Department of Energy Technology

Power-2-Electrolysers

Final Report (Project No.: 64013-0128)

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1.1 Project details

Project title	Power-2-Electrolysers
Project identification (program abbrev. and file)	64013-0128
Name of the programme which has funded the project	Hydrogen and Fuel cells
Project managing company/institution (name and address)	Aalborg University, Department of Energy Technology Pontoppidanstraede 111, 9220 Aalborg East, Denmark
Project partners	Aarhus University, Center for Energy Technology GreenHydrogen.dk Aps LeanEco A/S Haldor Topsøe A/S
CVR (central business register)	231 023 84
Date for submission	31-12-2017

1.2 Short description of project objective and results

Objectives: The project should optimize the MW electrolysis technology by developing a highly efficient power supply. The power supply should provide ancillary services in terms of power and frequency regulation for grid balancing and power factor correction in order to improve the efficiency of the grid. Business models for intelligent electrolysis systems have also been studied.

Results: Two 250-kW prototypes (a simple and an advanced one) have been developed and practically implemented at Aalborg University (AAU) for GreenHydrogen (GH). A low power (6 kW) prototype has been practically realized by LeanEco for HaldorTopsoe (HTAS) for their prototype. A heat recovery system (to be used with the advanced prototype) has been realized by Aarhus University (AU Herning) for GH. Studies regarding the stakeholders, technical boundaries and business model in relation to the electrolysis system have been carried out by AU Herning and documented through various publications.

Mål (Dansk): Projektet skal optimerer et MW Elektrolyseanlæg ved at udvikle en højeffektiv strømforsyning. Denne skal levere systemydelser i form af frekvensregulering og regulerbarkraft til balancering af nettet, samt fasekompensering for at forbedre effektiviteten i nettet. Forretningsmodeller for intelligente elektrolysesystemer er også blevet studeret.

Resultater: De to 250 kW prototyper (en simpel og en avanceret) er blevet udviklet og testet på Aalborg Universitet (AAU) for Green Hydrogen (GH). En lavspængdingsprototype (6 kW) er lavet af LeanEco for Haldor Topsøe (HTAS) til deres prototype. Et varme recovery system (skal bruges med den avancerede prototype) er blevet udvilket af Aarhus Universitet (AU Herning) til GH. Studier vedrørende interessenter, tekniske forhindringer og forretningsmodel i forhold til eletrolysesystemet er blevet lavet af AU Herning og dokumenteret i forskellige publikationer.

1.3 Executive summary

Executive summary: The Danish ambition to reach 100% renewable energy by 2050 makes the energy conversion and storage imperative. In such a scenario, electrolysis becomes a key in today's energy systems.

In this project, GH and HTAS have established a unique collaboration with LeanEco as well as AAU and AU Herning in order to develop highly efficient power supplies for electrolysis systems. Hereby, skills within electrolysis, power electronics, heat recovery, and business have been united.

In all, the project parties have worked together to address the issues for electrolysis, to reduce the overall cost, and to increase the efficiency of the technology, which has been established in the Danish Partnership for Hydrogen and Fuel Cells Strategy and Roadmaps. Furthermore, the objective of this project was also to build up electrolysis systems as a part of a future balanced intelligent power system. In this regard, the power supplies had to provide ancillary services to the grid, where were designed accordingly in this project. The economic sustainability of the developed technology is also important. Therefore, the project has developed and optimized business models for the operation of large electrolysis systems in terms of intelligent purchase of electricity and smart sale of ancillary services to the grid.

The power supplies used in the electrolysis process convert AC power to DC power. Standard power supplies have an efficiency of approx. 90%. Criteria of the successful implementation of this project include the efficiency improvement and also the utilization of the waste heat from the converter, which will be used to heat the feed water in the electrolysis process.

GH and HTAS have spent many years working on developing Alkaline Electrolysis and Solid Oxide Electrolysis systems, respectively. GH has demonstrated the first high-power electrolysis plant in 2016. LeanEco took part in the project in order to expand their business from power supplies in the class of 5-15 kW to power supplies for MW electrolysers. LeanEco has also considered the project as an opportunity to establish a strategic partnership with GH.

AAU has been the manager of the project, in which two prototypes of power converters have been developed – a simple low-cost version and an advanced system that can provide a number of system services. The timeliness of developing the advanced models can be recognized in several ongoing projects aiming at developing 'Smart City' concepts, e.g., 'Smart Copenhagen', where both GH and HTAS are involved in.

Summary of results: Within this project, two 250-kW prototypes (a simple one and an advanced one) have been developed and implemented at AAU for GH. The simple prototype has been delivered to GH in the beginning of 2015 and has been used to test electrolysis stacks since then. The advanced prototype has been delivered to GH by the end of 2016 and has been tested for functionality at low power with only one of the phases of the DC/DC stage so far. It is expected that the simple prototype will be used for laboratory tests in the future. The advanced prototype is expected to be integrated into future electrolysis systems (in containers).

LeanEco has developed and implemented a 6-kW prototype power supply, which will be used by HTAS.

AU Herning has developed and practically realized a heat recovery system, which is now installed at GH. It is expected that the recovery system will be used and tested with the advanced prototype in order to improve the overall system efficiency.

AU Herning has also carried out studies through various publications regarding the stakeholders, technical boundaries, and business model in relation to the electrolysis system.

1.4 Project objectives

Project objective: The project should optimize the MW electrolysis technology by developing highly efficient power supplies. The power supplies should provide ancillary services in terms of power and frequency regulation, e.g., grid balancing and power factor correction, in such a way to improve the overall efficiency. Integrating the developed power supplies into the electrolysis systems enables an intelligent energy conversion. Following, the entire intelligent electrolysis systems have thus been studied from the business and economic perspectives.

In this project, GH and HTAS have established a collaboration with LeanEco, AAU, and AU Herning in order to develop highly efficient power supplies for next-generation electrolysis systems. The primary goal was thus to reduce the overall cost and increase the efficiency of the technology as described in the Danish Partnership for Hydrogen and Fuel Cells - Strategy and Roadmaps. More specifically, the aim was to develop electrolysis systems as a part of future balanced intelligent power systems. In that case, the developed power supplies should be able to provide ancillary services to the grid. Additionally, the economic sustainability of the technology was also important. Therefore, business models for the operation of large-scale electrolysis systems should be developed and optimized in this project. Conventional power supplies used in the electrolysis process have an efficiency of approx. 90%. A successful implementation of this project should increase the overall system efficiency to a level of close to 99%. This improvement is to tackle the increasing power efficiency concerns and recovery of waste heat from the converters for heating the feed water to the electrolysis process.

In the first project year, specifications of two types of power supplies have been detailed. That is, specifications of a simple 250-kW power supply for GH and an advanced 6-kW power supply for HTAS have been documented. A model for the heat balance in an electrolyser system has been established. One of the challenges with the state of the art electrolyser technology is that the efficiency is relatively low, and it has to be further increased. Finally, an activity on business models for electrolysis systems has been initiated, and so far, the stakeholders have been identified.

In the second year of the project, the focus has been put on the design and implementation of the 250-kW power converters. A pre-prototype of 250-kW has been installed at GH, which is functional and used to test the electrolyser stacks since the beginning of 2015. The time plan has been modified in this year so that all the tasks related to the pre-prototype have been prioritized (therefore some deliverables are delayed). It, however, ensured quick operations and tests of the pre-prototype, and also is beneficial to build up the advanced prototype (i.e., using the operational experience in the pre-prototype system). The 250-kW advanced prototype was implemented at AAU. LeanEco has realized the 6-kW low-cost prototype for HTAS. Furthermore, the heat recovery system is being designed and will be installed at GH in order to improve the electrolyser system efficiency. Finally, regarding the business model, three reports have been prepared with focuses on a) determination of stakeholders and responsibilities in the electricity market, b) survey on technical boundaries for price formations and c) development of business plans for electrolysis plants.

In the third project year, the main focus was on the final implementation of the advanced 250-kW prototype, the low-cost 6-kW prototype, and the hardware for the heat recovery system, and finalizing the documentation regarding the business model.

As a conclusion, the project has been running satisfactorily through the past three project years. However, there are system challenges with the existing electrolysis technology to recover all power losses from the power supplies, as the efficiency of the electrolysers is not very high.

In the following, each work package (WP) of the project and its status will be described in terms of goals and achievements:

WP0: Project Management & Administration

This WP provided the project management and administration and facilitated the Steering Committee, which acted as the overall decision and supervision body of the project, with the aim to secure a successful realization of the overall project objectives and deliverables.

WP status: We had an organization with frequent meetings between the partners.

Status of deliverables and milestones:

D0.1 Project Agreement between participants (Other) – OK

D0.2 EUDP grant acceptance form & project info form (Other) – OK

D0.3 Quarterly grant payment request (Other quarterly) – OK

D0.4 1st Annual report (Report) – OK

D0.5 2nd Annual report (Report) – OK

D0.6 Project end report, end financial report and project end form (Report) - OK

M0.1 SC kick-off-meeting (Meeting summary) – OK

M0.2 Project agreement signed (Signed agreement) – OK

M0.3 End Project & Financial reports (Reports) - OK

WP1: Study and specification of concept for simple and advanced MW-size power converters

The aim of this WP was to specify in details the system and concept for highly-efficient power supplies in terms of interfaces, topologies, specifications, standards, and software designs. Two final concepts were expected.

WP status: We have first specified the necessary performance of the power supplies for electrolysis. One of the concerns is about the system isolation, requiring an isolation transformer. In addition, some discussions have been on how to protect the entire system if a failure occurs. Power supply specifications have been done for a simple power converter, for an advanced power supply with grid ancillary services, and also a low-cost 6-kW power supply, which is especially useful for HTAS high-temperature electrolysis system. In addition, different possible power converters have been studied.

Status of deliverables and milestones:

D1.1 Specification of interfaces (Data sheet /Report) – OK

D1.2 Specification of converter (Data sheet /Report) – OK

D1.3 Final concept specifications (Data sheet /Report) – OK for 250-kW prototypes

M1.1 Final concepts selected (Report) – OK

WP2: System design for simple and advanced MW size converters

In this WP, the conceptual design of a simple and an advanced power converter was determined based on calculations and simulations.

WP status: We have designed the first 250-kW power supply for electrolysis, which consists of a 50-Hz transformer for galvanic isolation, a switchgear with breakers in case of emergency, a 12-pulse rectifier to limit the grid current harmonic distortion, a DC-link, and then an interleaved power conversion stage to control the current in the electrolyser. The interleaved technique ensures reducing current ripples into the electrolyser, and thus smaller filters at the output. Additionally, it is possible to optimize control schemes for the electrolysis process. The current control techniques have been developed and studied.

The advanced 250-kW prototype consists of a safety installation, AC/DC, and DC/DC blocks, and all the blocks have been designed. The safety block includes full-current-rated contactors and an inrush current limiting circuitry. The AC/DC block is a Danfoss power converter as an active rectifier with an LCL filter. The DC/DC block has 4-phase interleaved isolated converters using Silicon Carbide (SiC) devices. The topology is an H-bridge topology with a high-frequency transformer, a current-doubler rectifier, and an output filter. The switching frequency for the DC/DC block is 50 kHz, which leads to a small isolation transformer. The basic control strategy has been developed in PLECS with C-Coding Blocks. Once the full-scale system is completed, further code optimization would be carried out.

Status of deliverables and milestones:

D2.1 Design concept for pre-prototype (Report) - OK

D2.3 Design of Advanced Power Converter (b) (Report) - OK

WP3: Development and construction of simple and advanced MW converters

The aim in this WP was to build up a pre-prototype and afterwards to construct and verify a simple but cost-effective prototype as well as an advanced prototype, which can deliver ancillary services to the power grid. Tests should be performed on individual parts of the converters as well as the assembled converters.

WP status: The 250-kW pre-prototype has been installed at GH and is being used to test the electrolyser stacks since the beginning of 2015. Great efforts have been made to realize and then to test this prototype, as the power rating is higher than the laboratory system. The advanced 250-kW prototype has been also realized. So far, functionality tests at low power have been performed.

Status of deliverables and milestones:

D3.1 Pre-prototype running for test (Report) - OK

D3.3 Prototype B constructed and tested (Other) – OK

M3.1 Pre-prototype approved (Hardware ready for WP5) – OK

WP4: Recover of waste heat from the MW converters

In this WP, a heat transmission system for moving the excess heat from the semiconductors in the power supply to the feed water for the electrolyser will be designed with the aim to increase the overall system efficiency potentially by 3-4%.

WP status: In the electrolyser system, there are heat-producing and heat-consuming components. The electrolyser stack can produce heat or consume heat. The outgoing gases – hydrogen and oxygen are heat sources if the gases can be cooled before leaving the system. The power supply needs cooling, and being a heat producer. If a dryer is included, it needs heat to generate drying media. The cabinet enclosing the whole electrolyser plant will have a heat loss through the insulation. Thus, it can treated as a heat consumer.

Status of deliverables and milestones:

D4.1 Model for heat balance elaborated (Note) – OK

D4.2 Heat recover from prototype B (advanced with systems services) implemented (Hardware delivered) – OK

WP5: Test of simple and advanced MW converters against electrolysator

In this WP, the pre-prototype as well as the two final prototypes will be tested in order to verify that all demands are fulfilled.

WP status: The 250-kW pre-prototype has been installed and used to test electrolyser stacks at GH from the beginning of 2015. A large number of tests have been carried out, the control of the pre-prototype has been optimized, and bugs have been fixed. So far, tests with a power output up to 250 kW have been successful. The advanced 250-kW prototype has been tested only at low power conditions (functionality tests).

Status of deliverables and milestones:

D5.1 Pre-prototype tested (Test report) - OK

WP6: Business Model and Dissemination plan

This WP aims at developing commercially-sustainable business models for an advanced power converter delivering ancillary services to the power grid. The WP will uncover and analyse the commercial framework in a number of scenarios and relation models. Based on the findings a selected number of econometric model analysis of the developed converter technology will be conducted. The project will be disseminated by articles, at conferences and if possible in a proposal for PhD and/or PostDoc projects.

Status of deliverables and milestones:

D6.1 Determination of stakeholders and responsibilities in the electricity market (Report) – OK

D6.2 Survey of technical boundaries for price formation (Report) – OK

D6.3 Development of business models for the operation of electrolysis plants with an active role in the electricity grid (Model) – OK

D6.4 Model Development for the operational organization (Model) – OK

D6.5 Dissemination (Other) – OK

CM 6.1 Survey of stakeholders, responsibilities and technical boundaries (Report) – OK

CM 6.2 Recommendations based on model computations (Report) – OK

In the following two pages, both the latest version (Fig. 4.1) and the original versions (Fig. 4.2) of the time plan are shown.

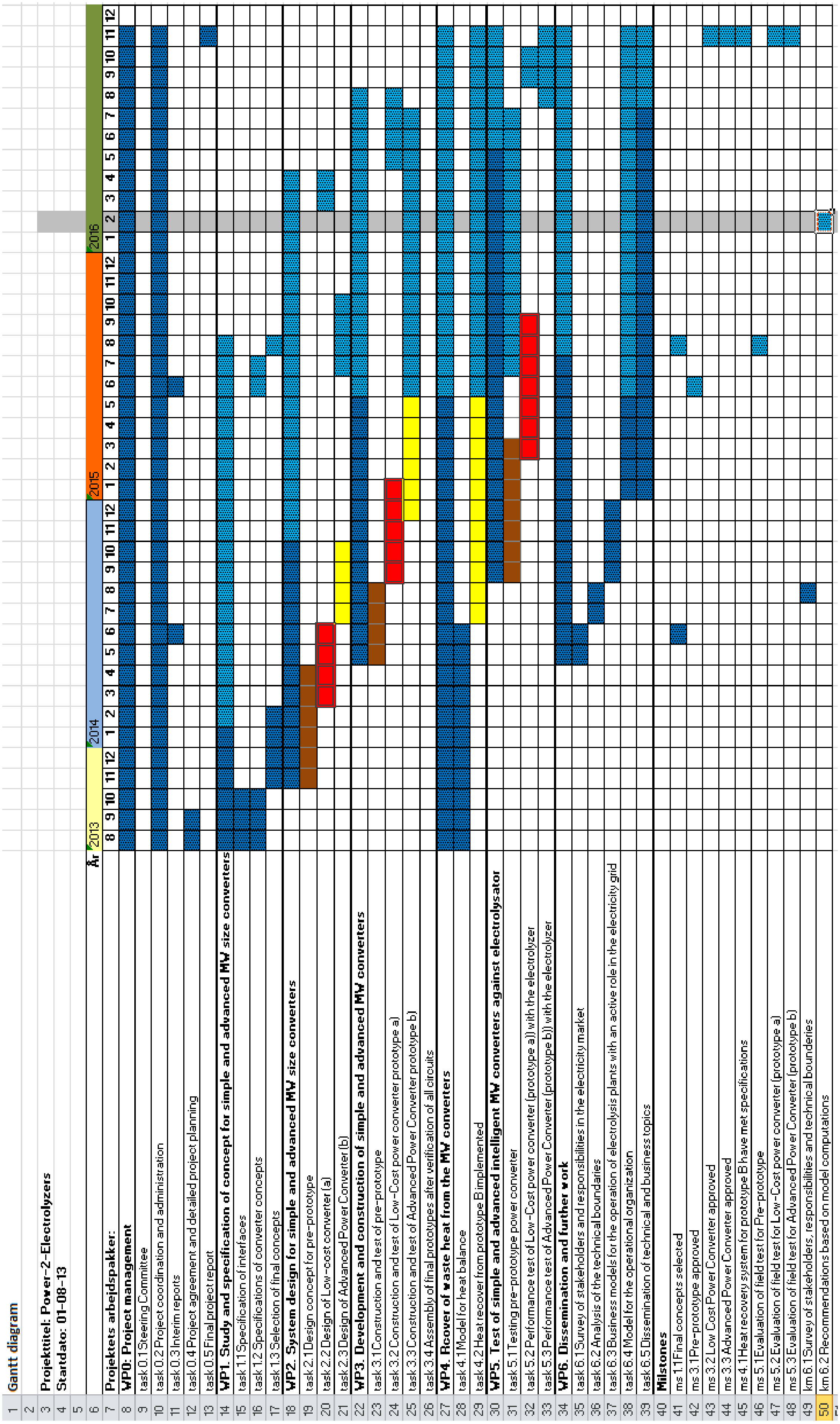


Fig. 4.1. Latest version of the time plan.

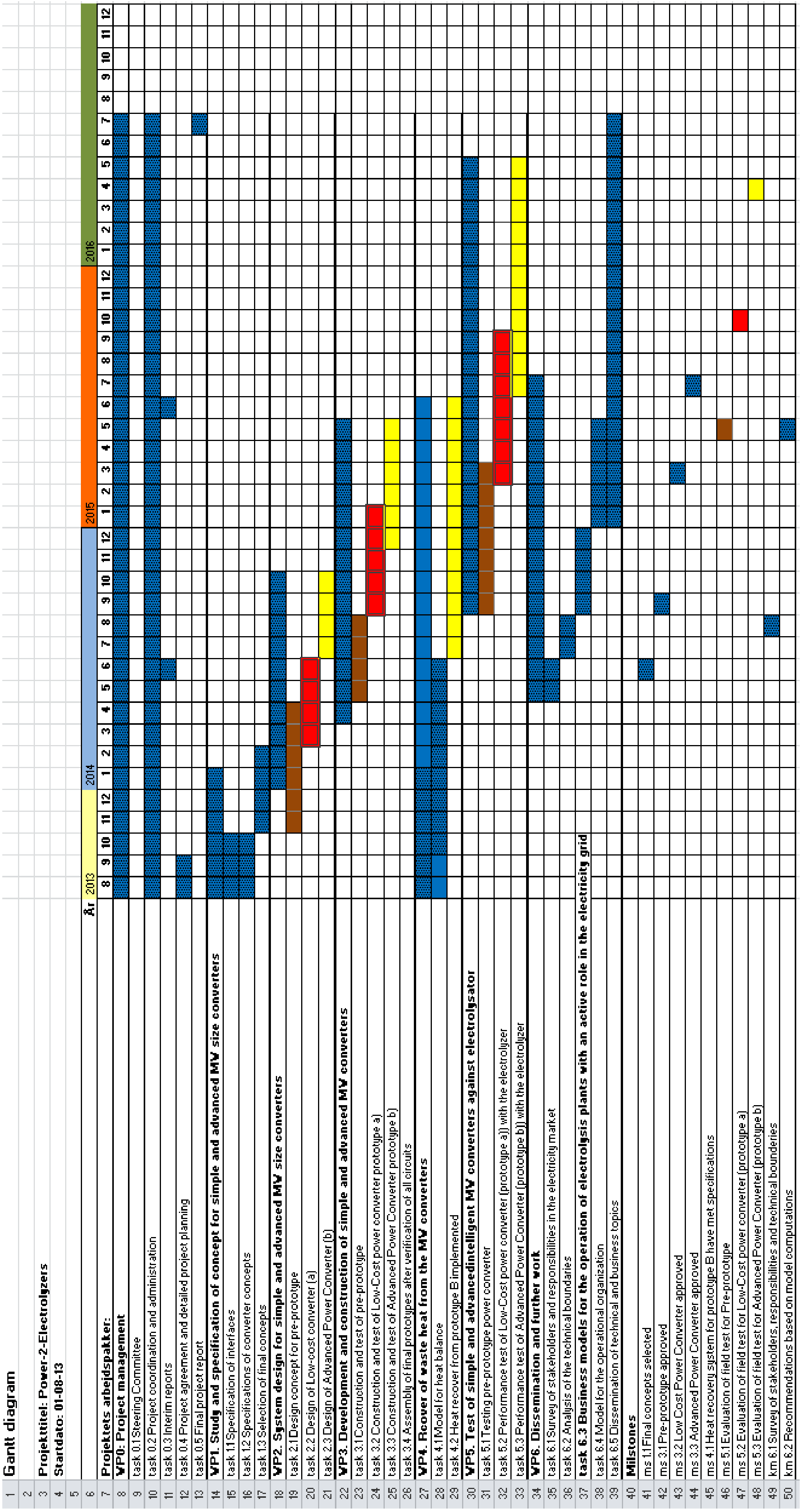


Fig. 4.2. Original time plan.

1.5 Project results and dissemination of results

The main technical results of the project are a number of prototype power supplies (including documentation) and the documented studies regarding the business model (publications). The prototypes developed during the project are: the simple 250-kW prototype, the advanced 250-kW prototype, the low-cost 6-kW prototype, and the heat recovery system.

250-kW simple prototype

The power electronics block diagram of the simple prototype is shown in Fig. 5.1. As it can be seen, there are circuit breakers on the grid side in order to disconnect the power supply from the grid in case of a fault or when the power supply is off. The soft starter is used to start up the power supply with a minimal inrush current. There is a 12-pulse rectifier, which contributes to low harmonics at the grid side. The DC/DC conversion stage is realized using six phase-interleaved buck converters, leading to the minimization of output filters.

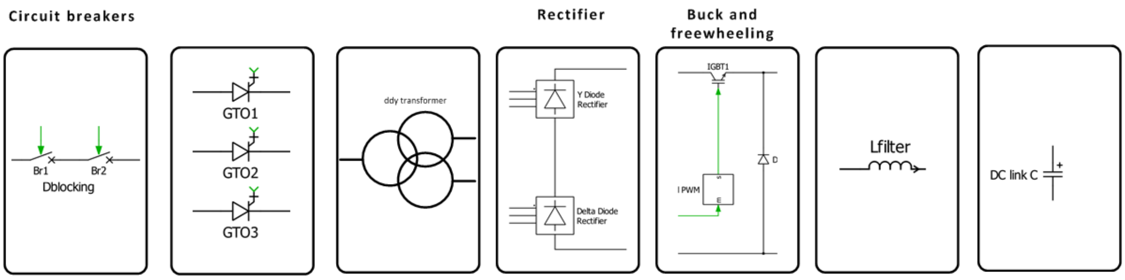


Fig. 5.1. Power electronics block diagram of the simple 250-kW prototype.

A 3-Dimenional (3D) drawing of the simple 250-kW prototype showing the physical layout is shown in Fig. 5.2.

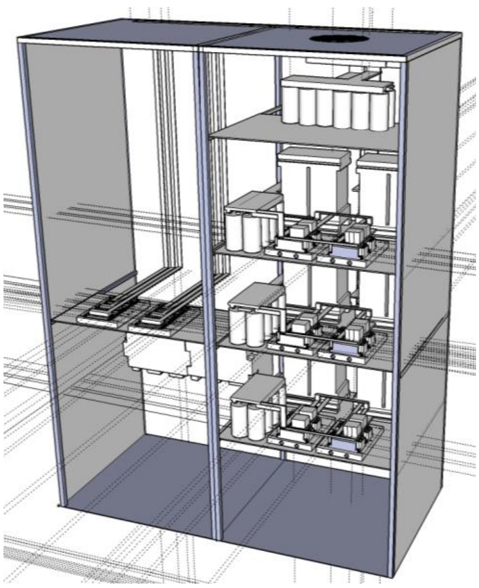


Fig. 5.2. 3D drawing of the simple 250 kW prototype.

Some pictures of the practically realized 250-kW simple prototype (installed at GH) are shown in Fig. 5.3 and Fig. 5.4. The simple prototype has been tested since the beginning of 2015.

Fig. 5.3. Pictures of the simple prototype installed at GH.

Fig. 5.4. Zoom onto the converter cabinet of the simple prototype.

Various test results including continuous load operation, pulsed power operation, and ramped power operation of the simple prototype are shown in Fig. 5.5 to Fig. 5.10.

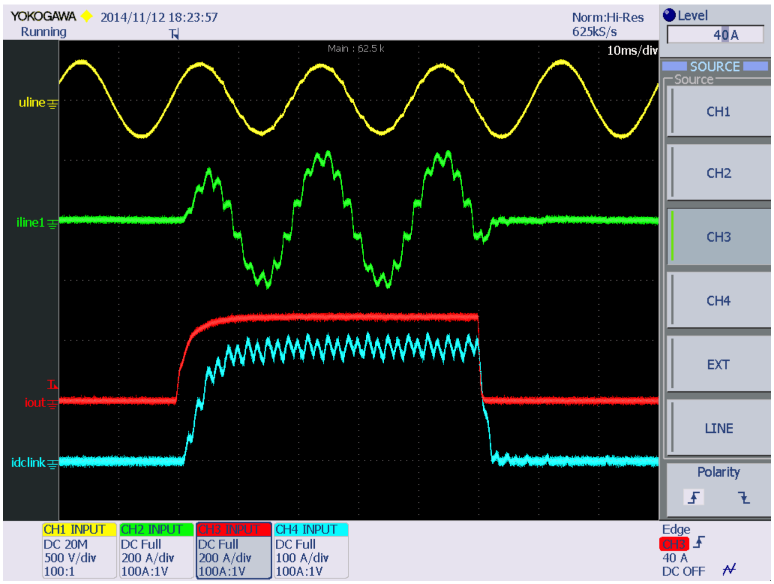


Fig. 5.5. Input side waveforms at 78.4-kW output – pulsed operation.

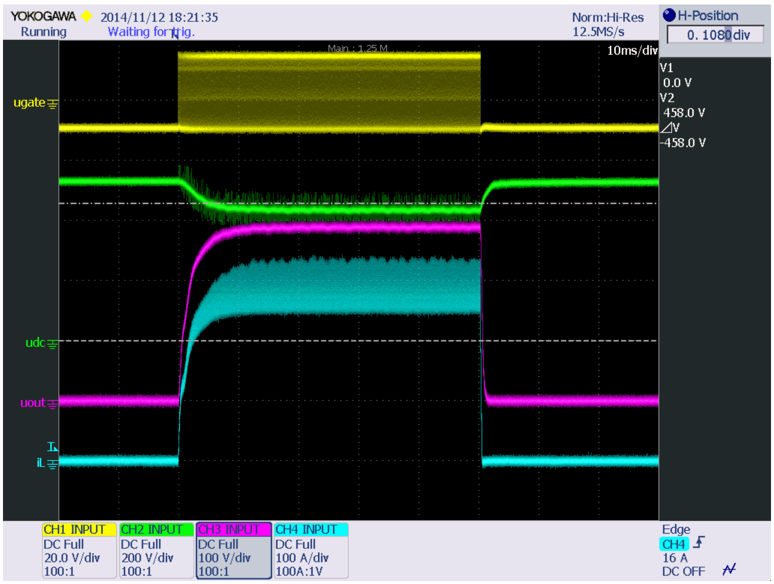


Fig. 5.6. Output side waveforms at 78.4-kW output – pulsed operation (188% single phase load!).

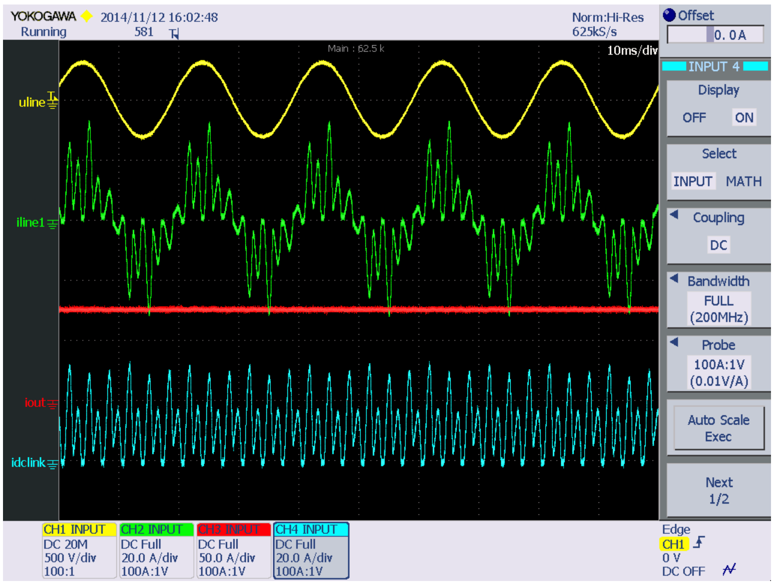


Fig. 5.7. Input side waveforms at 5.6-kW output.

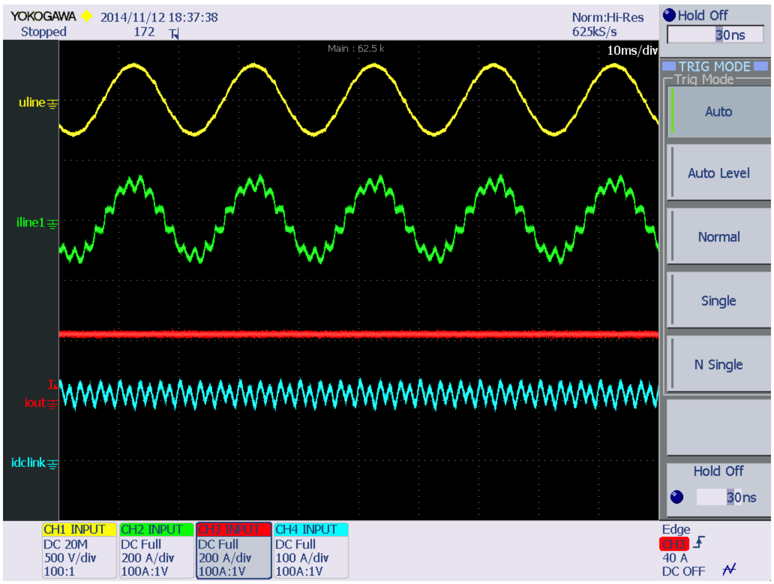


Fig. 5.8. Input side waveforms at 50.6-kW output.

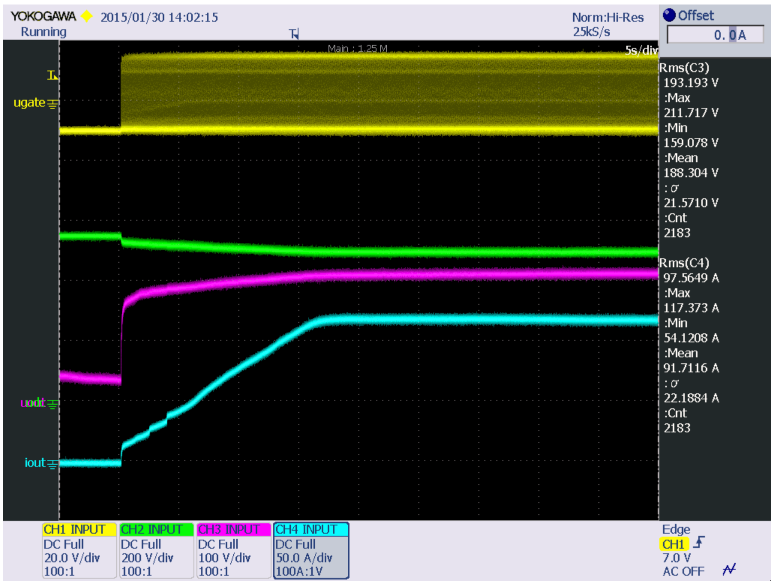


Fig. 5.9. Output side waveforms at 120-A current ramp-up (at GH).

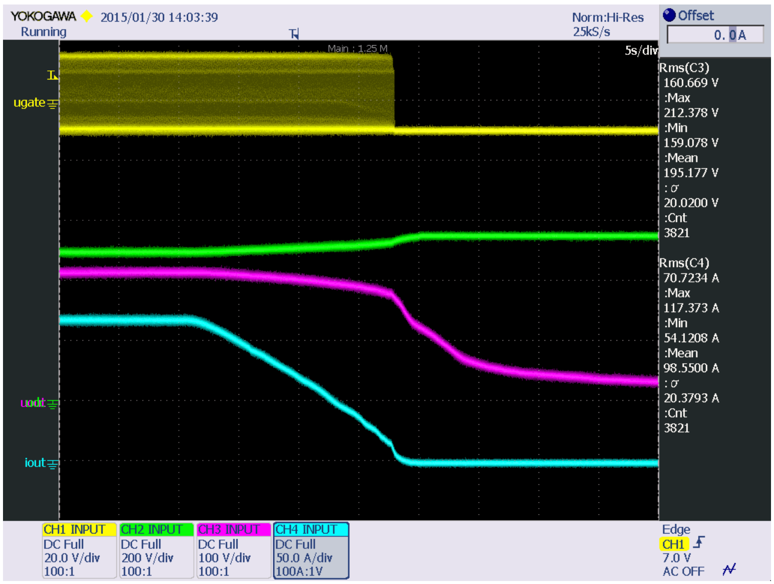


Fig. 5.10. Output side waveforms at 120-A current ramp-down (at GH).

After installation at GH, a large number of tests have been carried out, the control of the pre-prototype has been optimized, and bugs have been fixed. So far, tests with power output up to 250-kW are successful.

250-kW advanced prototype

The power electronics block diagram of the 250-kW advanced prototype is shown in Fig. 5.11. As it can be seen, a safety block that connects or disconnects the power supply from the grid should be included in the system. It also minimizes the inrush current during the grid connection. The AC/DC block consists of an LCL filter and an active rectifier. The DC/DC block consists of 4-phases interleaved H-bridge converters with high frequency isolation transformers followed by current-doubling rectifiers.

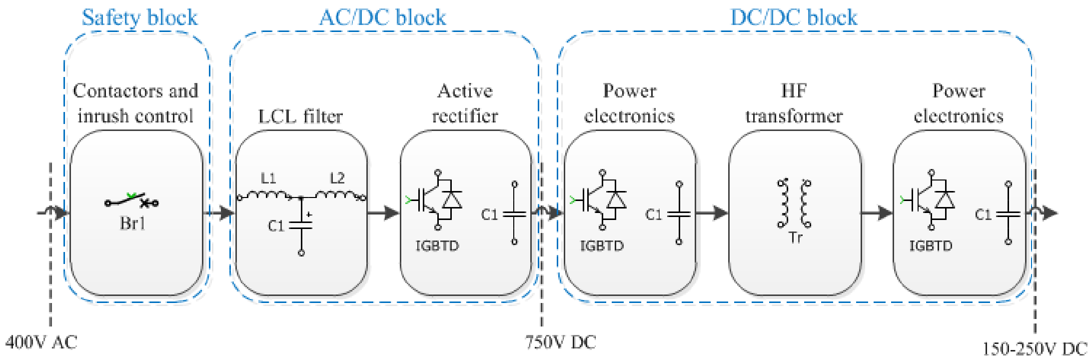


Fig. 5.11. Power electronics block diagram of the 250 kW advanced protype.

The circuit diagram of the AC/DC stage is shown in Fig. 5.12.

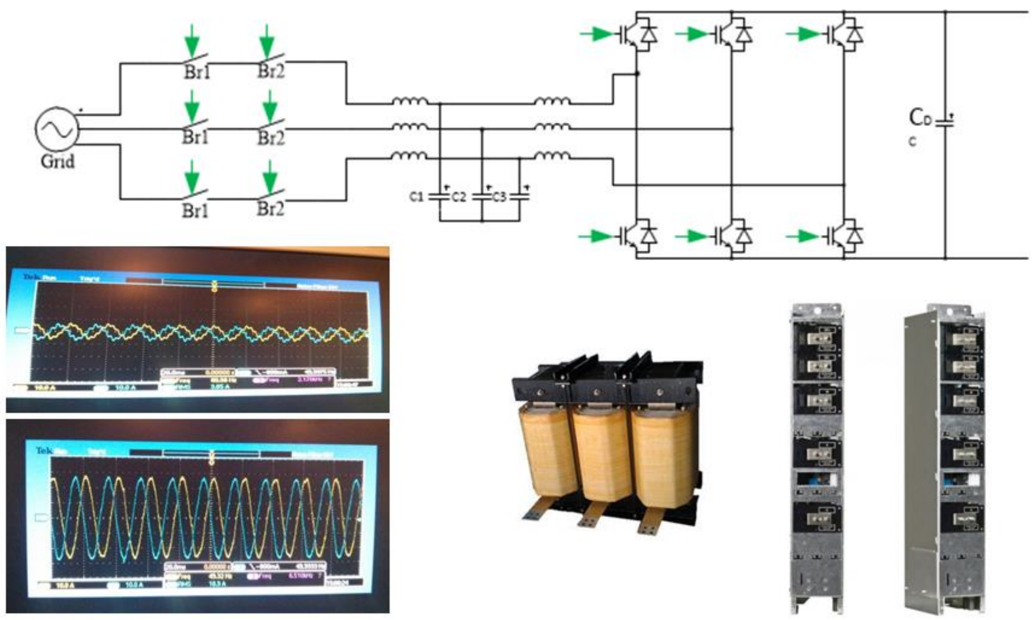


Fig. 5.12. Advanced prototype – AC/DC stage. Circuit, measured waveforms, filter and power stage.

The circuit diagram of the DC/DC stage is shown in Fig. 5.13.

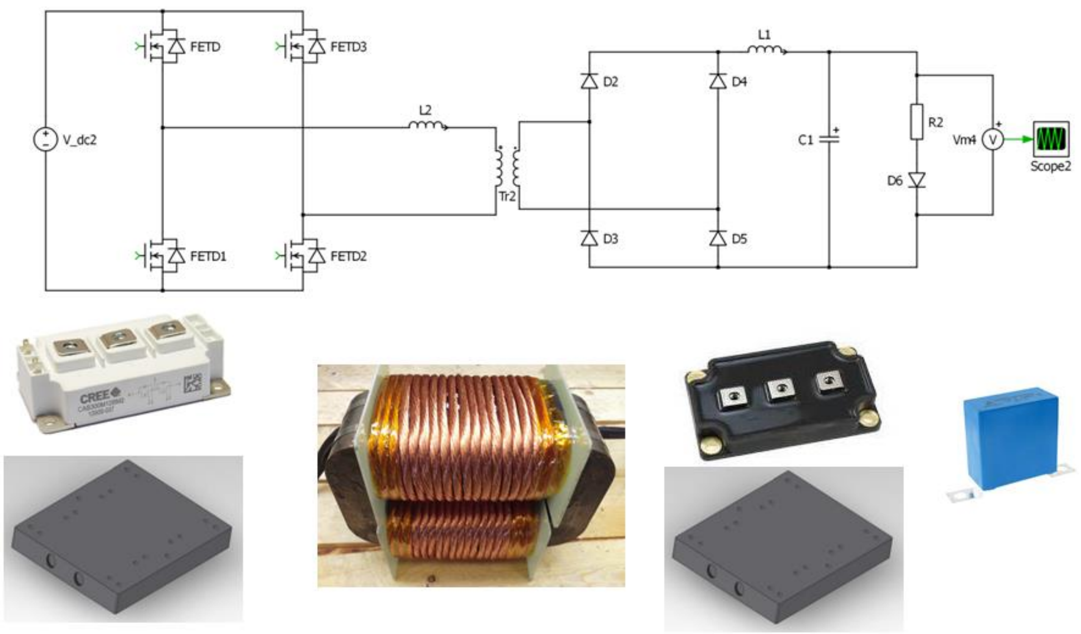


Fig. 5.13. Advanced prototype – DC/DC conversion stage.

Fig. 5.14. Testing of a new DSP adapter board.

Fig. 5.15. Picture of the advanced prototype at GH.

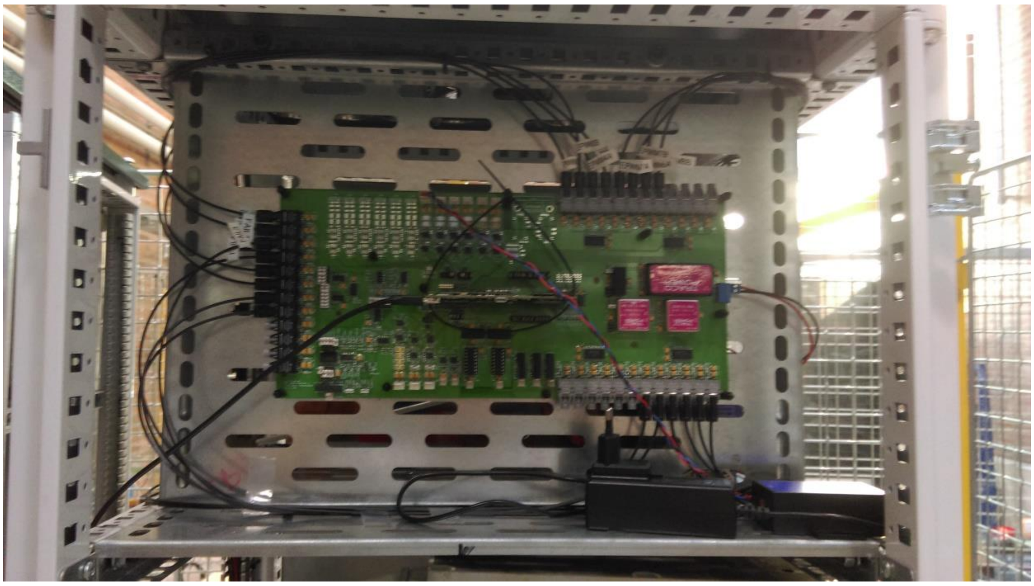


Fig. 5.16. The new DSP adapter board in the 250 kW advanced prototype.

Various test results obtained with the advanced prototype are shown in Fig. 5.17 to Fig. 5.20. Most of these are functionality tests at low power conditions.

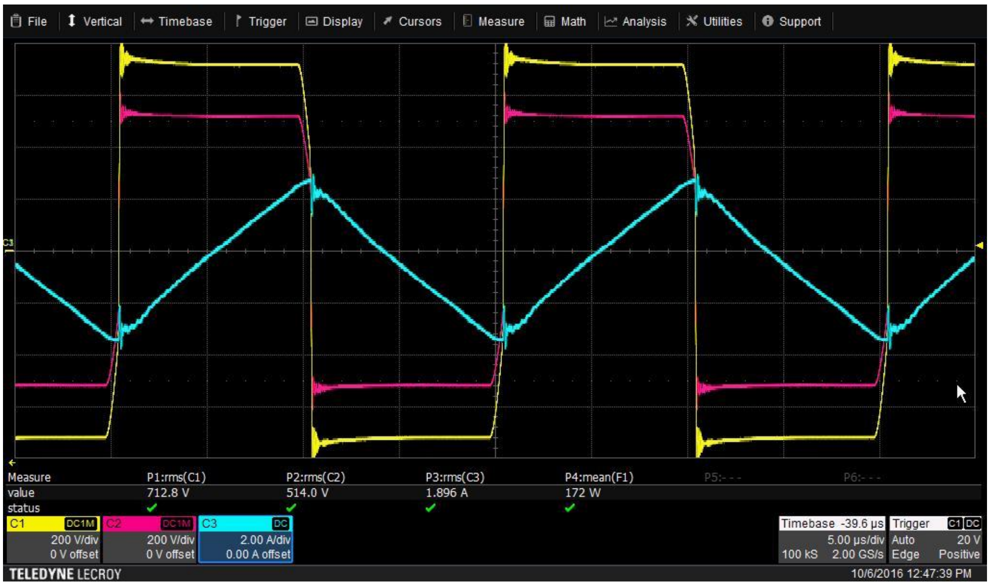


Fig. 5.17. Testing of the high-frequency transformer for DC/DC converter.

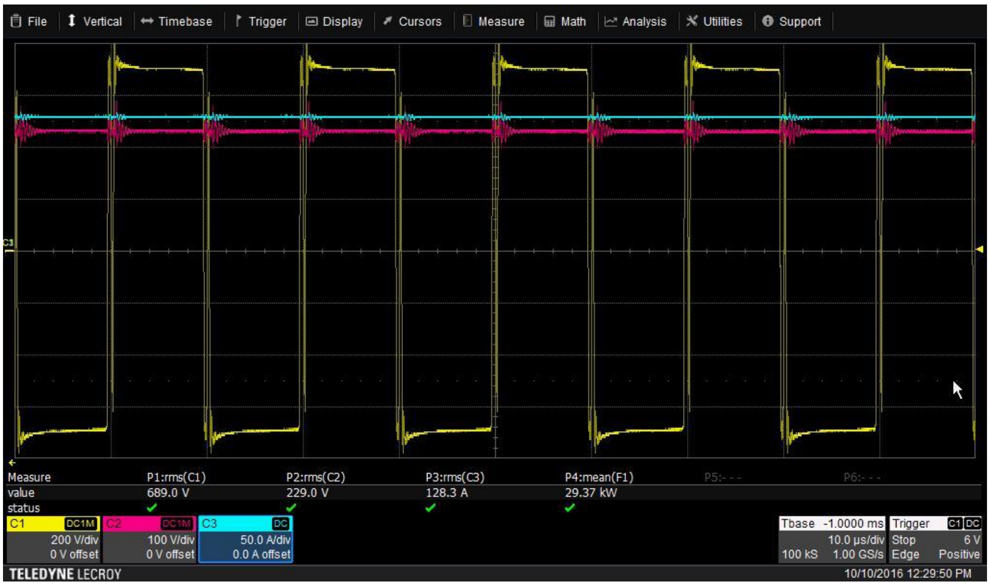


Fig. 5.18. Continuous operation testing of one phase of the DC/DC converter block (low power).

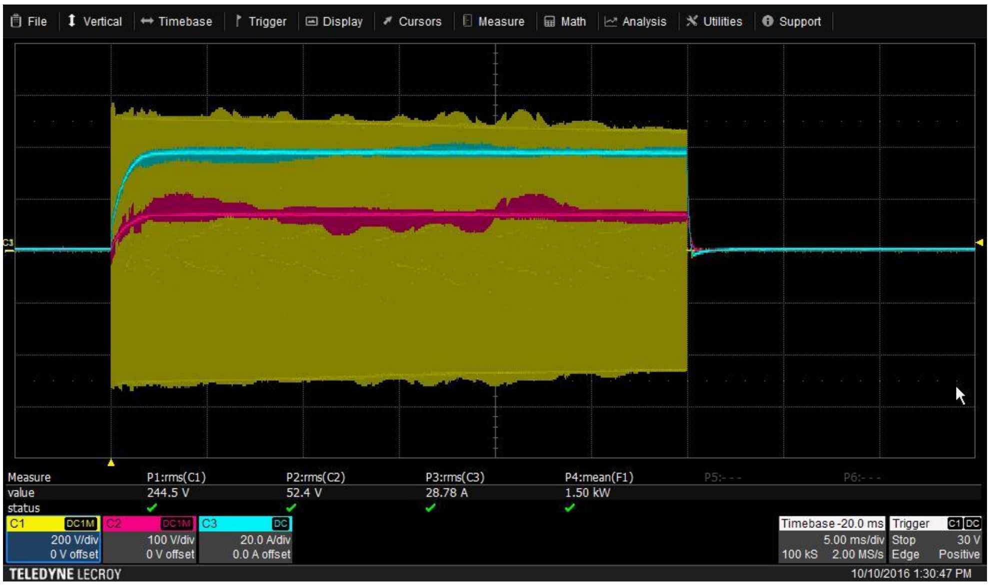


Fig. 5.19. Closed-loop control for one phase of the DC/DC block (low power).

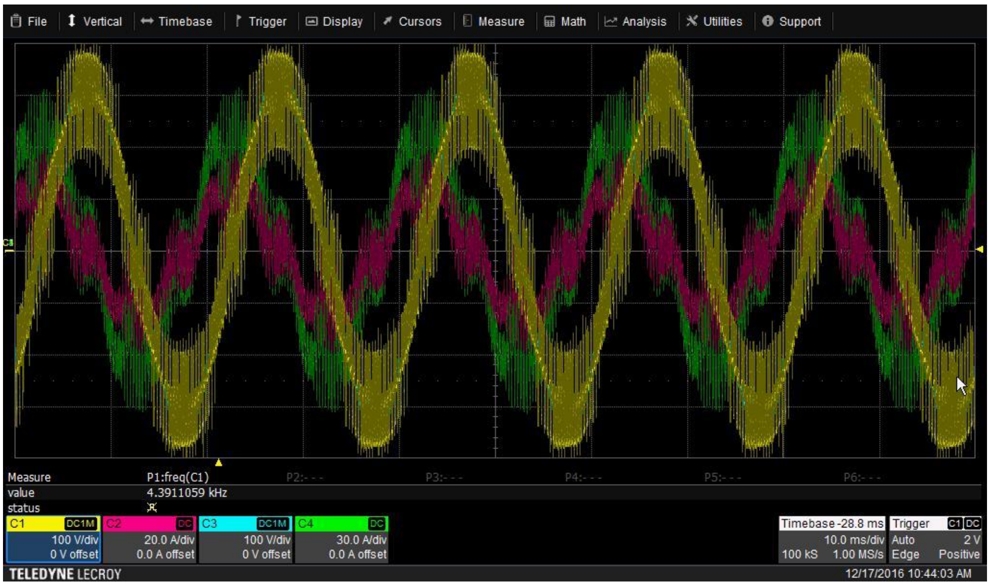


Fig. 5.20. Input side waveforms – continuous operation test (low power).

Heat recovery system

In WP4 - Task 1, a design was suggested on how to use and transfer the heat from the power supply for pre-heating the feed water. This design did not consider the fact that the flow of feed water into the electrolyser stack is not constant. The flow actually only takes place in about every 10 minutes, when the stack is operating at the full power condition. Since the power supply needs constant cooling water, heat storage must be established.

A hydrophone, which can contain the required amount of water, is used (one for the feed water and one for the rinse water). The rinse water cleans the membrane in the reverse osmosis water purification unit and will contain all salts after the purification of the feed water. The ratio between feed water and rinse water depends on the quality of the raw water but in the following calculation it is considered to be 1:1.

The electrolyser is assumed to produce 60 Nm^3/h of hydrogen. Under a 250-kW DC power, it is equal to 250/60 = 4.167 kWh/Nm3. Considering the HHV of 3.54 kW/Nm^3, the efficiency can be calculated to 3.54/4.167 = 0.85.

The water consumption for the production of one Nm^3 of hydrogen is 0.8 L, and therefore, 60 Nm3/h will require 60*0.8 = 48 L/h. Intake of water every 10 min means 60/10 = 6 times per hour and 48 L/6 = 8 L at a time.

It is assumed that the water can be heated from the tap water temperature of 10 ^oC up to the specified cooling circuit temperature of the power supply, i.e., 55 ^oC. The cooling power can then be calculated as

Q = 0.048*1.163*(55-10) = 2.5 kW

Assuming the same amount of rinse water, the total cooling power will be 5 kW. The total cooling power needed for the advanced power supply is 15 kW. Therefore, an additional cool system must be installed in order to dissipate the excess power of 10 kW.

Dimensioning of hydrophone

A hydrophone is a rubber bag inside a steel vessel. When the water is pumped into the bag, the air between the bag and the vessel is compressed.

The reverse osmosis plant delivers purified water at a pressure between 2.5 and 5.5 bar and the input is 8 L at each intake. Therefore, the air pressure in the hydrophone must not rise more than from 2.5 to 5.0 bar at water intake.

Because the water and air pressure will be the same and the volume multiplied by the pressure is constant at constant temperature, the relations between the water pressure and the air volume can be calculated as shown below:

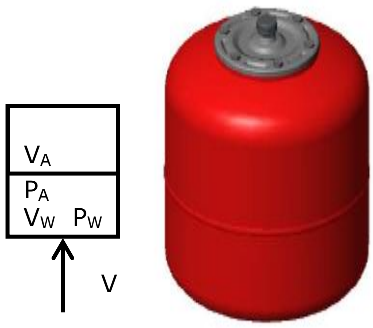


Fig. 5.21. Hydrophone diagram and picture.

V_A = Volume of air

P_A = Pressure of air

V_W = Volume of water

P_W = Pressure of water

1. $V_{A1} * P_{A1} = V_{A2} * P_{A2}$
2. $V_{W1} * P_{W1} = V_{W2} * P_{W2}$

1. $P_{A2} = (V_{A1} * P_{A1}) / V_{A2}$

2. $V_{A2} = (V_{A1} * P_{A1}) / P_{A2}$

A hydrophone of 11 L is integrated into the purification unit and an external capacity of 25 L is used. Assuming the volume of the rubber bags of 1 L each, the total air volume becomes 34 L. The calculation results in Tab. 1 and Fig. 5.22 show that the hydrophone can absorb 19 L of water when operating inside a pressure window of 2.5 to 5.5 bar.

Tab. 1. Feed water side calculations.

Feed water side									
V_{A1}	Litre	Volume Air at 0 bar	34						
P_{A1}	Bar	Pressure air preset	2,5						
V_{A2}	Litre	Volume	34	28	24	21	19	17	15
P_{A2}	Bar	Pressure	2,5	3	3,5	4	4,5	5	5,5
$V_{A1} - V_{A2}$	Litre	Volume change	0	6	10	13	15	17	19

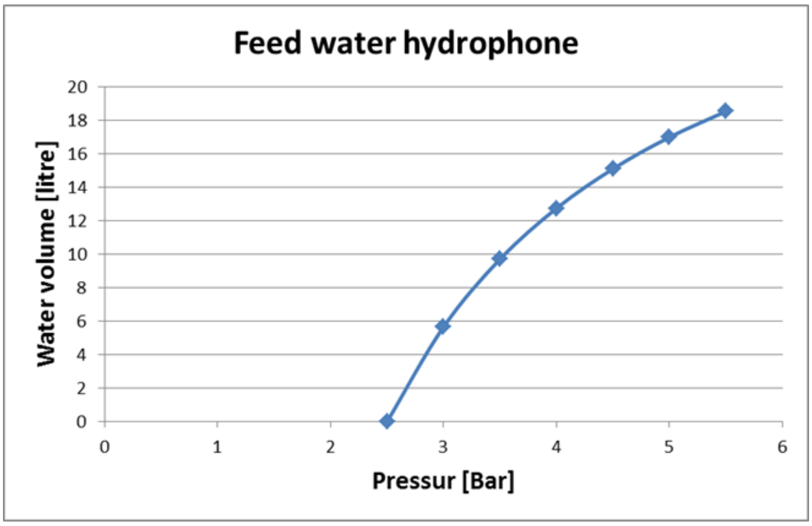


Fig. 5.22. Feed water side calculation results.

The rinse water side of the water purification unit operates between 0.25 and 1.5 bar. The reason for the low pressure is that the higher pressure on the rinse, the lower will the purity of the feed water be, due to more salts passing through the membrane. The calculation results for the rinse water side are given in Tab. 2 and Fig. 5.23.

Tab. 2. Rinse water side calculations.

Rinse water side								
V_{A1}	Litre	Volume of air at 0 bar	24					
P_{A1}	Bar	Preset air pressure	0,25					
V_{A2}	Litre	Volume of air	24	12	8	6	5	4
P_{A2}	Bar	Pressure of air	0,25	0,5	0,75	1	1,25	1,5
$V_{A1} - V_{A2}$	Litre	Volume of water	0	12	16	18	19	20

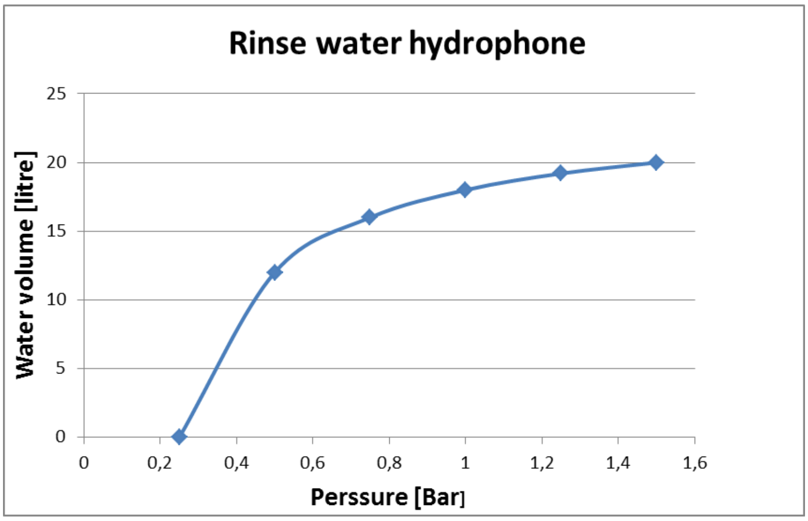


Fig. 5.23. Rinse water side calculation results.

The drawing from Fig. 5.24 shows the setup of the entire system. Two circulation pumps operate continuously and transfer the heat from the IGBTs through the heat exchangers to the water storage in the hydrophones. When the feed water is needed, the hydrophone is partly emptied by the 40 bar pump. The refill from the reverse osmosis plant will start when the pressure reaches 2.5 bar and continues until 5.5 bar. During the refill of the feed water storage the rinse water storage will be filled simultaneously and when the pressure reached 1.5 bar the pressure valve will start to release excess water to the drain.

Since the heating of the feed and rinse water is not sufficient to cool the IGBTs, an extra outdoor water to air heat exchanger is added. When the efficiency of the power supply and the allowable temperature for cooling the IGBTs become higher, the extra outdoor unit will not be necessary.

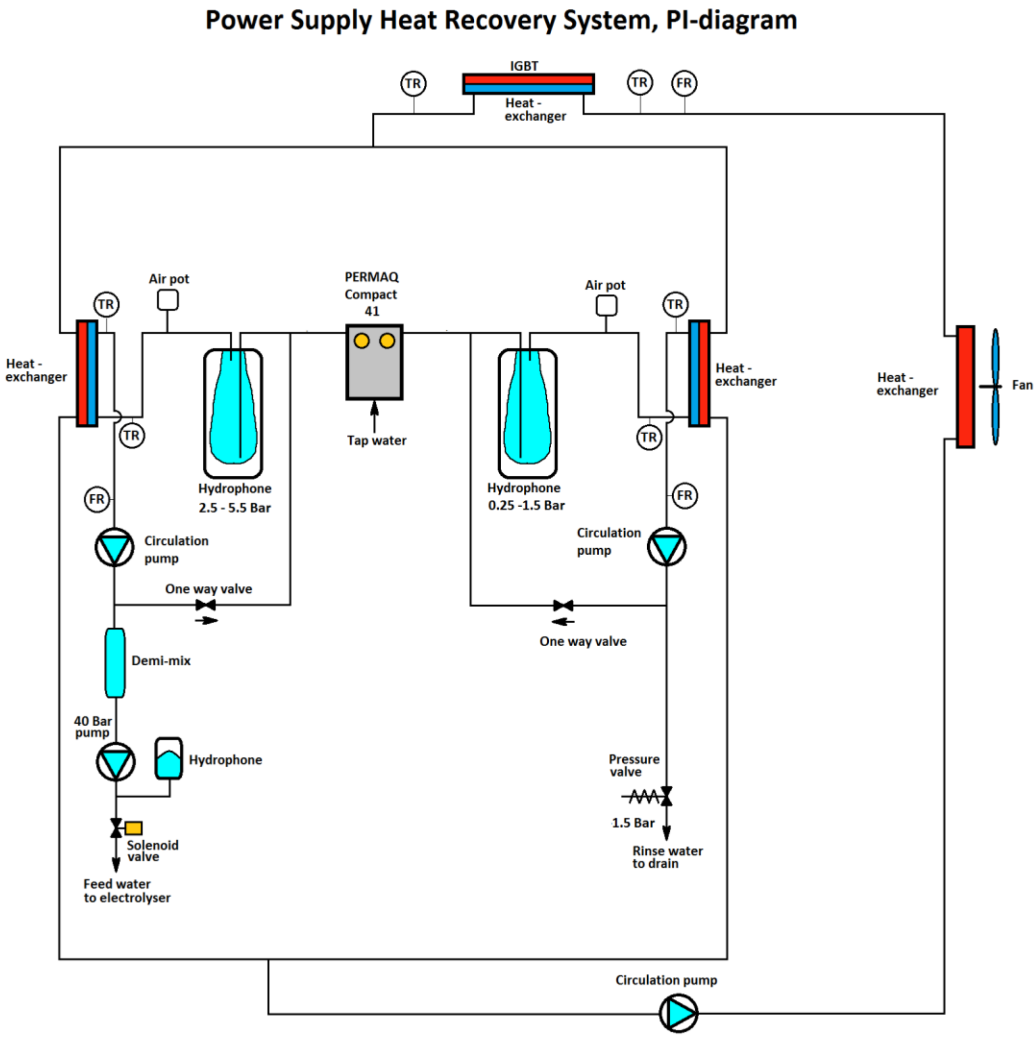


Fig. 5.24. PI-diagram of the heat recovery system.

Dimensioning of heat exchangers

In the advanced prototype, the water-cooled component is the Danfoss power stack (IGBTs), which have internally more cooling plates that are parallel-connected based on the required flow rate of 25 L/min. The other water-cooled components are in the DC/DC converter, for which the PTZed1421 cooling plates are used. Eight of these cooling plates, each requiring 5 L/min connected in parallel, add up to 40 L/min. In this case, the total flow rate is 65 L/min.

The total power to be dissipated is 15 kW and the maximum allowable temperature difference between inlet and outlet of the IGBTs cooling units is 5 ^{o}C. Using the flow of 65 L/min equal to 3.9 m^3/h and the delta T of 5 ^{o}C, the cooling power can be calculated.

Q = 3.9*1.163*5 = 22.7 kW

This leaves a good margin for lower flow or delta T when implementing the system.

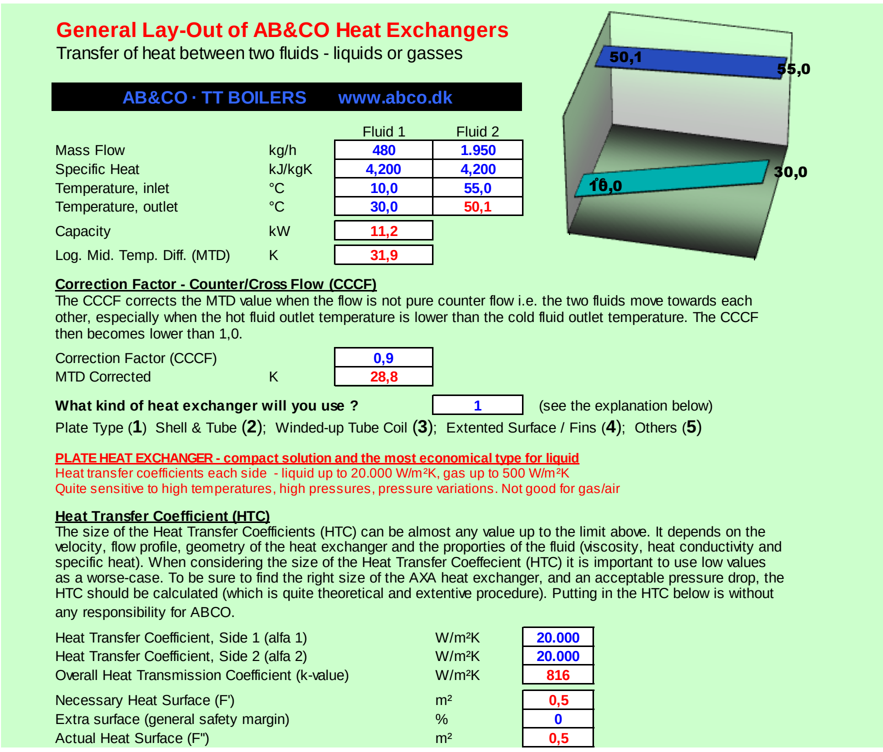
From the system drawing, it can be seen that the flow from the power supply (IGBTs) is divided into two. The same flow through the two heat exchangers is 1.95 m3/h. Two plate heat exchangers are used and the dimensions of the 30 heat exchanger plates are 0.202 * 0.077 m, giving a total area of 0.47 m^2.

The calculation of the heat exchangers for the feed and rinse water is not straightforward, because the water is pumped into the hydrophones in batches of 8 litres and then heated by circulating between the heat exchanger and the hydrophone. At the next intake of feed water, the hot water is fed into the electrolyser stack, and when the pressure in the hydrophone drops, a new batch of cold water enters into the hydrophones.

Using a calculation tool from AB&CO, several calculations have been made in order to verify that the heat exchangers of 0.47 m^2 can achieve so. Assuming that a water intake is 8 L at a time and it takes 1 min and that the water will be circulated between the hydrophone and the heat exchanger by the same flow, the flow will be 8 * 60 = 480 L/h.

The water consumption is, as calculated above, 48 L/h, equivalent to 0.8 L/min. Consuming the 8 L water by producing hydrogen and oxygen will therefore take 8/0.8 = 10 min and leave 10 min for heating the next batch of 8-L water. Because it takes 1 min to circulate the 8-L water between the hydrophone and the heat exchanger, there will be a period for eight circulations before the batch is pumped into the electrolyser stack by the high-pressure pump.

Using the flow of 480 L/h, it can be calculated how the temperature of the water will rise during each cycle. The first iteration from Fig. 5.25 shows that the water is heated from 10 to 30 ^{o}C. The 30-^{o}C water is then used as the inlet temperature for the next iteration, giving an outlet temperature of 41 ^{o}C. Iterations continue, and then the water is heated up.


General Lay-Out of AB&CO Heat Exchangers

Transfer of heat between two fluids - liquids or gasses

AB&CO · TT BOILERS www.abco.dk

		Fluid 1	Fluid 2
Mass Flow	kg/h	480	1.950
Specific Heat	kJ/kgK	4,200	4,200
Temperature, inlet	°C	10,0	55,0
Temperature, outlet	°C	30,0	50,1
Capacity	kW	11,2	
Log. Mid. Temp. Diff. (MTD)	K	31,9	

Correction Factor - Counter/Cross Flow (CCCF)

The CCCF corrects the MTD value when the flow is not pure counter flow i.e. the two fluids move towards each other, especially when the hot fluid outlet temperature is lower than the cold fluid outlet temperature. The CCCF then becomes lower than 1,0.

Correction Factor (CCCF)		0,9
MTD Corrected	K	28,8

What kind of heat exchanger will you use ? 1 (see the explanation below)

Plate Type (**1**) Shell & Tube (**2**); Winded-up Tube Coil (**3**); Extented Surface / Fins (**4**); Others (**5**)

PLATE HEAT EXCHANGER - compact solution and the most economical type for liquid

Heat transfer coefficients each side - liquid up to 20.000 W/m²K, gas up to 500 W/m²K

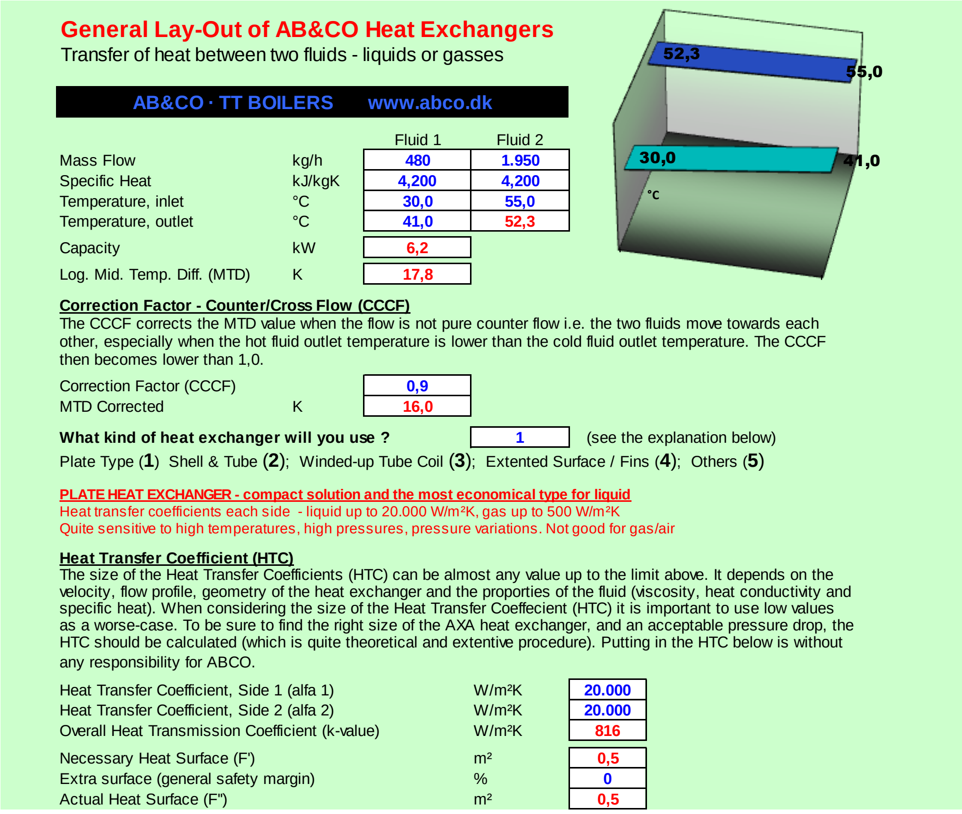
Quite sensitive to high temperatures, high pressures, pressure variations. Not good for gas/air

Heat Transfer Coefficient (HTC)

The size of the Heat Transfer Coefficients (HTC) can be almost any value up to the limit above. It depends on the velocity, flow profile, geometry of the heat exchanger and the proporties of the fluid (viscosity, heat conductivity and specific heat). When considering the size of the Heat Transfer Coeffecient (HTC) it is important to use low values as a worse-case. To be sure to find the right size of the AXA heat exchanger, and an acceptable pressure drop, the HTC should be calculated (which is quite theoretical and extentive procedure). Putting in the HTC below is without any responsibility for ABCO.

Heat Transfer Coefficient, Side 1 (alfa 1)	W/m²K	20.000
Heat Transfer Coefficient, Side 2 (alfa 2)	W/m²K	20.000
Overall Heat Transmission Coefficient (k-value)	W/m²K	816
Necessary Heat Surface (F')	m²	0,5
Extra surface (general safety margin)	%	0
Actual Heat Surface (F")	m²	0,5

Fig. 5.25. Water temperature calculations for the first iteration.



General Lay-Out of AB&CO Heat Exchangers
Transfer of heat between two fluids - liquids or gasses

AB&CO · TT BOILERS www.abco.dk

		Fluid 1	Fluid 2
Mass Flow	kg/h	480	1.950
Specific Heat	kJ/kgK	4,200	4,200
Temperature, inlet	°C	30,0	55,0
Temperature, outlet	°C	41,0	52,3
Capacity	kW	6,2	
Log. Mid. Temp. Diff. (MTD)	K	17,8	

Correction Factor - Counter/Cross Flow (CCCF)
The CCCF corrects the MTD value when the flow is not pure counter flow i.e. the two fluids move towards each other, especially when the hot fluid outlet temperature is lower than the cold fluid outlet temperature. The CCCF then becomes lower than 1,0.

Correction Factor (CCCF)		0,9
MTD Corrected	K	16,0

What kind of heat exchanger will you use ? 1 (see the explanation below)
Plate Type (**1**) Shell & Tube (**2**); Winded-up Tube Coil (**3**); Extented Surface / Fins (**4**); Others (**5**)

PLATE HEAT EXCHANGER - compact solution and the most economical type for liquid
Heat transfer coefficients each side - liquid up to 20.000 W/m²K, gas up to 500 W/m²K
Quite sensitive to high temperatures, high pressures, pressure variations. Not good for gas/air

Heat Transfer Coefficient (HTC)
The size of the Heat Transfer Coefficients (HTC) can be almost any value up to the limit above. It depends on the velocity, flow profile, geometry of the heat exchanger and the proporties of the fluid (viscosity, heat conductivity and specific heat). When considering the size of the Heat Transfer Coeffecient (HTC) it is important to use low values as a worse-case. To be sure to find the right size of the AXA heat exchanger, and an acceptable pressure drop, the HTC should be calculated (which is quite theoretical and extentive procedure). Putting in the HTC below is without any responsibility for ABCO.

Heat Transfer Coefficient, Side 1 (alfa 1)	W/m²K	20.000
Heat Transfer Coefficient, Side 2 (alfa 2)	W/m²K	20.000
Overall Heat Transmission Coefficient (k-value)	W/m²K	816
Necessary Heat Surface (F')	m²	0,5
Extra surface (general safety margin)	%	0
Actual Heat Surface (F")	m²	0,5

Fig. 5.26. . Water temperature calculations for the second iteration.

The result of all 10 iterations is shown in Fig. 5.27. As it can be seen, the feed water will reach the same temperature as that of the power supply cooling circuit before being fed into the electrolyser stack.

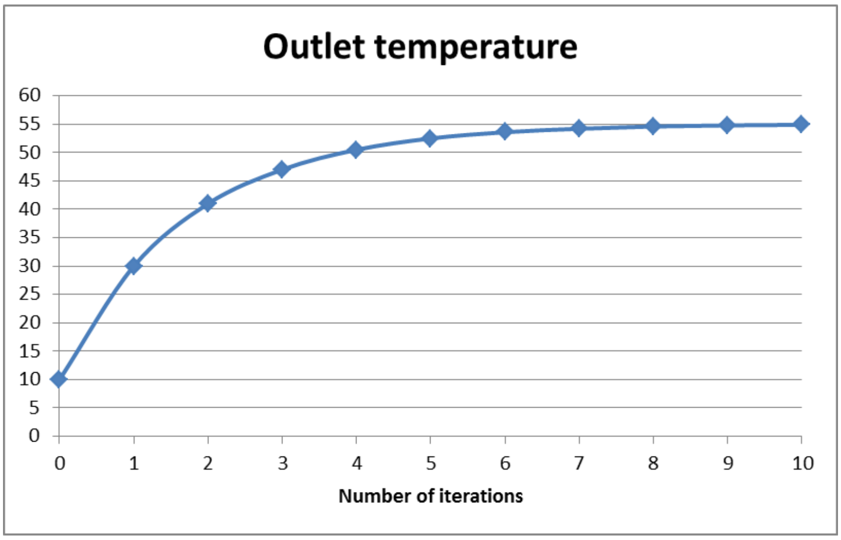


Fig. 5.27. Water temperature calculations for all 10 iterations.

Dimensioning of pump and pipes

The dimensioning of the pipes and pump is actually straightforward by just checking that the pump can deliver sufficient pressure to overcome the pressure drop in the pipes, knees, one-way valve, and heat exchanger.

The pipes or hoses to be used have the dimensions of 25x2.5 mm, and therefore, an inner diameter of 20 mm. The flow will be 1.95 m^3/h, which is equal to 0.54 L/s, as calculated previously. From the curve shown in Fig. 5.28, it can be read that this flow will create a pressure drop of 1.5 kPa/m. The total length of the hoses will be about 10 m given a total pressure drop of 15 kPa equal to 15.000 Pa = 15.000*10^{-5} bar = 150.000 *10^{-5} mWc = 1.5 mWc

The pressure drop in the 10 knees can be calculated by

$\Delta H = \zeta * v^2/2g$ [mWc]

Z = resistance number

v = velocity

g = acceleration of gravity: 9.81 m/s^2

For pipes with an inner diameter smaller than 20 mm, ζ is 1.0; for diameters larger than 20 mm, ζ is 0.5. Therefore, we will adopt ζ = 0.75.

To calculate the velocity of the water in the hose, we need to know the flow, which is 0.54 L/s equal to 0.54*10^{-3} m^3/s, and the cross area of the hose is:

$A = \pi * r^2$

$= \pi * (10*10^{-3})^2$

$=314.1*10^{-6}$ m^2

$= 0.314 *10^{-3}$ m^2

Now the velocity can be calculated as

v= Flow/A

= 0.54*10^{-3} m^3/s / = 0.314 *10^{-3} m^2

= 1.72 m/s

Furthermore, the pressure drop in a knee can be calculated as

$\Delta H = \zeta * v^2/2g$

$= 0.75*(1.72)^2/ 2*9.81$

= 0.11 [mWc]

Considering 10 knees, the pressure drop will be 1.1 [mWc]. The pressure drop inside the heat exchanger is assumed to be the same. As for a hose of the same length, it is included in the total hose length. The pressure drop at the inlet and outlet of the heat exchanger is calculated as a knee and is included in the 10 knees.

The pressure drop through the one-way valve is assumed to be equal to the pressure drop across a knee. Now the total pressure drop can be added up as 1.5 + 1.1 + 0.11 = 2.71 [mWc].

From the flow – pressure curves of the Alpha pumps shown in Fig. 5.29 and Fig. 5.30, it can be seen that the Alpha2 XX-40 pumps might not be able to achieve the goals and the Alpha2 XX-60 pumps have to be used.

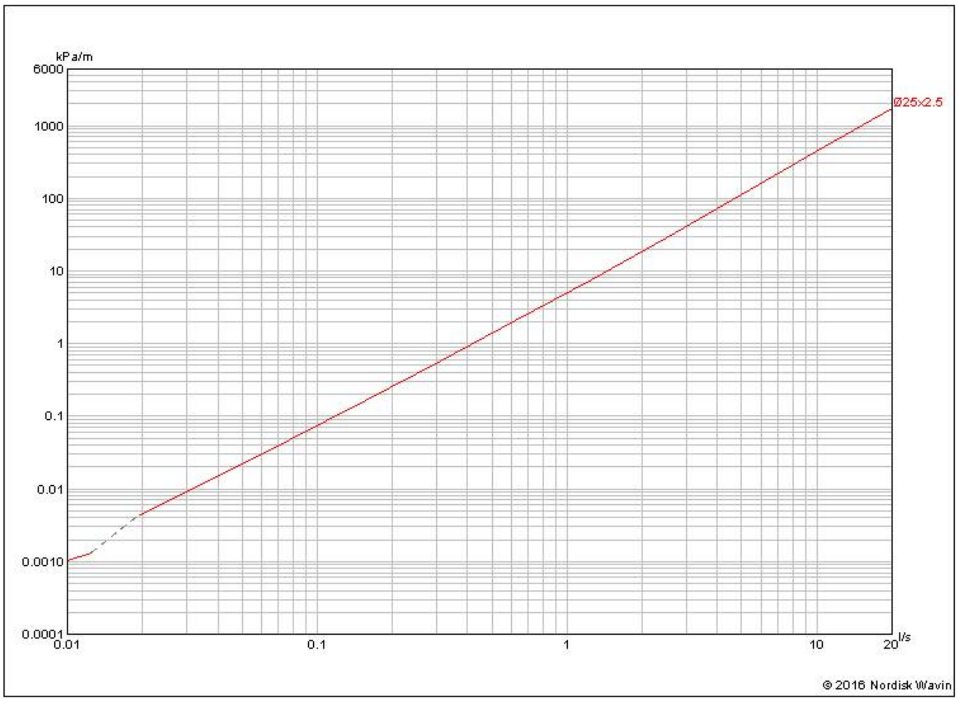


Fig. 5.28. Flow-pressure curve requirement.

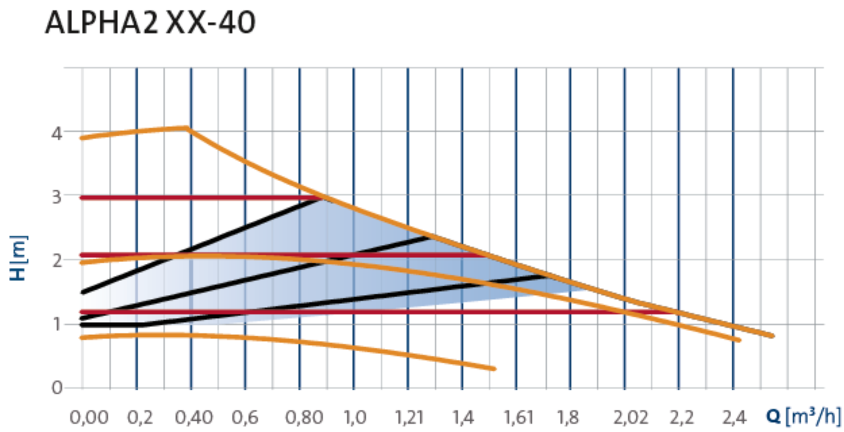


Fig. 5.29. Flow-pressure curves for the Alpha2 xx-40 pumps.

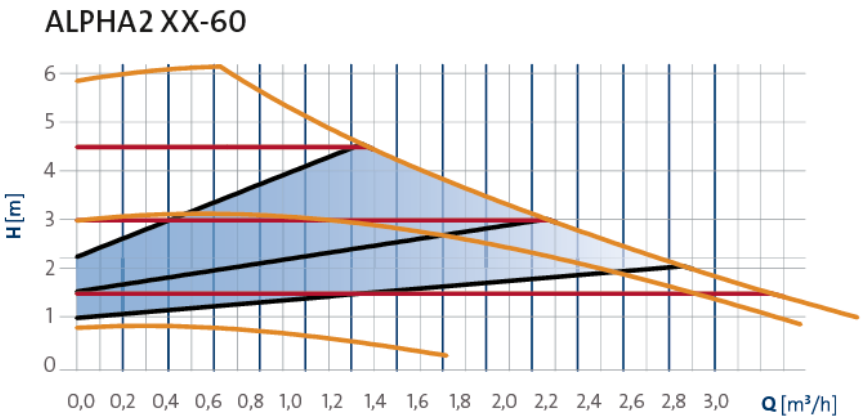


Fig. 5.30. Flow-pressure curves for the alpha2 xx-60 pumps.

Implementation

A mock-up of the heat recovering system have been built up at GH and connected to the cooling system of the power supply as shown in Fig. 5.31. Due to the delay in the delivery of the advanced power supply, the tests were only carried out on the simple 250-kW prototype. The calculated maximum power (heat) to be dissipated was 11.59 kW.

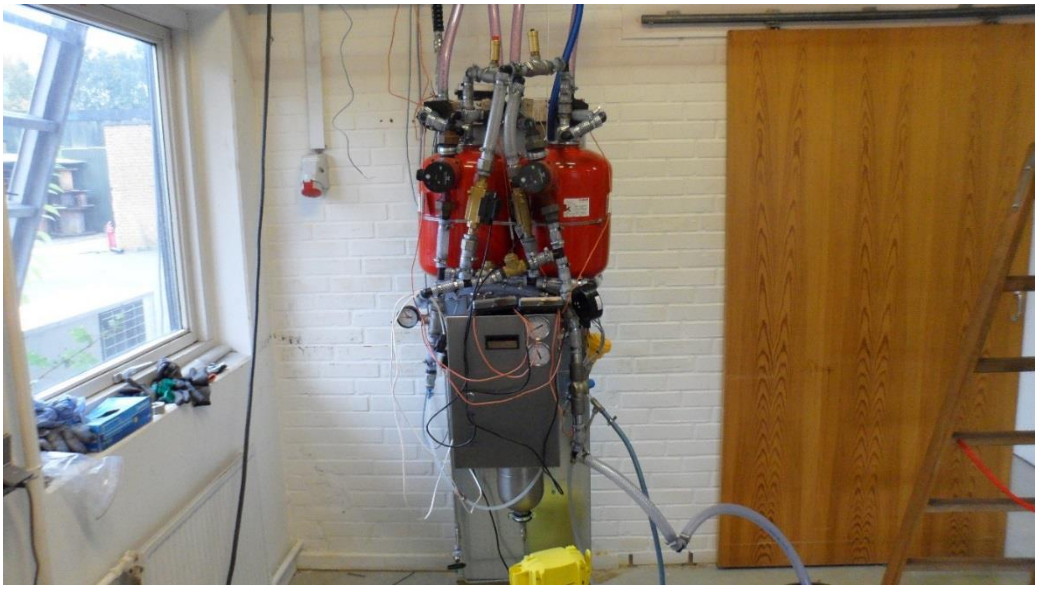


Fig. 5.31. Picture of the installed heat recovery system at GH.

During the operation of the electrolyser, the parameters given in Tab. 3, Tab. 4 and Tab. 5 were measured by manually reading the installed district heating energy meters as indicated in Fig. 5.32.

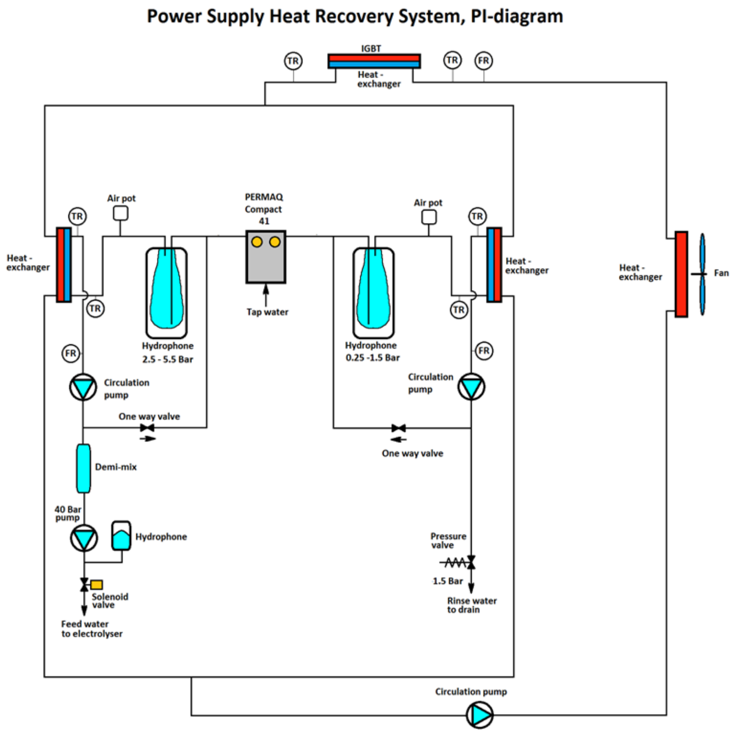


Fig. 5.32. PI-diagram of the heat recovery system – meter installation points.

It can be seen in Tab. 3 that the flows were somewhat less than the calculated. In reality, 313 to 391 L/h for the rinse water and feed water was against the calculated 480 L/h. The maximum average power dissipated from the power supply was measured as 10 kW against the calculated 11.59 kW.

Tab. 3. Heat recovery system test results – power supply.

P2E Data aquisition												
Power Supply Energy Meter												
Date	Time	Water volume circulated	Hour counting	Delta hour counting	T1 Heate exchanger	T2 Heate exchanger	T1-2 Heate exchanger	Flow	Power	Energy accumulated	Delta Energy accumulated	Average power
dd-mm-åå	tt:mm	m3	Number	Number	Celsius	Celsius	Celsius	m3/h	kW	MWh	kWh	kW
14-12-2016	09:40	435,02	1684		30,87	30,61	0,26	1,54	0	0,133		
	10:10	435,72	1685	1	31,49	31,27	0,22	1,54	0	0,134	1	1,00
	15:10	442,28	1690	5	45,53	41,77	3,76	1,58	6	0,136	2	0,40
	17:05	445,19	1692	2	42,25	38,18	4,07	1,56	5	0,140	4	2,00
20-12-2016	09:15	500,60	1828	136	49,94	47,77	2,17	1,53	3	0,156	16	0,12
	10:10	501,95	1829	1	46,06	44,92	1,14	1,52	1	0,160	4	4,00
	11:25	503,88	1830	1	48,56	40,46	8,1	1,52	10	0,165	5	5,00
	12:25	505,37	1831	1	43,57	42,5	1,07	1,52	2	0,171	6	6,00
	13:25	507,00	1832	1	28,42	26,46	1,96	1,66	2	0,174	3	3,00
	14:35	508,63	1833	1	45,54	40,39	5,15	1,52	8	0,179	5	5,00
	15:35	510,16	1834	1	48,35	40,95	7,4	1,53	10	0,189	10	10,00

Measurements not shown in the table revealed that the flow of rinse water was about the double of the feed water. This is in a good agreement with the average power cooled by the rinse water, which is the double of the power cooled by the feed water.

Tab. 4. Heat recovery system test results – feed water.

P2E Data aquisition												
Feed water energi meter												
		Water		Delta	T1	T2	T1-2				Delta	
		volume	Hour	hour	Heate	Heate	Heate			Energy	Energy	Average
Date	Time	circulated	counting	counting	exchanger	exchanger	exchanger	Flow	Power	accumulated	accumulated	power
dd-mm-åå	tt:mm	m3	Number	Number	Celsius	Celsius	Celsius	l/h	kW	MWh	kWh	kW
14-12-2016	09:40	140,51	1707		29,89	28,43	1,46	391	0,6	0,020		
	10:10	140,69	1708	1	30,74	29,8	0,94	385	0,4	0,021	1	1,00
	15:10	142,62	1713	5	36,07	33,32	2,75	381	1,2	0,022	1	0,20
	17:05	143,35	1715	2	39,32	34,35	4,97	388	2,3	0,025	3	1,50
20-12-2016	09:15	157,98	1851	136	46,03	45,09	0,94	362	0,3	0,028	3	0,02
	10:10	158,33	1852	1	45,03	44,18	0,85	362	0,3	0,029	1	1,00
	11:25	158,81	1853	1	41,59	42,16	-0,57	362	0,7	0,029	0	0,00
	12:25	159,16	1854	1	43,88	43,15	0,73	364	0,3	0,029	0	0,00
	13:25	159,54	1855	1	26,5	25,79	0,71	361	0,2	0,03	1	1,00
	14;35	159,93	1856	1	42,48	37,14	5,34	360	2,1	0,031	1	1,00

Tab. 5. Heat recovery system test results – rinse water.

P2E Data aquisition												
Rinse water energy meter												
		Water		Delta	T1	T2	T1-2				Delta	
		volume	Hour	hour	Heate	Heate	Heate			Energy	Energy	Average
Date	Time	circulated	counting	counting	exchanger	exchanger	exchanger	Flow	Power	accumulated	accumulated	power
dd-mm-åå	tt:mm	m3	Number	Number	Celsius	Celsius	Celsius	l/h	kW	MWh	kWh	kW
14-12-2016	09:40	124,20	1707		29,7	28,37	1,33	314	0,4	0,018		
	10:10	124,34	1708	1	30,43	29,06	1,37	313	0,4	0,019	1	1,00
	15:10	125,93	1713	5	28,13	19,05	9,08	313	3,3	0,021	2	0,40
	17:05	126,54	1715	2	33,79	19,7	14,09	325	5,4	0,024	3	1,50
20-12-2016	09:15	139,04	1851	136	46,51	44,67	1,84	325	0,6	0,028	4	0,03
	10:10	139,35	1852	1	45,12	44,19	0,93	324	0,3	0,029	1	1,00
	11:25	139,79	1853	1	50,68	46,89	3,79	325	1,4	0,030	1	1,00
	12:25	140,09	1854	1	44,72	43,56	1,16	322	0,4	0,031	1	1,00
	13:25	140,43	1855	1	25,75	23,95	1,8	315	0,7	0,033	2	2,00
	14:35	140,78	1856	1	42,39	34,18	8,21	316	3	0,035	2	2,00

Business model and dissemination

WP status (deliverables explained):

D6.1 Determination of stakeholders and responsibilities in the electricity market

The first purpose of this WP was to reveal important stakeholders for the project, by determining the stakeholders in the Danish electricity industry with an impact on the hydrogen industry. The research has been conducted using a self-constructed model for determination of relevant stakeholders, based on their technological and commercial influence on the project. The approach of determining stakeholders by using a developed model has been based on a literature review performed on the Hydrogen industry and its cooperation within the Electricity industry and on qualitative interviews performed with the members of the P-2-E project. The research has revealed which stakeholders were affected and could affect the P-2-E project both as complementor and competitors from a technological and also commercial point-of-view. However, the stakeholders who made the largest impact on the project were not necessarily the stakeholders that were affected the most. The research results revealed a need for future research on the development of a stakeholder strategy in order to make it possible for the P-2-E project to take advantage of their existing and proposed relationships to actors in industries. This future research of achieving commercial advantage for the P-2-E project is possible, due to the division of stakeholders, which makes it possible to plan strategies for each relationship.

D6.2 Survey of technical boundaries for price formation

The purpose of this research was to reveal the technical boundaries for the P-2-E project, by determining relevant electricity production and relevant hydrogen consuming technologies, and the boundaries that may exists when these technologies cooperate with electrolysers. The report has used some of the results from WP 6.1 in the P-2-E project to determine the relevant technologies. A comprehensive literature review has been performed for each of the technologies including the boundaries for the electrolyser technology itself. This has resulted in a number of technical boundaries, which have been analysed and compared, in order to determine which general boundary exists. Recommendations for overcoming these boundaries have been presented, as they are considered vital to fulfil the business potential for electrolysers and thereby also for more smart power supplies.

D6.3 Business models for operation of the electrolysis plants with an active role in the electricity grid

A number of business models have been developed to reflect different market scenarios and roles including balancing power, regulating, free players, and aggregator models. The models will be based on the analysis of historical electricity prices and include price estimations for the electricity in 2020 and 2050. The business models will primarily focus on achieving optimal operating economy for the converter based on actual and predicted power prices. Nevertheless, relevant data for marketing the hydrogen will considered to some extent. The models are digital and transparent-structural to support future modelling work.

D6.4 Model for the operational organization

A model for the operational organization including legal, economic, geographic and grid-bound conditions has been developed. Functionality of the model has been tested with selected players and the results have been evaluated.

D6.5 Dissemination of technical and business topics

Proposals for PhD and/or PostDoc projects. Produced 3-5 articles on technical and business topics for popular and scientific/technical journals. Papers and presentations on 1-3 national or international conference.

Dissemination of results

The results of the project have been disseminated by participating in the conference called: "Den danske brint- og brændselscelledag 2016" which took place in Odense at Syd Dansk Universitet (SDU).

Furthermore, the WP6 team has written a series of scientific publications and reports in order to document the potentials of the hydrogen inclusion in the energy grid, the business modelling perspectives, the research methodologies and implications, and the impact of ancillary services in the grid design:

1. Sovacool, B., & Tambo, T. (2016). Comparing Consumer Perceptions of Energy Security, Poli-cy, and Low-Carbon Technology: Insights from Denmark. Energy Research & Social Sci-ence, 11, 79-91.
2. Valuing the manufacturing externalities of wind energy: Assessing the environmental profit and loss of wind turbines in Northern Europe. / Sovacool, Benjamin; Perea, Mario Alberto Munoz ; Matamoros, Alfredo Villa; Enevoldsen, Peter. / Wind Energy, Vol. 19, Nr. 9, 02.11.2015, s. 1623–1647. DOI: 10.1002/we.1941
3. Tambo, T., & Enevoldsen, P. (2015). Towards a framework for evaluation of renewable ener-gy storage projects: A study case of hydrogen and fuel cells in Denmark. IProceedings of the 24th International Association of Management of Technology Conference. (Vol. 24). Cape Town.

4. Enevoldsen, P., & Tambo, T. (2014). Survey of stakeholders and responsibilities in the electrici-ty market: Part 6.1 of work package 6 in the Power-2-Electrolysers project.
5. Enevoldsen, P., Sovacool, B., & Tambo, T. (2014). Collaborate, Involve, or Defend? A Critical Stakeholder Assessment and Strategy for the Danish Hydrogen Electrolysis Indus-try.International Journal of Hydrogen Energy, 39(36), 20879–20887. 10.1016/j.ijhydene.2014.10.035
6. Optimizing Investments in Coupled Offshore Wind -Electrolytic Hydrogen Storage Systems in Denmark. / Hou, Peng; Enevoldsen, Peter; Eichman, Joshua; Hu, Weihao; Jacobson, Mark; Chen, Zhe. Journal of Power Sources. 2017
7. Operational Optimization of Wind Energy Based Hydrogen Electrolysis Storage System Con-sidering Electricity Market's Influence. / Hou, Peng; Enevoldsen, Peter; Hu, Weihao ; Chen, Zhe. 2016. Abstract from IEEE PES Asia-Pacific Power and Energy Engineering Conference
8. Tambo, T., & Enevoldsen, P. (2014). Designing Business and Technology Management Work-Packages in Cleantech Research Projects. I Y. Hosni (red.), Proceedings of the 23rd Interna-tional Association for Management of Technology Conference. (s. 1-11). Washington DC, USA: International Association for Management of Technology (IAMOT).
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1.6 Utilization of project results

The simple 250-kW prototype will be used for laboratory tests of the new electrolyser stacks at GH in the future.

The advanced 250-kW prototype will probably be optimized and included in an electrolysis system (container) and then commercialized.

The low-cost 6-kW prototype will be used by HTAS for testing.

The heat recovery system will be used to test the advanced prototype with the aim to improve the overall system efficiency.

The business modelling and perspectives of ancillary services are forming a platform for further research at the Center for Energy Technology.

1.7 Project conclusion and perspective

As a conclusion, the project has been running satisfactorily. However, there are system challenges with the existing electrolysis technology to recover all power losses from the power supplies, as the efficiency of the electrolysis is not very high and the waste heat from the power supply can not be used very efficient..

1.8 Future work

The advanced 250-kW prototype is not completely finished yet, because there have been long delays in the delivery of the customized inductors and also due to unforeseen EMI issues, which takes some time to solve. So far, the advanced prototype is almost completely assembled except for the output filtering inductors (arrived late). The advanced prototype has been tested for functionality at low power with the grid-connected AC/DC stage and 1 out of 4 phases of the DC/DC stage running. After the inductors will be assembled, the whole system testing will be carried out including debugging and optimization of the control code. After the control is running satisfactorily, long term high power tests will be carried out in order to see if there are any issues regarding the thermal management of the system and also to make sure that the system is stable.