Optimised biogas upgrading by methanation in full scale

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Preface

This master's thesis was carried out by Christian Bloch and Leopold Thomas von Broich at the Institute of Chemistry-, Bio and Environmental technology, University of Southern Denmark Lifecycle center during the 3rd and 4th semester in the master study of Energy Technology. The study has been written between September 2016 and June 2017 and covers work corresponding to 40 ECTS points. Main supervisor is Henrik Wenzel, professor at the department of Chemical Engineering, Biotechnology and Environmental Technology at the Faculty of Engineering, University of Southern Denmark.

The topic of the thesis is optimisation of biogas upgrading by methanation in full scale.

In order to carry out the thesis several people has provided data which the authors wish to thank for the assistance:

- Lars Ditlev Mørck Ottosen, Aarhus University
- Torben Kvist, Dansk Gasteknisk Center
- Panagiotis Kougias, Technical University of Denmark
- Leif Holm Tambjerg, EMD International
- Birgir Norddahl, University of Southern Denmark

Summary

The thesis set out to examine the differences between catalytic and biological methanation with a technical and economical perspective. This was carried out in scale of Nature Energy Midtfyn biogas plant. Additional to the methanation process, it was decided to investigate the possibility of producing hydrogen in “low” electricity price periods by adding hydrogen storage.

The economical aspect was decided to include a socio- and business-economic analysis, to identify the setup with the lowest production cost per kWh methane. Furthermore an optimisation of the hydrogen production for hydrogen storage will be done.

Further it will be examined if the current subsidies for upgrading of biogas by methanation is suffice to make it feasible with the current cost of electrolyser, methanator and hydrogen storage.

Both the socio- and business economics analysis will be conducted from year 2020 to 2040, as the life time is estimated to 20 years for the methanator and electrolyser. Through the socio- and business-economics there will be investigated two scenarios, one without hydrogen storage and one with hydrogen storage. The first scenario will consist of a 10 MW electrolyser with an efficiency of 84 % and a methanator reactor with an out of 600 Nm3 methane per hour. For the hydrogen the higher heating values are used. The catalytic methanator operates at a temperature of 250 °C while the biological operates at 60 °C. Both the electrolyser and the methanator produces excess heat that can be utilised in a biogas plant or sold as district heating.

Based on future electricity price for 2020-2040, the production cost for catalytic methanation is found for both socioeconomic and business-economic at 1,07 DKK/kWh and 1,4 DKK/kWh. For biological this is 1,01 DKK/kWh and 1,38 DKK/kWh methane. With a storage added the cost of methane for catalytic increases to 2,76 DKK/kWh for socio-economic and 3,3 DKK/kWh for business-economic. For biological this is 2,64 DKK/kWh and 3,17 DKK/kWh per methane. If the excess heat were to be credited for heat recovery the catalytic would be able to decrease the cost of methane by 0,11 DKK/kWh and 0,10 DKK/kWh for biological in a socio-economic perspective. In a business-economic aspects the heat sale would result in a 0,18 DKK/kWh lower methane production cost for catalytic and 0,17 for biological.

The two largest cost bears are respectively electricity cost and capital cost depending on the adding of storage or not. Without storage, electricity is the largest cost bearer and with storage, capital cost is the largest.

In the optimisation of the hydrogen cost with hydrogen storage, the cost associated with increased capital cost due to increased capacity of electrolysis and hydrogen storage, did not outweigh the avoided electricity cost.

In examination of the current subsidy, assumed to be eligible for biogas upgrade by methanation by 2020, the biological methanation will require an increase of subsidy of 9,1 from 135,4 to 144,5 DKK/GJ to be feasible.

1 Problem identification

1.1 Introduction

Denmark has a long term energy policy, to achieve fossil independency by year 2050. To achieve the goal, increasing renewable energy and biomass is introduced into the energy system. This poses challenges for the Danish supply system, as this causes fluctuating energy production and as such large variations in electricity prices. A fossil free society also implies a set of conditions that will make biomass in high demand which cannot be supplied potentially creating a biomass bottleneck (Wenzel, 2010). To accommodate these problems hydrogen should be seen as a mean, to introduce more wind and lessen the amount of biomass in the system.

If renewable electricity is used in the electrolysis process, the hydrogen will be renewable. The hydrogen can then be combined with a flow of carbon dioxide, producing methane in either a catalytic- or biological methanation process.

The storing of electricity is expensive, therefore the conversion of electricity to methane could balance the power market. This concept is called “Power to Gas” and is demonstrated in Germany at several sites. In Denmark biogas is mainly used at decentralised combined heat and power plants, thus the concept offers a way to convert electricity to fuel.

In a catalytic- or biological methanation process the 35% carbon dioxide usually contained in biogas can be transformed into methane, increasing the production in existing biogas plants.

The transition from demonstration to full scale is still missing thus optimisation of hydrogen production is required, as vast amount of electricity is being consumed.

1.2 Purpose

The purpose of this thesis is to evaluate the economic and technical status of catalytic and biological methanation of hydrogen and carbon dioxide. This is carried out by scaling a methanation facility to the Nature Energy Midtfyn biogas plant.

Both a socio- and business-economic analysis will be done for hydrogen and synthesis methane gas integration with NEM, to achieve the solution with the lowest upgrading cost of methane.

Hydrogen production based on a “low” electricity price will be done to examine its impacts on the methane production cost.

Furthermore an optimisation of hydrogen production and hydrogen storage capacity will be done, to find the lowest cost per hydrogen produced.

The feasibility of the production cost of methane will be investigated to identify whether or not the current subsidies are suffice to support the upgrading of biogas by methanation.

2 Methodology

This section will give an overview of the report structure, where to begin reading if interested in a specific area of the study and where data for the study has been obtained.

The report was written by Christian Bloch and Leopold Thomas von Broich. The project was guided by Henrik Wenzel, Lars Yde and Abid Rabbani. The study was carried out through literature studies, manufacturer contacts and modelling in EnergyPRO.

2.1 Report structure

This report has been structured in seven main sections. In the first section (section 2), the data used are outlined and any uncertainty concerning the data used is pointed out. Sankey diagrams are presented in section 3. In section 4, a technology description of relevance to biogas methanation is examined. Section 5 consists of a description the scenarios together with framework conditions. In section 6 the EnergyPRO models are presented. Section 7 contains economics analyses where socio- and business economics for methane production are calculated. In section 8 there will be a sensitivity analysis of the result gained in section 7.

The results of the scenarios, the economics and the sensitivity analysis are discussed in section 9 and concluded upon in section 10.

On figure 1 the structure of the report is presented in a flow diagram.

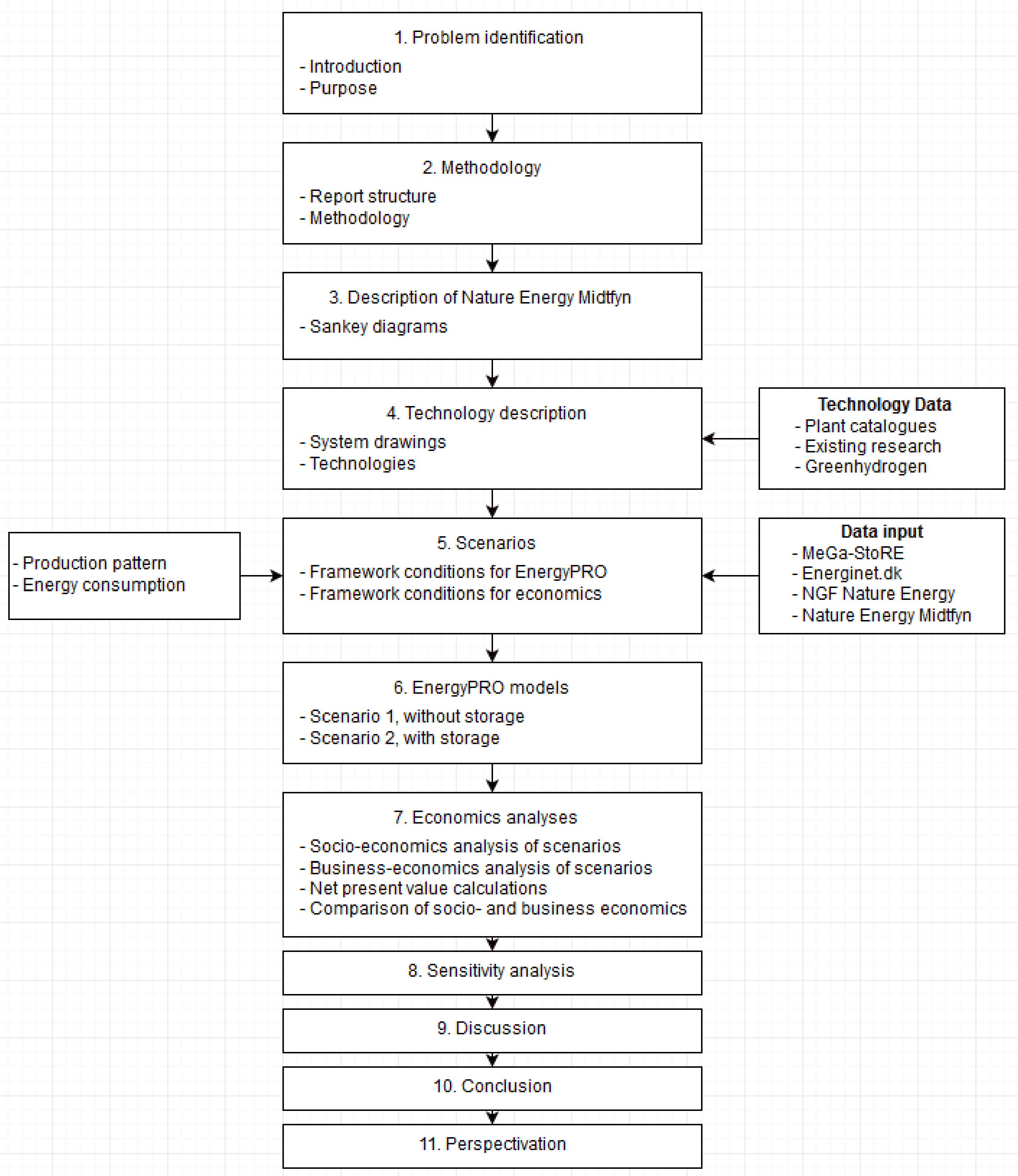

Figure 1: The overall structure of the report.

The report begins with a technical description of the different technologies used which are, biogas upgrading, electrolysis technologies, hydrogen storage, biological and catalytic methanation and a technical description of the gas grid. In order to quickly get an overview of the technologies the reader is referred to start reading section 3 and 4.

2.2 Methodology

All data that has been used through different stages of this report are presented and reviewed in methodology. The topics are reviewed separately to obtain transparency from where the data originate. The sections are as follows:

- Characteristics for Nature Energy Midtfyn
- Scenarios
- Technical situation
- Economics

2.3 Characteristics for Nature Energy Midtfyn

The data reviewed in this part are data with characteristics that apply for NEM. By understanding the NEM characteristics it is believed that it gives a good foundation for dealing with biogas production.

2.3.1 The natural gas grid

As the main objective in this paper is to investigate the possibility to upgrade the biogas production by methanation at NGF Nature Energy Midtfyn and deliver the methane to the natural gas grid, a key factor is to make sure the methane meets the requirement and conditions of the natural gas grid.

	Data	Source	Description	Available in
1	Operation of the grid	Torben Kvist, Dansk Gasteknisk Center A/S	Information on limits of the gas grid and distribution	Personal contact
2	Europe restrictions	Torben Kvist, Dansk Gasteknisk Center A/S	European Standard - Gas infrastructure - Quality of gas	(FprEN 16726, 2015)
3	Natural gas price	Gaspoint Nordic Market	Current natural gas prices	(Gaspoint Nordic, 2017)
4	Natural gas price projections	World Energy Outlook 2016 made by International Energy	Projections on natural gas prices	(International Energy Agency, 2016)

		Agency		
5	German gas grid	BS-NETZ Veolia Environment	Germen gas requirements for gas grid.	(BS-Netz, 2009)

1) During a discussion with Torben Kvist information on pressure, restrictions and conditions of gasses flowing into the gas grid was obtained

2) From the European standard (FprEN 16726, 2015) the gas quality restrictions were obtained.

3) The current natural gas prices are based on the market price from Gaspoint Nordic.

4) The future natural gas price is based on the report World Energy Outlook published by the International Energy Agency. The report projects prices on natural gas for 2020, 2030 and 2040 from the new policies scenario. Prices have been adjusted to DKK per GJ to fit Danish standards.

5) The technical requirement for decentralized power plant to feed the natural gas grid in Germany.

2.3.2 Current and future electricity production and price

The electricity price is a key parameter when calculating on large different electrical units like an electrolyser. As this report will analyse the NPV from the year 2020 to 2040 for methanation and electrolyser units the electricity prices will be of significance. The data is presented below.

	Data	Source	Description	Available in
1	Current electricity production and price on the Elspot market	Market data from energinet.dk	Time series for 2015 and 2016 downloaded from energinet.dk market data.	(Energinet.dk, 2017)
2	Future electricity spot prices	Danish Energy Agency [Energistyrelsen]	Calculation expectations for socioeconomic analyses [Beregningsforudsætninger for samfunsøkonomiske analyser] estimated electricity prices until 2040	(Ens.dk. 2017b)
3	Price determi-	Tariffs from En-	The current tariffs for elec-	(Energinet.dk,

	nation of tariffs for electricity	erginet.dk	tricity	2017b)

1) The time series for electricity production and the Elspot market prices have been achieved from energinet.dk's market data. The data from 2015 has been used.

2) The future electricity prices have been obtained from the Danish Energy Agency in their expectation of the future electricity prices until the year 2040. The main objective for the calculation on the expectations of the prices is to establish a solid foundation in order to qualify and distribute resources in a progressive way.

3) The tariffs are a large part of the electricity price. As no tariffs are estimated for the future current tariffs are used. The tariffs are determined by Energinet.dk

2.3.3 Subsidies and taxes

In Denmark projects are often subject to subsidies to promote and develop new technologies. In this part there will be outlined the subsidies and taxes that are given and forced onto biogas production and utilization of biogas upgrading.

	Data	Source	Description	Available in
1	Tax payment regarding biogas utilization	SKAT.DK	Relevant taxes for biogas utilization	(SKAT, 2017)
cont.	Tax payment regarding methane and electricity consumption	pwc - Tax guide 2017	Overview over payment and reimbursement of excise duties [Samlet overblik over afregning og godtgørelse af afgifter]	(pwc, 2017)
2	Subsidies to upgraded biogas	Energinet.dk	Subsidies provided to upgraded for higher and lower heating values	(Energinet, 2017)

1) By law there are no CO2-taxes or methane-taxes to be paid of biogas if the biogas is produced by biomass, however there is to be paid tax according to the CO2-tax law if the biogas is utilized by a stationary piston engine with an effect of over 1.000 kWh. As gas turbines are not classified as stationary piston engines natural gas and biogas are not affected by the methane taxes.

The taxes included in this study are:

- Methane tax: Clarified in legal guidance and explained under E.A.4.4.11.3.2. Biogas is covered by the rules of the methane tax.

- Electricity tax: Clarified in legal guidance and explained under E.A.4.3.6.1 and the price used until year 2040 are based on the price of the year 2017.
- When exceeding a consumption of 100.000 kWh per year for process the excise is 0,04 DKK/kWh.
- System tariff
- Net tariff
- PSO
- VAT

2) Ways to receive subsidies when utilizing biogas produced by biomass.

2.4 Scenarios

There will be modelled two scenarios in the study. One scenario with storage and one without storage for hydrogen.

2.4.1 Scaling of models

	Data	Source	Description	Available in
1	Scale of capacities for electrolyser and SNG methanation for NEM	Partnership for Hydrogen and Fuel Cells [Partnerskabet for Brint og Brændselsceller]	Analysis for commercialization of hydrogen technologie	(EUDP, 2016)
2	Biogas production	NGF Nature Energy Midtfyn	Amount of biogas produced a year.	(NEM, 2017)

1) (EUDP, 2016) is a collection of technologies within the hydrogen area that aim to give an overview of the current situation. The technologies were described and analysed. Costs for hydrogen technologies can be found in the EUDP, 2016.

2) Nature Energy Midtfyn produces 11 mio. m^3 upgraded biogas every year, used for the scaling of electrolyser and methanator.

2.5 Information on EnergyPRO

The different scenarios were modelled in EnergyPRO and therefore the information on guides is essential for this report. The data used is presented below.

	Data	Source	Description	Available in

1	EnergyPRO the Program	EMD International A/S	EnergyPRO can simulate an energy system with a large number of different units.	(EMD, 2017)
2	EnergyPRO modelling	Leif Holm Tambjerg, Consultant	Methanator refuses to run - troubleshooting	Personal contact
3	EnergyPRO modelling	Anders N. Andersen, Head of Energy Systems	Information on operation strategies	Personal contact
4	EnergyPRO modelling	EMD International A/S	EnergyPRO overall user's guide	(EMD, 2017b)
5	EnergyPRO modelling	EMD International A/S	Electrolysis with storage - Fuel producing units	(EMD, 2017c)

1) EnergyPRO is created by EMD International A/S. EnergyPRO provides the opportunity to model an energy system with weather conditions, technical conditions of units and economics. The optimisation of this paper's data is collected through papers on MeGa-StoRE, NEM, electrolysis technologies, methanation technologies, biogas and through personal contact with gas grid companies.

2) Through personal contact with Leif Holm Tambjerg a troubleshooting of the EnergyPRO modelling was performed. EnergyPRO operates in a way that fuel storages has to be filled at the end of the time period operating in, which is either a day, month or year.

3) General introduction of operation strategies in EnergyPRO.

4) The general information on all settings in EnergyPRO is described in this overall user's guide.

5) Information on how to build an electrolyser with storage in EnergyPRO.

2.6 Technology description

Information in the electrolysis process and methanation were achieved through data sheets and papers on the current situation of the technologies and future perspectives of the technologies.

2.6.1 Electrolysis

The three most known electrolysis technologies are on different stages. Information on the three technologies is listed below.

	Data	Source	Description	Available in
1	1) Alkaline 2) Proton Exchange Membrane (PEM) 3) Solid Oxide Electrolyser Cell (SOEC)	Partnership for Hydrogen and Fuel Cells [Partnerskabet for Brint og Brændselsceller]	Data sheet on the three different electrolysis technologies with future potential considerations	(Elektrolyse i Danmark, 2009)
2	The functioning of PEM, SOEC and alkaline electrolysis.	Partnership for Hydrogen and Fuel Cells [Partnerskabet for Brint og Brændselsceller]	Analysis for commercialization of hydrogen technologie	(EUDP, 2017)
3	Chemical aspect of electrolysis, construction cost and operation and maintenance for alkaline electrolyser	Swedish Gas technical CenterAB [Svenskt Gas-tekniskt CenterAB]	Composition of the electrolysers	(Benjaminsson et. al, 2013)

1, 2 and 3) Data on the electrolysis technologies are obtained from this paper. A large collaboration of companies has taken part in (Elektrolyse i Danmark, 2009).

2.6.2 Methanation

The data on methanation were achieved through data sheets and papers.

	Data	Source	Description	Available in
1	General data on catalytic and biological methanation	Swedish Gas technical CenterAB [Svenskt Gastekniskt CenterAB]	Difference on the catalytic and biological methanation processes. Construction cost and operation and maintenance for catalytic and biological methana-	(Benjaminsson et. al, 2013)

			tion.	
2	Biogas upgrading	Partnership for Hydrogen and Fuel Cells [Partnerskabet for Brint og Brændselsceller]	Biogas upgrading by methanation.	(EUDP, 2017)

1) Thought the report of Benjaminsson et. al, 2013 they compare the different electrolysis technologies and catalytic methanation with biological methanation.

2) Greenhydrogen.dk summarises their catalytic methanation with data sheets, future expectations and general information of the technology.

2.7 Economics analysis

A socio-economic analysis is developed from the guide (Energistyrelsen, 2007). The purpose of a socio-economic analysis is to be used as decision-making in choosing the solution most optimal for the society. In a socio-economic analysis, no taxes or subsidies is featured, as these would distort the decision basis when comparing different solutions to each other, hence all prices used are factor prices. The data used are presented below.

A business economic analysis is presented as well for the purpose of showing how the economy will relate in praxis. In a business-economic analysis, taxes and subsidies are featured.

	Data	Source	Description	Available in
1	Construction cost and operation and maintenance cost for alkaline electrolyser and SNG by methanation of biogas	Partnership for Hydrogen and Fuel Cells [Partnerskabet for Brint og Brændselsceller]	Analysis for commercialization of hydrogen technologies	(EUDP, 2017)
2	Construction cost and operation and maintenance for alkaline electrolyser and biological catalyst.	Swedish Gas technical CenterAB [Svenskt Gastekniskt CenterAB]	Technical review of power-gas fuels.	(Benjaminsson et. al, 2013)
3	Natural gas price projections	World Energy Outlook 2016 made by International Energy	Projections on natural gas prices	(International Energy Agency,

		Agency		2016)
4	Price determination of tariffs for electricity	Danish Energy Agency [Energistyrelsen]	Calculation expectations for socioeconomic analyses [Beregnings-forudsætninger for sam-funsøkonomiske analyser] estimated electricity prices until 2040	(International Energy Agency, 2016)

Prices used are adjusted so expenses and cost are 2020 prices.

1) The construction cost and maintenance and operation cost is supplied by Partnership for Hydrogen and Fuel cells part of the project “Analysis for commercialization of Hydrogen Technologie” under the Danish Energy Technology Development and Demonstration Program (EUDP). The data presented covers the prices and expenses of components in relation to methanation of carbon dioxide from biogas and is mainly presented in either €/MW/year or €/Nm^3/h CH4.

2) Key financial data are achieved from (Benjaminsson et. al, 2013) in order to analyse the catalytic and biological methanation.

3 and 4) The future natural gas price is based on the report World Energy Outlook published by the International Energy Agency. The report projects prices on natural gas for 2020, 2030 and 2040 from the new policies scenario. Prices have been adjusted to DKK per GJ to fit Danish standards.

3 Description of Nature Energy Midtfyn

NEM consist of a biogas facility for degassing of the biomass and an upgrading facility, which removes the CO2 from the raw biogas so the gas can be transferred into the natural gas grid.

The facility produces yearly 11 mio. Cubic meter upgraded biogas.

The flows of how Nature Energy Midtfyn could look like will be shown in sankey diagrams.

3.1 Sankey diagrams

In the Sankey diagrams the widths of the connections between the processes are proportional to the energy production. The sankey diagrams shown below visualize the energy content and the volume on that energy from process to process. The diagrams are scaled after the MeGa-StoRE concept, however the values fit those of Nature Energy Midtfyn by a difference of 1 %. The biogas plant that produces the biogas is not shown on the sankey diagram as it is outside the scope of this paper.

Figure 2 shows the energy flow from the electricity to the gas grid and district heating grid.

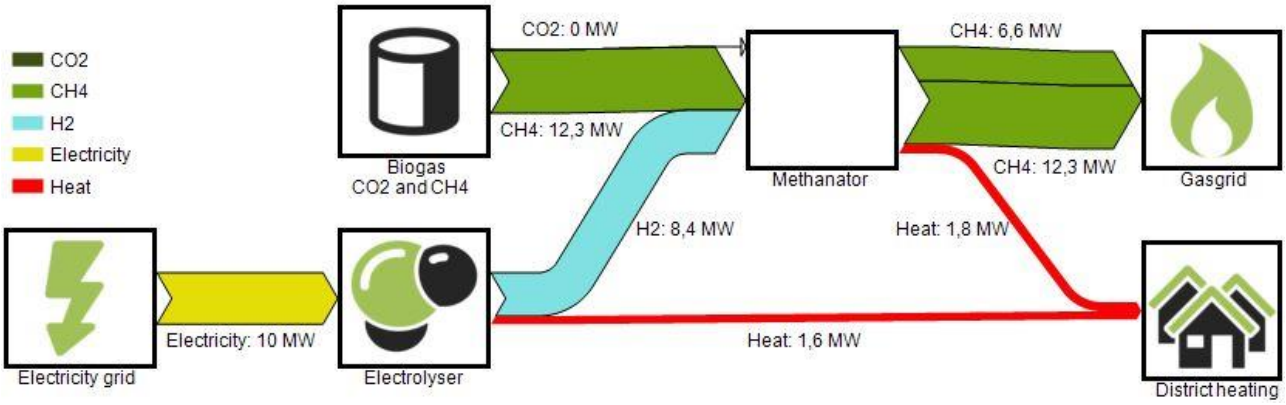

Figure 2: Sankey diagram of energy content flow of the limitation of this paper.

On figure 3 the sankey diagram displays the volume flow of the gasses. The biogas consists of 35 % carbon dioxide and 65 % methane. As seen the 600 m3 CO2 combined with the 2.400 m3 H2 equals and methane output of 600 m3.

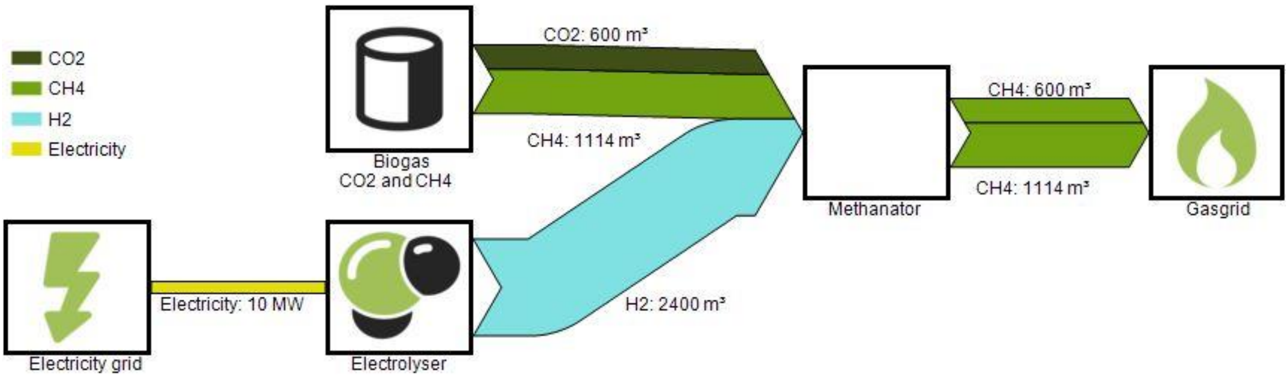

Figure 3: Sankey diagram of the volume flow from biogas and electrolyser to the gas grid.

Each component in the sankey diagram has an input, output and efficiency. They parameters are shown the table below.

Unit	Input type	Input	Output type	Output	Efficiency
Electrolyser	Electricity	10 MW	Hydrogen	8,4 MW	**84 %**
Electrolyser	Electricity	10 MW	Heat	1,6 MW	**16 %**
Methanator	Methane	12,3 MW	Methane	12,3 MW	**100 %**
Methanator	Hydrogen	8,4 MW	Methane	6,6 MW	**78,5 %**

Methanator summurized	Methane + Hydrogen	20,7 MW	Methane	18,9 MW	**91 %**
Methanator	Hydrogen	8,4 MW	Heat	1,8 MW	**21 %**

All values are based on higher heating values. (EUDP, 2017)

4 Technology description

In this chapter there will be a description of the technologies that are relevant when examining optimisation on methanation. Also there will be an overview of the hydrogen storage possibilities and roadblocks. Furthermore, there will be system drawings of the flow from the electricity grid to the end product as natural gas.

4.1 System drawings

The system designs vary from company to company. In the following two drawings of the MeGa-StoRE concept and Krajete an overall view of a setup in which a catalytic and a biological methanation is in focus.

On figure 4 a system drawing is shown of how the catalytic methanation may play a role in an energy system. The main products from a biogas plant are methane and carbon dioxide, however the gasses are purified for sulphur and other compounds which can contaminate the catalyst in the methanation reactor. On the other side the hydrogen is shown to enter the methanator from an electrolyser. The electrolyser may store hydrogen for later use. The methanator operates at approximately 250 °C and as this process is exothermic there is excess heat that can be utilized as district heating or in the biogas reactor. This is also the case for the excess heat of the electrolyser. The produced methane from the methanation goes to the natural gas grid.

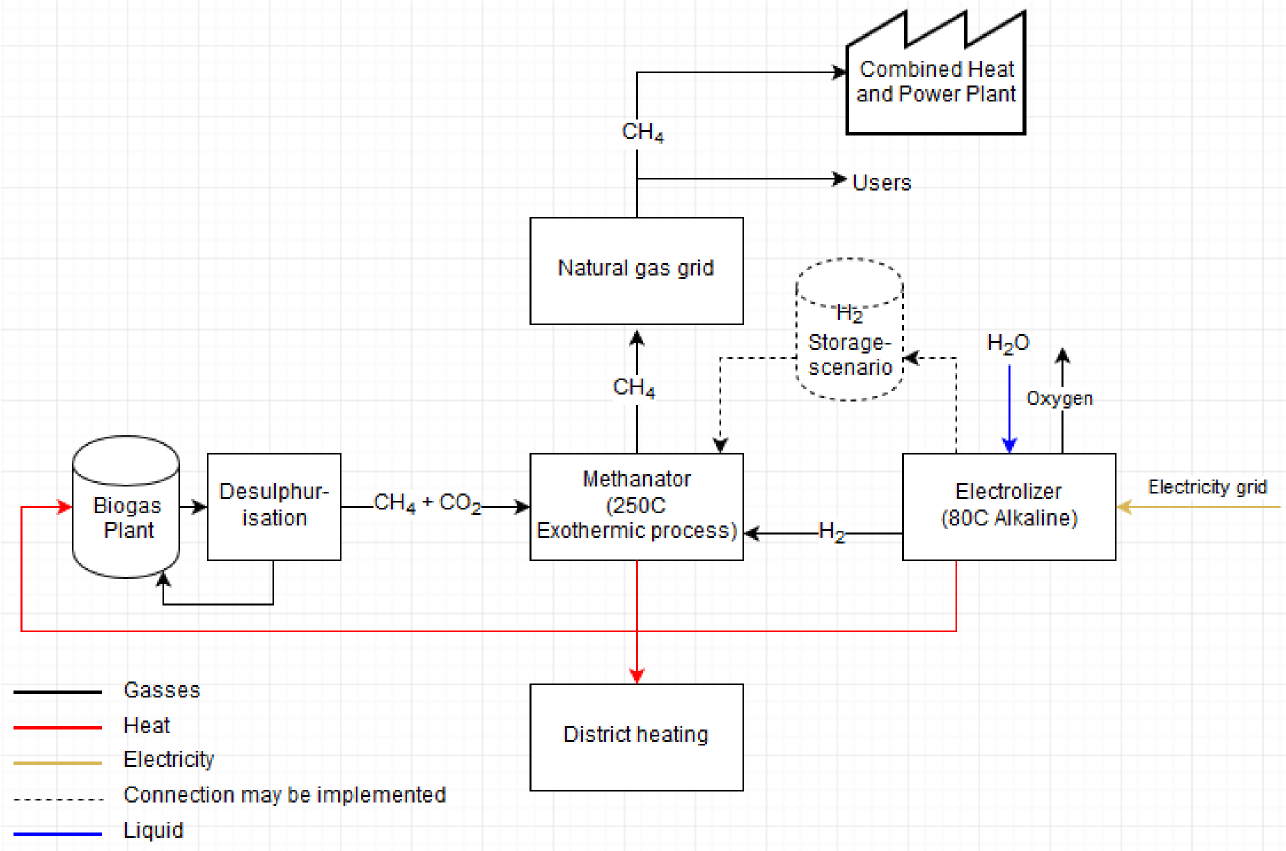

Figure 4: System drawing of the MeGa-StoRE concept which utilizes a catalytic methanation process.

On figure 5 a system drawing is shown of how biological methanation may play a role in an energy system. The biological methanation does not require the biogas to be purified for sulphur as there is no catalyst in the biological process. The biogas enters the methanator at the bottom where it is mixed with the hydrogen to form methane. The biological methanation is working at a temperature of 60 °C.

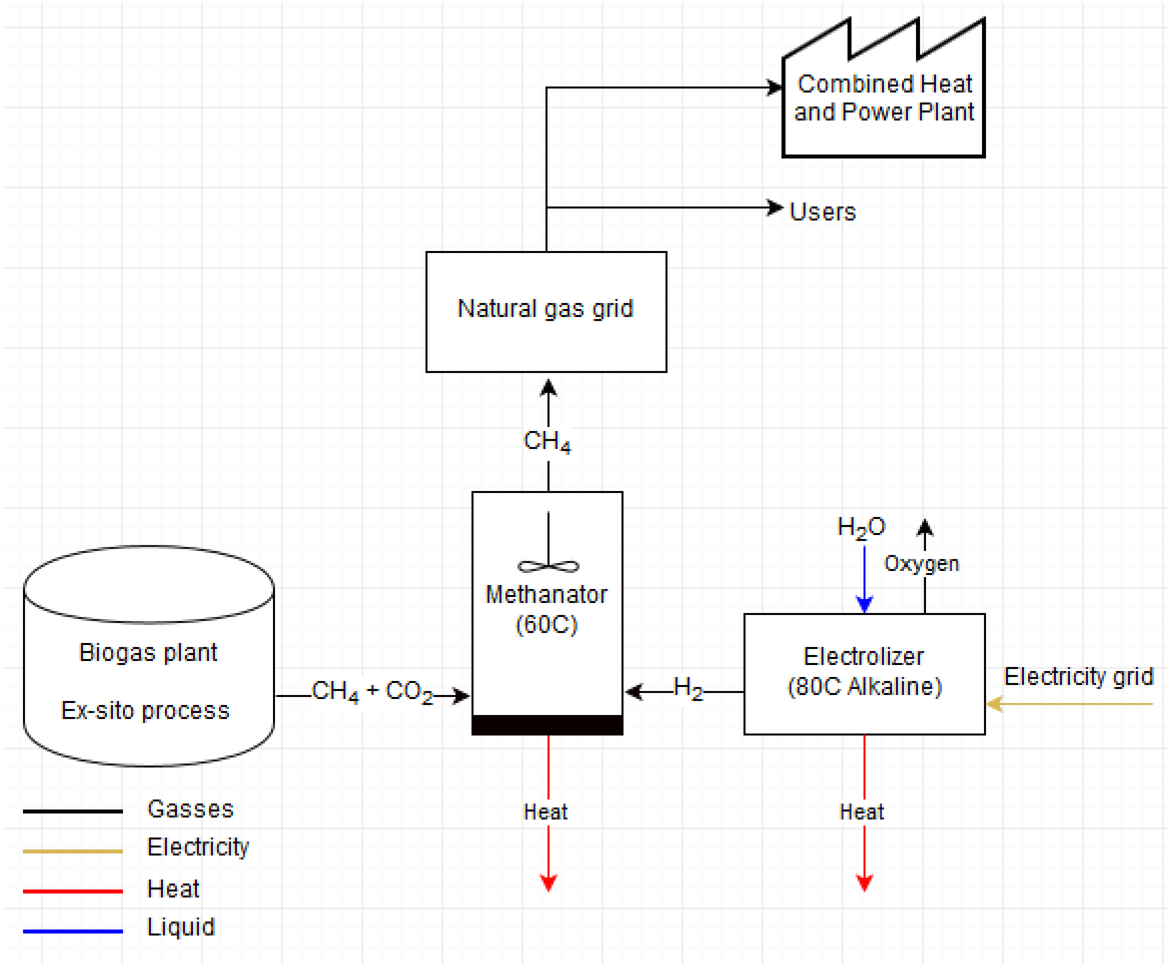

Figure 5: System drawing of the how Krajete can build a biological methanation process.

4.2 Biogas upgrading - Methanation

Upgrading the biogas that is produced in the biogas plant can be forced in two different ways, either by waterscrubbing which is commercialized or by methanation which is on demonstration.

The method of water scrubbing is a technology that is used in biogas plants in which the carbon dioxide (CO2) and the methane (CH4) is separated. The ratio is usually 65 % methane and 35 % carbon dioxide although this depends on the type and rate of the biomass that is reacting inside the plant. The catalytic and the biological reactions are described in section 4.2.1 and in section 4.2.2, respectively. The methanation process converts carbon dioxide and hydrogen to methane. The formula for the methanation process is seen below.

$$CO2 + 4H \rightarrow CH4 + 2H2O$$

The transformation of CO_2 and 4H is 100 % as there is no excess of carbon, oxygen or hydrogen on the right-hand side of the equation and therefore the utilisation of biomass is 100 %.

4.2.1 Catalytic methanation

The catalytic methanation is accelerated by a catalyst and therefore also called catalytic methanation. The catalyst speeds up the chemical reaction and in the process the catalyst brings the reacting molecules together while catalyst remains intact.

The reaction is called a sabatier process which was discovered in the 1910s. The energy-output of the reaction will be shown below.

$$CO_2 + 4H \rightarrow CH_4 + 2H_2O + \text{energy} \qquad \Delta H_R = -189 \text{ (kJ/mol) (T=523 K)}$$

The energy of the system can be described as enthalpy (H), which is the sum of the internal energy of the system plus the pressure of the gas in the system times the volume of the system. If the enthalpy is negative it indicates that the reaction is an exothermic process, which means the process releases energy. Exothermic is the opposite of endothermic in which heat is consumed.

Biogas must be purified for sulphur and other compounds before entering the methanation reactor to spare the catalyst in the reactor for contamination. A limit of 5 ppb of sulphur can be accepted at the methanation reactor inlet.

The methanation plant can be up and running within 15 minutes with an operation temperature at between 200-300 C.

4.2.2 Biological methanation

The formation of methane is performed by methanogenic archaea, or methanogens, that convert carbon dioxide and hydrogen or acetic acid (CH_3COOH) to methane. Methanogenic archaea is a group of microorganisms that produce methane under anaerobic conditions. The methanogenic archaea is distinct from bacteria. Biological methanation is supplied only with carbon dioxide and hydrogen. If the concentration of hydrogen becomes too high, the reaction would be thermodynamically unfavorable. The hydrogen content in the reactor is low because it gets consumed by the methane producing archaea. Hydrogen is important to the anaerobic oxidation of propionate. The propionate is the molecule that forms acetic acid by oxidation. There is a fine limit of the allowed pressure in a biological methanation process as the propionate oxidizing organisms prefer a low pressure of hydrogen while the methanogens needs a high pressure of hydrogen. When this occurs, it opens an opportunity to create the methanation process directly inside an existing biogas plant if just the right amount of hydrogen is added. It must be done in such a way that no significant effect on the anaerobic oxidation occurs. Hydrogen formation by syntrophic acetate oxidation is not thermodynamically favorable, however by combining the reactions of a methane formation it would be thermodynamically favorable. The two reactions can be seen below (Benjaminsson et. al, 2013).

Formula 1 Hydrogen formation

$$CH_3COO^- + 4\ H_2O \rightarrow 2\ HCO^-_3 + 4H_2 + H^+ \qquad \Delta G = 104{,}6\ kJ/mol$$

Formula 2 Methane formation

$$4H_2 + HCO^-_3 + H^+ \rightarrow CH4 + 3H_2O \qquad \Delta G = -135{,}6\ kJ/mol$$

The two reactions happens in the reaction and therefore they are added together. The sum of the two reaction is a negative value which means it is a spontaneous reaction as this is a calculation of the Gibbs free energy.

When there is hydrogen oxidation that means the bacteria produce acetic acid from the combination of hydrogen and carbon dioxide, as seen below.

Formula 3

$$4H_2 + 2\ CO_2 \rightarrow CH_3COOH + 2H_2O$$

The acetic acid then gets cleaved into carbon dioxide and methane as seen in formula below.

Formula 4

$$CH3COOH \rightarrow CH4 + CO2$$

The remaining CO2 of this reaction is utilised when hydrogen is added.

In the biological methanator a purifier for the sulphur is not needed unlike the catalytic methanation where the sulphur has to be purified. The biological process is running at a temperature of 40-65 °C (Benjaminsson et. al, 2013).

4.3 Electrolysis technology

In this section a brief description of what water electrolysis is, is given and followed by the different technologies that are and might be commercially available in the near future. Each of the technologies will be described and compared in a table.

Water electrolysis is a process in which a water molecule gets split into oxygen and hydrogen by applying electricity. This happens in two different reactions apart from one another by two electrodes that is separated by an ion conducting electrolyte. The negative electrode (cathode) produces hydrogen while the positive electrode (anode) produces oxygen. These electrodes are separated in two different containers. There are three technologies commonly known for electrolysis namely Alkaline Electrolyser Cell (AEC), Proton Exchange Membrane Electrolyser Cell (PEMEC) and by Solid Oxide Electrolysis Cell (SOEC). The general view of components contained in electrolytic cell shown in figure 6.

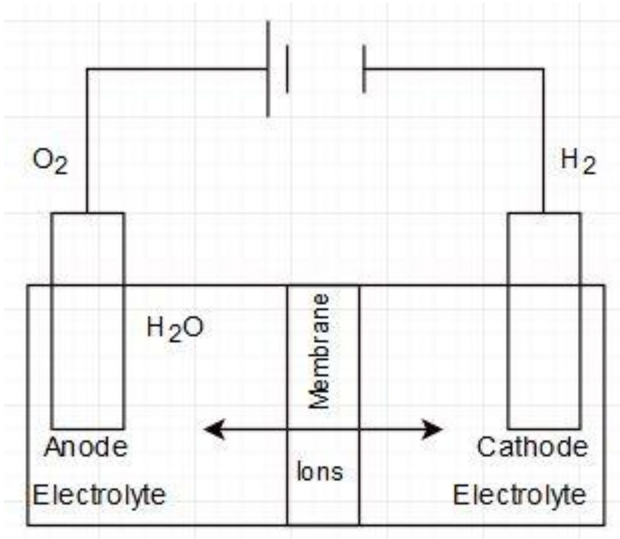

Figure 6: Components in an electrolytic cell.

The chemical reaction for the water electrolysis is shown below:

$$H_2O \rightarrow H_2 + \frac{1}{2} O_2$$

Note that, input = output. This counts for both materials and energy. Generally the heat from the electrolysis processes can be utilized in other units.

The three technologies are on different stages which represent the challenges they are facing. The alkaline is a full commercial technology and the most dominating in Denmark. Larger PEM electrolysis plants are still in the demonstration phase although smaller plants are being commercialized. The SOEC is under development but it has promising prospects.

All these three electrolysis technologies needs higher efficiencies and the cost must be lowered in order to have electrolysis fill the role as stabilizer in the energy system when there are renewable energy sources to feed the electricity grid, and thereby being a part of the solution of 100 % fossil free by year 2050.

Alkaline and PEM technologies are technologies that are both being used in facilities and can deliver on site and on demand hydrogen when needed, they both produce pressurized hydrogen without a compressor. This factor makes it possible for companies that need hydrogen to produce it themselves. The SOEC technology is on demonstration phase but will likely be on the market and ready to produce hydrogen more effectively and cheaper than PEM and alkaline in roughly 4-5 years.

	AEC	PEMEC	SOEC
Operation temperatures	60-80 C	60-80 C	750-950 C
Commercially available capacity	Up to 100 MW	0,01 Nm^3/h (2014)	Not available yet
Being demonstrated	Already commercialised	240 Nm^3/h (2014)	150 Nm^3/h up to 15.000 Nm^3/h by the year 2020.
Compressed to:	32 bar	100-200 bar	100 bar
Efficiency	75-85 %	80-85 %	90 %

In the table it is shown different parameters for each of the three electrolysis cells. *Note that the efficiencies depend on the current density. Current density is written as A/cm^2*. (Elektrolyse i Danmark, 2009)

The electricity used to produce hydrogen can come from fossil fuels and from renewable energy sources. Renewable electricity produces renewable hydrogen. The concept is called power-to-gas where electricity applied to an electrolyser produces hydrogen that can be used for a methanation process. The methanation process is covered in section 4.2.

By commercializing the electrolysers the units can function as a balancing tool for the electricity grid and for times when the spot prices are negative the electrolysers can use the electricity rather than paying other countries to take the electricity.

4.3.1 Alkaline Electrolyser Cell (AEC)

Alkaline electrolysis process has been used for hydrogen generation since the end of the 18th century. The compartment of anode and cathode are separated by micro-porous diaphragm, as to avoid the blending of gasses. The alkaline electrolysis is affected by the ion that transfers the charges and affects the occurring reaction and the intermediates that are formed.

The alkaline differs from the other technologies PEM and SOEC electrolytes in being less complex. The disadvantage is the efficiency being 75-85 % is typically lower than PEM electrolytes and significantly lower than SOEC electrolytes. Also the possibility of reversing the electrolysis process, i.e. electricity production from hydrogen is available for PEM and SOEC but not alkaline.

The current development of the alkaline is focusing on increasing output pressure of gasses and higher efficiencies which includes new electrode technology, new materials and higher system temperature. The electrolysis can be up and running within seconds.

4.3.2 Proton Exchange Membrane Electrolyser Cell (PEMEC)

The PEM technology was first introduced in the 1960s by General Electric to overcome the drawbacks of the alkaline electrolysis technology, since then the alkaline has improved. In a PEMEC the electrolyte is a polymer membrane that is in contact with two gas diffusion electrodes which increases the conductivity and thereby gives higher efficiency. The efficiency of the PEMEC is 80-85 % typically. The polymer has good conductivity at the intended temperature range. The conductivity in a specific temperature range is dependent of the polymer used. Over time the polymer degrades which means it will require replacement. The timespan of electrodes and electrolytes is between 5-10 years.

The PEM technology can respond fast to incoming electricity load changes, whereas the SOEC if cold require several hours depending on the design.

Since 2014 the technology is commercially available on small scale while larger scales are being demonstrated.

The stack prices are high as the materials are hard to come by. The iridium price which is used in the PEM has been rather constant for more than a decade.

4.3.3 Solid Oxide Electrolyser Cell (SOEC)

Solid Oxide Electrolysis Cell uses a ceramic electrolyte meant to provide increased high conductivity and thermal resistance. This enables SOEC to operate at higher temperatures than alkaline and PEM electrolysis allowing for higher efficiencies

The process for steam electrolysis, gaseous H2O is introduced at the negative cathode, where it is split into H2 and oxide ions $O2^-$. The oxygen is then transported through the ceramic materials, by vacancies in the atomic structure. SOEC differs here from alkaline and PEM electrolysis, as it is the oxygen that transfers the charge.

4.4 Hydrogen storage

Storing hydrogen can be done in multiple ways; pressurised gas, as liquid, in chemical compounds or absorption in hydrides. In this report only hydrogen stored as pressurised gas is used and therefore only described.

The most commonly used storage is tanks and bottles seen in the form of a sphere. Theoretical the sphere is the most optimal design for a tank, as this optimises the surface to the volume and most effective form for a pressurized container. Large spheres however are limited in size by gravity.

Pipe containers are another way of storing and consist of horizontal pipes of 200 m to a few kilometres in length and a diameter of around 1,5 m. The pipes are placed underground and connected, forming a large storage.

The most commonly standard of hydrogen storage is using a metal vessel, 25 to 100 m^3 in volume stored at 30-35 bar.

4.5 Gas grid

By utilizing the methanation technology it is possible to store huge amounts of the renewable energy produced by wind turbines and solar cells in the gas grid. The natural gas grid can partly be stored in the pipe systems and in the underground gas storages in which there can be stored enough gas to service the Danish gas demand for months.

The gas grid consists of a transmission net and distribution net. The transmission net covers Denmark with north-south and east-west transmission lines and is operated by Energinet.dk. The net is connected to gas storages, The North Sea and to the gas infrastructure of Germany and Sweden. The transmission net provides for a few large consumers and regional gas providers with gas.

The distribution net connects the transmission net to the consumers and is handled by regional providers, which is also responsible for meters and measurement data at the individual consumers. Upgraded biogas producer's deposits gas to the distribution net, why this will be examined further.

The transmission net is operated at up to 80 bars, whereas the distribution grid is operated at 40 bars or 19 bars. This is the reason biogas producers are depositing to the distribution net, as it otherwise would need to raise the pressure, making it more costly.

The requirement for gas quality deposited to the transmission net, is specified by the Danosh Security Technology Authority, and is found in Gas Regulations section C-12.

Currently no regulation regarding hydrogen exists in section C-12. For regulation, the system operator in Denmark has been following the German standards. These states for a maximum of 5 vol%, but with a new European Standard (FprEN 16726, 2015) this is expected to change (Kvist, Torben. 2017).

With a new European Standard (FprEN 16726, 2015), a new specified requirement for hydrogen is recommended to 2 vol%. This is mainly due to the steel tank in natural gas vehicles which stipulates a limit value for hydrogen of 2 vol%. Gas turbines could also face problems coping with a hydrogen fraction in natural gas of 1% or even lower. Higher values of 5 % or up to 15 % hydrogen fraction are achievable with either modifications or new types of turbines.

5 Scenarios

First a description of the two scenarios is given. This is followed by the two scenarios modelled in EnergyPRO, where the system designs will be shown. The first scenario will not be presented by graph in EnergyPRO as it just shows that the system is running. The second scenario will be presented by graphs and system designs with a description of what these illustrate. The purpose of the scenarios is to determine the DKK/kWh methane for each of the designs.

In scenario 1 the electrolyser runs all year regardless of the electricity price to produce hydrogen in order to saturate the produced carbon dioxide by the biogas plant.

The goal in scenario 2 is to examine the capacity of a storage and the capacity of an electrolyser in terms of a defined “low” electricity price. It will be investigated if the added hydrogen storage and increased electrolyser would lower the cost of methane price compared to scenario 1.

5.1 Framework condition for EnergyPRO

In this chapter there will be a description of how the EnergyPRO model is working and what parameters have been taken into consideration. Besides parameters, all framework conditions that have been estimated or assumed is described.

5.1.1 “Low electricity price” defined.

A “low electricity price” is needed in the scenario with storage, and therefore defined as the electricity spot price below the average yearly electricity spot price. With the average yearly electricity price of 170,75 DKK/MWh for 2015, a low electricity price is defined as below 170,75 DKK/MWh.

5.1.2 Electricity price

The electricity price used is based on 2015 spot prices from energinet.dk. The year 2015 was chosen instead of 2016, as 2016 had an abnormally 498 hour period with an electricity price above the average yearly electricity price compared to the previous three years shown in the table below.

	Unit	2013	2014	2015	2016
Yearly avg. electricity price	DKK/MWh	283	229	171	199
Hours below avg. electricity price	hours	4828	4474	3991	4951
Longest period in hours below avg.	hours	212	191	235	498

The 498 hours period of “high electricity price”, would prove to be problematic for the scenario with storage, as the storage would have to be able to cover all 498 hours. This would require an already large storage and electrolyser to become even larger and possible distort the average required size and price for the methanation plant. With 2015 having the second largest period of "high electricity prices", this could serve as an indication for the storage to be able to handle years with large periods.

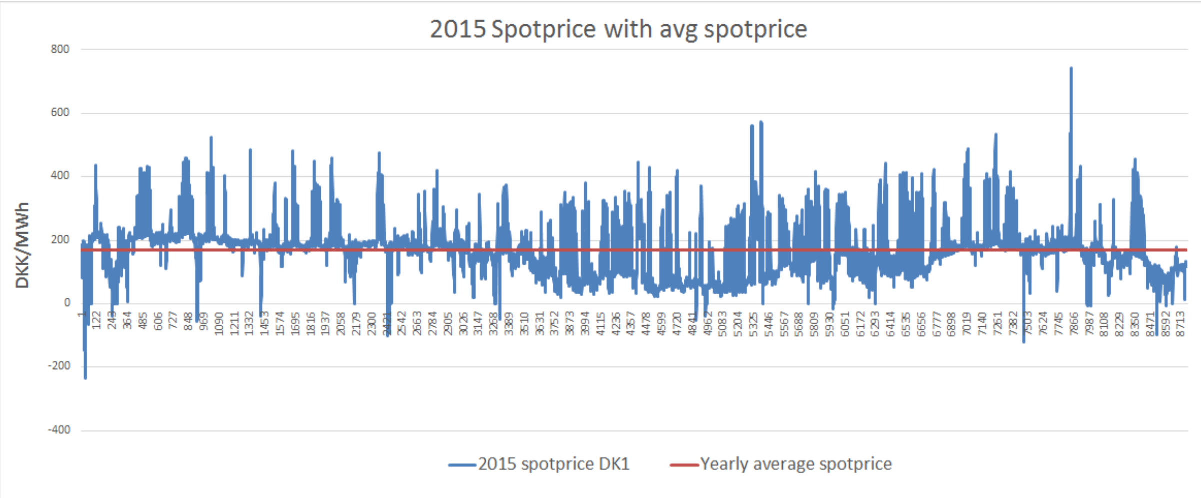

Figure 7: Spot prices for 2015 with red line at 170,75 DKK/MWh showing the average price.

On figure 7 the yearly average electricity price has been marked with red overlaying the spot price for the year 2015. The 235 hour period that the storage was initially scaled for, is between the hours 947 and 1.181.

5.1.3 EnergyPRO components

Description of the components and the connections made in EnergyPRO is shown below.

Component name and type	Description of the component.	%-efficiency
Spot market (Electricity market)	Based on the spot prices in DK1 for the year 2015.	-
Electrolyser (Energy conversion unit)	The electrolyser is set to run if the spot price is below a set point. The capacity of the electrolyser varies.	84 %
Hydrogen_H2 (Fuel and storage)	The heating value of hydrogen is set to 3,546 kWh/Nm3. In this unit the storage and storage restrictions are available. It is also possible to set fixed amount of stored content for the start and end of the simulation. The settings of max fuel content and the fuel content at the start and the end of the year varies	-

	throughout scenario 2, in which storage content and the capacity of the electrolyser varies due to the set electricity price.	
Biogas_CH4andCO2 (Fuel)	The heating value is set to 6,5 kWh/Nm3. 35 % carbon dioxide and 65 % methane.	-
Methanator_H2 (Energy conversion unit)	The Methanator_H2 must run at all times as there is a constant biogas production. This unit is set to run when Methanator_Biogas is running which always runs.*	Produced fuel efficiency: 91 %
Methanator_Biogas (Energy conversion unit)	The Methanator_Biogas continues to run as long there is biogas available. The methane of the biogas is going to the gas grid.*	Produced fuel efficiency: 91 %
Methane_CH4	The heating value is set to 11 kWh/Nm3 as default from EnergyPRO.**	-
Gas grid	The gas grid is modelled to form a demand. The input is equal the output.	-
Natural gas demand	The natural gas demand is modelled to form a demand of MWh.	-
District heating demand	The district heating demand is set to take all heat from the CHP.	-

Note that, in reality the methanator is a single unit but as it has to be two units in EnergyPRO the input and output efficiencies has been split between Methanator_H2 and Methanator_Biogas. That is why Methanator_Biogas has 12,3 MW input and 11,2 MW output, even though both input and output is methane. The sum of the heating value of hydrogen and biogas is 10,046 which is lower than the methane heating value of 11 kWh/Nm3.*

Black connection	**Electricity flow**
Yellow connection	Hydrogen flow
Green connection	Methane flow
Purple connection	Methane in biogas flow
Pink connection*	Carbon dioxide in biogas flow
Blue connection	Workaround of methane flow to the grid.
Red Connection	Heat flow

** The pink line has been drawn manually, as the user-defined units cannot take two fuel flows.*

Time Series Function

It is possible to add a “Time series function” to inputs and outputs in EnergyPRO. The time series function was used in order to design the different scenarios modelled in EnergyPRO.

5.2 Framework conditions for economics

In this chapter, the framework condition that is applied to the socio- and business-economics analysis is listed.

Discount rate

All future revenue and cost has been discounted back to year zero, based on the lifetime of the unit, with a discount rate of 4 % (Energistyrelsen, 2013).

Stock exchange

Many of the data received, i.e. investment cost, maintenance cost were all listed in € and needed to be converted to DKK. For the conversion of Euro to DKK, an exchange rate of 745 DKK was used.

Data were also listed in SEK and needed to be converted to DKK and an exchange rate of 76,53 DKK were used.

Tariffs

Energinet.dk have set the Net- and System Tariffs for first quarter of 2017, which will be effective for the whole of 2017 and used in all scenarios. The grid tariff represents the cost for Energinet.dk to maintain the transmission grid (400/150/132 kV), i.e. the cost of transporting the electricity from the producer to the consumer. System tariff covers the cost of reserve capacity, system operation etc.

Both of these are applied to socio- and business-economics, and is assumed constant for all years.

Tarif	Price DKK/MWh
Grid tariff	59
System tariff	24

Figure 8: Tariffs for grid and system

5.2.1 Taxes and subsidies

Electricity tax

The use of electricity for electrolysis is categorized as process energy, and can as a main rule be reimbursement for the majority of the electricity-tax of the consumption of electricity to process. Reimbursement for the entire electricity tax is available, except for 0,4 øre pr. kWh. The electricity tax is applied to business economics and is assumed constant for all years (pwc, 2017.).

PSO

The European Commission has ruled the PSO tax for unlawful. It is a binding task to find a long term solution that secures financing of the transition to green energy. The government, along with the Danish parties, have agreed to abolish the PSO-tax and move the cost of renewable energy to the finance act. The PSO tax will be fully abolished by 2022 and as no future projections exits, the PSO tax is calculated for each year, with the constraint that is must be zero by 2022, hence a linear decline is assumed.

Subsidy

When biogas is upgraded or purified, subsidies are added when selling to the natural gas grid. You are eligible to funding if you own a biogas upgrading plant which delivers to the natural gas grid. (Energinet.dk. 2017c)

Even though biogas upgraded by methanation does not currently receive subsidy, it is estimated that it will be eligible in the near future.

In the business-economic analysis the following taxes and subsidies are included.

Tax	Price [DKK/MWh]
Electricity tax	4
PSO - 2017	16,1
PSO - 2018	12,88
PSO - 2019	9,66
PSO - 2020	6,44
PSO - 2021	3,22
Subsidy	**Price [DKK/GJ]**
Upgraded biogas	135,4

Figure 9: Shows taxes and subsidies.

Future variable electricity price

For the storage scenario, a future indication of the fluctuation of the electricity price was needed as this would affect the saving or cost of the storage. This was calculated based on the yearly average electricity price of each year for 2015 and up until 2016. With this, the average "low- and high electricity price" for each year is found seen in (Ens.dk. 2017b). By taking the ratio between the "low and high electricity price" for each individual year and then the ratio from each year to the subsequent year, we have an indication of the fluctuation of electricity price between the years 2015 and 2016. The average of all the ratios between each year, indicates an average increase of fluctuating electricity prices by 1,1 %.

Lifetime

As the maturity of alkaline electrolysis is a commercial technology, with methanation being ready for demonstration (EUDP, 2016), the year 2020 have been chosen as starting point.

The expected lifetime for electrolysers varies depending on the manufacture. The NEL Alkaline Electrolysis Cell are 25 years. Throughout the years the efficiency are degrading. Therefore the lifetime might be shortened.

The methanation unit has a lifetime of 20 years. The economics were based on a lifetime expectancy of 20 years because of the methanators lifetime (EUDP, 2017).

Future electricity price

The electricity price used, are spot prices from (Ens.dk, 2017) and are used for all years up until 2040. The increase of the spot price is due to an expected increase of production cost, with the increasing introduction of RE.

Heat price and heat waste

The heat price used for socio-economics is 65 GJ/DKK (EA Energianalyse. 2016).

The heat price used for business-economics is 373,5 DKK/MWh, and is based on the sales price from Fjernvarmefyn (Fjernvarme fyn. 2017).

The heat price is assumed constant for all years, as heat price based on historical data have little variation.

The waste heat from the electrolyser is 16 %. For catalytic methanator it is 21 % and biological methanator it is 18 %.

Upgraded biogas by methanation

When calculating for gas sales, it is assumed that the biogas on NEM contains 35 % CO2 of which 100 % will be converted to methane. With that assumption the yearly amount of methane produce is 5,25 mio. Nm^3.

Capital cost and maintenance

A collection of the used capital and maintenance cost is shown in the table below.

Technology	Capital cost	Maintenance	Source
NEL - Alkaline electrolyser	0,045 [MSEK / Nm^3/h H2]	3 % of investment/year	(Benjaminsson et. al, 2013)
Sunfire - catalytic, electrolyser included	0,357 [MSEK / Nm^3/h CH4]	3 % of investment/year	(Benjaminsson et. al, 2013)
Krajete - biological, electrolyser included	0,28 [MSEK / Nm^3/h CH4]	3 % of investment/year	(Benjaminsson et. al, 2013)
H2 storage in tanks	3,51 [€/MJ]	3 % of investment/year	(EUDP, 2016)

6 EnergyPRO models

In each of the scenarios there will be a description how EnergyPRO was modelled in order to run the scenarios. Each scenario is represented by the appropriate figure.

Conditions for scenario 1 and 2 in EnergyPRO

In order for a methanation unit to run there always has to be a hydrogen supply to saturate the carbon dioxide. This is also the case when modelling in EnergyPRO. If there are not enough hydrogen available, the methanation cannot run, which means the carbon dioxide is not upgraded. Therefore a scrubber has to be installed. In scenario 1 and 2 the methanation process has to run without a scrubber. The hydrogen is supplied by the electrolyser.

The operation strategy for scenario 1 and 2 are the same. They prioritise the electrolyser, Methanator_H2 and Gas grid. The Methanator_Biogas has a lower priority. The Methanator_H2 has priority as it is essential that the carbon dioxide can be utilized, otherwise a scrubber is required. In order to have the Methanator_H2 running it requires hydrogen from either the electrolyser or the storage. The Gas grid must always take the methane that is produced from the Methanator_H2.

6.1 Scenario 1, without hydrogen storage:

In scenario 1 the electrolyser runs all year regardless of the electricity price to produce hydrogen in order to saturate the produced carbon dioxide by the biogas plant. EnergyPRO simulates the monthly revenue for the year 2015.

EnergyPRO model of scenario 1:

The electricity price on the spot market is connected to the electrolyser. The electrolyser produces hydrogen which will be used in the methanator. The Biogas that is produced on a biogas plant, which is not shown on figure 10, is set to consist of 35 % CO2 and 65 % CH4. The unit “Biogas_CH4andCO2” delivers CH4 to the “Methanator_Biogas” while the CO2 is shown to be delivered to “Methanator_H2”.[1] The output from the “Methanator_H2” and the “Methanator_Biogas” is methane.[2] The CH4 is delivered to a “Gas grid” that is

[1] *Note1 that, as EnergyPRO will not accept two fuel inputs in a user-defined unit, the hydrogen has been set to produce methane without CO2. This is a workaround in order to model the system. This does not affect the results.*

[2] *Note2 that, in order to model the system a workaround has been done by creating two methanators. In reality this is one unit.*

connected with "Natural gas demand".[3] As the methanation process in the the Methanator_H2 and the Methanator_Biogas goes on, heat is produced which is delivered to district heating.

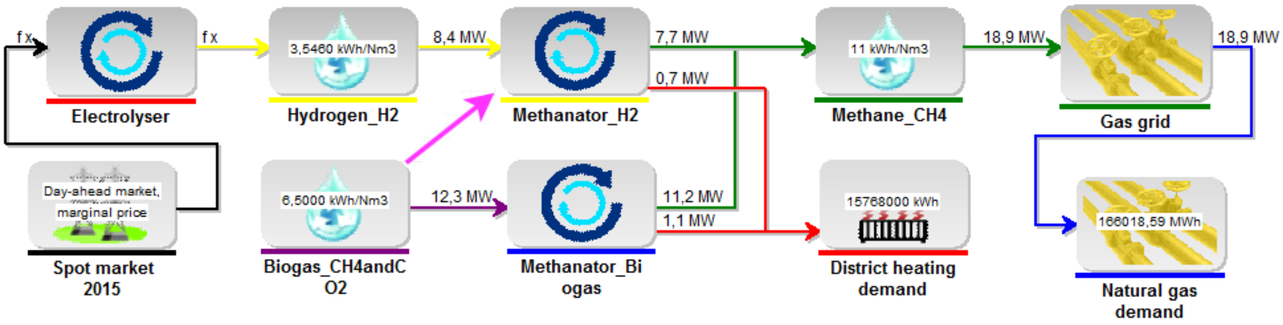

Figure 10: Design of the EnergyPRO model. See section 5.1.3 EnergyPRO components for information on each of the components.

As there is no storage and no preset limitation on scenario 1, this results in a stable electrolysis run time producing hydrogen regardless of the electricity price. As the data for this scenario is predetermined from the sankey diagram the revenue can be calculated. The revenue comes from amount of methane and heat sold, while the operating expenditures is the spot price. See appendix 5

6.2 Scenario 2, with hydrogen storage:

The goal in scenario 2 is to examine what storage capacity and electrolyser capacity is required to run at a certain electricity spot price.

There are three parameters that are examined, the storage capacity, the electrolyser capacity and the electricity spot price. For this paper the electricity prices was set to a specific value, increasing with 10 DKK/kWh each step as shown in table 1. When a storage capacity and electrolyser capacity was found fitting the set electricity price value, the next set electricity price step was examined. The electricity prices set value starts at 170,75 DKK/kWh, which is the average spot price of the year 2015.

The capacity of the electrolyser and the capacity of the storage vary for each set electricity price. When the electricity price is set to a specific value, either the storage capacity has to increase while the electrolyser capacity decreases or the electrolyser capacity has to increase while the storage capacity decreases. At the end of this scenario the methane produced is goes to the gas grid.

Note, this approach can be done for each of the three parameters.

[3] *Note3 that, in order to make a natural gas demand in EnergyPRO, a cooling demand can be modelled as a workaround. EnergyPRO does not offer a natural gas demand unit as default. The essential part is that a demand is created.*

The table below shows the approximate size of the storage capacity and electrolyser capacity based on the electricity spot price limits of when the electrolyser should run.

<= Spot price	Electrolysis capacity	Storage capacity
170,75 DKK/kWh	100 MW	1.100.000 Nm3
180,75 DKK/kWh	80 MW	1.000.000 Nm3
190,75 DKK/kWh	60 MW	800.000 Nm3
200,75 DKK/kWh	35 MW	600.000 Nm3
210,75 DKK/kWh	20 MW	500.000 Nm3
220,75 DKK/kWh	15 MW	250.000 Nm3

Table 1: The parameters for each of the spot prices.

The table above shows the settings for scenario 2 simulations. The smallest capacity simulated of 250.000 Nm3 corresponds approximately the size of half a football field with a storage of 1 meter in height at 32 bar(AEC output).

The storage constraints of how much the storage contains at the start and at the end are set to half the amount of the storage capacity. This is the case for simulations in which the electrolysis capacity is below 100 MW. The storage content is set to half because this offer the best conditions to either store hydrogen if the spot price is below or to use hydrogen if the spot price is above average.

The storage is dimensioned to saturate the Methanator_H2 at times when the spot price is above a specific point. During these periods the storage is emptied. As shown on figure 11 the storage has to be dimensioned for less than 10 % of the year otherwise the storage cannot saturate the Methanator_H2. This means that 90 % of the year the storage is above half full.

Figure 11: Graphs for the system with electricity price at 220,75 DKK/kWh, 15 MW electrolyser unit and a 250.000 Nm3 hydrogen storage.

The upper most graph displays the spot prices during a year. The middle graph displays the runtime of the electrolyser and the bottom graph shows the hydrogen storage content over a year. For the whole graph see appendix 4.

During the runtime of the simulation the electrolyser sometimes makes a step as shown on figure 11, the date 01-04-2015 wednesday is an example, marked with a green circle. This occurs as the storage is full. If the electrolyser cannot run on part load there are three options. The first being to have two electrolysers, one with the capacity to fuel the Methanator_H2 with hydrogen and one electrolyser that fuels the storage. The second option would be to turn off the electrolyser when the storage is full and the third option would be to increase the capacity of the storage.

On figure 12 the storage content in the case of a 100 MW electrolyser and a 1.100.000 Nm3 storage capacity. It can be observed that most of the year the hydrogen storage is nearly full.

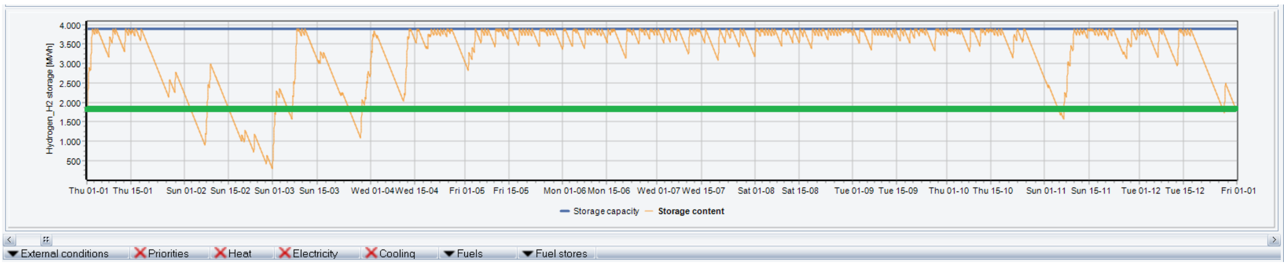

Figure 12: the graph for the system with electricity price at 170,75 DKK/kWh ("Low price"), 100 MW electrolyser unit and a 1.100.000 storage. The green line indicates half of the storage.

EnergyPRO model of scenario 2:

The electricity price on the spot market is connected to the electrolyser. The electrolyser produces hydrogen that can either be used directly in the methanator or stored in the hydrogen storage. The biogas that is produced on a biogas plant, which is not shown on figure 13, is set to consists of 35 % CO2 and 65 % CH4. The unit "Biogas_CH4andCO2" delivers methane to the "Methanator_Biogas" while the carbon dioxide is shown to be delivered to "Methanator_H2".[1] The hydrogen_H2 unit is a fuel and a storage in which the storage capacity is defined and the restraint setting for the amount of fuel stored at the start and at the end of the simulation is found. The output from the "Methanator_H2" and the "Methanator_Biogas" comes in methane.[2] The methane is delivered to a "Gas grid" that is connected with "Natural gas demand".[3] As the methanation process in the the Methanator_H2 and the Methanator_Biogas goes on, heat is produced which is delivered to district heating.

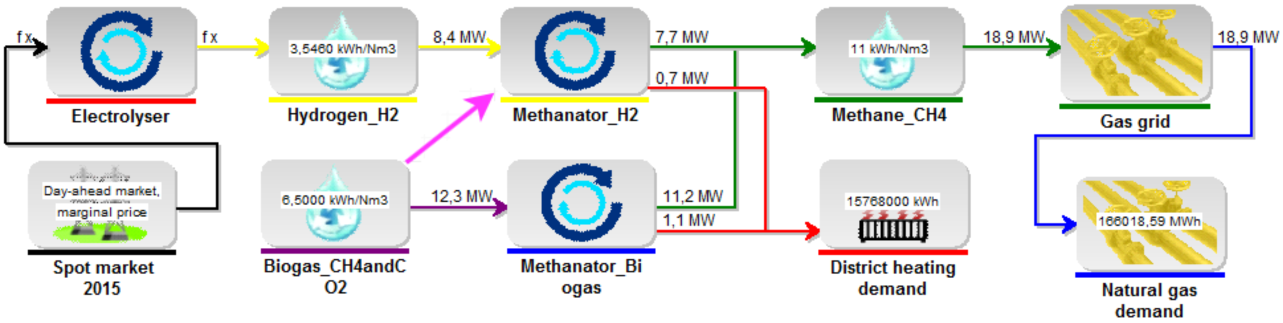

Figure 13: Design of the EnergyPRO model. See section 5.1.3 EnergyPRO components for information on each of the components. The figure is the same as for scenario 1, figure 10, but the “Hydrogen_H2” has the setting to be used as storage in this model.

7 Economics analyses

In this chapter both the socio-economic and business-economic analysis is done for scenario 1 and 2.

The calculations which underlies our results are found in the excel sheet “Economic calculations for master’s thesis – Optimised biogas upgrading by methanation in full scale”.

7.1 Socio-economics analysis of scenarios

This chapter shows the socio-economics analysis for the different scenarios. The analysis contains all the costs associated with the cost bearing methane produced from carbon dioxide supplied by biogas.

The calculated methane price is found by dividing the total amount of cost in DKK in its lifetime with the total amount of produced methane in its lifetime. The production cost does not take sales of heat generated from the alkaline and methanator nor sale of upgraded biogas into account.

7.1.1 Scenario 1 – Methanation without hydrogen storage

The results for the socio-economic analysis of methane production cost per kWh methane without hydrogen storage are shown.

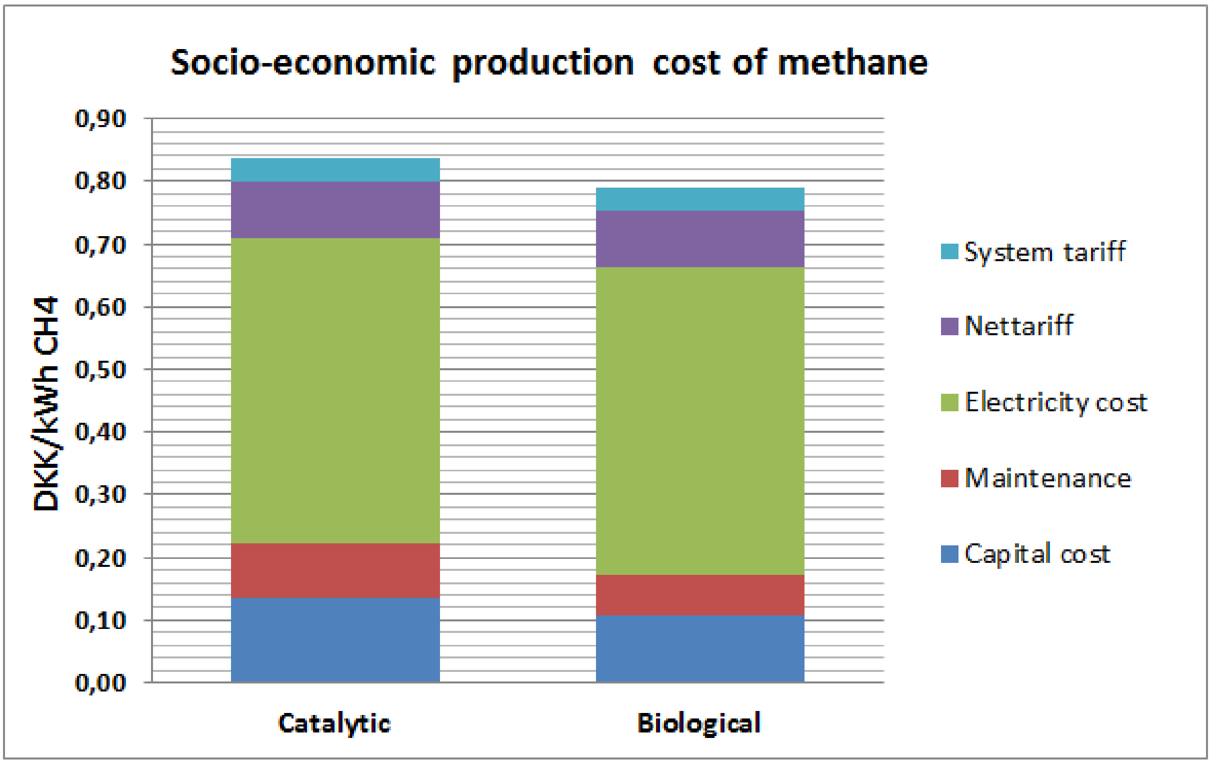

Figure 14: Shows the cost composition of socio-economic production cost of methane.

With catalytic methanation having a total cost of 1.015 mio. DKK, system tariff only make up a marginal composition with 44 mio. DKK. It is visible that the largest cost bearer is the electricity cost with a total cost of 593 mio. DKK.

The total methane price for catalytic in this scenario is 0,84 DKK/kWh methane.

Biological methanation have a total cost of 957 mio. DKK. and are similar to catalytic in cost, as they both have the same electricity cost. The difference lies in the capital cost, which consist of the same electrolysis but different methanation technology. The capital cost for catalytic is 165 mio. DKK. opposed to biological´s 129 mio. DKK.

The total methane price for biological in this scenario is 0,79 DKK/kWh methane.

7.1.2 Scenario 2 - Methanation with hydrogen storage

The results for the socio-economic analysis of methane production cost per kWh methane with hydrogen storage are shown.

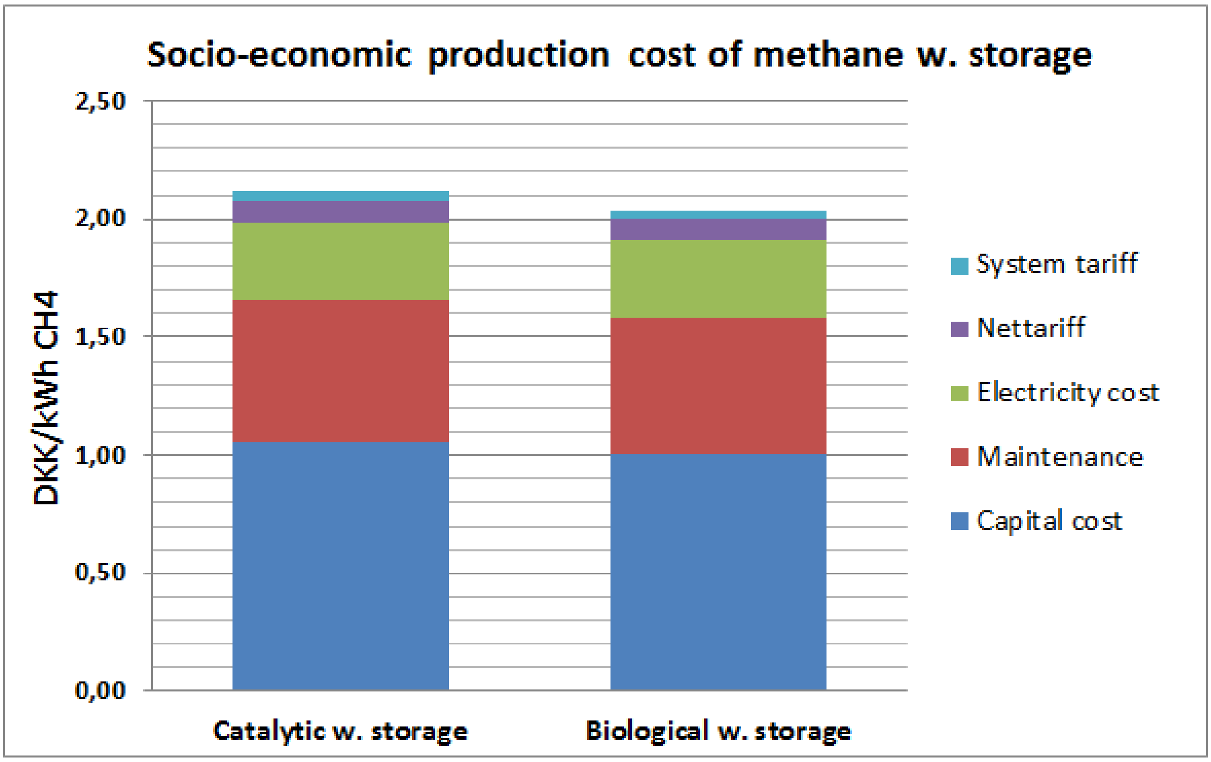

Figure 15: Shows the cost composition of socio-economic production cost of methane w. storage.

The total cost of catalytic with storage is 2.564 mio. DKK and is influenced heavily by the cost of the storage and the increased electrolysis. The capital cost is 1.280 mio. DKK and is composed of the alkaline electrolyser with a cost of 663 mio. DKK, hydrogen storage tank with a cost of 367 mio. DKK. and a catalytic methanation at 82 mio. DKK.

With the high capital cost, the maintenance increased greatly and makes for the second largest cost with 729 mio DKK.

The cost of electricity has decreased from scenario 1, due to hydrogen production only happening in “low” electricity hours and now totals 402 mio. DKK.

The total methane production in this scenario for catalytic with storage is 2,1 DKK/kWh methane.

The total cost of biological with storage is 2469 mio. DKK with capital cost of 1.222 mio. DK wherein biological methanator makes up 23 mio. DKK, setting it aside from catalytic.

The maintenance makes for the second largest cost, costing 693 mio. DKK.

The total methane production in this scenario for biological with storage is 2 DKK/kWh methane.

7.1.3 Results

With socio-economic analysis done for the cost of methane per kWh, the two scenarios are compared and shown in figure 16.

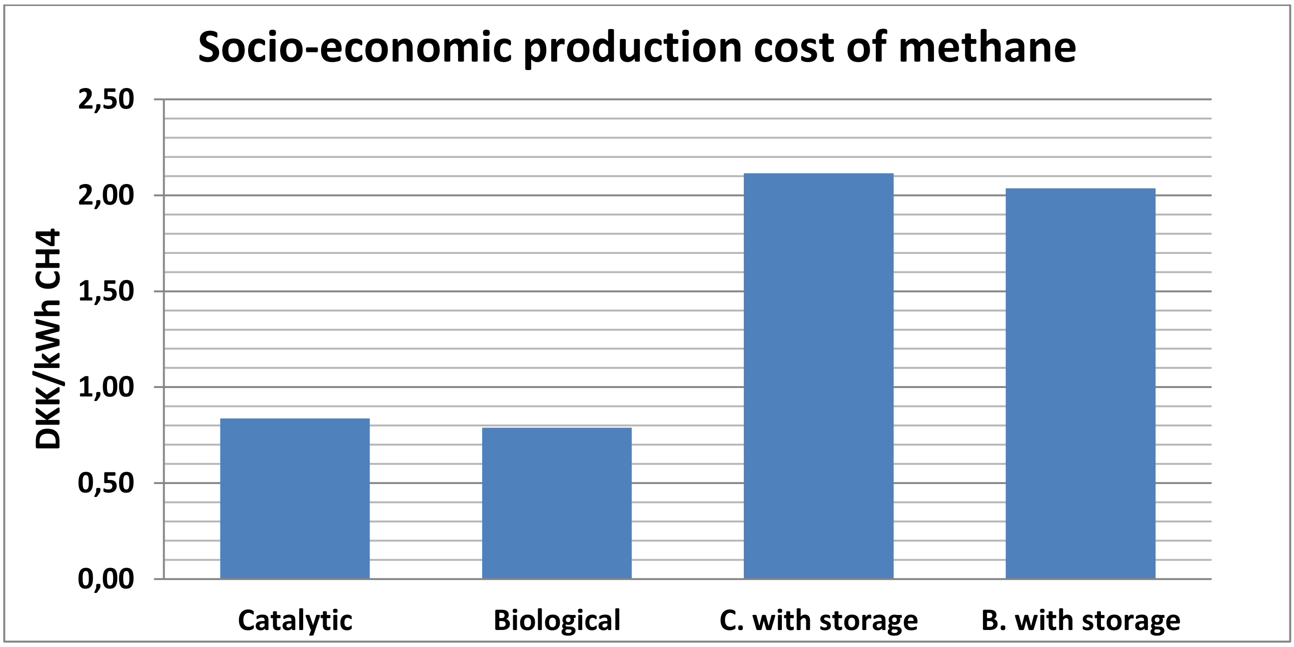

Figure 16: Shows the total socio-economic cost for catalytic and biological methanation with and without hydrogen storage.

It's clear that the investment cost with an added hydrogen storage and an oversized electrolysis for refill of storage in short periods in between “high” electricity price periods increases cost of methane significantly.
The cost of electricity in scenario 1, where it totals 593 mio. DKK, has decreased due to hydrogen production only happening in “low” electricity hours, and totals 402 mio. DKK in scenario 2. The decreased cost is marginal when compared to the increased investment cost of 1116 mio. DKK for catalytic and 1092 mio. DKK for biological.
With maintenance cost being dependant on investment cost, this increases significantly as well from scenario 1 to scenario 2, with 625 mio. DKK for catalytic, and 611 mio. DKK biological.

7.2 Business-economics analysis of scenarios

In this chapter the business- economic prices are done for the different scenarios. This is done by adding the electricity tax and PSO to the electricity price. Furthermore, VAT is added to the electricity bought and the sales of bio natural gas.

Subsidies are added to the sales of the upgraded biogas reflecting the actual price of sold bio natural gas, seen in figure 9.

7.2.1 Scenario 1 - Methanation without hydrogen storage

The results for the business-economic analysis of methane production cost per kWh without hydrogen storage is shown below.

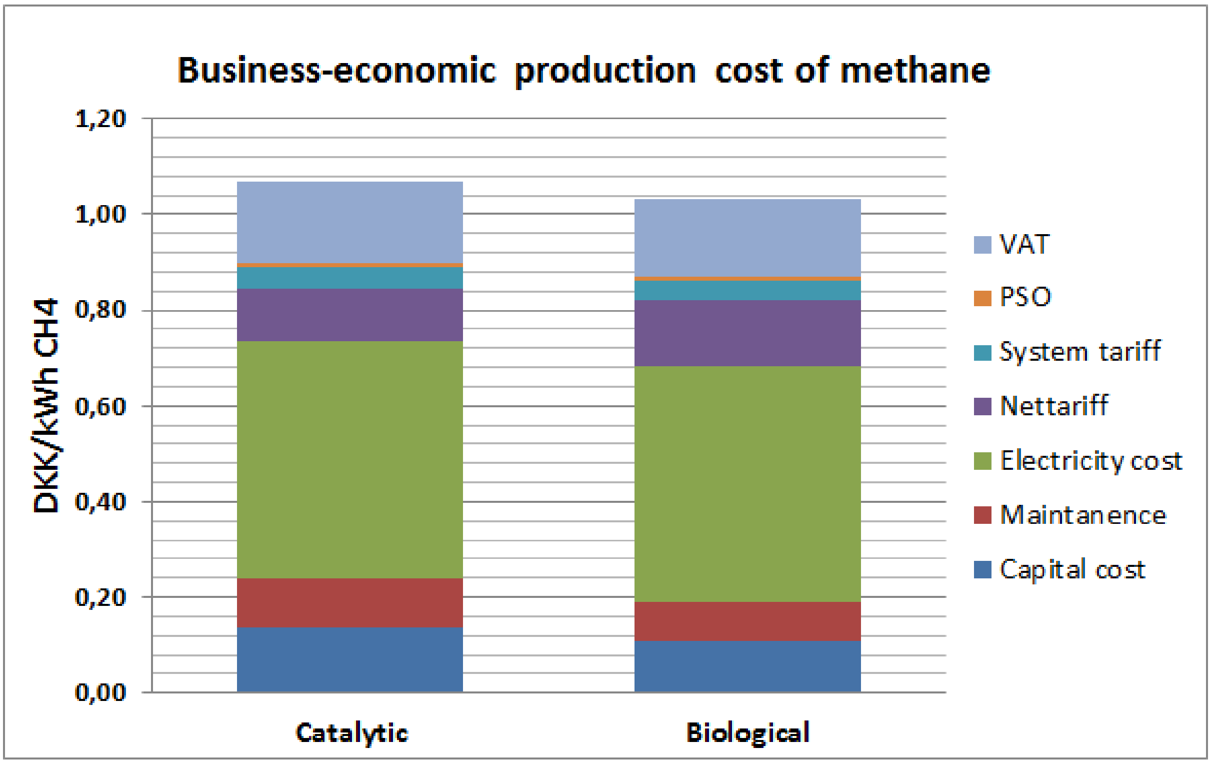

Figure 17: Shows the cost composition of business-economic production cost of methane.

With a cost of 9,7 Mio. DKK, PSO makes up only a marginal of catalytic cost, compared to the total of 1.294 mio. DKK due to only being in effect two years before being abolished.

It's visible that the largest cost bearer in the cost of methane is the electricity price, with a cost of 601 mio. DKK. In the electricity cost lies the electricity tax, with a cost of 7,4 mio. DKK. due to reimbursement.

VAT cost is 206 mio. DKK and comes from purchase of electricity and capital cost.

The total methane production in this scenario for catalytic is 1,07 DKK/kWh methane.

With a total cost for biological at 1.254 mio. DKK. the cost is similar to that of catalytic, with difference found in capital and maintenance. Capital cost being 129 mio. DKK, with maintenance at 99 mio. DKK.

The total methane production in this scenario for biological is 1,01 DKK/kWh methane.

7.2.2 Scenario 2 - Methanation with hydrogen storage

The results for the business-economic analysis of methane production cost per kWh methane with hydrogen storage are shown.

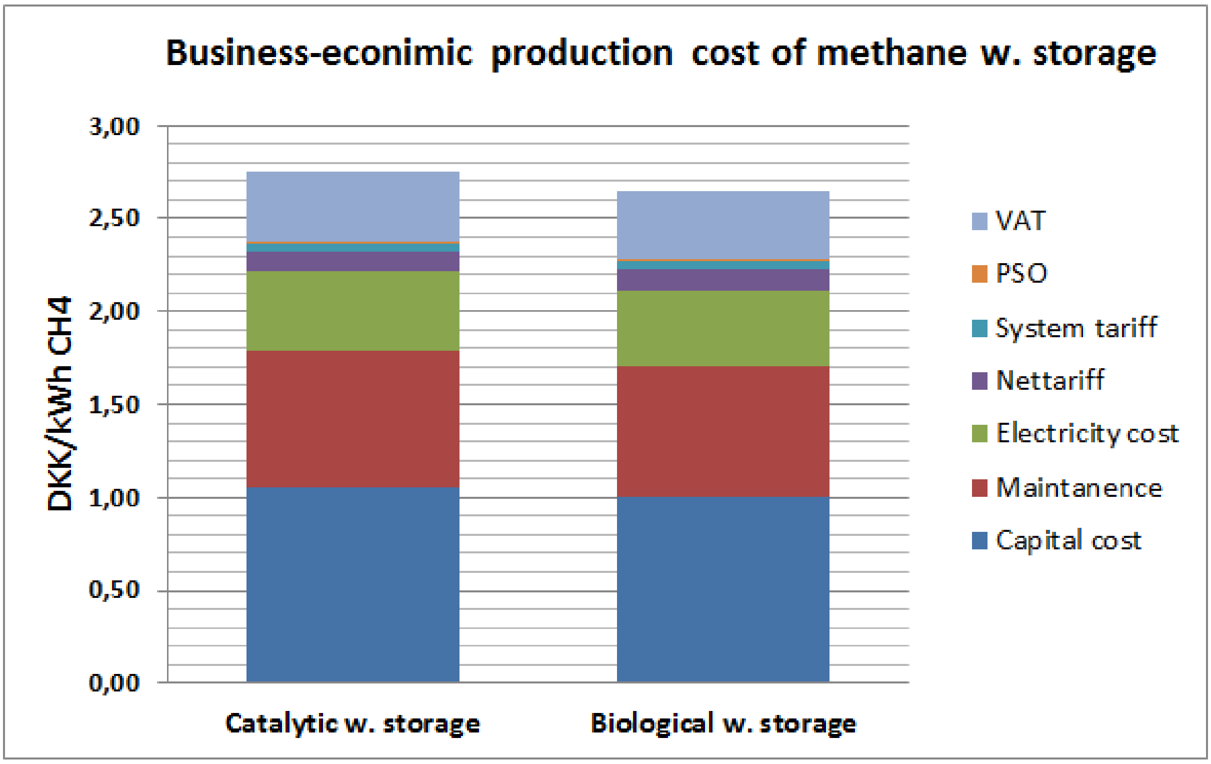

Figure 18: Shows the cost composition of business-economic production cost of methane w. storage.

The production cost of methane for catalytic with storage is greatly increased due to capital cost of 1.280 mio. DKK out of a total of 3.341 mio. DKK.

Total maintenance cost is 889 mio. DKK and is the second largest cost bearer.

The total methane production cost in this scenario for catalytic with storage is 2,76 DKK/kWh methane.

The total cost of biological w. storage is 3.203 mio. DKK. The capital cost is 1.222 mio. DKK and maintenance cost at 844 mio. DKK.

The total methane production in this scenario for biological with storage is 2,64 DKK/kWh methane.

7.2.3 Results

With business-economic analysis done for the cost of methane per kWh, the two scenarios are compared and shown in figure 19.

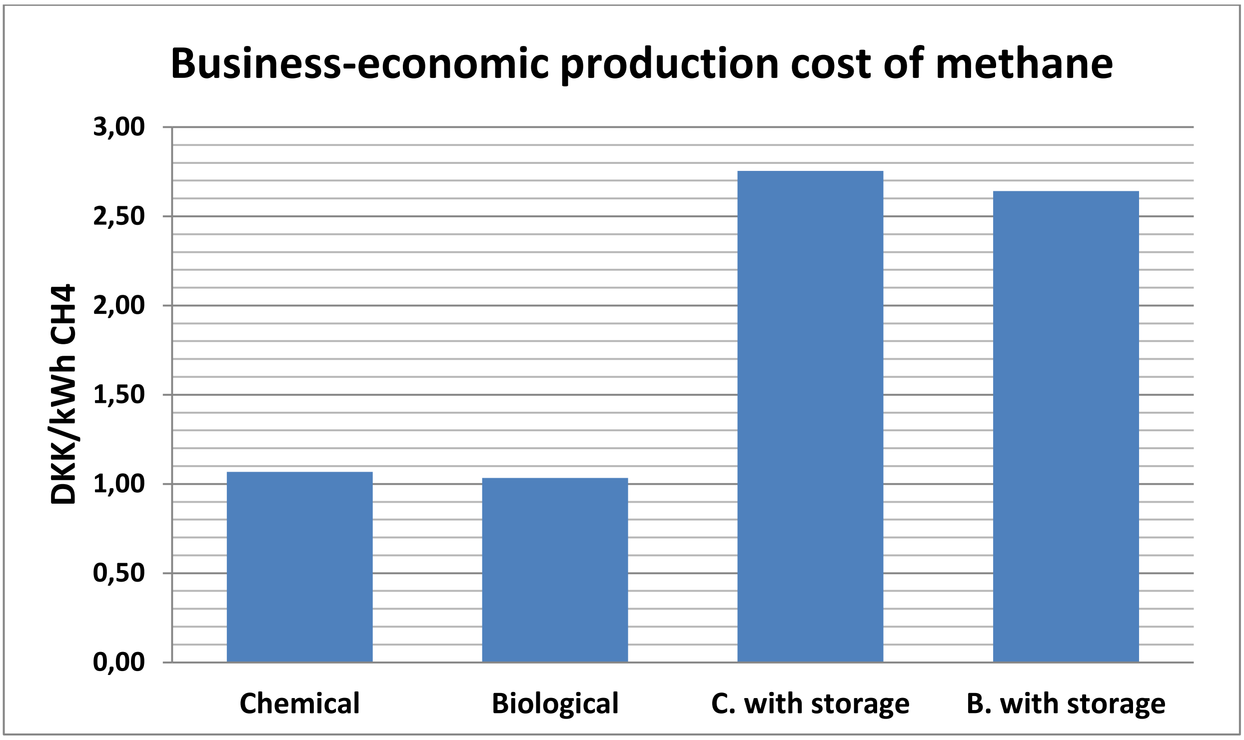

Figure 19: Shows the total socio-economic cost for catalytic and biological methanation with and without hydrogen storage.

The picture is the same as socio-economics with the investment cost for hydrogen storage and an oversized electrolysis far outweighs the lower electricity cost from production in “low” electricity periods.
The cost of electricity in scenario 1 totals 601 mio. DKK, has decreased to 417 mio. DKK for both catalytic and biological. The added electricity tax increases the cost of electricity marginally due to most being reimbursed.

7.3 Net present value

In this chapter the NPV is calculated for both socio- and business.economic. All cost and revenue are discounted back to year 0 to identify the profitability of the investment. A positive NPV indicates a profit and a negative indicates a net loss. In the NPV, sale of “gas sales” is credited to revenue, while the waste heat from electrolyser and methanator has not. For socio-economic the cost parameters “Investment cost”, “maintenance”, “electricity cost”, “net tariff” and “system tariff” are used. The same goes for business-economics with added parameters of PSO and VAT, with subsidies added into the “gas sales”.

In figure 20 the socio-economic NPV is calculated, and overall indicates a large net loss for every setup.

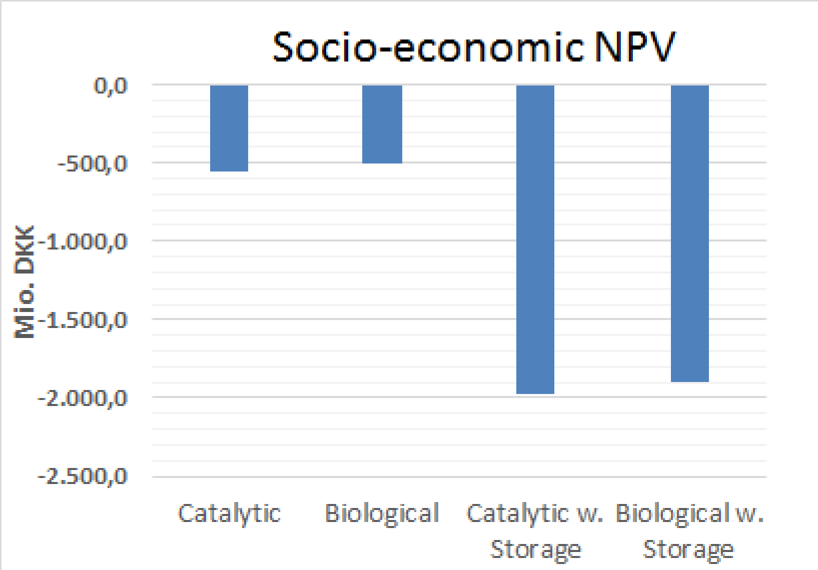

Figure 20: Shows the socio-economics net present value for catalytic and biological methanation with and without storage.

For catalytic and biological, the NPV is negative 555,6 mio. DKK and 504,6 mio. DKK. WIth storage. The sale of gas simply does not outweigh the cost of methanation,

With storage added, huge cost are added associated with the necessary overcapacity of electrolyser and the large hydrogen storage. The NPV for catalytic with storage is -1.979 mio. DKK with biological -1.895 mio. DKK.

The difference between the catalytic methanation and biological is the capital cost of the methanator.

In figure 21 the socio-economic NPV is calculated and indicates less negative NPV for biological.

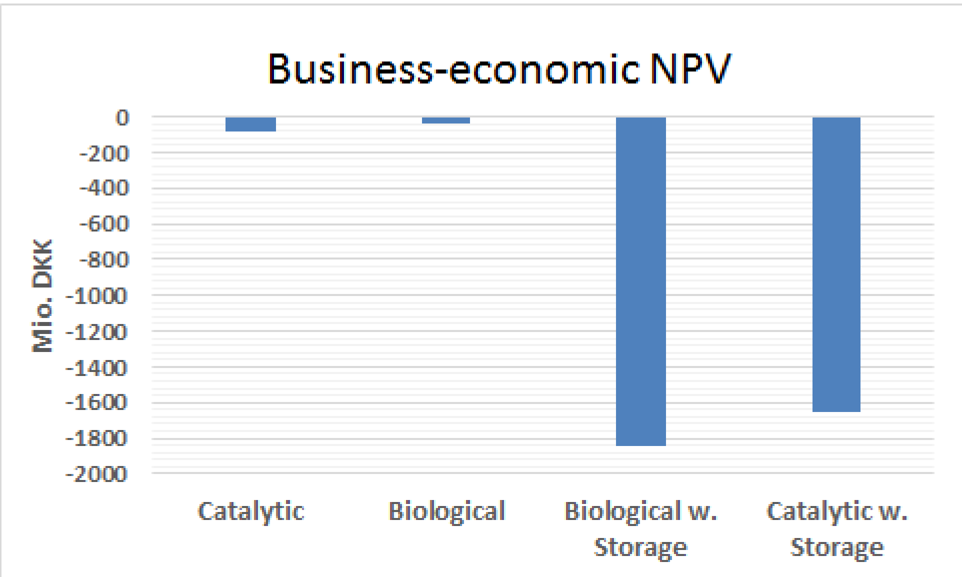

Figure 21: Shows the business-economics NPV for catalytic and biological with and without hydrogen storage.

For catalytic the NPV is now -83,8 mio. DKK not far from being feasible. The biological NPV is -39,1 mio. DKK. The much less negative NPV is carried by the added subsidies to the upgraded biogas, and is close to being profitable.

The storage scenarios still have a huge net loss for catalytic -1.847 mio. DKK and biological -1.651 mio. DKK. The subsides does not have a huge impact, compared to the huge capital costs.

Sale of heat

This chapter seeks to examine if the waste heat from alkaline electrolysis and the catalytic and biological methanation were utilized for sale. The sold heat would be a benefit and would lower the production cost of methane.

Common for both catalytic and biological in the scenarios, are that they both make use of alkaline electrolyser. The NEL alkaline electrolysis converts 84% of the electricity to hydrogen, while the rest is transformed into heat.

Catalytic and biological make use of different methanations, affecting the amount of hydrogen converted to heat and the temperature of the heat. For catalytic methanation, 21 % of the ingoing hydrogen is converted to heat with a temperature of 250° degrees. For biological methanation 18 % of the hydrogen is converted to heat with a temperature of 60°c. In the calculation of heat sale, the heat price is assumed constant regardless of temperature.

In figure 22 the effect of sale of heat added to the socio-economic cost for methane production for both scenarios is shown.

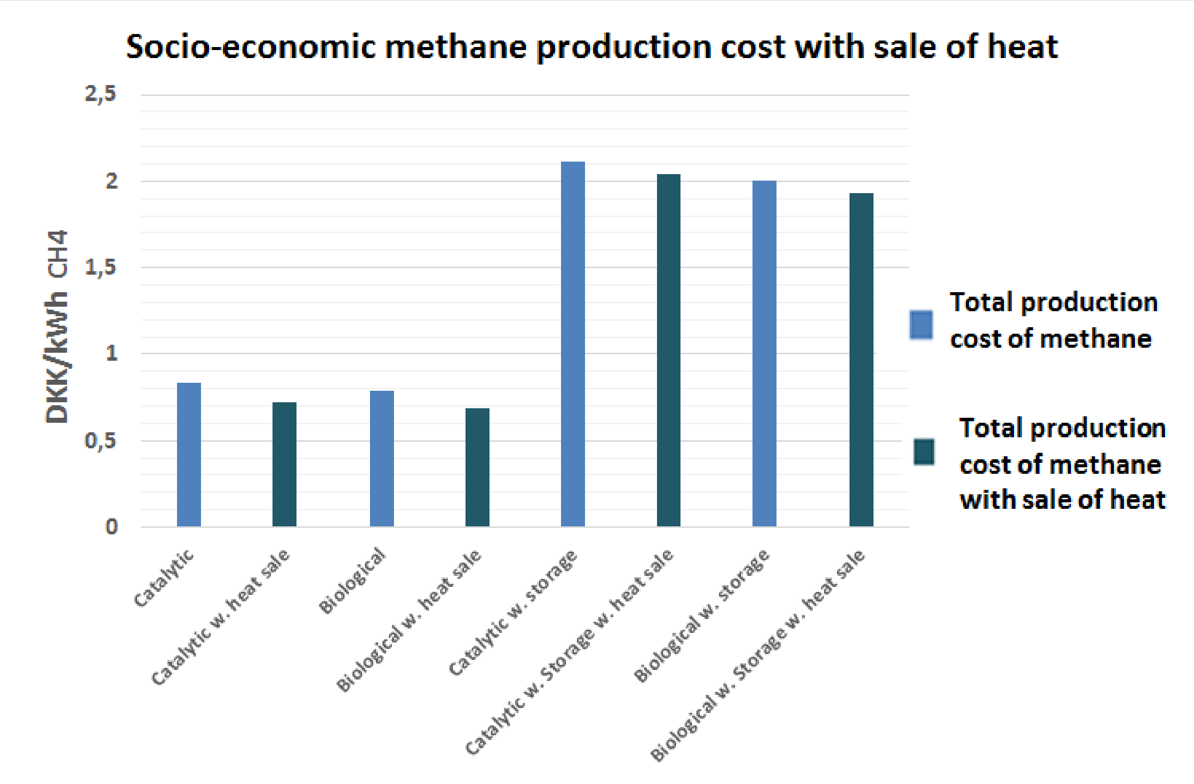

Figure 22: Shows the total cost with waste heat being credited – Socio-economic.

It's visible that if the waste heat were to be sold, it would make an impact in the total cost of methane. The credit of sale of heat for catalytic amounts to 0,11 DKK/kWh methane and for biological 0,1 DKK/kWh methane. Usually however not all heat is sold, as some is used in heat exchangers for recirculation of heat to electrolysers and methanator. If heat price were dependent of the temperature, catalytic would see a higher benefit of heat sale.

In figure 23 the effect of sale of heat added to the business-economic cost for methane production for both scenarios is shown.

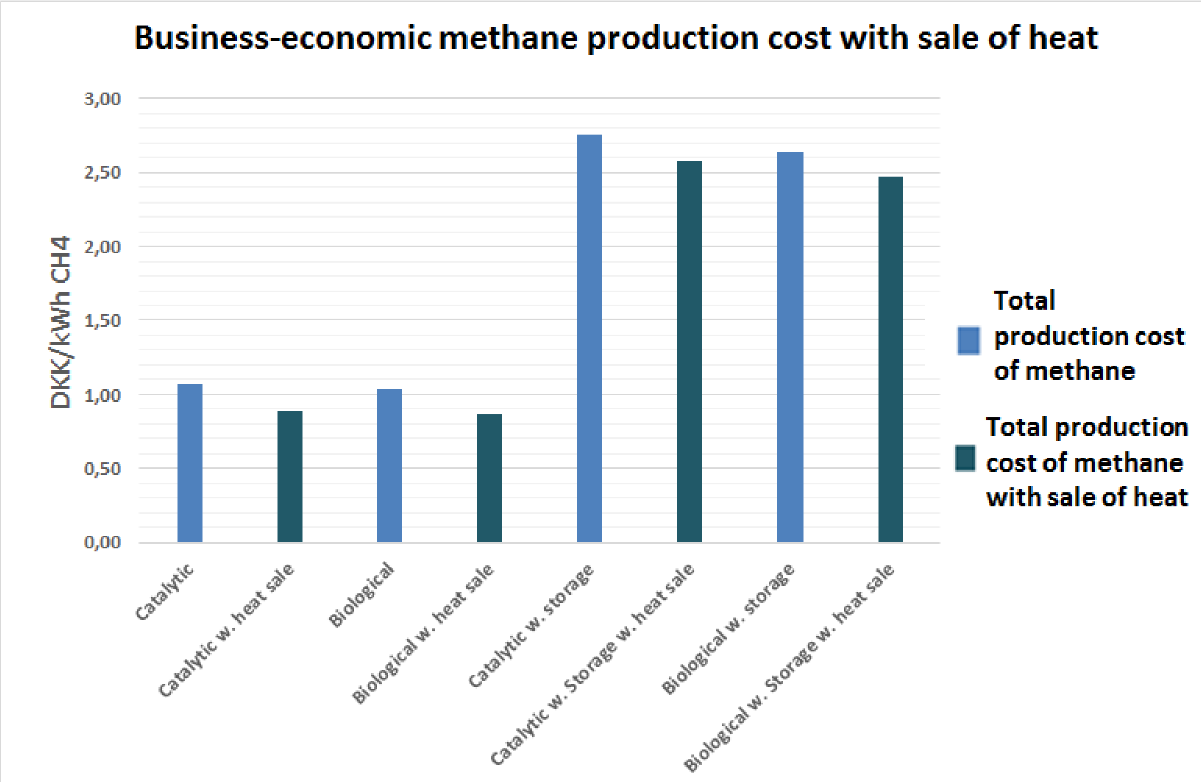

Figure 23: Shows the total cost with waste heat being credited. - Business-economic.

The price of heat is increased and the credit for sale of heat for catalytic is 0,18 DKK/kWh methane and 0,168 for biological. When added to methane production cost the change is now significant, especially for scenario without storage.

7.4 Comparison of socio- and business economic

The chapter seeks to compare the socio-economic results with the business-economic results.

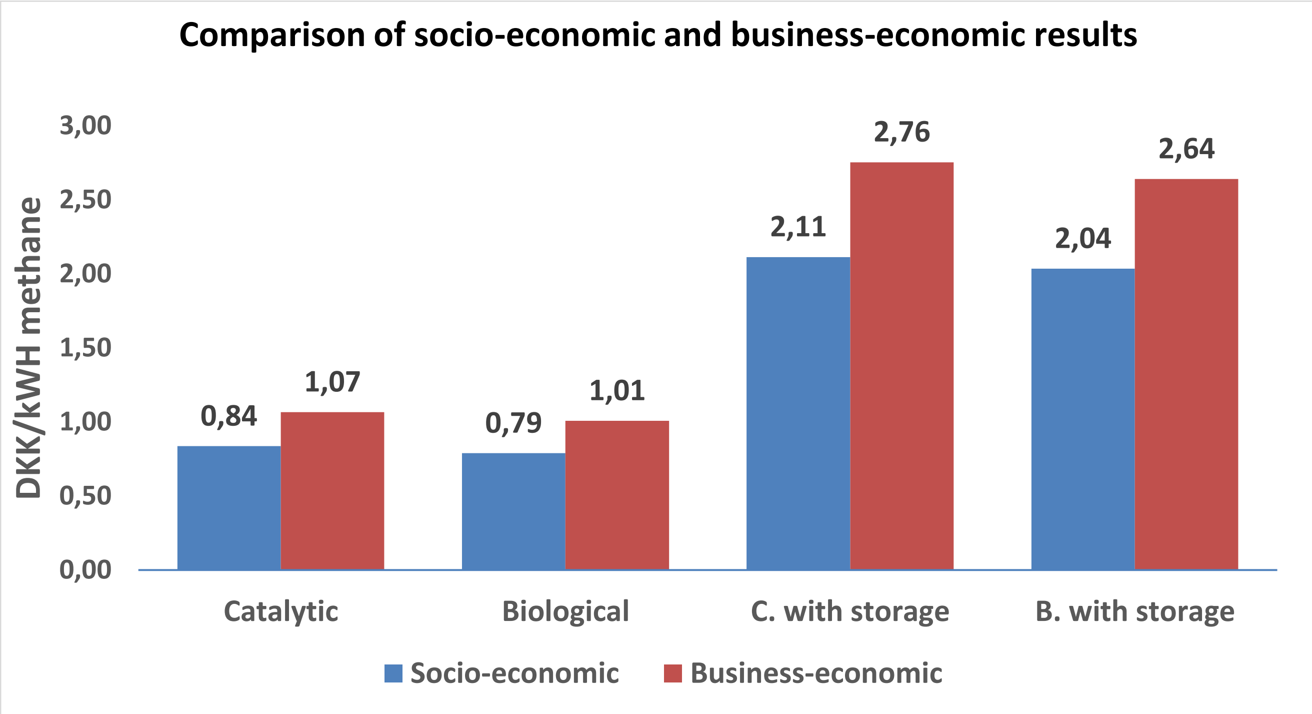

Figure 24: Comparison of socio- and business economics.

Even though it's close between catalytic and biological, the biological is the cheapest solution for both social- and business economic. This due to taxes and subsidies affecting the different solutions equally.
It is visible that the catalytic with storage is the most expensive, close followed by biological with storage.

8 Sensitivity analysis

This chapter examines the methane production price´s sensitivity to changes with different costs. The previous scenarios costs were analysed and the major cost bearers identified and chosen for sensitivity.

Electricity price

In figure 25, the socio-economic methane production price is seen with a respective change to electricity price from -30 % to 30 % where 0 % is the default value.

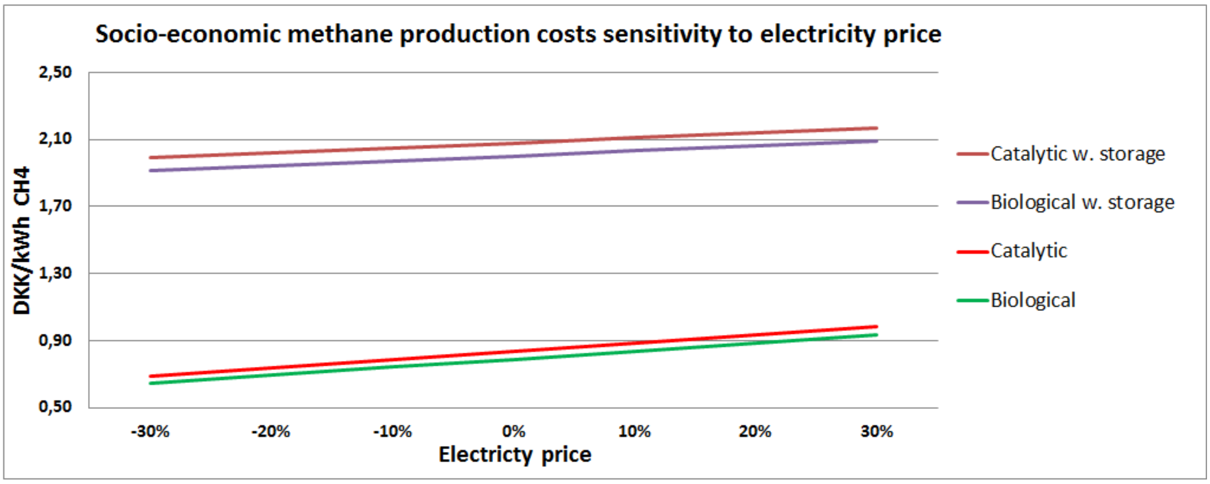

Figure 24: Shows the different scenarios socio-economic methane production costs sensitivity to a change in electricity price.

Electricity price identified as the largest cost in the total cost of methane production for scenario 1, a change of 30 % in electricity price would result in a fall of catalytic to 0,69 DKK/kWh from its default at 0,84 DKK/kWh. Vice versa an increase of 30 % in electricity price would result in a methane price of 0,98 DKK/kWh.

For scenario 2 a fall in electricity price of 30 %, would result in a cost for catalytic with storage at 1,99 DKK/kWh with default at 2,08 DKK/kWh. An increase of electricity price by 30 % changes the methane cost to 2,17 DKK/kWh. The smaller changes in methane cost are due to the increased identified capital cost.

In figure 26, the business-economic cost of methane production is shown, with its sensitivity to a change in electricity price is shown.

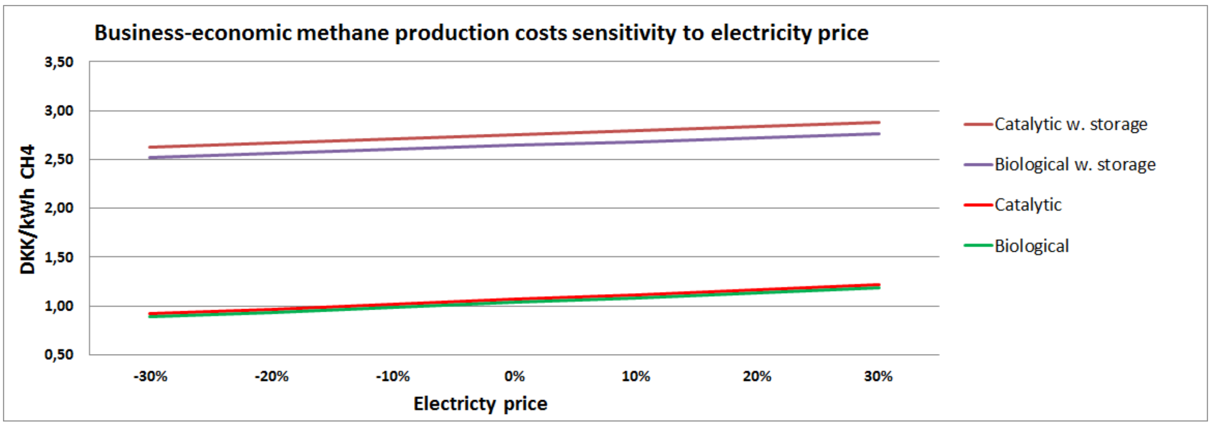

Figure 25: Shows the different scenarios business-economic methane production costs sensitivity to a change in electricity price.

For scenario 1, the methane production cost sensitivity to change in electricity price, is not much different from socio-economic as the electricity tax added to the electricity price is mostly reimbursed. With a 30 % lower electricity price, the methane cost for catalytic is 0,92 DKK/kWh and with a 30 % increase the cost is 1,22 DKK/kWh methane.

For scenario 2 the 30 % lower electricity results in 2,63 DKK/kWh methane, and a 30 % increase in 2,88 DKK/kWh.

Production cost

In figure 27, the socio-economic methane production costs sensitivity to investment cost is shown, with a respective change to investment cost from -30 % to 30 %.

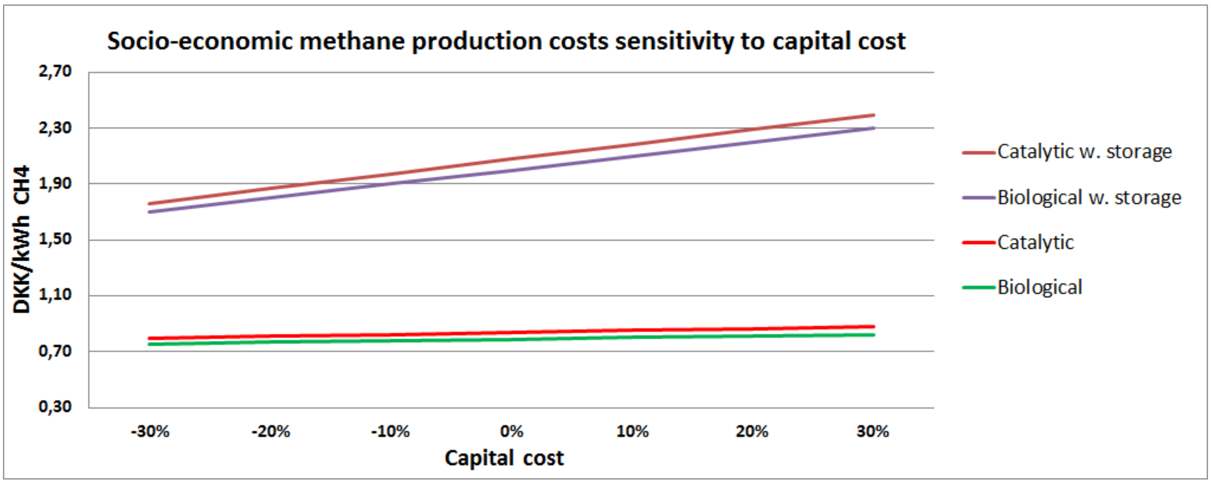

Figure 26: Shows the different scenarios socio-economic methane production costs sensitivity to a change in capital cost.

For scenario 1 a lower capital cost of 30 % lowers the methane production cost to 0,80 DKK/kWh methane from the default 0,84 DKK/kWh. Vice versa an increase of 30 % would result in a cost of 0,88 DKK/kWh methane. The changes in methane cost, is a result of capital cost having a smaller impact on the total cost.

For scenario 2 the largest cost were identified as capital cost and lowered by 30 % results in a cost of methane at 1,76 DKK/kWh with default at 2,08 DKK/kWh. Increased capital cost would increase methane cost to 2,4 DKK/kWh. The large change in methane cost caused by the sensitivity is because of the huge impact the capital cost has on the total cost with storage.

An increasing change between the catalytic and biological with storage, as the capital cost increases. For biological a 30 % lower capital cost results in a 1,7 DKK/kWh methane production cost, while an increase of 30 % increases the methane production cost to 2,3 DKK/kWh.

In figure 28, the cost for business-economic methane production is shown with its sensitivity to change in capital cost.

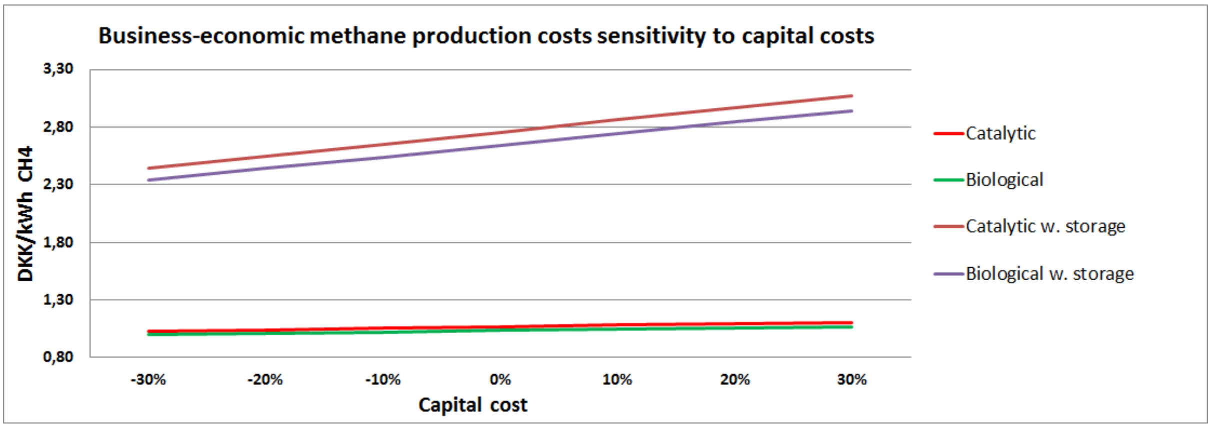

Figure 27: Shows the different scenarios business-economic methane production costs sensitivity to a change in electricity price.

In scenario 1 a decrease in capital cost for catalytic have minor influence on the cost of methane, as a 30 % lower capital cost have a cost of 1,03 DKK/kWh methane. With a 30 % increase, the cost of methane increases to 1,11 DKK/kWh.

In scenario 2, catalytic with storage a decrease in capital cost of 30 % decreases methane production cost to 2,44 DKK/kWh methane and an increase of capital cost by 30 % results in a methane cost of 3,07 DKK/kWh.

Subsidy for feasibility

This chapter seeks to give an indication of the needed subsidy if the NPV were to become positive. As subsidies are included, this is only done for business-economics.

Figure 29, shows the required subsidy for NPV to become positive, together with the current subsidy at 135,4 DKK/GJ applied to all upgraded biogas.

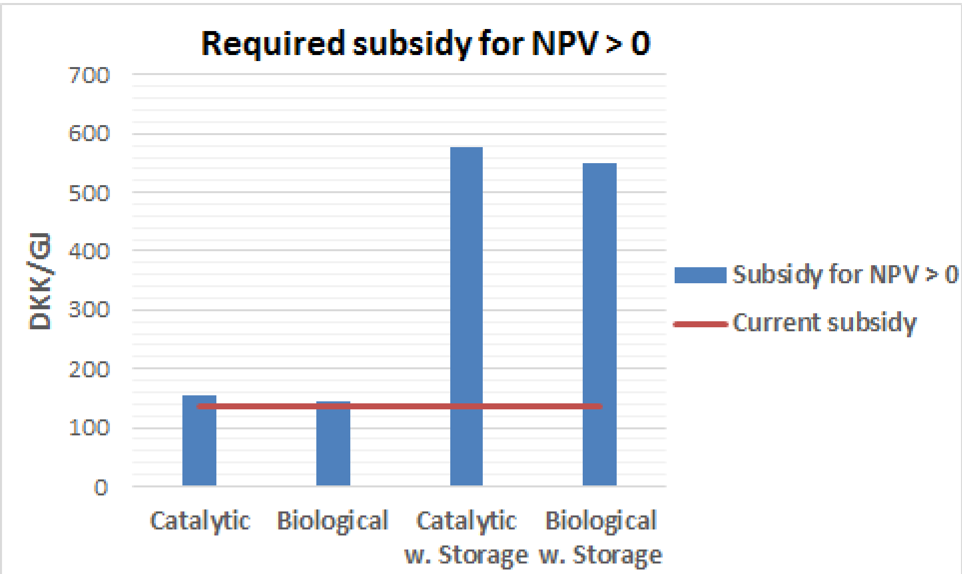

Figure 28: The figure shows the current subsidy given to upgraded biogas and the required subsidies for the scenario to have appositive NPV.

Catalytic were proven to have a negative NPV close to zero, and as such only needs a small increase in subsidies of 19,5 DKK/GJ to become positive. The same is the case for biological which needs 9,1 DKK/GJ more in subsidy.

For catalytic and biological with storage, the need for subsidies is clear, as both of these have a large negative NPV. For catalytic with storage an increased subsidy of 428,8 DKK/GJ is needed for its NPV to be positive. Biological with storage needs an increase of 383,4 DKK/GJ to come positive.

It is clear, that the subsidy required for the methanation with storage is unlikely to become reality, as the current subsidy would need to be thrice as high. For catalytic the small increase is needed is more realistic, for it to become feasible.

9 Discussion

In the scaling of electrolysis and methanation for NEM the data used were from EUDP and few key-data accessible from NEM homepage. Even though the method is indirectly, in relation to NEM specifically, the full scaling should be seen as template applicable to other biogas plants as well.

In optimising of hydrogen production for hydrogen storage, the purpose was producing hydrogen in low electricity price periods for hydrogen storing to high price periods. The definition of "low" electricity price could have been done differently to allow for a more feasible and realistic scenario, which would make the comparison between scenarios more interesting.

Through a year the storage goes below half full capacity only a few times. Scaling the storage and electrolysis for these periods is expensive. Instead the operation strategy would be set to produce at spot price at these extreme periods and as such a much lower electrolyser and storage would be required.

As the electrolysis production and storage were optimised for the year 2015, the setup could have difficulties covering other years, if long periods of "high" electricity price occurred.

In the economic analysis, key financial data for the electrolysis and methanators did not allow for many differences between the scenarios.

A decrease of electrolyser cost would favor the scenario 2 more than scenario 1 as the investment cost has a huge impact on the total cost of kWh methane.

As the electrolysers are dependent on constant electricity supply if no storage is invested in, the requirement for reliability of supply also plays a role when installing methanation and electrolyses as the methanator is depended on hydrogen production in order to saturate the carbon dioxide coming from the biogas plant.

The alkaline electrolysis was chosen because of its maturity and its scalability for high capacities. Other electrolysis technologies could have been chosen and would have altered the economy and possibly the optimisation. Especially the PEM would have altered the storage capacity as it produces hydrogen at a 100-200 bars pressure ready for use.

The chosen biological methanator utilised an ex-sito reactor which have increased the cost compared to in-sito. If in-sito biological methanation was chosen the cost would descrease for the methane production.

10 Conclusion

This thesis set out to examine the economics of a catalytic methanation compared to a biological methanation. Further the necessary capacities for electrolyser and storage were optimised to achieve the lowest hydrogen production cost.

The examination were based on NEM 35 % CO2 from biogas which with a 100 % conversion rate resulted in a methane production of 525.000 Nm^3 per year.

From the examined scenarios, biological without storage is concluded to be the cheapest solution. This holds for both socio- and business-economics which with a cost of 1,03 DKK/kWh methane and 1,38 DKK/kWh methane.

It is also concluded that the current subsidies does not cover the cost for biogas upgrading by methanation. For biological with the least negative NPV an increase of subsidy of 9,1 DKK/GJ is needed to make it feasible.

For the scenarios with storage and a hydrogen production based on a “low” electricity price, it can be concluded that this solution is not feasible with biological as the cheapest solution have a cost of 2,64 DKK/kWh methane and is much more expensive than catalytic and biological without storage.

In optimising for hydrogen production cost with storage, it is concluded that regardless of how many operation hours the electrolyser were allowed to run, the cost associated with increased capital cost of the electrolyser capacity and storage capacity did not outweigh the avoided electricity cost.

11 Perspective

For further work there could be look upon a scenario with a scrubber and a CHP that produces electricity and heat when revenue of selling the heat and electricity at spot prices exceeds the revenue coming from natural gas sales.

The optimisation of scenario 2 could be investigated more in, by optimising more on the three parameters of spot prices, capacity of storage, and capacity of electrolysis and operation time.

Future work could also consist of examining other form of utilising hydrogen for methane production. Technologies that could work for comparison would be Climeworks which extracts carbon dioxide from the atmosphere.

The usage of methane for heavy transport could be looked into. Having airplanes using methane would increase the fuel cost and increase the cost of flight as well. This would cater to people that supports an environmental friendly fly transport. This would reduce the amount of greenhouse gases polluted by transport.

Complementary to this paper it would be relevant to examine the tax and subsidy structure to see if this supports the electrolysis as energy system stabilizer, in a future energy system with an increasing fluctuating energy production. Regardless the operation strategy of the energy system in Denmark there is a need for the electrolysers to be cheaper and yet more effective. It is still not possible to say which electrolysis technology is the best as they all have their ups and downs. The alkaline is available now and compresses air while the PEM electrolyser compresses further more than the alkaline electrolyser. The SOEC however might be the overall best technology as it may be more effective and cheaper than the two others but they still are not commercial available.

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Appendix 1

Yearly avg "low" electricity price	Yearly average electricity price	Electrolysis capacity	Storage capacity	Storage optimzied for Start/end [500k/500k]	Investment of electrolyser	Investment of storage	O&M	Electricity cost
	Parameter optimisations - part 1							
DKK/MWh	DKK/MWh	MW	Nm^3	k	Mio. DKK	Mio. DKk	Mio. DKk	Mio. DKk
104,52	170,96	100	1.100.000	500	663,05	367,20	7,34	10
115,92	180,96	80	1.000.000	500	530,44	333,81	6,68	11,19
127,52	190,75	60	800.000	400	397,83	267,05	5,34	11,99
134,47	200,00	35	600.000	300	232,07	200,29	4,01	12,29
139,30	210,00	20	500.000	250	132,61	166,91	3,34	12,34
143,03	220,00	15	250.000	125	99,46	83,45	1,67	13,68

Yearly avg "low" electricity price	Yearly average electricity price	Electrolysis capacity	Storage capacity	Storage	Operation hours	Produced MWh	Cost	
	Parameter optimisations - part 2							
DKK/MWh	DKK/MWh	MW	Nm^3	MJ	hours	MWh	Mio. DKK	DKK/kWh H2
104,52	170,96	100	1.100.000	14.042.160	980	82.320	1.048	12,73
115,92	180,96	80	1.000.000	12.765.600	1.207	81.110	882	10,88
127,52	190,75	60	800.000	10.212.480	1.567	78.977	682	8,64
134,47	200,00	35	600.000	7.659.360	2.611	76.763	449	5,84
139,30	210,00	20	500.000	6.382.800	4.431	74.441	315	4,23
143,03	220,00	15	250.000	3.191.400	6.377	80.350	198	2,47

On appendix 1 is shown the coherence of the three parameters, the electrolysis capacity and the storage capacity and the yearly average electricity price, which is the constraint. In the upper table, part 1, the costs are shown for each of the capacity sizes. In the lower table, part 2, are shown the amount of MJ, operation hours, produced MWh and the cost per kWh hydrogen produced. The operation hour and the yearly average electricity price follow each other. As a result it can be seen that the smaller the investment cost is, there lower is the hydrogen price.

Note that the produced MWh should be the same during all six average spot prices. This affects the calculated hydrogen prices.

Appendix 2

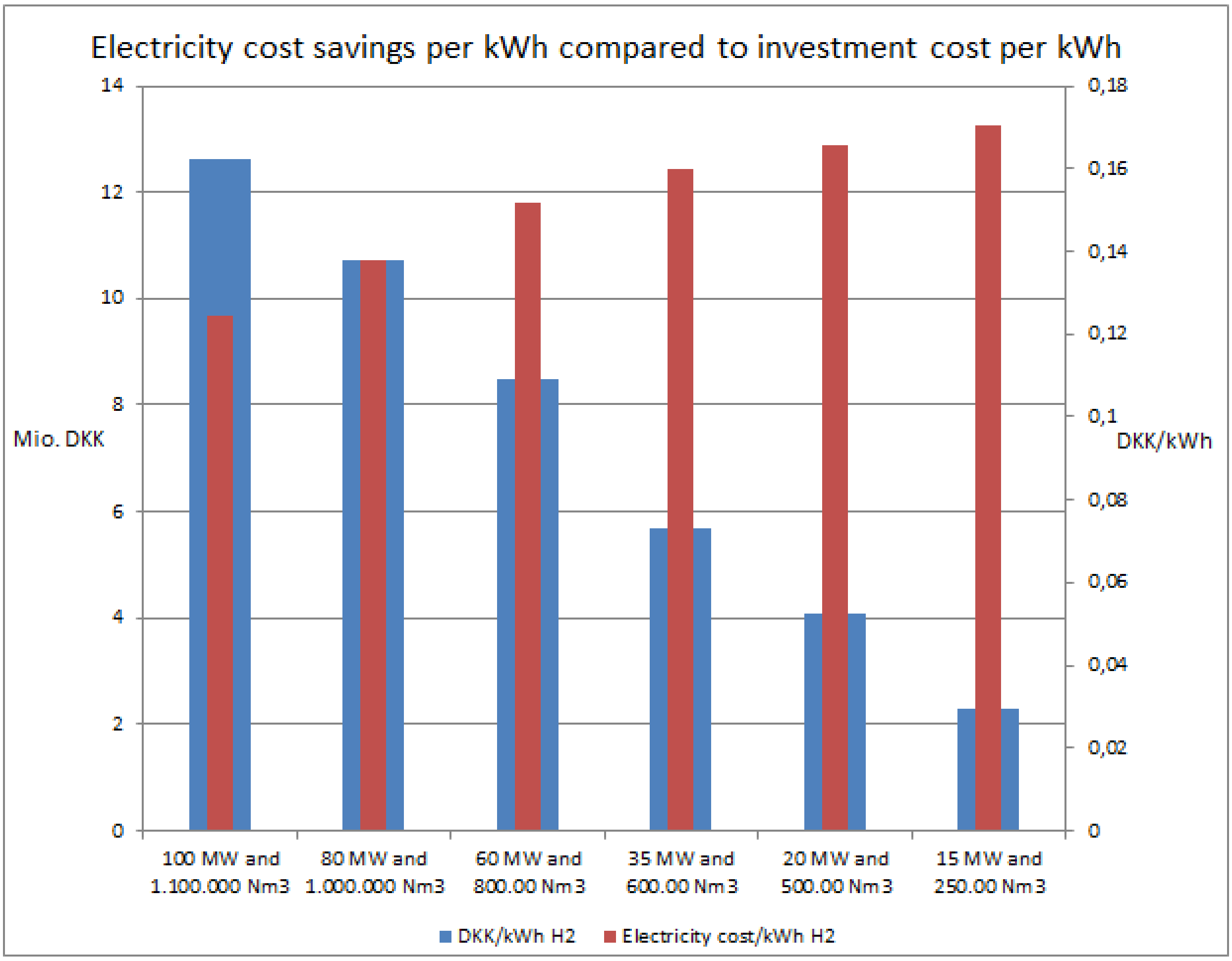
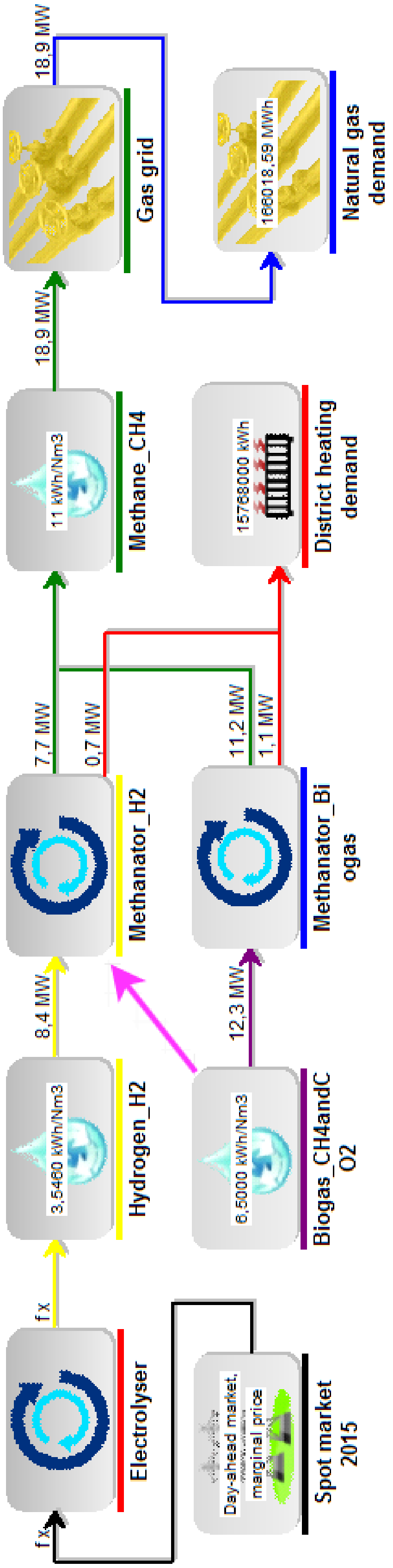


Figure 29: Electricity savings per kWh compared to investment cost per kWh.

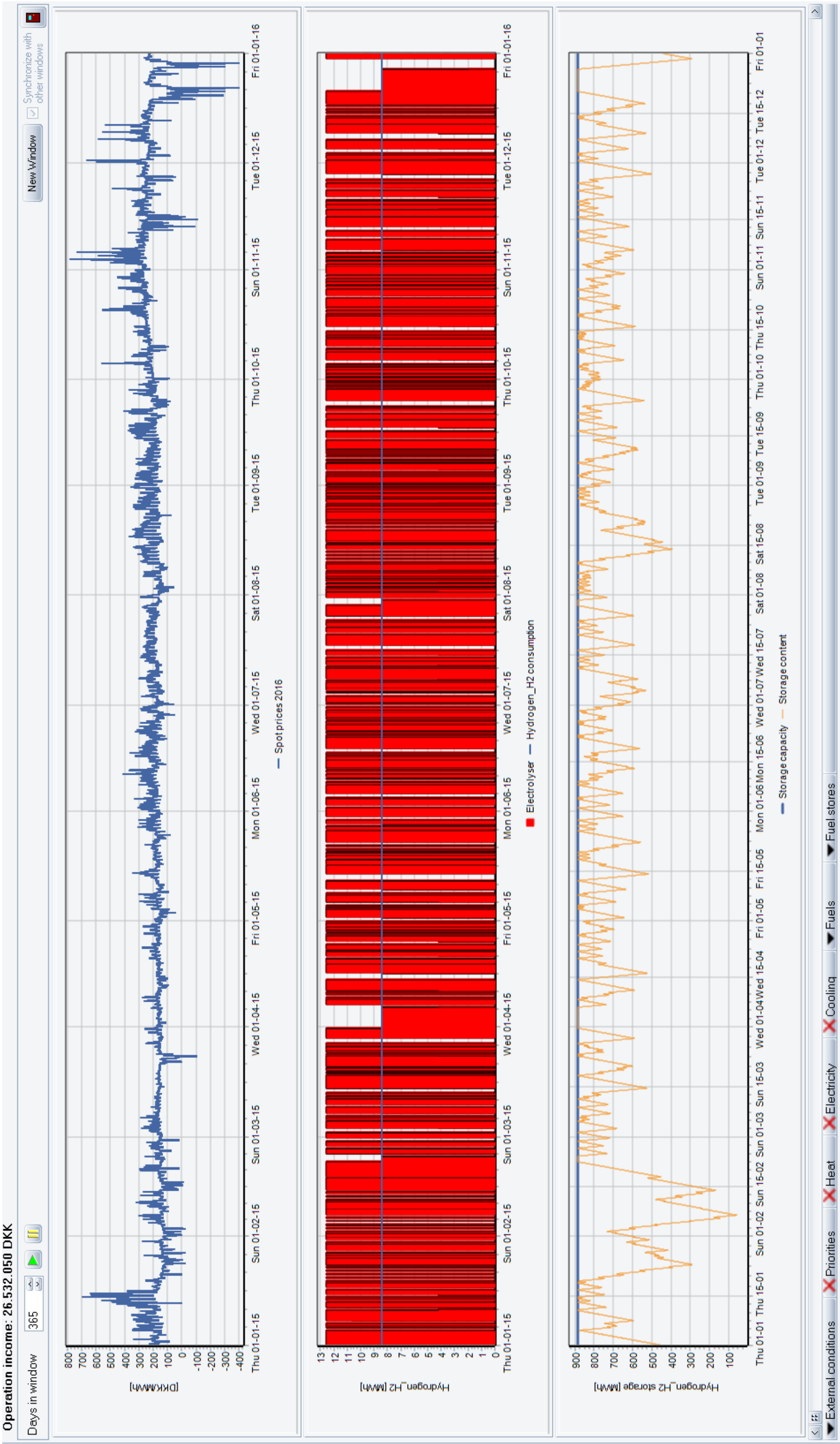
On Figure 30 it is shown that the smaller the electrolyser and the storage are, the more hydrogen per electricity is achieved. The hydrogen price falls even though the electricity prices increases. The reason is the enormous investment cost of the storage for the system.

Appendix 3



Electrolyser
f x
f x
Day-ahead market,
marginal price
Spot market 2015
Hydrogen_H2
3,5460 kWh/Nm3
8,4 MW
Biogas_CH4andCO2
6,5000 kWh/Nm3
12,3 MW
Methanator_H2
7,7 MW
0,7 MW
Methanator_Biogas
11,2 MW
1,1 MW
Methane_CH4
11 kWh/Nm3
District heating demand
15768000 kWh
18,9 MW
Gas grid
18,9 MW
Natural gas demand
166018,59 MWh

Appendix 4



Operation income: 26.532.050 DKK
Days in window
365
New Window
Synchronize with other windows
[DKK/MWh]
Spot prices 2016
Hydrogen_H2 [MWh]
Electrolyser
Hydrogen_H2 consumption
Hydrogen_H2 storage [MWh]
Storage capacity
Storage content
External conditions
Priorities
Heat
Electricity
Cooling
Fuels
Fuel stores

Appendix 5

Cash Flow, monthly

Calculated Period: 01-2015 - 12-2015
(All amounts in DDK)

	Total	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Revenues													
Natural gas sales	33.112.800	2.812.320	2.540.160	2.812.320	2.721.600	2.812.320	2.721.600	2.812.320	2.812.320	2.721.600	2.812.320	2.721.600	2.812.320
Heat sales	5.889.348	500.191	451.786	500.191	484.056	500.191	484.056	500.191	500.191	484.056	500.191	484.056	500.191
Total Revenues	**39.002.148**	**3.312.511**	**2.991.946**	**3.312.511**	**3.205.656**	**3.312.511**	**3.205.656**	**3.312.511**	**3.312.511**	**3.205.656**	**3.312.511**	**3.205.656**	**3.312.511**
Operating Expenditures													
Payment	14.954.297	1.425.262	1.465.116	1.468.600	1.370.005	1.223.798	1.026.246	759.298	1.216.437	1.140.744	1.456.582	1.352.320	1.049.889
Total Operating Expenditures	**14.954.297**	**1.425.262**	**1.465.116**	**1.468.600**	**1.370.005**	**1.223.798**	**1.026.246**	**759.298**	**1.216.437**	**1.140.744**	**1.456.582**	**1.352.320**	**1.049.889**
Net Cash from Operation	**24.047.852**	**1.887.249**	**1.526.829**	**1.843.912**	**1.835.651**	**2.088.713**	**2.179.410**	**2.553.213**	**2.096.074**	**2.064.912**	**1.855.929**	**1.853.336**	**2.262.622**
Cash Account	**24.047.852**	**1.887.249**	**3.414.079**	**5.257.990**	**7.093.641**	**9.182.355**	**11.361.765**	**13.914.978**	**16.011.053**	**18.075.965**	**19.931.894**	**21.785.229**	**24.047.852**

Appendix 6

At the MeGa-StoRE concept it was important that the concept was simple and it did not produce any non-disposable waste. With this the concept was made with only one very effective catalyst whereas other methanation facilities typically uses three catalysts and must seperate the water from each step in order to make the combination of CO2 and hydrogen (H2) more effective.

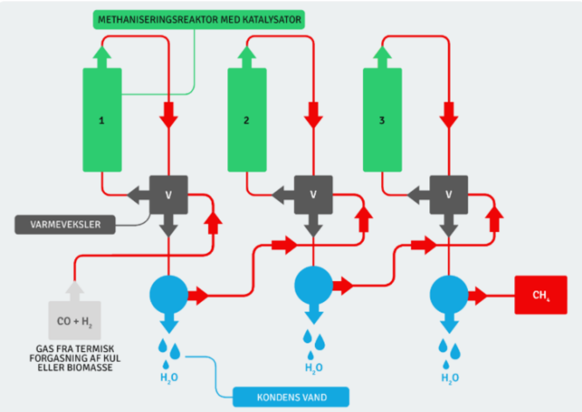


Figure 30: Methanisation facility with 3 catalysts and 3 condensers.

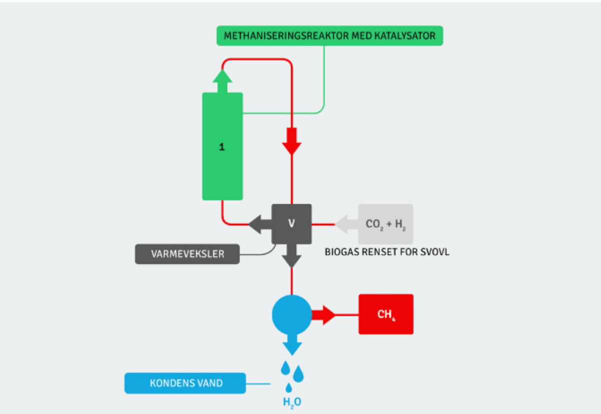


Figure 31: Methanisation facility at MeGa-StoRE with only one very effective catalyst and one condenser.

MeGa-StoRE succeeded with the single catalyst which may be described as a breakthrough in regards to upgrading biogas.