Final report

Optimization of 2nd generation alkaline electrolysis
EUDP file no. 64010-0419

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Final report
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Content

1. Introduction

Background for the need for new electrolyser technology is the changing energy system, in Denmark as well as globally, with the goal of becoming more independent of fossil based energy sources, of becoming more self-sufficient in the energy supply and with renewable energy providing an ever increasing share of the energy supply. Energy storage is key in energy systems with a large share of renewable energy and converting power to gas through electrolysis is a key enabling technology for new energy systems based on renewable energy to become a reality. Power produced from renewables can be stored as hydrogen and be converted back into power when needed or utilized as CO2-free transportation fuels.

Alkaline electrolysis has been known and used for many years but to become commercially attractive, the production and investment costs have to be reduced and the electrolyser must be adapted to the requirements of an energy storage solution.
A reduction of the investment costs may be achieved by increasing the operational pressure and temperature of the electrolyser. This will result in production of pressurized hydrogen and oxygen, improved electrical efficiencies and increased current density, and thereby increased hydrogen production rate in regards to the investment.

The first step towards a product was mainly research and proof of concept. With the support from EUDP, GreenHydrogen.dk, AU-Herning (previously known as HIRC) and DTU as the main partners, the consortium[1] was able to conduct the first project from 2009-2012. The project was titled "2nd Generation Alkaline Electrolysis", EUDP file no. 63011-0200 and was planned as the first phase of several phases[2] towards the development of the technology for the market.
The purpose of the first project was to develop 2nd generation alkaline electrolyser technology with main development focus on: increased electrode efficiency, increased operation temperature, higher operation pressure, electrolyser stack architecture, modular design of electrolyser and the project was concluded with a demonstration of a 20 kW electrolyser system.

The first project showed promising results[3] and to follow up phase two of developing a competitive electrolyser system started.

This phase two project is called "Optimization of 2nd generation Alkaline Electrolysis" project, and the project has been supported by EUDP.

This report provides the results of the "Optimization of 2nd generation Alkaline Electrolysis" project conducted from Q1 2011- Q1 2014, EUDP file no. 64010-0419.

1 The entire consortium consisted to: Aarhus University Business and Social Science – Centre for Energy Technologies (CET); Technical University of Denmark – Mechanical Engineering (DTU-ME); Technical University of Denmark – Energy Conversion (DTU-EC); FORCE Technology and GreenHydrogen.dk.
[2] See the description of following phases for the development of technology for the market in section 2.1
[3] http://www.energiforskning.dk/da/projects/detail?program=7&teknologi=64&field_bevillingsaar_value=&start=&slut=&field_status_value=All&keyword=&field_company_nid=All&with_partners=0&field_partner_nid=All&page=52

In the project period GreenHydrogen.dk also participated in the projects listed below. These projects have also contributed to findings and results from this project.

- FCpoweredRBS (EU / EUDP project)
- MW electrolysis (EUDP and HTF)
- HyProvide HRS (EUDP project)

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2. Scope

The project was started at the beginning of 2011 with the main goal of developing a prototype electrolyser system based on the results achieved in the first project "2nd Generation Alkaline Electrolysis". More specifically, the goal was to further develop process modules; implementing findings from work done in DTU´s laboratory and testing production methods to optimize the cost of the electrolyser unit.

When planning the project, the project work was split into 7 Work Packages (WP's listed below). This report will run through each WP and summarize the goals set and describe what has been accomplished. Challenges and opportunities for further improvements will be discussed. Finally, a conclusion on the project will be drawn and recommendations on following steps will be given.

The work packages:

WP1: Specification of complete electrolyser unit
WP2: Approvals
WP3: Product development
WP4: Development of production methods
WP5: Construction and testing
WP6: Demonstration
WP7: Project management

2.1 The development of the technology for the market

To give the reader of this report a better understanding of where in the process of "developing the technology and preparing it for market" this project is, the following section shortly describes the phases of the project.

- Phase 1 (not part of this report, done):
  Has mainly been research and built up of a first "mock-up" model as concept verification. Development of electrode surfaces, stack components and process modules has also been part of the first phase.
- **Phase 2 – this project -** Product development
- Phase 3 (Planned for - not part of this report)
  Product maturing and alpha production of 3 to 5 systems. The main focus will be on getting the product matured and using the first 1-2 units for approvals and testing preferable with installation in Denmark.
- Phase 4 (Planned for - not part of this report)
  Beta-testing and manufacturing of 5-10 units, train manufacturing staff and global testing.
- Phase 5 (Not part of this report)
  Ramp-up of production if market is requesting
- Phase 6 (Not part of this report)
  Market introduction and launching of product globally

3. Project summary, conclusions and recommendations

The project “Optimization of 2nd generation alkaline electrolyser” has been conducted in the period 2011 to 2014 and has been supported by the EUDP.
Focus has been on bringing the results from the first project “2nd generation alkaline electrolyser” from the laboratory to a demonstration unit and to further develop and optimize the technology.

During the project the electrolyser system has been optimized on several points including Balance Of Plant (BOP), stack design, process design, cooling and controlling. New concepts for circulating electrolyte have been developed along with new software for handling pressure and water balance more accurately. The stack and the electrodes have been taken to the next level in terms of efficiency, durability, production methods and approvals.
The development has resulted in an electrolyser system ready for demonstration with CE-approvals. The system is not ready for commercialization yet. Long time testing is still necessary to find weaknesses and system errors and cost reductions must be done before placing the system on the commercial market.

The goals set before project start for the demonstration system to be built and the actually achieved parameters are as following:

Goals	Achievements
• Modular design in an 800x1000x2000mm cabinet	• Modular design integrated in a 800x1000x2000mm cabinet
• Hydrogen production of 4Nm^3/h (2 stacks)	• Hydrogen production capacity 3Nm^3/h (2 stacks)
• Stack production capacity of 2Nm^3/h	• Stack production capacity of 2Nm^3/h can be build
• Current density 200mA/cm2	• Current density up to 300mA/cm2
• Efficiency of 90% for the stack at 100°C	• Efficiency measurements of over 90% at 80°C
• System pressure of 30bar	• System pressure 30bar
• Operational temperature of 100-150°C	• Operational temperature 80°C
• Power consumption of 4,3kW/Nm^3	• Power consumption of total system needs to be verified

Not all goals have been met for the demonstration system:

- The production capacity of the electrolyser demo unit is lower than what was planned for but the capacity can be achieved after further work.
- The operational temperature has not exceeded 100°C. However as electrodes tested in a stack showed efficiency of over 90% at 80°C, it is therefore not necessary to reach 100°C yet even though it will further improve the system efficiency. The research and know how gained in this project enables GreenHydrogen.dk to increase the temperature in the system higher than 80°C and maybe up to the limit of the diaphragm. However, a higher system temperature means other production methods and higher investment cost and other alloys have to be expected. Thus, the next phase of getting the electrolyser ready for marked should include a cost benefit analyses to show if a higher temperature will give value enough to change alloys and production methods.

The project has taken Greenhydrogen.dk's kW electrolyser system to the next level and made it ready for demonstration projects. Knowledge and experience have been gained which will not only benefit the kW system development but also Greenhydrogen.dk's MW electrolyser development. This project has delivered a system ready for the next phase of testing, cost optimizing and demonstration.

The recommendation for further work with the electrolyser system includes:

- Cost optimization, an important task to engage in the next phase to make the electrolyser competitive

- Increasing production capacity by implementing "zero gap" electrode design in the electrolyser system, would make it possible to increase the current density

- Balance of plant with implementation and testing of new membranes developed which will enable increasing temperature. Also implementation of newly developed regulating concept enabling fluctuation loads

- Increasing corrosion resistance

- Long time testing on proto types as this was not extensively carried out during this project due to complications with the site. Long time testing is essential to verification of corrosion resistance, cost reduction and performance

- Production and assembly lines have to be established at Greenhydrogen.dk facilities but also at partner organizations, as significant cost reduction lies here.

- Software for on-site control has to be further developed. A touch screen should to be implemented and interface software developed.

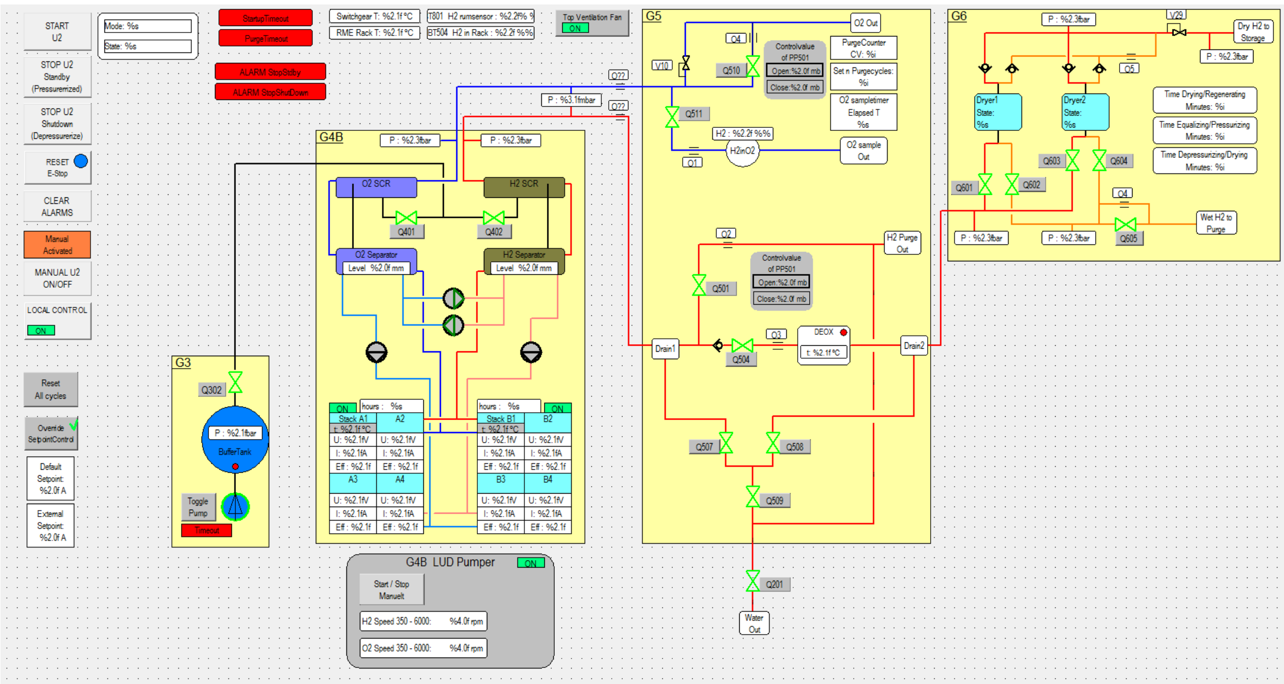
- US approvals to be ready for overseas marked

4. Project report

4.1 WP1: Specification of complete electrolyser unit

The 1st WP was to specify the electrolyser unit with focus on installation concept, service concept and user interface. Through the project a lot of work has been put into all tree tasks due to working with extern clients with interest in using the electrolyser commercially. GreenHydrogen has gained a lot of experience in relation to installing electrolyser systems at different sites and the work has contributed with insight in requirements in relation to approvals by authorities.
Furthermore, safety issues when working with gas producing units has been identified and the findings are already implemented in the ongoing activities at GreenHydrogen.

The work done in this WP relating to the tasks of installation concept and user interface has been taken further than the scope described. The reason for this is that alongside this project GreenHydrogen.dk has been participating in development efforts in the other projects mentioned in the introductory section. In these projects the installation concept has been tested and a site preparation and installation manual has been prepared.
To communicate with extern costumer systems, fuel cells for instance, Modbus protocols have been developed and tested. The protocols enable the costumer to control the electrolyser unit as well as to read different values of interest e.g. system pressure, temperature, level etc. Furthermore the electrolyser can be remotely monitored and controlled using the software developed.
The electrolyser itself is controlled by a Beckhoff PLC with software developed during the project. On site control and visualization is provided by a PC running Twincat with the interface software. A screen shoot of the interface is shown in the picture below.



Further work with user interface, which have to be conducted in the next phase, will include implementation of a touch screen placed in the door of the power and control rack and development of an interface suitable for controlling the system from this platform instead of using a PC. Implementing a touch screen would improve user friendliness and give the system a professional appearance.

Work has been done of the task of developing a service concept in both this project as well as in other GreenHydrogen.dk projects and the work done fulfills the scope of this project.

As an example, the installation and servicing of electrolyser units in a container can be mentioned. At this kind of site there is very little space to operate in and with several valves to regulate during system start up and compact modules, there is only limited space to work in. These are some of the challenges that GreenHydrogen.dk has been working on and some of the challenges has been tricking system modifications and giving initiative to creating more service minded solutions.
Thus, service has been eased and in some cases BOP has been improved. Worth mentioning is the change from regulating pressure swings with manually preset valves to more intelligent control valves with automatic regulation.

Although changes and modifications have been conducted due to experience from servicing demo electrolyser units at customer sites, the service concept is still based on GreenHydrogen.dk staff doing the work. So clearly this aspect needs more attention when taking the next step towards a commercial system. In particular, a more detailed service manual has to be prepared along with training material for external personal.

To summarize, the results of WP1 are that the installation concept has been developed further, it has been tested in “real life” on a demo site[4] and a site preparation and installation manual has been prepared. The service concept has also been tested and the need of further work regarding manuals and training material is clear. Finally, interfaces for the Twincat control PLC and a Modbus protocol for communication has been developed.

4.2. WP2: Approvals

The goal of WP 2 was to conduct research of legislations for installation and operation of alkaline electrolyser in the EU and if possible also in the USA. The work in this WP has been taken further then the scope in the EUDP application because of the need of approvals in relation to other previously mentioned GreenHydrogen.dk projects.

The regulatory requirement for alkaline electrolysis in the size and production range in which this unit operates has been clarified and 3rd party approval gained where legislation requires it. The electrolyser is CE-marked in accordance with existing legislations.

To get started with this WP the first task was to determine which directives the electrolyser had to apply to. The following list is the result of this research:

- 2006/42/EF Machinery Directive (MD) (Self- declaration)
- 2006/95/EF Low Voltage Directive (LVD) (Self- declaration)

[4] The site was part of another project not related to this project

- 2004/108/EC Electromagnetic Compatibility (EMC) (Self- declaration)
- 97/23/EC Pressure equipment directive (PED) (Notified body needed)

As shown above, three out of the four directives applicable to the electrolyser are handled with a self-declaration of compliance. The fourth directive which is the pressure equipment directive states that the compliance with PED requires a notified body for approval. To get the approval comprehensive documentation was necessary and included PI-diagrams, functionality descriptions, drawings, calculations etc. In general the extent of documentation for approval depends on which category the pressure vessels are falling under. How to calculate this is defined in the directive. In our case the 2nd Generation alkaline electrolyser unit falls under category II.

Due to initial work and sparring with external consultants GreenHydrogen.dk had the opinion that the electrolyser was also falling under the directive 94/9/EC which is handling and named "equipment and protective systems intended for use in potentially explosive atmospheres (ATEX)". After working with area classification calculations and gaining knowledge during project work, it became clear that the electrolyser unit is not falling under the ATEX directive. The reason for this is that the chance of leakage of hydrogen is unlikely under normal conditions; the ventilation rate is high and the availability is good. The electrolyser is not falling under this directive, however as hydrogen is a potential explosive element when mixed with oxygen, electrolyser systems should be designed properly to eliminate dangerous situations. Therefore the directive has been used for designing.

- 94/9/EC Equipment and protective systems intended for use in potentially explosive atmospheres Directive (ATEX) (Self- declaration)

The electrolyser developed during this project has been CE-marked and approved by notified body and this should eliminate the technical barriers of placing the equipment on within the European Union and the European Economic Area.
Thus, the need of researching requirements for approval in the USA is still there because of the marked potential overseas and should be approached in the next phase.

4.3. WP3: Product development

The goal of this WP was in general to develop and optimize solutions for existing modules in the electrolyser system. Prior to this project, a great effort has been put into analyzing the electrolysis system to determine how the different components could be split onto modules. The end result was that following modules were designed.

- Electrolyser module
- Deoxer Module
- Dryer Module
- Water Treatment Module
- Power supply and Control unit
- Rack mount

In the “Optimization of 2nd Generation Alkaline Electrolyser” application development tasks for the electrolyser module, Deoxer/BOP, dryer module and the power supply and control unit were described. During the project work, it became clear that all modules in the electrolyser unit needed updates either to comply with legislations and/or be compatible with other system components. Thus, the whole system has been undergoing changes which will be described in the following sections.

Electrolyser module

During the project WP 3 has focused on product development of the electrolyser module with stack and balance of plant (BOP). Furthermore the results of the electrode efficiency achieved in the laboratory during the first project had to be implemented in the existing stack-design.

To name the tasks demanding the most attention, the design of the stack and testing of production methods has been very time-consuming. Looking further into the work conducted, design of the stack turn out to be very important for system efficiency and system BOP. This became apparent during the project as H2 production was increased. Also the CE-marking and approvals process made some design challenges necessary. When producing hydrogen in the stack it turned out to be a challenge to ensure even distribution of power on the electrode surface, avoid stray current and getting the electrolyte cooled to avoid overheating. Along with the process of designing the electrolyser stack GreenHydrogen worked on getting the whole system CE-marked and as part of this process the stack went through a 3rd party approval. It turned out that the design from the first project had to be adjusted to comply with the existing legislations. A lot of hours therefore has been put into optimization and approval of the stack and has now led to a CE-marked stack with high efficiency, more about this in WP5.

Another important issue addressed in the project was to find a way to produce electrodes in larger scale with the same properties as those made in the lab, and to a cost realistic from a commercial perspective. This also turned out to be a tough task but in collaboration with a strategic supplier, it has been realized. Worth mentioning is that a production process for electrodes has been developed and a lot of testing conducted. GreenHydrogen has built up facilities for parts of the production processes, testing facilities and also made an effort to ensure quality, more about this in WP4.

To increase the efficiency of the hydrogen production in the stack, the target was initially set to raise the operational temperature to 100-150 degrees. A lot of materials and components have been tested during the project and a good understanding of corrosion processes and material properties has been gained in regards to alkaline electrolysis. The goal of the high operational temperature has not been reached within this project. As main reason the knowledge that the electrolyte used combined with pure oxygen and elevated temperatures is very aggressive must be mentioned. A lot of components are specified to withstand corrosion from the electrolyte, the oxygen or hydrogen but when those are combined and at elevated temperatures, most suppliers don’t have sufficient data supporting the durability expectations. Thus, durability has to be tested in realistic environment in electrolyser systems and custom made test setups. Particularly challenging issues has been the pumps used in the system and to find a supplier who can insure the corrosion resistance. Different types of pumps have been tested and the pumps currently used can handle electrolyte up to 80 degrees which is determining the system temperature. In GreenHydrogen test lab, temperatures are currently raised to 100 degrees where special deigned pumps are part of the system configuration and so far with excellent results.

Another challenge has been to find a gas separating diaphragm which is suitable for the electrolysis process at temperatures above 90 degrees as project goal was 100-150degrees. In collaboration with AU-Herning, CET, GreenHydrogen managed to find a type suitable for temperatures up to 120 degrees. The diaphragm has been tested intensively and is currently implemented in the GreenHydrogen electrolyser.

Due to the intensive testing and researching, alternative alloys that are suitable for the electrolyser systems have been identified and production methods tested. This will enable GreenHydrogen.dk to raise the system temperature above 100 degrees in the future so as the diaphragm will set the limit. The alloys identified are not implemented in the demo setup described in WP 5 as the results of the researching and testing are delivered late in the project.

To show the progress in electrode implementation in the stack the pictures below are showing sets of IU-curves from different electrode batches produce during the project. Figure 1 shows a measurement on the new type of electrodes implemented in the optimized system. The curve was generated at 30bar system pressure and 80°C process temperature. The second curve shown in Figure 2 is a measurement with same parameters as the first one, but with a batch of electrodes before the optimization. The cell voltage at 200mA/cm2 shows an improvement of almost 200mV.

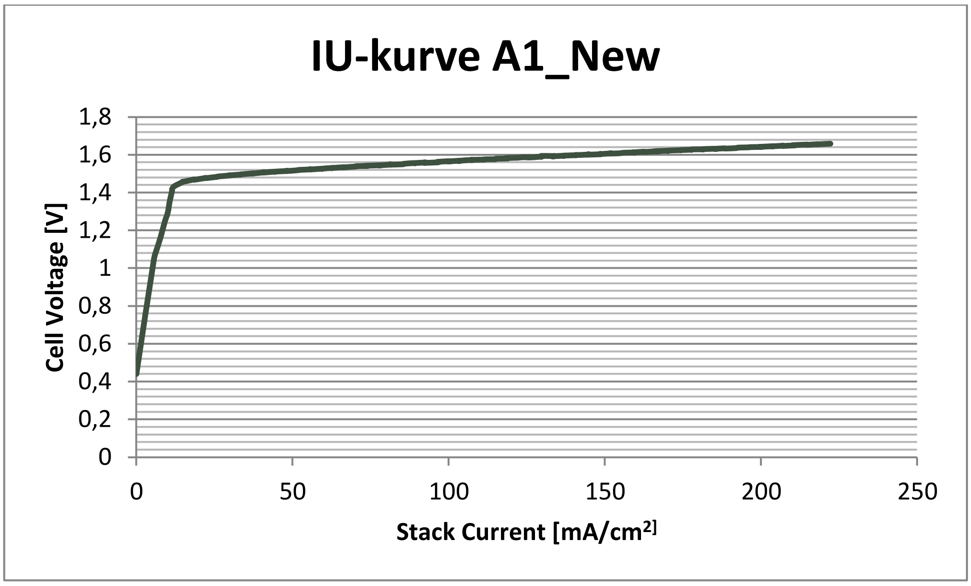


Figure 1: IU curve of a new batch of electrodes

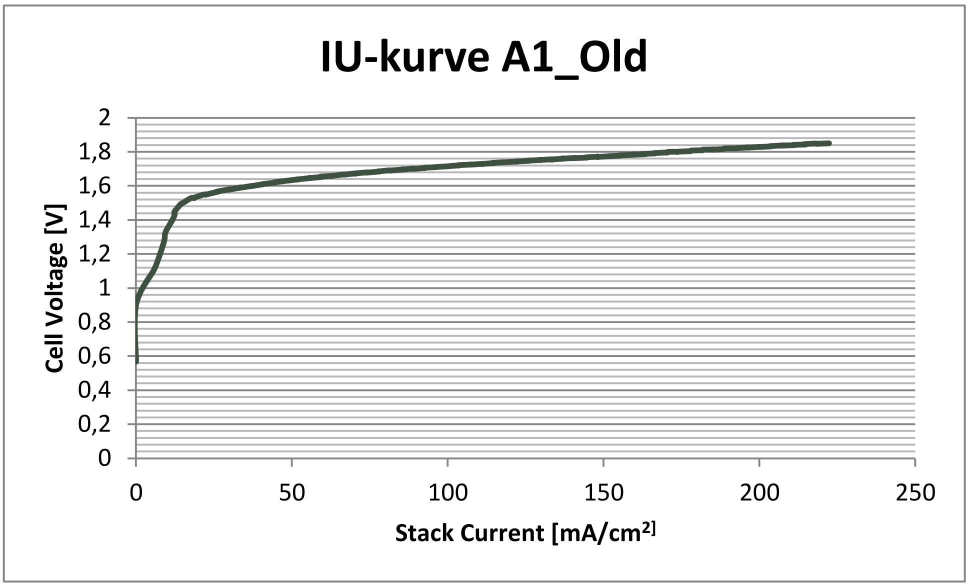


Figure 2: IU curve of older generation of electrodes

A picture of the updated electrolyser module as well as the stack is also shown.

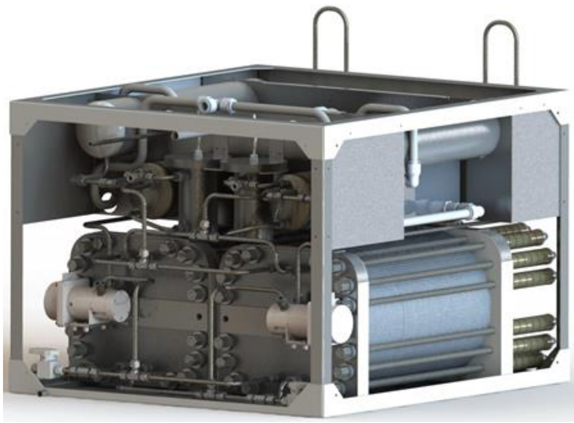


Figure 3: Electrolyser module

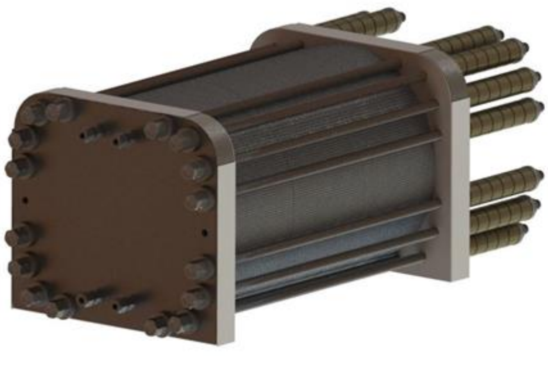


Figure 4: Electrolyser stack

Deoxer/BOP

The Deoxer module, which is holding the vital regulation components for BOP (balance of plant) and the unit responsible for cleaning residues of oxygen in the hydrogen (Deoxer vessel), has been undergoing a significant change during the project.

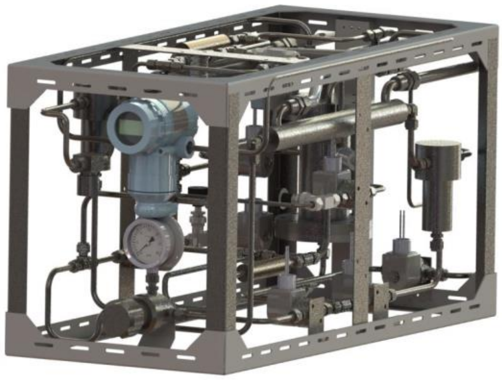


Figure 5: Deoxer module

A new system for controlling the electrolyte level and the pressure on each side of the membranes separating the hydrogen and the oxygen in the stack has been developed. Before this project, a custom made valve was used that ensured the pressure and level balance in the system but this valve had some safety issues. By developing and implementing a different setup with circulation pumps and special control valves during the project, the safety issues has been solved and the electrolyser has a more accurate, flexible and reliable BOP.
The circulation of the electrolyte by the pumps has also contributed to a more efficient way of regulating the temperatures in the system.

In the WP description in the EUDP application, optimization of the water treatment is also mentioned as a task in relation to Deoxer/BOP. This task has not been realized as in the process of optimizing the whole system, it turned out not to be of significant value to the product to integrate a water treatment unit into the electrolyser system. Service, repair and modification of the water treatment unit would be complex. The collaboration with potential electrolyser customers made it clear that at the current state it would not be worth the effort. Thus, it was decided not to design the water treatment into the electrolyser enclosure but to specify the requirement in the specifications (WP1).

Dryer module

The gas drying unit has been tested intensively in the first project of developing a compact electrolyser unit. Only minor changes have been carried out in this project and the module is operating as designed for. The hydrogen gas has a dew-point low enough to comply with fuel cell standards when passed through the dryer. In regards to this module further work will be conducted, after project end, to optimize the amount of hydrogen used for regeneration.

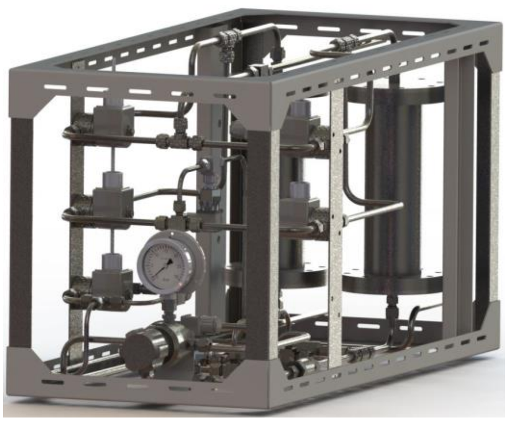


Figure 6: Dryer module

Control module

Due to the implementation of pumps and the described changes in BOP, the control system and software has also been optimized and undergone extensive changes. New software for the control of each module has been developed along with user interfaces and the results are already implemented in electrolyser units installed at different demo sites. Experience in communication between external systems operated by project partners and connected with GreenHydrogen electrolyser unit has been gained and communication protocols are developed and adapted continuously.

Complex sequences have been invented for controlling electrolyte circulation in the system; pressure balance of the system has been improved significantly and purification processes optimized. The system has furthermore been improved with regards to safety as the safety circuit has been upgraded.

Over all the software and the main system control has been upgraded extensively during the project period and has reached a high level. To get the control system ready for commercialization a longer test period with abnormal tests, stress test etc. has to be conducted, and software for a touch panel should be developed to ease on site control.

Figure 7: Controle module

Summary WP3

To summarize the work accomplished in WP 3, all modules mentioned in the beginning of this section has been optimized significantly due to gained knowledge and experience. The electrolyser module is equipped with pumps which has improved BOP and cooling, the stack has been optimized in regards to cell frame geometry and has been CE-marked by a notified body and electrodes with high efficiency has been integrated in the stack. The BOP is improved, new valves are implemented and software has been developed for more efficient system control and communication with extern systems. The operational temperature of 100-150 degrees and the implementation of the water treatment system have not been accomplished but research and gained knowledge has made it evident as entirely doable in the next phase.

4.4. WP4: Development of production methods

This WP had two goals set; a) to develop production processes for the electrodes developed in the 2nd Generation Alkaline Electrolyser project; b) to conduct tests of injection molding as production method for the cell frames. Here under testing of degradation of the polymer and its fillers. Testing should be conducted under operational condition which means high pressure, elevated temperatures and longtime exposure.

Electrode production processes

In collaboration with the project partners GreenHydrogen has established a solid knowledge of electrode production processes. During the project several methods has been tested and various parameters has been investigated.

The production process of the electrode is comprehensive and a lot of parameters are to be managed carefully to get electrodes with high efficiency and durability. During the project the partners have been working intensively to find the optimal process for electrode production in large scale.

The first step was to find the right base material; in this case a normal steel plate is used. The base material is plated with a kind of nickel and a filler material to create a surface structure optimized for hydrogen production. The process takes place in different tubs where the base material is soaked in chemical baths consisting of special formulas where the plating material is added. One tub pr. material. Current is added to the base plate and the electroplating process is running.
After the electroplating the electrodes are going through a process to make the material plated onto the base material diffuse into the surface.
The next step in the process is to send the electrodes through an process where the filler is removed in order to create a micro structure on the surface. Finally a purification process of the electrodes has to be carried out to get the last filler out of the electrode.

The challenges has been to optimize the plating process to get exact the same amount of material in the right mixture plated onto the base material in every run and to find the optimal treatment parameters for the diffusion process to happen effectively. Also optimizing the process to remove all the fill material from the surface of the electrode to avoid contamination in the electrolyser system later on has been difficult.

There are not used any noble metals in the process which is one of the forces of the alkaline electrolyser technology compared with other competing technologies.

Cell frame production and testing

Two topics have been examined during the project with regards to the cell frames for the electrolyser stack; injection molding and material properties.
In the first project “2nd generation alkaline electrolyser”, a prototype cell frame was designed. To manufacture the frame without investing in an expensive tool for injection molding the frames were at first cut out of plates of polymer. This method was sufficient for building systems for “proof of concept” but not the right way in case of mass production.
In addition to the high cost when scaling up, cell frames cut out of polymer plates are problematic because of mechanical properties after machining.
An effective way of producing polymer components with complex geometry in larger batches is injection molding. When invested in a tool the components are relative inexpensive depending on polymer material and batch size.

A lot of work has been put into researching literature for suitable materials and a lot of testing has been conducted to establish a positive list of polymer types suitable for both the chemical exposure during operation but also with regards to the injection molding process.
The environment for which the cell frames are designed combines the corrosive elements hydrogen, oxygen, and potassium hydroxide at elevated temperatures. Each element is highly corrosive by itself and when combined the effect is even worse.
When vendors and material manufactures are documenting their products they often describe the chemical properties regarding hydrogen, oxygen, and even potassium hydroxide separately. They also indicate allowable temperatures but the problem is that they almost never mentioned all elements combined. This has led to a real challenge in finding the right material.

Below is shown a material which was used for first prototypes of the electrolyser stack. The literature screening indicated that the mechanical properties as well as the chemical resistance of this material could withstand the environmental challenges in the electrolyser system. Intensive testing at “real life” parameters resulted in the findings clearly shown in the pictures bellow:

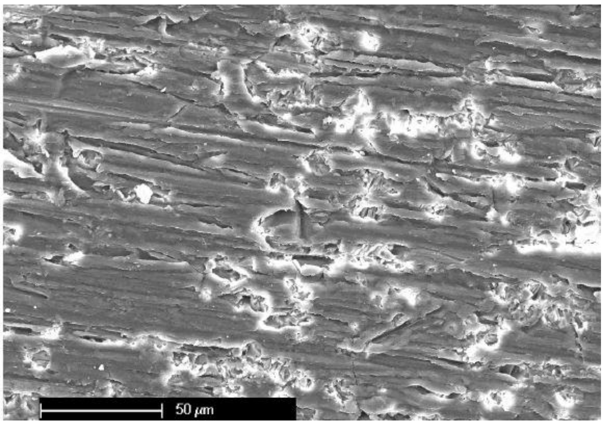


Figure 9: Before exposure to electrolyser medium

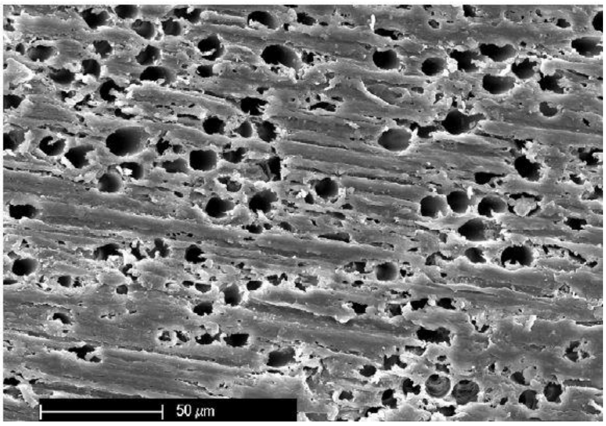


Figure 8: After exposure to electrolyser medium

The picture to the left is the material before it is been exposed and the picture to the right is after it has been exposed. The filler in the polymer, which gives the mechanical strength to the frame in this type of polymer, has been dissolved and the frame has therefore lost a great deal of strength.

Details of the testing cannot be reveal in this report but the pictures above indicates the high requirements for the polymer. The intensive work during the project with testing a variety of different polymers has resulted in a solution and a polymer with the required properties has been found.

The work has been conducted in collaboration between project partners as well as with external vendors and knowledge from different specialist teams have been gathered. The knowledge has been used for choosing a polymer type suitable for both the operational conditions and the injection molding properties.

After choosing the material a tool for injection molding has been designed. The challenge was to design the frame in a way which meets several criteria such as the right thickness of the frame, the placement of ejecting pins, the slag in all corners and edges of the tool for easy ejection of the frame from the tool etc. which should fit together with the mechanical properties of the frame for operational conditions. To mention is the optimal design regarding stray current, strength to withstand the internal pressure, flow of the gas and electrolyte for proper circulation and cooling and more.
Due to close collaboration with a key supplier, GreenHydrogen.dk has managed, after some adjustment, to design the tool for the injection molding process.
Several batches of cell frames have been produced at this point with the required properties and the task is solved with very good results.

As summary of WP 4 it can be concluded that during the project electrode production methods has been developed and tested which enables GreenHydrogen.dk in collaboration with our vendor to build up a production line in the next phase. Additionally it should be mentioned that the production method also applies to electrodes in larger dimensions than used in this project which is very interesting for GreenHydrogen.dk with regards to related projects.
Furthermore cell frame material has been chosen after series of testing and a lot of research. A tool has been manufactured for injection molding and the concept has been proven as several batches of cell frames have been produced and used in electrolyser systems with success.

4.5. WP5: Construction and testing

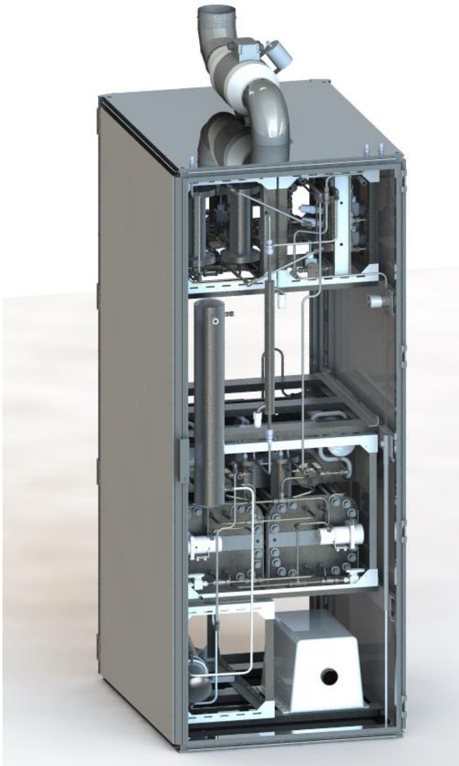


Figure 10: Prototype of entire electrolyser system

Goal of this WP was to build an electrolyser module for optimization purpose for the stack design from the 2nd Generation Alkaline Electrolyser project. Furthermore a prototype of the complete system should be ready and used for verifying data as part of WP6. The intension was to use the electrolyser system for testing life cycle of the system and critical components in particular. The specification goal for the prototype is listed below:

- Modular design in a 800x1000x2000mm cabinet
- Hydrogen production of 4Nm^3/h (2 stacks)
- Stack production capacity of 2Nm^3/h
- Current density 200mA/cm2
- Efficiency of 90% for the stack
- System pressure of 30bar
- Operational temperature of 100-150°C
- Power consumption of 4,3kW/Nm^3

An electrolyser unit has been build and almost all of the above mentioned specifications have been met. The system is design into a standard cabinet with the measures 800x1000x2000mm.
To unify the product, the power and control rack has been placed in the same type cabinet. Production unit and power and control unit are placed side by side. The original idea was to design a unit in one cabinet but already in the first project "2nd Generation Alkaline Electrolyer", it was clear that for safety reasons and compliance the right approach when building a prototype, was to separate the process units from the power and control units. In the next phases, it would make sense to work with optimization of the foot print of the power and control unit.

In the pictures below, a 3Nm^3 electrolyser system unit is shown. This unit is built as part of the project delivery.

The project plan stated a goal of 4Nm^3 in the prototype unit and the reason for this was to demonstrate a production rate of 2Nm^3/stack. For the stack to produce 2Nm^3/h it requires 100 cells with a current density of 200mA/cm^2. During the project several challenges regarding 100 cell stacks where discovered.
To mention a few: stray current and pre-tensioning of the stack is pretty complex when combining it with the environment described previously. Stray current can damage the stack and the pre-tensioning affects the number of spring washers and thereby the length of the stack. By optimizing design of the stack and the BOP all at this time known challenges for a 4Nm^3 electrolyser unit has been solved but to build two stacks fully extended to 100 cells would require changes in the electrolyser frame as well as the back plane because of the length of the spring washer staples. The fact that the length of the stack would be greater than first calculated was first discovered after purchasing the mechanical components for the unit. Thus, for the prototype it has therefore been decided not to purchase new module frames and make a rebuild of the backplane as scaling up from 3 to 4Nm^3 would not give further knowledge of system functionality in regards to life cycle testing and approvals. Another argument for not conducting the changes in this

project is that further work with the unit includes testing of new electrodes where the current density will be higher than 200mA/cm^2 and thereby increase the hydrogen production.
In the next phase of the project, the system will therefore undergo testes with the planned production rate anyway. Moreover all resources for building the unit had been spend.

During the last weeks in the project period GreenHydrogen.dk succeeded in implementing electrodes produced in the lab into the electrolyser and has now proven efficiencies of over 90% on the stack but without elevating the system temperature to values between 100 and 150°C. The wish of operation temperatures in the range of 100-150°C is because of the fact that the process efficiency is getting higher when elevating the temperature. But high temperatures will affect life time of the system. This has already been discussed in WP 3 and will not be further elaborated further in this section.

The last two parameters to be discussed is the goal of a system pressure of 30bar when operating. Approvals have been given from notified body with certificate of the electrolyser unit that allows a maximum system pressure of 31bar for the process system and 35bar in the water feeding system. Thus, 30bar system pressure is achieved.

Worth considering for the next phase/project would be to raise the system pressure even more due to the fact that some pressure loss must be anticipated from the stack to storage. The higher the pressure the more hydrogen can be stored at the given storage capacity.

Finally, the power consumption of the whole system where targeted for 4,3kW/Nm^3. This has to be examined during a longer test period as degradation of the electrodes could be greater than anticipated.

Pictures of the proto type:

4.6. WP6: Demonstration

This WP has not been fully realized. The original plan was to install the electrolyser proto type unit from WP5 at a demonstration site called “Brint Demonstratoriet” where the long time testing should have been conducted. The “Brint Demonstratorium” has in the meantime been closed down due to changes in the organization at Aarhus University Business and Social Science – Centre for Energy Technologies (CET) who are running the place.

Therefore, the prototype has been operated at GreenHydrogen, however not yet for as long time as originally planned for. The prototype unit remains at GreenHydrogen and will be utilized for further development and longtime testing.

Simultaneously, towards the very end of this project, a 2Nm^3 electrolyser unit was delivered to SP Group in Sweden. The delivery reflects the results and stage of advancement achieved in this project and gives GreenHydrogen the valuable opportunity to gain experience with installation, service and longtime run with an external customer. , The system will be installed by GreenHydrogen.dk Staff and operated by SP staff after receiving instruction and education by GreenHydrogen.dk technicians.

4.7. WP7: Project management

Project management has been conducted and will for this phase end with this report. The knowledge and experience from this project will be the platform of further development of the system, the software and user interfaces, as well as for development of other electrolysis products.