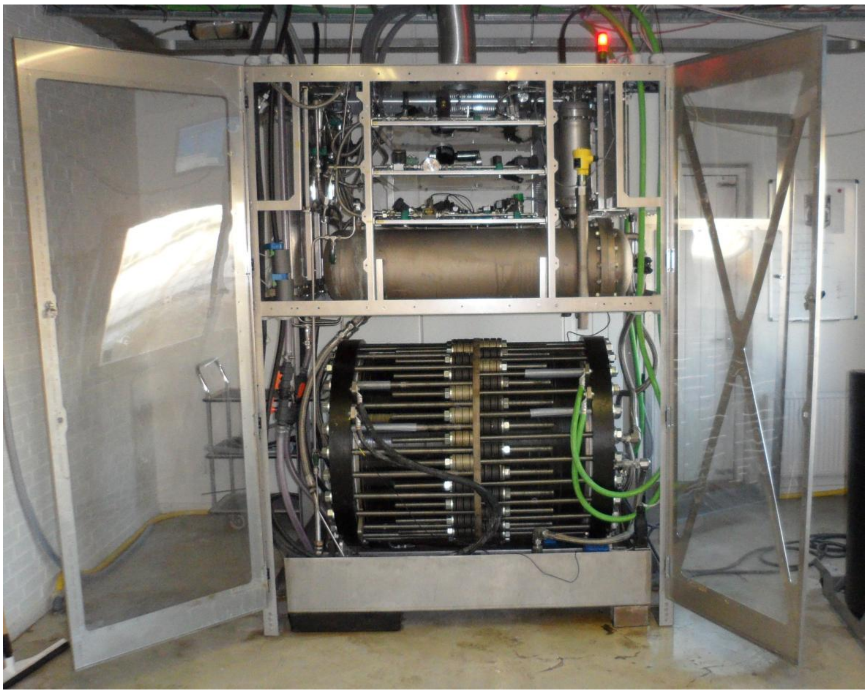
Final report

HyProvide Large-Scale Alkaline Electrolyser (MW)

Project: EUDP 11-II, 64011-0105



GreenHydrogen.dk, Siemens, DTU, and AU

March, 2016

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1. Project details

Project title	HyProvide Large-Scale Alkaline Electrolyser (MW)
Project identification (program abbrev. and file)	EUDP 11-II, 64011-0105
Name of the programme which has funded the project	Energy Technology Development and Demonstration Program (EUDP) Area of Technology: Hydrogen and Fuel Cell Technologies
Project managing company/institution (name and address)	GreenHydrogen.dk Platinvej 29B DK-6000 Kolding
Project partners	GreenHydrogen.dk Siemens Corporate Technology Denmark Technical University of Denmark – Mechanical Engineering Aarhus University – Centre for Energy Technologies (previously HIRC)
CVR (central business register)	GreenHydrogen.dk: 30 54 87 01
Date for submission	March, 2016

2. Short description of project objective and results

2.1 English version

The overall objective of the project is to develop a concept for large-scale alkaline electrolysers (megawatt size) for hydrogen production. The target is to create a scalable electrolysis plant in the range from 125Nm^3/h to 1000Nm^3/h, e.g. for storage of energy from renewable sources. The major achievement of the project is the development of a high-efficiency, low-cost and modular electrolyser unit with a hydrogen production capacity of 60 Nm^3/h at a power consumption of about 250 kilowatt. At the time of project completion the unit has been successfully operated in the laboratory for several thousand hours. The modular nature of the electrolyser unit makes it ideal for hydrogen production plants with capacities in the range of 60 Nm^3/h to 1000Nm^3/h. The electrolyser unit has been demonstrated to several potential customers, who have all given positive feedback.

2.2 Danish version

Det overordnede mål med projektet er, at udvikle et koncept for alkalisk elektrolyse til brintproduktion i stor skala (megawatt-størrelse). Målet er at udvikle skalerbare elektrolyseanlæg i størrelsesordenen 125Nm^3/h til 1000Nm^3/h til eksempelvis lagring af energi fra vedvarende energikilder. Projektets hovedresultat er udviklingen af en højeffektiv, prisbillig og modulær elektrolyseenhed med en produktionskapacitet på 60 Nm^3/h ved et effektforbrug på cirka 250 kilowatt. Ved projektets afslutning har enheden været i drift i laboratoriet i adskillige tusinde timer med tilfredsstillende resultat. Enhedens modulære natur gør den ideel til brintproducerende anlæg med kapaciteter i størrelsesordenen 60Nm^3/h til 1000Nm^3/h. Elektrolyseenheden er blevet demonstreret for adskillige potentielle kunder, som alle har givet positive tilbagemeldinger.

3. Executive summary

The HyProvide project is concerned with the development of a concept for large-scale alkaline electrolysers (megawatt size) for hydrogen production. The project's target of creating a scalable electrolysis plant in the range from 125Nm3/h to 1000Nm3/h is achieved by the project partners through the development of a high-efficiency, low-cost and modular electrolyser unit with a hydrogen production capacity of 60 Nm^3/h at a power consumption of about 250 kilowatt, see Figure 1 and the front page figure of the present report. The modular nature of the developed electrolyser unit makes it ideal for hydrogen production plants with capacities in the range of 60 Nm^3/h to 1000Nm^3/h. The electrolyser unit developed within the HyProvide project is ready for its next phase, which will be focused on optimising the production-steps in producing each module and the total system. This next phase will also include the start-up of a first production and field-test, i.e. external demonstrations. Once this next phase is accomplished it is expected that the electrolyser unit is ready for market introduction. Further on the electrolyser unit will be marketed using the term HyProvide as a trademark.

The HyProvide electrolysis unit is developed with the green energy market in mind. The unit is fully configured – ready to deploy for a variety of energy applications, e.g. power-to gas applications, on-site hydrogen production for hydrogen refuelling stations (automotive), on-site hydrogen generation for power back-up solutions for e.g. PV plants, off-grid and critical installations, and industrial applications. Furthermore, the HyProvide electrolyser unit is developed with focus on lowest possible Total Cost of Ownership. The design is made modular and compact – including dryer and deox unit - with minimal footprint. In future applications the unit will be delivered as a 250 kW building block module. For MW installations modules are simply parallel connected. The electrolyser module can be used as stand-alone units for in-building/plant floor installations - or the unit/units may be fitted in a 10, 20 or 40 ft. container. The HyProvide electrolyser unit is developed for easy installation, i.e. no significant site preparation is required and cables, pipes and hoses all connect at the top of the unit. Maintenance and service is easily conducted, since components are tray mounted and easily accessible. Furthermore, the stack may be easily disconnected and extracted from the system. An accompanying automatic service trolley is developed for trouble-free and safe handling and refill of lye. A software system for on-site and remote monitoring and electrolyser system management is also developed in the HyProvide project. This system allows for monitoring and managing of modules as one resource – e.g. one MW. Or alternatively, individual management of each module for optimal production, availability for grid balancing and scheduling of service intervals.

Figure 1. Staff from the participating partners Siemens, Aarhus University, Technical University of Denmark, and GreenHydrogen.dk in front of a prototype of the HyProvide 250 electrolyser unit in GreenHydrogen's laboratory in Kolding. Due to safety precautions eye protection is worn in the vicinity of the electrolyser, which operates at high pressure.

4. Project objectives

Alkaline electrolysis represents a mature technology, in particular for the purposes of producing hydrogen for industrial purposes where alkaline electrolysis has been used commercially for long. However, in order for hydrogen produced by electrolysis to be able to compete with current technologies and fuels in the energy market, as well as established suppliers of conventional electrolysis technology, it is pivotal that the electrolysis technology is further improved. The reason for this is that the main driver for the commercialisation of products for the new energy market is the efficiency in order to reduce the costs of operation. In addition to this, if the product is too expensive, it is impossible to make it commercially viable, for which reason it is important to not only focus on the system efficiency but also to keep production costs at a minimum. Along with this comes a large need for flexible/scalable systems that are easily integrated into different energy setups and combinations.

The overall objective of the project is to develop a concept for large-scale alkaline electrolysers (MW size) for hydrogen production. The target is to create a highly efficient, low cost, and scalable modular electrolysis plant in the range from 125Nm3/h to 1000Nm3/h. This project serves as the first of three phases in the product development. The purpose of this phase is to verify that it is possible to advance GreenHydrogen’s electrolysis technology into megawatt (MW) size. The production capacity of the technology available at GreenHydrogen prior to this project is limited to the kilowatt (kW) range. The second and third phases of the product development are concerned with external demonstration of the product and full product launch towards broad customer segments. The second and third phases are not addressed in the HyProvide project.

More specifically the objectives of the project are:

- GreenHydrogen wishes to offer a large-scale electrolyser with improved overall system efficiency with a future potential efficiency up to 90% whilst at the same time offering the electrolysers at a lower cost than competitors already on the market. This phase is the first step at the roadmap and the total efficiency at the end of this project should be 4.4kW/Nm^3

- The project focus area is development of the first generation of the modular concepts with focus on the electrolysis stack, including design of a prototype for verification of the design and concept. A modular concept is opted for in order to facilitate easier production, installation and maintenance as well as increased adaptability.

- Development of a new stack that allows for operation at high pressure and high temperature. The stack must be made from materials that are durable in the highly corrosive alkaline environment.

- The balance-of-plant (BOP) from GreenHydrogen's kW-range electrolyser units must up-scaled to MW-size.

- Detailed system and software specifications must be developed in order to facilitate robust and user-friendly control of the electrolyser unit.

- Failure mode and effects analysis (FMEA) should be conducted in order to guarantee safe operation of the electrolyser unit.

- Compliance review must be conducted in order to form the basis of CE marking of the electrolyser unit, which is a prerequisite for market introduction.

- Optimization of gas-evolving electrodes and gas-separating diaphragm for high efficiency and high durability at low cost.

- The objective is to obtain proof of concept in order for the customers to establish confidence in adapting the application of their product portfolio.

Project plan and implementation

The work required to realise the project objectives is divided into five stages:

1) Detailed specification of requirements and concept

2) R&D of components and sub-systems

3) R&D and construction of laboratory test systems

4) Test of systems in laboratory verifying reaching of targets

5) Dissemination of results, planning of commercialisation and continued R&D

The actual work that is required in these stages is undertaken by the following five work packages as outlined in the original project application:

WP1 – Specification of concept
Specification of concept and detailed development targets and interfaces between the technologies and markets. The specification and concept will be reviewed with potential customers, and approved by steering committee.

Participating partners: GreenHydrogen, Siemens

WP2A – AEC stack development
Development of AEC stacks, including the development and optimisation of cell and stack components as well as cell and stack manufacturing techniques based on the specifications from WP1. Efforts will be made to optimise material and component costs and performance.

Participating partners: GreenHydrogen, Siemens, DTU, Hirc

WP2B – AEC system development

Identification and development of balance-of-plant components and integration of these with the developed electrolyser stack into a product laboratory test system. Evaluation of the manufacturing process and suggestions for improvements to this. Estimations of the total production costs.

Participating partners: GreenHydrogen, Siemens

WP2C – AEC prototype test

Testing of the developed AEC laboratory test system resulting in a proof-of-concept. Describing the technical and economic feasibility of the system, as well as the technical and socio-economic impact and possibilities of implementing the system. Internal demonstration projects for potential customers.

Participating partners: GreenHydrogen, Siemens, Hirc

WP3 – Dissemination & planning R&D and commercialisation

Dissemination of project results. Plan & secure initiation regarding further development and commercialisation activities.

Participating partners: GreenHydrogen, Siemens, DTU, Hirc

In general, the tasks of each of the work packages were taken care of as planned in the original project application. The technical results of the work packages are described in sections 5.1 to 5.5. The efforts of all participating project partners have been focused towards the development of a fully working alkaline electrolyser unit that fulfils the original project objectives, e.g. large scale, high efficiency, and low cost. It has been given high priority to bring the development of the electrolyser unit as close as possible to a finalised product ready for field testing (external demonstration).

Throughout the duration of the project, the work has been characterised by a close collaboration between the project partners. Employees from Siemens, DTU, and HIRC have made regular visits to GreenHydrogen in Kolding in order to assist in the development, construction, and testing of prototypes of fully working electrolyser units, including electrolyser stack and balance-of-plant. Development, analysis and optimization of the electrolyser components (e.g. gas-evolving electrode surfaces, gas-separating diaphragm, and polymer material for stack construction) have been conducted in the laboratories at DTU, Siemens, and HIRC. The new and optimized components/materials resulting from these efforts have been tested in fully functional electrolyser units at GreenHydrogen. Very often laboratory facilities and expertise of DTU, Siemens, and HIRC have been used for analysis of components and materials that have been tested/operated at GreenHydrogen. This has ensured a feedback of real-life experience from the fully-functional electrolyser unit into the fundamental laboratory-scale development and optimisation of new advanced materials for the alkaline electrolyser unit. This close interplay has been pivotal in order to develop new and optimised materials that have the properties that make them applicable/useable outside the laboratory, i.e. in real-life alkaline electrolyser units.

Every Friday at 10 AM throughout the duration of the project online web meetings with participation of staff from all project partners have been organised. The meetings have had the character of status meetings where each project partner has reported the current status of her/his activities related to the project. Occasionally project partners have contributed to the online meetings with lectures or presentations of relevant knowledge and/or results obtained. The weekly online web meetings have given rise to many fruitful discussions related to the project. Also the meetings have facilitated an efficient coordination of project activities.

Milestones and project progression

In order to ensure a steady progression of the project the following primary milestones were agreed upon prior to the initiation of the project:

- Specification and review of concept as well as approval by steering committee.
- End 2012: Test of first electrode in the laboratory and review of cell frame/membrane design, stack concept and safety regulations. BOP and secondary components ready for manufacturing.

- End 2013: Review of final stack concept. Phase 2 plan.
- End 2014: AEC review final electrode and membrane, laboratory test conducted and evaluated. Demonstration of system for customers.

By and large the project implementation developed according to these milestones, however, in a more continuous manner. The electrodes, for instance, were developed and optimised throughout the duration of the project. The most promising electrode candidates developed in the laboratory were tested/operated in fully functional (real-life) electrolyser units at GreenHydrogen. Further development and optimisation of electrodes on the laboratory-scale was to a large extent based upon the results of the real-life tests performed at GreenHydrogen. This feedback loop continued throughout the project, resulting in electrodes with increasing durability and efficiency. Also the electrolyser balance-of-plant was developed and optimised continuously throughout the duration of the project. The kW-scale balance-of-plant developed by GreenHydrogen prior to the present project was up-scaled to MW-scale early in the project. The new MW-scale BOP was continuously further developed and optimised throughout the project. This development was based on thoroughly testing the electrolyser unit using varying electrolyser stack sizes. Analysis of the experimental data obtained provided the basis for a further development and optimisation of the BOP.

The major achievement of the project is the development and construction of an electrolyser unit (HyProvide 250) with a hydrogen production capacity of 60 Nm^3/h at a power consumption of about 250 kilowatt. A single prototype of the HyProvide 250 was constructed and installed in the laboratory of GreenHydrogen in Kolding, see *Figure 2*. Laboratory test were conducted and evaluated. The electrolyser was demonstrated to several potential customers. This is in agreement with milestones established prior to the project.

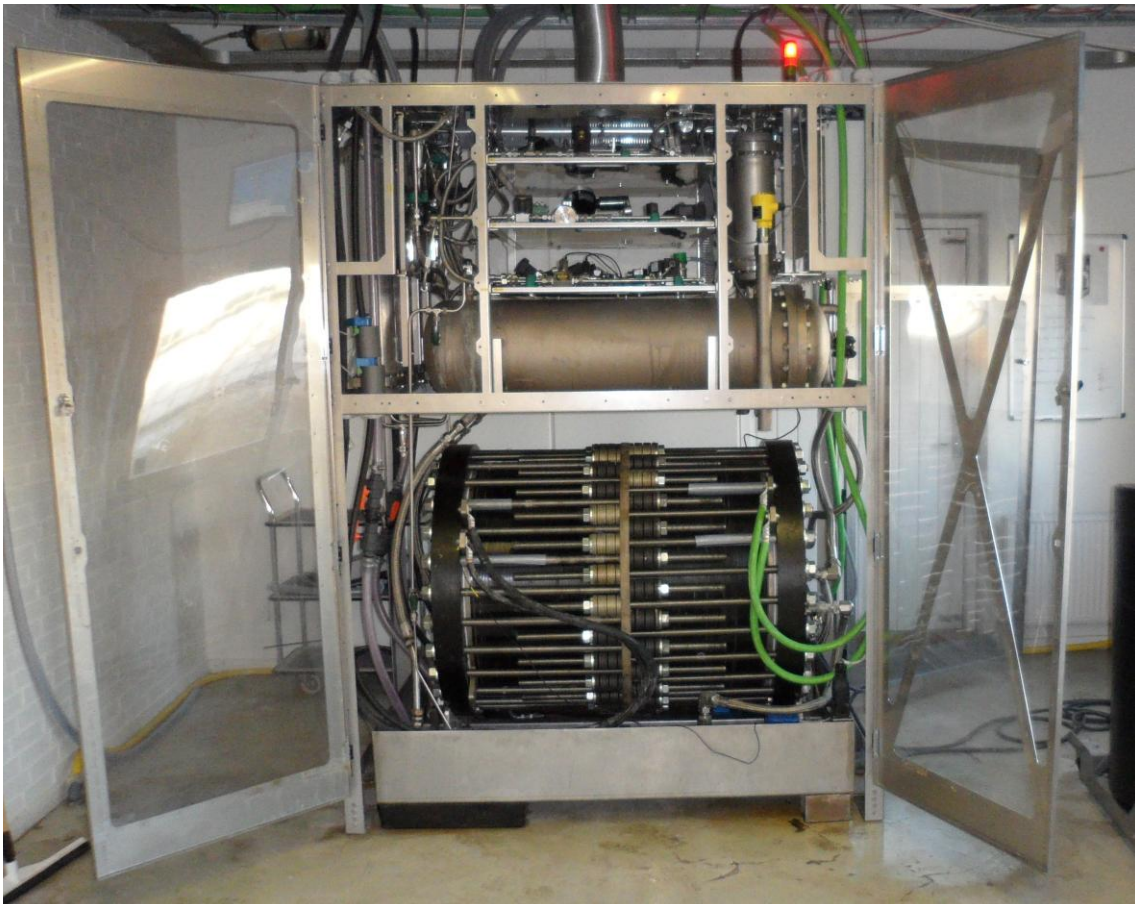


Figure 2. Prototype of the HyProvide 250 electrolyser unit being tested in GreenHydrogen's laboratory.

Problems experienced in the project

In any research and development project unforeseen technical challenges eventually arise. This project being no exception. Among the technical challenges encountered some major ones, which are critical for stable and proper operation of the electrolyser, are mentioned here.

Early in the project the electrode surfaces developed for GreenHydrogen’s kW-scale technology was thoroughly tested. This was in order to determine the suitability of this electrode surface as a starting point for further development and optimisation in this project. Unexpectedly, these tests showed that the durability of the electrode surfaces was not satisfactory. For this reason research and development in new types of innovative electrode surfaces were initiated. A large amount of time and effort was put into this work, which eventually led to the development of new electrode surfaces with much improved durability as well as high efficiency.

Early in the project a decision was made to up-scale the electrolyser stack in two steps. The stack available from GreenHydrogen prior to the project, had an active electrode area of 270cm2. The target stack size for the HyProvide project defined in WP1 has an active area of 3000cm2. However, an intermediate stack size with an active area of 705cm2 was designed, constructed, and tested, prior to the design of the 3000cm2 stack. This had the clear advantage that the design of the 3000cm2 stack could be based on experience and data obtained from tests conducted with the intermediate stack size. The tests conducted with the intermediate stack size, however, revealed critical mechanical weaknesses in the stack construction, which under certain circumstances could cause the stack to break at high pressure. The solution to this problem required both thorough experimental and theoretical analysis of the problem. The problem was solved in the target stack size (3000cm2), resulting in a stack design with significantly increased mechanical strength, that were proved to withstand almost twice the nominal operating pressure of the electrolyser.

Another unforeseen challenge that arose during the project was thermal/electrical degradation of gasket material used in the stack. This problem required detailed analysis of distribution of electrical potentials in the electrolyte in the stack. The problem was eventually solved by making changes to the stack design, which resulted in a more favourable distribution of electrical potentials. This completely eliminated the problem of break-down of gasket material.

It was of prime importance to the project consortium to develop the technology to a level as close as possible to a finalised product ready for field testing (external demonstration). Therefore, in order to have the necessary time to solve all critical technical challenges it was decided to extend the project period with 16 month. In addition to give time to solve all critical technical challenges, the prolongation of the project duration also made possible the construction of a full-scale electrolyser unit of 250 kW, although a specific target size was not specified in the project application. Construction of a full-size electrolyser made it possible to experimentally investigate all aspects of large scale electrolysis. Furthermore, being able to demonstrate a full-scale 250 kW electrolyser unit in active operation to potential customers was very much compelling.

5. Project results and dissemination of results

Sections 5.1 to 5.4 describe the main activities and technical results obtained in the project work packages. Dissemination of the results obtained and commercial potential in the project are described and discussed in section 5.5.

In general the project succeeded in realising its objectives, i.e. the development of a concept for large scale, high efficiency, and low cost electrolysis. A prototype of a full-scale 250 kW electrolyser unit was constructed, installed and tested in GreenHydrogen’s laboratory. As described in the following sections, the project answered/solved the problems stated in the project proposal which the funding has been based upon.

5.1 WP1 – Specification of Concept

The original (and current) goal in the project was to develop a MegaWatt (MW) electrolyser for commercial use. The scope of the project in this connection was to end up with at least one fully functional demo in 2014 (while we had a functioning prototype in 2014, we did not finish the fully scaled prototype stack before end of 2015).
The focus in the development period was that we acquired the necessary theoretical knowledge and experimental background to be able to construct high-quality electrolysers with high performance and great flexibility for the customers. By systematic work we expected that our demo can be quite close to the final product with respect to the concept, the layout of the electrolyzer modules and the fundamental functionality of the main components of the electrolyzer. After this project is finished, the electrolyser is ready for field testing (external demonstration).
The vision for GreenHydrogen product development is to develop systems that are suitable for mass production, and it was therefore important that this philosophy permeated the early concept development phase. The clear goal is to develop solutions where standardized modules can fit into a customer tailored solution. We will not make custom made solutions for each customer. The most important decision to make before beginning the concept definition was to consider the size and capacity of the electrolyzer system.
The focal points for determining the size of the MW project was twofold: The first focus is to increase production capacity significantly compared to the previous GH electrolyzer units of 2-8 Nm^3/h. The second goal is to constrain the physical size of modules in the system, so the modules can be easily moved and have high installation flexibility.
The MW project has therefore revolved around answering the following question: How much electrolyzer capacity can be achieved in a module with a size that can be transported on a pallet lift? The current answer to that question is a module size of around 250 kW equating a H2 production of roughly 60Nm^3/h. This estimate was based on the size of a plus sized pallet, and weight limit of 2300kg, resulting in stack dimensions of 400mA/cm^2 current density, 620mm cell diameter, and 110 electrolyzer cells. Figure 3 illustrates the concept for large scale electrolysis specified in WP1. Photographs of real-life prototypes of the electrolyser unit, water supply system, and service trolley constructed during the HyProvide project are shown in *Figure 2*, x, and x, respectively.
The MW project was launched to satisfy the H2 requirements for 3 different segments: H2 Refueling stations for cars, Energy Storage of Renewable Energy and Biogas upgrading. Of these segments the dimensioning of the module matches the size of Hydrogen refueling stations very well. And while the 250kW module is suitable for early adaptation in projects within energy storage and biogas upgrading, it is expected that a further increase in module size will be desirable for these types of applications in the future. The next logical step to take after the pallet size would therefore be to develop modules matching sizes used in intermodal transport.

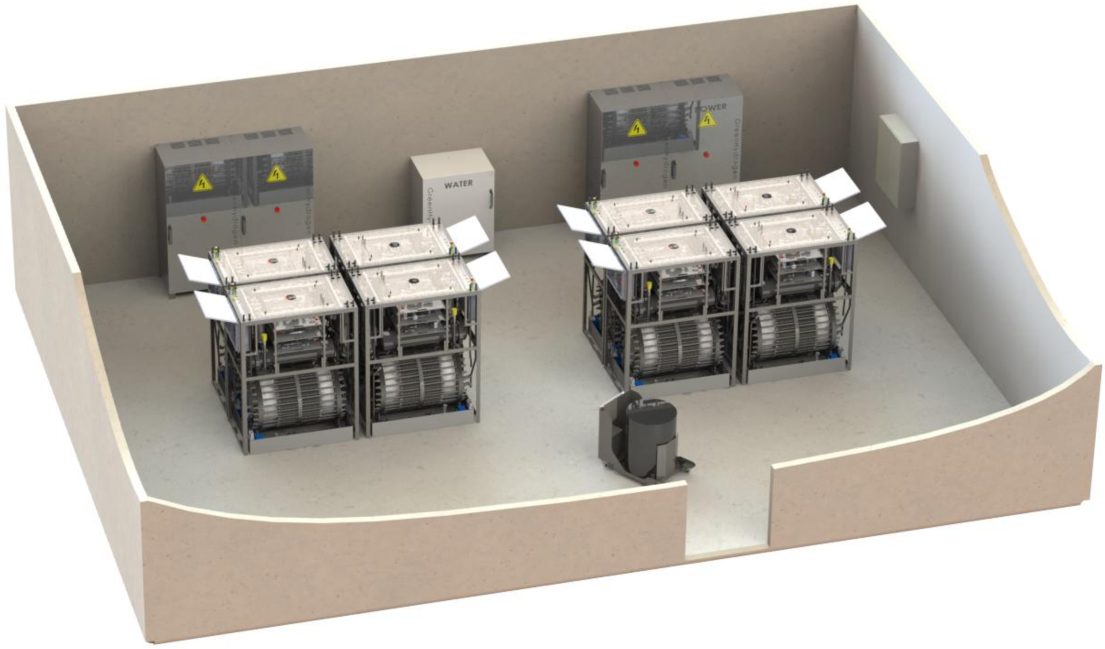


Figure 3. Concept for large scale electrolysis as specified in WP1. Shown here is an example of a hydrogen production plant with 8 HyProvide 250 electrolyser modules with a total hydrogen production capacity of 480 Nm3/h at a power consumption of about 2 MW. Shown in figure are also the required water supply system, power supply system, electronic control system, and service trolley.

Design Goals

Besides the cost and efficiency of the electrolyzer facility we see the size, the scalability and the needed on-site installation work as the three most important parameters in the design. These three parameters have not been very important in many old designs. If alkaline electrolysis is going to be a big contributor to the green energy field of the future, we are sure that these parameters must play a central role in modern electrolyzer concepts.
Our main design goals for the concept are given in the following as bullet points:

- Easy scaling by modular design
- High performance
  - High system efficiency
  - High capacity per footprint size
  - Intermittent and continuous operation
  - Low weight
  - Long lifetime
- Low manufacturing cost
  - Simple manufacturing processes
  - Easy assembly
- System is manufactured on factory
  - Minimum on-site installation
  - Simple service
  - Simple commissioning

The goal of this concept is to suggest a modular system that fulfils the requirements stated above and which is designed so that each module can be moved without need of special lifting equipment or comprehensive assembly/dismantling tools. Moreover, the total system should support scaling up to a few MWs and provide easy customization depending on the application.

Turnkey solutions

With the current 250kW Electrolyzer module size, there has been put an effort into dimensioning the complete Alkaline Electrolyzer System including all auxiliary components so it fits into an intermodal container unit, see Figure 4. This product development effort is done to accommodate the future demands for turnkey solutions.

Traditionally the electrolyzer market has been aimed at industries, where manpower has been available to ensure constant operation of the complete system, providing service to the machine whenever needed. For the future applications of electrolysers, these systems will be installed at sites where neither manpower of this type, or facilities for old fashioned machine shop maintenance will be available, and the customers subsequently requesting turnkey solutions, where the regular service is outsourced. Therefore the machine has been built in such a way that periodic and minor maintenance can be performed on site with a few utility tools. And that major maintenance will require the module in question to be moved and serviced on specialized service facilities. This is most relevant when it comes to servicing the cell stack.

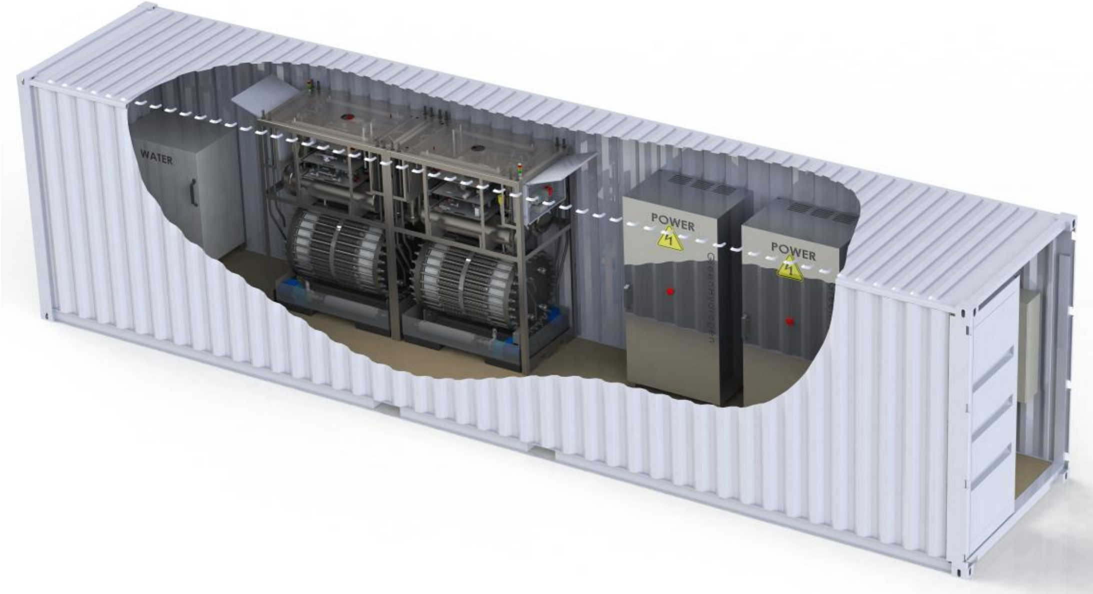


Figure 4. Example showing two HyProvide 250 electrolyser units, power supplies, and water supply system installed inside a container.

Specifications

After the preliminary analysis, a set of specifications were determined for the Electrolyzer system. And while the specifications were for the most part attempted to be kept during the project, there was during the project made a series of smaller adjustments, as research resulted in new knowledge about electrolysis.

Initial specifications

- Footprint: 1500x1000x2200mm
- Weight: 2300kg in total
- Temperature: 150C
- Pressure: 40bar
- Power consumption stack: 250KW
- 80% System efficiency
- 1 second load change response time

Final specifications at the end of this project

- Power consumption Stack: 250 kW
- Hydrogen production: 60 Nm^3/h or 5.4 kg/h
- Stack voltage: < 250 V
- Stack current: < 1300 A
- System pressure: 35 - 40 bar
- System temperature: 150°C (80 °C)
- Response time: < 1 second
- Dynamic range: 10-100%
- Lifetime: >10 year
- Footprint: 1800x1100x2300mm
- Weight: 3500 kg dry, 4000 kg wet

The goal for this project, as mentioned earlier, was always to develop a commercial product, so this is also what reflected the smaller corrections to the specifications during the product development.

In general, the initial specifications were maintained to a large degree in the project. It should be noted that the specifications listed are extremely ambitious when compared to existing commercial products, where temperature, pressure are areas that require a good deal of research and development to overcome the technical challenges. On the same note, the power consumption within the specified footprint is very compact compared to other alkaline systems, and still maintaining a very competitive price.

During the development process, it was discovered that one of the primary challenges is high temperature. And while temperature gives the advantage of increased electrode activity, and thereby higher system efficiency, it also increases the corrosion rate (more on this later), and certain threshold temperatures will also enable decomposition of polymer elements in the stack. Specifically, the diaphragm becomes very vulnerable as temperature approaches 100C.

The other area, where the specification has been modified during development, was in regards to footprint size. While we still maintain it is possible to achieve the original specification with further development time. We have also come to the conclusion that the achieving this footprint might not be worth it in terms of cost.

The size of the electrolyzer module was increased to 1800x1100x2300. And the stack weight alone was increased 2300kg dry weight. This decision was made for the reason we wanted some amount of flexibility in the design of the prototype, in case things did not turn out as expected. On evaluation of the overall system, the conclusion is that while we might be able to compress the process parts of the electrolyzer module, it will be very hard to compress the cell stack further, without the use of very exotic materials and expensive manufacturing techniques. So the overall evaluation became, that we would rather retain the initially specified production capacity, and then adjust the footprint slightly to keep the manufacturing costs reasonable.

Standard components

As brushed upon earlier in this document, there has been specific focus on using standard components whenever possible to control the overall system costs. One area where this has been particularly important was when selecting the tube size in the gas processing system. When it comes to sizing, there is a very steep jump in component prices, as the pipe size increase. This is especially true when counting high pressure equipment. The unfortunate part about operating at 40bar is that many standard components are divided roughly into 2 groups. The first are components designed for compressed air and refrigeration systems, where pressures are usually in the range of 8-10 bar, and fairly simple and cheap. The second group is outright high pressure equipment, where the pressure is often 200bar or more, with a large degree of options and features, which results in more costly components. So for many components, where it would be sufficient with components rated for 45bar, cheaper options are simply not available.

However expensive options are better than no options. So one thing that was quickly understood is that the module size should be small enough to accommodate the standard pressure equipment components, while still being large enough that these components do not become primary cost drivers when calculating total price divided by hydrogen production capacity.

When it comes to the cell stack, the dimensioning is nearing the absolute limit of what is possible from standard components. The primary dimensioning challenge is here to design a stack that is operational at 40bar. Because of the size of the electrodes, the forces required to compress the cells are no longer trivial. The limiting factor for the electrode area was therefore in the end, the size of bolts and spring washers, as standard components beyond M30 became both very costly and had low availability. And going beyond M30 size for the spring washers will require custom production. The limitation is resultant simply from the proximity of the nuts and washers in the periphery of the end flanges.

5.2 WP2A – AEC Stack R&D

5.2.1 Electrodes

Considerable effort was put into the development of alternatives to the Raney based electrodes, that were used in the GreenHydrogen kW-scale electrolysers prior to the HyProvide project. These electrodes did on several occasions show stability problems and delamination. Two concurrent activities were carried out; one with focus on stabilizing the Raney-type catalyst and the other dealing with modified and optimized nickel-based catalytic active coating developed and examined as alternative.

Initially it was shown that a new nickel based catalyst had both beneficial durability and activity and therefore the potential to become a preferred combined OER-HER catalyst (a catalyst suitable for both reactions). This variant was therefore examined and tested in both the laboratory and later in the full-scale electrolysers. The durability of the new nickel base coating was later optimized by addition of an adherence layer between the coating and the substrate.

Figure 5 shows the longest recording from the laboratory tests. More than 9200 hours were recorded with the nickel based cathode. At this time in the project the cathode was tested without the adherence layer. At 0.2 Acm^{-2} a cell potential as low as ≈1.60 V could be obtained even after several thousand hours.

The various fluctuations in the long-term recording shown in Figure 5 are caused by current interruptions or lost connections to the acquisition setup. These occurred since the cell was located in a laboratory with occasional power outages.

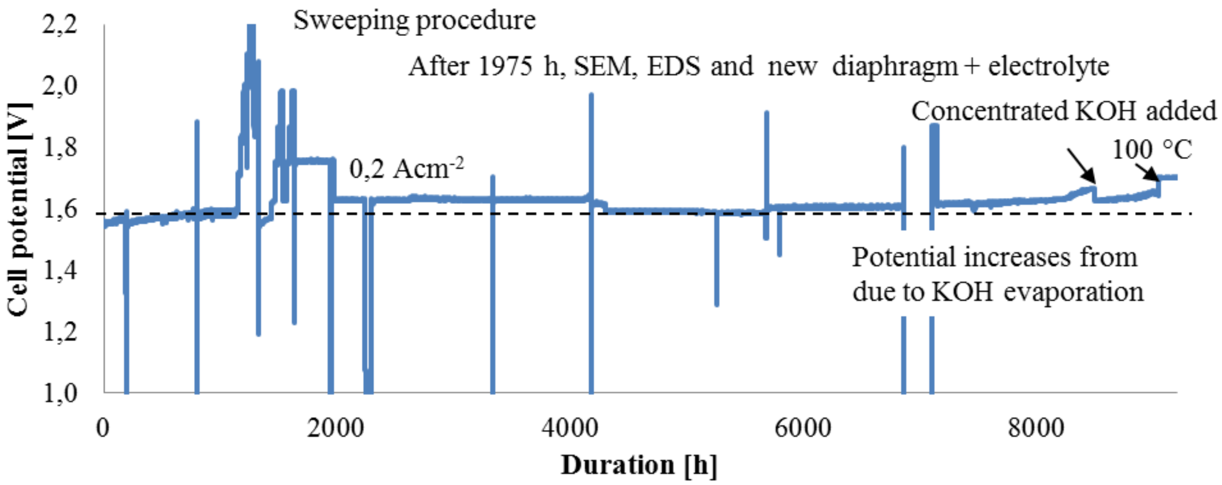


Figure 5: Long-term test of activated (Anode) – nickel based (Cathode), on R075T15 geometry. The various fluctuations are caused by current interruptions, sweeping procedures electrolyte evaporation etc. SEM images were taken after ≈1975 hours. The cell was assembled again with new diaphragm and electrolyte (0,2-0,8 Acm^{-2}, 120 °C and 50 wt% KOH).

The anode used for the test shown in Figure 5 was selected on basis of results from the anode testing. On basis of these tests a cobalt based anode was believed to be a relatively good suggestion as a durable an effective anode. Later it was shown that the OER activity of this anode was comparable to that of plain nickel as anode (Figure 6).

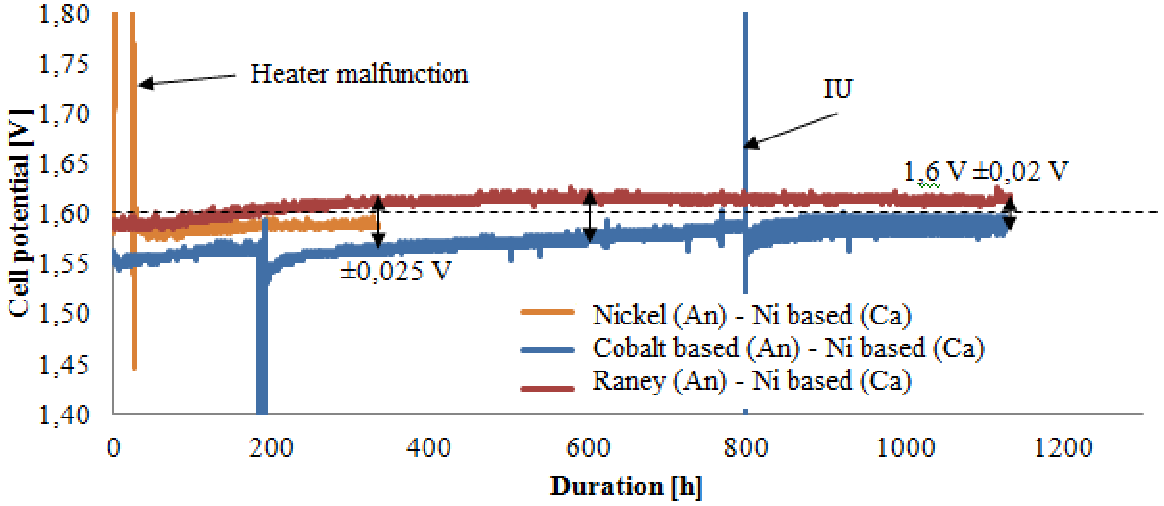


Figure 6: Long-term tests of a cobalt based, Raney based, and non-activated nickel as anodes vs. nickel based cathodes. (0,2 Acm^{-2}, 120 °C and 50 wt% KOH).

From a cost-optimization perspective it could not be justified to scale up any of the anode-coatings.

The optimized nickel based type catalyst was later developed, refined and tested – mostly as cathode. This electrode presented promising catalytic properties for HER even at elevated current densities. This was confirmed in several long term tests. At 0,4 Acm^{-2} a cell potential of ≈1,67 V could be demonstrated even after 3000 hours of electrolysis (Figure 7).

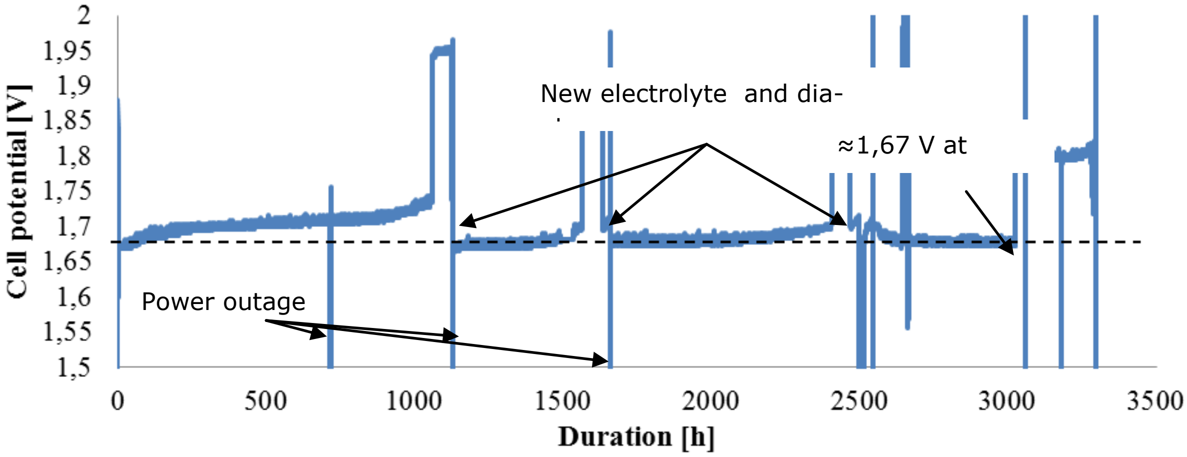


Figure 7: Long-term test of a nickel (Anode) – optimized nickel based (Cathode), on ZP100034 geometry. The cathode coating was deposited directly onto NiC on a ZP100034 welded sandwich. (mostly 0,4 Acm^{-2}, 120 °C and 50 wt% KOH).

During the experiment the electrolyte and diaphragm was exchanged at several occasions. After these replacements the activity went back to the starting point near ≈1,67 V which was even reached after 3000 hours at a current density of 0,4 Acm^{-2}. A vertical line indicates this potential for comparison.

A subsequent evaluation of the up-scaled electrodes was later carried out in GH stacks. In this part of the verification only a few promising candidates were tested. These included the optimized nickel based catalyst. The first round of verification was carried out on electrodes with a surface area of 270 cm^2. Based on the lack of a superior anode coating only HER or combined OER-HER coatings were up-scaled. Non-catalysed nickel was used as anodes.

The highlights from the up-scaling was that optimized nickel based cathodes operated at a potential as low as 1,71 V and 1,75 V in respectively the 270 and 700 cm^2 stacks at a current density of 0,4 Acm^{-2}. This corresponds to efficiency between 85 - 86 % vs. HHV at this current density – or more than 90 % at 0,2 Acm^{-2}. Both tests were carried out at 80 °C with non-activated nickel anodes (Figure 8). At 95 °C an efficiency of 88 - 90% vs. HHV was obtained at 0,4 Acm^{-2}.

Selected long-term results from tests with the 270 cm^2 electrode as well as IU curves from test with both the 270 cm^2 and the 700 cm^2 electrodes are reported in the following.
Figure 8 shows IU curves for tests with the optimized nickel cathodes in the 270 cm^2 and 700 cm^2 stack. Both measurements were made in a zero-gap configuration but with different geometries on the substrates.
It was determined that the performance of both the 270 and 700 cm^2 electrodes was almost similar despite of the differences in geometry and size.

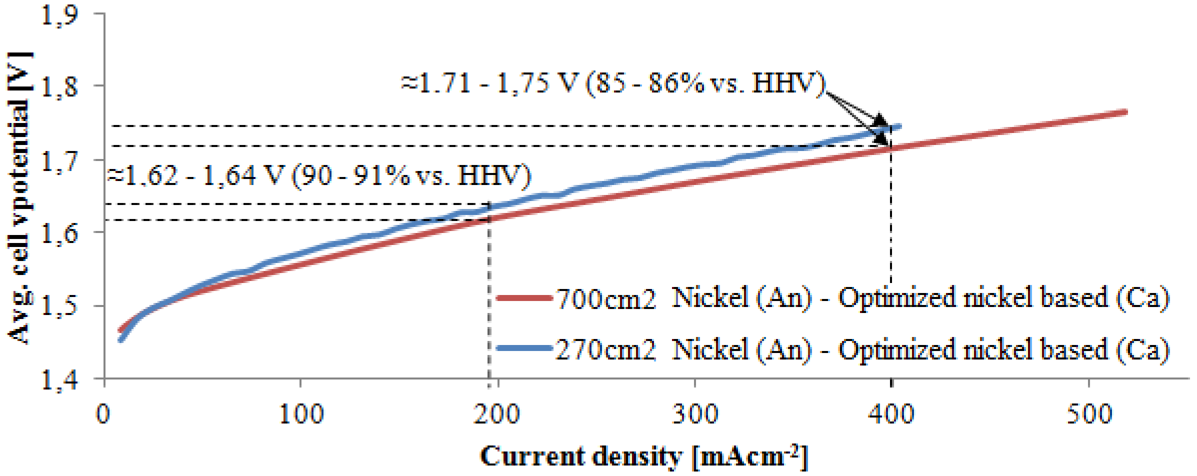


Figure 8: IU curves showing the cathode performance of optimized nickel based coatings in the 270 cm^2 and 700 cm^2 stack. In the case of the 270 cm^2 tests, the anodes were non-activated nickel on R05T109. In the case of the 700 cm^2 test the anodes were ZP100034. (80 °C and 30 wt% KOH).

At a current density of 0,4 Acm^{-2} an efficiency between 85 - 86 % vs. HHV was demonstrated at 80 °C. Figure 9 shows a series of IU curves from a test with the optimized coatings as either cathodes or for combined OER-HER. From this test it was found that there were only insignificant differences between cells operated with optimized nickel and non-activated nickel as anode coatings. This confirmed the observation from the test cell presented in Figure 6.

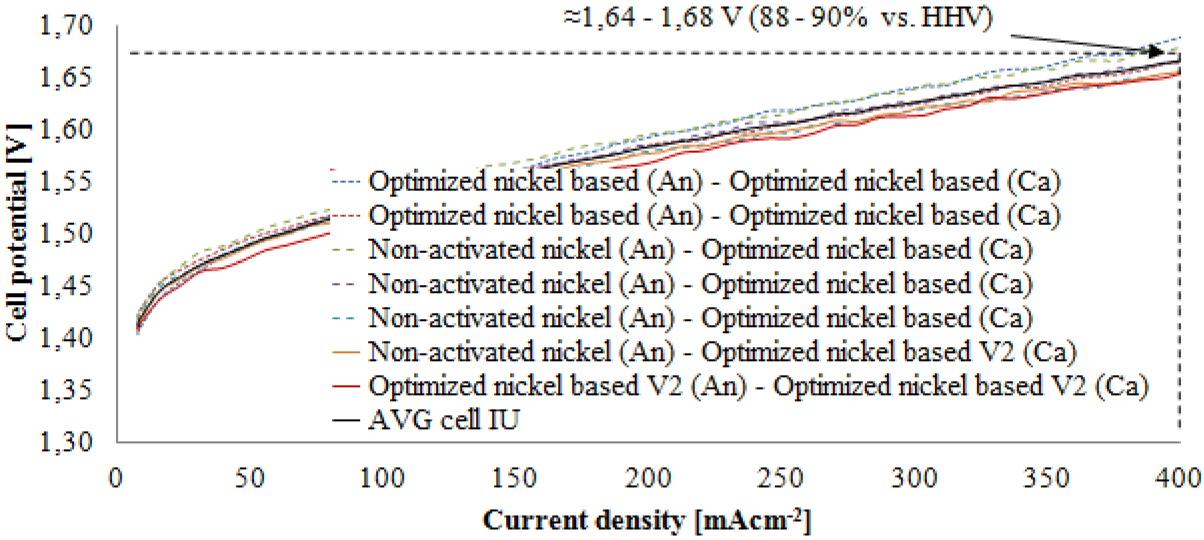


Figure 9: IU curve for a stack test with optimized nickel based zero-gap electrodes as either cathodes or as combined OER-HER coatings. Each curve represents one cell in a 270 cm^2 stack. (95 °C and 30 wt% KOH).

At a current density of 0,4 Acm^{-2} an efficiency between 88 - 90 % vs. HHV was demonstrated at 95 °C for the different optimized nickel based coatings.

Since the first version of Raney electrodes showed stability issues during electrolysis much effort was made to optimize this feature of the coatings. This was done by improving the process parameters for the manufacturing of these electrodes, constituting the two vital steps of proper heat treatment and leaching before ending up with the Raney structure.

From a population of 80 electrodes specimens Figure 10 shows how the percentage of intact Raney coating (y-axis) could be raised from average 62% to 99% by optimization.

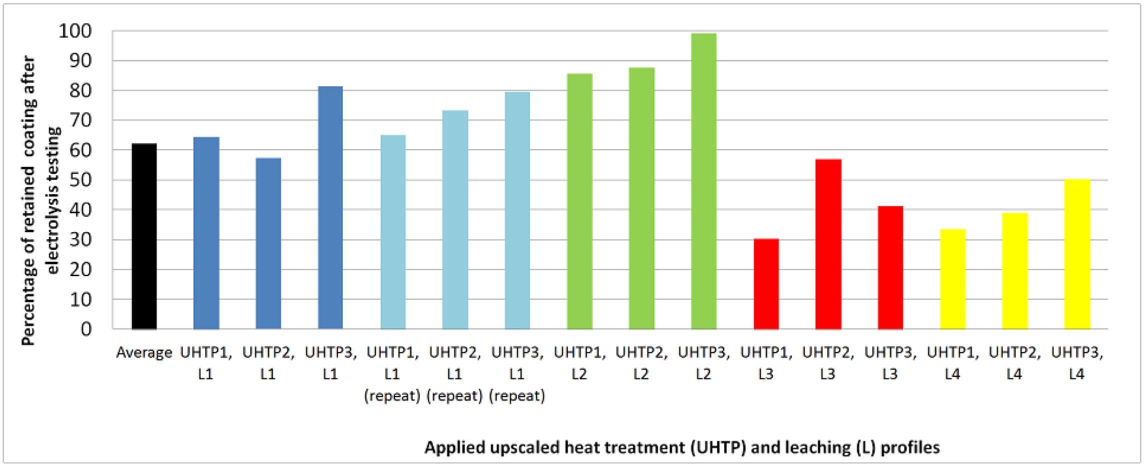


Figure 10: Percentage of intact Raney coating after 1 week of electrolysis depending on type of heat treatment 'UHTPx' and leaching procedure 'Lx'.

Whereas coating damage initially occurred within a day or two (at low current densities) for the original Raney catalyst the improved version could run stable with no coating failure for 1000h (at high current densities), as seen in Figure 11.

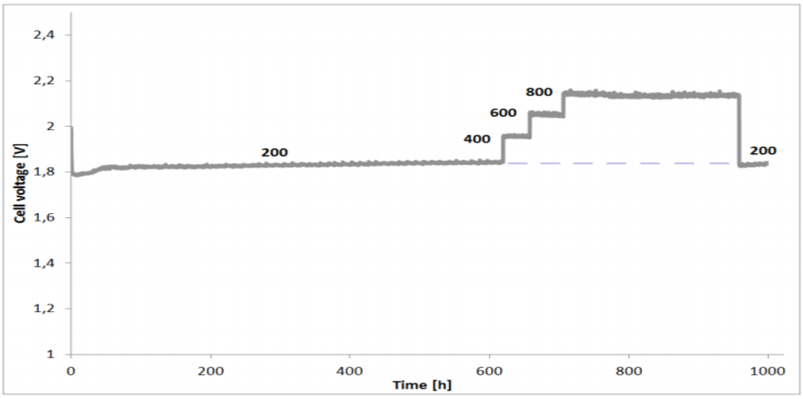


Figure 11: Electrolysis testing of improved Raney catalyst running at increments of 200-400-600-800-200 mA/cm2. When ramping up and afterwards down to 200 mA/cm2 the potential is restored.

Four batches of Raney electrodes were manufactured and tested in an industrial electrolyser at GreenHydrogen.dk for 3000 hours with full coating stability as result (Figure 12).

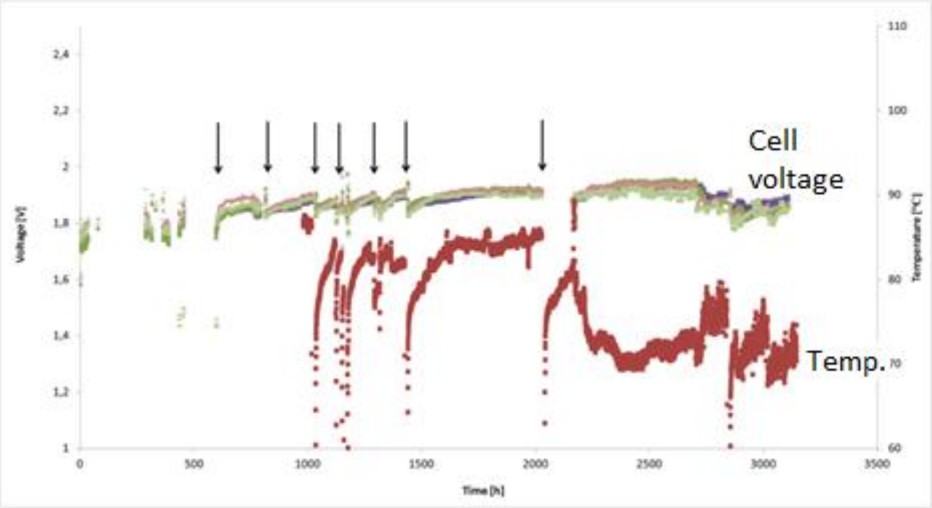


Figure 12: Left: Electrolysis testing of upscaled Raney electrodes for 3000h at 200 mA/cm2, right: SEM image showing intact Raney coating after test.

Near the project end a Raney electrode solution was also developed for zero-gap setup, which on short term showed activity comparable to the nickel-based electrodes, see Figure 13.

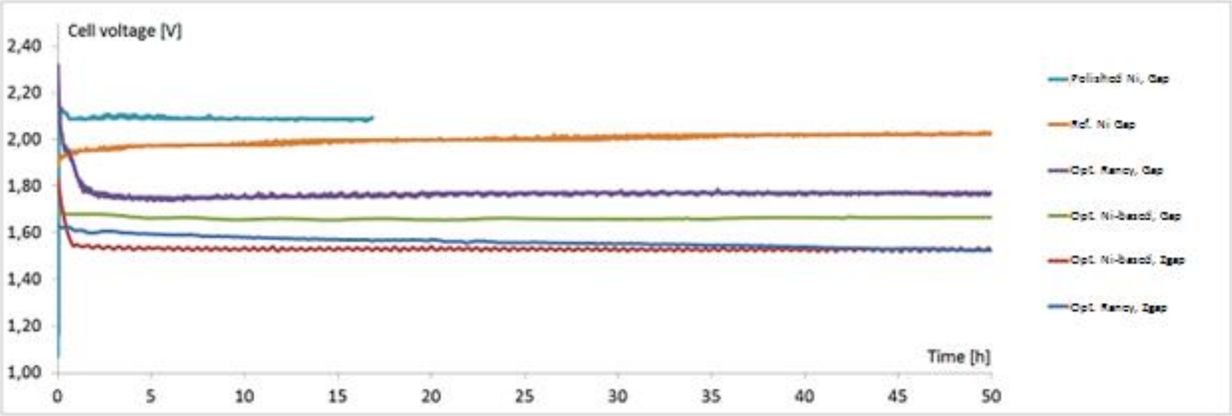


Figure 13: Comparison of electrode type and cell design (gap and zero-gap) tested under same conditions.

Conclusively, both sets of electrodes are considered as promising candidates for implementation in industrial sized alkaline electrolysers, both in respect to efficiency and durability.

5.2.2 Diaphragm

The state-of-the-art composite diaphragm material was identified and a scanning electron microscopic examination was conducted to see the micro structure of the composite diaphragm, i.e. promoting the understanding of how the composite diaphragms work. In Figure 14 two scanning electron micrographs are shown for the state-of-the-art composite diaphragm material. The micrograph to the left is an overview of the state-of-the-art diaphragm material. The micrograph to the right in Figure 14 shows a close-up of the same diaphragm here the inorganic particles can be seen as white particles and the grey strings are a polymeric material. The hydrophobic polymer works as a matrix fixating the hydrophilic inorganic particles. The amount of polymer on the surface and the pore size has a great influence on the composite diaphragm properties. Small pores give more capillary force hence a larger difference pressure across the diaphragm is necessary to press the electrolyte out. It is the electrolyte in the porous diaphragm which gives it, its gas separation capabilities. Too much hydrophobic polymer in the diaphragm surface will negatively affect the wettability of the diaphragm, thus lowering the ionic conductivity.

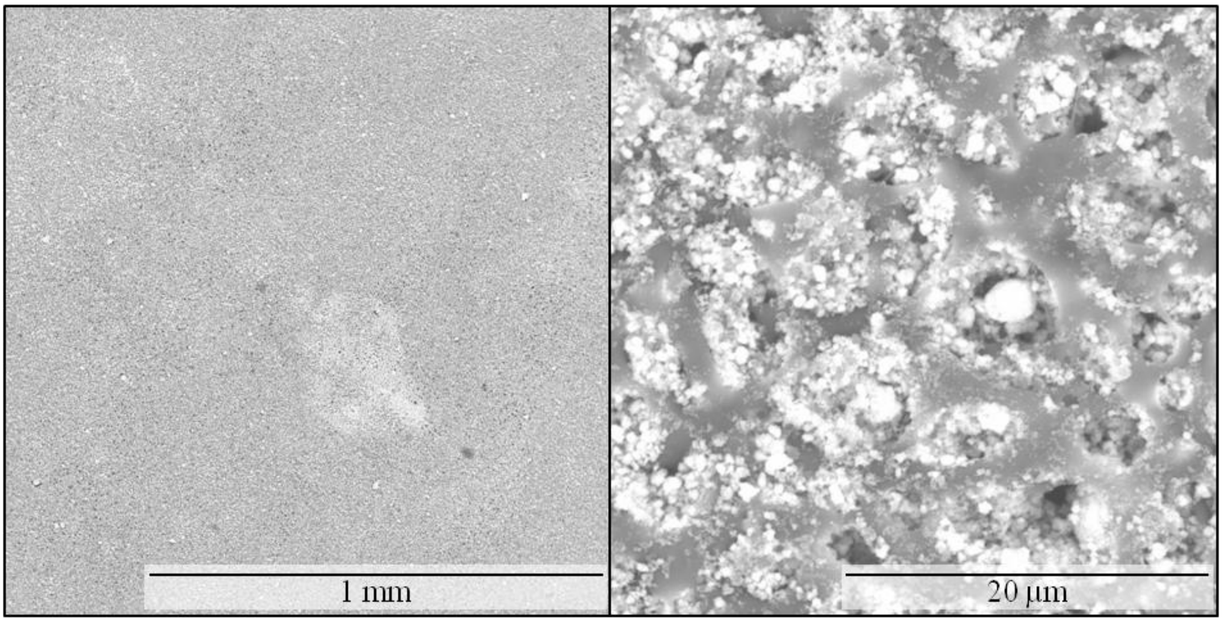


Figure 14: Scanning electron micrographs of state-of-the-art composite diaphragm material. To the left an overview and to the right a magnified section of the same material.

With inspiration from literature concerning casting of composite diaphragms and with the knowledge gained from the microscopic investigation of state-of-the-art, composite diaphragms were cast by Siemens Corporate Technology. Several different compositions and techniques were tested and evaluated by testing the ionic conductivity and gas separation properties while comparing the results to those obtained by the state-of-the-art diaphragm material.

By different compositions is meant different ratios between the inorganic and organic component as well as different inorganic components. Addition of pore former were also evaluated and found beneficial for the ionic conductivity.
By different techniques are meant different ways to cast the composite membranes. Either cast by the doctor blade method where the casting suspension is spread over a glass plate either with or without reinforcement and the overall thickness of the diaphragm is determined by a doctor blade. The other casting method is a continuous casting method where reinforcement always is used.

Two parameters were used to quantify the diaphragm material, the ionic conductivity and the gas separation properties. The ionic conductivity is supposed to be as high as possible to ensure as little as possible ohmic loss and hence loss in efficiency. The gas separation properties are tested by the ability to with hold a differential pressure across the membrane using a bubble point pressure (BPP) test cell. As a rule of thumb the higher BPP value the better is also the case here, however high BPP can be at the expense of ionic conductivity. Hence it should be the system (how good the differential pressure from anode to cathode chamber can be controlled) which determines how high a BPP that is necessary. In this project the differential pressure can be controlled well, rarely being more than 25-50 mbar, hence it was decided that a BPP of 500 mbar should be sufficient.

Results
In the Table 1 ionic conductivities for in-house cast composite diaphragms are presented together with the value for state-of-the-art diaphragm material for comparison.

Table 1: Ionic conductivity for in-house cast diaphragms cast using the doctor blade method.

Name	Inorganic	Reinforced	Conductivity [S/cm]
State-of-the-art			0.20
060813-1	With pore former	NO	0.30
200813-2	With pore former	NO	0.24
141113-1	With pore former	NO	0.26

As it can be seen from Table 1 good conductivities are achievable when a pore former is used. In most cases with an optimized casting procedure is used higher conductivities compared to state-of-the-art are achieved.

For the same diaphragms the bubble point pressures are listed in Table 2. It can be seen that all of them fulfill the requirement of above 500 mbar differential pressure across. However it can also be seen that the consecutive following measurements on the same pieces (the values after the forward dash) are lower or impossible to measure because the diaphragm burst (two asterisks).

Table 2: Bubble point pressure for in-house cast diaphragms cast using the doctor blade method.

Name	Inorganic	Reinforced	BPP [mbar]

State-of-the-art			2000
060813-1	With pore former	NO	735*/192
200813-2	With pore former	NO	792*/227
141113-1	With pore former	NO	1040**

* Violent bubbling
** Diaphragm burst

This is due to deformation of the diaphragm when applying a pressure across it. For the state-of-the-art composite diaphragm material this has been eliminated by incorporating a reinforcement mesh to give the structure improved strength.

The same where carried out during this project with the difference that a non-woven paper was used as reinforcement instead. In Table 3 the ionic conductivities for three reinforced diaphragm cast by a continuous casting method are listed.

Table 3: Ionic conductivity for in-house cast diaphragms cast using a continuous casting method.

Name	Inorganic	Reinforced	Conductivity [S/cm]
170614-2	With pore former	PS0020	0.22
291014-1	With pore former	PS0020	0.19
050515-1	With pore former	PS0040	0.11

It is clear that the conductivity goes down some when reinforcement is added, especially for the more dense reinforcement paper (Torcon PS0040 from Toray).

Concerning the bubble point pressure it can be seen that all are above the set threshold of 500 mbar, and the reinforcement have solved the deterioration for the following measurements, due to less deformation. In Table 4 the bubble point pressures for reinforced diaphragms cast with the continuous casting method are listed. Also due to the reinforcement, none of the diaphragms burst during testing.

Table 4: Bubble point pressure for in-house cast diaphragms cast using a continuous casting method.

Name	Inorganic	Reinforced	BPP [mbar]
170614-1	With pore former	PS0040	763/739
170614-2	With pore former	PS0020	643/648
291014-1	With pore former	PS0020	778/740

Hence it was during the project shown it is possible to cast in-house composite diaphragms which surpassed the state-of-the-art composite diaphragm material with respect to ionic conductivity and which fulfil the project specific requirements to gas separation properties.

Future development of diaphragms should emphasize on using mesh as reinforcement, then it is believed that also in-house cast reinforced diaphragm will surpass the ionic conductivity for the state-of-the-art composite diaphragm material.

Finally it should be mentioned that by using a continuous casting system and casting onto reinforcement it was easily achievable to cast several square meter of diaphragms at the time. In principle this could be up-scaled to a small-scale production.

5.2.3 Alkaline Electrolyser cell stack development

History

In order to introduce how the stack was developed for this project, we will start with a short resume of the stack development conducted by GreenHydrogen prior to this project. Previously two electrolyser stacks were developed by GreenHydrogen. One of them operating at atmospheric pressure and the other operating at high pressure.

The first stack ever constructed by GreenHydrogen, was an atmospheric zero gap electrolyser system, with a rating of 20kW@100mA/cm^2. Because of the atmospheric pressure, the system had a very large footprint, and would also incorporate a 30bar compressor system to be able to dry and store the produced hydrogen. The atmospheric system had a largely passive control system, where the natural lift from the gas production circulated the electrolyte, and a series of water locks controlled the water refill and pressure. While this system was in many ways simple and stable, it had many drawbacks because of the large footprint, causing the stack was relatively expensive in materials. As well as the entire system took up a lot of space.

The second stack developed by GreenHydrogen was an attempt to construct a high pressure electrolyser, operating at up to 30bar. This system was in many ways the antithesis to the first system, as the goal here was to reduce the footprint as much as possible, creating a compact unit, where the entire system including gas control and drying could be placed within a rack corresponding in size to a standard server rack, see Figure 15. The idea here was to modularize the system where a unit could produce anything from 1Nm^3 to 8Nm^3. This system did a lot of innovation, and had a lot of very good features, especially how to design a compact system and how to balance an electrolyser system under high pressure. However, for a commercial product, the unit price was costly compared to the gas output. And while the system was indeed a success for the purpose of testing electrodes and other technology in a field environment, and demonstrating electrolyser technology in smaller projects, the size of the unit was not sufficient to satisfy the demands in connection with solar/wind energy storage and hydrogen refuelling stations for cars. We still believe there are niche applications for a product like this, but the bulk of applications require larger scale electrolysers.

Figure 15. Small-scale electrolyser (kW-range) developed by GreenHydrogen.

Stack Development

When the HyProvide project started, it was quickly determined that the product development would need to be performed in stages, where the gap between the current electrolyser stack and the 250kW target would be bridged by an intermediate stack size, see Figure 16. The focus of the development was to have as much testing time as possible, so it was desired to have a machine that was operational on some level through the entire process. The following plan was agreed upon:

1. Designing a mock up gas control system using existing stack.
2. Designing a middle sized stack, running at 30-50kW.
3. Designing the prototype gas control system.
4. Designing the fully scaled cell stack (250 kW), based on the experience from the intermediate stack.

Figure 16. These cell frames are used for construction of the GreenHydrogen stacks. Left: cell frame developed prior to the HyProvide project (270cm2 active area). Center: cell frame for intermediate stack (705cm2 active area). Right: cell frame for target stack size for the HyProvide project (3000cm2 active area).

Intermediate stack

When beginning the development of the intermediate stack, the goals was to firstly improve on technical issues that had arisen in earlier versions of electrolyser stacks, and at the same time make a design we believed would be scalable to the full sized stack, with only limited conceptual changes. The design goals set for development of the intermediate stack was:

- Stack suitable for both Normal electrodes, and Zero-gab electrodes.
- Manifold and Port design to ensure even flow to each cell.
- Manifold and Port design to reduce parasitic currents.
- As few unique parts as possible
- Polymer cell frames manufactured by injection moulding

The first prototype constructed of the intermediate design, was a 5 cell stack, made from machine milled frames, for the purpose of testing if the overall concept was good. The milled frames were also fitted with probes to measure the cell voltage of each individual cell. A feature that is not available for standard frames. This 5 cell stack seemed to be a success, and from that, minor adjustments were made to the design to accommodate injection moulding, and subsequently, a tool was made, and a batch of cell frames was produced. During the next several months, a series of tests where made with stacks of increasing length. And in this time, a lot of the infrastructure in the laboratory and system was also developed to accommodate the increasing gas production capacity. The development of the intermediate stack, culminated in the test of a cell stack with 98 cells, see Figure 17. A significant amount of effort was put in to investigations of properties of various polymer materials for cell frame construction, see Figure 18 and Figure 19. This was in order to find the best suited material and furthermore to prove its stability for long-term operation in the electrolyser.

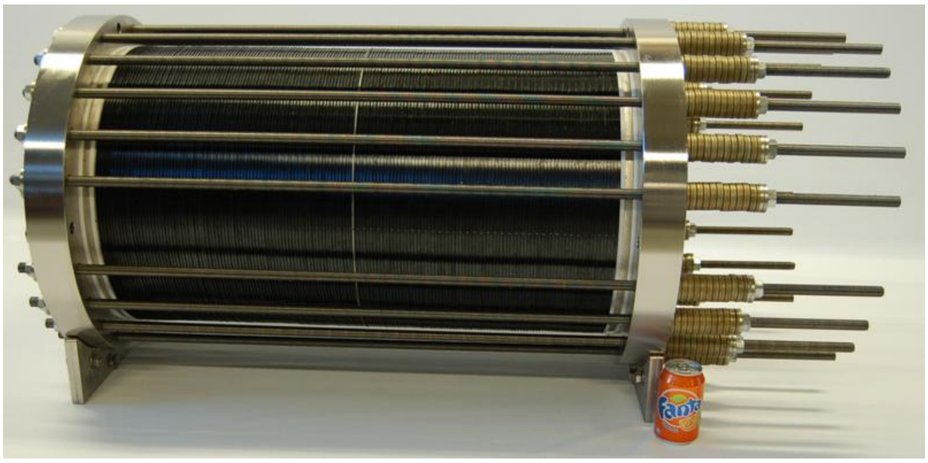


Figure 17. Intermediate stack size developed in the HyProvide project.

250kW stack

After concluding the intermediate stack test a success, production and experimentation of the fully scaled stack was undertaken. For the most part, the design choices for the intermediate stack was good, and what choices was not good, could be improved upon. And finally, there were some areas where direct scaling was not possible, so a series of new solutions was developed. The stack is seen in *Figure 2*.

The most radical change for the final system, was the desire for implementing a fully Ni coating of the electrolyte circuit (e.g. nickel coated vessels and fittings). This was done in order to avoid impurities from e.g. stainless steel to have an unfavourable impact on the electrolyser efficiency. Any eventual loss of efficiency is when all things considered not large, but it is still worth taking into account. Another factor that was observed during the development was also that stainless steel exposed to high anodic over potential would erode over time. The problem was solved by coating all metallic surfaces in the stack with Ni. And for some select parts, manufacture these in pure Ni, Monel or Hastelloy alloy grades. (More on corrosion protection later)

Electrode Geometry

When designing an alkaline electrolyser, you need to make the design decision if the electrodes should have Gap or Zero-Gap geometry. The Gap geometry is the simplest concept, where the electrode consists of a simple metal sheet that operates as a bipolar electrode. This design is the least efficient design, because it leaves an electrolyte distance between the electrodes. The Zero-Gap geometry reduces the gap between electrodes in the bipolar stack, by placing perforated electrodes on each side on the metal sheet slightly elevated, so when the stack is assembled, these electrodes will press up towards the membrane, leaving a very short electrolytic distance between the electrodes. The technical challenge with Zero-Gap electrodes, is to make a design that is cost efficient from a manufacturing perspective. And the solution for this project was to use full Nickel alloy electrodes, and fixate the perforated electrodes to the bipolar plate by spot welding.

Figure 18. Tensile test bars made from different polymer types are tested in order to find the most suited polymer material for the cell frame. Mechanical strength, thermal and chemical stability of the polymer materials is investigated.

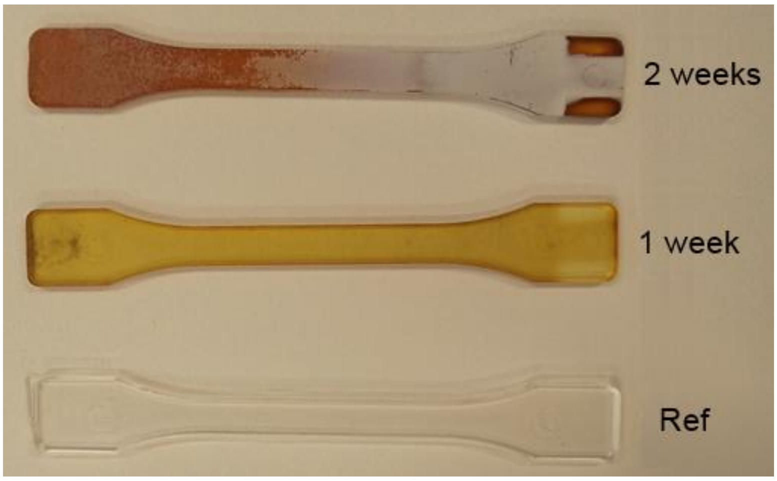


Figure 19. After being exposed to a combination of a highly aggressive chemical environment and elevated temperature for two weeks, this polymer test sample shows significant weight-loss and change in visual appearance. For this reasons this polymer is found to be unsuitable for cell frame material.

5.3 WP2B – AEC System Development

As mentioned earlier, the electrolyzer control system and auxiliary systems was developed in tandem with the development of the stack. To give an overview of the system, we can start with presenting the primary components an alkaline electrolyzer system.

- Separator - Separates electrolyte from gas.
- Scrubber – Prevents aerosolized electrolyte from escaping the system
- Differential Pressure Control – An elaborate system to ensure equal pressure on H2 and O2 side.
- Process Cooling – Cooling of electrolyte and Gas
- Deox – Purification of H2 by catalytically burning away residual O2
- Dryer – Water removal by Temperature Swing Adsorption (TSA)

Describing the development in broad terms, the first challenge was to make a bare minimum electrolyzer system that could operate under pressure.

For this very first iteration of the system a temporary separator and scrubber was designed and manufactured. The cooling problem was initially solved by integrating a cooling jacket on the separator. Level sensors, flow sensors and pumps were procured, mounted and connected with compression fittings. The control system was mocked up using solenoids valves,

back pressure regulators mass flow controllers, temperature, pressure and gas sensors. A PLC system was used for controlling and data logging. And during this development, the construction of a more elaborate data logging infrastructure was begun.
All the procured components were mounted in a test rack assembled from square steel profiles, mounted on a sturdy drip pan. The advantage of this approach was that we could with relative ease modify the frame, to test different positions for the components.
Aside from the big main components mentioned, all valves, regulator and sensors where placed on the horizontal panels, in order to reduce footprint, but still be able to remove the panel in case of major maintenance.

Balance of Plant

The great challenge once the physical machine was built, and a basic control system was programmed, was to build a robust control system for high pressure operation. The basic problem with operating on high pressure is that the machine is very vulnerable to pressure differential, as the H2 and O2 sides are connected hydraulically through the electrolyte. And since one mbar of pressure differential is equal to roughly 1cm of water column, the observant reader will quickly realize that even small fractional changes in the absolute pressure when operating on 40bar, will result in a relatively large electrolyte displacement.
With this problem in mind, the approach to build the system was to first make a system that could operate on atmospheric pressure, or very close to it, and then slowly increase the operational pressure as the system became increasingly more fleshed out. Developing a system with stable operation at higher pressures was a significant challenge, but after many trials and different configurations, we believe we have found a series of methods that are very suitable for achieving stable and resilient system.

Corrosion Protection

While carbon steel in itself is quite resistant in alkaline environment, it does however have problems with strong alkaline solutions at high temperatures. The same have also been experienced to be true for stainless steel, as the chrome would slowly leach out and pollute electrodes.
After some research, it was determined that there are only one family of alloys that is suitable for high temperature alkaline solution, and that is Pure Ni, and alloys with high Ni content (~>50%). So with this in mind, we worked towards building the entire system that was in direct contact with Electrolyte with either Ni or Ni-alloy surfaces.
For parts that needed to be machined, such as fittings, Monel was the material of choice, since it is the cheapest in the family, and the most easily machined. For tube segments, Pure Ni tubing was used. The circulation pump that was chosen was magnetically coupled, with hastelloy housing. And for the remaining components, where it was too expensive to build them fully in Ni-alloys, these where build in carbon steel and exposed surfaces coated with nickel. However, since the geometries of the tubing system in itself is full of cavities, concave and convex shapes, galvanic plating these parts was not an option. So the method used was chemically depositing the Ni, also called electroless Ni-coating.

Full Scale Prototype

The specifics of the fully scaled prototype have been discussed in greater detail in other parts of this report, so this section will be limited to description of the development process. After the intermediate electrolyzer stack was completed, the currently seen Electrolyzer module, as well as all its contents was developed. A great deal of the sensors, pumps, valves and the control system was moved from the first prototype into a freshly manufactured rack, which in time would become the fully scaled prototype. At this time, all the pressure vessels for a fully scaled system was designed manufactured, complete with corrosion protection for components with direct contact to electrolyte. From this point on, the system was in many ways complete. Our experience has been that the system from a balance of plant perspective became much more stable with the increased volumes of fluid. Though as the capacity of the electrolyzer stack was increased (from 12 - 60 Nm^3/h), we had some concerns that the system would become unstable. However, this turned out to be much lesser of an issue than expected.

Figure 20. Bare minimum electrolyzer system build in the HyProvide for testing purposes.

Manufacturing & cost and evaluation
From the beginning of the project it has been a goal that the machine should be designed to accommodate mass production. The main concept is that all components of the machine are sourced externally, and all assembly is then done in a GreenHydrogen Factory. When the Machine leaves the manufacturing line in GreenHydrogen, it will be fully assembled and tested, with all major components assembled in racks/cabinets suitable for transportation. These components can then be installed in either a high cube container, or any site with equivalent footprint available.

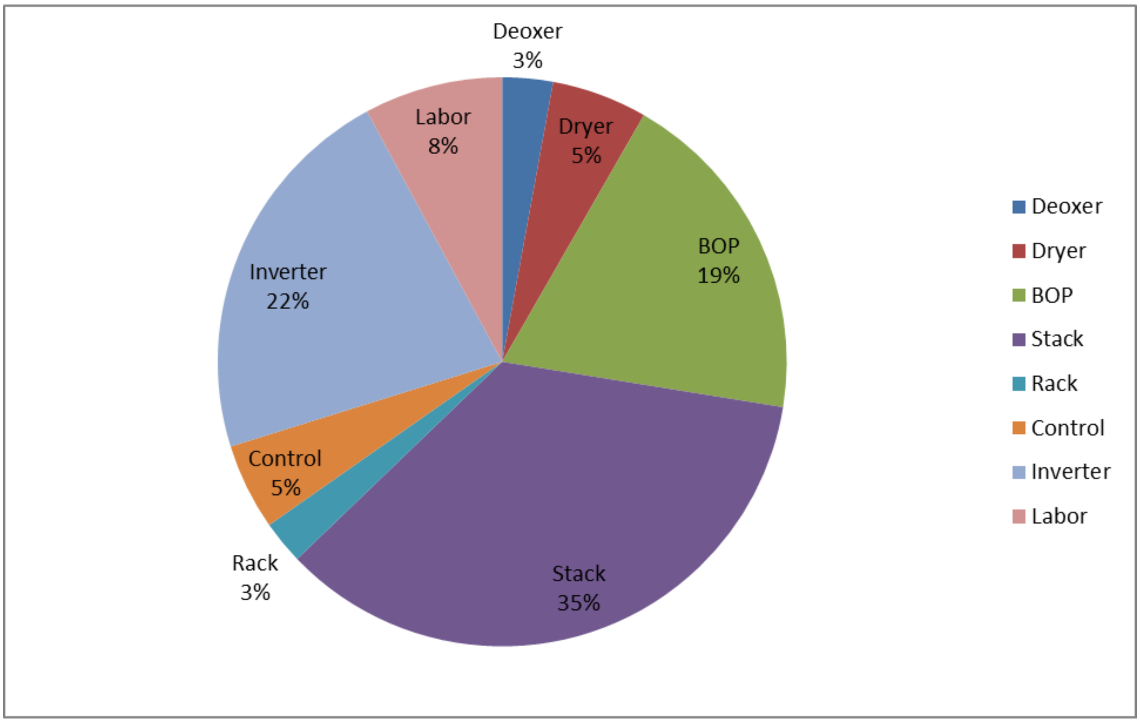
The general manufacturing strategy have been to purchase standard components from vendors when available (Sensors, valves, bolts etc.), and custom design components where no components exist (Electrodes, Stack cell frames, Pressure vessels etc.). To keep the cost low, there has been focus on keeping the number of unique parts as low as possible, which applies both for the standard components, as well as the designed components. As an example, it can be mentioned that one core features of the stack, is that all cell frames are identical, so only one injection molding tool was necessary for manufacturing all cell frames.

To support the manufacturing strategy, a database has been constructed, that contains all parts and components used in the machine, as well as component price, supplier information, and alternative supplier.
This approach have enabled us to have an overview over the production cost during the entire development process, as well as it is a great tool for identifying cost drivers and give an overview over where cost can be reduced, and by how much.
At the end of the day, we are therefore able to determine the exact material cost of the prototype, and from there, it is possible to calculate a reasonably accurate manufacturing cost, including labor for future manufacturing of the electrolyzer system.

The overall goal has been met at a production price of 30.000 kr./Nm3 in 2016. And with increased production volume, as well as components optimization, we believe it will be possible to reduce this price to 20.500 kr./Nm3 in 2020

Current production prices for Hyprovide 250 including Inverter (60Nm3/h)

• Prototype price including labor	DKK 1.779.665 (EUR 238,561)
• Estimated price on low volume 10 pcs.	DKK 1.513.999 (EUR 202,949)
• Labor included	400 hour
• Cost /Nm3	DKK 25.229 (EUR 3,382)
Accessory cost	
• Service module	DKK 22.350 (EUR 3000)
• Water treatment	DKK 18.650 (EUR 2500)
• Cooling	DKK 22.350 (EUR 3000)



Cost distribution in prototype

Future production prices 2020 Hyprovide 375 (90Nm3/h)

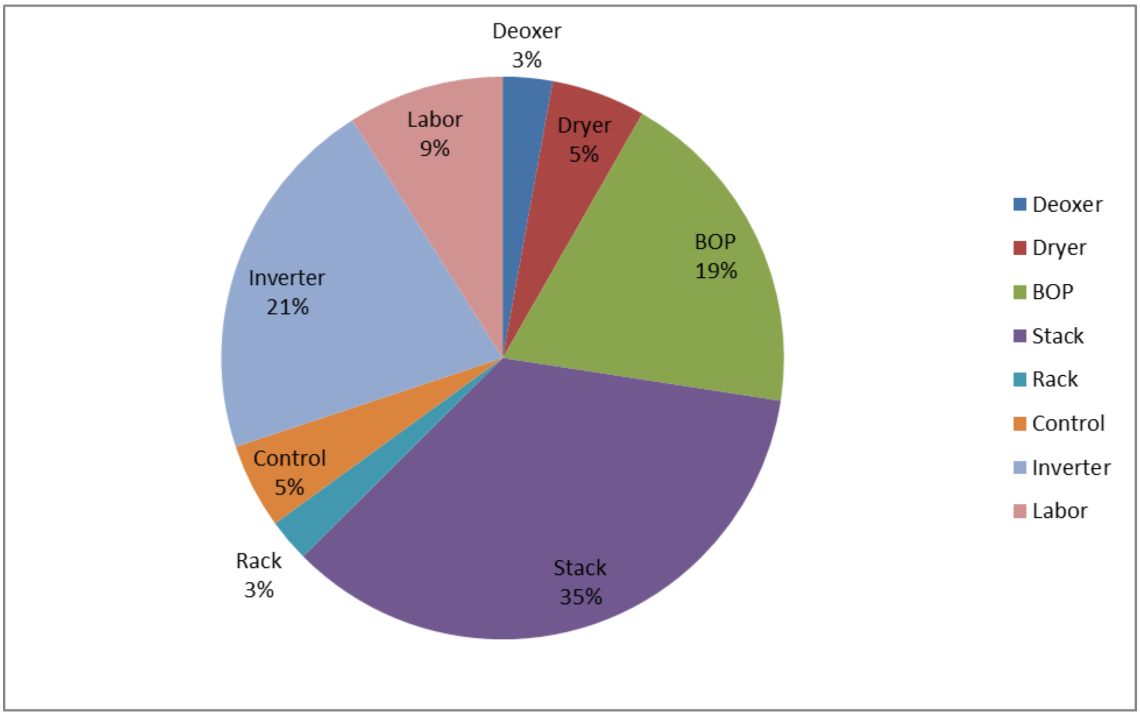
While the maximum current density of the prototype is set to 400mA/cm^2, a series of laboratory tests of the electrodes, reveal promising signs for increasing this capacity to 600mA/cm^2.

Increasing the capacity in such a way will result in some dimensioning changes of the remaining system, but nothing that should affect the overall price in a significant way. Breaking down the manufacturing cost to include the expected 30% cost reductions on parts and components, as well as the increasing the overall production capacity by increasing the current density, we can calculate the future expected cost per Nm^3 hydrogen production capacity.

- Cost reduction
    - Increase in current density from 400mA to 600mA/cm2
    - Cost reduction parts 30 %
- low volume 20 pcs. DKK 1.330.446 (EUR 178,344)
- Labor estimated 400 hour
- Cost /Nm3 DKK 14.785 (EUR 1,982)

Accessories for installation

- Service module DKK 18.650 EUR 2500
- Water treatment DKK 18.650 EUR 2500
- Cooling system DKK 22.350 EUR 3000



Future Cost distribution 2020 Hyprovide 375 (90Nm3/h)

5.4 WP2C - AEC Laboratory Test

The large-scale electrolyser unit developed in this project has been thoroughly tested in order to provide a proof-of-concept describing the technical feasibility of the system. The system in combination with increasing stack sizes has been tested throughout the project. Initial tests were conducted using the GreenHydrogen 270 cm2 stack available prior to project (see Figure 21). Further on, tests were conducted using the developed intermediate stack size (705 cm2) - starting out with 5 cells and eventually increasing stack length up to 98 cells, see Figure 17. Once the target stack size (3000 cm2) was developed, we started with 8 cells and eventually build a stack consisting of 98 cells capable of handling about 250 kW of electrical power. Summing up all time in operation (i.e. power supplied to the stack and the stack producing hydrogen and oxygen) during the HyProvide project yields 4400 hours (705 cm2 stack and 3000 cm2 stack). A more detailed summary of operation and operating conditions is given in Table 5. The nominal current density for the stacks/electrodes is 400 mA/cm2, however operation at higher current densities is possible. In order to investigate operation above the nominal operating point, the 705cm2 stack was occasionally operated at 600 mA/cm2. Due to limitations of the power supply is was not possible to operate the 3000 cm2 stack above 400 mA/cm2. As discussed earlier in this document, the mechanical strength of the 3000 cm2 was improved compared to the 705 cm2 stack. Thus, the 3000 cm2 stack may be operated at higher pressure. In the HyProvide project, however, the 3000 cm2 the stack has been operated only up to 20 bar (which is only 50% of the nominal operating pressure of 40 bar). The reason for this lower test operating pressure is that the stack construction used for tests in the HyProvide project incorporates a number of temperature and electrical sensors for in-situ stack diagnostics. These sensors do not allow operation at more than 20 bar. The sensors have been used for verification of proper operation of the stack and are not needed further on. Hydrostatic testing of the 3000 cm2 stack construction using water at room temperature have shown that the stack can withstand more than 70 bar.

Table 5. Summary of operation during the HyProvide project.

Stack	Start-up date	Time in operation	Current density	Pressure	Temperature
705 cm^2	October, 2013	3350h	20 to 600 mA/cm2	0 to 30 barg	20 to 90 deg.C
3000 cm^2	May, 2015	1050h	20 to 400 mA/cm2	0 to 20 barg	20 to 80 deg.C

Figure 21. Alkaline electrolysis stack available from GreenHydrogen prior to the HyProvide project. Active electrode area: 270cm^2

Generally, the tests of the developed electrolyser unit and stack have been successful. As discussed earlier in this document various technical challenges did arise on the way. But in every case counter measures were developed and implemented, resulting in a stable fully functional electrolyser unit. A large amount of experimental data has been collected during the testing of the system. These data include e.g. temperatures, pressures, electrical current and potential, electrolyte level in separators, etc. Evaluation of the electrolyser performance has been based on careful analysis of these data. Furthermore, the data are collected and stored in a database and therefore available for future analysis. In the following we present examples of data collected through the HyProvide project.

Stack efficiency, IU-curve

The efficiency of the conversion from electrical energy to hydrogen can be determined from the cell electrical potential at a given current density. Using the thermoneutral voltage of 1.48V the stack efficiency is obtained as 1.48/U_{cell}, where U_{cell} is the stack average cell potential. Figure 22. IU-curve obtained from measurements performed with the HyProvide 250 electrolyser unit. shows an example of an IU-curve obtained from measurements performed with the HyProvide 250 electrolyser unit. In the present measurement the unit was equipped with the 3000cm2 stack with 98 cells (unit and stack are shown in Figure 2. Prototype of the HyProvide 250 electrolyser unit being tested in GreenHydrogen's laboratory.). The stack used for the measurements was equipped with zero-gap electrodes, which were treated with state-of-the-art catalytic active surface coating developed in the HyProvide project (described in detail in Section 5.2.1). New manufacturing facilities were established in order to treat the full-scale (3000cm2 = Ø60cm) electrodes with the surface coating, which was developed on a much smaller scale in the laboratory. From the figure it can be seen that at 400 mA/cm2 the average cell potential is 1.76 V. This corresponds to an efficiency of 85% (electricity to hydrogen), which is a satisfactory result at 80 deg.C. As a side note it can be mentioned that a diesel generator (see Figure 23) was necessary in order to supply the required electrical power to the stack (at 400 mA/cm2 the stack consumes about 250 kW). The in-house electrical supply available in GreenHydrogen's laboratory was not sufficiently powerful.

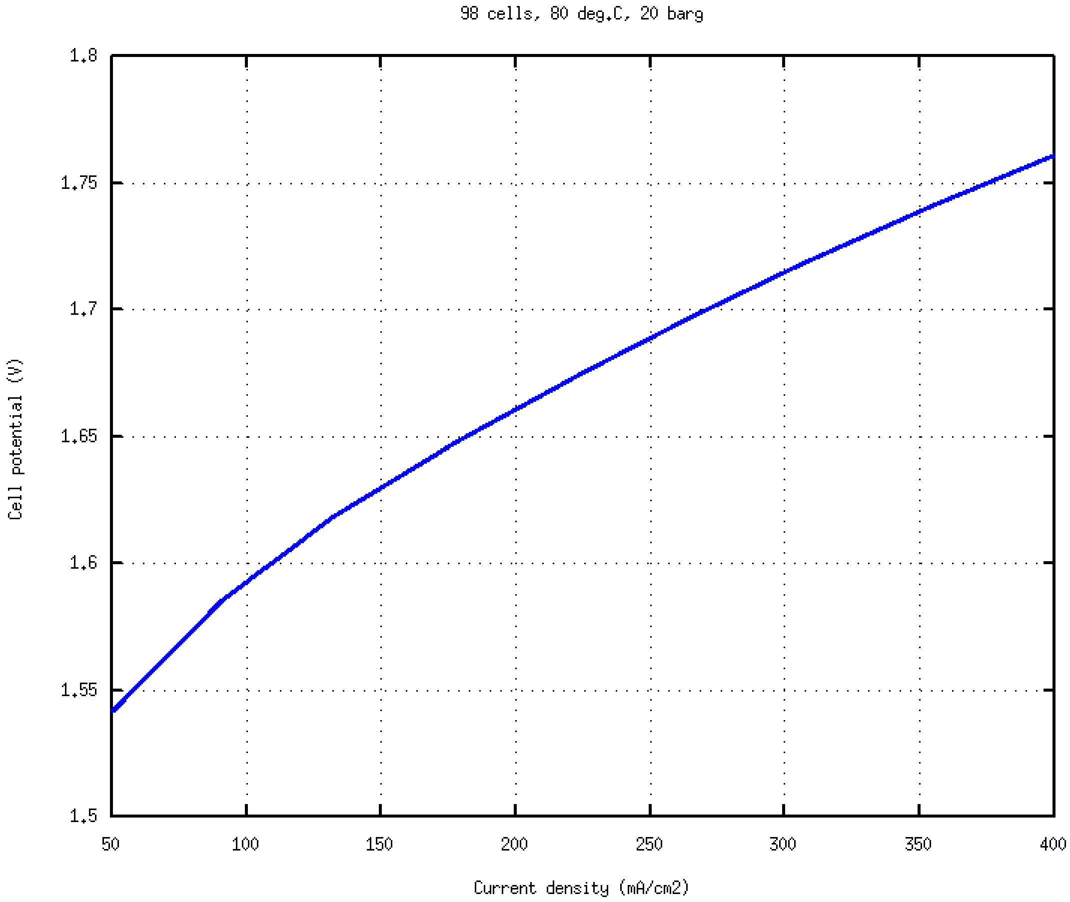


Figure 22. IU-curve obtained from measurements performed with the HyProvide 250 electrolyser unit. Stack: 3000cm2, 98 cells. Temperature: 80 deg.C. Pressure: 20 barg.

Figure 23. Diesel generator outside GreenHydrogen's laboratory in Kolding. The diesel generator supplies electricity to the electrolyser unit and stack located inside the building.

Dynamic operation

In several applications involving large scale hydrogen production by electrolysis, the electrolyser is connected to the electric grid. Today and in the years to come, an increasing amount of the energy in the electric grid come from renewable sources. Due to the intermittent nature of renewable energy, grid connected electrolysers must be capable of highly dynamic operation (e.g. fast load ramp-up/down). In order to investigate the capability of dynamic operation of the HyProvide 250 electrolyser unit developed in this project a number of tests were conducted. An example of data collected during a fast ramp-up of the electrolyser is show in Figure 24. The data presented in the figure shows a ramp-up from 10% to 100% of the nominal load of 400 mA/cm2 in about 4 seconds. The system differential pressure and the levels of electrolyte in the gas separators show no sign of instability, indicating that the system is capable of dynamic operation at this time scale.

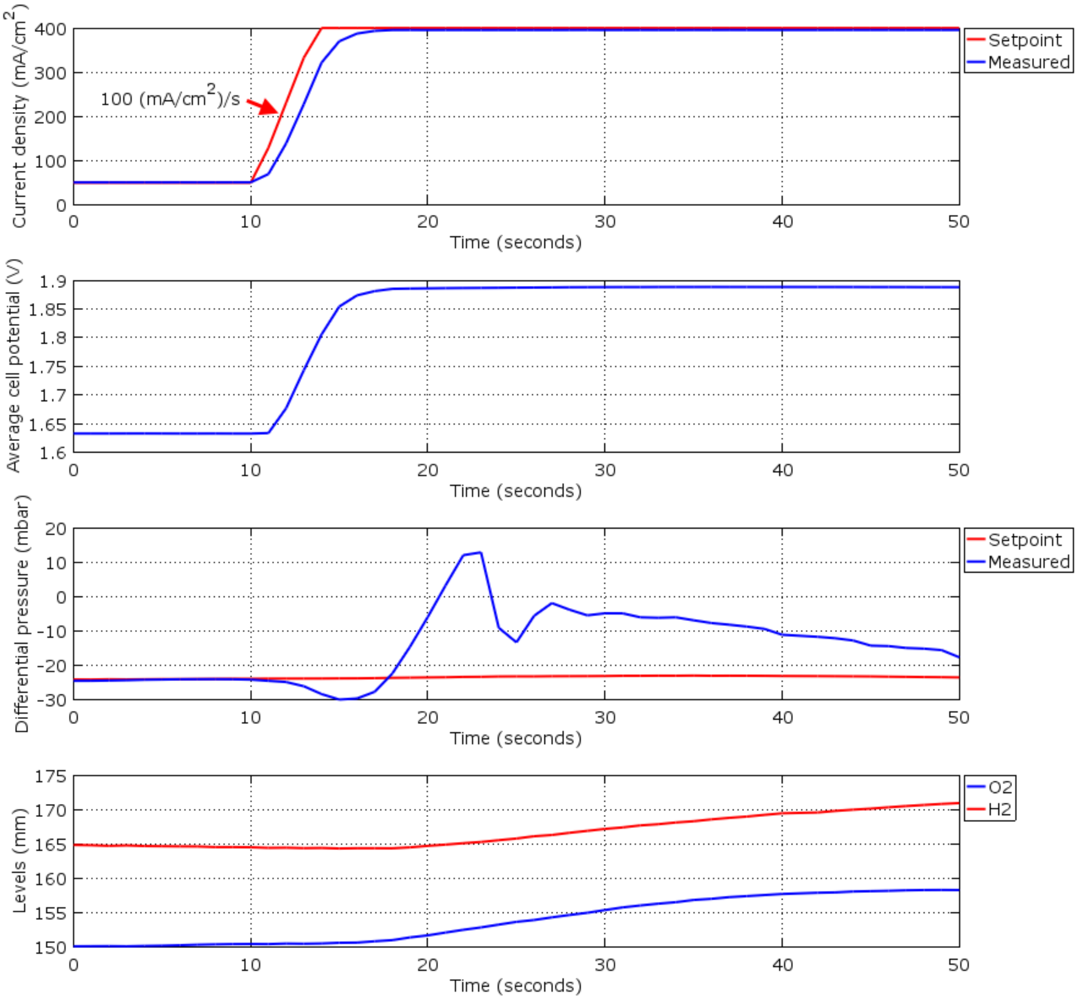


Figure 24. Ramp-up from 10% to 100% of the nominal load of 400 mA/cm2 in about 4 seconds. Temperature: 80 deg.C. Pressure: 20 bar.

Gas quality

Inside the stack H2 and O2 are separated by a diaphragm. It is desirable that the two gasses do not mix. A high degree of mixing of H2 and O2 leads to safety hazards. Furthermore, depending on the use of the produced hydrogen a high degree of purity may be required. Continuous measurements of the gas qualities of the hydrogen and oxygen produced by the cell stack of the HyProvide 250 electrolyser unit during dynamic/varying load profiles have been performed. The electrolyser being the subject for the measurements described in the following contains a 3000cm2 stack with 98 cells. The electrolyser operating pressure is within the range of 16 to 20 barg. An amount of the produced hydrogen or oxygen gas from the cell stack is guided to a gas analyser. Several meters of plastic piping connect the electrolyser unit/cell stack and the gas analyser. The gas analysed has not been subject to any gas conditioning. The particular gas analyser used is the SERVOFLEX MiniMP (5200) high performance CO_2 and O_2 gas analyser.

Figure 25 shows an example of data illustrating the purity of the produced hydrogen. Presented in the figure is the current density, differential pressure, electrolyte temperature, and fraction of O_2 in the H2 during a time interval of about 5 hours. As can be observed from the figure the current density has been alternating between 40, 80, and 350 mA/cm^2. This corresponds to 10%, 20%, and 87.5%, respectively, of the nominal load of 400 mA/cm^2. Generally, the fractions of O_2 reach stady states of about 0.4%, 0.5%, and 0.65% at loads of, respectively, 350, 80, and 40 mA/cm^2. These measurements show that the gas qualities remain stable also in the case of dynamic operation.

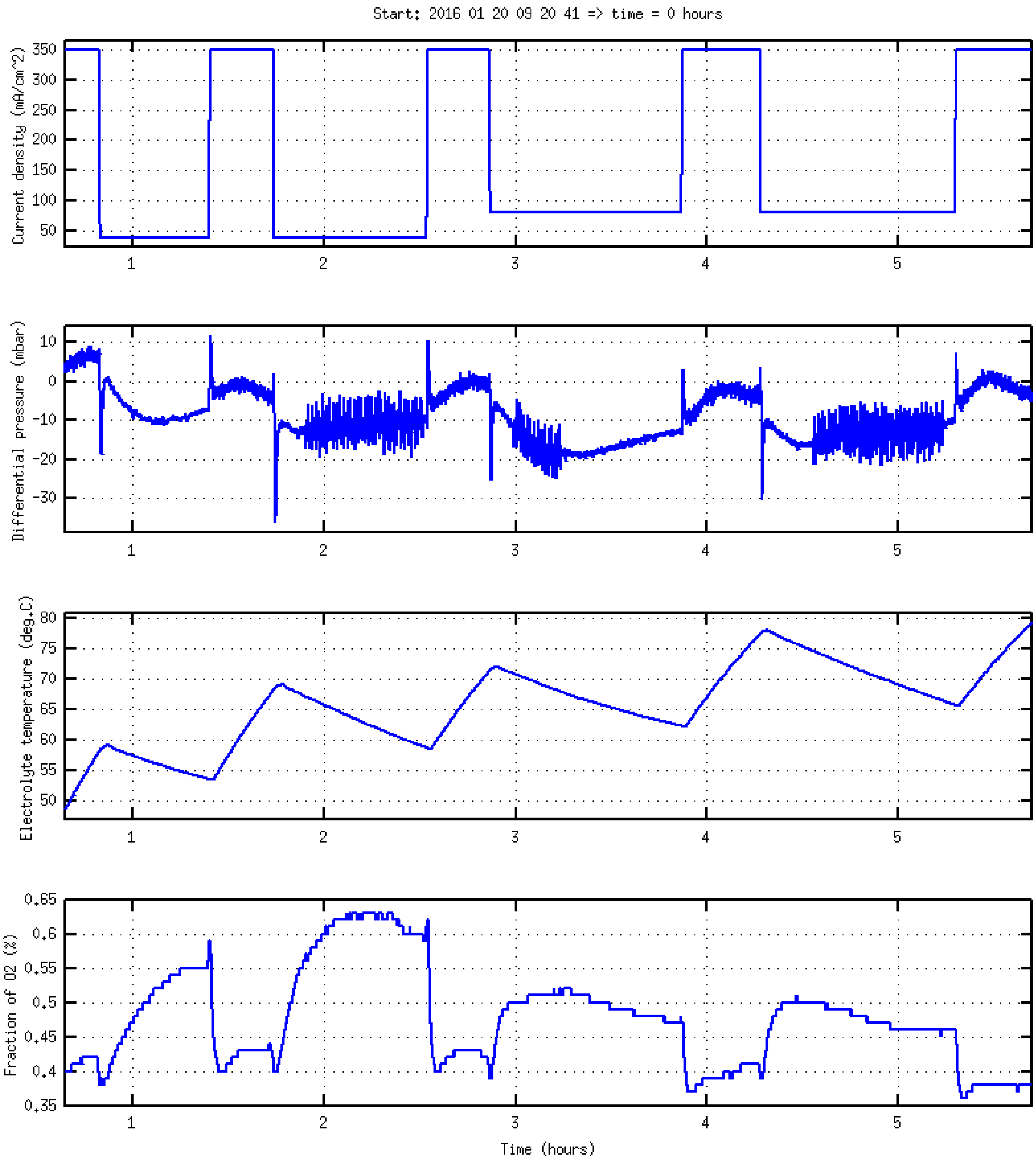


Figure 25. Purity of the produced hydrogen under varying load profile.

Compliance review

Ensuring the machine can be approved has largely followed the same approach as the sourcing of components and manufacturing. For the most part, we aim to purchase components that already have the relevant approvals (for our case, it is mostly ATEX approval that is relevant). In the same vein, for many custom made components, such as the pressure vessels, the PED and CE approval of these can be performed by the supplier. This leaves us with 2 approvals that must be taken care of directly by GreenHydrogen. The CE Approval of the Stack, and the CE approval of the overall system.

To ensure no sudden setbacks, we have therefore made use of external consultants through the development process, and had our overall concept reviewed. And from the feedback by our consultants, we expect the overall system to pass approval.

Remarks on future potential of alkaline water electrolysis

The efficiency of water electrolysis increases with the temperature due to higher conductivity in the electrolyte and higher electrochemical reaction speed at the electrodes. Therefore the higher operating temperature of the electrolysis cell, the higher efficiency can be obtained. It means more of the applied electrical energy is used for hydrogen production and less for heat generation. At a certain temperature all electricity will be used for converting water into hydrogen and oxygen and no heat is produced. That is when the cell voltage reach 1.48 V called the thermo neutral voltage. At this temperature and voltage the efficiency is said to be 100%. For the electrodes developed in this project, the cell temperature where 100% efficiency is reached is 156 degree Celsius. Therefore at temperature below 156 °C the cell is producing heat and above it is consuming heat.

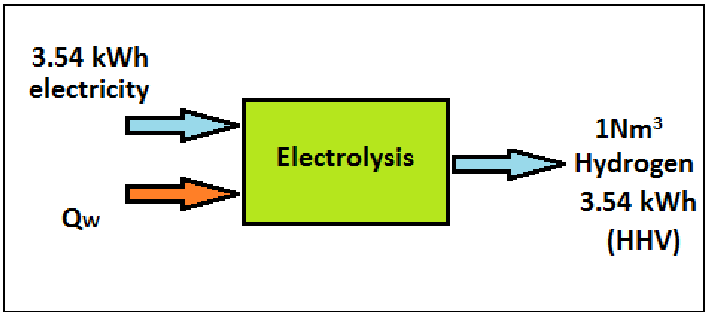


Figure 26. Efficiency of water electrolysis.

The water to be split into hydrogen and oxygen has to be heated to the temperature of the electrolysis cell. This requires energy. To heat the 0.8 kg water needed for production of one cubic meter of hydrogen, from 25 °C to 156 °C takes 0.123 kWh. Because the cells are pressurized the water will not boil into steam, which would have required extra supply of energy.

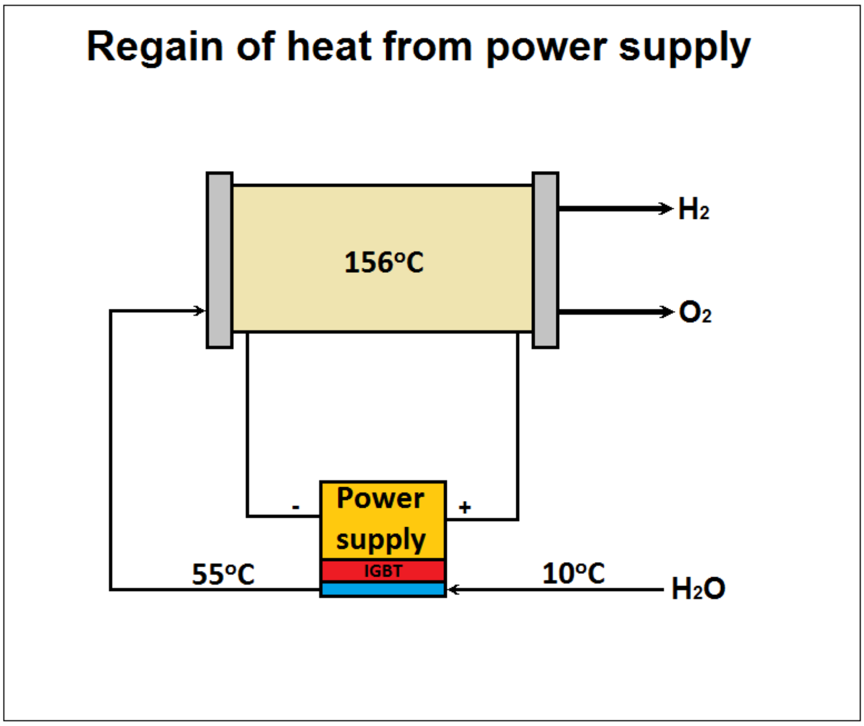
The energy content in 1 Nm^3 (Normal cubic meter) of hydrogen is 3.54 kWh. Therefore the energy needed to produce 1 Nm^3 hydrogen will as a minimum be 3.54 + 0.123 = 3.663 kWh. And the efficiency will be 3.54/3.663 = 0.966 or 97%.

High temperature electrolysis as solid oxide electrolysis cells (SOEC) operates at a temperature of 750 °C in order to obtain cell efficiency of 100%. Due to the SOEC technology the water supply must be in the form of steam. Therefore the feed water first is heated from tap water temperature to 100 °C, and then evaporated to 100 °C steam.
Heating of 0.8 kg water from 25 to 100 C takes 0.070 kWh, evaporation takes 0.502 kWh in total 0.572 kWh.
The energy needed to split steam into hydrogen and oxygen is only 3.1 kWh/Nm^3.

The theoretical minimum energy needed to produce 1Nm^3 hydrogen is there for 3.10 + 0.572 = 3.672 kWh. And the efficiency maximum 3.54 / 3.672 = 0.964 or 96%

The reason for the lower SOEC efficiency is that the lower energy of 3.1 kWh/Nm^3 to split steam to hydrogen and oxygen, compared to the 3.54 kWh/Nm^3 for water, can not compensate for the 0.502 kWh/Nm^3 it requires to evaporate the water to steam.

In order to increase the efficiency and cool the power supply delivering the DC power to the electrolysis process, the feed water can be preheated by the power supply before entering the electrolysis stack.



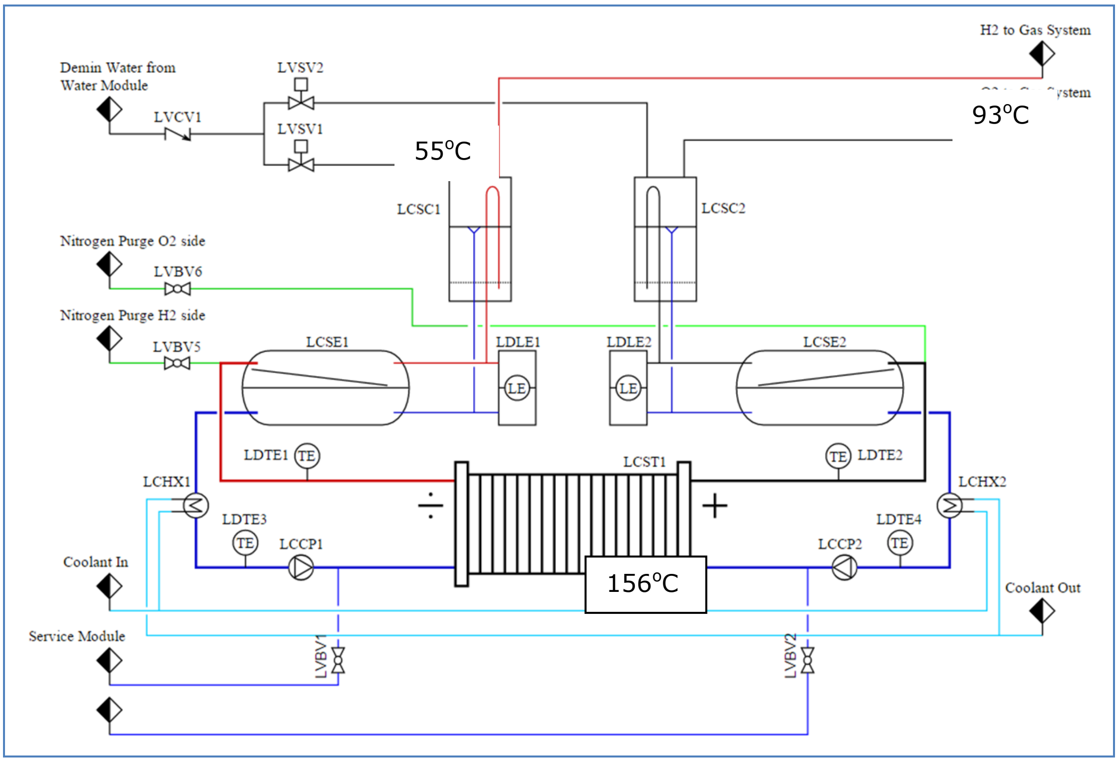
Regain of heat from power supply

Now the water only has to be heated from 55°C to 156°C which only requires 0.094 kWh/Nm^3 hydrogen produced. The energy needed is then 3.54 + 0.094 3.634

Therefore the improved efficiency will be 3.54/ 3.634 = 0.974 or 97,4%
An improvement of 97.4 – 96.6 = 0.8%

In case the temperature of the feed water is lower the improvement will be higher.

When the hydrogen and oxygen leaves the electrolyser there temperature will be 156°C. By heatexchanging the outgoing gasses with the incoming feed water, some of the heat can be regained in the system. The heat exchanging will reduce the temperature of the gasses to 93 °C. The saved energy is used to increase the temperature of the feed water from 55 to 93oC and equals 0.035 kWh per cubic meter of hydrogen produced.
The energy to be supplied to the system to produce 1Nm3 hydrogen is then 3.54 + 0.094 – 0.035 = 3.599
And the efficiency 3.54/3.599 = 0,98 or 98%.



5.5 WP3 – Dissemination & Planning R&D and Commercialisation

The project did not to this point result in increased turnover, exports or employment, but marketing activities for HyProvide will start in spring 2016 and new employments are planned to start late 2016. Initially we have used the positive project results as a basis for a comparative analysis of HyProvide – technically a well as price/performance - with other electrolysers currently available in the market. Sharing and discussing the results with – primarily - the project partners and a few other international partners, have confirmed our own high expectations as to the competitiveness of HyProvide. Furthermore it has yielded specific and valuable input for our go-to-market strategy and how to best position HyProvide in the market.

The interest for HyProvide shown from the market has been very high, and in the later stage of the project, it was decided to give live demos to specially invited partners and customers - with unanimous positive results. It also led to requests for proposals and specific discussions for early delivery of units. Two proposals in particular - with delivery of proposed units late 2016/early 2017 - look interesting and are currently being pursued.

Based on the comparative analysis, the reactions from our project partner Siemens and other potential, international partners it is our clear expectation that the HyProvide project will lead to considerable revenues and new employments over the next 3 years. We have worked out a conservative 5 year budget showing that GreenHydrogen revenues will grow from 0 revenues in 2015 to 12 million DKK by 2017 and 30 million DKK by 2019. In the same period our staffs is budgeted to grow from 6 employees to 15. Based on the budgeted sales and staff increase, GreenHydrogen expects to reach a break-even result in 2018.

6. Utilization of project results

The Agreement between the project partners states that GreenHydrogen has the commercial rights to utilize the project results and to market HyProvide in the global market.

As a first step GreenHydrogen starts the approval process for HyProvide in early 2016, and a new go-to-market/business plan is currently in process. Below actions are already decided and planned for.

A number of meetings will be set up for the Hannover Industry fair with new potential customers and partners as well as follow up meetings with earlier contacts as a first introduction of HyProvide in the market. Short term focus is on partners and stakeholders in the Hydrogen Refuelling Stations market, which is starting to act as a commercial market. HyProvide fits the market demand for onsite hydrogen generation with regards to capacity, efficiency and compactness. It is already a highly competitive market, and major players are currently in the market to find high efficiency electrolysers that meet their requirements.

In the HRS market, GreenHydrogen focus on establishing 1-2 "live test" customers/partners in primarily Denmark or nearby markets. We aim for one unit order booking in Q4 2016 for delivery early 2017, and a second unit order booking in early 2017 to be delivered in Q3 2017. For these live test customer projects, we look for customers or partners, who have experience and understanding of the technology, and are willing to enter a partnership where both partners participate and contribute to a successful implementation. These projects will yield valuable information on HyProvide's long term performance and stability when operated under real production conditions. These first sales are seen as an extremely important part of the product maturing process for HyProvide, before larger volume sales can start Q4 in 2017.

In the Power-to-Gas market/methanation market, we are in close dialog with a number of interesting project customers in primarily Denmark and Germany. While this market represents a much larger electrolyser volume, it is still in its early stage and primarily driven by publicly funded projects. Furthermore the market development is dependant of political initiatives on energy taxes and regulations. However with current plans for the build out of the green gas market in e.g. Denmark and Germany, the methanation market is extremely interesting. The German Energy Agency estimates the market for electrolysers for methanation in Germany to be 1 GW electrolyser capacity in 2022. This would translate into a market value (conservative) of app. 1.2 billion EURO. HyProvide is a tailored and attractive solution for small to mid-sized biogas plants planning for methanation. The methanation market is expected to become very active from early 2018 and onwards, when HyProvide is a fully matured solution, ready for MW size installations.

In general, the objective of GreenHydrogen is to ramp up sales from 1 unit sales in 2016 to at least 8 unit sales in 2018. GreenHydrogen expects to grow its market presence and sales mainly based on partners and system integrators.

On the marketing side, HyProvide has already caught the attention of the press and information has been published in 3 Danish magazines in the energy business. It is the plan to follow up on these articles with new information when HyProvide is released as an approved product, and to have the articles translated and sent out to relevant international green energy magazines as well.

Finally Workshops are planned for 3rd, and GreenHydrogen expects to participate as an exhibitor in the Hannover Industry Fair in April 2017.

7. Project conclusion and perspective

This project has demonstrated a successful up-scaling of GreenHydrogen's alkaline electrolysis technology to MW size. In particular the project succeeded in the development of a high-efficiency, low-cost and modular electrolyser unit with a hydrogen production capacity of 60 Nm3/h at a power consumption of about 250 kilowatt. The electrolyser unit developed within the HyProvide project is ready for its next phase, which will be focused on optimising the production steps in producing each module and the total system. This next phase will also include the start-up of a first production and field-test, i.e. external demonstrations. Once this next phase is accomplished it is expected that the electrolyser unit is ready for market introduction. Further on the electrolyser unit will be marketed using the term HyProvide as a trademark.