Final report

MeGa-stoRE

Project no. 12006

Index – final report

1.1 Project details

Project title	MeGa-stoRE
Project identification (program abbrev. and file)	Energinet.dk project no. 12006
Name of the programme which has funded the project	ForskEL
Project managing company/institution (name and address)	Aarhus University Business and Social Sciences AU Herning – Center for Energy Technologies Birk Centerpark 15 DK-7400 Herning
Project partners	GreenHydrogen.dk Elplatek A/S Lemvig Biogasanlæg A.m.b.A DTU Mekanik AU – Herning
CVR (central business register)	31 11 91 03
Date for submission	31/01-2015

1.2 Short description of project objective and results (English version)

The objective of this project was to provide technical proof-of-concept of a Power-to-Gas technology. The project was set out to prove a new concept for methanation of carbon dioxide (CO_2) by using ground-breaking gas cleaning processes and an optimized Sabatier reactor based upon CO_2 as carbon source. The technology is to upgrade biogas by methanation to a quality similar to natural gas. The Power-to-Gas concept provides dual benefit for the energy system.

- By operating on electricity, the system will be able to store considerable amounts of RE-resources from the electricity grid as methane gas.
- Utilization of the CO_2 source in biogas for production of methane will increase the utilisation of the carbon source from 65% to 100%.

The objective regarding the cleaning process was to build a unit capable of removing any impurities of sulphur containing compounds from ppm level down to ppb levels, as they will cause damage to the catalyst in the following methanation process.
The methanation process is based on the Sabatier reaction:

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

The process is reversible and highly exothermal, and therefore the objective was to build a Sabatier reactor that could be controlled very precisely temperature wise, as it was found that the temperature was very important for the reaction to happen with high conversion rates.

Upon field-testing with real biogas at Lemvig biogas, the MeGa-stoRE project has come to completion. Results have shown that the technical proof-of-concept of the cleaning process and the Sabatier reactor has been successful.

The cleaning unit proved capable of cleaning the biogas for any sulphur containing compounds and other impurities such as siloxanes, which was important for the following methanation process.
Optimizing the methanation unit during several test runs has been completed in order to find the right operating temperature, gas flow rates and pressure in the reactors. The final results from testing with real biogas showed that by keeping the temperature at a certain point and with the right amount of gas flow, the reactors where capable of self-regulating the temperatures without need for additional heating, and the conversion rate into methane reached close to 100%. Additionally it was possible to control the excessive amount of CO_2 in the output gas, which proved to be a vital indicator of how well the process was operating.

It can be concluded in general that the MeGa-stoRE technical proof-of-concept project of the Power-to-Gas technology was very successful.

1.2.1 Short description of project (Danish version)

Formålet med dette projekt har været at skabe teknisk proof-of-concept for en Power-til-gas teknologi. Projektet skulle bevise at et nyt koncept for methanisering af kuldioxid (CO_2) ved hjælp af banebrydende gasrensnings processer og en optimeret Sabatier reaktor baseret på CO_2 som kulstofkilde. Teknologien er at opgradere biogas ved methanisering til en kvalitet svarende til naturgas. Power-to-gas koncept giver flere fordele for energisystemet.

- Ved at bruge elektricitet, vil systemet være i stand til at lagre store mængder af VE-ressourcer fra el nettet som metangas.
- Udnyttelse af CO_2 kilden i biogas til produktion af metan vil øge udnyttelsen af karbon kilden fra 65% til 100%.

Formålet med rensningen af biogassen var at bygge en enhed i stand til at fjerne eventuelle urenheder af svovlholdige-forbindelser fra ppm niveau ned til ppb niveauer, da de vil forårsage skade på katalysatoren i den følgende methanisering proces. Methanisering processen er baseret på Sabatier reaktion:

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

Processen er reversibel og yderst eksoterm og derfor var målet at opbygge en Sabatier reaktor, hvor temperaturen kan styres meget præcist. Det blev konstateret i løbet af projektet at temperaturen var meget vigtigt for at reaktionen kan ske med høj virkningsgrad.

Efter forsøg med rigtig biogas hos Lemvig Biogas anlæg har MeGa-stoRE projektet nået sin afslutning. Resultaterne har vist, at det tekniske proof-of-concept anlæg med renseprocessen og Sabatier reaktoren har været vellykket.

Renseenheden viste sig i stand til at rense biogas for svovlholdige forbindelser og andre urenheder, såsom siloxaner, hvilket var vigtigt for den følgende methanisering proces.

Optimering af methaniserings enheden igennem flere prøvekørslerne er afsluttet og har været en vigtig del af at finde den rette driftstemperatur, gasstrømningshastigheder og trykket i reaktorerne. De endelige resultater fra forsøg med rigtige biogas viste, at ved at holde temperaturen på et bestemt punkt, og med den rigtige mængde gas flow, var reaktorerne i stand til at være selv-regulerende med temperaturerne uden behov for yderligere opvarmning, og omsætningen til metan nåede tæt på 100%. Derudover var det muligt at kontrollere overskydende mængde af CO_2 i gassen, som viste sig at være en vigtig indikator for hvor godt processen fungerer.

Det kan konkluderes, at MeGa-stoRE projektet omhandlende power-til-gas teknologien har været meget vellykket.

1.3 Executive summary

Synthetic natural gas as upgraded biogas is already on its way into the natural gas grid and according to the Danish Energy Agency all biogas must be upgraded and sent into the natural gas grid from 2035 and by 2050 increase to an amount able to replace all fossil natural gas.

Biogas consists of approx. 65 % methane (natural gas) and 35 % CO_2. By 1st generation upgrading, the CO_2 is removed from the biogas and the pure methane is sold as natural gas via the natural gas grid. In the MeGa-stoRE concept, which is the next generation upgrading plant, the CO_2 containment in the biogas is used to produce natural gas.

It becomes possible by letting CO_2 react with hydrogen (H_2) thereby forming methane (CH_4) and water according to the following reaction, also called the Sabatier reaction:

$$CO_2 + 4H_2 \rightarrow CH_4 \text{ and } 2H_2O$$

By exploring this technology, it becomes theoretically possible to increase the methane production up to 50% without adding more biomass to the biogas plant.

The hydrogen used to 2nd generation upgrade of biogas is produced through electrolyzes where the electricity is generated from wind turbines and solar panels. By using wind power to produce hydrogen and hydrogen to produce methane (natural gas) large amount of wind power and alternatively solar power can be stored in the natural gas system.

By utilizing 2nd generation upgrading, the CO_2 source in the biogas together with hydrogen becomes an opportunity to direct storage of wind energy as hydrocarbons, which are much easier to store than pure hydrogen due to the three times higher heating value.

So in addition to save the atmosphere from CO_2 emissions from the first-generation upgrading, and a much better utilization of biomass fed to the biogas plants, the 2nd generation technology stores wind energy in the natural gas system.

Subsequently, the gas can be used as fuel in cars, buses and ships or in the natural gas-fired power plants to generate electricity when the wind turbines and solar cells cannot deliver sufficient energy to meet the electricity requirement. Another possibility is to use the very clean methane for further processing in petrochemical industry, producing liquid fuel for aircrafts or diesel engines.

The opportunities to go fossil-free is now demonstrated via the MeGa-stoRE proof of concept plant at Lemvig Biogas (see figure 1). The plant can produce 24 m^3 upgraded biogas per day. The plant is also the first of its kind, where the CO_2 in the biogas is utilized directly. The amount of energy the plant can produce corresponds approximately to 24 liters of diesel oil per day. Using an energy-efficient car (20 km / l), this small micro system could deliver synthesized fuel for driving needs of 480 km a day.

Figure 1 MeGa-stoRE, proof-of-concept plant. Consisting of a cleaning unit and a methanation plant with computer controlled process regulation with comprehensive data collection from both units.

The cleaning unit and methanation plant are both very simple in its construction and can be produced for gas upgrading at an affordable price. Both process concepts are introduced by DTU-MEK. Green natural gas produced by this principle has difficulty competing with natural gas cost; but with the gloomy outlook for the world can oil and gas extraction from fossil sources shortly be described as history and will certainly be settled rapidly. The continued extraction of fossil fuels is simply too risky and no responsible political leaders would dare to continue, the consequences would be incalculable for humanity.

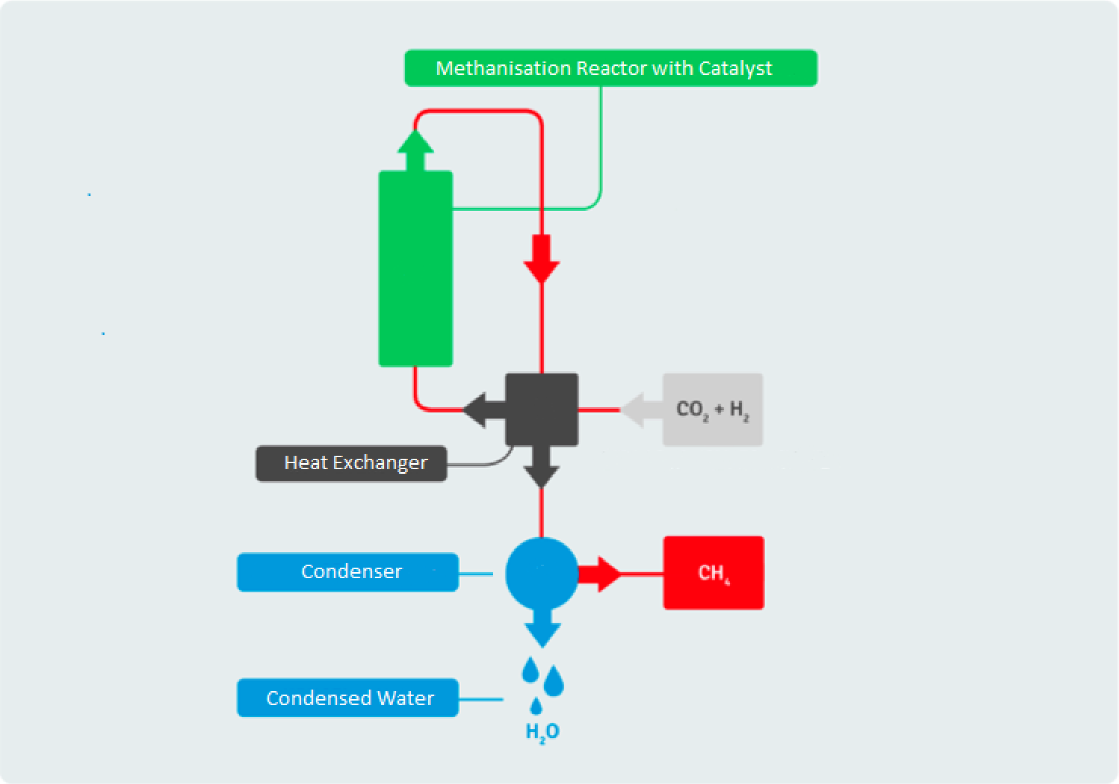


Figure 2 The Sabatier process for CO2 methanation.

The MeGa-stoRE concept consists of two steps. First, the biogas undergoes a two-step catalytic purification process that removes the many contaminants and transforms them into substances that can be added to the digested slurry as useful micronutrients. After cleaning, the biogas is lead to the methanation plant where the CO_2 and methane content in the gas, along with the necessary amount of hydrogen is fed into a specially developed reactor that converts CO_2 and hydrogen to methane.

By using this process technology, renewable energy sources such as solar and wind, can be converted into synthetic fuels - methane or later liquid fuel. This opens the possibility to replace fossil fuels in different sectors such as the transport sector with new synthetic fuels of high quality and without contamination of any kind.

The mindset behind the MeGa-stoRE project was from the beginning to keep both units as simple as possible. Therefore, regarding the cleaning unit is was very important that the process was simple and with no waste product in form of absorber materials derived from the gas cleaning, which would later needs to be deposited or reprocessed.
Regarding the methanation plant, it was important to develop a very effective catalyst to carry out the process in one-step. A one-step process will minimize the complexity of the plant and thereby make it easier scalable and cost efficient.

Ultimately, the project team has succeeded in building two simple units that both work according to the original idea behind the processes, successfully demonstrated during a workshop held at Lemvig Biogas. The successful result will carry over into the next MeGa-stoRE project where specific knowledge and different ideas will be put into building a larger demonstration plant. That plant should demonstrate that this technology could play a significant role in achieving the Danish Energy Agency goals for upgraded biogas in 2035.

1.4 Project objectives

No.	Name	Nature	Deadline
M0.1	Project agreement signed	Other	31.01.2013
M0.2	End Project & Financial reports	Reports	31.08.2014
M1.1	Recommendation to system design for gas cleaning and methanation approved		31.03.2013
M2.3	Gas cleaning unit ready for performance test	Others	31.06.2013
M3.1	Methanation unit ready for performance test	Others	31.06.2013
M4.1	Single module and optimization tests completed.	Other	31.08.2013
M4.2	System integration test completed	Other	31.12.2013
M4.3	Field test at Lemvig Biogas completed	Other	30.07.2014
M4.4	Final test rapport	Report	31.08.2014
M5.1	Market survey and Economic analysis finalised	Part of final report	31.08.2014
M6.1.	Workshop at Lemvig Biogas Plant to have taken place	Other	31.08.2014
M6.2.	Plan for further work finalised	Note	31.08.2014

This project is based on the Sabatier process, and the objectives for the project are:

- Based on a gas cleaning process without expensive filter materials
- Based on a gas cleaning process which does not produce hazardous waste or waste that requires special treatment
- Reactor based on more simple construction which makes it more cost-efficient

Developed with standardisation and industrialisation in mind – whereas traditional Sabatier plants is based on “engineering to order”

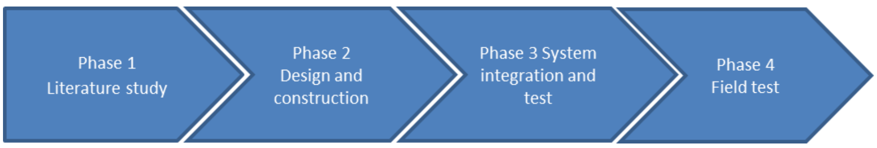
- Build a "Proof of concept" plant, with a capacity of biogas $1Nm^3/h$.
- Desulfurization of H_2S in the biogas down to concentrations below 30ppb - NO WASTE PRODUCTS.
- The product must have a CH_4 concentration of 97.3% and a CO_2 concentration below 3%. The process is carried out in ONE STEP.

Design Philosophy:

- Aim for the maximum simplicity in the construction of the facility
- Aim for the maximum stability in the process.
- Achieve balance in the process so that the need for control, regulation and active intervention in the process is minimized.

1.4.1 Project structure

The project consists of the following four phases:



Phase 1: Includes a literature study on gas cleaning and methanation as well as an initial economical assessment of the concept. Furthermore, user involvement will be planned and initiated.

Phase 2: Design, specification and construction of separate units for gas cleaning and methanation, initial market survey, initiation of dissemination planning.

Phase 3: System integration of the cleaning and methanation unit, planning for Phase II technology development project initiated.

Phase 4: Test and verification of concept, workshop for stakeholders.

1.4.2 Project evolvement

Phase 1:

The literature study for purification of biogas, lead to a two stage process with two different oxidation fluid designed in a such way, that no waste is produced. The first step use a cheap oxidation agent and remove 95% of the impurities in the biogas.
The second step is a process using an oxidation agent, with a higher kinetic. The second step is more costly when calculated in equivalents, than the first step. Therefore it is important to have a high conversion in step 1. The second step brings the impurities in the biogas down in the low end of the ppb regime.
It is very important that the purification process do not introduce pure oxygen. A special catalyzer has been developed for the two steps, which makes it possible for the impurities in the gas to be immobilized at the catalyzer surface and in the next step oxidized to the following compounds (see below).

$$H_2S(g) + 2O_2(g) \rightarrow SO_4^{-2} + 2H^+$$
$$2H_2S(g) + O_2(g) \rightarrow 2S + 2H_2O$$

$$CH_4S(g) + 3.5O_2 \rightarrow CO_2 + SO_4^{-2} + 2H^+ + H_2O$$
$$CH_4S(g) + 2O_2(g) \rightarrow CO_2(g) + S + 2H_2O$$
$$CH_4S(g) + 1.5O_2 \rightarrow CH_3SO_3H \text{ (methansulfonsyre)}$$
$$C_6H_{18}Si_2O(g) + 12O_2(g) \rightarrow 6CO_2(g) + 7H_2O + 2H_2SiO_3$$

The reaction equations above shows how the different impurities such as hydrogensulphide, mecaptanes and siloxanes are converted to other compounds, which can be transferred to the manure again and be a part of the biological cycle.

Biogas is a large challenge for gas specialist, which wants to remove impurities, because the large amount of impurities and especially the many different impurities are difficult to remove in a simple way. The new techniques have shown, that it is possible. A lot of methods has been proposed of conventional catalyzer specialist during the time - covering combination of active carbon, alkaline copper carbonate and zinc oxide. If oxygen is present because of biological removing of sulphides, which is important for reducing cost of absorbermaterials - then the excess of oxygen has to be removed afterwards from the biogas before entering the Sabatier reactor. The oxygen removal need a deoxidizer based upon a platinum catalyzer, where hydrogen is used as the reducer.
In the new technique developed at MeGa-stoRE the purification of biogas becomes quite simple and no waste has to be treated afterwards. The process is already more cheap, than conventional techniques. A further development based on electrochemical processes will be demonstrated in MeGa-stoRE, Optimizing and Upscaling, and bring costs down further.

Phase 2:
The design and initial construction of the system was conducted at AU Herning from the project start at January 2013. The first months was dedicated to development of the system architecture and system design. In Marts 2013, the construction of the Cleaning and Methanation units was initiated.

The units where built into standard industrial racks.

It was decided to make the main components of the cleaning unit in transparent Plexiglas, to give the possibility to monitor the flow pattern of the gas and fluids in the cleaning columns and the reservoirs. The tubing was done with standard plastic plumbing fittings. A special catalytically fillers where found for the columns.
To control the gas flow through the unit, a gas panel was built with Mass Flow Controllers for the biogas and additional H_2S. A measurement system for measuring the H_2S concentration before and after the columns has been developed based on OEM sensors.
For controlling the system, a PLC controller has been implemented and software developed. Before the shipment to GreenHydrogen in Kolding in early July 2013, as stated in milestone M2.3, the system was tested on ambient air. Due to the lack of raw biogas on the test site, a gas bottle of H_2S was acquired for testing the system. This ensures a pure H_2S mixture with compressed air with no additional gases to commit the results.

Parallel to the development of the cleaning unit the design and construction of the Methanation unit was done.
The initial condition for the reactor was that it should run at 400˚C and 10bar. A temperature that demands a thermal resistant type of gasket for the Plate Heat Exchangers (PHE) used for preheating the gas and the reactor. To handle the cooling of the reactor at 400˚C an oil cooling system was developed. Hot oil at that temperature is very hazardous and much percussion was taken to avoid accidents with this, witch lead to a quite complicated system.
To seal the PHE´s a graphite gasket was developed. The graphite material could handle the temperature, but it appeared to be very difficult to obtain a gas tight sealing because the graphite material lacks the elasticity that the original rubber gasket had. Many attempts were made with use of different pastas in conjunction with the gasket to make the sealing tight. A complete tightness was not achieved, but to minimize the leakages the reactor was reduced half in thickness (number of plates) that original designed. The same sealing problem was recognized with stainless steel tubing in the hot oil circuit. During the construction process, it was decided to try to cool with compressed air instead of the oil. The air-cooling was tested and found sufficient for the cooling of the reactors. As an impact of this decision, the oil cooling system was removed and the simpler air cooling system was implemented. That led to a dramatically reduction of the overall complexity of the system. To capture the small gas leaks from the reactors, an encapsulation was made, connected to a ventilation system in the rack.

It has been essential that the system should be designed to be able to run on synthetic reference gas; therefore, the unit is equipped with tree gas bottles containing CH_4, CO_2 and H_2. The presence of CH_4 gives the possibility to mix synthetic biogas with varying CO_2/CH_4 ratio.
To control the gas flow through the unit, a gas panel was built with Mass Flow Controllers for the CH_4/biogas, CO_2 and H_2. A measuring system for measuring the CH_4, CO_2 and humidity concentration was developed.

For controlling the system, a PLC controller has been implemented and PLC and SCADA software developed. The data from the system is stored on two redundant Microsoft SQL Servers. Before the shipment to GreenHydrogen in Kolding November 1st 2013 the system was tested with compressed air. The problems of the cooling system and the gasket problem of the reactor, followed by a redesign- and construction phase, led that the milestone M3.1 was delayed by four months.

At GreenHydrogen in Kolding, the Methanation unit was leak tested with H_2 and the PHE based preheater was not sufficient tight for running. This was replaced by a soldered PHE. After this modification, the system was tested with CO_2 and H_2. During the next couple of months, several attempts was made to make the reactor working but it was only possible to produce a small amount of CO. Parallel to this an alternative process was been developed at DTU. Due to extremely positive test Medio December 2013, it was decided to make a new reactor in January 2014. Early in February 2014, the reactor was implemented in the Methanation unit, and tests began. After a short time, it was possible to replicate the test from DTU, and the conversion of CO_2 to CH_4 was initiated.
Due to these upcoming delays, it was decided to extend the project duration by 6 months, so the new project ending date would be 31th of December 2014.

Initially the exothermal process was very hard to control and the temperature vent often above 500°C. During the next months, a new backpressure valve was introduced and a be-havior study was made on the catalyst. As the pressures were now constant, a systematic investigation of the temperature was made. By releasing the temperature at 400°C and let it fall, it was found that the process stabilized around 280°C, and at up to a certain gas flow range, it maintain the reactor temperature without need for neither external heating nor cooling. After that an investigation of the flow dependencies was made and it was found that the most stable and steady condition was reaches at a flow rate approximately 0.8Nm^3/biogas. The biogas composition was mostly set to 35% CO_2 and 65% CH_4, but other compositions were also tested.

To handle the biogas at Lemvig Biogas, which is delivered at very low pressure only a few Mbar, two compressors were added to the units, one in the cleaning unit for raising the pres-sure to approximately 1Bar and one for the Methanation unit for raising the pressure to ap-proximately 10Bars. Some small piston compressors were found and the capacity adjustment was done by using frequency transformers. PID regulators were implemented in the PLC program.

As a final task in Kolding, the two units were mounted in a 20-foot container, and the total system integration was done.

At September the 17th 2014 the container arrived at Lemvig Biogas. During the following two weeks, the container was connected to the plant, and the commissioning began. Due to the fact that the raw biogas is totally wet, the pipes to and from the plant was equipped with heating wires to maintain gas temperature into the container at approximately 60°C. These heating wires were also attached to biogas tubes inside the container.

Initially the system was tested on bottles (CH_4 and CO_2) and the reactor was performing well. After that, the Cleaning unit was tested with raw biogas. Very early it was recognized that H_2S sensors were behaving inaccurate. Both the sensors for measuring in the range of 0-2000ppm and 0-100ppb, where implemented in a system with purging and regeneration, for compensating the anaerobic the gas measurement. A dialog was initiated with the suppli-er of the sensors to find the errors. At that point, a new issue showed up concerning flow dependencies of the sensors. The system was redesigned with bypass and Low Flow Rotame-ter around the sensors. But still after these modifications, the sensors did not perform as expected. A couple of new ppb sensors were purchased and tested, without success. At that time it was decided to use the readings from the nearby biogas sensor at the biogas plant. A coupling was made between the biogas plant PLC and the PLC of the cleaning unit, transfer-ring the values for the raw biogas composition, CH_4, CO_2, H_2S and O_2. By that point, the H_2S concentration (ppm) was established to the cleaning unit.

Several attempts were made to get new equipment to measure H_2S concentration, in the very difficult ppb area. Very fine candidates were found, but the fact that the project was running out of time, no suitable instrument could be delivered in the remaining project time. To compensate for this, manual measuring was made on the cleaned biogas after the Cleaning unit, by use of "Dräger Tubes". During the following tests, during the next months, of the Cleaning unit, it was not possible to detect any remaining H_2S in the cleaned biogas.

The system was now ready to run on real biogas from the plant, which was initiated by running the compressors on the cleaning- and methanation units. A few seconds after the biogas was led into the reactors the police filter before the reactors showed an extreme exothermal reaction. The gas was immediately shut down, and an investigation was done to find the answer for this reaction. It was found that the reaction was coursed by the presence of oxygen in the biogas. After a systematic debugging, a leakage in the pistons of the compressors was found, where a vacuum occurred on the inlet side of the compressors. Attempts were made to find alternative diagraph compressors, but it was not possible to get this in a very short time. Instead, the existing compressors were modified with a bypass tube from the outlet to the inlet, with a needle valve to adjust the flow through bypass. That solution secured that no atmospheric air was led in to the methanation unit. To monitor the O_2 concentration in the biogas, an O_2 sensor was built in.

The following tests showed that it now was possible to deliver the biogas to the reactor with no presence of oxygen; the only consequence of this setup was that the capacity of the compressors has been reduced to $0.8m^3/h$.

After these final adjustments, the longtime test period initiated with very fine results. That will be described in the following chapter along with other tests made along the way to learn the nature of both units.

1.5 Project results and dissemination of results

1.5.1 Technical activities and results

In the following, an explanation of key technical activities and results from the project is described. These activities has been major achievements and all contributed to the successful results of the MeGa-stoRE project. Without that learning process, vital knowledge upon how to operate the plant would not have been found, and have affected the project outcome.

Main activities on the cleaning unit

The cleaning unit has been built with the purpose of cleaning the biogas without creating any waste product. The construction of the unit is very simple, which has been a design criterion from the beginning.

The biogas typically contains around 150 to 200 ppm of H_2S, but for the catalyst to work in the methanation plant the H_2S level must be below 30 ppb. Several tests have been done on the clean-

Picture 1 Cleaning unit.

ing unit to demonstrate that it is cleaning the biogas from sulphur. The graph below illustrates a test with around 300 ppm H_2S (blue graph) and the results in the output gas (red graph) way below the upper limit of 30 ppb. This test indicates that the cleaning unit is cleaning the gas sufficiently to enter the catalyst in the methanation unit.

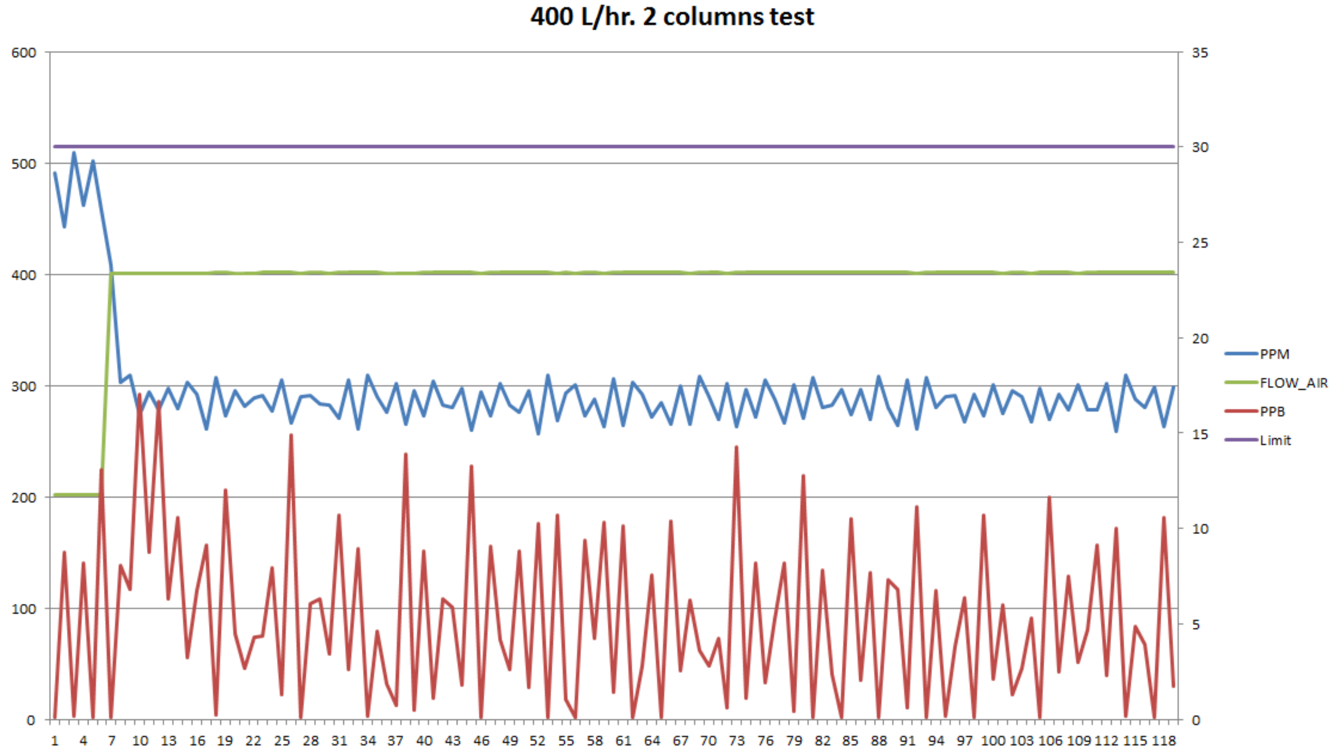
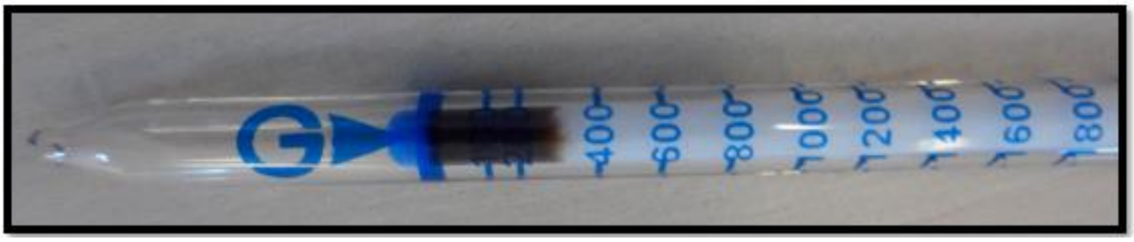


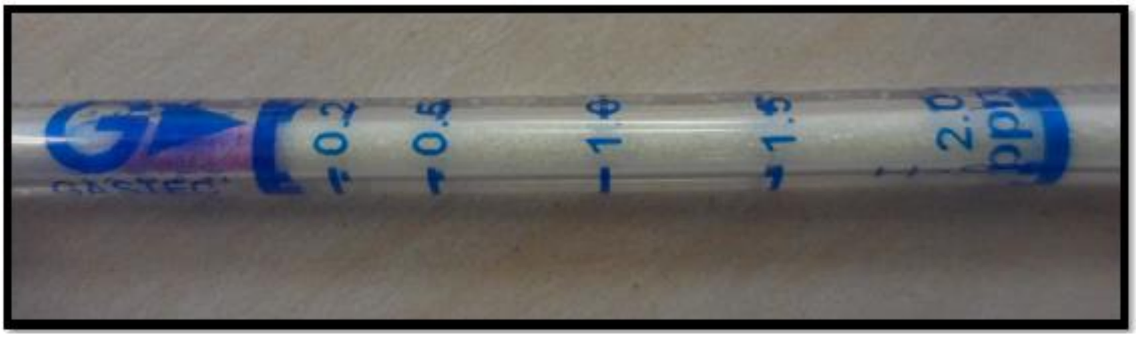
Figure 3 H2S test on the Cleaning unit.

In addition to the test shown in the graph above, the gas was also tested using Dräger tubes. That test was to ensure that the installed H_2S in the cleaning unit was trustworthy.
First, a test sample was taken with the inlet gas containing around 300 ppm H_2S. The results are shown in the picture below.



Picture 2 Dräger test at ppm level.

The tube indicates around 300 ppm H_2S, which is similar to the sensor, installed in the cleaning unit.
However, testing on the output gas is more interesting because it could verify if the cleaning unit in fact is cleaning the sulphur on a sufficient level.
Another Dräger tube was used that could measure in the level of 0,2 – 2,0 ppm H_2S. Unfortunately, there does not exist any Dräger tubes that measures in the ppb level. However, according to the manufacture it is possible to draw several gas samples through the same test tube.
Therefore, 10 gas samples were sucked through the same test tube, and if a reading wasn't detected it would indicate that the gas is cleaned to levels below 20 ppb of H_2S.



Picture 3 Dräger test at ppb level.

The results from the gas sample test can be seen in the picture above where no reading could be seen, which indicates that the cleaning unit is cleaning the gas very well.

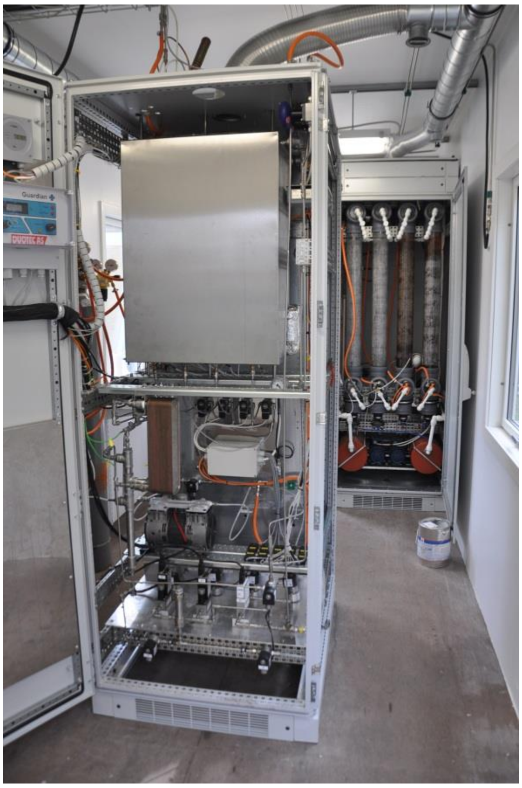
Upon many similar tests conducted with the cleaning unit, it was concluded by the project team upon arrival at Lemvig that the cleaned biogas could be led into the methanation plant, which was a big milestone for the project, as that made it possible to start the testing with real biogas for both units.

Main activities on the methanation plant

Developing and building the methanation plant has been an on-going process from the beginning and is explained in the chapter before. During the building process several experiments has been conducted along the way in order to learn the nature of the plant and the Sabatier process, but also to suggest new ideas and features to build into the plant in order to make it more efficient.

From the beginning of the project, the overall goal has always been to develop and build a simple construction that is capable of upscaling and which handles the methanation process in one-step. Going in to the process with that mind-set has helped the project team to progress along the way and ultimately completing the project. Early on in the experiments with the methanation unit, it was learned that the was to be able to control the process very precisely in order to maintain high conversion rate into methane.

The determining factors for controlling the process was the variables that can be changed in the plant setting, which would be reactor temperature, pressure, gas flow rate and ratio between H_2 and CO_2. These factors were the key to test upon in order to find the perfect combination that ensures reproducibility, high stability and high conversion into methane.



Picture 4 Methanation unit.

In order to measure the effect of the different variables it was decided from the beginning that a CO_2 and H_2 sensor should be part of the plant so it was possible to measure the outcome gas. However, along the way a methane sensor was also build into the plant to measure the methane in the output gas. The hydrogen sensor was removed at a point because it is very difficult to measure hydrogen, and it was simply not working. Therefore, in the end of the project the most important measurement was the CO_2 sensor, because it tells how much CO_2 is converted into methane.

- Temperature tests:

The first parameter tested was the reactor temperatures. Some of the initial test showed that the reaction is very exothermal and the project team experienced temperatures in the reactors above 500°C, which was very critical for different components in the plant. Therefore, it was decided to do a temperature drop test, since it was known from the literature review that the Sabatier reaction was optimal in the range of 250-400°C.

The experiment started with reactor temperatures set to 380°C and the heating wires was shut off. The plan was then to observe what happened to the productivity of methane as the temperature inside the reactors fell towards 250°C. The pressure was kept between 8 and 8,5 bar throughout the test. Synthetic biogas consistent of 70% CH_4 and 30% CO_2 was used. The gas flow was 120 L/h H_2, 70 L/h CH_4 and 30 L/h CO_2 so it was kept at the stoichiometric ratio of 4:1. Towards the end of the test, the synthetic biogas was changed to 65 % CH_4 and 35 % CO_2.

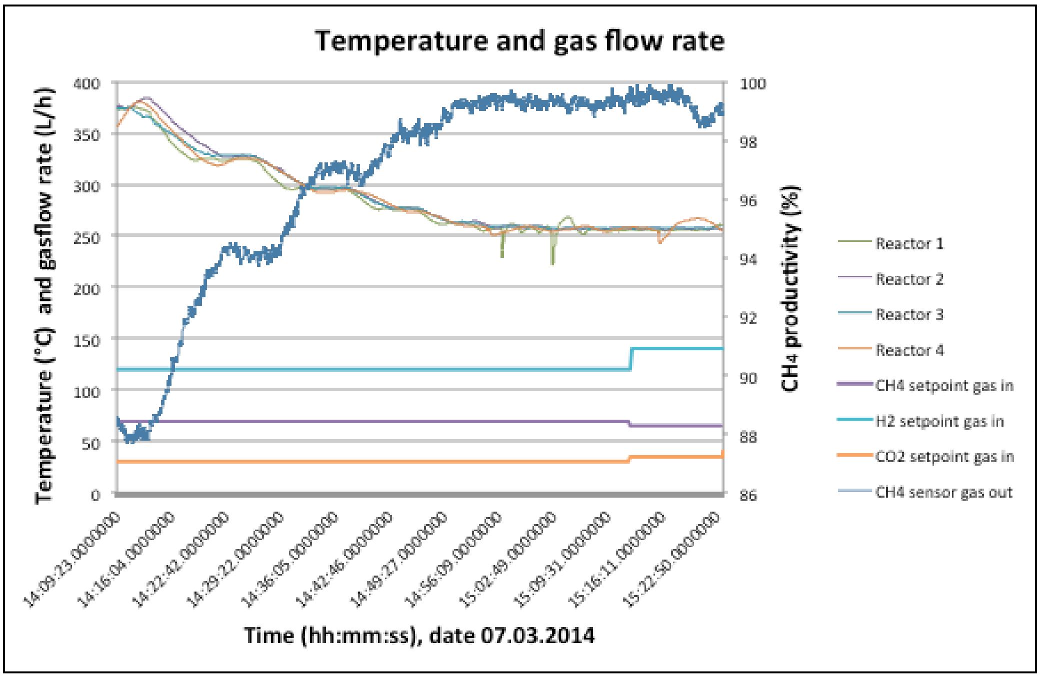


Figure 4 Temperature test.

Results from the temperature test indicated that the highest conversion into methane was obtained once the temperature in all 4 reactors were around 270 °C, which can be seen in the graph above. It is a very important discovery to make, because it says something about the effect of temperature on the reaction process and something could indicate that this methanation plant prefers lower temperature than what could have been expected, based on the learning outcome from the theory.

- Gas flow rate test:
After the right temperature for the process to happen in the methanation plant was discovered, the next test was to investigate if the gas flow rate (Space velocity) affected the conversion rate of methane. Several tests were made with steady temperature and pressure and it could be concluded that the conversion rate of CH_4 is not affected once space velocity increases. However, the process becomes very unstable with higher gas flows, which results in temperature spikes inside the reactors towards 400 °C. So the optimal gas flow was found to be below 1000 L/h of synthetic biogas, which resulted in a stable process that could be controlled.

- Right amount of hydrogen
After identifying the right temperature and the importance of gas flow rates, the project team could now focus on finding the right amount between CO_2 and H_2 in order to minimize the waste of hydrogen and CO_2 in the output gas. After conducting several tests with the focus on minimizing the CO_2 containment in the output gas by chancing the stoichiometric ratio between CO_2 and H_2 it was found that the ratio could be lower than 4:1. The methanation plant was capable of high conversion into methane with a ratio between H_2 and CO_2 as low as 3,6:1. Additionally, it was discovered that it was possible to control the rest amount of CO_2 in the output gas by changing the H_2 level. Further, there proved to be a good linkage between the installed methane sensor and CO_2 sensor so they equalled close to 100 %. That indicates that a minimal amount of hydrogen is left, which is very good as the hydrogen will be the costly parameter in this case, and therefore minimal waste is preferable. It can be seen in the graph below.

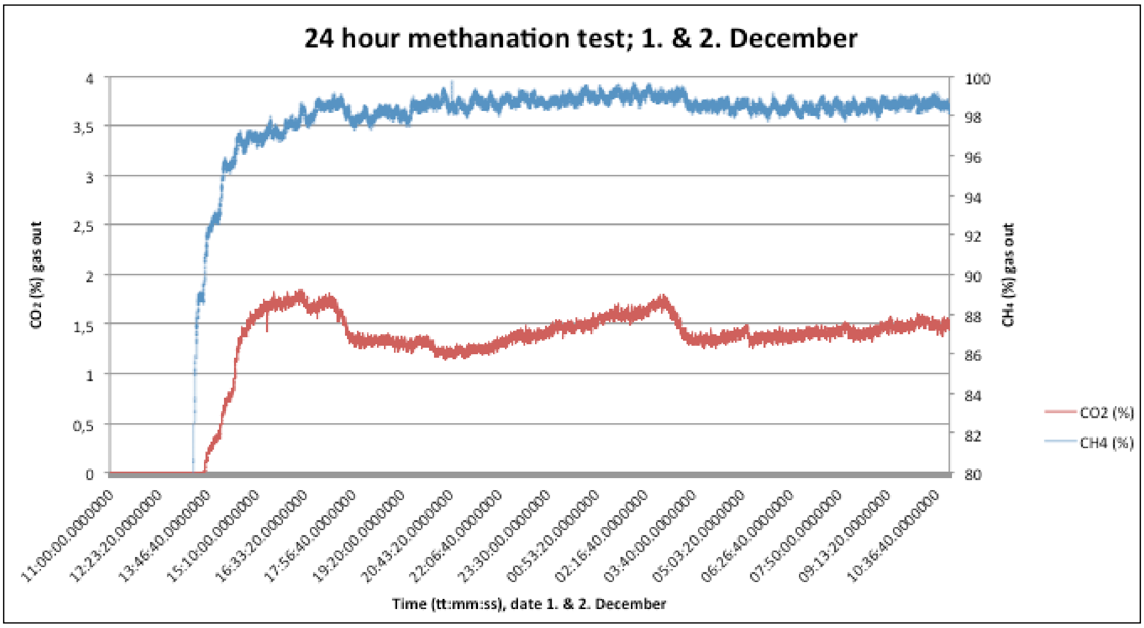


Figure 5 Test on linkages between CH4 and CO2 sensor.

Concluding remarks on main activities on the methanation plant
These experiments have all served the same purpose of identifying the different variables effect on the methanation process. By identifying the different settings, the methanation plant was now ready for field-testing in Lemvig with real biogas, where a series of long-term test (24-hours) was the goal to complete from the project team. That will serve to prove the stability of the plant.

1.5.1.1 Technical results from the project

According to phase 4 in the project plan, the final phase of the MeGa-stoRE project was test and verification of the technology in real life settings. After a thorough test period with synthetic gases in Kolding the container, containing the cleaning unit and the methanation plant, was thereby ready for field-testing with real biogas at Lemvig Biogas.
Upon arrival at Lemvig Biogas, the container was installed and the necessary connections to the biogas plant were made.

Picture 5 The container installed at Lemvig Biogas plant.

Once the container was installed, it was time to start testing with real biogas. A series of different experiments was conducted initially, which resulted in some modifications to the cleaning unit and the methanation plant.
Given the different variables identified through experiments with synthetic gases, the project team had learned how to operate the plant under stable conditions. It was now time to do some long-term experiments that should finally make the proof-of-concept for both technologies.

A total of 4 long-term test ranging from 15 to 24 hours was conducted in the period from 11 of November to 2nd of December. All the experiments showed high stability and high conversion into methane. The graphs below shows details from the test made from the 1st to the 2nd of December.
The reactor temperature was set to 270°C, the pressure was kept at 8 bars and the biogas flow rate was 720 L/h.

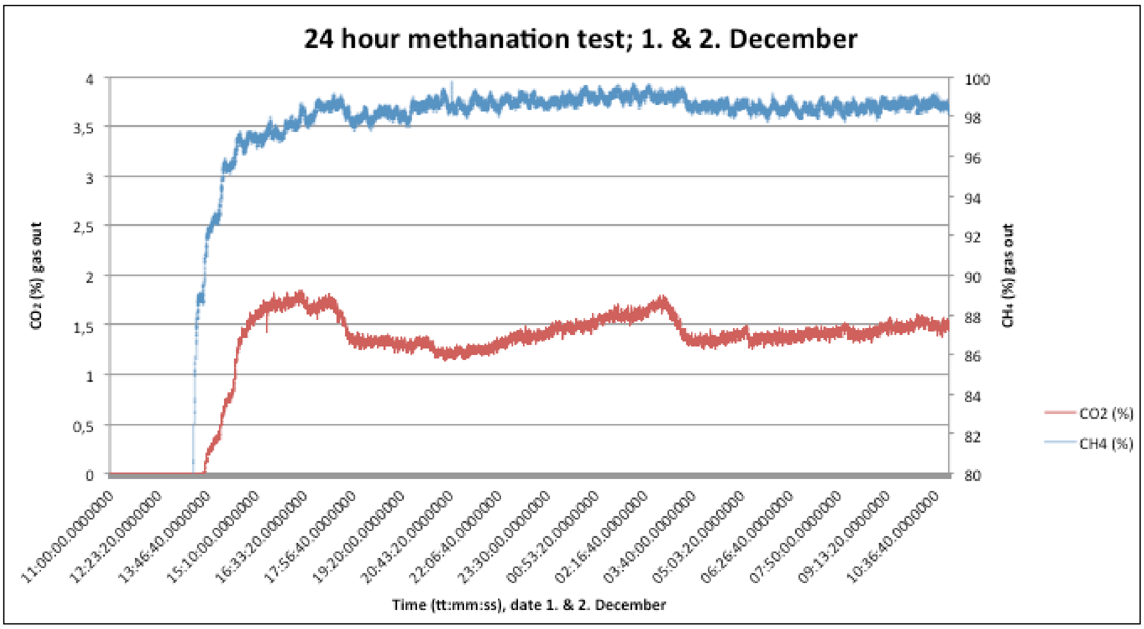
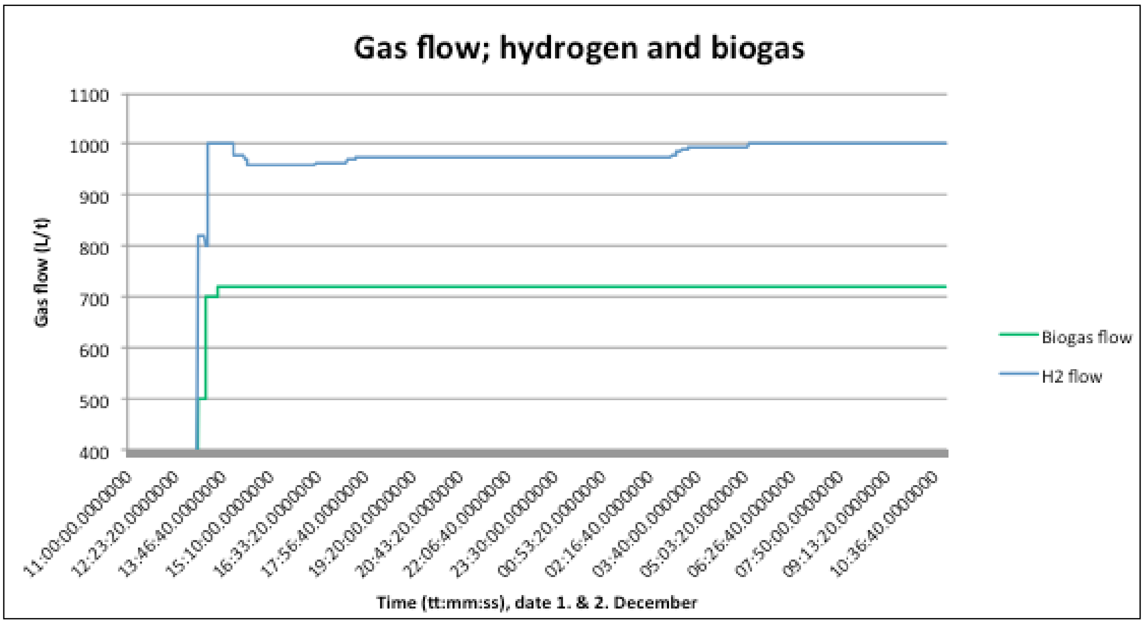


Figure 6 Methane and CO2 in the output gas.

The methane level was kept very stable between 97 % and 99 % during the whole test and the CO_2 level was kept stable around 1,5% in the output gas. The graph below shows the gas flow and one can see that some changes were made to the hydrogen flow rate during the test in order to maintain the CO_2 level around 1,5%.



Figur 7 Gas flow rates.

Another reason why this experiment went really well, was the reactor temperature (see graph below). First, it was very stable between 280 °C and 300 °C. Second of all the reactors were capable of maintaining the temperature at that point without any additional heat added from the heating wires. That is a very good indication of the fact that a point has been found where a combination of reactor size, reactor temperature, gas flow rates, pressure and ratio between H_2 and CO_2 makes the process self-regulating. That has been the ultimate goal for the project team because it demonstrates that the nature of the process has been learned and that gives very important knowledge that will become very useful in the next project, when the right size of the reactors will be upscaled.

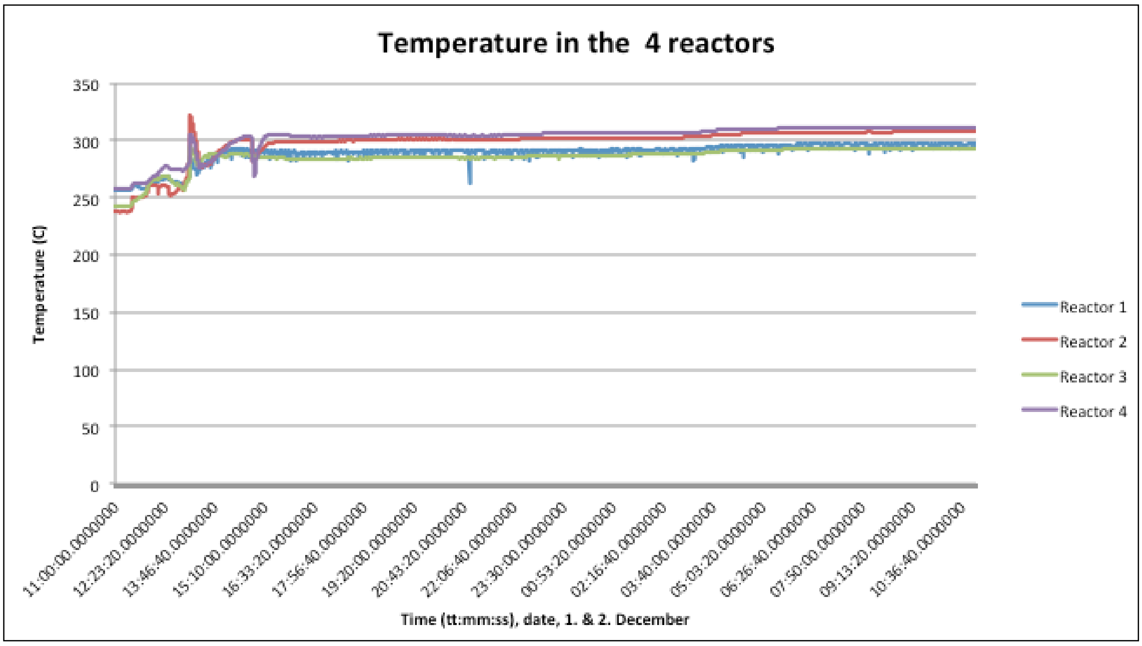


Figure 8 Temperature in all 4 reactors are very stable.

The final indicator that shows the stability of the process is the Water Separator build into the plant. See graph below.

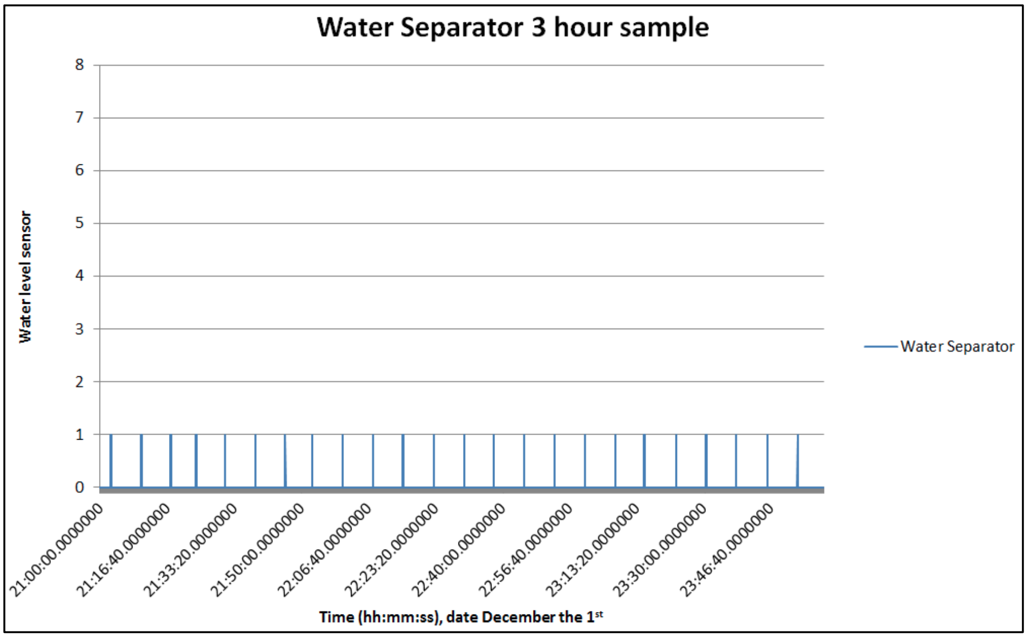
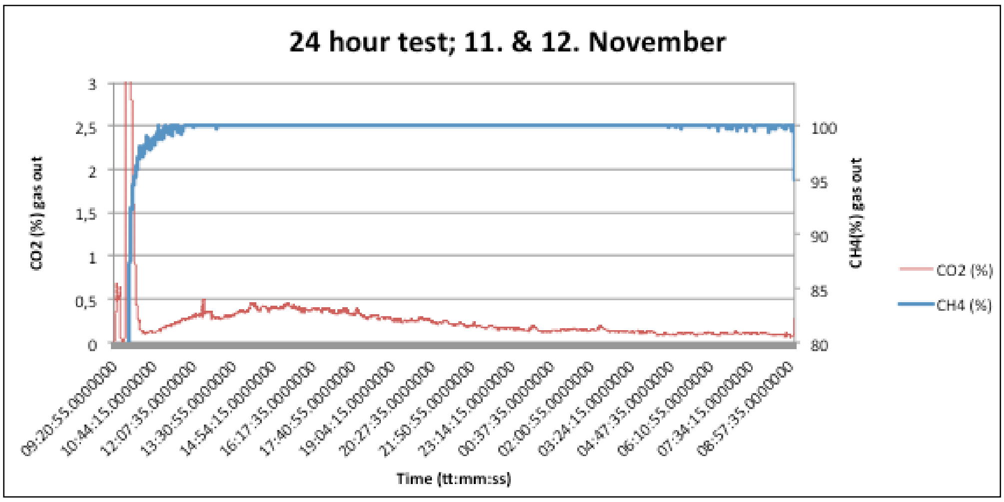
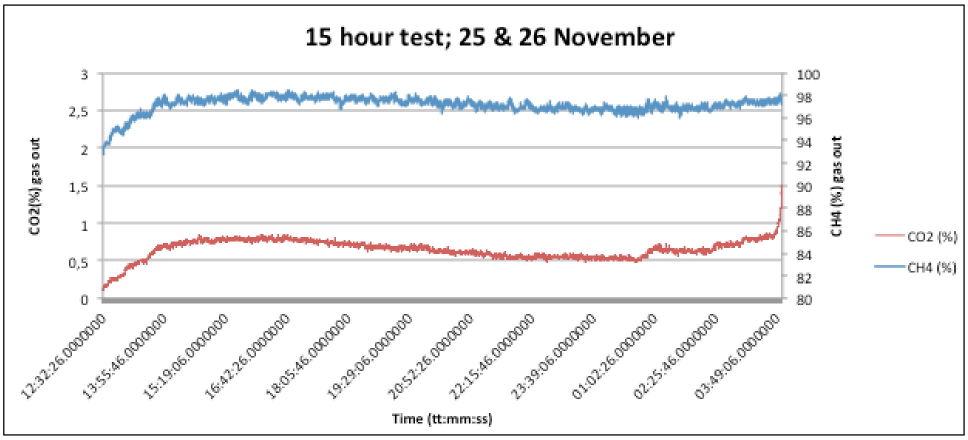


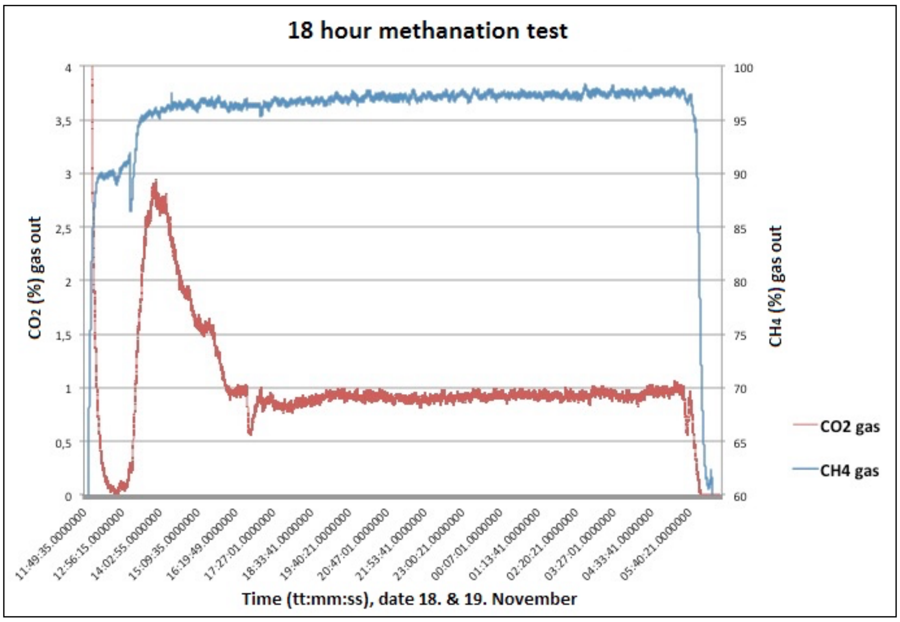
Figure 9 Water Separator.

As water is a by-product of the process it is a very good indication when the water separator is full, because it shows that the reaction is taken place. To come to the point where the water separator is full with the same interval of time in between is a remarkable proof of a stable process.

Three other graphs showing the methane level and CO_2 level from other long-term test conducted in Lemvig, is displayed below.







Ultimately, one can conclude upon the technical results and achievements from this MeGa-stoRE project, that a cleaning and methanation unit has successfully been built. However, in order to obtain a stable process, which is highly recommendable in a chemical process, it was found that it is a matter of finding the right settings rather than chasing high capacity according to catalyst capability, because that will make the process uncontrollable temperature wise. That is a very valuable lesson learned from building and testing this proof-of-concept plant that the project team directly can implement into the design thinking of the upcoming project of building a larger plant for developing the technology.

1.5.2 Commercial results

The poof-of-concept has generated valuable input as a base for "productization" and for developing the technology to solutions - as a first step in the commercialisation. It has demonstrated the significant perspectives in using electrolysis and methanation as key technologies in converting the energy supply system to a coherent, green energy supply system, and earned us broad attention and interest from the market- including from potential customers, energy authorities, policy makers, universities and politicians.

Our open House arrangement at Lemvig Biogas attracted app. 80 people form the energy business and organisations, and we have experienced an increasing interest for our solution and requests for information following the event.

The project made it possible for us to initiate specific dialogs with a number of customers with specific projects – mainly commercial customers in the biogas industry - and potential partners, who may become instrumental or at least important for new demo projects, and especially when we are ready to take the technology to the international markets.

We plan to develop a turnkey, standard modules based methanation platform that match GreenHydrogen's MW electrolyser concept and capacity 1:1. This will offer customers a fully integrated solution platform, including electrolysis and methanation. The modular concept makes it easy to adapt to different customer installations and different volume requirements without any re-engineering required and on a pay-as-you-grow basis.

The use of standard modules provides for low Total Cost of Ownership; it minimizes technical risks and delivery time, eliminates the need to design each project, minimizes installation time, makes it easy to operate and maintain and facilitates standard training and service programs.

The integrated, standard modules also facilitates an international partner strategy where we may deliver our integrated platform to providers of turnkey biogas plants and projects, for global, project partner strategy - and for rapid scaling of production capacity – e.g. through OEM programs.

The methanation platform has been included in our business plan for 2015-2018 – primarily in manning and equipment for R&D but also commercially with an application engineer and increased marketing budget (from 2017).

Our networking activities for the solutions has started and we are looking for demo customers and partners, who will participate in the next phase of development where we will mature the technology an scale it for increased upgrade capacity.

Marketing of the solution will start in 2016/17, where we plan to start showing our solution in international events and exhibitions. We plan for launching demo versions of products/solutions in 2017. Commercialisation and full market activities in 2018 or before.

1.5.3 Expectations of the project

Further to the above answers we generally expect that our methanation project may be a major breakthrough in developing cost efficient, standardised and integrated solutions that will eventually – when ready for large volume sales - lead to fast acceptance and penetration in the market.

Over and above the increased upgraded biogas and CO_2 delivered from biogas plants, the integrated methanation solution requires a lot of MW electrolyser capacity. The electrolyser used for the project may be available as additional balance capacity for the primary balance requirement of the power balance – with the capability of dynamic production capacity and rapid powering up and down in sub-seconds.

1.5.4 Environmental impact

The methanation technology developed in this project has the capability of providing a significant environmental contribution. The most important environmental impact is the CO_2 repression. By methanation of the CO_2 in biogas or a pure CO_2 source the produced methane repress fossil natural gas in the natural gas net. An example of a methanation plant matching a large biogas plants that produces 15 mill. m^3 biogas per year repress 15 *0.35 = 5.25 mill. m^3 fossil natural gas per year. As 1 m^3 of fossil natural gas produces around 11 kWh and 1 kWh equals 200 gram of CO_2, the above example will save the environment from 0,2 kg * 11 kWh * 5,25 mill. m^3 = 11.550 tons of CO_2 on a yearly basis when the upgraded biogas is repressing natural gas. And that is only production from one biogas plant.
As the project obtained successful results with the methanation technology it is possible to assume that the total biogas potential of approximately 42 PJ based on residual biomass could be upgraded into approximately 65 PJ, and thereby store a considerable amount of renewable energy, if this upgrading technology were to be used.
Therefore, this technology has the capability to help meet future energy goals for Denmark. Based on the environmental potential of this technology and environmental calculations the following table has been made for the environmental impact of this technology in Denmark.

	Not relevant	Smaller contribution	Significant contribution
Energy system is supplied by renewables in 2050			X
Electricity and heat is covered by renewables in 2035			X
Phasing out coal and oil in 2035			X
Integration of 50 % wind energy in 2020		X	
40 % reduction of greenhouse gas emission in 2020		X	

Therefore, based on the calculated environmental impacts giving the use of a methanation plant with several different CO_2 sources, severe climate mitigation can be achieved. As the table above shows, it could have major contributions towards environmental and political goals in Denmark and provide a solution to store renewable energy and lowering greenhouse gas emission. Since the technology, according to the energy scenarios form the Energy Agency, is expected to enter the energy system in 2020, the impact on integration of wind power and reduction of greenhouse gasses before 2020 is small.

1.5.5 Increased turnover, exports, employment?

So far we didn't see increased turnover since the project was a proof-of-concept and not a ready for sale solution. However, based on the learning of the project and the interest seen from the market, GreenHydrogen foresee a great potential in taking the technology to the market. GreenHydrogen have budgeted and planned new hires starting from 2015 and gradually increasing over the next 3 years in order to increase R&D efforts in integrated methanation solutions, and to eventually commercialize the technology internationally with an expected increased revenue contribution starting in 2017.

1.5.6 How has project results been disseminated?

A workshop at Lemvig Biogas concluded the project. More than 80 people from different organizations and businesses were presented at the workshop in which the project was explained and a demonstration of both the cleaning unit and the methanation plant was made. Since the workshop, the different partners have received increasing interest regards regarding the project.

The project has also been disseminated with articles in the magazine called Ingeniøren in week 50, 2014 along with an article in Gasteknik nr. 6, 2014.
Furthermore, a website www.Methane.dk has been setup where the knowledge regarding the technology and its perspectives are disseminated.

1.6 Utilization of project results

1.6.1 Do project participants expect to take out patents?

It is in the moment not decided. Some of the elements could probably be patented - We have large strategic knowledge about patents - and sometimes does patent not gives any meaning for a university, because we can´t protect the ideas in a global world, before they become a part of a large international group. We have a large risk only to give away ideas from the MeGa-stoRE project - if we start to makes patents.

1.6.2 How do project results contribute to realize energy policy objectives?

The results of the MeGa-stoRE project has already been communicated via Partnership for Hydrogen director Aksel MortensgaardMortensen to relevant parts of the political system, because the technique makes it possible to store wind energy as hydrocarbons. This is an important goal for the Danish Energy sceneries (see later).

1.6.3 Have results been transferred to other institutions?

The project has just been finished - but we have already after an article in INGENIØREN got several contacts from abroad for instance Israel, Switzerland, Japan and the US. A very large company in Japan has already visit us for getting more information, and a large producer and developer of catalytic material in the US has offered cooperation in future project - bringing methane to liquid fuel. They are also interested in our purification techniques. A booklet describing the project has been edited and handed to relevant organisation in Denmark, such as members of the Danish parliament, companies and engineer schools. All students at DTU-MEK and all high schools in Denmark has got a copy of the book - distributed by Partnership for Hydrogen. Furthermore a homepage has been established - metan.dk in English has been opened. We will let master students become a part of the further development.

1.6.4 Elplatek A/S

Elplatek A/S has big expectations to scaling up the technology based on the very impressive results achieved and presented in Lemvig and the enormous interest shown by the many attendees. Elplatek A/S will be part of upscaling the plants in the next project MeGa-stoRE, Optimizing and UpscalinUpscaling. The next part will be to look into opportunities to transform the methane into methanol in a new context. Furthermore Elplatek has large international experience operating outside Denmark with clean tech projects and are able to contribute with leadership for an international development of the technology.

1.6.5 GreenHydrogen.dk

The project made it possible for us to initiate specific dialogs with a number of new customers with specific projects – mainly commercial customers in the biogas industry - and with potential partners, who may become instrumental or at least important for new demo projects. This development will make it possible for GH to improve the electrolysers and get more practical and commercial experience with alkaline electrolysers with high efficiency, integrated with methanation units developed as modules matching the capacity of the electrolyser. This minimizes the need for engineering in each methanation project and reduces customer risk. Furthermore a new technology for the supply will make the electrolysers attractive to balance the grid, which can improve the customers' business case and ROI considerably.

1.6.6 Lemvig Biogas

Lemvig Biogas has been very excited about hosting the final field-testing of the technologies described in this report. They were impressed with the results and are regretful about not participating in the next project regarding the MeGa-stoRE technologies. Lemvig Biogas is specifically very interested in looking into scaling up the gas-cleaning unit, as they are experiencing troubles themselves regarding cleaning the sulphur from the gas. The gas-cleaning unit could become very beneficial for the general economy of producing biogas. Additionally, they like the possibility of turning methane gas into liquid fuel and will be willing to participate in such a project.

1.6.7 For all partners

The perspectives in this field (*storing energy as hydrocarbons*) is so large that the actors in the MeGa-stoRE project today must consider themselves as technology developers instead of large energy players - it will require groups in size with Siemens, Eon, General Electric and maybe Maersk to get these technologies realized. Therefore the group has to focus on technology and bring it to the next step. It is important for Green Hydrogen to develop electrolysers which can fulfil - the need in the next steps.
To change the Danish energy- system to fossil free and bring it to gigawatt on electrolysis and subsequently produce "green hydrogen" is very useful for synthetic fuels. But it will require investments running into billions - like a new Great belt bridge. In the near future it is important that all partners - GreenHydrogen, Elplatek etc. Continue the large success at Lemvig Biogas - and put the global agenda - demonstrating new ideas for Energy Factories in Denmark. That will bring a lot of benefit to Denmark. The beginning of international interest for MeGa-stoRE has already shown that large companies abroad want to be a part of the sustainable energy we want to establish.
No organization in Denmark can realize this project alone. Therefore we need international partners. Therefore our technology has to be developed further, so we are sure, that we avoid both the TECHNOLOGICAL VALLEY OF DEATH and the COMMERCIALIZATION VALLEY OF DEATH. The MeGa-stoRE project is on its way to the next step - which can be viewed as a pre-commercialisations step, where purifications cost and investigation of a ~~more smart~~smarter Sabatier reactor has to be investigated. Probably during this part of the project large commercial partners will be attracted - and speed up the development in DK and cause new green jobs for upgrading biogas to green methane. But at the same time also deliver technology to hydrogen fuel stations.

1.7 Project conclusion and perspective

Given the very impressive technical results achieved in the MeGa-stoRE project, one can now conclude on the project in general. The project team succeeded with the original purpose of developing a cleaning that proved capable of cleaning the biogas from sulphur and other purities without any hazardous waste. Additionally, the team succeeded on building and de-

veloping a methanation unit that were capable of converting the cleaned biogas, containing approximate 65 % methane and 35 % CO_2 into around 97-99 % pure methane, with a very little residue of hydrogen and CO_2. The conversion is in one-step, which was one of the objectives set out from the beginning of the project. Another criterion for the methanation unit was also to investigate into finding a stable operation mode. Through development of the right reactor size and several testing on temperatures and gas flows, a stable process was achieved at the end of the project, which lead to several long test periods with high conversion into methane.
At the end, one can conclude that the technical aspect of building and developing a gas-cleaning unit and methanation plant was very successful. Both units were constructed in a simple way that makes upscaling to a larger demonstration plant possible. Ultimately, the technologies involved proved capable of cleaning raw biogas, upgrading it over a catalyst using hydrogen and add additionally 50 % more methane to the original gas. The upgraded renewable gas can be sent directly into the natural gas grid for storage purposes, providing a solution to store excessive renewable electricity and get the highest energy potential out of the biomass. Therefore, the technical aspect of this project was very successful.

Regarding the economical aspect of the project one can conclude that political support to upgrading of biogas must be enhanced for the technologies to be profitable. Given the calculations made in table 1 below it is clear that for this technology to produce green renewable gas competitive with existing natural gas prices, some incentives must be in added. By assuming that the electricity can be bought for net-price (approx. 0,30 DKK/kWh) without PSO and grid charge and upgraded grant for converting CO_2 into renewable methane were given, this technology could be attractive to the commercial market. Additionally, it could provide an agreement with wind turbine owners to buy the electricity at a given price, to make sure there is a foregoing incentive to build new wind turbines into the Danish electricity grid, despite the periods with excessive wind energy resulting in lower prices.

Year	2015	2020	2025	2030
Scenario	EU report	EU report	EU report	EU report
	Central	Central	Central	Central
Price reduction ratio		-23%	-3%	-5%
10MW Electrolysis, mill. DKK	69,8	46,9	45,4	43,2
Methanation, mill. DKK	7,7	5,9	4,6	3,5
Investment ex. works mill. DKK	77,4	52,9	50,0	46,7
Installation 15% mill. DKK	11,6	7,9	7,5	7,0
Investment and installation mill. DKK	89,1	60,8	57,5	53,7
O&M: 2 + 5,7= 7,7% per annum, mill. DKK	6,0	4,1	3,9	3,6
Capital costs 4,0% per annum, mill. DKK	3,6	2,4	2,3	2,1
Depreciation pre annum in 10 years, mill.DKK	8,9	6,1	5,8	5,4
Costs in total per annum, mill DKK	18,4	12,6	11,9	11,1
CH4 production Nm3 per year	15.000.000	15.000.000	15.000.000	15.000.001
Costs, DKK/Nm3 CH4	1,23	0,84	0,79	0,74
Hydrogen, DKK/ Nm3 CH4	1,77	1,77	1,77	1,77
Biogas, DKK/Nm3	3,60	2,77	2,13	1,64
Productionsprice, DKK/Nm3 CH4	6,60	5,38	4,70	4,15
Upgrading grant, DKK/m3	3,81	3,81	3,81	3,81
Net price, DKK/ Nm3 CH4	2,79	1,57	0,89	0,34
Natural gas price, DKK/m3	3,1	3,1	3,1	3,1
Contribution margin, DKK/ Nm3 CH4	0,31	1,53	2,21	2,76
Return of investment %	6,69	48,88	73,02	95,64

Table 1 Price calculations for MeGa-stoRE project.

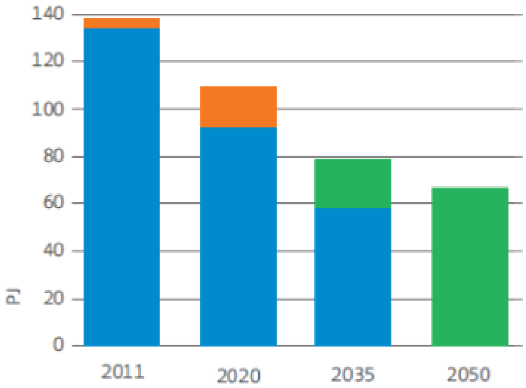
1.7.1 Perspective

In March 2012 the Danish Parliament almost unanimously agreed upon an ambitious energy agreement for the period 2012-2020 with directions to be independent of fossil fuels in 2050.

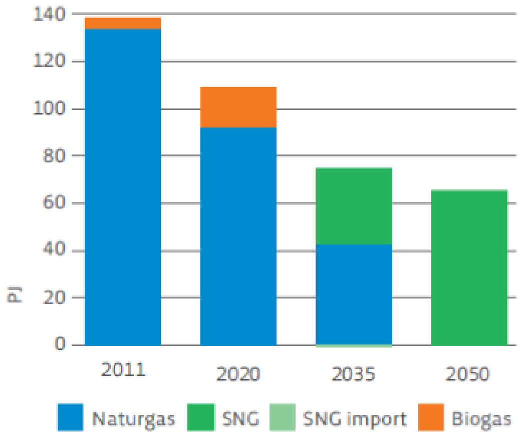
In March 2014 The Energy Agency, submitted the result of their analysis on how to reach this goal in the following 4 reports:

1. Energiscenarier for 2020, 2035 og 2050
2. Fjernvarmens rolle i den fremtidige energiforsyning
3. Den fremtidige anvendelse af gasinfrastrukturen
4. Analyse af elnettets funktionalitet

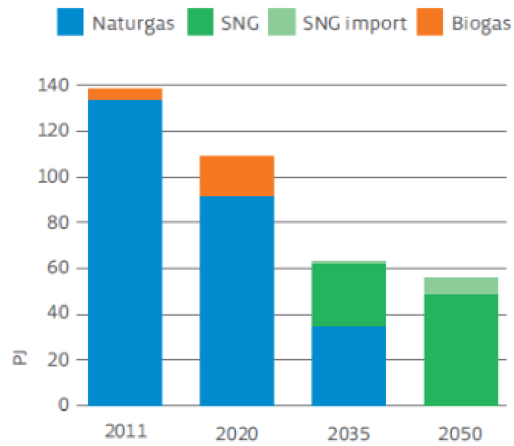
In report no. 3, "The Future Application of the Gas Infra-Structure", the following figures show how the extended use of biogas is forecasted to take place.



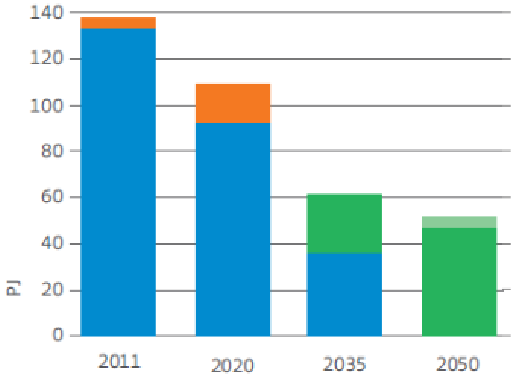
Figur 4. Gasforbrug i Energistyrelsens brint-scenarie



Figur 1. Gasforbrug i Energistyrelsens vind-scenarie

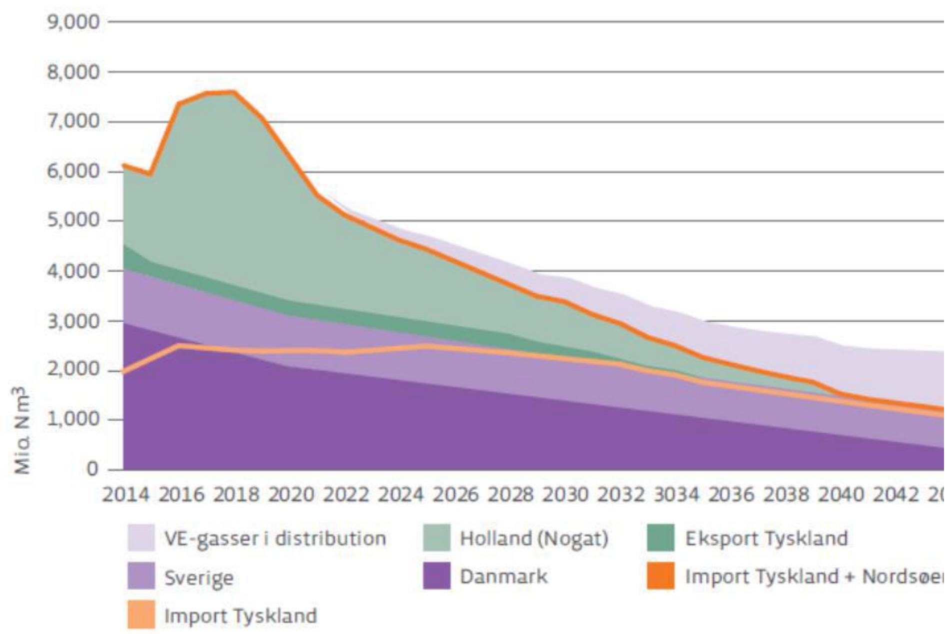


Figur 2. Gasforbrug i Energistyrelsens biomasse-scenarie



Figur 3. Gasforbrug i Energistyrelsens Bio+-scenarie

As it can be seen, the SNG (Synthetic Natural Gas = 2nd generation upgraded biogas) amounts in all four scenarios to between 50 and 65 PJ. The Biomass and Biomass+ are based on import of biomass and therefore not self-sufficient scenarios.



Figur 6. Gasforsyning 2014-2050 i vindscenariet.

From the graphic above it can be seen, implementation of the SNG in the gas system is to start already in 2020. At page 55 in "The Future Application of the Gas Infra-Structure" it is stated: In all the Energy Agency scenarios an expansion of biogas to about 42 PJ in 2050 is assumed. And at page 12 it is stated as an assumption in all four scenarios that all biogas is to be converted to SNG from 2035. By 2nd generation upgrading of biogas to SNG the energy contends is to be increased to 65 PJ.

The now completed MeGa-stoRE project indicates it will be possible for Danish companies to deliver CO_2 methanation plants from 2020, if the necessary financing for the research and development can be provided.

The new grand from ForskEL make the next step in this development possible, as described in the proposal MeGa-stoRE, Optimising and Upscaling.
But one issue is the technology another is the economy. Basically one can say, if payment is not obtainable for the benefit / service it is to store wind power and thus stabilize / balance the electricity network and enable an energy supply based 100% on renewable energy, then there is no business case for upgrading biogas by CO_2 methanation.

Electricity costs about 0.3 DKK/KWh and gas about the same or perhaps slightly less, so there is no difference to cover the costs of conversion from electricity to gas (CH_4).

But in Denmark, we have decided that we in 2050 shall be free of fossil energy and it is only possible by converting and storing of wind power. Therefore, today a grant is given to up-grading of biogas at 0,381 DKK/KWh in order to promote the expansion of biogas. One can say the upgrading subsidy is the amount available for running the methanation plant.

The chemical reaction, the stoichiometry, energy (HHV) and economy are shown in the table below and indicate a profit of 1.54 DKK/m³ CH_4.

Volumen and energy	CH_4	+	CO_2	+	$4H_2$	=>	CH_4	+	CH_4	+	$2H_2O$	+	Q	(%)
m3		1		+	1,4	=>		1						
m3	0,65	+	0,35	+	1,4	=>	0,65	+	0,35					
kWh	7,15	+	0	+	5,90	=>	7,15	+	3,85					
kWh		13,05				=>		11				+	2,05	0,16
Economy													**Grand**	**Profit**
DKK/m3, CH4 produced	3,6		+		1,77	=>		3,1		+			3,81	
DKK/m3, CH4 produced			5,37			=>				6,91				1,54

The assumptions for the calculation are given in the table below.

Heating value LHH CH4			10	kWh/m3
Heating value HHV CH4			11	kWh/m3
CH4 in biogas			0,65	
Heating value HHV biogas			7,15	kWh/m3
Heating value HHV H2			3,54	kWh/m3
Elektrolysis efficiency			0,84	
Electricity price			0,30	kr/kWh
Natural gas price			3,10	kr/m3
Natural gas price LHV			0,31	kr/kWh
Natural gas price HHV			0,28	kr/kWh
Biogas price			3,60	kr/m3
Biogas price LHV			0,36	kr/kWh
Biogas price HHV			0,33	kr/kWh
Biogas CH4 price LHV			0,55	kr/kWh
Biogas CH4 price HHV			0,50	kr/kWh
Upgrading grant LHV			0,1058	kr/MJ
Upgrading grant LHV			0,381	kr/kWh
Upgrading grant HHV			0,346	kr/kWh

The question is then; will a profit of 1.54 DKK/m^3 be sufficient to cover the depreciation, capital and O&M costs on the electrolysis and methanation plants? In order to answer that question the following calculations have been made.

Year	**2015**	**2020**	**2025**	**2030**
Scenario	EU report	EU report	EU report	EU report
	Central	Central	Central	Central
Price reduction ratio		-23%	-3%	-5%
10MW Electrolysis, mill. DKK	69,8	46,9	45,4	43,2
Methanation, mill. DKK	7,7	5,9	4,6	3,5
Investment ex. works mill. DKK	77,4	52,9	50,0	46,7
Installation 15% mill. DKK	11,6	7,9	7,5	7,0
Investment and installation mill. DKK	89,1	60,8	57,5	53,7
O&M: 2 + 5,7= 7,7% per annum, mill. DKK	6,0	4,1	3,9	3,6
Capital costs 4,0% per annum, mill. DKK	3,6	2,4	2,3	2,1
Depreciation pre annum in 10 years, mill.DKK	8,9	6,1	5,8	5,4
Costs in total per annum, mill DKK	18,4	12,6	11,9	11,1
CH4 production Nm3 per year	15.000.000	15.000.000	15.000.000	15.000.001
Costs, DKK/Nm3 CH4	1,23	0,84	0,79	0,74
Hydrogen, DKK/ Nm3 CH4	1,77	1,77	1,77	1,77
Biogas, DKK/Nm3	3,60	2,77	2,13	1,64
Productionsprice, DKK/Nm3 CH4	6,60	5,38	4,70	4,15
Upgrading grant, DKK/m3	3,81	3,81	3,81	3,81
Net price, DKK/ Nm3 CH4	2,79	1,57	0,89	0,34
Natural gas price, DKK/m3	3,1	3,1	3,1	3,1
Contribution margin, DKK/ Nm3 CH4	0,31	1,53	2,21	2,76
Return of investment %	6,69	48,88	73,02	95,64

It can be seen that the profit calculated above of 1.54 DKK is sufficient to cover the depreciation, capital and M&O costs, in the spread sheet calculated as (6.0 + 3.6 + 8.9)*1,000,000 / 15,000,000 = 1.23 DKK/m^3, leaving a contribution margin of 1.54 – 1.23 = 0.31 DKK/m^3 CH_4.
As can be seen from the return of investment, already before 2020 there will be room for reducing the upgrading grant. On the other hand even after 2030 an upgrading grant will be necessary, if all other conditions is unchanged, as can be seen by comparing the contribution margin by the upgrading grant.
In order to schedule the future development for CO_2 methanation, that matches the foreseen development of alkaline electrolysis in Denmark, and the wind and hydrogen scenario from the Danish Energy Agency, the roadmap below has been elaborated, using the same timing as the energy scenarios from the Energy agency.

Roadmap for CO2 Methanation plants (june 2014)

	2015	2020	2035	2050
Purifier	Flow density: 21 m3/m3 / h Operating temperature 20 °C Operating pressure: 1 Bar H2S in and out : 5.000 ppm - 10 ppb CAT lifetime (30ppb): 10.000 h	Flow density: 21 m3/m3 / h Operating temperature 20 °C Operating pressure: 1 Bar H2S in and out : 10.000 ppm - 10 ppb CAT lifetime (30ppb): 10.000 h	Flow density: 21 m3/m3 / h Operating temperature 20 °C Operating pressure: 1 Bar H2S in and out : 20.000 ppm - 10 ppb CAT lifetime (30ppb): 10.000 h	Flow density: 21 m3/m3 / h Operating temperature 20 °C Operating pressure: 1 Bar H2S in and out : 20.000 ppm - 10 ppb CAT lifetime (30ppb): 10.000 h
Reactor	Flow density: 2500 m3/m3 / h Operating temperature: 260 °C Operating pressure: 8,0 Bar CO2 in outlet: 2 % Ramp up time: 20 min CAT lifetime ???	Flow density: 5000 m3/m3 / h Operating temperature: 260 °C Operating pressure: 8,0 Bar CO2 in outlet: 2 % Ramp up time: 15 min CAT lifetime ???	Flow density: 5000 m3/m3 / h Operating temperature: 260 °C Operating pressure: 8,0 Bar CO2 in outlet: 2 % Ramp up time: 15 min CAT lifetime ???	Flow density: 5000 m3/m3 / h Operating temperature: 260 °C Operating pressure: 8,0 Bar CO2 in outlet: 2 % Ramp up time: 15 min CAT lifetime ???
System	H2: 1,4Nm3/h CH4: 1Nm3 /h @ 35% CO2 Purifier volume: 0,14 m3 Reactor volume: 0,0004 m3 Heat consumption at ramp up: 0,4 kW Heat generation: 0,0 kW System price: No	250 kW / 60 Nm3/h H2 electrolysis 43 Nm3/h CH4 @ 35% CO2 Purifier volume: 6,0 m3 Reactor volume: 0,009 m3 Heat consumption at ramp up 100 kW Heat generation: 85 kW System price: 4.500 Kr. / Nm3/h CH4 Modular and scalable unit design	10MW / 2400 Nm3/h H2 electrolysis 1710 Nm3/h CH4 @ 35% CO2 Purifier volume: 240 m3 Reactor volume: 0,344 m3 Heat consumption at ramp up: 4 MW Heat generation: 3,4 MW System price: 3.600 Kr. / Nm3/h CH4 Modular and scalable unit design	10MW / 2400 Nm3/h H2 electrolysis 1710 Nm3/h CH4 @ 35% CO2 Purifier volume: 240 m3 Reactor volume: 0,344 m3 Heat consumption at ramp up: 4 MW Heat generation: 3,4 MW System price: 3.100 Kr. / Nm3/h CH4 Modular and scalable unit design
MARKET INTRO	**MeGa-stoRE 1 Bio-gas upgrade Proof of concept plant**	**MeGa-stoRE 2 Bio-gas upgrade 0,25 MW size demo**	**MeGa-stoRE Com Bio-gas upgrade 10 MW size**	**MeGa-stoRE Com Bio-gas upgrade 10 MW size**

The now concluded MeGa-stoRE project is mirrored in the 2015 column and the new project MeGa-stoRE, Upgrading and Upscaling, is the next step towards the 2020 column.