: 283 kJ/Mole, H_2: 244 kJ/Mole

1 Mole of cleaned syn gas has a LHV at: 255 kJ/Mole

0.46 Mole of H_2 has a LHV at: 112 KJ

Thus the energy input to Methanol synthesis unit has to be: 69% cleaned syn gas and 31 % H_2.

By fixing this ratio in the Production Unit for Methanol Synthesis in Sifre, the simulation forces to model to produce the needed H_2 either by Electrolysis or by Water Shift Reaction.

The power consumption is quit high due to syn gas compression (90 bar) prior to methanol synthesis.

Added up power consumption: 2.17 MW [3]

There are a lot of processes where heat either has to be added or removed from the stream. Summed up following heat demand/production is achieved:

Net heat output [3]:

- HTPH: 1.48 MW
- LTPH: 9.16 MW
- DH: 5.68 MW

This gives a net energy balance for the Methanol Synthesis and Purification. The Energy balance in Figure 12 is based on a set up with no electrolysis hydrogen.

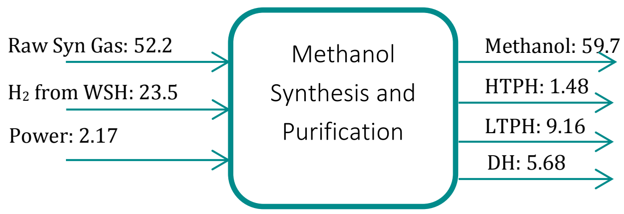

Figure 12: Net energy balance for Methanol Synthesis and Purification (no H2 from Electrolysis).

As Sifre only can handle two output streams from a Production Unit, is has been necessary to group the heat outputs (HeatMix2 and 3) and split them in two subsequent Heat Splitters (2 and 3).

Sifre input (Methanol Synthesis and Purification Unit):

- Type: Backpressure (Methanol and HeatMix2)
- Cb: 3.66
- Production efficiency: B: 4.696
- Fuel Consumption: Syn gas: 67%, H_2: 30.18%, El: 2.787%
- ADAPT: Investment cost: 1.32 MDKK/MW [2]
- ADAPT: O&M cost: 39,600 DKK/MW/y [6]
- ADAPT: Life time: 20 y [2]
- Maintenance: 2 Weeks/y [G]
- Outage Probability: 2% [G]
- Operating Cost:
- Ramping up/down: 25%/min [G]
- Min production: 15% [G]

Sifre input (HeatSplitter2):

- Type: Backpressure (HeatMix3 and DH)
- Cb: 1.873
- Production efficiency: B: 5.522
- Fuel Consumption: HeatMix2: 100%
- All other inputs are 0, as this component isn't a physical component

Sifre input (HeatSplitter3):

- Type: Backpressure (HTPH and LTPH)
- Cb: 0.162
- Production efficiency: B: 325.82
- Fuel Consumption: HeatMix3: 100%
- All other inputs are 0, as this component isn't a physical component

3.5 Water Shift Reactor Unit

As mentioned under the Methanol Synthesis and Purification description the methanol production needs more H2 the available in the raw syn gas. The H2 can come from electrolysis but in periods with high power prices is could be more feasible to produce the extra H2 from conversion of CO in the raw syn gas to H2. This can be done in a Water Shift Reaction where the following process occurs:

$CO + H_2O \rightarrow H_2 + CO_2$

The H_2O is added as high pressure high temperature steam (HTPH). The process is exothermic so cooling down of the produced gas brings energy to the LTPH area. Based on data from [3] the energy balance of the water shift reaction becomes:

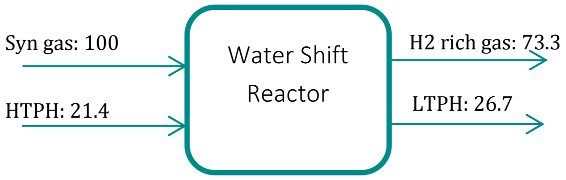

Figure 13: Energy balance Water Shift Reactor Unit

Sifre input:

- Type: Backpressure (Hydrogen and LTPH)
- Cb: 2.745
- Production efficiency: B: 5.96
- Fuel Consumption: SynGas: 82.37%, HTPH: 17.63%
- ADAPT: Investment cost: 0.54 MDKK/MW [2]
- ADAPT: O&M cost: 26,200 DKK/MW/y [6]
- ADAPT: Life time: 20 y [2]
- Maintenance: 2 Weeks/y [G]
- Outage Probability: 2% [G]
- Operating Cost:
- Ramping up/down: 25%/min [G]
- Min production: 15% [G]

3.6 Electrolysis Unit

The electrolysis unit converts electricity (and process heat) to Hydrogen and Oxygen (and process heat).

Two electrolysis technologies will be simulated:

3.6.1 SOEC

A high temperature concept that have high electricity to Hydrogen ratio. The technology is under development. The energy balance for the SOEC technology is taken from The Technology Data Catalogue for Energy Plants-aug. 2016 [7]:

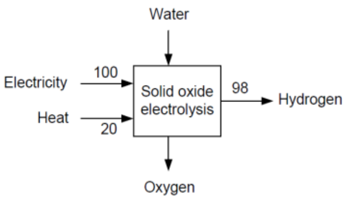

Figure 14: Energy balance for SOEC electrolysis

The temperature of the heat source should be the same as the working temperature, i.e. 800 – 1000°C [7].

3.6.2 Alkaline Electrolysis

This is the market standard today and has been commercial available for almost hundred year. The energy balance for the SOEC technology is:

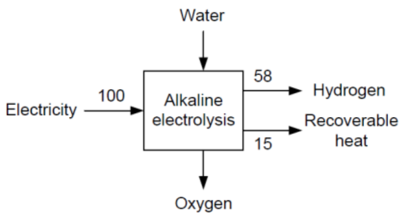

Figure 15: Energy balance for Alkaline Electrolysis [7]

Sifre can only handle two output streams. Therefore the Electrolysis is modeled with two Production Units. One unit producing heat and EC gas (mixture of H_2 and O_2) and an EC gas Splitter converting the EC gas to H_2 and O_2.

Sifre input (SOEC):

- Type: Condensation (EC gas)
- Production efficiency: B: 4.41
- Fuel Consumption: El (max): 100 %, HTPH (max): 16.67% [7]
- ADAPT: Investment cost: 4.4 MDKK/MW [7]
- ADAPT: O&M cost: 109,888 DKK/MW/y [7]
- ADAPT: Life time: 20 y [7]
- Maintenance: 2 Weeks/y [G]
- Outage Probability: 2% [G]
- Operating Cost:
- Ramping up/down: 100%/min [G]
- Min production: 15% [G]

Sifre input (Alkaline):

- Type: Backpressure (ECGas and DH)
- Cb: 3.87 [7]
- Production efficiency: B: 6.207 [7]
- Fuel Consumption: el: 100%
- ADAPT: Investment cost: 7.4 MDKK/MW [7]
- ADAPT: O&M cost: 296,000 DKK/MW/y [7]
- ADAPT: Life time: 30 y [7]
- Maintenance: 2 Weeks/y [G]
- Outage Probability: 2% [G]
- Operating Cost:
- Ramping up/down: 100%/min [G]
- Min production: 15% [G]

3.7 EC gas Splitter Unit

The EC gas Splitter is set to Back pressure Plant to fix the relation between H_2 and O_2.

H_2 set to primary production.

C_b is difficult to set. It ought to be infinity as all the energy follows the H2 stream. But to be able to track the O_2 production and consumption, it is necessary to assign the O_2 an LHV. It is chosen to set an arbitrary LHV value for O_2 to: 0.001 MJ/kg. Low enough not to corrupt the general energy balance but high enough to be calculated correctly (I hope)

Mass balance for EC gas:

1000 EC gas = 111 H_2 + 889 O_2.

LHV for H_2 is 120 MJ/kg. LHV for O_2 is chosen to: 0,001 MJ/kg.

Energy balance:

1000 EC gas = 999.933 H_2 + 0.0667 O_2

That results in a c_b-value of: 999.933/0.0667 = 14991

The efficiency is set to 99.9933%

Sifre input:

- Type: Backpressure (Hydrogen and Oxygen)
- Cb: 14991
- Production efficiency: B: 3.60024
- Fuel Consumption: EC gas: 100%
- All other inputs are 0, as this component isn't a physical component

3.8 GT SC Unit

It is chosen to use a simple cycle GT unit for peak load power production. The advances of the simple cycle GT is fast regulation (0-100% in 15 min. typically) [8] and low investment cost per MWe.

The electric efficiency of a large (40-125 MWe) single cycle GT is in the Technology Data Catalogue for Energy Plants- UPDATE 2016 [8] estimated to 41% in 2030 on an annual average and C_b = 1. The exhaust flue gas can be directed to the HTPH area for use in the Methanol process or in the Steam Turbine if capacity is available. Utilizing the flue gas heat only in the HTPH area expects to raise the C_b to 1.5. The link from the HTPH to DH and heat sink makes it possible to ramp up the GT faster than the Steam Turbine and thereby keep the regulation capacity.

Sifre input [8]:

- Type: Backpressure (El and HTPH)
- Cb: 1.5 [G]
- Production efficiency: B: 8.78
- Fuel Consumption: Syn Gas: 100%, NGas: 100%
- ADAPT: Investment cost: 4.17 MDKK/MW

- ADAPT: O&M cost: 138,570 DKK/MW/y
- ADAPT: Life time: 25 y
- Maintenance: 2.5 Weeks/y
- Outage Probability: 2%
- Operating Cost: 31.3 DKK/MWh (modeled in Sifre as a tax)
- Ramping up/down: 20%/min
- Min production: 15%
- Emissions: NO_x: 10g/GJ, CH_4: 1.5 g/GJ, N_2O: 1 g/GJ

3.9 Steam Turbine Unit

The biomass to methanol process generates a high amount of high temperature heat, especially from syn gas cooling. These heat outputs are gathered in the HTPH Area. High temperature heat can produce high pressure and high temperature steam for power production. It has been chosen to implement a Steam Turbine unit for utilizing the excess HTPH. It is assumed, that all excess HTPH can be converted to 100 bar steam at 500°C [3]. This is let to the Steam Turbine Unit that is set up as an extraction turbine for DH production if needed.

Shows a pinch diagram for a quit similar process [3]:

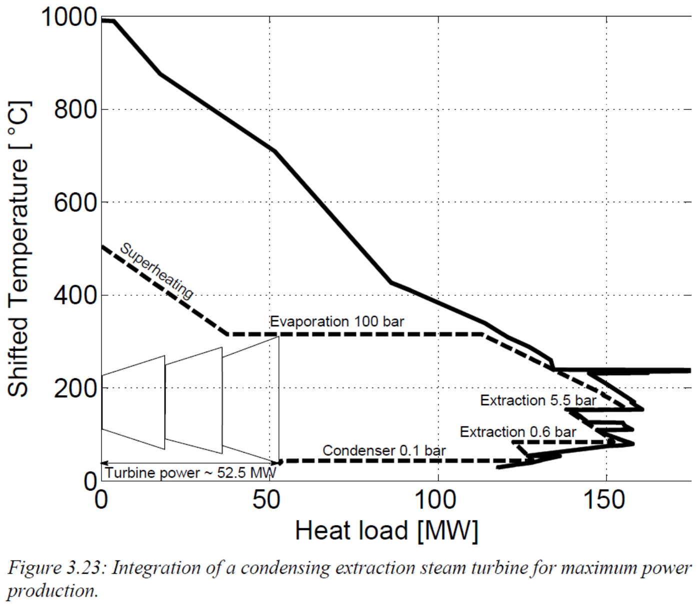

Figure 16: Pinch diagram for similar biomass to methanol proces [3]

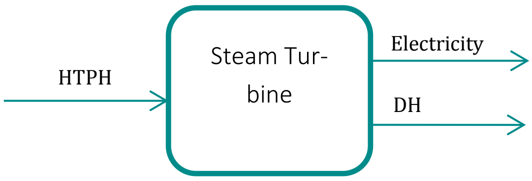

Figure 17: Input / outputs for Steam Turbine Unit

The split between electricity and DH is flexible. The Unit is modeled with a max electricity efficiency at 45% and C_v = 0.15 and C_b = 1 [8].

3.9.1 Cost of Steam Turbine

The investment cost of steam generation and steam turbine is taken from the NREL report:

Gasoline from Wood via Integrated Gasification, Synthesis, and Methanol-to- Gasoline Technologies, Steven D. Phillips et al., 2011. [9]

In this study the total installed cost of steam generation and extraction type steam turbine is M23.1 USD.

From the mass- and energy balance is the power generation found to 35 MWe at a steam pressure at 33 bar and a steam temperature at 482°C. In this Sifre model the steam turbine produce approximately 50 MW and the steam conditions are: 500°C and 50 bar. These sizes and conditions are in the same range and therefore, is it assumed, that the specific prices of investment in the US study can be used. The investment cost is in 2007 USD. In 2007 the price in EUR is M16.9 EUR[1]. The specific price then becomes: 0.48 MEUR/MWe

Sifre input:

- Type: Extraction (El and DH)
- C_b: 1, C_v: 0.15 [8]
- Production efficiency: B: 8 [8]
- Fuel Consumption: HTPH: 100%
- ADAPT: Investment cost: 3.59 MDKK/MWe (2007) [9]
- ADAPT: O&M cost: 107,700 DKK/MW/y [6]
- ADAPT: Life time: 30 y [G]
- Maintenance: 2 Weeks/y [G]
- Outage Probability: 2% [G]
- Operating Cost:
- Ramping up/down: 5%/min [G]
- Min production: 15% [G]

3.10 Air Separation Unit

The air separation unit is producing high pressure oxygen from air. The only input to the process is electricity. Based on the paper: *Oxygen Specific Power Consumption Comparison for Air Separation Units by Yas A. Alsultanny and Nayef N. Al-Shammari [10]* the specific power consumption for an ASU type 31 is 0.608 KWh/Nm3 O_2. This has to be recalculated to energy streams, and with an arbitrary LHV for O_2 set to 0.001 MJ/kg and a weight of O_2 at 1.429 kg/Nm3, the results becomes: 5508 GJ/MWh O_2. This is a very low "energy efficiency" but it does not give any sense to talk about efficiencies as the LHV of O_2 is set arbitrary.

[1] http://www.x-rates.com/average/?from=EUR&to=USD&amount=1&year=2007: 1.37 USD/EUR

The investment cost of the ASU is based on data from the NREL report: *Techno-Economic Analysis of Biofuels Production Based on Gasification, Ryan M. Swanson et al., 2010 [11].*

The ASU in this report has a production rate at 714 t/d O_2 and costs 24.3 MUSD. With a LHV for O_2 set to 0.001 MJ/kg the specific investment cost will be: 2942 MUSD/MW = 15988 MDKK/MW

Sifre input (Option 1):

- Type: Condensation (Oxygen)
- Efficiency: B: 5508
- Fuel: Electricity
- ADAPT: Investment cost: 15988 MDKK/MW (2007) [11]
- ADAPT: O&M cost: 480,000,000 DKK/MW/y [6]
- ADAPT: Life time: 20 y [G]
- Maintenance: 2 Weeks/y [G]
- Outage Probability: 2% [G]
- Operating Cost:
- Ramping up/down: 5%/min [G]
- Min production: 15% [G]

Another ASU option is to generate liquid oxygen (ASU-51) [10]. This option has higher energy consumption per t O_2 but the liquid O_2 makes it less costly to store. The cost of such a plant is approximately the same as option 1, but the efficiency is changed. The energy consumption for an ASU-51 is 0.772 KWh/Nm3 O_2 [10].

Sifre input (Option 2):

- Type: Condensation (Oxygen)
- Efficiency: B: 7001
- Fuel: Electricity
- ADAPT: Investment cost: 15988 MDKK/MW (2007) [11]
- ADAPT: O&M cost: 480,000,000 DKK/MW/y [6]
- ADAPT: Life time: 20 y [G]
- Maintenance: 2 Weeks/y [G]
- Outage Probability: 2% [G]
- Operating Cost:
- Ramping up/down: 5%/min [G]
- Min production: 15% [G]

3.11 Gas Boiler Unit

The gas boiler unit produces LTPH from three different gas sources. Ngas, SynGas and H_2. It is assumed, that the boiler can operate with all possible mixtures of the three gas sources.

Sifre input [8]:

- Type: Heatboiler
- Efficiency: B: 3.46

- Fuel: Ngas, SynGas, H2
- ADAPT: Investment cost: 0.37 MDKK/MW
- ADAPT: O&M cost: 14,155 DKK/MW/y
- ADAPT: Life time: 25 y
- Maintenance: 0.4 Weeks/y
- Outage Probability: 1%
- Operating Cost: 7.45 DKK/MWh (modeled in Sifre as a tax)
- Ramping up/down: 15%/min
- Min production: 15%

4. Storages

4.1 District Heating Storage

The energy content of a typical district heating storage: 70 kWh/m^3 [8]

Investment: 1192 DKK/m^3 [8]

Sifre input [8]:

- Type: DH storage
- ADAPT: Investment cost: 0.017 MDKK/MWh
- ADAPT: O&M cost: 0 DKK/MW/y
- ADAPT: Life time: 30 y [G]
- Maintenance: 0 Weeks/y
- Outage Probability: 0%
- Operating Cost:
- Charge rate: 200 MW [G]
- Discharge rate: 200 MW [G]
- Start-up capacity : 10 MWh (to avoid very high DH price in the first hour)
- Charge efficiency: 100%
- Discharge efficiency: 100%
- Loss: 0.0001 %/h

4.2 Oxygen storage

It has been very difficult to find investment costs for pressurerized oxygen storage vessels. The best available data, is has been able to find under the given timeframe is data for compressed air storage. It is assumed, that a storage vessel for compressed air also can be used for Oxygen. The found vessel is a 3105 m^3 vessel operating at 103 bar. This is a fine match as many ASU unit deliver the oxygen at 90 bar (has to be checked, if the energy consumption for the used ASU concept includes compression to 90 bar).

The purchase cost for this vessel is estimated to M16 USD and the installed cost to M49 USD [12]. As this storage “vessel” consists of 34 storage vessels, it is assumed, that the pricing for other sizes are linear.

To calculate the amount of oxygen stored in such a vessel, The Ideal Gas Law is used:

PV=nRT, R= 0.082, P: pressure in atm, V: volume in liter, n: number of mole gas, T: temperature in Kelvin.

n = PV/RT

n = 88.8*3105000/0.082*310 = 10,846,735 mole O_2

To be able to deliver gas to the pressurised gasifier, it is assumed, that the lowest pressure in the O_2 storage is 30 bar. The content of the storage is then:

n = 29.6*3105000/0.082*310 = 3,615,578 mole O_2

The active storage capacity is therefore: 7.23 mill mole O_2 that equals 231.4 t O_2

With the arbitrary LHV on O_2 set to 0.001 MJ/kg, the "energy" content of the storage is: 0.0643 MWh

The specific cost of the storage then becomes: 274 MDKK/0.0643 MWh = 4261 MDKK/MWh

Sifre input (option 1):

- Type: O2 storage
- ADAPT: Investment cost: 4261 MDKK/MWh [12]
- ADAPT: O&M cost: 0 DKK/MW/y [G]
- ADAPT: Life time: 30 y [G]
- Maintenance: 0 Weeks/y
- Outage Probability: 0%
- Operating Cost:
- Charge rate: 1 MW
- Discharge rate: 1 MW
- Charge efficiency: 100%
- Discharge efficiency: 100%
- Loss: 0 %/h

If liquid oxygen is produced for storage (ASU-51) the storage is a totally different kind. The storage then should not be able to manage high pressure but instead very low temperature, as Oxygen is liquid below -183°C. The density is much higher than compressed Oxygen. The storage tank in option 1 can contain 231 t O_2 while the same storage volume can contain 3,543 ton liquid oxygen. It has not been possible to find investment cost for liquid O_2 storage in this projects timeframe, but it is recommended to get such budget data from tank suppliers. For now the tank cost for compressed oxygen/air storage is used. But as the density is 15 times higher the cost per MWH is estimated to be 15 times lower. Normally there is a need for heat supply for evaporation before use in gasification but it is assumed that mixing with the main stream oxygen from Electrolysis at 850-1000°C will supply enough heat.

Sifre input (option 2):

- Type: O2 storage
- ADAPT: Investment cost: 284 MDKK/MWh [12]
- ADAPT: O&M cost: 0 DKK/MW/y [G]
- ADAPT: Life time: 30 y [G]
- Maintenance: 0 Weeks/y
- Outage Probability: 0%
- Operating Cost:
- Charge rate: 1 MW
- Discharge rate: 1 MW
- Charge efficiency: 100%
- Discharge efficiency: 100%
- Loss: 0 %/h

4.3 SynGas storage

It has been very difficult to find investment costs for pressurerized gas storage vessels. The best available data, is has been able to find under the given timeframe is data for compressed air storage. It is assumed, that a storage vessel for compressed air also can be used for compressed SynGas. The found vessel is a 3105 m^3 vessel operating at 103 bar. The SynGas is produced at 25 bar. In the Methanol Synthesis the syngas is compressed up to 90 bar. It is assumed, that the storage at this point in the process and therefore a storage at 90 bar will require no extra compression of the syngas at inlet to storage. A minor compression at the outlet of the storage is necessary to 90 bar again, if the storage level is low. The energy consumption for this compression is not jet included in the simulation. The temperature just before the Methanol Synthesis is approximately 60°C [3]

The purchase cost for this vessel is estimated to M16 USD and the installed cost to M49 USD [12]. As this storage "vessel" consists of 34 storage vessels, it is assumed, that the pricing for other sizes are linear.

To calculate the amount of SynGas stored in such a vessel, The Ideal Gas Law is used:

P*V=n*R*T, R= 0.082, P: pressure in atm, V: volume in liter, n: number of mole gas, T: temperature in Kelvin.

n = P*V/R*T

n = 88.8*3105000/0.082*333 = 10,097,561 mole SynGas

To reduce the power consumption for compression at the outlet it is assumed, that the storage operates between 90 bar and 30 bar. The content of the storage is then:

n = 29.6*3105000/0.082*333 = 3,365,854 mole SynGas

The active storage capacity is therefore: 6.73 mill mole SynGas that equals 75.7 t SynGas (11.25 g/Mole [3])

With LHV on Syngas just before Methanol Synthesis at MJ/mole, the energy content of the storage is: 457.7 MWh.
The specific cost of the storage then becomes: 274 MDKK/457.7 MWh = 0.60 MDKK/MWh

Sifre input:

- Type: SynGas storage
- ADAPT: Investment cost: 0.6 MDKK/MWh [12]
- ADAPT: O&M cost: 0 DKK/MW/y [G]
- ADAPT: Life time: 30 y [G]
- Maintenance: 0 Weeks/y
- Outage Probability: 0%
- Operating Cost:
- Charge rate: 100 MW
- Discharge rate: 100 MW
- Charge efficiency: 100%
- Discharge efficiency: 100%
- Loss: 0 %/h

5. Market Prices

5.1 Oxygen Market

An Oxygen Market has been added to receive excess O_2. The oxygen market could be just flaring the oxygen or it could be selling it. Price is set to 0 DKK/MWh

5.2 Natural gas

Ngas prices are assumed to be constant over the evaluated period.

Ngas: 59.7 DKK/GJ in 2030 in 2016 prices [14]

5.3 Wood Chips

WoodChip prices are assumed to be constant over the evaluated period.

Wood Chips: 57.5 DKK/GJ in 2030 in 2016 prices [14]

5.4 Bio Methanol

Bio Methanol prices are assumed to be constant over the evaluated period.

EA-analyse has estimated the future production cost of 2. Generation bioethanol to be 230 DKK/GJ (828 DKK/MWh) [14]. This price is assumed to be the upper limit. The lower limit is the expected gasoline price. ENS estimates this price to be 129.1 DKK/GJ in 2030 and the associated CO_2 cost to be 37 DKK/GJ gasoline. The lower limit is therefore set to: 166.1 DKK/GJ (598 DKK/MWh)

In this study average of the two limits has been chosen as the basic price: 198.1 DKK/GJ (713 DKK/MWh)

5.5 Electricity

The electricity price is assumed to follow the price profile in Energinet's Analyseforudsætninger 2016: AF2016 + 50 DKK/MWh as a tax. The tax is put on the electricity price because the total plant is a net consumer of electricity.

6. Heat demands

6.1 District heating

- Profile: Varmeprofil
- Type: non Flexible
- Amount: 500,000 MWh/year

6.2 Process Heat

- Profile: Varmeprofil
- Type: non Flexible
- Amount: 100,000 MWh/year

6.3 District Heat Sink

The district heat sink is put in the model to be able to operate the biomass to methanol process also when there is very low heat demand. The heat sink could be seen as a “summer cooler”. The demand is set very high and the type is set to price cutting to make the District Heat Sink taking excess heat, when the price comes near zero.

- Profile: Varmeprofil
- Type: Price cutting (0.1 DKK/MWh)
- Amount: 10,000,000 MWh/year

NB: Sifre calculated in general very high costs of the heat streams and in some hours extremely high prices. It has not been possible in this project to figure out why. Because of that the prices for the heat streams are fixed in the economy calculation. The high prices in the internal heat streams do not affect the optimization of the operation or equipment sizes [Thomas Sejr Jensen]

7. Simulation Results without ADAPT optimisation

The described energy system is simulated in Sifre. To show how Sifre optimize the operation with regard to the electricity price, the operation of all major Production Units and energy storages are shown for one day. The day chosen is the 4.th of January 2030.

7.1 Energy flows

In Figure 18 the total amount of energy transported between the different Production Units and Areas is shown.

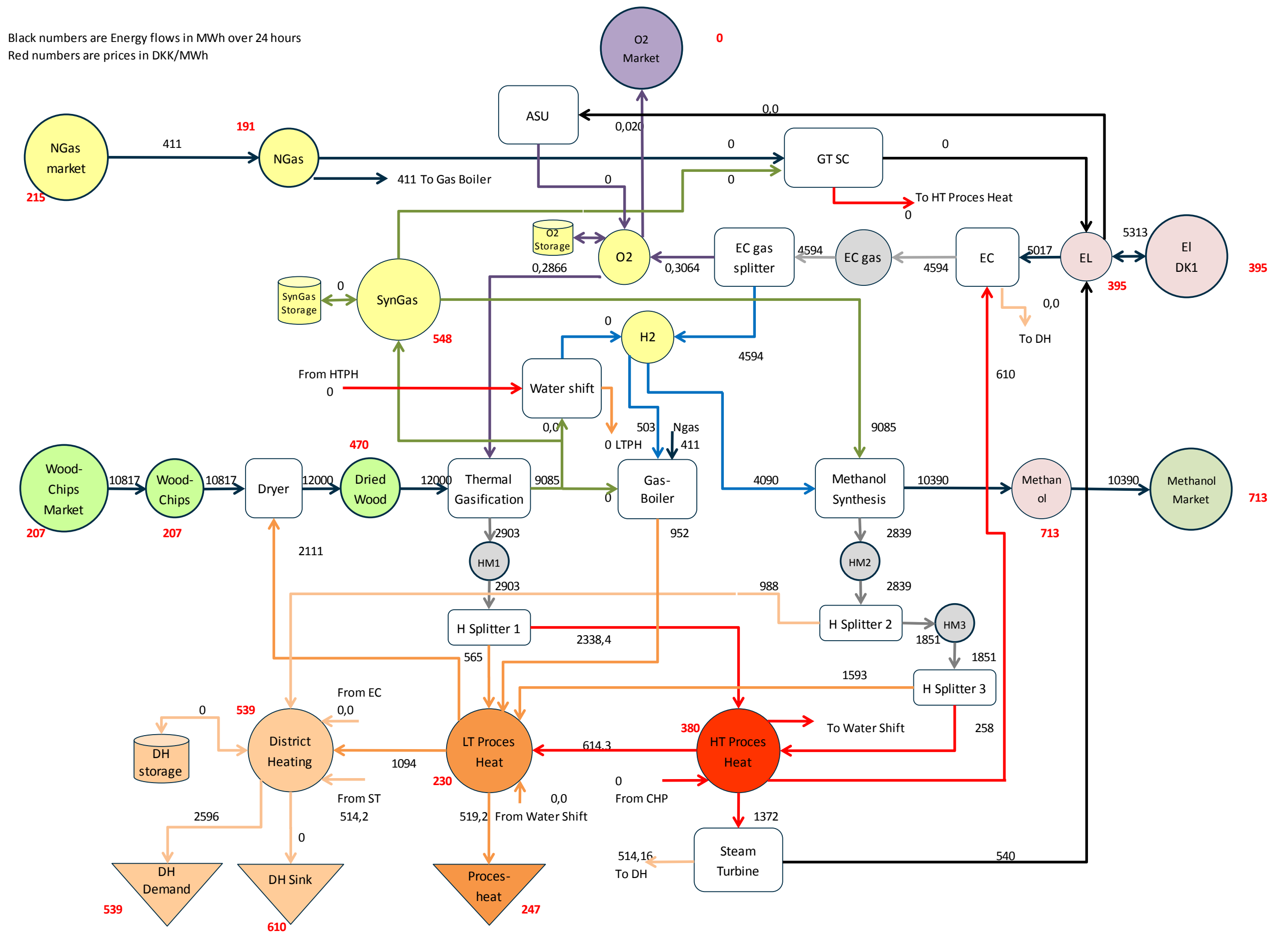

Figure 18: Simulated process without ADAPT optimization

In the following graphs the Production Units and Energy Storages operation variations is shown.

7.2 Power price profile and heat demand per hour

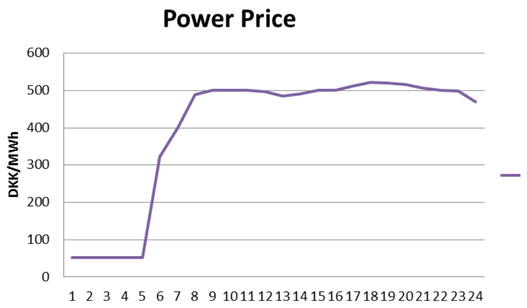

Figure 19: Electricity price 4th Jan. 2030

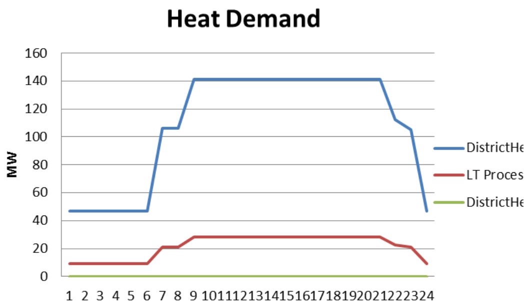

Figure 20: Heat Demand 4th of Jan. 2030

7.3 Operation profile for the production units

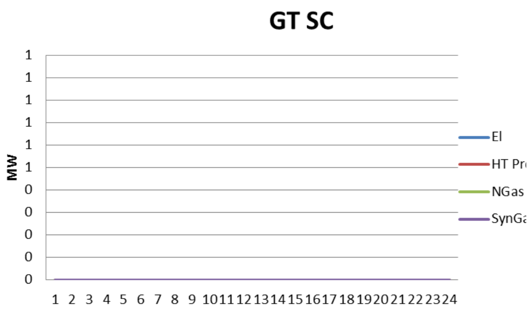

Figure 21: GT operation 4th of Jan. 2030

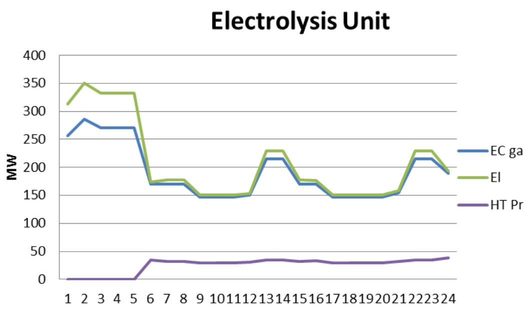

Figure 22: Electrolysis operation 4th of Jan 2030

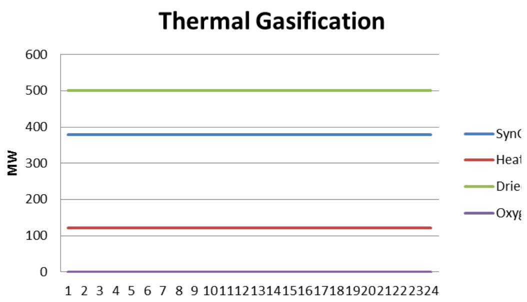

Figure 23: Gasification operation 4th of Jan 2030

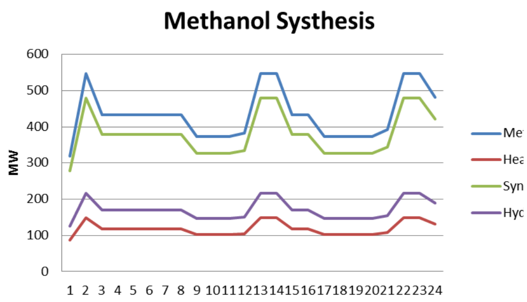

Figure 24: Methanol Synthesis operation 4th of Jan 2030

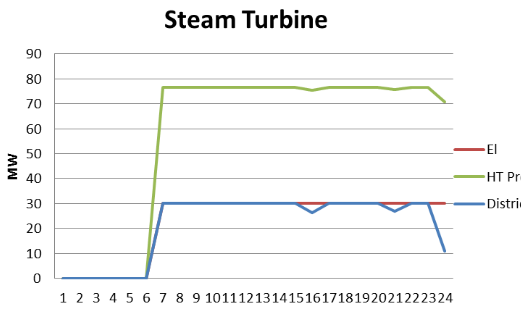

Figure 25: ST operation 4th of Jan 2030

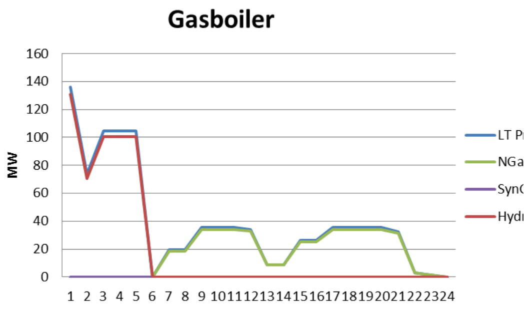

Figure 26: Gasboiler operation 4th of Jan 2030

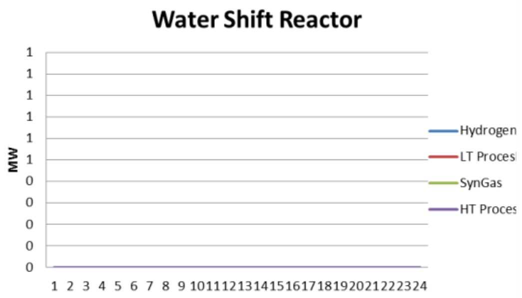

Figure 27: WSR operation 4th of Jan 2030

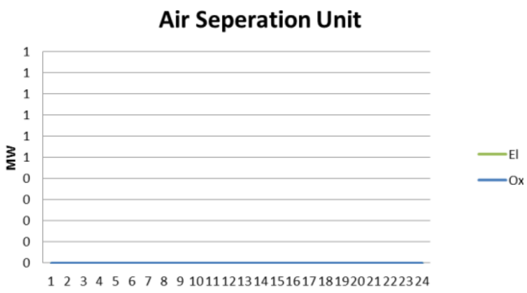

Figure 28: ASU operation 4th of Jan 2030

7.4 Storage levels

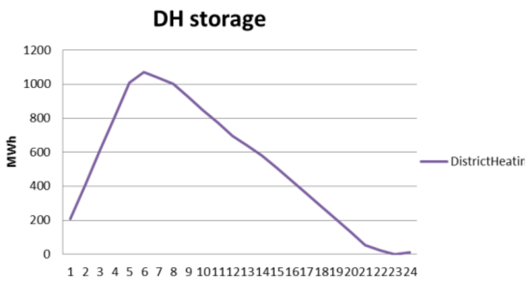

Figure 29: DH storage level operation 4th of Jan 2030

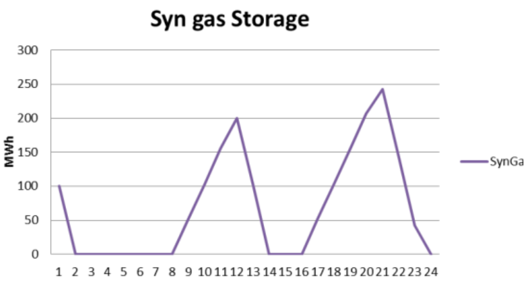

Figure 30: Syn Gas storage level operation 4th of Jan 2030

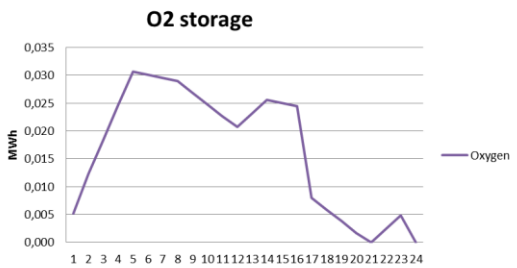

Figure 31: O_2 storage level operation 4th of Jan 2030

8. Simulation Results with ADAPT optimisation

The described energy system is simulated in Sifre utilizing the ADAPT function to optimize the size of each Production Unit and each Energy Storage. To lower the amount of data only one day is simulated. It is the 4.st of January 2030. The investment optimization is performed for only one day of operation. This is not the way to determine the best sizes for the processes, but only to make the two simulations with and without ADAFT comparable.

8.1 Energy flows

In Figure 32 the total amount of energy transported between the different Production Units and Areas is shown.

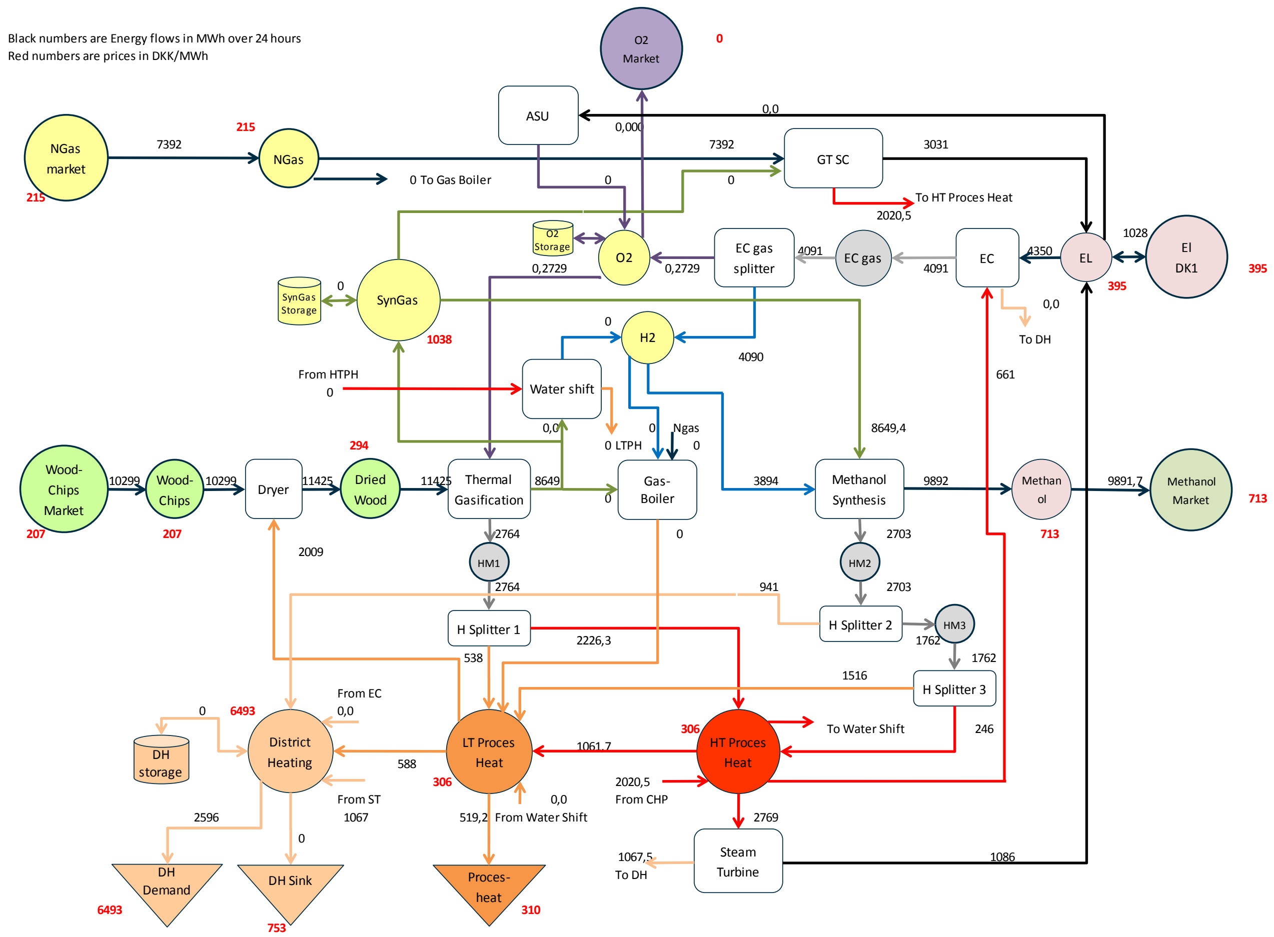

Figure 32: Simulated process with ADAPT optimization

In the following graphs the Production Units and Energy Storages operation variations is shown.

8.2 Power price profile and heat demand per hour

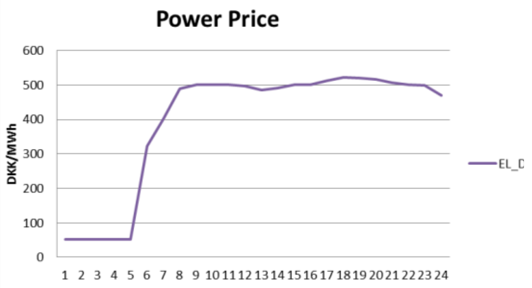

Figure 33: Electricity price 4th Jan. 2030

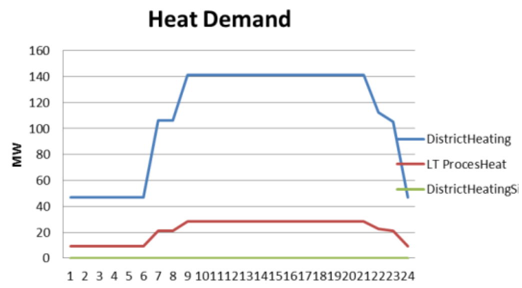

Figure 34: Heat Demand 4th of Jan. 2030

8.3 Operation profile for the production units

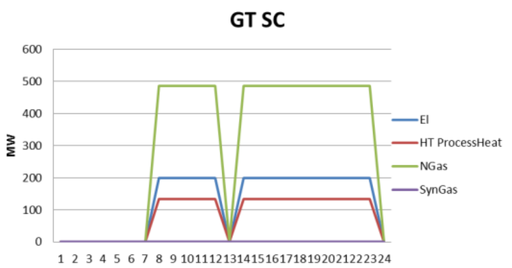

Figure 35: GT operation 4th of Jan. 2030

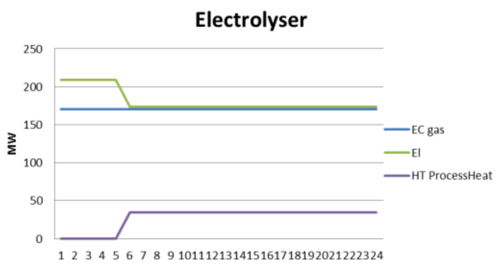

Figure 36: Electrolysis operation 4th of Jan 2030

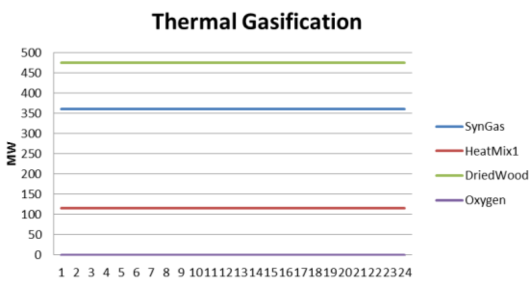

Figure 37: Gasification operation 4th of Jan 2030

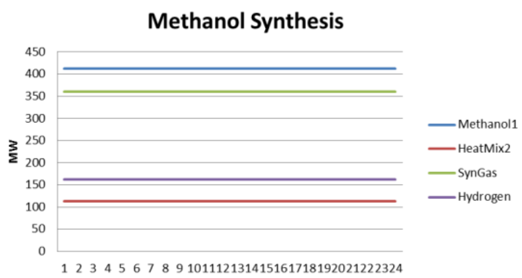

Figure 38: Methanol Synthesis operation 4th of Jan 2030

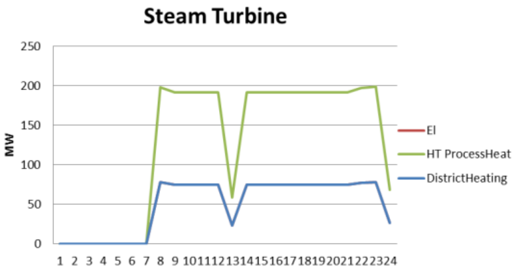

Figure 39: ST operation 4th of Jan 2030

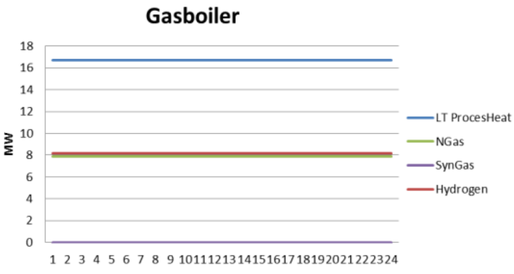

Figure 40: Gasboiler operation 4th of Jan 2030

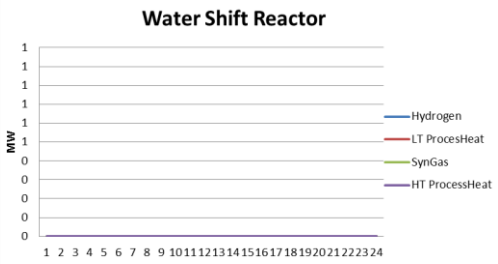

Figure 41: WSR operation 4th of Jan 2030

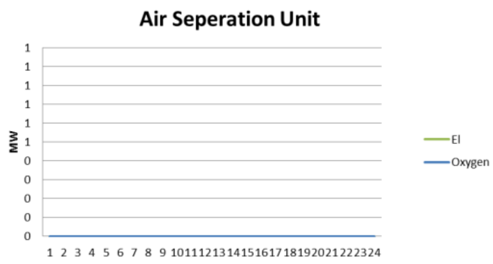

Figure 42: ASU operation 4th of Jan 2030

8.4 Storage levels

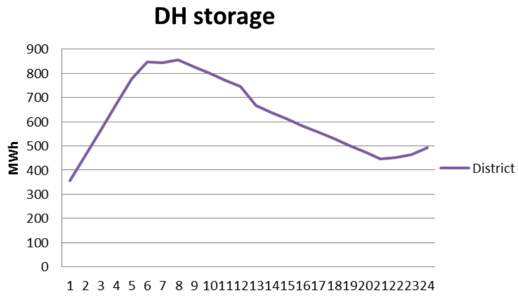

Figure 43: DH storage level operation 4th of Jan 2030

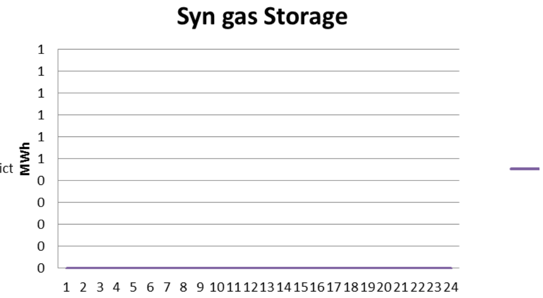

Figure 44: Syn Gas storage level operation 4th of Jan 2030

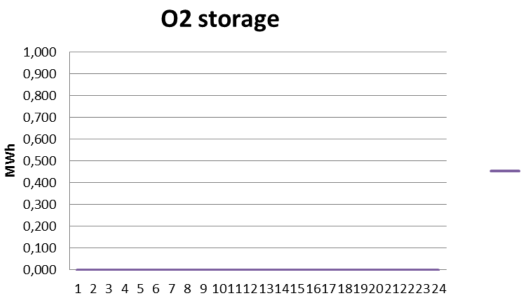

Figure 45: O2 storage level operation 4th of Jan 2030

9. Sensitivity analysis

9.1 Baseline model

The baseline model for the Energy Plant Type III simulation is briefly described and the energy flows and standard output data are presented.

9.1.1 General issues

The baseline model includes all processes described in this document. For the ASU, option 2 is chosen with production of liquid oxygen and therefore also option 2 for oxygen storage. For the Electrolysis Unit the SOEC technology is used in the baseline scenario. All production units and energy storages are variables in the model and the ADAPT module in Sifre optimize the production based on the economy of operation. This means the some production units can be optimized out of the system, because they don't generate enough value to pay for the investment cost. Sifre + ADAPT choses the most profitable sizes for all production units and for all energy storages. The production is limited in two places. The dry wood inlet is limited to 500 MW and the Gas Turbine electricity production is limited to 200 MW.

The plant operation is optimized for one year (2030) using time steps at one hour.

9.1.2 Prices

The prices, described under the "Market Prices" section, is used in the baseline model. Sifre calculate internally prices for the heat outputs from the plant. The prices are sometimes very high compared to the fuel used. In calculation the total plant economy it has therefore been chosen to operate with fixed prices for sale of District Heating, LT Process Heat and for the District Heating Sink in all scenarios. This is done to be able to compare the plant operational economy in different sensitivity scenarios. These prices are set to:

- District Heating sale: 85 DKK/GJ
- LT Process Heat sale: 120 DKK/GJ
- District Heating Sink: 0 DKK/GJ

9.1.3 CAPEX

The total plant CAPEX is calculated by adding up the CAPEX of all the processes and adding a 30% contingency for plant cost not coupled directly to one production unit and for general major uncertainties in the CAPEX data input. This is a very rough estimate like the CAPEX cost for the processes, and it is strongly recommended to set up a more thorough study of all aspects of the plant cost.

NB: The ADAPT/SIfre simulation sets the size of the Water Shift Reactor Unit to 106 MW output even though the unit has zero operation hours. It has not been possible to find the reason to this in this project.

9.1.4 OPEX

The expenses and income related to product flows are calculated based on the Sifre energy balance and the market prices set.

Fixed O&M are calculated from the size of the individual process steps and their specific fixed O&M costs. Specific O&M cost are for some production units found in the Technology Data Catalogues [6,7,8]. But for the main production units in the biomass-to-methanol process no data are available in the Technology Data Catalogues. But for a Biomass-to-Methanol black box process a 3% of CAPEX per year level is set in [8]. This value is used for all processes not listed specific in the Technology Data Catalogues.

Variable O&M are found for the process steps available in the Technology Data Catalogues and put in the Sifre model as taxes. For process steps not found in the Technology Data Catalogues no variable O&M has been set. It is recommended to look more into this area.

9.1.5 Key economic figures

CAPEX expense per year is used to calculate the yearly revenue for the plant. The CAPEX expense is calculated by adding up the yearly payment based on lifetime and an interest at 4% for each process step and adding the payment for the contingency over 30 years.

Yearly Revenue for the plant is calculated as the operational revenue (based on the energy flows) subtracted the fixed and variable O&M and the yearly CAPEX expense. No taxes, credits, grants or other posts are in-calculated at this level.

The IRR is estimated by finding the internal rate of return for a cash flow, where the investment (CAPEX) is split up over two years and the Yearly Revenue (without the CAPEX expense per year) is put in as yearly income streams for 20 years after the two years of investment. This is a very rough model, not taking reinvestment of equipment with shorter lifetime than 20 years or scrap values of equipment with longer lifetime into consideration. But as most equipment groups have a lifetime at 20 years is assumed to be a fair simplification at this level.

Methanol Shadow Price is defined as the methanol selling price at which the Yearly Revenue is zero.

9.1.6 Baseline model Energy Flows

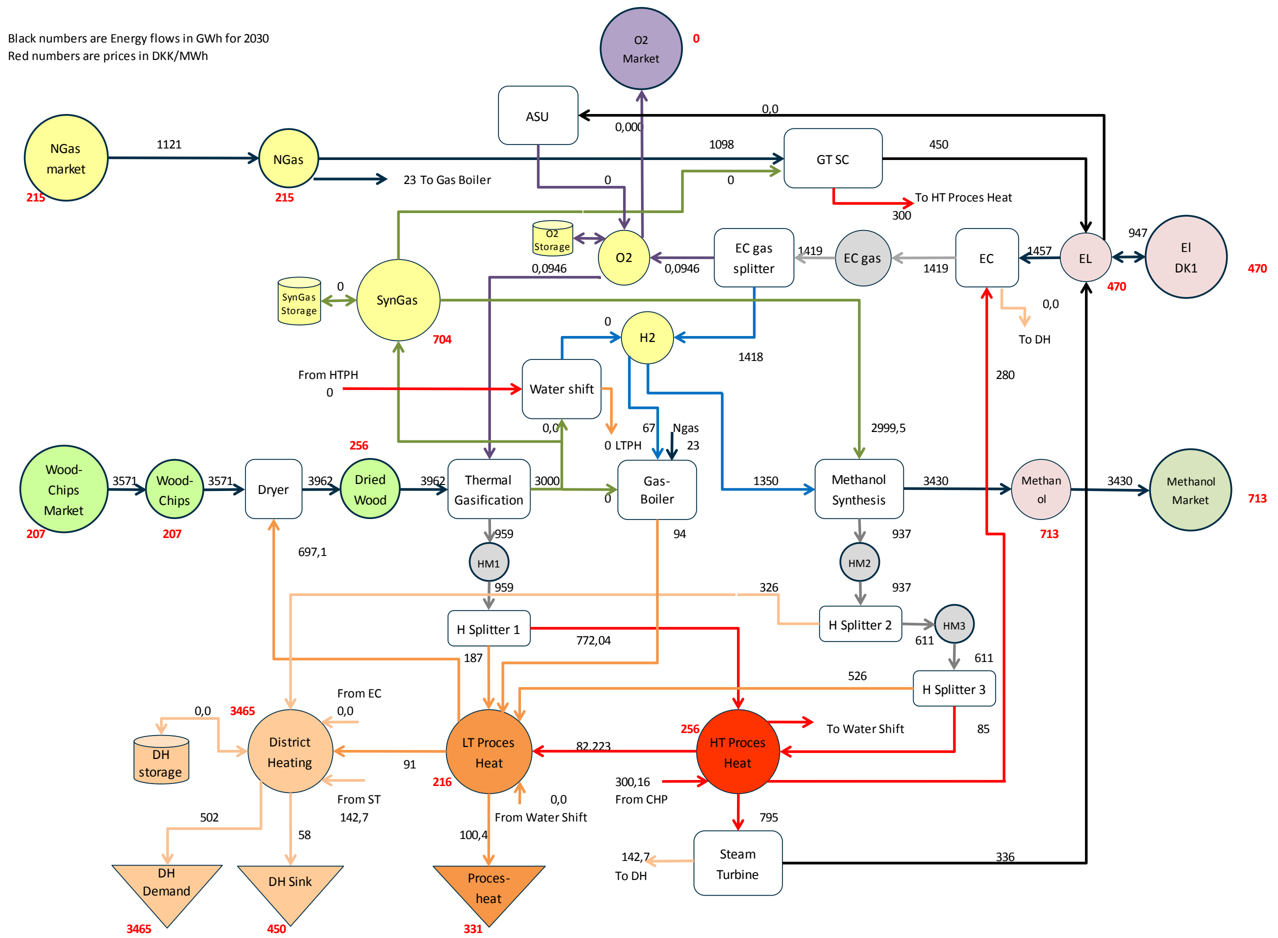

Figure 46: Energy flows for baseline model in 20130

9.1.7 Baseline model Key Figures

Plant Summary				
Production units	**Opt Size** *MW p Out.*	**Plant cost** *MDKK*	**FLE Op h** *h/y*	
Wood Chip Dryer	500	180	7.924	
Thermal Gasification and GC	379	1.779	7.924	
Methanol Synthesis and purification	433	571	7.924	
Water Shift Reactor	106	57	-	
Electrolysis Unit	170	750	8.323	
Simple Cycle Gas Turbine	200	834	2.251	
Steam Turbine	93	333	3.622	
Gas Boiler	17	6	5.638	
Air Separation Unit	-	-	-	
Energy Storages	**Opt. Size** *MWh*	**Plant cost** *MDKK*		
District Heat Storage	855	15		
Syn Gas Storage	0	-		
Oxygen Storage	0	-		
Total installed equip. CAPEX (MDKK)		**4.526**		
Total Plant CAPEX- incl. 30% cont. (MDKK)		**5.884**		
Production and consumption	**Quantity** *GWh/y*	**Price** *DKK/MWh*	**Income** *MDKK/y*	**Expenses** *MDKK/y*
Methanol produced	3.430	713	2.446	
District Heat produced (fixed price 85 DKK/GJ)	502	306	154	
Electricity produced	786	566	445	
Process Heat produced (fixed price 120 DKK/GJ)	100	432	43	
Heat sink (fixed price 0 DKK/GJ)	58	0	-	
Wood Chips consumed	3.571	207		739
Electricity consumed	1.733	461		799
Natural Gas consumed	1.121	215		241
Other costs				
O&M fixed				148
O&M var				85
CAPEX expense per year				397
Total			**3.088**	**2.409**
Yearly revenue				**678**
MeOH shadow price				**515**
IRR				**16%**
Energy efficiency (MeOH/input)				**61%**
Energy efficiency (MeOH+heat/input)				**72%**

Figure 47: Key figures for baseline model 2030

9.1.8 Baseline model Electrolysis Unit operation

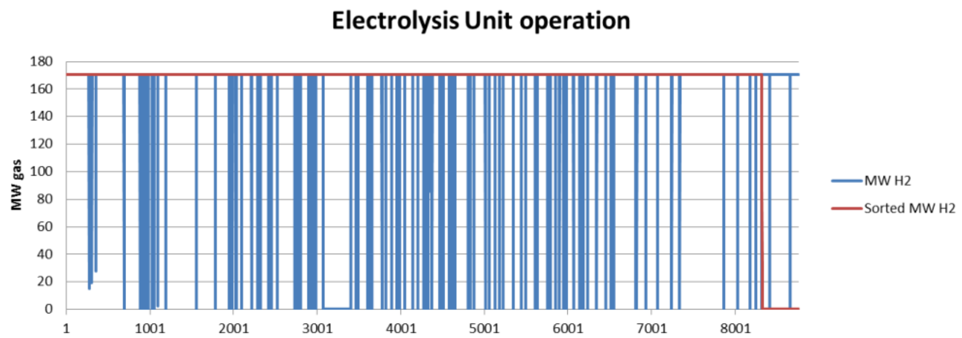

Figure 48: Electrolysis Unit operation for baseline model in 2030

9.2 Internal Rate of Return (IRR) at different MeOH prices

In this simulation the plant is optimized at different methanol price levels. The upper level is the estimated future production cost of 2. Generation bioethanol at 828 DKK/MWh [14] and the lower level is the estimated cost of gasoline plus CO_2 at 598 DKK/MWh.

High MeOH price:

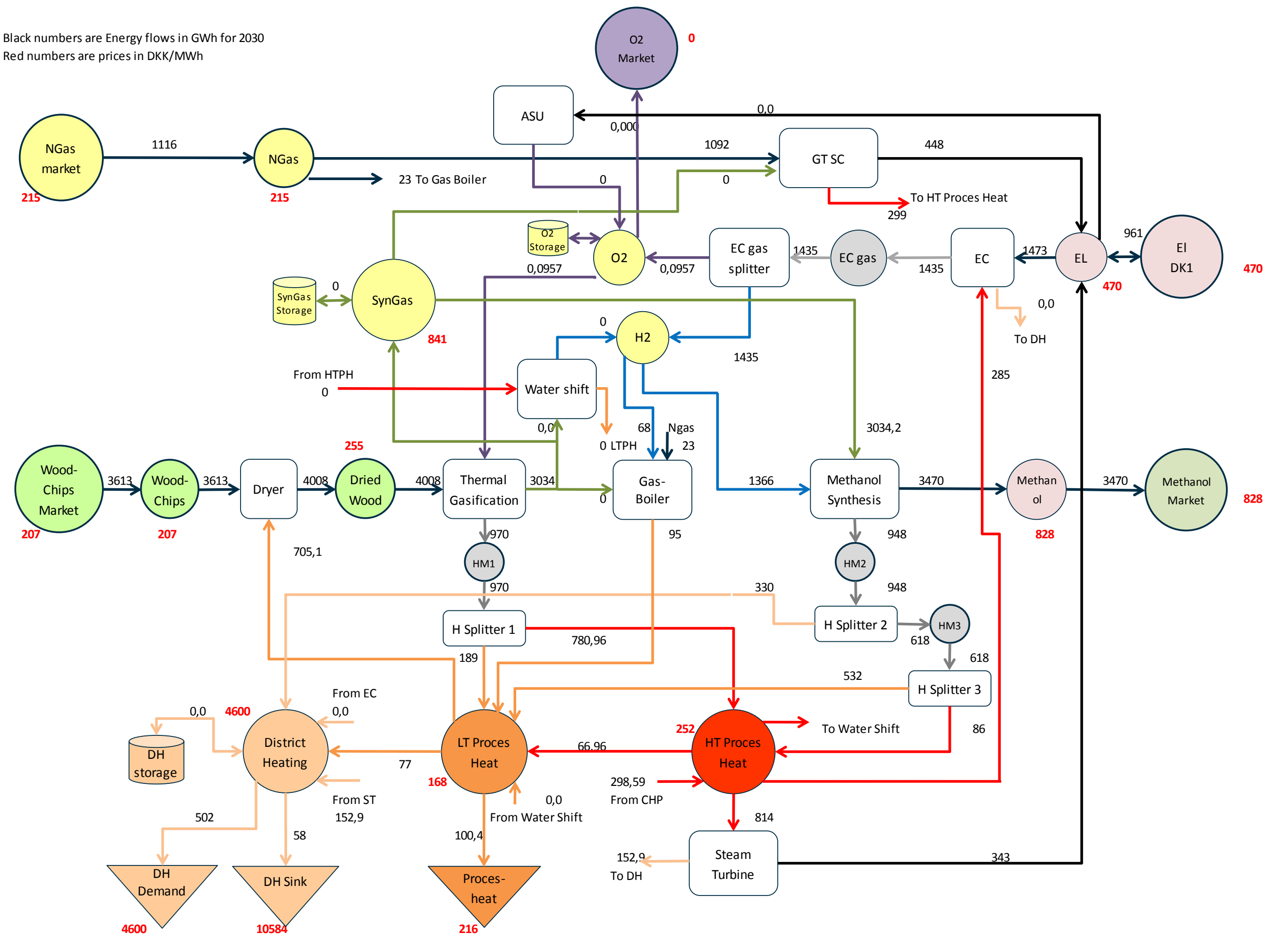

Figure 49: Energy flows for a high MeOH price scenario

Plant Summary				
Production units	**Opt Size** *MW p Out.*	**Plant cost** *MDKK*	**FLE Op h** *h/y*	
Wood Chip Dryer	500	180	8.015	
Thermal Gasification and GC	379	1.779	8.015	
Methanol Synthesis and purification	433	571	8.015	
Water Shift Reactor	-	-	-	
Electrolysis Unit	170	750	8.419	
Simple Cycle Gas Turbine	200	834	2.239	
Steam Turbine	91	326	3.780	
Gas Boiler	18	7	5.269	
Air Separation Unit	-	-	-	
Energy Storages	**Opt. Size** *MWh*	**Plant cost** *MDKK*		
District Heat Storage	847	14		
Syn Gas Storage	0	0		
Oxygen Storage	0	-		
Total installed equip. CAPEX (MDKK)		**4.462**		
Total Plant CAPEX- incl. 30% cont. (MDKK)		**5.801**		
Production and consumption	**Quantity** *GWh/y*	**Price** *DKK/MWh*	**Income** *MDKK/y*	**Expenses** *MDKK/y*
Methanol produced	3.470	828	2.873	
District Heat produced (fixed price 85 DKK/GJ)	502	306	154	
Electricity produced	791	564	446	
Process Heat produced (fixed price 120 DKK/GJ)	100	432	43	
Heat sink (fixed price 0 DKK/GJ)	58	0	-	
Wood Chips consumed	3.613	207		748
Electricity consumed	1.752	466		817
Natural Gas consumed	1.116	215		240
Other costs				
O&M fixed				145
O&M var				86
CAPEX expense per year				391
Total			**3.516**	**2.427**
Yearly revenue				**1.089**
MeOH shadow price				**514**
IRR				**23%**
Energy efficiency (MeOH/input)				**61%**
Energy efficiency (MeOH+heat/input)				**72%**

Figure 50: Key figures for high MeOH price scenario

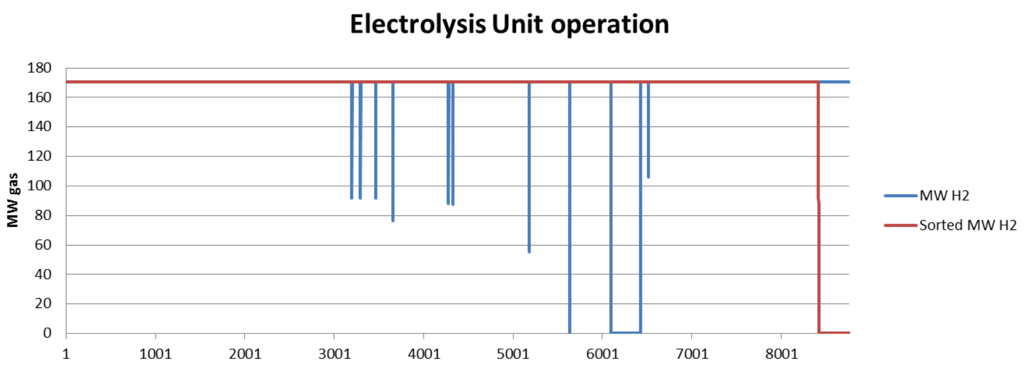

Figure 51: Electrolysis Unit operation at high MeOH price

Low MeOH price:

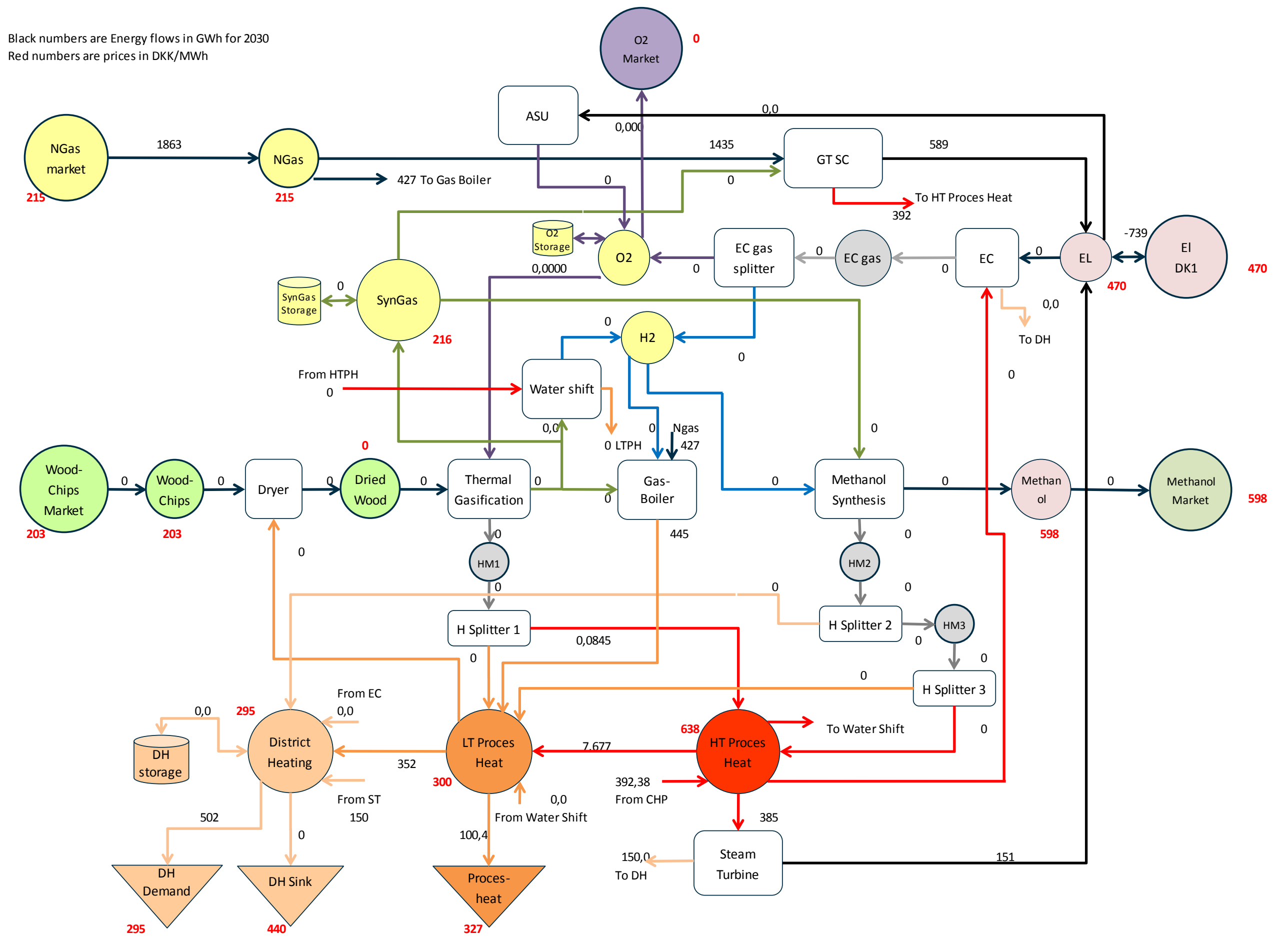

Figure 52: Energy flows for a low MeOH price scenario

Plant Summary				
Production units	**Opt Size** *MW p Out.*	**Plant cost** *MDKK*	**FLE Op h** *h/y*	
Wood Chip Dryer	500	180	-	
Thermal Gasification and GC	-	-	-	
Methanol Synthesis and purification	-	-	-	
Water Shift Reactor	-	-	-	
Electrolysis Unit	-	-	-	
Simple Cycle Gas Turbine	200	834	2.943	
Steam Turbine	60	215	2.517	
Gas Boiler	106	39	4.183	
Air Separation Unit	-	-	-	
Energy Storages	**Opt. Size** *MWh*	**Plant cost** *MDKK*		
District Heat Storage	591	10		
Syn Gas Storage	0	-		
Oxygen Storage	0	-		
Total installed equip. CAPEX (MDKK)		**1.279**		
Total Plant CAPEX- incl. 30% cont. (MDKK)		**1.662**		
Production and consumption	**Quantity** *GWh/y*	**Price** *DKK/MWh*	**Income** *MDKK/y*	**Expenses** *MDKK/y*
Methanol produced	-	598	-	
District Heat produced (fixed price 85 DKK/GJ)	502	306	154	
Electricity produced	739	576	426	
Process Heat produced (fixed price 120 DKK/GJ)	100	432	43	
Heat sink (fixed price 0 DKK/GJ)	0	0	-	
Wood Chips consumed	-	0		-
Electricity consumed	-	0		-
Natural Gas consumed	1.863	215		400
Other costs				
O&M fixed				36
O&M var				18
CAPEX expense per year				104
Total			**623**	**558**
Yearly revenue				**64**
MeOH shadow price				**-**
IRR				**8%**
Energy efficiency (MeOH/input)				**0%**
Energy efficiency (MeOH+heat/input)				**54%**

Figure 53: Key figures for low MeOH price scenario

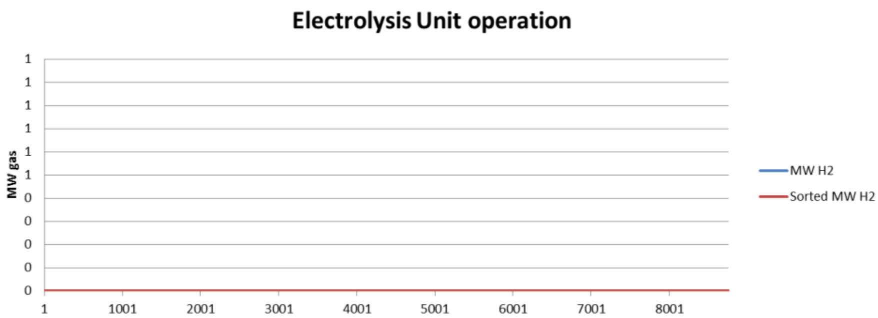

Figure 54: Electrolysis Unit operation at low MeOH price

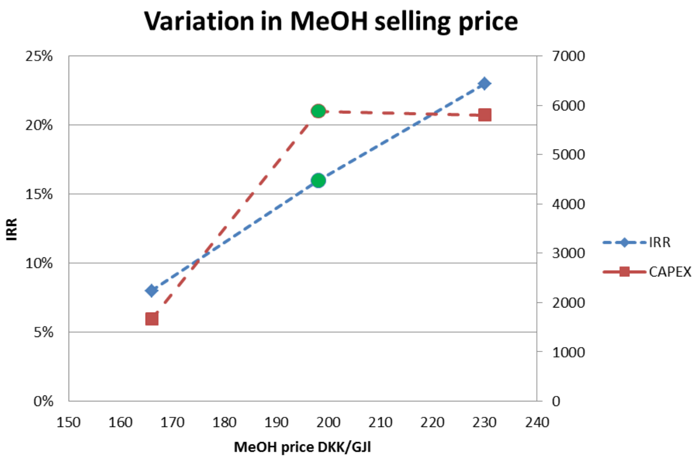

Figure 55: Variations in MeOH selling price. Green dots are baseline scenario

9.3 Variation in electricity price and profile

9.3.1 More oscillating electricity prices

In the 2030 electricity price estimate over a year, the oscillations in the price are not that high. With a much higher penetration of wind and PV, and a reluctance to invest in back-up capacities the oscillations could increase further. In the first sensitivity simulation, the average cost of the electricity in the 2030 forecast is found and for each hour the price distance to the average price is doubled. For negative prices, the price is set to 0 DKK/MWh as Sifre can't operate with negative prices. Figure 56 shows how the new price forecast looks like for the fourth of January 2030.

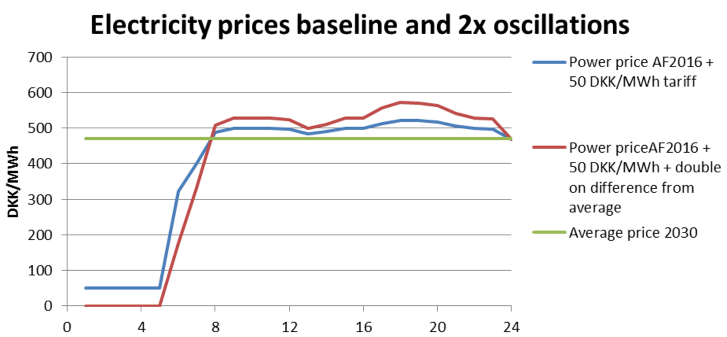

Figure 56: New electricity price forecast for 4.th Jan. 2030

9.3.1.1 Results

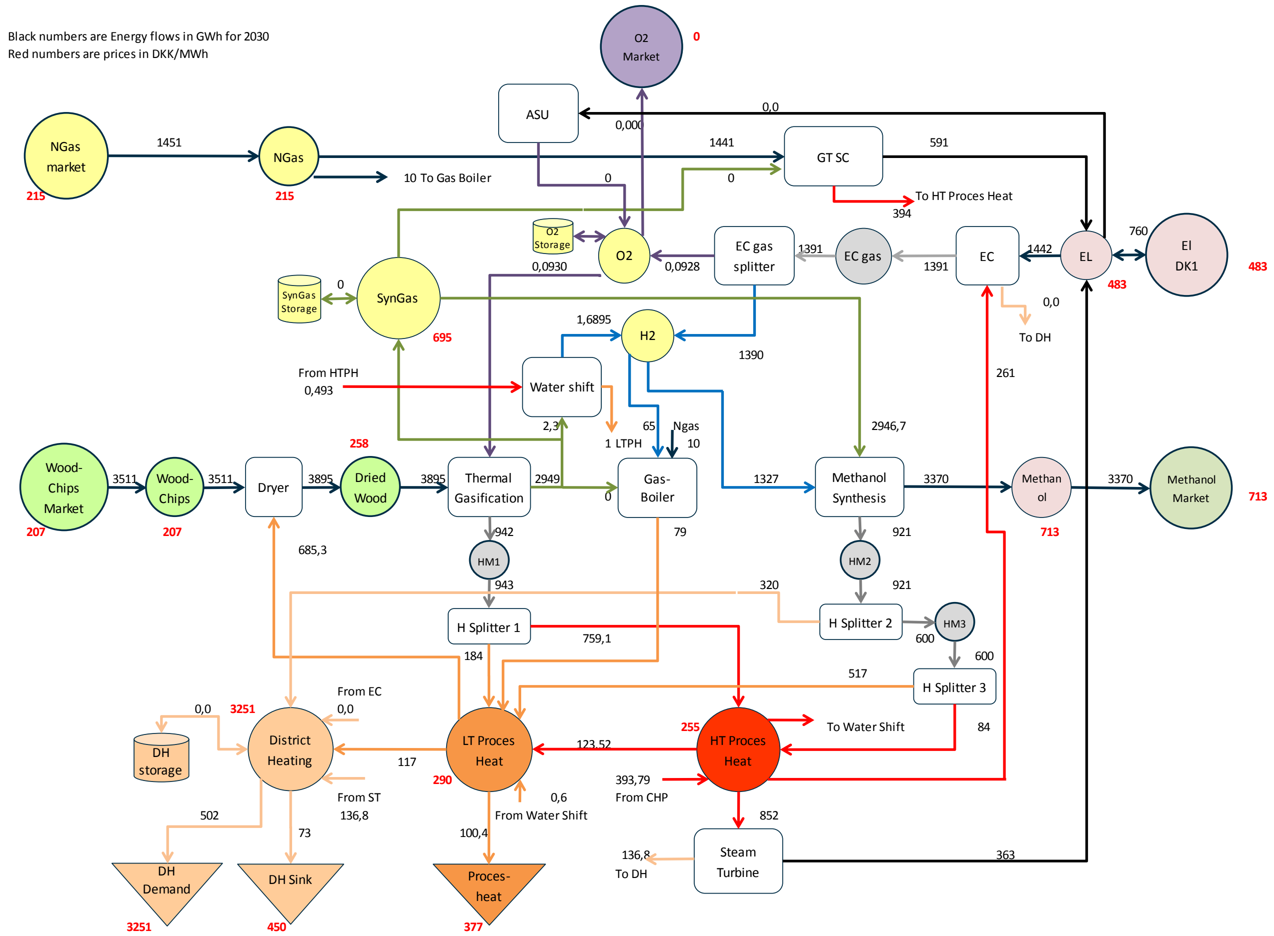

Figure 57: Energy flows for a 2x oscillating electricity price scenario

Plant Summary				
Production units	**Opt Size**	**Plant cost**	**FLE Op h**	
	MW p Out.	*MDKK*	*h/y*	
Wood Chip Dryer	500	180	7.790	
Thermal Gasification and GC	379	1.779	7.790	
Methanol Synthesis and purification	433	571	7.784	
Water Shift Reactor	106	57	16	
Electrolysis Unit	170	750	8.158	
Simple Cycle Gas Turbine	200	834	2.953	
Steam Turbine	93	333	3.908	
Gas Boiler	11	4	7.166	
Air Separation Unit	-	-	-	
Energy Storages	**Opt. Size**	**Plant cost**		
	MWh	*MDKK*		
District Heat Storage	1062	18		
Syn Gas Storage	0	-		
Oxygen Storage	0	-		
Total installed equip. CAPEX (MDKK)		**4.527**		
Total Plant CAPEX- incl. 30% cont. (MDKK)		**5.885**		
Production and consumption	**Quantity**	**Price**	**Income**	**Expenses**
	GWh/y	*DKK/MWh*	*MDKK/y*	*MDKK/y*
Methanol produced	3.370	713	2.403	
District Heat produced (fixed price 85 DKK/GJ)	502	306	154	
Electricity produced	953	642	612	
Process Heat produced (fixed price 120 DKK/GJ)	100	432	43	
Heat sink (fixed price 0 DKK/GJ)	73	0	-	
Wood Chips consumed	3.511	207		727
Electricity consumed	1.713	455		779
Natural Gas consumed	1.451	215		312
Other costs				
O&M fixed				148
O&M var				88
CAPEX expense per year				397
Total			**3.212**	**2.451**
Yearly revenue				**761**
MeOH shadow price				**487**
IRR				**17%**
Energy efficiency (MeOH/input)				**59%**
Energy efficiency (MeOH+heat/input)				**69%**

Figure 58: Key figures for 2x oscillating electricity price scenario

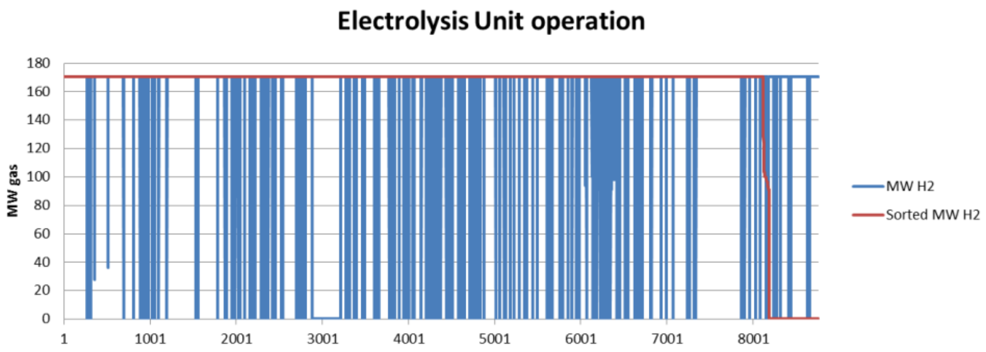

Figure 59: Electrolysis Unit operation at 2x oscillating electricity price scenario

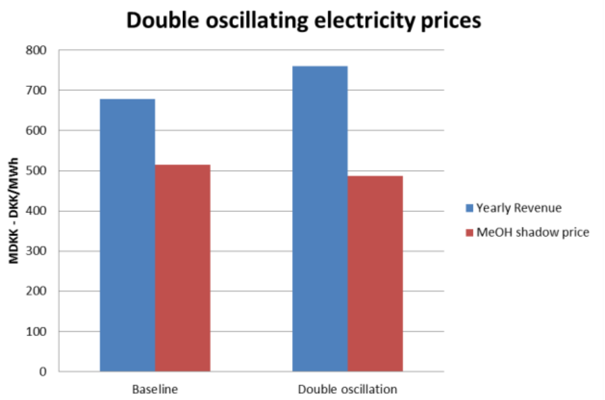

Figure 60: Yearly revenue and MeOH shadow prices at double oscillating power prices

9.3.2 Lower electricity prices

In the second sensitivity calculation the electricity price in the baseline scenario is lowered by 100 DKK/MWh and 200 DKK/MWh. These simulations shows scenarios where the electricity price still only reflects the marginal costs of power production and the VE penetration is very high. Again the lower limit for the price is 0 due to Sifre.

9.3.2.1 Low electricity price

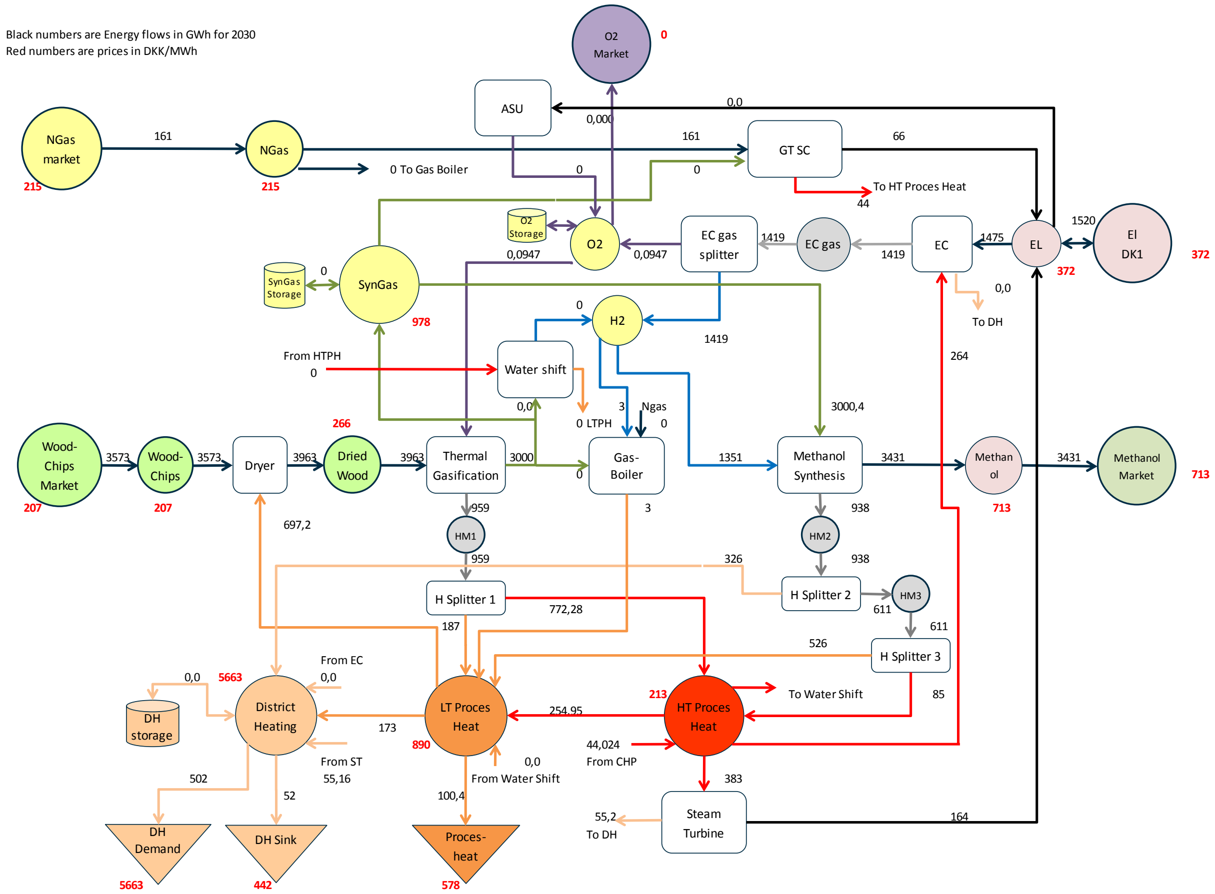

Figure 61: Energy flows for a baseline electricity price minus 100 DKK/MWh scenario

Plant Summary				
Production units	**Opt Size**	**Plant cost**	**FLE Op h**	
	MW p Out.	*MDKK*	*h/y*	
Wood Chip Dryer	500	180	7.926	
Thermal Gasification and GC	379	1.779	7.926	
Methanol Synthesis and purification	433	571	7.926	
Water Shift Reactor	-	-	-	
Electrolysis Unit	170	750	8.325	
Simple Cycle Gas Turbine	200	834	330	
Steam Turbine	32	115	5.112	
Gas Boiler	0	0	8.371	
Air Separation Unit	-	-	-	
Energy Storages	**Opt. Size**	**Plant cost**		
	MWh	*MDKK*		
District Heat Storage	1074	18		
Syn Gas Storage	0	0		
Oxygen Storage	0	-		
Total installed equip. CAPEX (MDKK)		**4.249**		
Total Plant CAPEX- incl. 30% cont. (MDKK)		**5.523**		
Production and consumption	**Quantity**	**Price**	**Income**	**Expenses**
	GWh/y	*DKK/MWh*	*MDKK/y*	*MDKK/y*
Methanol produced	3.431	713	2.447	
District Heat produced (fixed price 85 DKK/GJ)	502	306	154	
Electricity produced	230	465	107	
Process Heat produced (fixed price 120 DKK/GJ)	100	432	43	
Heat sink (fixed price 0 DKK/GJ)	52	0	-	
Wood Chips consumed	3.573	207		740
Electricity consumed	1.751	361		632
Natural Gas consumed	161	215		35
Other costs				
O&M fixed				138
O&M var				73
CAPEX expense per year				375
Total			**2.751**	**1.993**
Yearly revenue				**758**
MeOH shadow price				**492**
IRR				**18%**
Energy efficiency (MeOH/input)				**65%**
Energy efficiency (MeOH+heat/input)				**77%**

Figure 62: Key figures for a baseline electricity price minus 100 DKK/MWh scenario

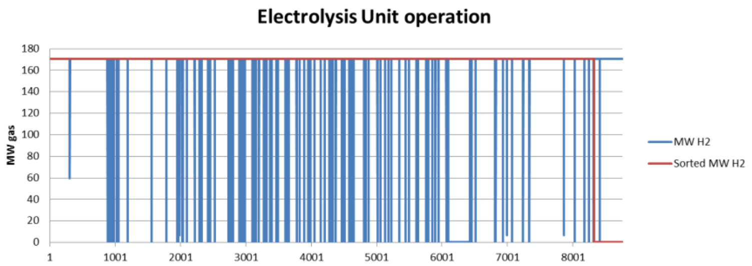

Figure 63: Electrolysis Unit operation at a baseline electricity price minus 100 DKK/MWh scenar-io

9.3.2.2 Very low electricity price

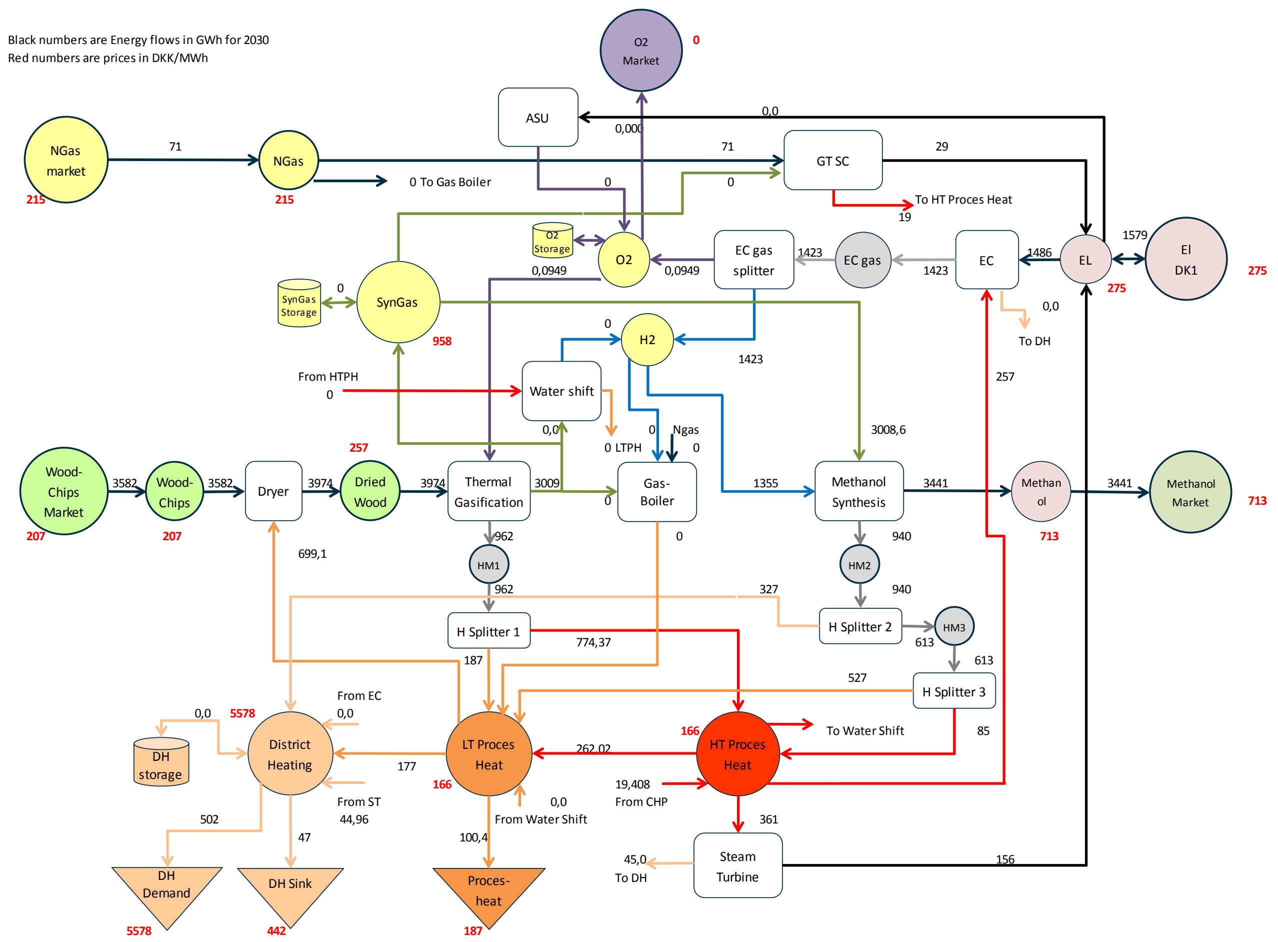

Figure 64: Energy flows for a baseline electricity price minus 200 DKK/MWh scenario

Plant Summary				
Production units	**Opt Size**	**Plant cost**	**FLE Op h**	
	MW p Out.	*MDKK*	*h/y*	
Wood Chip Dryer	500	180	7.948	
Thermal Gasification and GC	379	1.779	7.948	
Methanol Synthesis and purification	433	571	7.948	
Water Shift Reactor	-	-	-	
Electrolysis Unit	170	750	8.348	
Simple Cycle Gas Turbine	200	834	146	
Steam Turbine	32	115	4.876	
Gas Boiler	-	-	-	
Air Separation Unit	-	-	-	
Energy Storages	**Opt. Size**	**Plant cost**		
	MWh	*MDKK*		
District Heat Storage	1043	18		
Syn Gas Storage	0	-		
Oxygen Storage	0	-		
Total installed equip. CAPEX (MDKK)		**4.247**		
Total Plant CAPEX- incl. 30% cont. (MDKK)		**5.521**		
Production and consumption	**Quantity**	**Price**	**Income**	**Expenses**
	GWh/y	*DKK/MWh*	*MDKK/y*	*MDKK/y*
Methanol produced	3.441	713	2.453	
District Heat produced (fixed price 85 DKK/GJ)	502	306	154	
Electricity produced	185	348	64	
Process Heat produced (fixed price 120 DKK/GJ)	100	432	43	
Heat sink (fixed price 0 DKK/GJ)	47	0	-	
Wood Chips consumed	3.582	207		741
Electricity consumed	1.763	267		471
Natural Gas consumed	71	215		15
Other costs				
O&M fixed				138
O&M var				72
CAPEX expense per year				375
Total			**2.714**	**1.813**
Yearly revenue				**901**
MeOH shadow price				**451**
IRR				**21%**
Energy efficiency (MeOH/input)				**66%**
Energy efficiency (MeOH+heat/input)				**77%**

Figure 65: Key figures for a baseline electricity price minus 200 DKK/MWh scenario

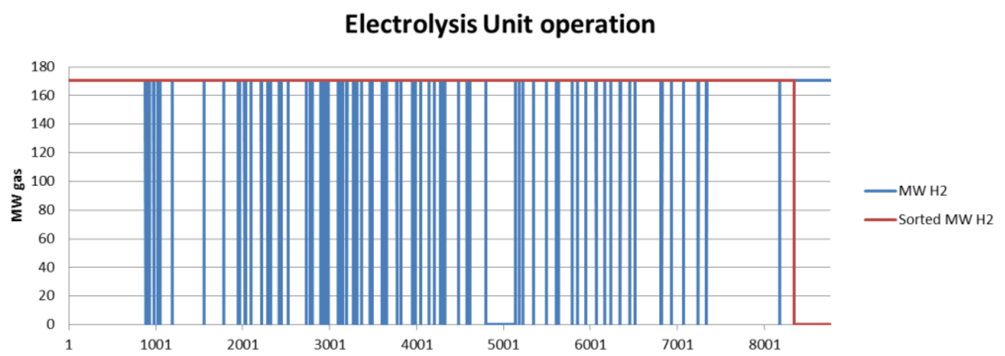

Figure 66: Electrolysis Unit operation at a baseline electricity price minus 200 DKK/MWh scenario

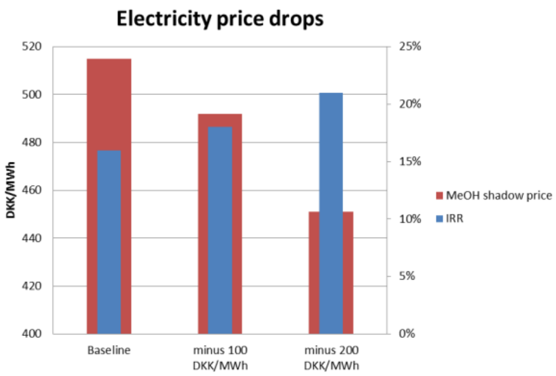

Figure 67: Changes in MeOH and IRR at lower electricity price

9.4 Higher biomass cost

In this scenario the biomass cost is higher than expected due to high demand and limited production. The biomass cost is raised by 20% and 40% compared to the baseline scenario.

9.4.1 Biomass price + 20% scenario

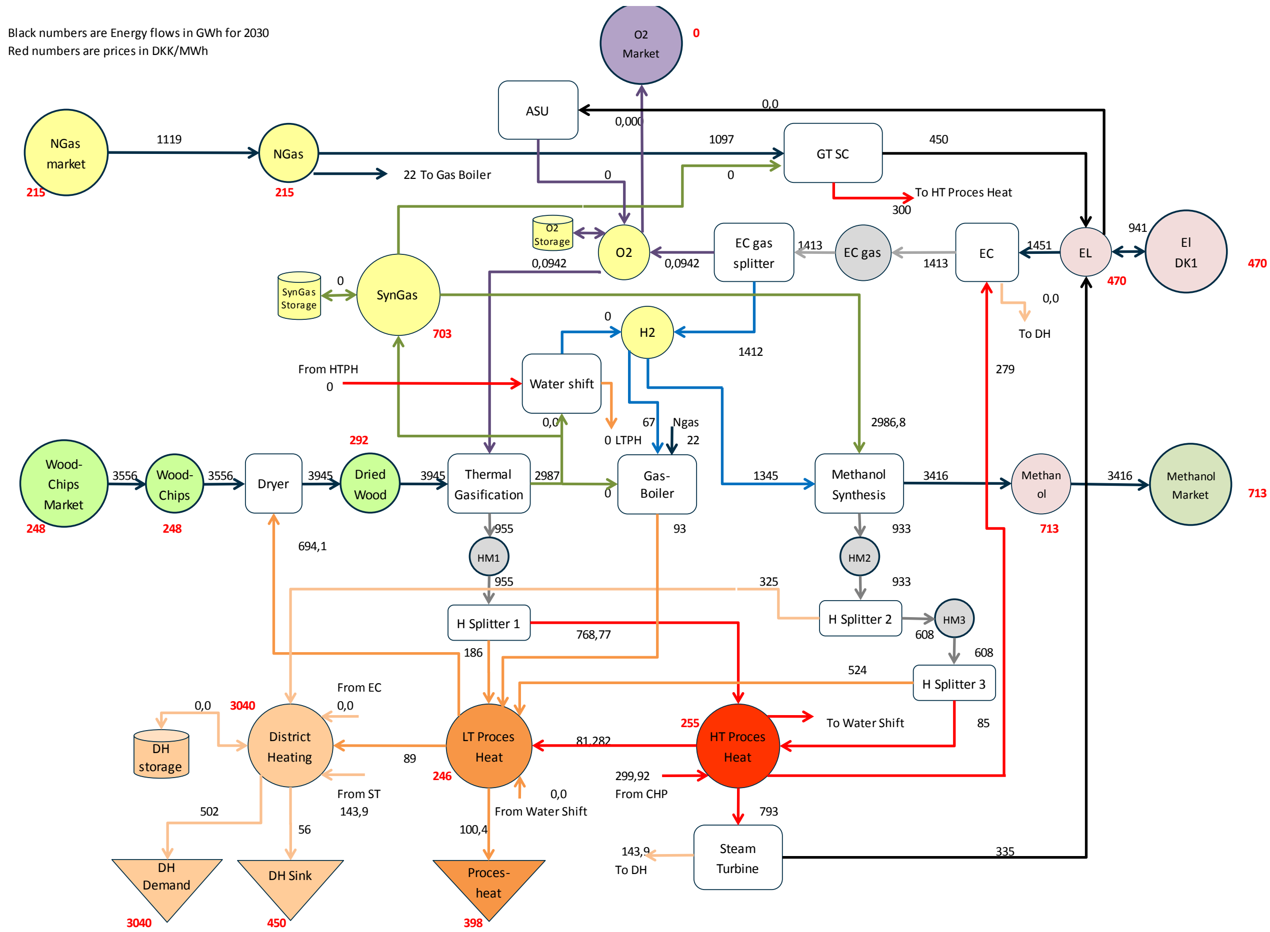

Figure 68: Energy flows for a high biomass price scenario

Plant Summary				
Production units	**Opt Size** *MW p Out.*	**Plant cost** *MDKK*	**FLE Op h** *h/y*	
Wood Chip Dryer	500	180	7.890	
Thermal Gasification and GC	379	1.779	7.890	
Methanol Synthesis and purification	433	571	7.890	
Water Shift Reactor	106	57	-	
Electrolysis Unit	170	750	8.288	
Simple Cycle Gas Turbine	200	834	2.249	
Steam Turbine	93	333	3.612	
Gas Boiler	17	6	5.547	
Air Separation Unit	-	-	-	
Energy Storages	**Opt. Size** *MWh*	**Plant cost** *MDKK*		
District Heat Storage	855	15		
Syn Gas Storage	0	-		
Oxygen Storage	0	-		
Total installed equip. CAPEX (MDKK)		**4.526**		
Total Plant CAPEX- incl. 30% cont. (MDKK)		**5.884**		
Production and consumption	**Quantity** *GWh/y*	**Price** *DKK/MWh*	**Income** *MDKK/y*	**Expenses** *MDKK/y*
Methanol produced	3.416	713	2.435	
District Heat produced (fixed price 85 DKK/GJ)	502	306	154	
Electricity produced	785	565	444	
Process Heat produced (fixed price 120 DKK/GJ)	100	432	43	
Heat sink (fixed price 0 DKK/GJ)	56	0	-	
Wood Chips consumed	3.556	248		883
Electricity consumed	1.726	460		793
Natural Gas consumed	1.119	215		240
Other costs				
O&M fixed				148
O&M var				85
CAPEX expense per year				397
Total			**3.076**	**2.547**
Yearly revenue				**530**
MeOH shadow price				**558**
IRR				**14%**
Energy efficiency (MeOH/input)				**61%**
Energy efficiency (MeOH+heat/input)				**72%**

Figure 69: Key figures for high Biomass price scenario

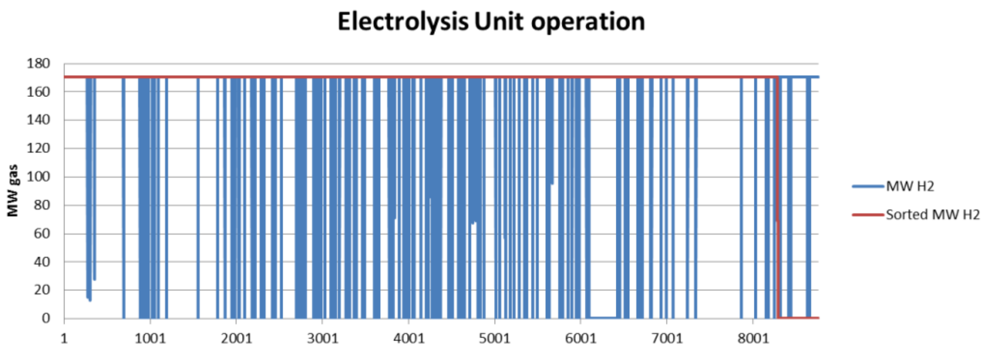

Figure 70: Electrolysis Unit operation at high biomass price

9.4.2 Biomass price + 40% scenario

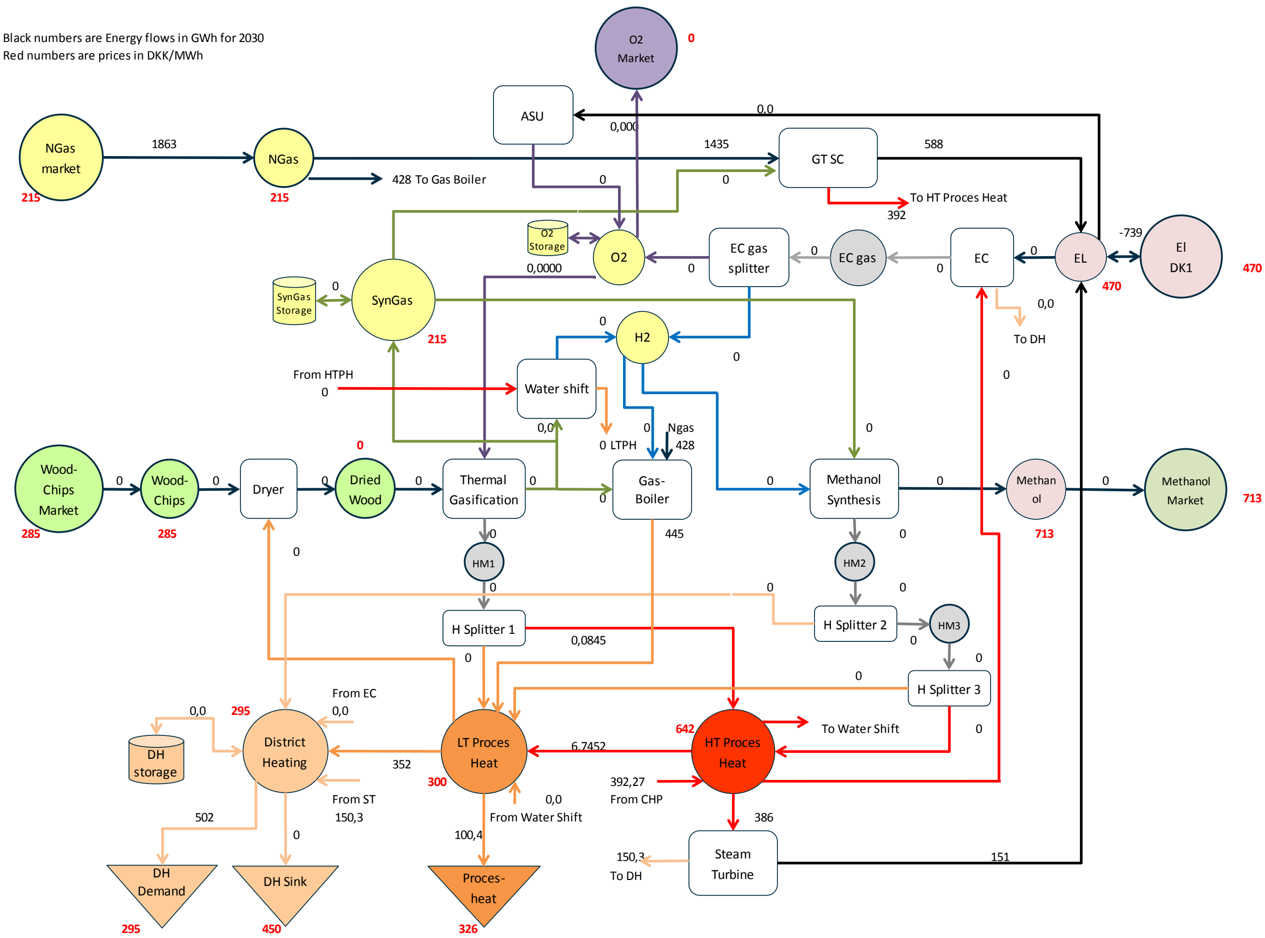

Figure 71: Energy flows for a very high biomass price scenario

Plant Summary				
Production units	**Opt Size** *MW p Out.*	**Plant cost** *MDKK*	**FLE Op h** *h/y*	
Wood Chip Dryer	500	180	-	
Thermal Gasification and GC	-	-	-	
Methanol Synthesis and purification	-	-	-	
Water Shift Reactor	-	-	-	
Electrolysis Unit	-	-	-	
Simple Cycle Gas Turbine	200	834	2.942	
Steam Turbine	60	215	2.523	
Gas Boiler	106	39	4.189	
Air Separation Unit	-	-	-	
Energy Storages	**Opt. Size** *MWh*	**Plant cost** *MDKK*		
District Heat Storage	591	10		
Syn Gas Storage	0	-		
Oxygen Storage	0	-		
Total installed equip. CAPEX (MDKK)		**1.279**		
Total Plant CAPEX- incl. 30% cont. (MDKK)		**1.662**		
Production and consumption	**Quantity** *GWh/y*	**Price** *DKK/MWh*	**Income** *MDKK/y*	**Expenses** *MDKK/y*
Methanol produced	-	713	-	
District Heat produced (fixed price 85 DKK/GJ)	502	306	154	
Electricity produced	739	576	426	
Process Heat produced (fixed price 120 DKK/GJ)	100	432	43	
Heat sink (fixed price 0 DKK/GJ)	0	0	-	
Wood Chips consumed	-	0		-
Electricity consumed	-	0		-
Natural Gas consumed	1.863	215		400
Other costs				
O&M fixed				36
O&M var				18
CAPEX expense per year				104
Total			**623**	**558**
Yearly revenue				**65**
MeOH shadow price				-
IRR				**8%**
Energy efficiency (MeOH/input)				**0%**
Energy efficiency (MeOH+heat/input)				**54%**

Figure 72: Key figures for very high Biomass price scenario

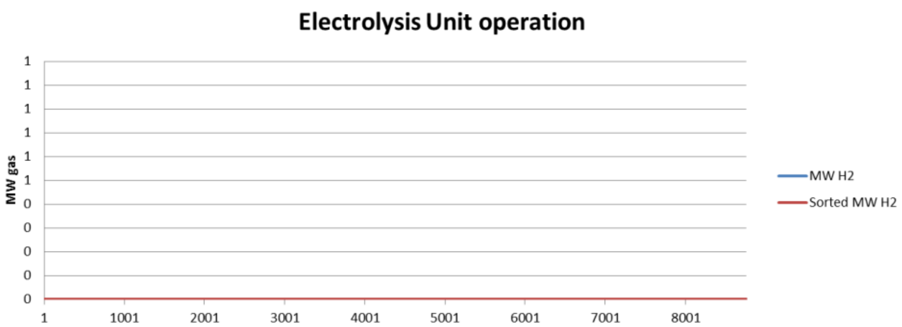

Figure 73: Electrolysis Unit operation at very high biomass price

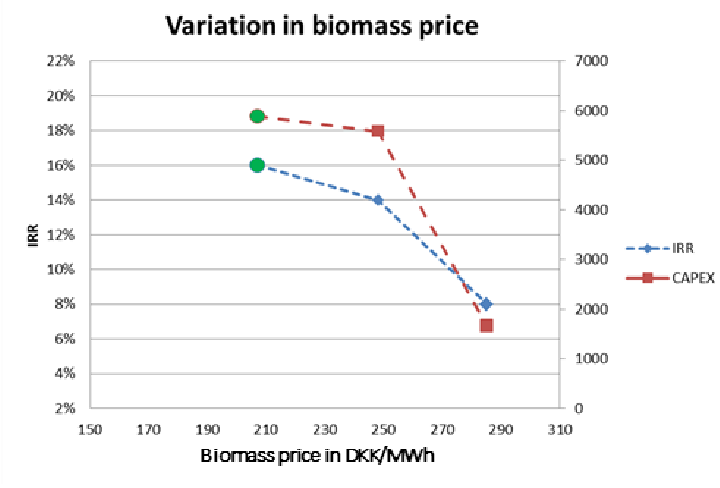

Figure 74: IRR and CAPEX at variation in biomass prices. Green dots is for the baseline scenario

9.5 Forced ASU operation – cost of flexibility

In the baseline model it is not feasible to invest in an oxygen production unit (ASU) and oxygen storage. But such a unit and storage would increase the flexibility of the plant considerably, as the biomass-to-methanol process would be able to operate without the Electrolysis Unit in operation. Then the Electrolysis unit with up to 200 MW of electricity consumption would be able to act directly in the regulation market without shutting down the total plant. The benefit of such a capability is not taken into account in the Sifre/ADAPTS optimization. Therefore has been chosen to calculate the cost of including this capability. This cost can then be compared to estimated benefits of acting on the regulation market in 2030.

In this simulation a minimum size of the ASU at 0.013 MW has been set. This is same output of oxygen as the Electrolysis Unit in the baseline scenario. Furthermore the Oxygen storage has been set with a minimum capacity of 2.5 hours O_2 production.

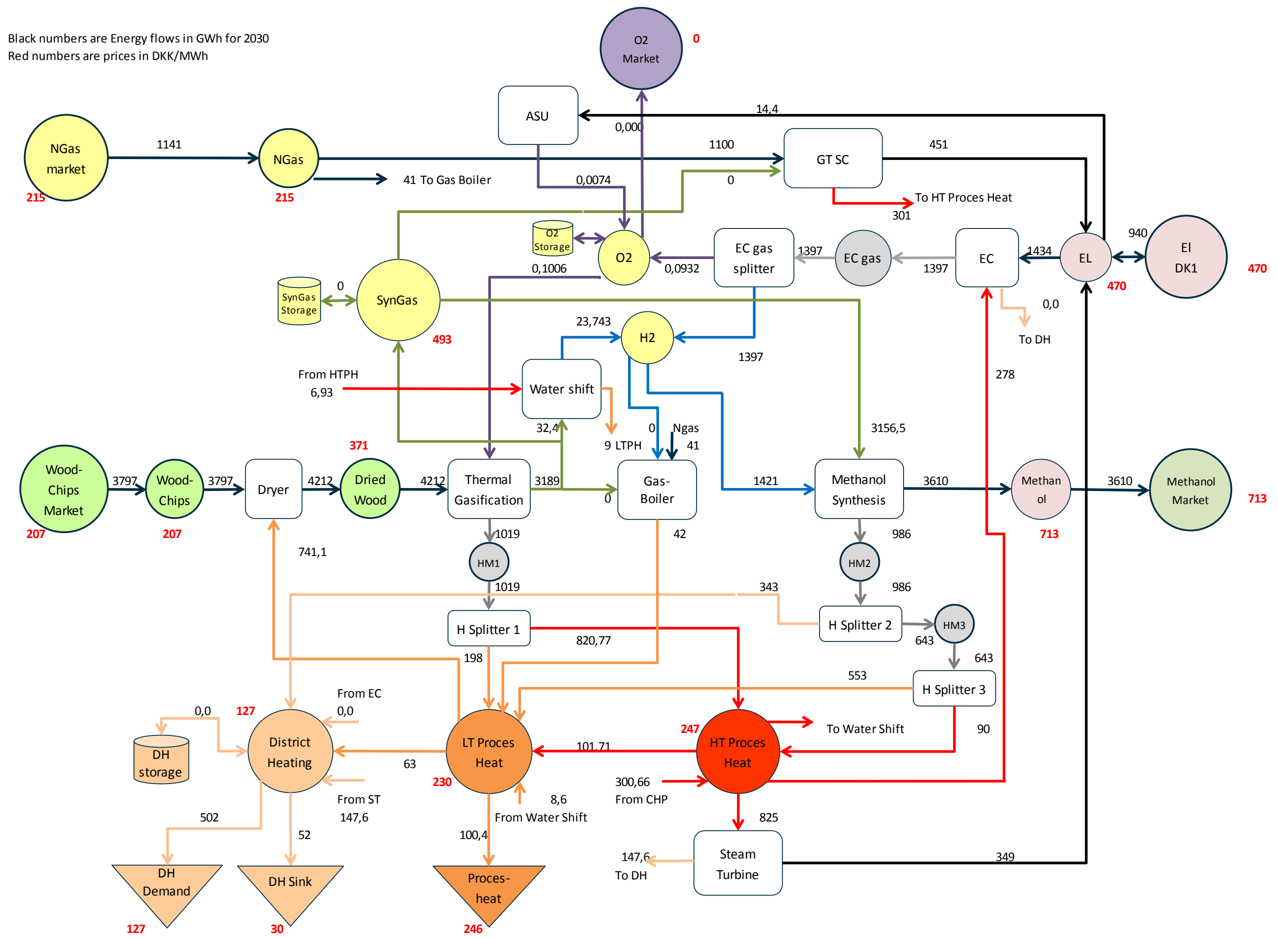

Figure 75: Energy flows for a forced ASU investment scenario

Plant Summary				
Production units	**Opt Size**	**Plant cost**	**FLE Op h**	
	MW p Out.	*MDKK*	*h/y*	
Wood Chip Dryer	500	180	8.424	
Thermal Gasification and GC	379	1.779	8.424	
Methanol Synthesis and purification	433	571	8.338	
Water Shift Reactor	106	57	225	
Electrolysis Unit	170	750	8.199	
Simple Cycle Gas Turbine	200	834	2.255	
Steam Turbine	93	333	3.761	
Gas Boiler	17	6	2.543	
Air Separation Unit	0,0114	182	647	
Energy Storages	**Opt. Size**	**Plant cost**		
	MWh	*MDKK*		
District Heat Storage	855	15		
Syn Gas Storage	0	0		
Oxygen Storage	0,030	9		
Total installed equip. CAPEX (MDKK)		**4.717**		
Total Plant CAPEX- incl. 30% cont. (MDKK)		**6.132**		
Production and consumption	**Quantity**	**Price**	**Income**	**Expenses**
	GWh/y	*DKK/MWh*	*MDKK/y*	*MDKK/y*
Methanol produced	3.610	713	2.574	
District Heat produced (fixed price 85 DKK/GJ)	502	306	154	
Electricity produced	800	564	451	
Process Heat produced (fixed price 120 DKK/GJ)	100	432	43	
Heat sink (fixed price 0 DKK/GJ)	52	0	-	
Wood Chips consumed	3.797	207		786
Electricity consumed	1.741	458		797
Natural Gas consumed	1.141	215		245
Other costs				
O&M fixed				153
O&M var				90
CAPEX expense per year				414
Total			**3.222**	**2.485**
Yearly revenue				**737**
MeOH shadow price				**509**
IRR				**17%**
Energy efficiency (MeOH/input)				**61%**
Energy efficiency (MeOH+heat/input)				**72%**

Figure 76: Key figures a forced ASU investment scenario

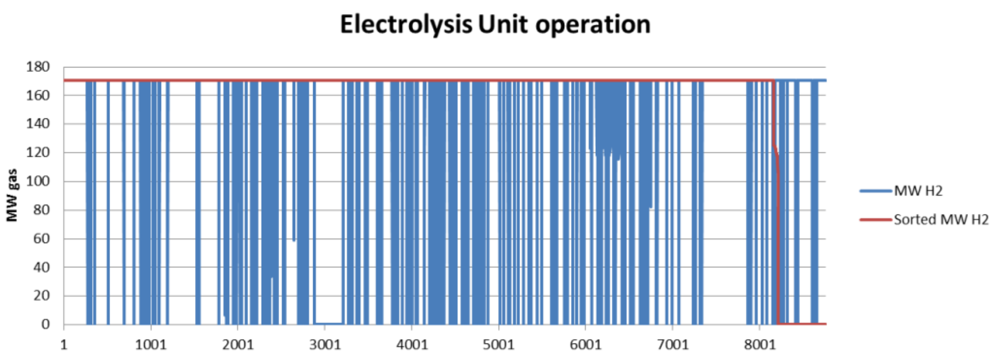

Figure 77: Electrolysis Unit operation at a forced ASU investment price

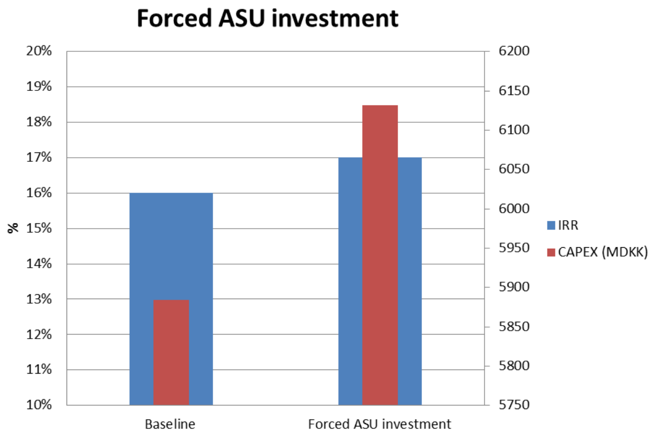

Figure 78: Key Figures at forced ASU investment

The results for the forced ASU investment scenario are quite surprising. In no single modeled scenario Sifre/ADAPT find a solution with ASU investment feasible. But in this scenario, where the ASU investment is forced into the baseline model, the feasibility of the plant actually increases despite of the higher investment cost.

It looks like the investment in extra flexibility is feasible without even taking the possible income from acting on the regulation market into account.

9.6 Green Syn Fuel composition on syngas versus baseline composition

The H_2/CO ratio of the raw syngas in the base case is: 20.1/15.8 = 1.27 [3]. This data is based on a 25 bar gasification process. I the Green Sun Fuel report [2] the gasification pressure is chosen to 10 bar. In this report, the H_2/CO ratio is lower (28.6/26.7 = 1.07) [2]. The lower ratio demands more H_2 supply, and thereby more electrolysis operation. This is interesting because it will change the H_2/O_2 consumption and result in an O_2 surplus instead of a H_2 surplus. An O_2 surplus will open the operation of the electrolysis for more flexible operation due to electricity market price changes.

A new H2/CO ratio from the gasifier demands a new SynGas/H2 ration to the Methanol Synthesis.

The M-ratio still needs to be 2.05 at the Methanol Synthesis inlet

$$M = \frac{H_2 - CO_2}{CO + CO_2}$$

As described some hydrogen is recirculated from the purge gas. This recirculation raises the M-ratio 0.13. So the M- ratio before the hydrogen is added has to be: 1.92.

As the CO_2 content is 3% after the CO_2 scrubber, the H_2 content can be calculated:

1.92 = (x-3)/(97-x+3)

x = 66.8

The mole fraction of hydrogen has to be 66.8% at the inlet to the methanol synthesis and purification unit. To raise the level to 66.8% further 58.7 mole of H_2 has to be added per 100 mole raw syn gas.

This has to be converted to energy terms to be used in Sifre.

As CO represents approximately 46% of the syngas after CO_2 and H_2O removal, approximately 0.46 Mole of H_2 has to be added to 1 Mole of cleaned syngas.

LHV:

CO: 283 kJ/Mole, H_2: 244 kJ/Mole

1 Mole of cleaned syn gas has a LHV at: 255 kJ/Mole

0.587 Mole of H_2 has a LHV at: 143 KJ

Thus the energy input to Methanol synthesis unit has to be: 64% cleaned syn gas and 36% H_2.

By fixing this ratio in the Production Unit for Methanol Synthesis in Sifre, the simulation forces to model to produce the needed H_2 either by Electrolysis or by Water Shift Reaction.

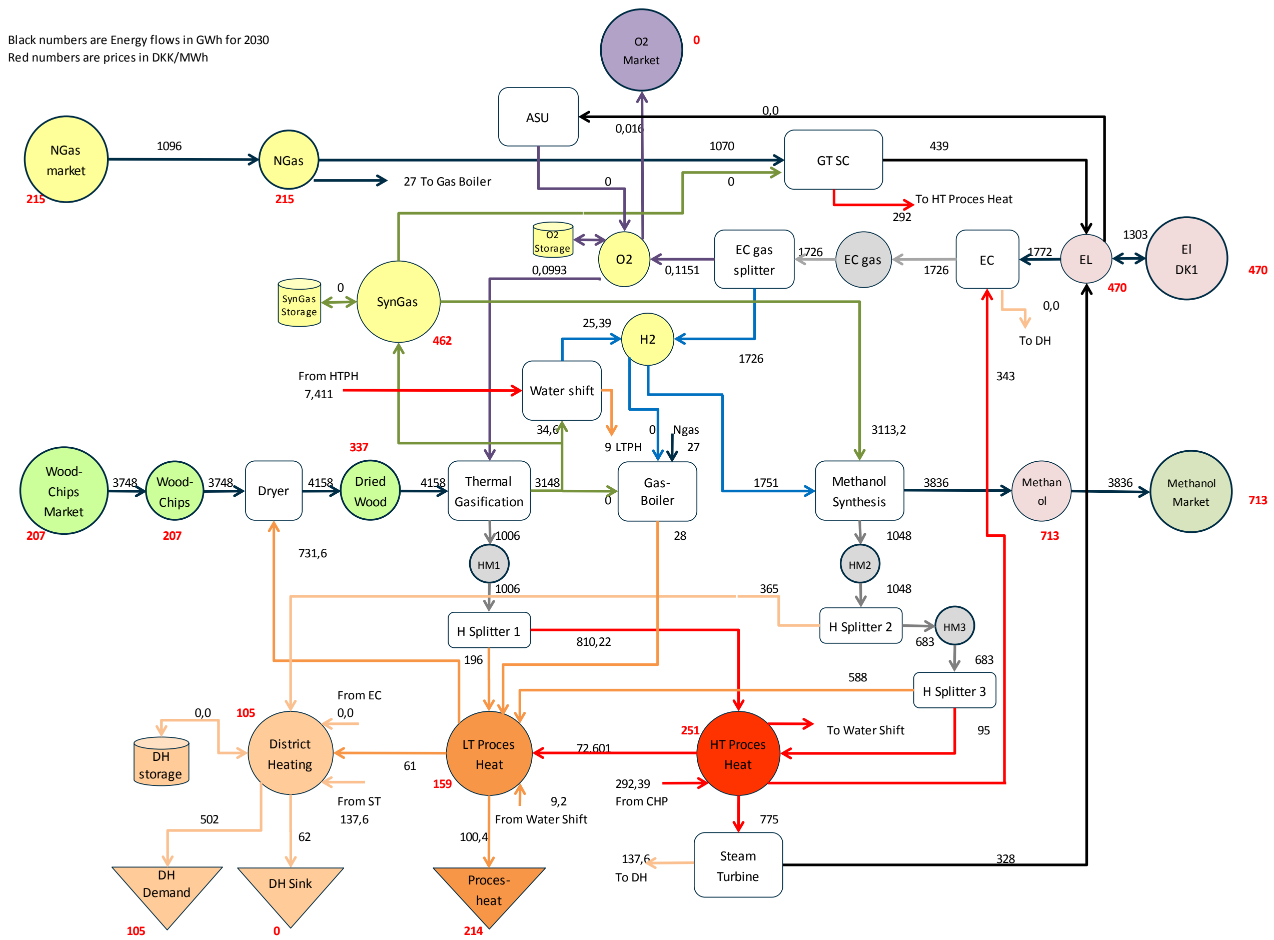

Figure 79: Energy flows for a GSF SynGas composition scenario

Plant Summary				
Production units	**Opt Size** *MW p Out.*	**Plant cost** *MDKK*	**FLE Op h** *h/y*	
Wood Chip Dryer	500	180	8.316	
Thermal Gasification and GC	379	1.779	8.316	
Methanol Synthesis and purification	466	616	8.224	
Water Shift Reactor	120	65	211	
Electrolysis Unit	213	937	8.105	
Simple Cycle Gas Turbine	200	417	2.193	
Steam Turbine	91	326	3.614	
Gas Boiler	12	4	2.351	
Air Separation Unit	-	-	-	
Energy Storages	**Opt. Size** *MWh*	**Plant cost** *MDKK*		
District Heat Storage	843	14		
Syn Gas Storage	0	0		
Oxygen Storage	0	-		
Total installed equip. CAPEX (MDKK)		**4.339**		
Total Plant CAPEX- incl. 30% cont. (MDKK)		**5.640**		
Production and consumption	**Quantity** *GWh/y*	**Price** *DKK/MWh*	**Income** *MDKK/y*	**Expenses** *MDKK/y*
Methanol produced	3.836	713	2.735	
District Heat produced (fixed price 85 DKK/GJ)	502	306	154	
Electricity produced	767	565	433	
Process Heat produced (fixed price 120 DKK/GJ)	100	432	43	
Heat sink (fixed price 0 DKK/GJ)	62	0	-	
Wood Chips consumed	3.748	207		776
Electricity consumed	2.069	457		946
Natural Gas consumed	1.096	215		236
Other costs				
O&M fixed				154
O&M var				88
CAPEX expense per year				384
Total			**3.366**	**2.584**
Yearly revenue				**782**
MeOH shadow price				**509**
IRR				**18%**
Energy efficiency (MeOH/input)				**62%**
Energy efficiency (MeOH+heat/input)				**72%**

Figure 80: Key figures for GSF SynGas composition scenario

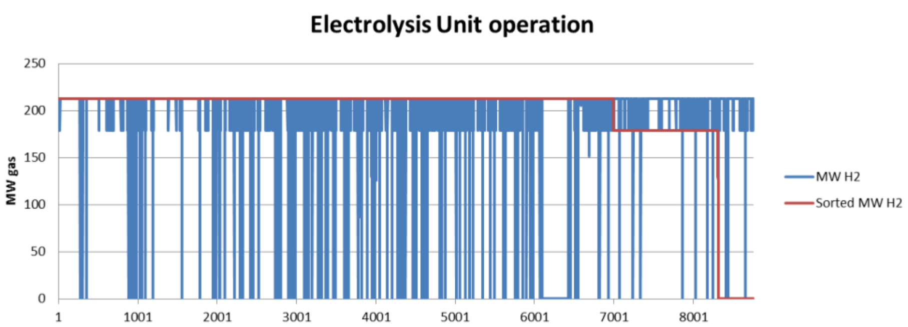

Figure 81: Electrolysis Unit operation at GSF SynGas composition

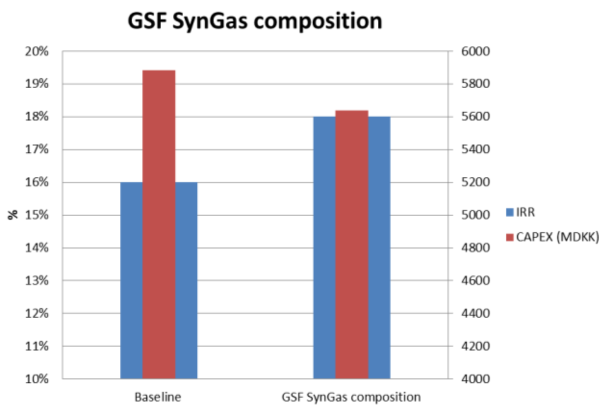

Figure 82: Key figures at GSF SynGas composition

9.7 Investment cost variations

All equipment cost are in the first simulation reduced 30% and then in the second simulation raised with 30%

9.7.1 Investment costs reduced with 30%

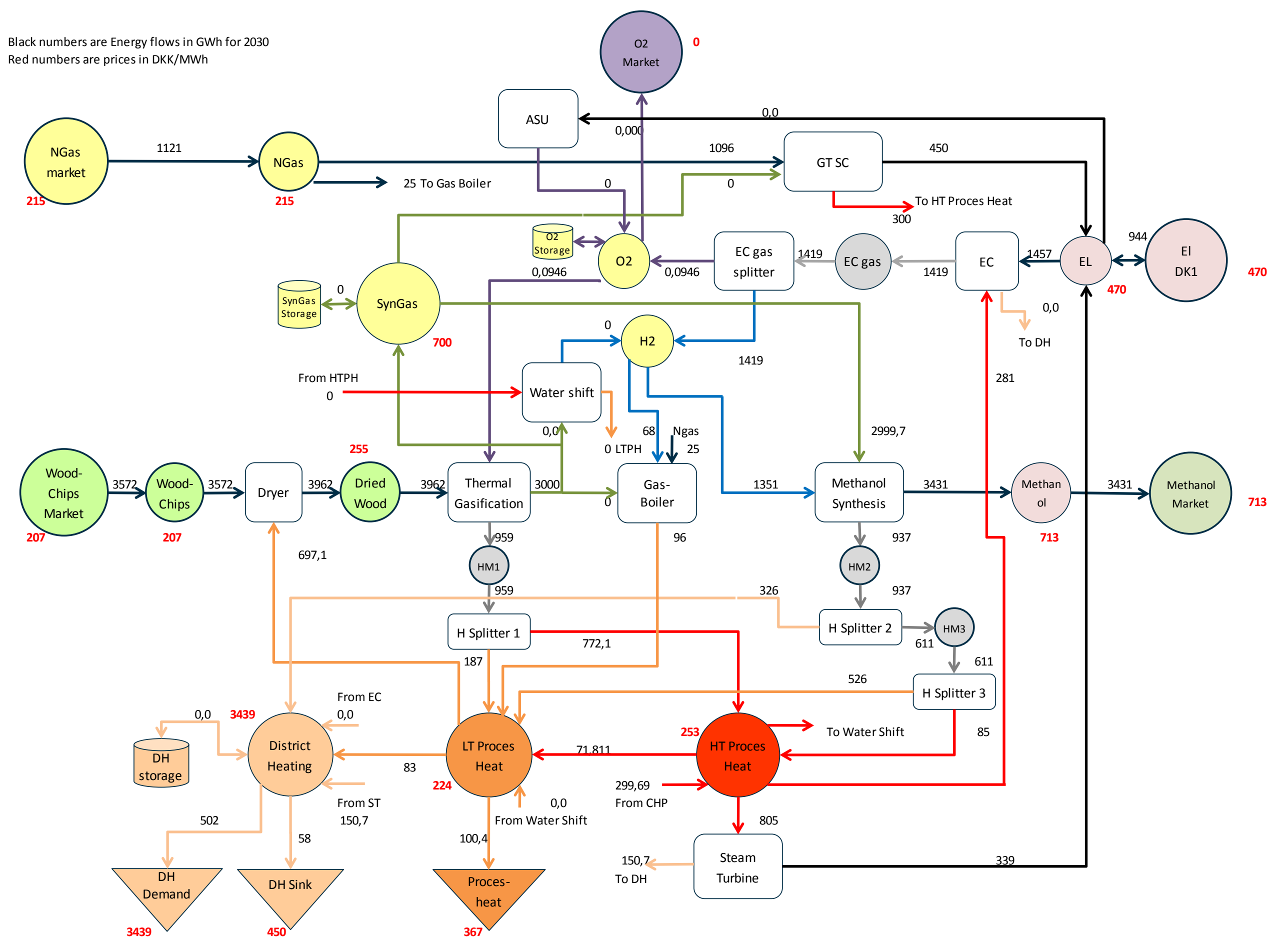

Figure 83: Energy flows for a low investment cost scenario

Plant Summary				
Production units	**Opt Size**	**Plant cost**	**FLE Op h**	
	MW p Out.	*MDKK*	*h/y*	
Wood Chip Dryer	500	126	7.924	
Thermal Gasification and GC	379	1.245	7.924	
Methanol Synthesis and purification	433	218	7.924	
Water Shift Reactor	106	40	-	
Electrolysis Unit	170	525	8.324	
Simple Cycle Gas Turbine	200	584	2.248	
Steam Turbine	93	233	3.657	
Gas Boiler	18	5	5.373	
Air Separation Unit	-	-	-	
Energy Storages	**Opt. Size**	**Plant cost**		
	MWh	*MDKK*		
District Heat Storage	999	12		
Syn Gas Storage	0	-		
Oxygen Storage	0,000	-		
Total installed equip. CAPEX (MDKK)		**2.988**		
Total Plant CAPEX- incl. 30% cont. (MDKK)		**3.885**		
Production and consumption	**Quantity**	**Price**	**Income**	**Expenses**
	GWh/y	*DKK/MWh*	*MDKK/y*	*MDKK/y*
Methanol produced	3.431	713	2.446	
District Heat produced (fixed price 85 DKK/GJ)	502	306	154	
Electricity produced	789	564	445	
Process Heat produced (fixed price 120 DKK/GJ)	100	432	43	
Heat sink (fixed price 0 DKK/GJ)	58	0	-	
Wood Chips consumed	3.572	207		739
Electricity consumed	1.733	461		799
Natural Gas consumed	1.121	215		241
Other costs				
O&M fixed				148
O&M var				85
CAPEX expense per year				262
Total			**3.088**	**2.273**
Yearly revenue				**814**
MeOH shadow price				**476**
IRR				**24%**
Energy efficiency (MeOH/input)				**61%**
Energy efficiency (MeOH+heat/input)				**72%**

Figure 84: Key figures for low investment cost scenario

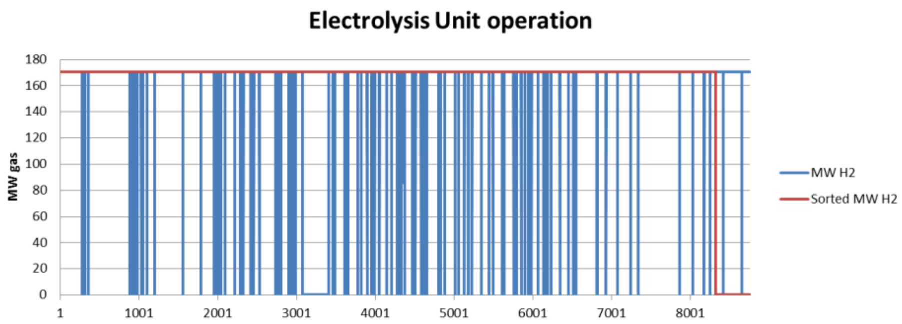

Figure 85: Electrolysis Unit operation at low investment cost

9.7.2 Investment costs increased with 30%

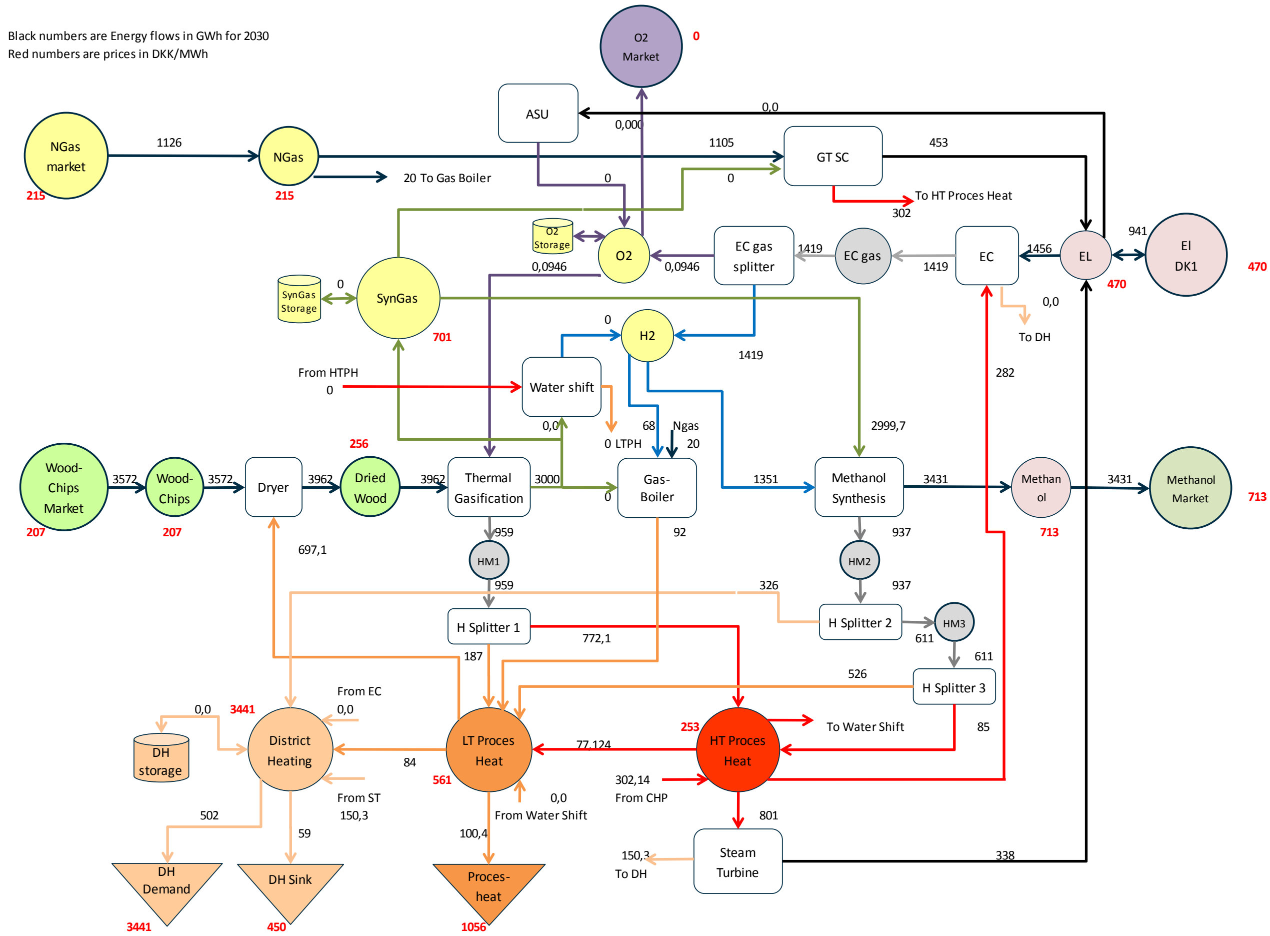

Figure 86: Energy flows for a high investment cost scenario

Plant Summary				
Production units	**Opt Size**	**Plant cost**	**FLE Op h**	
	MW p Out.	*MDKK*	*h/y*	
Wood Chip Dryer	500	234	7.924	
Thermal Gasification and GC	379	2.313	7.924	
Methanol Synthesis and purification	433	743	7.924	
Water Shift Reactor	106	74	-	
Electrolysis Unit	170	975	8.324	
Simple Cycle Gas Turbine	200	1.085	2.266	
Steam Turbine	93	433	3.639	
Gas Boiler	16	7	5.913	
Air Separation Unit	-	-	-	
Energy Storages	**Opt. Size**	**Plant cost**		
	MWh	*MDKK*		
District Heat Storage	759	17		
Syn Gas Storage	0	-		
Oxygen Storage	0,000	-		
Total installed equip. CAPEX (MDKK)		**5.881**		
Total Plant CAPEX- incl. 30% cont. (MDKK)		**7.645**		
Production and consumption	**Quantity**	**Price**	**Income**	**Expenses**
	GWh/y	*DKK/MWh*	*MDKK/y*	*MDKK/y*
Methanol produced	3.431	713	2.446	
District Heat produced (fixed price 85 DKK/GJ)	502	306	154	
Electricity produced	791	562	445	
Process Heat produced (fixed price 120 DKK/GJ)	100	432	43	
Heat sink (fixed price 0 DKK/GJ)	59	0	-	
Wood Chips consumed	3.572	207		739
Electricity consumed	1.732	461		799
Natural Gas consumed	1.126	215		242
Other costs				
O&M fixed				148
O&M var				85
CAPEX expense per year				516
Total			**3.088**	**2.529**
Yearly revenue				**559**
MeOH shadow price				**550**
IRR				**12%**
Energy efficiency (MeOH/input)				**61%**
Energy efficiency (MeOH+heat/input)				**72%**

Figure 87: Key figures for high investment cost scenario

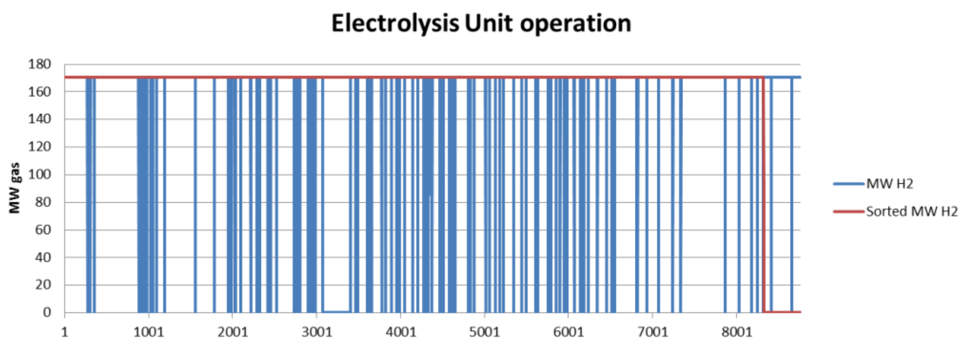

Figure 88: Electrolysis Unit operation at high investment cost

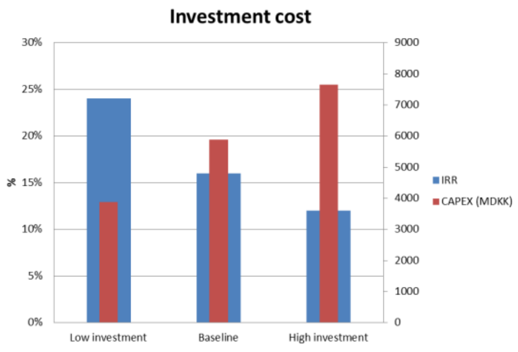

Figure 89: Investment cost +/- 30%

9.8 Gas turbine investment halved

The CAPEX of the Gas Turbine unit is taken from the Technology Catalogue Data [7]. This cost is for a standalone GT power plant including all necessary facilities. In this study a lot of these common facilities is covered in the contingency on the overall CAPEX. It is therefore assumed, that the CAPEX for the gas turbine is set to high in this study. This simulations shows the impact of a 50% reduced GT CAPEX.

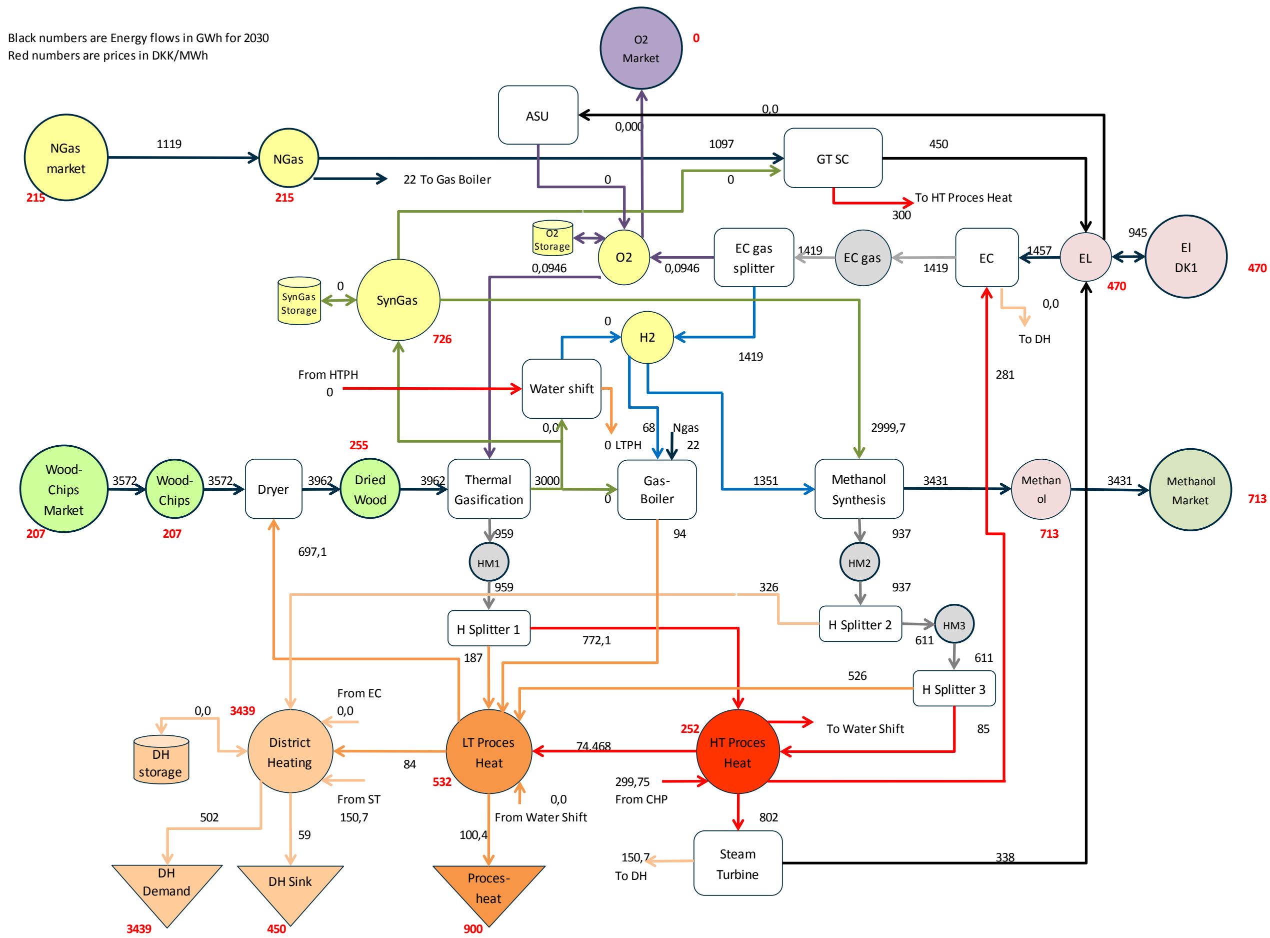

Figure 90: Energy flows for a low GT investment scenario

Plant Summary				
Production units	**Opt Size** *MW p Out.*	**Plant cost** *MDKK*	**FLE Op h** *h/y*	
Wood Chip Dryer	500	180	7.924	
Thermal Gasification and GC	379	1.779	7.924	
Methanol Synthesis and purification	433	571	7.924	
Water Shift Reactor	106	57	-	
Electrolysis Unit	170	750	8.324	
Simple Cycle Gas Turbine	200	417	2.248	
Steam Turbine	93	333	3.642	
Gas Boiler	17	6	5.637	
Air Separation Unit	-	-	-	
Energy Storages	**Opt. Size** *MWh*	**Plant cost** *MDKK*		
District Heat Storage	855	15		
Syn Gas Storage	0	0		
Oxygen Storage	0	-		
Total installed equip. CAPEX (MDKK)		**4.109**		
Total Plant CAPEX- incl. 30% cont. (MDKK)		**5.341**		
Production and consumption	**Quantity** *GWh/y*	**Price** *DKK/MWh*	**Income** *MDKK/y*	**Expenses** *MDKK/y*
Methanol produced	3.431	713	2.446	
District Heat produced (fixed price 85 DKK/GJ)	502	306	154	
Electricity produced	788	562	443	
Process Heat produced (fixed price 120 DKK/GJ)	100	432	43	
Heat sink (fixed price 0 DKK/GJ)	59	0	-	
Wood Chips consumed	3.572	207		739
Electricity consumed	1.733	461		799
Natural Gas consumed	1.119	215		240
Other costs				
O&M fixed				148
O&M var				85
CAPEX expense per year				363
Total			**3.086**	**2.375**
Yearly revenue				**711**
MeOH shadow price				**506**
IRR				**18%**
Energy efficiency (MeOH/input)				**61%**
Energy efficiency (MeOH+heat/input)				**72%**

Figure 91: Key figures for low GT investment cost scenario

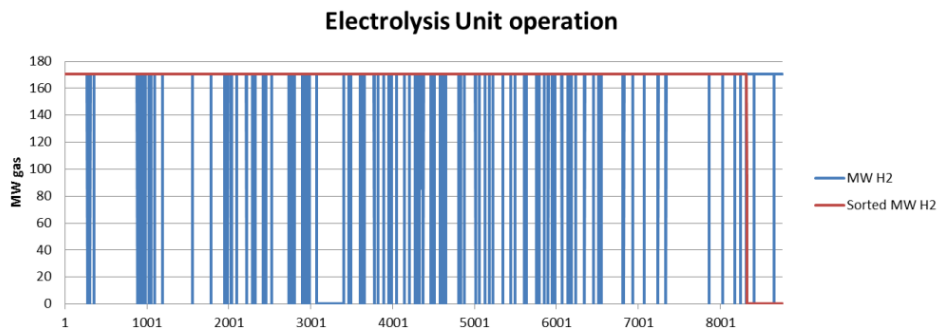

Figure 92: Electrolysis Unit operation at low GT investment cost

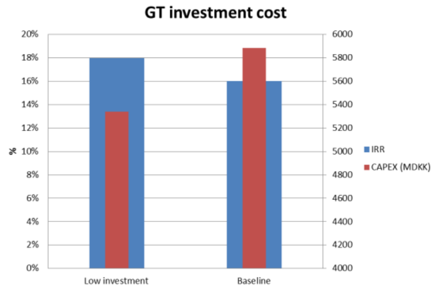

Figure 93: GT investment 50% down

9.9 SOEC versus Alkaline

In this simulation the SOEC electrolysis unit is replaced with an alkaline electrolysis unit. The SOEC technology is under development and the cost estimation is very rough. The Alkaline electrolysis is commercially available and the cost estimates therefore more precise. So a switch to alkaline will reduce the technology risk of the total plant. The performance and economic data for the alkaline electrolysis is found under the description of the Production Units. Shifting from SOEC to Alkaline electrolysis changes the heat flow to the Electrolysis Unit. With the SOEC technology HT process heat was supplied to the process while the alkaline technology has a district heat output.

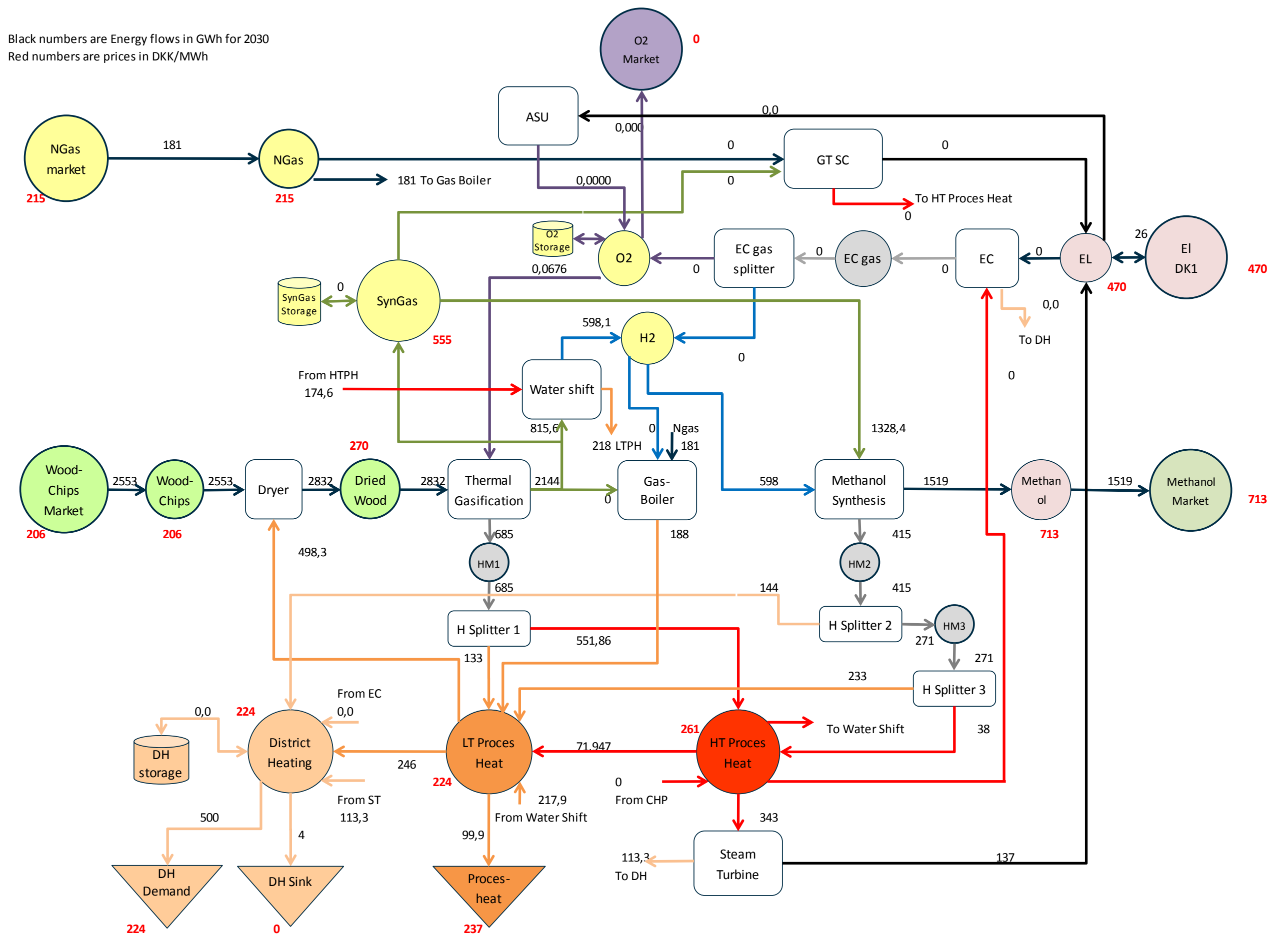

Figure 94: Energy flows for an alkaline electrolysis scenario

Plant Summary				
Production units	**Opt Size**	**Plant cost**	**FLE Op h**	
	MW p Out.	*MDKK*	*h/y*	
Wood Chip Dryer	500	180	5.664	
Thermal Gasification and GC	379	1.779	5.664	
Methanol Synthesis and purification	268	354	5.664	
Water Shift Reactor	106	57	5.664	
Electrolysis Unit	-	-	-	
Simple Cycle Gas Turbine	-	-	-	
Steam Turbine	33	118	4.167	
Gas Boiler	41	15	4.609	
Air Separation Unit	-	-	-	
Energy Storages	**Opt. Size**	**Plant cost**		
	MWh	*MDKK*		
District Heat Storage	720	12		
Syn Gas Storage	0	0		
Oxygen Storage	0	-		
Total installed equip. CAPEX (MDKK)		**2.516**		
Total Plant CAPEX- incl. 30% cont. (MDKK)		**3.271**		
Production and consumption	**Quantity**	**Price**	**Income**	**Expenses**
	GWh/y	*DKK/MWh*	*MDKK/y*	*MDKK/y*
Methanol produced	1.519	713	1.083	
District Heat produced (fixed price 85 DKK/GJ)	500	306	153	
Electricity produced	137	500	69	
Process Heat produced (fixed price 120 DKK/GJ)	100	432	43	
Heat sink (fixed price 0 DKK/GJ)	4	0	-	
Wood Chips consumed	2.553	207		528
Electricity consumed	163	463		76
Natural Gas consumed	181	215		39
Other costs				
O&M fixed				89
O&M var				51
CAPEX expense per year				226
Total			**1.348**	**1.008**
Yearly revenue				**340**
MeOH shadow price				**489**
IRR				**15%**
Energy efficiency (MeOH/input)				**55%**
Energy efficiency (MeOH+heat/input)				**77%**

Figure 95: Key figures for an alkaline electrolysis scenario

Shifting to alkaline electrolysis simply makes ADAPT/Sifre not invest in an electrolysis at the given price.

10. References

[1] Martin Møller et al. Polygeneration, DONG Energy, PSO Report, 2011

[2] Danish Technological Institute, GreenSynFuel, final project report, EUDP 64011-0011, 2011

[3] Matteo Morandin et al. Methanol via biomass Gasification, Chalmers University og Technology, 2015

[4] Hannula and Kurkela, Liquid transportation fuels via large-scale fluidised-bed gasification of lignocellulosic biomass, VTT, 2012

[5] Spath, Aden et al., Biomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly-Heated Gasifier, NREL 2005

[6] Anders Evald et al. Technology data for advanced bioenergy fuels, FORCE Technology, 2013

[7] Technology Data Catalogue for Energy Plants, aug. 2016

[8] Technology Data Catalogue for Energy Plants- UPDATE 2016

[9] Steven D. Phillips et al., Gasoline from Wood via Integrated Gasification, Synthesis, and Methanol-to- Gasoline Technologies, NREL, 2011. [9]

[10] Yas A. Alsultanny et al. Oxygen Specific Power Consumption Comparison for Air Separation Units, Engineering Journal, 2014

[11] Ryan M. Swanson et al., Techno-Economic Analysis of Biofuels Production Based on Gasification, NREL, 2010

[12] Jonathan Chou et. al. Compressed Air Energy Storage, *University of Pennsylvania, 2014*

[13] Analyseforudsætninger, Energinet, 2016

[14] EA Energianalyse, Samfundsøkonomiske aspekter ved produktion af 2. generations bioethanol, 2009

[15] GRØN ROADMAP 2030. SCENARIER OG VIRKEMIDLER TIL OMSTILLING AF TRANSPORTSEKTORENS ENERGIFORBRUG, November 2015:

[G] Internal estimated value.

11. Appendix 1

During the sensitivity simulations the ADAPT/Sifre tool was updated. All simulations up to and including: *Forced ASU operation – cost of flexibility* was performed with the Sifre Frontend 300.1.1 version and all simulations descriped after *Forced ASU operation – cost of flexibility* has been performed with the Sifre Frontend 300.2.0 version.

The simulation of the Energy Plant Type III baseline model in the old version and in the new version is compared hereunder. The output data shows minor differences but not really changing the optimization results.

11.1.1 Baseline model Energy Flows

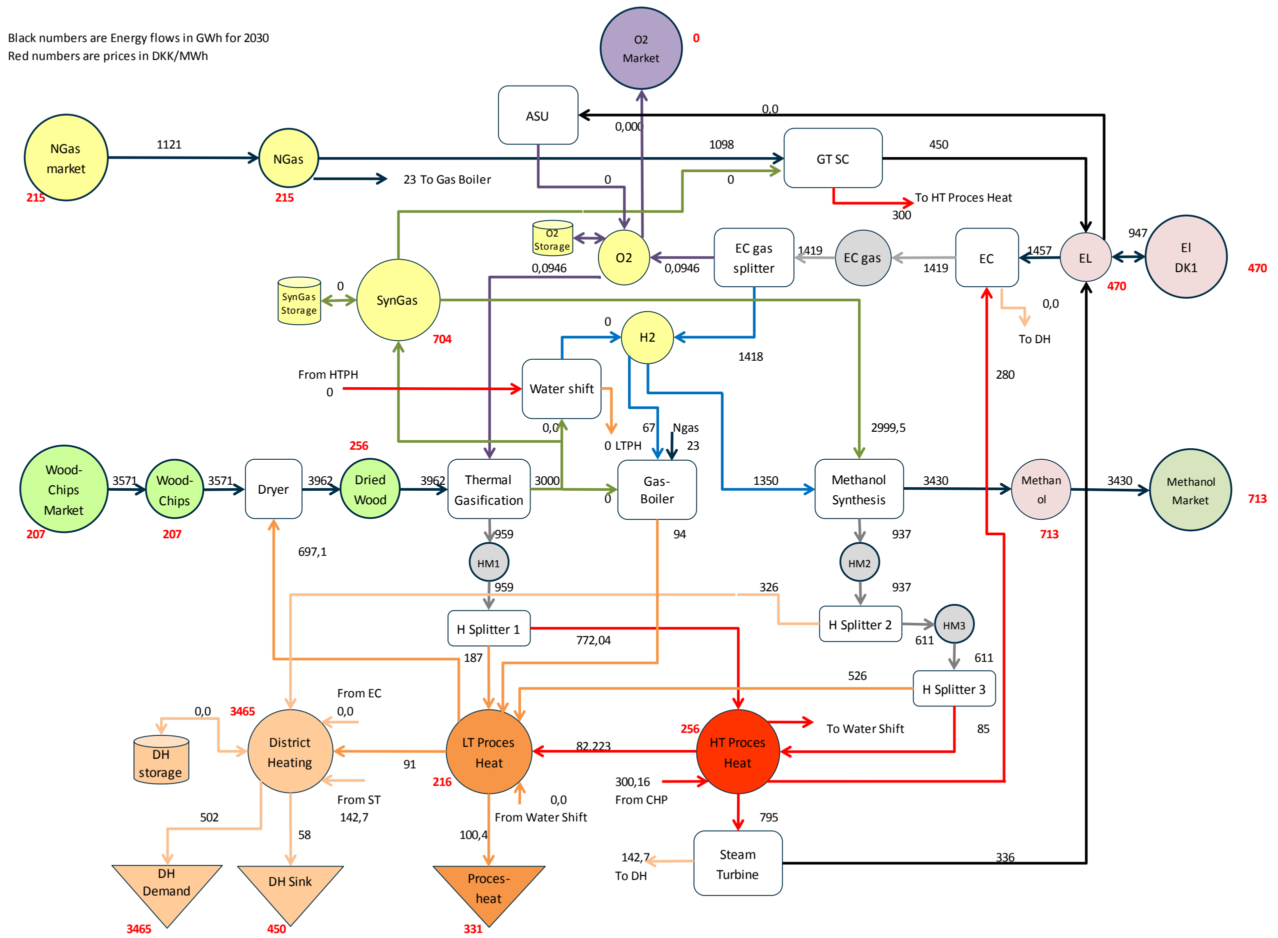

Figure 96: Energy flows for baseline model in 2030

11.1.2 Baseline model Key Figures

Plant Summary				
Production units	**Opt Size**	**Plant cost**	**FLE Op h**	
	MW p Out.	*MDKK*	*h/y*	
Wood Chip Dryer	500	180	7.924	
Thermal Gasification and GC	379	1.779	7.924	
Methanol Synthesis and purification	433	571	7.924	
Water Shift Reactor	106	57	-	
Electrolysis Unit	170	750	8.323	
Simple Cycle Gas Turbine	200	834	2.251	
Steam Turbine	93	333	3.622	
Gas Boiler	17	6	5.638	
Air Separation Unit	-	-	-	
Energy Storages	**Opt. Size**	**Plant cost**		
	MWh	*MDKK*		
District Heat Storage	855	15		
Syn Gas Storage	0	-		
Oxygen Storage	0	-		
Total installed equip. CAPEX (MDKK)		**4.526**		
Total Plant CAPEX- incl. 30% cont. (MDKK)		**5.884**		
Production and consumption	**Quantity**	**Price**	**Income**	**Expenses**
	GWh/y	*DKK/MWh*	*MDKK/y*	*MDKK/y*
Methanol produced	3.430	713	2.446	
District Heat produced (fixed price 85 DKK/GJ)	502	306	154	
Electricity produced	786	566	445	
Process Heat produced (fixed price 120 DKK/GJ)	100	432	43	
Heat sink (fixed price 0 DKK/GJ)	58	0	-	
Wood Chips consumed	3.571	207		739
Electricity consumed	1.733	461		799
Natural Gas consumed	1.121	215		241
Other costs				
O&M fixed				148
O&M var				85
CAPEX expense per year				397
Total			**3.088**	**2.409**
Yearly revenue				**678**
MeOH shadow price				**515**
IRR				**16%**
Energy efficiency (MeOH/input)				**61%**
Energy efficiency (MeOH+heat/input)				**72%**

Figure 97: Key figures for baseline model 2030

11.1.3 Baseline model Electrolysis Unit operation

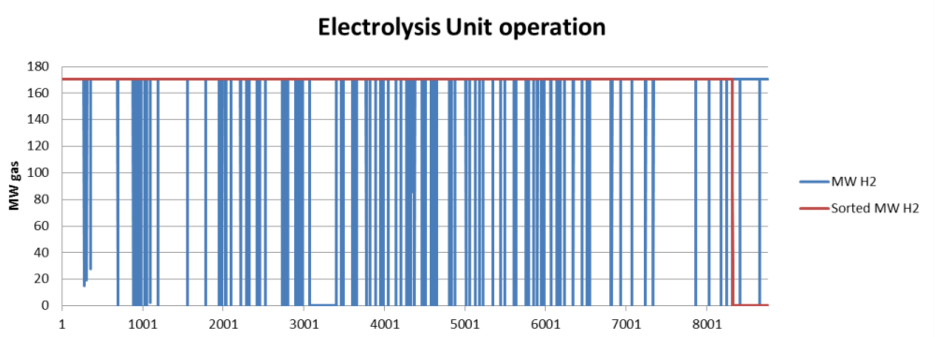

Figure 98: Electrolysis Unit operation for baseline model in 2030

11.1.4 Baseline model Energy Flows *new Sifre version*

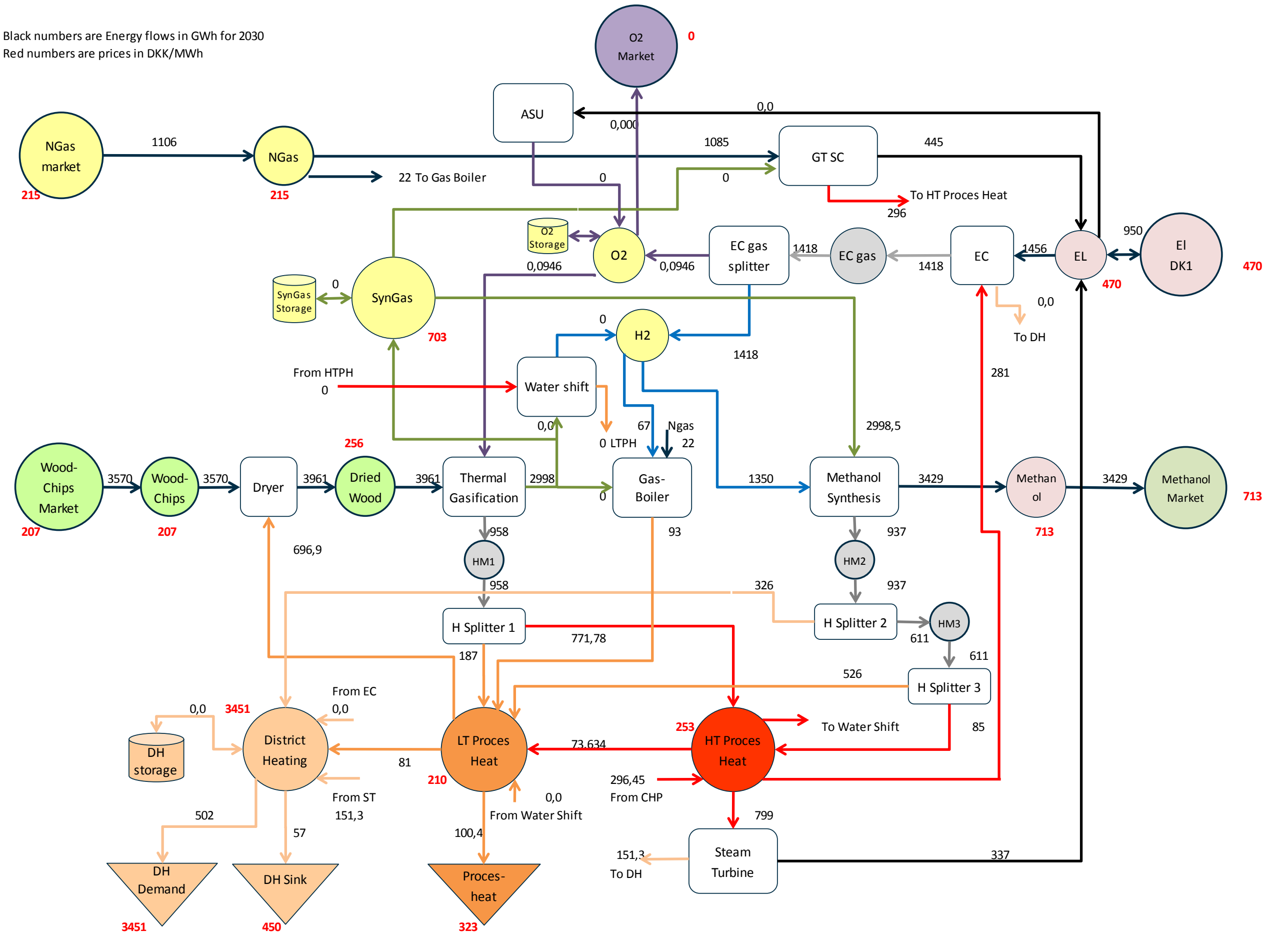

Figure 99: Energy flows for baseline model in 2030 new Sifre version

11.1.5

11.1.6 Baseline model Key Figures *new Sifre version*

Plant Summary				
Production units	**Opt Size**	**Plant cost**	**FLE Op h**	
	MW p Out.	*MDKK*	*h/y*	
Wood Chip Dryer	500	180	7.921	
Thermal Gasification and GC	379	1.779	7.921	
Methanol Synthesis and purification	433	571	7.921	
Water Shift Reactor	106	57	-	
Electrolysis Unit	170	750	8.320	
Simple Cycle Gas Turbine	200	834	2.223	
Steam Turbine	93	333	3.628	
Gas Boiler	17	6	5.548	
Air Separation Unit	-	-	-	
Energy Storages	**Opt. Size**	**Plant cost**		
	MWh	*MDKK*		
District Heat Storage	855	15		
Syn Gas Storage	0	-		
Oxygen Storage	0	-		
Total installed equip. CAPEX (MDKK)		**4.526**		
Total Plant CAPEX- incl. 30% cont. (MDKK)		**5.884**		
Production and consumption	**Quantity**	**Price**	**Income**	**Expenses**
	GWh/y	*DKK/MWh*	*MDKK/y*	*MDKK/y*
Methanol produced	3.429	713	2.445	
District Heat produced (fixed price 85 DKK/GJ)	502	306	154	
Electricity produced	781	563	440	
Process Heat produced (fixed price 120 DKK/GJ)	100	432	43	
Heat sink (fixed price 0 DKK/GJ)	57	0	-	
Wood Chips consumed	3.570	207		739
Electricity consumed	1.732	461		798
Natural Gas consumed	1.106	215		238
Other costs				
O&M fixed				148
O&M var				85
CAPEX expense per year				397
Total			**3.082**	**2.404**
Yearly revenue				**678**
MeOH shadow price				**515**
IRR				**16%**
Energy efficiency (MeOH/input)				**61%**
Energy efficiency (MeOH+heat/input)				**72%**

Figure 100: Key figures for baseline model 2030 new Sifre version

11.1.7 Baseline model Electrolysis Unit operation *new Sifre version*

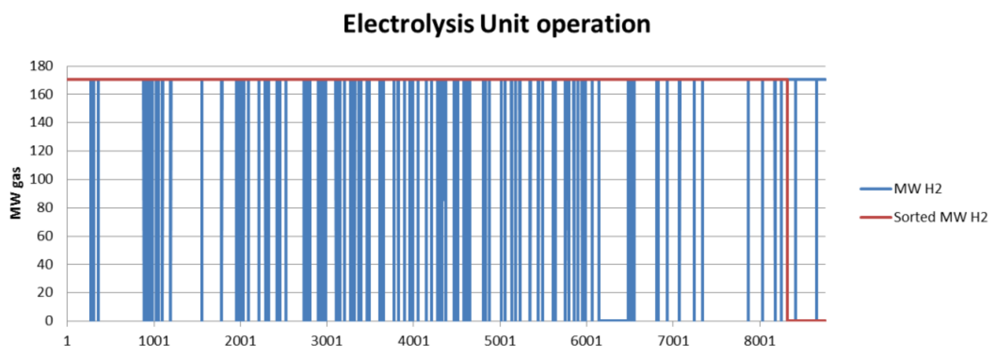

Figure 101: Electrolysis Unit operation for baseline model in 2030 new Sifre version

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