1. Final report

1.1 Project details

Project title	Power2Hydrogen
Project identification (program abbrev. and file)	2015-1-12313
Name of the programme which has funded the project	ForskEL
Project managing company/ institution (name and address)	CEMTEC Foundation Majsmarken 1 9500 Hobro
Project partners	Air Liquide CEMTEC Foundation NEAS Energy A/S EMD International A/S Aalborg University, Department of Energy Technology Aalborg University, Department of Development and Planning
CVR (central business register)	2626 3328 (CEMTEC Foundation)
Date for submission	2018-11-30

1.2 Short description of project objective and results

English version

The main purpose of the project has been to demonstrate - in an industrial scale – how hydrogen for high value markets can be produced by water electrolysis and how - at the same time – power grid balancing services can be offered in a feasible way.

The project was also selected for funding under the EU program FCH-JU and consequently only Phase I (WP1 - WP5 and WP11 - WP12 partly), Analysis was completed under the Power2Hydrogen project. The results obtained in Phase I was used as basis for Phase II, design, construction and test and commissioning of the hydrogen plant, which has been completed in the HyBalance project.

The result of the analysis phase is a report on the potential of hydrogen in energy systems, a model for how to estimate the annual production cost based on an optimal trading strategy and delivery of ancillary services, further development of the energyPRO energy systems analysis tool to include facilities to simulate hydrogen production plants participating in both wholesale markets and in the balancing markets as well as two reports on performance and degradation of PEM cells under realistic operation and a number of in peer-reviewed journals.

Dansk version

Projektets hovedformål har været at vise, hvordan brint til høj-værdi markeder kan produceres ved hjælp af elektrolyse i industriel skala, samt hvordan balancering af elnettet samtidig kan tilbydes.

Da projektet også blev tildelt støtte fra EU-programmet FCH-JU, er det kun fase 1 (WP1 - WP5 og WP11 - WP12 delvis) dvs. analysedelen af projektet, der er gennemført i Power2Hydrogen projektet. Resultaterne, der er opnået i fase 1, er brugt til gennemførelse af fase 2 - dvs. til design, konstruktion samt test og idriftsættelse af et brintanlæg i HyBalance projektet.

Resultatet af analysefasen er en rapport om potentialet af brug af brint i energisystemer, en model til beregning af de årlige produktionsomkostninger for brint baseret på en optimal handelsstrategi for køb af el samt levering af balancerings-ydelser, videreudvikling af modelleringsværktøjet energyPRO, så det nu indeholder en model for modellering af elektrolyseanlæg, der deltager i såvel el-engros som el-balance markedet, samt to rapporter om ydeevne og slitage af PEM-celler under realistiske driftsforhold, beskrevet i en række videnskabelige artikler.

1.3 Executive summary

The report on the potential of hydrogen in energy systems provided the conclusion that, anticipating the increasing penetration of wind turbines in the electricity mix, electrolysis could be one of the key enablers to relevant power grid balancing services.

The preparation of the report has, among other things, consisted of looking into and analysing various Danish and international energy scenarios, in order to evaluate hydrogen's role from different scientific and political perspectives.

On the basis of the analysis of the energy scenarios a model was developed, which is based on a Danish 2013 energy system and a Danish 2035 renewable energy system. Many parameters are factored in the model, such as the electricity prices, the flexibility and the reactivity of the electrolysis unit to offset in real time the power grid unbalances.

Based on projections of 2035, the report highlights how electrolysis will be able to bridge the electricity network and green transport fuel supply. At the convergence of much higher production of energy from wind turbines and massive deployment of fuel-cell electric vehicles, electrolysis can provide both energy storage solutions and energy conversion in renewable fuel to energize the hydrogen vehicles. The production of synthetic biogas or direct injection of hydrogen in the gas network is another promising pathway to increase the share of renewable in the natural gas grid.

The Matlab model developed in the Power2Hydrogen project is used to estimate the annual production cost based on an optimal trading strategy and delivery of ancillary services. The model simulates the operation of the Pover2Hydrogen plant for one full year. Two systems are defined, one including a local hydrogen storage and one without. By simulating the operation of the two systems, the results of implementing a storage is determined.

The purpose of the model is to estimate the annual production cost for producing a fixed amount of hydrogen for onsite and offsite customers. The optimisation is constructed as a linear optimization problem that minimizes the electricity cost based on hourly spot prices for seven days ahead. This means that the electrolyser is able run flexible within 0-100% load. The model finds the optimal solution within the constraints and the objective of minimizing the electricity cost.

The version of the energyPRO model developed in the Power2Hydrogen project allows simulating how to optimize hydrogen production plants both on the short and long term, thus allowing estimating the optimal design of the hydrogen production plant at the present regulation conditions and market prices, further on to estimate the optimal design of the hydrogen production plant at future regulations and market prices.

On the basis of the experiences and results created in the Power2Hydrogen project, the HyBalance project will show how to store renewable energy in the form of hydrogen, and then use it in the transport sector. The project will validate dynamic PEM electrolysis and innovatory processes for the deliverance of hydrogen. This will be demonstrated in a real industrial environment by applying the latest high-pressure hydrogen production and delivery equipment.

The HyBalance plant in Hobro was inaugurated in September 2018.

1.4 Project objectives

The objective of the Power2Hydrogen project was to get started with industrial scale water PEM electrolysis as PEM was identified to be the most promising choice of technology at the start of the project. Furthermore, the expectation was that the experience could be used in the role out of big scale sustainable hydrogen production and the usage in future national and international energy systems.

The aim of the Power2Hydrogen project was via dynamic operation of a PEM water electrolysis plant to demonstrate feasible load shifting and the possibility of balancing the electricity system while at the same time producing green hydrogen for high value markets such as industry and transportation.

As only phase I, which is the analysis part, was completed in the project, the full objective of the project will only be reached when the HyBalance project is completed.

As phase II of the project was agreed completed in the HyBalance project and the design and construction of the plant consequently was scheduled on a different time line a 1-year extension of time was granted in the Power2Hydrogen project mainly to allow AAU ET to follow the start-up of the hydrogen plant and include some of the results in their work.

The knowledge obtained in the project has been and is being used as described in the following chapters.

Project risks

The main technical risk was at the start of the project identified to be the flexible operation mode of PEM electrolysis at or above the 1 MWe size as it was a relatively new technology.

The risk has been addressed in the models developed in the Power2Hydrogen project where the optimal operation modes has defined. The risk has furthermore been investigated in the PEM degradation testing done at Aalborg University.

How to reducing the financial risks of hydrogen production through electrolysis by combining grid balancing, hydrogen supply to existing industries and hydrogen supply to new mobility markets, was furthermore at the start of the project identified to be one of the key interests of the project.

The knowledge of how the technology can be used to balance the grid obtained in the project have been and is being used by the project partners to develop business cases with validated figures to attract investors interested in investing in the future transmission towards a fossil free energy system. The projects described in chapter 1.7 seeks to demonstrate this.

1.5 Project results and dissemination of results

The analysis work in the project has resulted in the following 2 internal reports, which have been used as basis for the work in the design and construction and furthermore will be used in the operation of the electrolysis plant in the HyBalance project.

Framework conditions and model documentation
Definition of the framework conditions that influence the operation of an electrolyser in Hobro. The framework conditions have been used as input to the model described below to secure a realistic simulation of the Pover2Hydrogen plant. The framework conditions include definition of the hydrogen demand, technical characteristics and operation and maintenance cost.

Evaluation of the hydrogen production cost
This report describes the actual framework conditions that influence the economy of operating the P2H plant. Furthermore, the report describes the Matlab model developed in the project to estimate the annual production cost based on an optimal trading strategy and delivery of ancillary services.

The purpose of the Matlab model is to simulate the operation of the P2H plant to determine the cost of operating the plant. Two systems are defined to compare the value of increasing the flexibility by implementing an onsite storage. In system 1, the electrolyzer operates base load to supply the hydrogen demand for a nearby industrial consumer but in system 2, an onsite storage is included to analyse the consequences of a more flexible system.

Two trading strategies are analysed for each system, which gives a total of four alternative scenarios. The first strategy includes trading electricity in the spot market and the second strategy includes trading electricity in the spot and regulating power markets.

The operation of the P2H plant is simulated in Matlab, in which linear optimization is used to find the optimal operation that minimizes electricity cost. The results from the four scenarios are compared to a reference scenario, in which the P2H plant is operated base load to supply the annual demand for hydrogen. The conclusion is the average electricity cost is lower when the P2H plant is operated in relation to power prices. The lowest cost is achieved in the scenario that includes a storage and where electricity is traded in as well the spot as the regulating power markets. The storage increases the flexibility and possibility of shifting operation to low price hours.

The scenario provides a total annual operation cost, which is approximately 45,000 EUR less that the reference scenario. The savings from implementing a storage is up to 10,000 EUR/year. Sensitivity analyses indicates that a larger storage capacity does not increase the savings significantly. A higher annual hydrogen demand increases the number of full load hours on the electrolyser. In a scenario with 90% operation time the unit cost (calculated from variable costs) does only increase slightly.

The model and work made in the Power2Hydrogen project has been continued in the Hy-Balance project.

Developing of the energyPRO model
The analysis work has furthermore resulted in a report, which has been used as basis for an upgrade of the energyPRO software.

The new features in the developed energyPRO-model has been made so general that it can be used to optimize other Power2Gas and Power2Fuel plants, including e.g. methanation of biogas. The big challenge for energy plants to participate in the integration of fluctuating productions from wind turbines and photo voltaic PV is having necessary energy stores. In the developed energyPRO model it is possible to add storage for hydrogen and storage for biogas. It is expected that a significant part of the earnings of a hydrogen production plant will be from selling heat to a nearby district heating company. Therefore, the developed energyPRO model allows modelling of a district heating plant, taking into account amongst others heat demands and thermal store. The final report can be found on EMD's homepage here.

The energyPRO-model allows simulating how to optimize hydrogen production plants both on the short and long term, thus allowing estimating the optimal design of the hydrogen production plant at the present regulation conditions and market prices, further on to estimate the optimal design of the hydrogen production plant at future regulations and market prices.

The features developed in the Power2Hydrogen project has been included in the energyPRO software developed by EMD International A/S and was released in version 4.4.156, April 29th 2016.

Test of PEM electrolysis

The objective of the tests made in the project was to investigate Membrane Electrode Assembly (MEA) efficiency, degradation and hydrogen purity. The influence of dynamic operation patterns was of particular interest.

To perform the work Aalborg University purchased a commercial test station from Greenlight Innovation. The test station is capable of testing single cells and short stack under varying operating conditions including pressures up to 30 bars.

The intention was to perform performance and lifetime/degradation studies on cell and short stacks supplied by the electrolyzer manufacturer selected as supplier for the full-scale demonstration plant. The investigations should consider realistic operating patterns to provide input for the plant design and operation. During the course of the project, it proved difficult to base the work at Aalborg University on cells from Hydrogenics, who was selected as supplier of the full-scale electrolyzer. Due to technical limitations it was not feasible to test full-scale electrolyzer cells as the current (several hundred amperes) required for testing exceed the limits of the test station. Aalborg University would be able to test MEAs from Hydrogenics with smaller active area than the full-scale plant hence demanding lower test currents. However, for reasons of confidentiality, Hydrogenics did not want to provide membrane electrode assemblies with small active area for testing at Aalborg University.

As a work around Aalborg University reached an agreement with EWII fuel cells who were willing to supply the required MEAs and a short stack. The MEAs and the stack from EWII use the same PEM electrolyzer technology as Hydrogenics. Since the scope of the work was to gain a better understanding of performance and degradation under dynamic load patterns, there are good reasons to expect this can be achieved from testing the EWII MEAs and that the general trends also apply for Hydrogenics' MEAs.

The obtained test results are briefly summarized here. Further details can be found in the deliverable's reports. Three setups were used in the tests:

1. A mini cell from EWII used for degradation mechanism studies and dynamic operation modes.
2. Single cells tested in the Greenlight test station to investigate performance and local current density distribution under different conditions
3. Short stack tests performed with the Greenlight test station to study performance as function of pressure, temperature and water circulation. This stack was also investigated with electrochemical impedance analysis as a monitoring and diagnostics tool.

Based on the state-of-the-art investigation, presented in detail in the deliverable report on this topic, a map of degradation mechanisms was drawn. Overall, the mapping considers the three components of the MEA; the anode, the membrane and the cathode. For the anode and cathode, respectively, both the porous transport layer and the electrodes were considered separately.

Single cell tests

To investigate the baseline degradation during constant load a 500 hours test was performed at a temperature of 60 °C and a current of 1,5 A/cm^2 with the mini cell. Every 24 hours, a I,V-curve was recorded by sweeping the current between 0,01 A/cm2 and 3,0 A/cm2. The recorded I,V-curve reveals that a significant portion of the cell voltage increase was recovered after the characterization.

The test showed, the cell voltage increases during the 24 hours test period but drops significantly following the I,V-curve and EIS test phase. Only a relatively minor irreversible voltage increase remains after the test phase. This behaviour in ascribed to a recovery of the electrochemically active surface area of the catalyst layer. This can be the result of several phenomena, the most likely being removal of contaminants and small gas bobbles from the catalyst and removal of larger gas bobbles blocking the flow channels.

A series of tests were performed to investigate the irreversible degradation resulting from constant and dynamic operation with the constant load test performed at varying cell temperatures. The tests were performed on as well the mini cell (1) as the single cell (2).

The most striking outcome of the testing was that negative degradation rates were found in two cases for the 500 hours test period. This means, cells cyc10s and solar showed an increase in performance (i.e. decrease in voltage). From the detailed report, it can be seen that this overall trend of negative degradation includes an initial period of performance increase followed by a performance decrease. The higher the current the longer a period of performance increase was found.

Furthermore, "type 1" cells generally showed higher degradation rate than "type 2" cells, while both of them were negatively affected by an increase in temperature. The experiments with "type II" cells only showed a moderate increase from 1.2 to 3.0 μV/h when going from 60 °C to 80 °C, while stepping to 90 °C caused a major rise to 183.8 μV/h. The "type I" showed a big increase from 74 to 126 μV/h when changing the temperature from 60 C to 80 C (no experiment was carried out at 90 C). The significant difference between type 1 and type 2 can be due to a couple of fundamental differences in the way the experiments were performed. The type 2 tests were performed under constant voltage whereas type 1 was under constant current operation. Additionally, one important difference that effects degradation rates is the quality of the feed water. Although a filter was implemented into the "type 1" test-stand, the nature of recirculation cannot fully ensure the purity of the "type 2" test stand feed water, where the cell was directly connected to the source and excess water drained after the outlet.

Stack tests, monitoring and diagnostics

At stack level, only performance tests were performed to avoid the risk of quickly degrading the stack. Having to replace MEAs in the stack would be relatively expensive and the degradation behaviour was assumed similar to the single cells hence only limited new information could be obtained.

A series of electrochemical impedance measurements were also conducted at different cathode pressure to investigate whether the expected change in hydrogen cross over could be detected. The impedance measurements were done using a GAMRY reference 3000 potentiostat available at Aalborg University and using a dedicated impedance analyser from AVL designed for diagnosing fuel cells.

Based on the collected spectra it was not possible to extract features that correlated well with the gas cross over. Since only limited time was available for the investigation and hardware problems resulted in noise in the signals no final conclusion can be drawn whether or not the method can be used for diagnostics purposes.

As mentioned above, it was not possible to use Hydrogenics' MEAs for the laboratory tests and hence making a link to the full-scale test became challenging. In addition, commissioning of the full-scale plant was delayed leaving little time for the monitoring activity.

Dissemination

The concept of the Power2Hydrogen project has been disseminated through comprehensive communication activities in connection with the HyBalance-project. These activities include

- the website www.hybalance.eu
- Posts on the LindkedIn accounts: Hybalance and Hydrogen Valley
- Posts on Hydrogen Valley's twitter-account @hydrogenvalley
- Brochures (www.hybalance.eu/brochures/)
- Videos (hybalance.eu/videos/)
- Presentations at conferences (hybalance.eu/events/)
- Media-coverage (hybalance.eu/media-coverage/)
- Events (hybalance.eu/latest-news-2/) - among which cutting the first sod by the Danish Minister for Energy, Utilities and Climate, Lars Chr. Lilleholt should be highlighted, as well as the inauguration of the HyBalance plant in September 2018.

The specific communication activities have targeted selected stakeholders – including policy makers and their influencers, academics, clients/consumers of hydrogen as well as the general public.

The following report has been developed in the project:

The potential of Hydrogen in Energy Systems. A summary of the report is available at the website HyBalance.eu. The entire report can be downloaded: www.hybalance.eu/reports/

Dissemination on the results of the specific tests on performance and degradation of PEM cells from the Power2Hydrogen project includes publication of the following **in peer-reviewed journals**:

Current and Temperature Distribution Measurement in a Polymer Electrolyte Membrane Water Electrolyzer Cell. / Zhou, Fan; Al Shakhshir, Saher; Kær, Søren Knudsen.
I: ECS Transactions, 2018, s. 1005-1012.

Model-supported analysis of degradation phenomena of a PEM water electrolysis cell under dynamic operation. / Frensch, S. H.; Olesen, A. C.; Araya, S. S.; Kær, S. K.
ECS Transactions. red. / H. Xu; K. E. Ayers; P. J. Kulesza; G. Wu. Bind 85 11. udg. Electrochemical Society Inc., 2018. s. 37-45.

Model-supported characterization of a PEM water electrolysis cell for the effect of compression. / Frensch, Steffen Henrik; Olesen, Anders Christian; Simon Araya, Samuel; Kær, Søren Knudsen.
I: Electrochimica Acta, Bind 263, 02.2018, s. 228-236.

Improving the Performance of an Air-Cooled Fuel Cell Stack by a Turbulence Inducing Grid. / Pløge, Line Justesen ; Fallah, Rasheed; Al Shakhshir, Saher; Berning, Torsten; Gao, Xin.
I: ECS Transactions, 2018, s. 77-87.

On the Effect of Bipolar Plate Mechanical Properties on the Current Distribution of Proton Exchange Membrane Water Electrolysis. / Al Shakhshir, Saher; Zhou, Fan; Kær, Søren Knudsen.
I: ECS Transactions, 2018, s. 683-393.

On the Effect of Clamping Pressure and Method on the Current Mapping of Proton Exchange Membrane Water Electrolysis. / Al Shakhshir, Saher; Zhou, Fan; Kær, Søren Knudsen.
2018. Poster præsenteret ved 233rd ECS Meeting, Seattle, USA

In-situ experimental characterization of the clamping pressure effects on low temperature polymer electrolyte membrane electrolysis. / Al Shakhshir, Saher; Cui, Xiaoti; Frensch, Steffen Henrik; Kær, Søren Knudsen.
I: International Journal of Hydrogen Energy, Bind 42, Nr. 34, 08.2017, s. 21597-21606.

On the Experimental Investigation of the Clamping Pressure Effects on the Proton Exchange Membrane Water Electrolyser Cell Performance. / Al Shakhshir, Saher; Frensch, Steffen Henrik; Kær, Søren Knudsen.
I: ECS Transactions, Bind 77, Nr. 11, 07.2017, s. 1409-1421.

1.6 Utilization of project results

The results from especially WP2 of the Power2Hydrogen project has been used by Air Liquide and Hydrogenics to design, construct and test and commission a 1,25 MWe PEM electrolysis hydrogen plant in Hobro in the HyBalance project.

Furthermore, the results from the Power2Hydrogen and HyBalance projects have in general been and are being used for further development and projects as described in chapter 1.7.

The knowledge obtained during the work in the Power2Hydrogen and HyBalance projects has also been used to develop an education program used in the local primary school to open the children's eyes to the potential of Hydrogen in the future energy system.

Furthermore, a project supported by the Erasmus program has been developed to teach car mechanics about fuel cells and hydrogen as part of their education.

1.7 Project conclusion and perspective

In the report "*The potential of Hydrogen in Energy Systems***"** the different electricity markets that flexible electricity demand could potentially participate in was analysed. Based on this market review it was concluded the most relevant markets for a P2H plant were determined to be the spot market and the regulating power market. The primary and secondary reserve markets are relatively small in DK1 compared to the other markets. The tertiary reserve market (regulating power market) is more interesting for flexible demand such as electrolysis. In this market, bids of just one hour can be offered and these bids can be changed until 45 minutes before operation. With this option, it is easier for a plant to participate in multiple markets and adjust the production plan according to the need for hydrogen. One strategy could be to buy the needed electricity for the coming day on the spot market and within the day of operation offer upward and downward regulation in the regulating power market to the extent that electricity is dispensable or extra electricity can be consumed. In addition to this strategy, the intraday market could also be used as a way of balancing the produced hydrogen and the demand for hydrogen.

The conclusions in the report as well as the knowledge of how the technology can be used to balance the grid obtained in the project have been used by the project partners to develop business cases with validated figures, which have been and are being used towards investors interested in investing in the future transmission towards a fossil free energy system.

The direct use of Hydrogen in gaseous form is being developed together with the Hobro based company Ballard who produces fuel cells for buses. As a direct result three fuel cell hydrogen busses is expected in operation in Aalborg by Q4 2019.

The use of Hydrogen as well the balancing potential on the synthetic fuel pathway is being developed together with partners in the project as well as new partner groups.

The first direct result is the support granted from EUDP to the C3U project where the objective is to develop a highly innovative concept that offers multimegawatt balancing power to the grid through cost efficient cryogenic carbon capture (CCC) technology coupled with biomass fired processes.

Furthermore, an application for the Power2Met project is currently being evaluated by EUDP. The Objective in the Power2Met project is to develop, design and build a pilot plant for a complete, standardised and modular power-to-methanol plant that can be offered to upgrading biogas plants, utilizing their CO2 and hydrogen in a synthetic process to produce green methanol while trading electricity on the spot market and the regulating power market, providing for a positive business case from day one.

On the same path, a new project where Hydrogen is being used for large-scale production of ammonia is currently being developed. The ammonia is intended for use as fuel in the shipping industry.

Finally, the large-scale storage potential is being developed together with Akzo Nobel under Green Hub Hobro as Akzo Nobel has the concession rights to the salt caverns located near Hobro. Salt caverns are highly applicable for large scale storage of Hydrogen and one of the reasons why the focus on the Hydrogen path through the last decade has been and still is so devotedly supported by the local and regional political system.

1.8 Annex

Link to the HyBalance project: www.hybalance.eu