Final report

1.1 Project details

Project title	MeGa-stoRE 2 – Phase 2
Project identification (program abbrev. and file)	2016-1-12393
Name of the programme which has funded the project	Originally ForskEL now EUDP
Project managing company/institution (name and address)	DTU Mekanik Danmarks Tekniske Universitet Institut for Mekanisk Teknologi Nils Koppels Allé Bygning 404 2800 Kgs. Lyngby
Project partners	Elplatek A/S NGF - Nature Energy Biogas A/S Green Hydrogen
CVR (central business register)	30060946
Date for submission	30.06.2019

1.2 Short description of project objective and results

English Version:
The objective was to build and test a small demonstration plant that can clean biogas for impurities and convert the CO_2-part of the biogas to CH_4 in a catalytic reactor as described in the following three subprojects:

- A new desulfurization technology that removes H_2S from biogas down to parts per billion (ppb) levels was developed and tested. The cleaning plant removed H_2S from the biogas down to non-detectable concentrations in a single step. The technology generates no waste, except for sulfur which leaves the plant as elemental sulfur and is reused as fertiliser.
- A 16 Nm^3/h hydrogen electrolyser was developed, and successfully longtime-tested under realistic operating conditions.
- A 10 Nm^3/h methanisation reactor was developed and tested under realistic operating conditions. The reactor was converting 85-90% of the CO_2 in the biogas into methane.

Dansk Version
Målsætningen var at bygge og teste et lille demonstrationsanlæg, der kan rense biogas for urenheder og omdanne kuldioxiden i biogassen til metan i en katalytisk reaktor; som beskrevet i de følgende tre underprojekter:

- En ny afsvovlingsteknologi som fjerner H_2S fra biogassen ned til ppb-niveau blev udviklet og testet. Rensningsanlægget fjernede H_2S i eet trin, ned til niveauer, der ikke var målbare. Teknologien genererer ikke noget affald udover svovlen, der forlader anlægget som elementær svovl, der bliver genbrugt som gødning.
- En 16 Nm^3/time hydrogen elektrolysator blev succesfuldt udviklet og langtidstestet under realistiske driftsforhold.

- En 10 Nm^3/time metaniseringsreaktor blev udviklet og testet under realistiske driftsforhold. Reaktoren omdannede 85-90% af kuldioxiden i biogassen til metan.

Figure 1: The picture is taken from top of one of the digestion reactors at Midtfyn Biogas (Nature Energy). The white 20' container in the lower right corner contains the electrolyser developed by GreenHydrogen. The blue container contains the gas-cleaning plant and the methanisation reactor developed by DTU MEK, Unicat Catalysts and Elplatek. The pipes and wiring between the containers and the biogas plant are also visible.

1.3 Executive summary

The executive summery is divided into the natural subprojects "Biogas Desulfurization", "Methane reactor" and "Electrolyser".

Biogas Desulfurization

The biogas desulfurization technology proved to work as intended during two campaigns at different biogas plants. The process was validated on real biogas and flows of 5-6 Nm3/h. Following the first successful campaign in the summer of 2017, the desulfurization technology was ready for the combined testing of the MeGa-StoRE 2 set-up. In the final version of the desulfurization technology, the system was optimized in regards to power consumption and proved to be competitive in OPEX with the cheapest desulfurization technologies currently on the market. Furthermore, the system was equipped for continuous operation without supervision, as components were added to make automatic operation possible, with only weekly supervision by trained personnel. The unsupervised operation was not tested. It is the plan to continue tests and developments of this novel cleaning technology with the goal of a commercialization within 3-5 years from today.

Methanisation Reactor

The reactor was successfully converting typically approx. 85-90% of the CO_2 into methane at Midtfyn Biogas. Various test data from the experiments performed under realistic operating conditions have been gathered. This is valuable information for further development and the future commercialisation of the methane reactor. Furthermore, the consortium has gained considerable experience and knowhow in designing and constructing container-sized chemical plants based on catalytic reactions. This is extremely valuable knowledge that will be used in our new projects. These projects are also based on converting biogas to more valuable products. We are at the present discussing and investigating how to continue the developments and tests and the later commercialization of the methanisation reactor. At the time of writing, it is still unclear how this part of the project will evolve and continue.

Electrolyser

Within the "MeGa-stoRE 2 phase 2" project, an alkaline electrolyser with a nominal hydrogen production rate of 16 Nm^3/h (which corresponds to a power consumption of approximately 70 kW) was built and tested at GreenHydrogen's facilities in the city of Kolding. This electrolyser was hereafter integrated with the methanisation unit at Nature Energy's biogas plant near the city of Ringe (see Figure). All hydrogen utilized by the methanation process during the field testing at Nature Energy's plant was supplied by the electrolyser. The test results from the long-term operating under realistic test conditions is valuable information for further developments and marketing of the electrolysers.

Figure 2. Moving the containers with the electrolyser (white) and cleaning plant and the methanisator (blue) to Midtfyn Biogas in late September 2018.

1.4 Project objectives

The name MeGa-StoRE is an acronym for "Methane Gas Storage for Renewable Energy" and describes very well the main concept idea behind this demonstration project. One of the challenges with increasing electrical renewable energy generated from wind turbines and solar panels is to find a way to store the energy temporarily in periods with excess production. We propose to store this excess energy as methane gas in the natural gas grid, see figure 3.

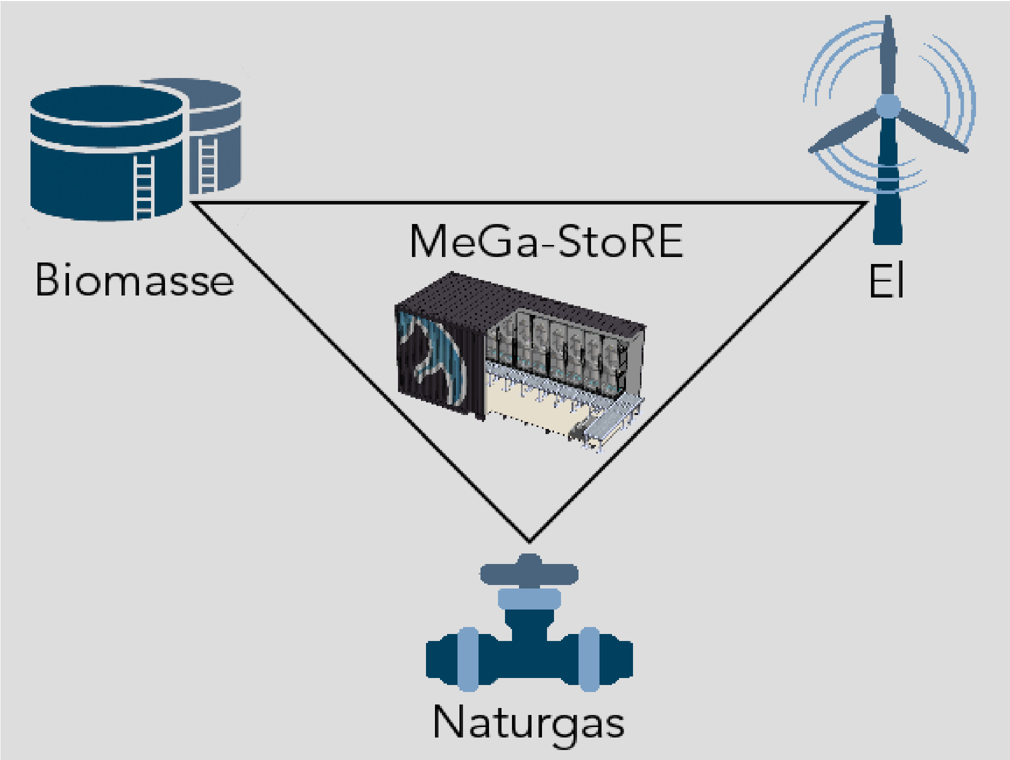

Figure 3: The concept idea for the MeGa-StoRE energy storage project. Excess electrical renewable energy is converted to methane gas and stored in the natural gas grid.

The project objective of Megastore 2, phase 2 was to build and test a small demonstration plant that can clean biogas for impurities and convert the CO_2 part of the biogas to CH_4 in a catalytic reactor.

- The project involved the development of a novel cleaning technology that can clean the biogas for impurities like H_2S, to avoid contamination and eventually deactivation of the catalyst. The conventional technologies were either not economically viable in a commercial set-up or not capable of cleaning the biogas down to the ppb levels of impurities that is needed to ensure long lifetime of the catalyst used in the methanisation reactor.
- A 16 Nm3/h hydrogen electrolyser had to be developed. The design for this electrolyser is based on a "downscaling" of bigger prototype alkaline electrolyser previously developed and tested by GreenHydrogen.
- The last component is the design, development and test of a 10 Nm3/h biogas methanisation reactor that converts CO_2 and H_2 over a catalysator to CH_4. The design for this reactor was originally intended to be an upscaling of a previously developed and tested reactor from the ForskEL-supported project MeGa-StoRE 1.

Overall, most of the objectives were met with good and satisfactory results. But it was not possible to meet all the deadlines in the project plan. We experienced several delays and therefore it was also necessary to extend the project a couple of times. Some of the reasons for these delays where:

- The development and construction of the methanisation reactor was more difficult than expected, and we ended up spending a lot more time on this part of the project than originally planned. See below.
- Getting a building permission from the local authorities to place and install the two test containers at Midtfyn Biogas. In hindsight we should probably have started this process much earlier. This is something that we will bring with us to future projects.
- Both test containers were placed and installed at Midtfyn at the same time. The main problem is that the methane reactor needs a lot of hydrogen to operate and can therefore not be commissioned before after the electrolyser was ready and commissioned; and the commissioning of the electrolyser took more time than planned. We should have started installing and commissioning of the electrolyser 3 months before the methanisation unit. This was even possible because GreenHydrogen had reported that their container was ready several months ahead.

Some of the subproject objectives are described more detailed below.

Biogas Desulfurization

The objective of the biogas desulfurization part of the project was to develop and implement a new desulfurization system in the MeGa-StoRE 2 container for field tests. The aim was to develop a cleaning method that would remove H_2S down to very low levels and not generate waste. The cleaning system was developed and utilized in the demonstration as planned. The desulfurization technology met the specification that no waste should be generated, as the sulphur extracted from the system (Figure 4) was found to be applicable as a high value fertilizer. Another specification was that the system should remove H_2S down to very low levels, preferably in the ppb range. Analysing H_2S down to such low contents proved very difficult. Within the MeGa-StoRE project, a gas chromatograph had been purchased for analysis, however, issues with the equipment meant that it was only used a few times for H_2S analysis. Instead, mobile analysis equipment was used which had a detection limit at 50 ppm. Results are shown in Figure 5, where also the power consumption is presented. Additional analysis was performed externally by Dansk Gasteknisk Center. In the external analysis, H_2S could not be detected and this system had a detection limit of 0.5 ppm. Unwanted trace compounds from the cleaning system was also found in the desulfurized gas, and these compounds will have to be removed in the future work.

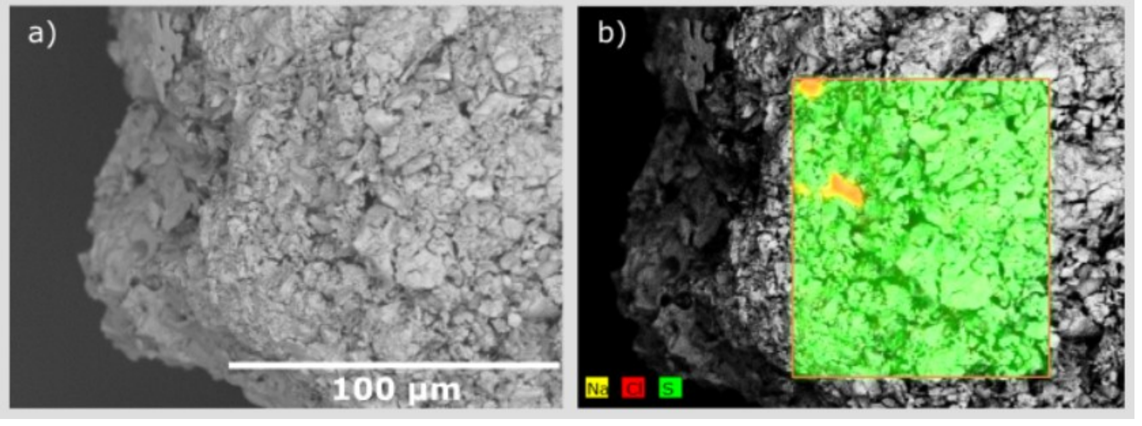

Figure 4: a) A scanning electron microscope (SEM) picture of sulfur extracted from the desulfurization system. b) An energy dispersion x-ray (EDS) analysis of the sulfur sample. The sample consisted almost entirely of sulfur with minor traces of NaCl. From: S.N.B. Villadsen, P.L. Fosbøl, M. Kaab, L.P. Nielsen, P. Møller, New Electroscrubbing Process for Desulfurization, unpublished work.

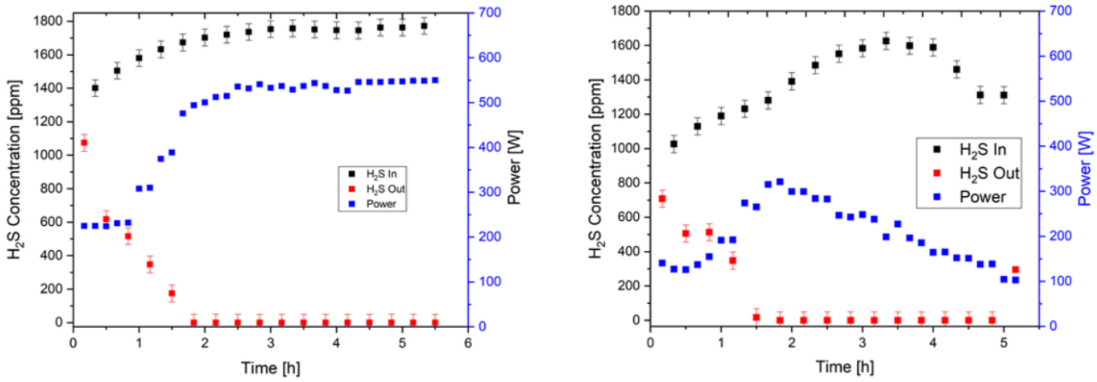

Figure 5: Results from two experiments with the desulfurization technology. For both days, it is observed that after an initial adjustment in power consumption, the H_2S content out of the system is decreased to non-detectable amounts. In the left figure, the power consumption and cleaning are kept constant. In the right figure, the power consumption is decreased to investigate the efficiency of the system. From: S.N.B. Villadsen, P.L. Fosbøl, M. Kaab, L.P. Nielsen, P. Møller, Pilot Plant Testing of New Electro-scrubbing Process for Biogas Desulfurization, unpublished work.

Methanisation Reactor

The methanisation reactor is basically a pressurised heat exchanger filled with a special developed catalyst. The operating pressure in this project is typically around 8 bar. The fundamentally catalytic reaction can be described with the equation:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \text{ (Sabatier reaction)}$$

This reaction is exotherm and generates a lot of heat that has to be removed. The temperatures in the reactor during operation are between 270°C and almost 550°C. The overall principle is sketched in figure 6.

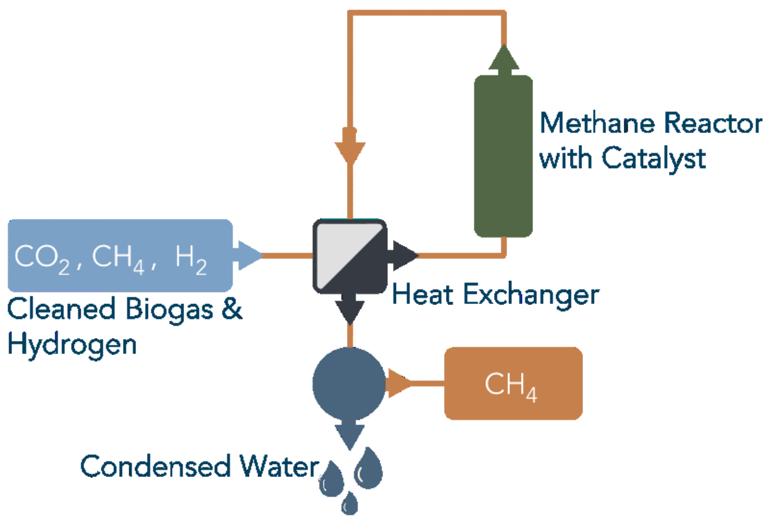

Figure 6: The figure shows the principle of the methanisation unit. The biogas (CO_2 & CH_4) and the hydrogen are preheated and enter the reactor with the catalyst. Here the CO_2 and H_2 react over the catalyst and become CH_4 and H_2O. Then the gas is cooled and the water is condensed and separated from the gas.

Even though the principle of a methanisation reactor can be easily described in a few sentences, it is not simple to design, construct and operate it. Working with highly exotherm processes at high pressure involving gasses like hydrogen and methane is bound to give some challenges. Furthermore, the catalyst is very sensitive to all the impurities that can be found in uncleaned biogas; especially sulfur.

The design and development of the 10 Nm^3/h biogas methanisation reactor for this demonstration project was intended as an upscaling of a previously developed and tested 1 Nm^3/reactor. This reactor had a very high conversion. The reactor was believed to be 100% adiabatic and the exhaust temperature of the gas leaving the reactor was measured to be around 270-300°C. This exhaust temperature matched the expected and calculated temperature for maximum conversion.

During the construction and test of the first 10 Nm^3/h reactor in the laboratory, it turned out that it was difficult to reach the conversion and keep the temperature low enough in the reactor with full gas flow. After several tests, including retesting the old reactor, it was discovered that the first version was not truly adiabatic. Due to the design (several parallel tubes) and the relatively small size there was a significant heat loss from the reactor walls to the surroundings. It was therefore concluded that some intermediate cooling in the 10 Nm^3/h reactor was needed to keep the final reaction temperatures close to the optimum 270-300°C. When this was realized this part of the project moved forward according to the new revised plans.

1.5 Project results and dissemination of results

This paragraph is divided into the following subsections "Biogas Desulfurization", "Methanisation Reactor", "Electrolyser" and "Dissemination of results"

Biogas Desulfurization

The development of the desulfurization system was done by a PhD student employed by DTU MEK with the PhD project starting in September 2016. Following testing in the laboratory in the fall/winter of 2016/2017 (Figure 7a), a pilot plant was constructed in the spring of 2017 (Figure 7b) and field-tested in a campaign at the Nysted biogas plant in the summer of 2017. Based on the successful results from the first campaign, an optimized pilot plant was constructed (Figure 7c) and implemented in the MeGa-StoRE 2 container.

Overall, the biogas desulfurization met the project objectives. The results from the pilot plant testing were very promising. The power consumption makes it comparable in OPEX with the cheapest available technology, while the other aspects of the cleaning, CAPEX, cleaning ability and no addition of oxygen, make the new technology better than that of the competitors. We expect to continue working with the desulfurization technology, as further development is required.

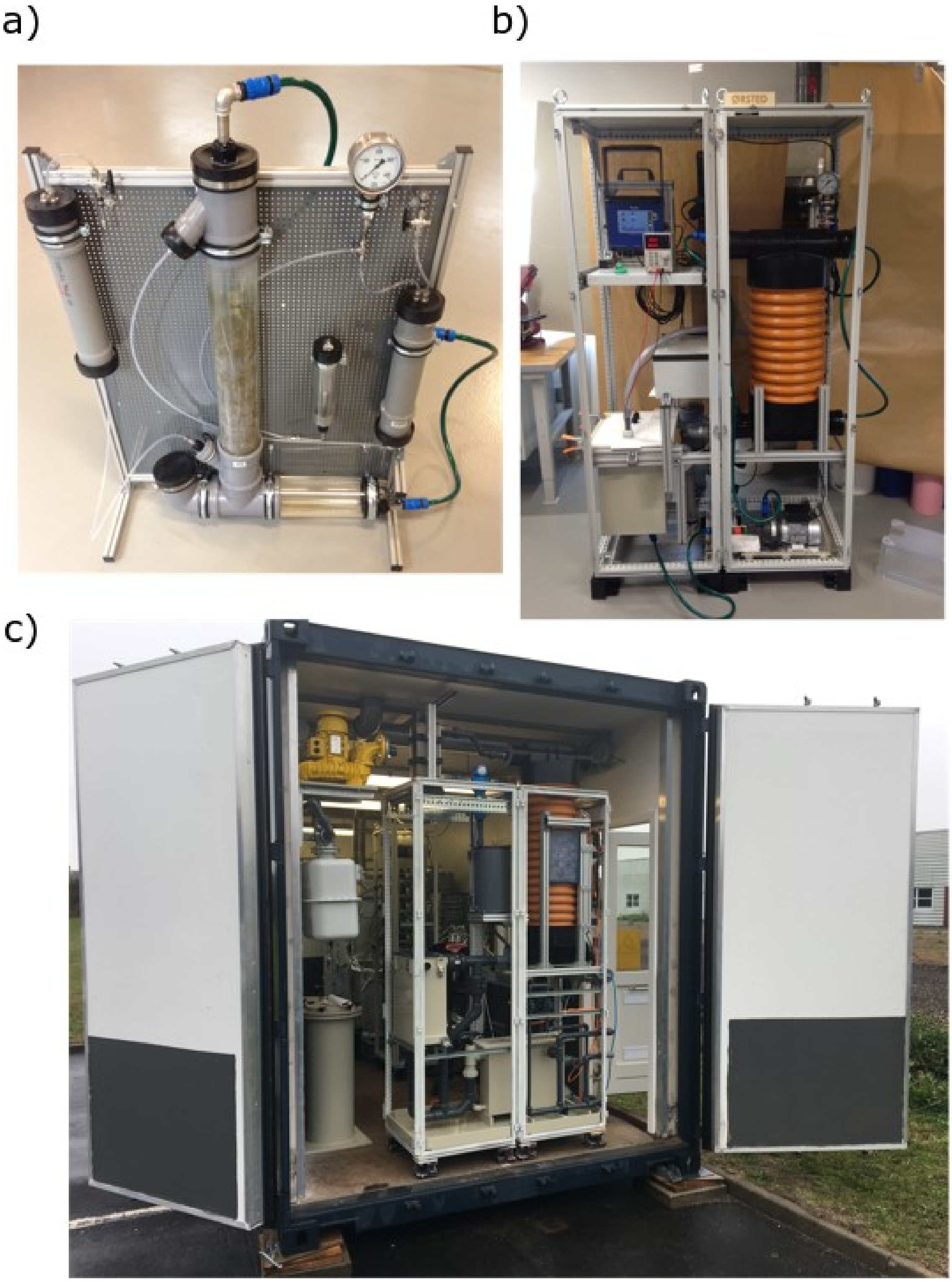

Figure 7: The biogas desulfurization units constructed and tested during the MeGa-StoRE project by PhD Student Sebastian Nis Bay Villadsen. a) The first unit constructed within 1 month of initializing the PhD project. b) The first unit to be tested on authentic biogas at a biogas plant. c) The unit is currently being tested at the Midtfyn biogas plant.

Methanisation Reactor

The design and construction of the container with the methanisation unit (and cleaning plant) involved a lot of measures. The main part is of course the design and test of the actual methanistaion unit in the laboratory. This part has already been briefly described and will be elaborated later. But there are many other actions to be taken, a few of these are briefly described in the following:

1. Build a container with the needed infrastructure (ventilation, electricity etc).
2. Design and construct the biogas delivery system for both the cleaning plant and the methanisation reactor. This involves among others:
    a. Automatic shutdown valves on the outside ensuring that the gas supply is shut off in case of an alarm or power shutdown.
    b. Design and construction of additional gas filters (activated carbon) to ensure continuous operation of the reactor in case of service on the cleaning plant.
    c. An ATEX-approved compressor to boost the biogas pressure to the needed 10 bars for the catalytic reaction in the methanisation unit. In combination with this, it was necessary to design a special cooling and bypass system to avoid overheating of certain parts during special operation conditions.
    d. Design and build the automatic gas delivering system for the reactor. This was built mainly with mass flow controller and valves from Bürkert.
3. Design and build the electronics cabinet that controls the compressor, side channel blower, heating elements, valves, oil pumps etc.
4. Design and build the PLC and software for controlling the above; including a user-friendly computer interface and data collection.
5. Install an inline product monitoring system. We chose to install an MRU SWT 1000 gas analyser that can measure on H_2S, CH_4, O_2, CO_2. There where measurement points before the gas cleaning plant (raw biogas), before the methane reactor (cleaned biogas) and after the methane reactor.
6. Build an independent hardwired safety circuit that involves two sensors for flammable gasses, a H_2S sensor, a fire sensor, exhaust alarm for both blowers (if too low), two (outside) emergency breakers. In case of any alarm, the power and gas shut off automatically.
7. Make a comprehensive ATEX description, evaluation and action plan. For this task we decided to involve a professional ATEX guidance company to ensure that the safety was not compromised in any way.
8. Make a complete and comprehensive safety and operating description for the Danish safety authorities.

As mentioned, the project had some challenges during the early phases of the design and development of the 10 Nm^3/h reactor. But as soon as the main reason for the problem was discovered and a solution was identified, the construction of the reactor and substeps proceeded with no major problems or delays.

Figure 8 shows the uninsulated reactor together with the cooling system. As to the reactor from the Megastore 1 project, it was believed that the product gas and water were cooled after the entire reaction process was finished. As mentioned previously this was not the case. Therefore, the rector in Megastore 2 has been designed and constructed with intermediate cooling of the product gas during operation. This ensures that the operating temperatures do not exceed the temperature where coke is forming and/or between the catalyst. Part of this cooling system is seen as the coils in figure 8. The heat exchangers are working with hot oil at temperatures up to maximum 400°C. The oil is cooled down to 200°C via an outside heat exchanger seen in figure 10 and returned to the hot oil drum seen in picture 8 to the left.

In this test rig, the reactor is made from four small reactors with a volume for the catalyst of 2 litres each. The demonstration reactor also involves compensation heaters that compensate for the heat loss from the walls of the reactors. This ensures that the results from the reactors can be regarded as being real adiabatic reactors and that the results are scalable when we decide to move to a much bigger next phase. I.e. that we will not make the same mistakes as going from Megastore1 to Megastore 2.

The design and construction of the new reactor was done in close collaboration between DTU MEK, Unicat Catalyst and Elplatek A/S.

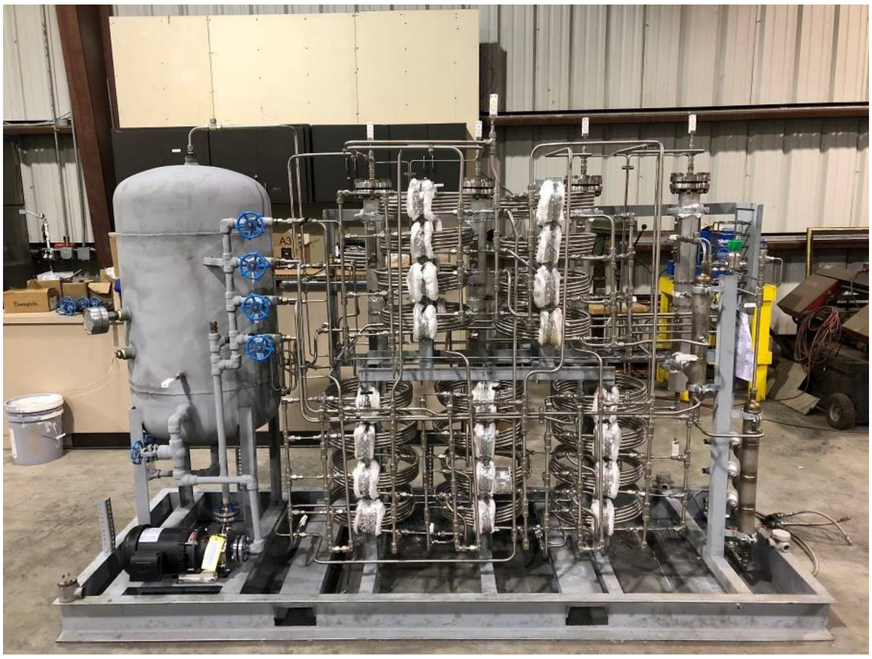

Figure 8: The picture shows the methanisation unit before all the parts where insulated. To the left there is an oil tank and pump below for the cooling oil that operates at temperatures between 200°C and up to 400°C. The coils are tube heat exchangers.

Figure: 9: The picture shows the methansation unit just after it was moved into the container. Following this step, the electric control cabinets, gas control cabinets, ATEX biogas compressor, biogas cleaning plant, gas analysers etc. were installed. The reactor was placed on four rails. This ensured that it was possible to do service on both sides, if necessary. During normal operation the reactor is placed close to the wall to the right.

Figure 10: The container with the biogas cleaning plant and the methanisation unit from the outside. Hanging on the side, it is possible to see the heat exchanger for the oil cooling system. On the end there is a cooler for the compressor. In a future commercial system, the excess heat will be reused or recovered for e.g. district heating. Especially the excess heat from the methanisation reactor is of a high quality (above 200°C). It is also possible to see two 50 mm OD pipes. One pipe is the "dirty biogas" going into the container from one of the digesters at Midtfyn Biogas (Nature Energy). The other pipe is the clean and upgraded biogas going back to another digester. This is almost pure methane. Above the door (left) there is a small box containing the automatic shutdown valves that will close for the gas in case of alarm.

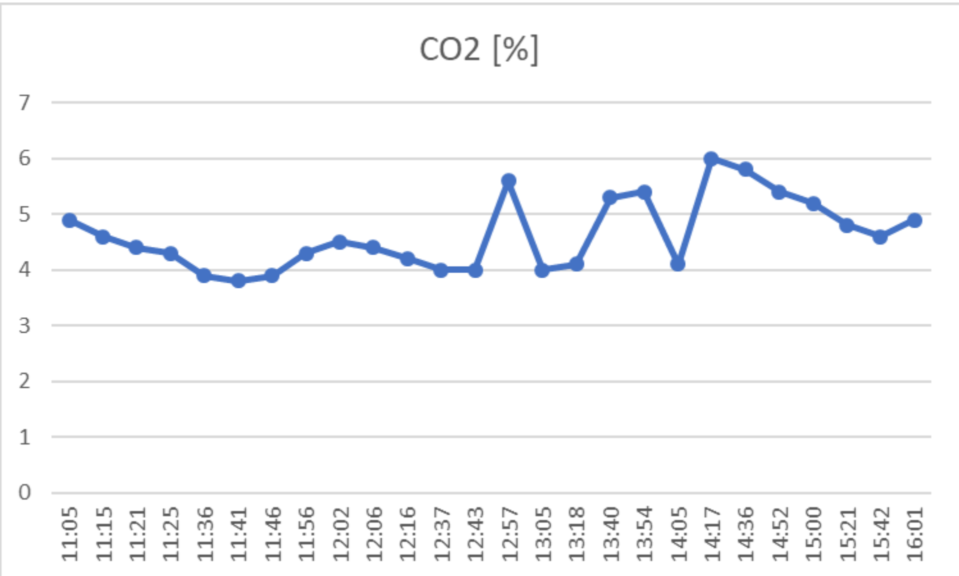

Figure 11: Graph shows some typical results from the methanisation unit during a 5-hour tests at Midtfyn Biogas. It shows the percentage of CO_2 of the total gas leaving the reactor measured on an MRU SWT 1000 gas analyser. The total biogas flow in this particular experiment was 6.5 m^3/h. The biogas contained on average 40% CO_2. This gives a conversion of around 85-90%. This is very satisfactory results.

Figure 11 shows some of the results from tests at Midtfyn Biogas. The experiments made in the relative limited test period (one month) gave some good and very valuable results. The conversion was around 80-95% in many of the test regimes. This is more than enough for a commercial application.

We had hoped to have a little more testing and optimizing time. But due to the delays in the project of more than one year and the fact that Nature Energy needed the space for expanding their facility (a construction team was waiting for us to leave the site) we had to discontinue the tests and move the containers.

But all in all, the methanisation part of project has been a technical success. Commercially we are not quite there yet. We need a little more design optimisation and probably also some further testing before we have a commercial product. At the time of writing, it is still unclear how this part of the project will evolve and continue. We are trying to find partners and sponsors and even a potential costumer.

We also plan to use the considerable experience and know-how in designing and constructing container-sized chemical plants based on catalytic reactions gained during this project. We are now investigating the possibility to produce methanol from biogas in another project (Biorefuel co-founded by EUDP). If this project gives the expected results, we will try to make a small demonstration plant that will be tested at Lemvig Biogas.

Electrolyser:

The electrolyser built for the "MeGa-stoRE 2 phase 2" project was developed during the project "HyProvide Large-Scale Alkaline Electrolyser (MW)" (EUDP 11-II, 64011-0105) during the years 2011 to 2015. The major achievement of that project was the development of a high-efficiency, low-cost and modular electrolyser unit (shown in Figure 11) with a hydrogen production capacity of 60 Nm3/h. The modular nature of the electrolyser unit makes it ideal for hydrogen production plants with capacities in the range of 60 Nm3/h to 1000Nm3/h.

Within the "HyProvide Large-Scale Alkaline Electrolyser (MW)" project, a single prototype of the electrolyser unit was built and thoroughly tested in GreenHydrogen's laboratory in Kolding. In the "MeGa-stoRE 2 phase 2" project, a more or less identical electrolyser unit was built and installed in a 20 ft. container (see Figure 12 to 16). The hydrogen production rate required in the "MeGa-stoRE 2 phase 2" project is 16 Nm3/h (and not 60 Nm3/h), hence, electrolysis stack and power supply were downsized accordingly. The "MeGa-stoRE 2 phase 2" electrolyser container represents a turnkey 16 Nm3/h electrolyser system with all required components including:

- Electrolyser unit. Splits water into hydrogen and oxygen as well as performs post processing necessary for the gasses, so that the hydrogen that is released from the unit does not contain any residual electrolyte, water or oxygen.
- Water pressurization module. Delivers water at high pressure to the electrolyser unit.
- Water treatment module. Purifies the tap water by means of a reverse osmosis plant followed by an ion exchange filter.
- Main control module. Contains programmable logic controller (PLC) and control electronics.
- Power supply module. Converts AC power from the electricity grid into DC power to be supplied to the electrolyser stack.
- Cooling. Removal of excess heat from the electrolysis process. Cooling of the hydrogen.
- Storage module. For storage of hydrogen.
- Room installations. Including safety sensors, ventilation, nitrogen for safe shutdown, etc.

The main efforts undertaken in the "MeGa-stoRE 2 phase 2" project regarding the alkaline electrolyser are the following:

- **Design, construction, and installation of container.** As mentioned above, the starting point for the electrolyser was a prototype installed and operated in GreenHydrogen's laboratory. Hence, effort was put into the design and construction of a container containing a turnkey electrolyser.
- **Pressure Equipment Directive (PED) approval.** The electrolyser operates at pressures up to 40 bar. Furthermore, electrolysis stack and other vessels in the electrolyser are several hundred litres in volume. By law such equipment must comply with the European Pressure Equipment Directive (PED) 2014/68/EU. The necessary documentation was prepared. This documentation together with the actual construction (complete electrolyser) was reviewed and inspected by a third part (notified body).
- **Safety system and procedures.** Being the first large scale electrolyser to be operated outside GreenHydrogen's laboratory, increased emphasis was put on the capabilities and robustness of the electrolyser safety system. The electrolyser contains a comprehensive surveillance system that stops the system if any anomaly is monitored. Hydrogen and oxygen are automatically evacuated, hereafter the system is flushed with nitrogen in order to bring the system to a safe state.
- **Autonomous operation.** In order to be useful, the electrolyser should be able to operate autonomously (unmanned). E.g. automatically start when there is need for hydrogen and otherwise stop. Such operation scheme was implemented and tested in the "MeGa-stoRE 2 phase 2" project.
- **Long-term testing.** Long-term testing is needed in order to verify long-term stability and proper performance of the electrolyser system. Within the "MeGa-stoRE 2 phase 2" project, the electrolyser was operated for a total of 2000 hours. The electrolyser was operated also at times when hydrogen was not needed by the methanation system. The test results are discussed in the next section.

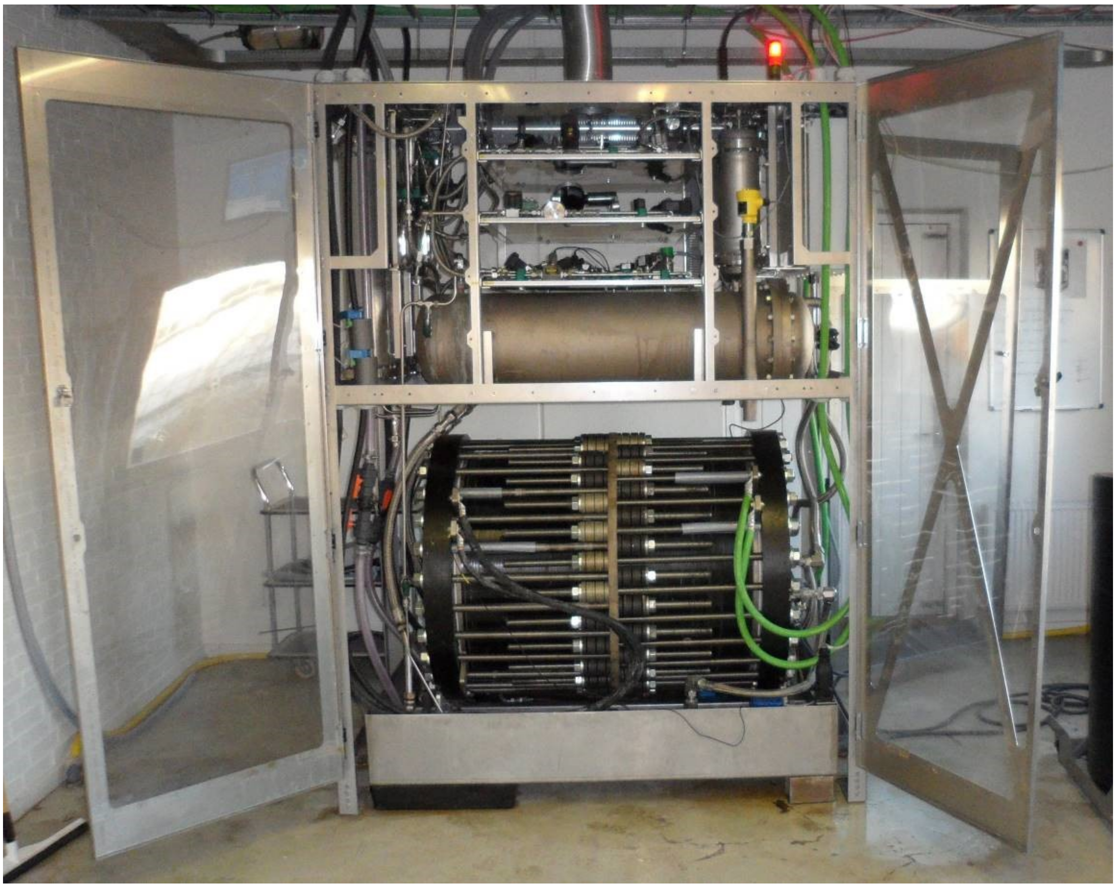

Figure 11. Prototype of a 60 Nm3/h alkaline electrolyser unit developed within the project "HyProvide Large-Scale Alkaline Electrolyser (MW)" during the years 2011 to 2015.

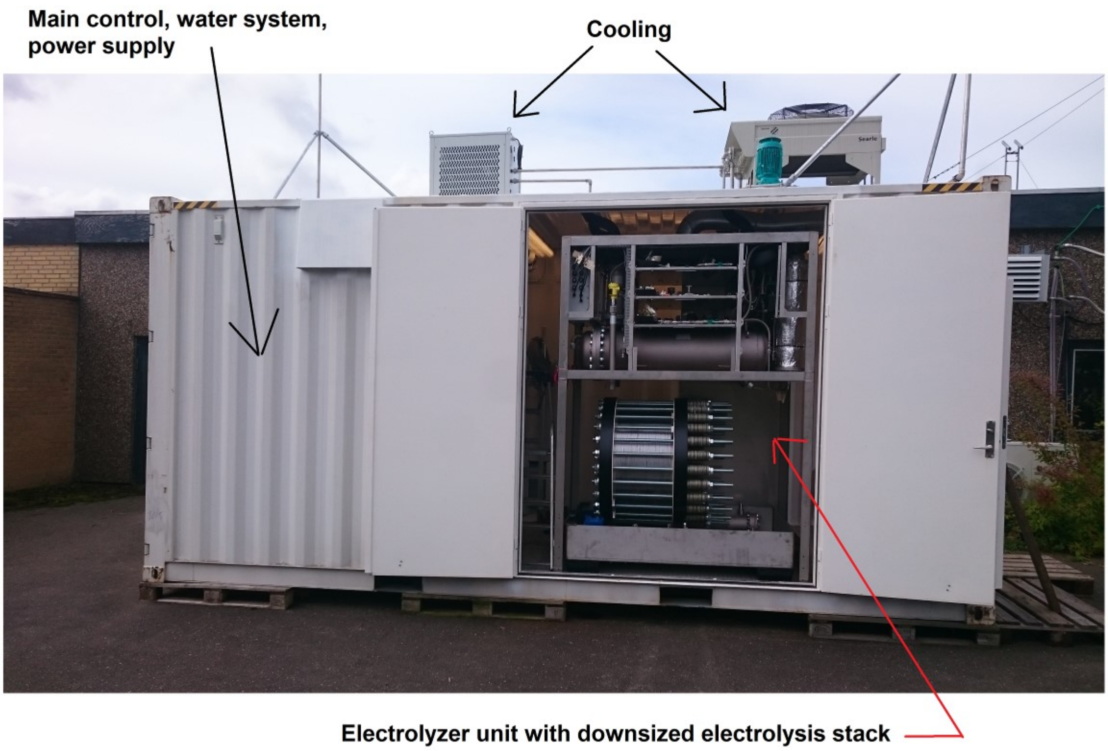

Figure 12. Turnkey 16 Nm3/h "MeGa-stoRE 2 phase 2" electrolyser installed in a 20 ft. container. The downsized electrolysis stack contains 40 cells, each with an active area of 3.000 cm^2.

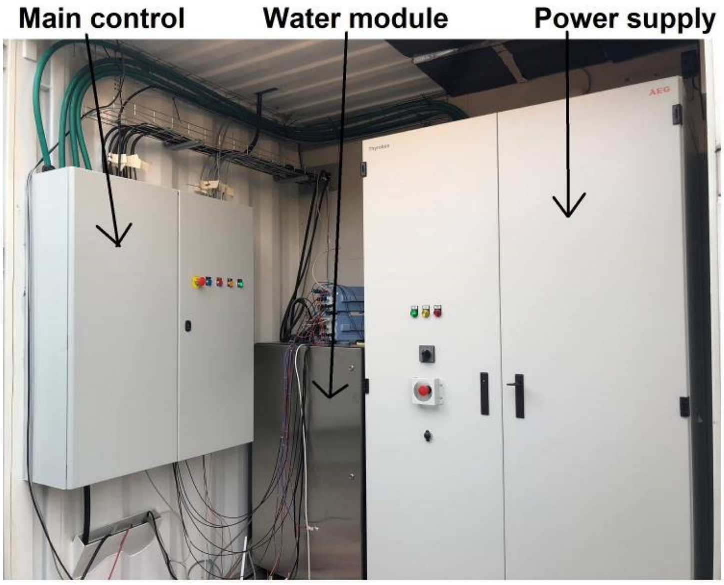

Figure 13. For safety reasons main control, water system and power supply are installed in a separate room in one end of the container.

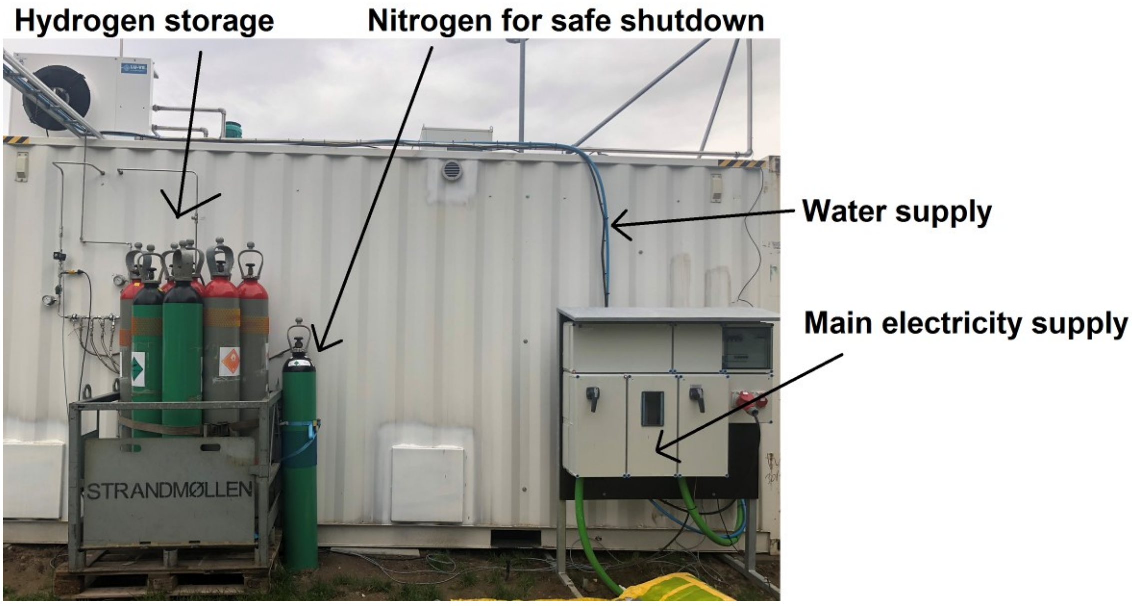

Figure 14. "MeGa-stoRE 2 phase 2" electrolyser installed at Nature Energy's site. Hydrogen storage and nitrogen are installed outside the container. Water and mains electricity are the only supplies needed by the electrolyser.

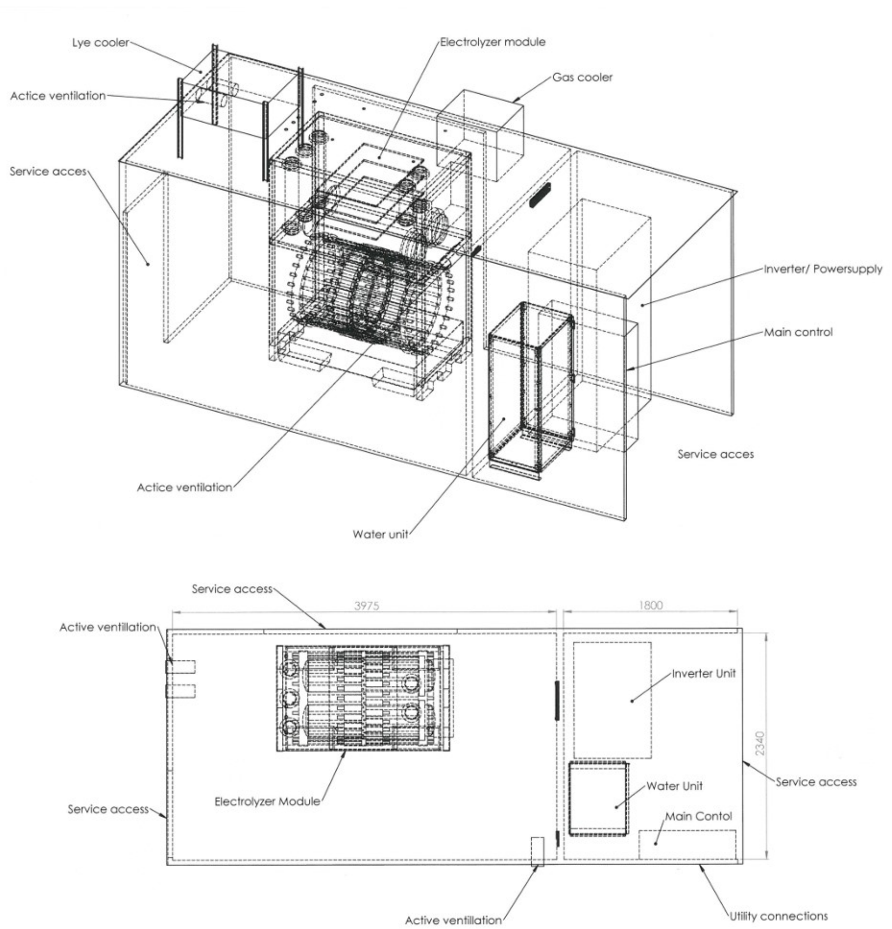

Figure 15. Drawing of the "MeGa-stoRE 2 phase 2" electrolyser. The drawing shows a full-size stack with 110 cells.

Dissemination of results

The results from the MeGa-StoRE 2 project have been disseminated in several ways. Some of these are described briefly here:

Figure 17: The picture is from the IDA all-day event "Omdannelse af vind-/solenergi til gas/brændstof og derved til det fossilefrie energiforsyning" at Elplatek A/S on 16th November 2016.

- **Workshop/Conference:** An all-day IDA event "Omdannelse af vind-/solenergi til gas/brændstof og derved til det fossilefrie energiforsyning" at Elplatek A/S in Horsens where results from MeGa-StoRE2 were presented and discussed with the guests. The arrangement took place on 16 November 2016. See figure 17.

- **Workshop/Conference:** On 19 November 2018 "Den danske brint- og brændselscelledag" was held at Syddansk Universitet in Odense. More than 80 people participated. GreenHydrogen gave a presentation of the results achieved during the EUDP project "H2Cost-2". The "MeGa-stoRE 2 phase 2" project was briefly described in GreenHydrogen's presentation due to its close relation to the "H2Cost-2" project.

- **Scientific Paper:** ChemSusChem 2019, 12, 1 – 8: "The Potential of Biogas; the Solution to Energy Storage". Sebastian N. B. Villadsen, Philip L. Fosbøl, Irini Angelidaki, John M. Woodley, Lars P. Nielsen, and Per Møller

- **Conference:** 6th International Conference on Renewable Energy Gas Technology (REGATEC). 20-21 May 2019 in Malmö, Sweden. "Biogas Desulfurization within the MeGa-StoRE (Power-to-gas) Project". Sebastian Nis Bay Villadsen, Philip Loldrup Fosbøl and Per Møller.

- **Conference:** EUBCE, 27th European Biomass conference and exhibition, 27-30 May 2019 in Lisbon, Portugal. "Storing Renewable Energy by Biogas Upgrading". Villadsen, Sebastian Nis Bay; Fosbøl, Philip Loldrup; Ramussen, Jan Pihl; Rønne, Anders; Svendsen, Jonas Clement Gonge; Møller, Per.

- **Conference:** International Methanol Conference (8. – 10. May 2017 in Copenhagen, Denmark). "Cleaning of Biogas for Synthesis Purposes" by Sebastian Nis Bay Villadsen.

Figure 18: Pictures from conferences. Left: The EUBCE conference in Lisbon. Right: The Regatec conference in Malmö.

The following scientific papers are expected to be submitted and published within 2019 or early 2020:

- **Scientific Paper:** "New Electro-scrubbing Process for Desulfurization" (Submitted). Sebastian Nis Bay Villadsen, Philip Loldrup Fosbøl, Malene Ahrensberg Kaab, Lars Pleth Nielsen and Per Møller.

- **Scientific Paper:** "Pilot Plant Testing of Novel Electro-scrubbing Process for Biogas Desulfurization" (Finalizing). Sebastian Nis Bay Villadsen, Philip Loldrup Fosbøl, Malene Ahrensberg Kaab, Lars Pleth Nielsen and Per Møller

- **Scientific Paper:** "Data from the field tests at Midtfyn biogas plant with the electroscrubber" (In the works). Sebastian Nis Bay Villadsen, Philip Loldrup Fosbøl, Jan Pihl Rasmussen, Jan Pedersen, Randi Neerup, Malene Ahrensberg Kaab, Peter Westermann, Lars Pleth Nielsen and Per Møller

- **Scientific Paper:** "Data from the field tests at Midtfyn biogas plant with the methanation unit" (In the works). Rohit Gaikwad, Jan Pihl Rasmussen, Sebastian Nis Bay Villadsen, Philip Loldrup Fosbøl, Jan Pedersen, Lars Pleth Nielsen and Per Møller

- **Scientific Paper:** "Review of electroscrubbers" (In the works). Sebastian Nis Bay Villadsen, Philip Loldrup Fosbøl, Lars Pleth Nielsen and Per Møller

Furthermore, throughout the project, several potential customers and business partners have visited the construction sites (GreenHydrogen.dk and Elplatek A/S) and the test site at Midtfyn Biogas (Nature Energy).

1.6 Utilization of project results

Biogas Desulfurization

The desulfurization was a success, and it is expected that it will be further developed. The technology is a combination of electrochemistry and gas-scrubbing, i.e. electro-scrubbing. Currently, there are no Danish companies that have similar technologies commercially available, and therefore two of the project partners (Elplatek and DTU) have found two new partners (Union and Dansk Gasteknisk Center) with whom they aim to commercialize the technology. Due to the high risk involved in developing the first commercial electro-scrubber, the partners have applied for funding at EUDP for a demonstration project (BE-Clean).

The desulfurization process has a large potential since it can be applied to all biogas plants, in both Denmark and other places. The pilot plant was comparable in OPEX with the cheapest available technology, and it is expected that further development will make the technology even cheaper to operate. The possibility to scale to biogas plant size makes it applicable to all biogas plants.

If the desulfurization technology is commercialized, it could help the Danish biogas industry and therefore the Danish energy policy objectives. The new cleaning process is especially suited for biomethane production, as it does not add oxygen to the desulfurized biogas. Therefore, implementation of the new technology could help improve the availability of the biomethane in the Danish natural gas grid.

The PhD student utilized the results from the MeGa-StoRE 2 project throughout his project. Initially employed at the mechanical department at DTU, he engaged in activities with the chemical engineering department at DTU as a supervisor (Associate Professor Philip Loldrup Fosbøl) from the Center for Energy Resources Engineering was added to the supervision team. The PhD student supervised two interns and one student during the MeGa-StoRE 2 project.

Methanisation Reactor

The design and construction knowhow, together with the test results will be used for further development of the methanisation reactor. The demonstration plant produced some good test results; but the test also showed room for improvements in the design and construction.

Electrolyser

In 2018, GreenHydrogen lauched its alkaline electrolyser (HyProvide A-series) as a commercial product. In 2018, a single electrolyser was sold to an operator of a hydrogen refueling station in Sweden. This system is a containerized 60 Nm^3/h electrolyser. The electrolyser system is similar to the turnkey electrolyser container developed in the "MeGa-stoRE 2 phase 2" project. Three similar systems are to be delivered to customers in 2019.

1.7 Project conclusion and perspective

Biogas Desulfurization

The new biogas desulfurization process proved successful as it could remove H_2S down to non-detectable concentrations in a single step, independent of the initial concentration. The process did not consume any chemicals and did not generate any waste, as only electricity was used. The quality of the sulfur extracted from the system allows for a use as a high-value fertilizer. The process will be developed further in the BE-Clean project, should it receive funding from EUDP.

Methanisation Reactor

A 10 Nm^3/h methanisation reactor was developed and tested under realistic operating conditions. The reactor was successfully converting 85-90% of the CO_2 in the biogas into methane. The tests also showed a need for some redesigns and maybe even further tests. The consortium is at the moment working on a plan to find a solution for this.

Electrolyser

The "MeGa-stoRE 2 phase 2" project has demonstrated that the alkaline electrolyser is functioning as expected and can be used for a complete turnkey electrolyser system ready for market introduction. Next development steps are to optimize costs and performance (capex and opex) in order to meet the long-term market targets.

Annex

Relevant links

DTU Mekanik: https://www.mek.dtu.dk/
Elplatek A/S: http://www.elplatek.dk/
GreenHydrogen.dk: http://greenhydrogen.dk/
Nature Energy: https://natureenergy.dk/
Unicat Catalyst: https://www.unicatcatalyst.com/