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Work Package 7

Deliverable 7.5

Final Technical Performance Report


Public

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EXECUTIVE SUMMARY

HyBalance is one of Europe's first facilities for the production of hydrogen by PEM water electrolysis on an industrial scale. The facility is a pioneer installation demonstrating the benefits of the whole value chain of hydrogen from the production to the distribution and enabling the storage of electricity from renewable sources.

One of the key objectives of the HyBalance project is to validate highly dynamic PEM (Proton Exchange Membrane) electrolysis technology and demonstrate this at megawatt-scale (1.2 MW) in an industrial environment. Demonstration of the level of performance in accordance with the State of the Art at design stage (2016) over a long period of service time represents an important challenge of the program.


From an operational point of view, the HyBalance facility has achieved a number of important results:

- PEM electrolysis technology achieves a **high level of availability and efficiency** over a long period of usage - more than 3 years producing hydrogen and still in operation
- Hydrogen produced at Hybalance can serve **clean transport and industry markets** at required specifications in terms of H₂ quality and supply chain management
- Power-to-Hydrogen is a viable way to **store energy** on a larger scale and support the increasing share of renewables in grid mix
- **High flexibility and short reaction-time** of PEM technology provide competitive advantages to balance the grid

Looking deeper into the technology and especially the PEM water electrolysis process, the program has produced great results for a first of its kind plant. In dedicated tests, the performance of the HyBalance PEM electrolyser plant has been assessed. It was found that :

- HyBalance is producing **high purity H₂** in the **expected efficiency** range at **nominal volume flow and pressure**.
- The electrolyser fulfills the conditions of grid service showing a high reactivity with **ramp-up in one second** and **ramp-down ramp time in a few seconds**.
- The cold start-up took longer than expected, as the plant was optimized for low H₂ vent losses during start-up. Nevertheless cold start-up time is not seen as a critical parameter, as a constant minimal operational load demand is given by the pipeline customer.
- The cell voltages at different current densities fit to the state of the art electrolyzers at project start in 2016. The first measurements are deemed extremely satisfactory and in accordance with expectations and the FCH 2 JU target value of the year 2020. Thus, the forecast on **lifetime is also very promising** and expected to be in line or even exceed the program targets.

All these achievements also represent key milestones for the next generation of PEM electrolyser solution developments at large scale (for example 20MW in Becancour, Canada, start-up 2021).

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1. INTRODUCTION

The hydrogen is produced from water electrolysis, enabling the storage of electricity from wind turbines. It helps balance the grid, which is essential for the stability in electricity systems. With the share of renewable energy growing in the energy mix, the need for storage and downstream use in fossil dependent sectors such as transportation has become a critical issue. Hydrogen is seen as one of the key enablers to solve these challenges.

The hydrogen produced is used to supply industrial customers as well as the clean mobility market.

One of the key objectives of the HyBalance project is to validate highly dynamic PEM (Proton Exchange Membrane) electrolysis technology and demonstrate this at megawatt-scale (1.2 MW) in an industrial environment.

From a technical point of view, demonstration of the expected level of performance over a long period of service time represents an important challenge of the program. The evaluation of performance under industrial constraints will enable the project to validate the state of the art testings made on prototype systems in the laboratory with a representative sequence of real conditions of work. Key parameters of the technology have been monitored either during daily operating hours and specific testing protocols timeslot. The focus has been set on the electrolysis process being the most innovative system of the plant.

These results also represent key milestones for the next generation of PEM electrolyser solution developments at large scale (for example 20MW in Becancour, Canada, start-up 2021).

1. OPERATIONAL RESULTS

HyBalance is one of Europe's first facilities for the production of hydrogen by PEM water electrolysis on an industrial scale. The facility is a pioneer installation addressing the whole value chain of hydrogen from the production to the distribution to end-users.


The plant is made of several subsystems :

- 1,25 MW PEM electrolyser composed of dual-stacks and several ancillaries : water filtration system, cooling unit, dedicated electrical substation...
- Compression unit to pressurized the hydrogen production
- High and medium pressure storage acting as regulation buffer capacities between upstream production and downstream demand
- Power transformer connected to the grid including the activation box for balancing services
- Pipeline connection for direct supply to a nearby customer
- Tube filling center for trucked-in delivery at customer sites

Hybalance equipment have proven their proper functioning in specific modes defined in the specifications, both at factory test before delivery and for the commissioning after installation on-site.



Figure 1: Hybalance facility overview

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The monitoring of the site by the program during two and half years enables it to provide many returns of experience on the operational performance. The program has achieved a number of important results described below. Air Liquide will continue to operate the site and produce hydrogen to supply its customers.

High availability supplying industry and clean transportation

The HyBalance plant has produced **more than 120 tons** of hydrogen since its inauguration in 2018 as shown in Figure 2. The installation has demonstrated a high availability considering the pilot nature of the project.

The plant ensures **24/7 delivery** of 60 tons of hydrogen to an industrial customer connected through a **pipeline**. The remaining 60 tons have been delivered by **tube trailer logistics** to other industrial applications as well as for clean transportation, such as a network of hydrogen stations fuelling a fleet of fuel cell taxis in Copenhagen.

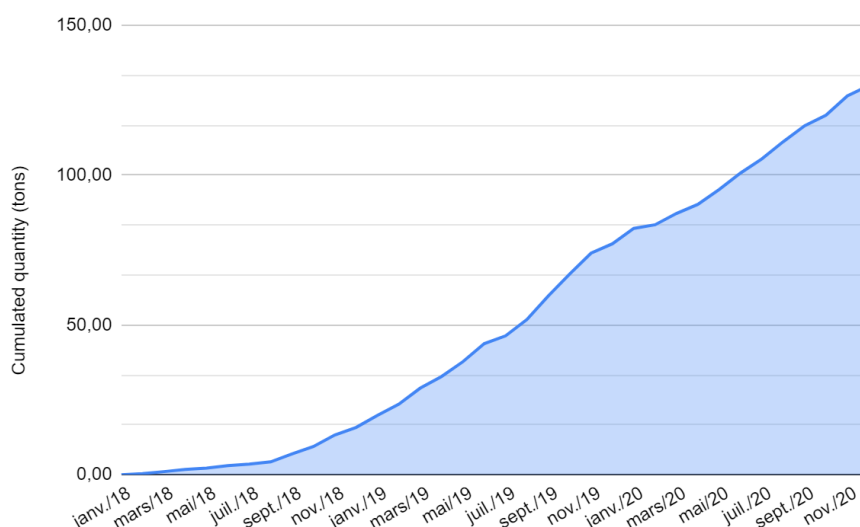


Figure 2: H2 production of Hybalance since the plant start-up

High flexibility and short reaction-time help balance the grid

The facility has validated the PEM (Proton Exchange Membrane) electrolysis technology as highly dynamic, able to cope with fast power ramps up and downs. HyBalance is thus **certified by the Danish energy authorities** as a bidder in all electricity markets. This is a great success as specifically in the primary reserve containment, only a few power installations are able to reach a reaction time below 10 seconds. The plant is able to help balance the Danish grid.

2. PERFORMANCE TEST RESULTS

2.1 Test matrix

Throughout the program duration, several performance tests campaigns have been conducted. The following test matrix was defined for testing the performance of the HyBalance electrolyser plant (Table 1).

It is also important to note that the tests have been performed during production hours thus the test protocol pictures the usual production operating conditions.


Variable	Unit	Tests			
		Nominal conditions	Cold start up	Ramp-Up & Ramp-Down	Ageing
Duration	[hours]	24	-	-	6 hours/month
Operating pressure	[barg]	32 ± 1.5*	0.1 to 32 ± 1.5*	29 to 32 ± 1.5	32 ± 1.5
Current	A	100%	0 → 100%	10% → 100% 100% → 10%	100%

Table 1: Test matrix for performance evaluation of HyBalance electrolyser system.

2.2 Reference case

For the sake of comparison, the test results will be compared to the state of the art in 2017 and eventually at a more recent stage.

The benchmark to define the reference case mostly relies on the MAWP 2014-2020 edited by the FCH 2 JU (cf. Table 2) as well as the design specifications of Hybalance and complementary scientific literature.

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No.	Parameter	Unit	State of the art		FCH 2 JU target		
			2012	2017	2020	2024	2030
Generic System							
1	Electricity consumption @nominal capacity	kWh/kg	60	58	55	52	50
2	Capital Cost	€/ (kg/d) (€/kW)	8,000 (~3,000)	2,900 (1,200)	2,000 (900)	1,500 (700)	1,000 (500)
3	O&M cost	€/ (kg/d)/yr	160	58	41	30	21
Specific System							
4	Hot idle ramp time	sec	60	10	2	1	1
5	Cold start ramp time	sec	300	120	30	10	10
6	Footprint	m²/MW	-	120	100	80	45
Stack							
7	Degradation	%/1000hrs	0.375	0.250	0.190	0.125	0.12
8	Current density PEM	A/cm²	1.7	2.0	2.2	2.4	2.5
9	Use of critical raw materials as catalysts PGM	mg/W	-	5.0	2.7	1.25	0.4
10	Use of critical raw materials as catalysts Pt	mg/W	-	1.0	0.7	0.4	0.1

Notes:

Availability is fixed at 98% (value from the electrolysis study)

1) to 3) and 7) similar conditions as for alkaline technology (previous table)


2) the time from hot idle to nominal power production, whereby hot idle means readiness of the system for immediate ramp-up. Power consumption at hot idle as percentage of nominal power, measured at 15°C outside temperature.

3) The time from cold start from ~20°C to nominal power

9) This is mainly including ruthenium and iridium as the anode catalyst and platinum as the cathode catalyst (2.0 mg/cm² at the anode and 0.5 mg/cm² at the cathode). The reduction of critical raw materials content is reported feasible, reducing the catalysts at a nano-scale.

Source: Addendum to the Multi-Annual Work Plan 2014-2020 of the Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU), 2018

Table 2: State-of-the-art and future targets for hydrogen production from renewable electricity for energy storage and grid balancing using PEM electrolyzers

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2.3 Nominal Conditions

For accessing the performance at nominal conditions a 24 h-test at nominal load, pressure and temperature has been performed. It needs to be mentioned that the temperature of the system is current load - dependent and therefore it is regulated by the process control. One main target was to determine the specific energy consumption at stack and system level.

Table 3 shows the testing results in comparison with the specifications of the electrolyser system of Hydrogenics.

Parameter	System Specifications	Test results
Nominal Flow	230 Nm ³ /h	227 Nm ³ /h
Nominal Pressure	30 barg @ battery limit	32.4 barg
Nominal system efficiency	5,3 kWh/Nm ³	5.08 kWh/Nm ³
Nominal avg stack efficiency	-	4.38 kWh/Nm ³

Table 3: Results of the nominal performance test in comparison with the systems specification

The production rate conforms to the specifications. As can be seen the nominal flow measured is ~1.5% lower than expected, which can be considered to be within the measurement accuracy of the H₂ flow meter.

Also the nominal system efficiency measured in the first 7000 h of operation is well below the specified range. With 56.5 kWh/kg the **electricity consumption at nominal capacity exceeds the State of the art** listed by the FCH JU for 2017 (58 kWh/kg), which is a great achievement as the project start was in 2016.

2.4 Cold Start Up

The reactivity of the electrolyser system gives information, how flexible the electrolyser can be operated. The complexity of operation increases, especially when grid service is activated and at the same time customers need to be supplied via pipeline and trailers. In case down regulation to 0% would be targeted and for example offered as grid service, a fast start up with minimized H₂ loss would be a need to ensure a fast reaction in case the customer demand increases.

For the cold start up test the electrolyser stacks were under depressurized conditions at 18 °C just before start up. In a start-up procedure controlled manually it took approx 30 min for start-up to nominal load. However, nominal load was not targeted directly, but the system was controlled manually and the load was only increased stepwise. It is expected, the system starts-up much faster in an automatically controlled way and additional testing will be repeated with this mode. However, the cold start-up is currently mainly limited by the hydrogen vent rate, which was designed for economical start-up with reduced H₂ loss during H₂ venting for pressure regulation. Also in standard operation the benefit of a complete shut-down is limited to the fact that the pipeline customer consumes a constant load so there is no critical impact on Hybalance.

2.5 Ramp-Up & Ramp-Down Rate

Figure 3 shows the hot ramp-up time for stack A (10% - 100%) and stack B (0% to 100 %). As can be seen both load changes take place within 1 s.

Within the FCH 2 JU for 2020 a hot idle ramp time of 2 s is targeted, for 2024 a hot idle ramp time of 1s is targeted. Therefore it can be concluded that the HyBalance electrolyser shows **an extraordinary reactivity**, already fulfilling the FCH 2 JU targets today.

However under standard operation conditions without unwanted tripping of the plant an idle start up will not be targeted. The agreed consumption of the pipeline customer assures constant production at 25% load for both stacks at minimum.

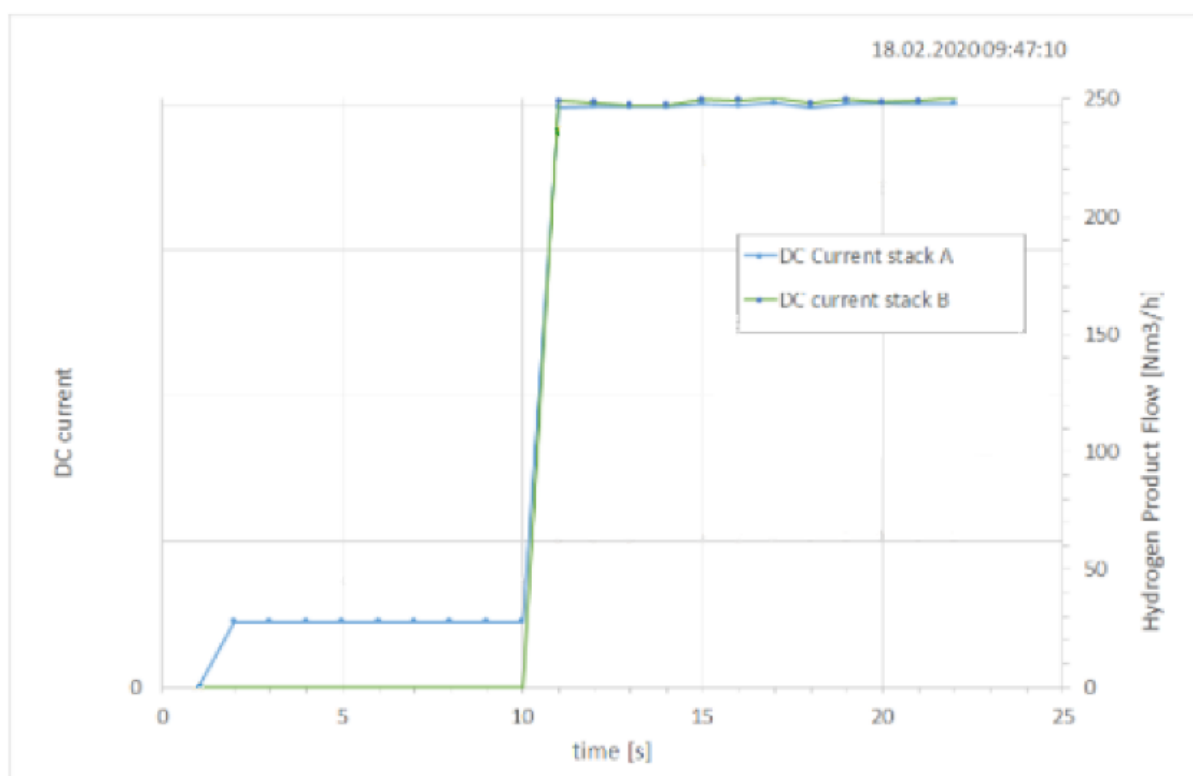


Figure 3: DC current of stack A and B and H₂ product flow during hot ramp-up.

Ramp-down of the electrolyser stacks from 100% to 10% current input takes place within 4 s. As shown in Figure 4 the H₂ product flow at the boundary limit decreases more slowly. After 60 seconds steady state is not reached yet, due to the remaining H₂ volume stored in the separators and the gas purification unit. Due to the heat capacity of the system, the stack temperature decreases even more slowly.

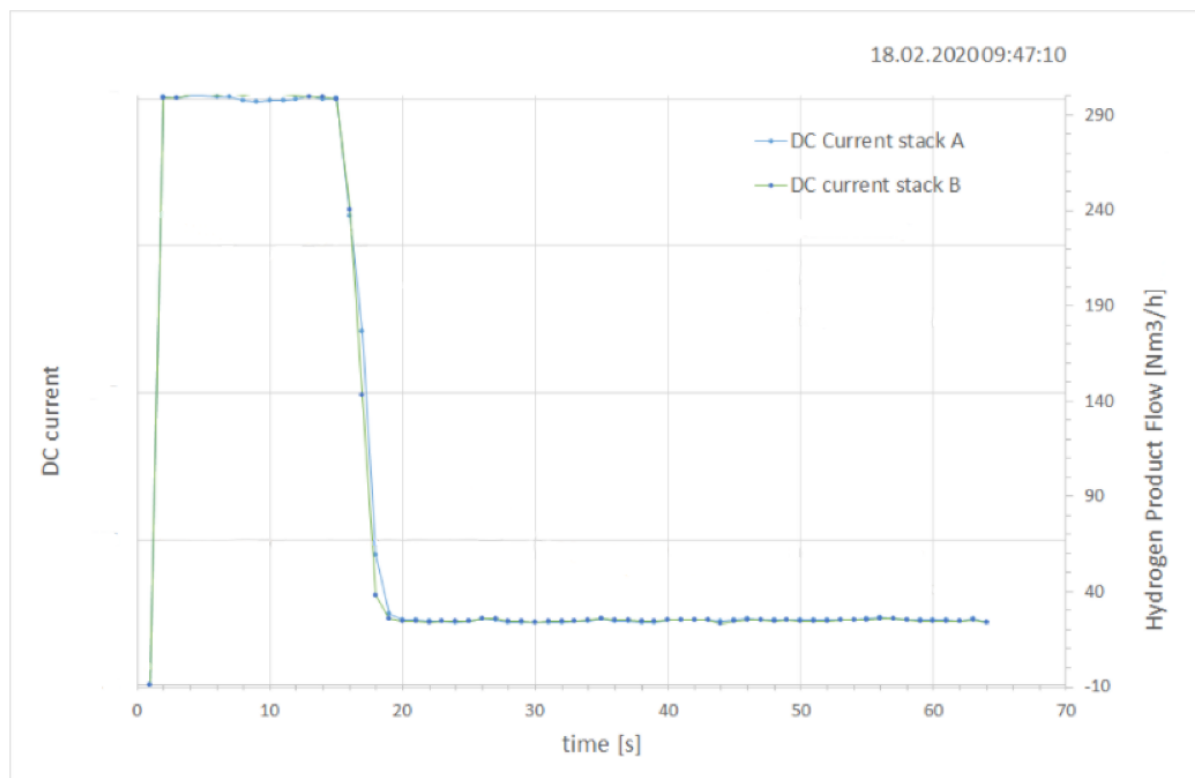
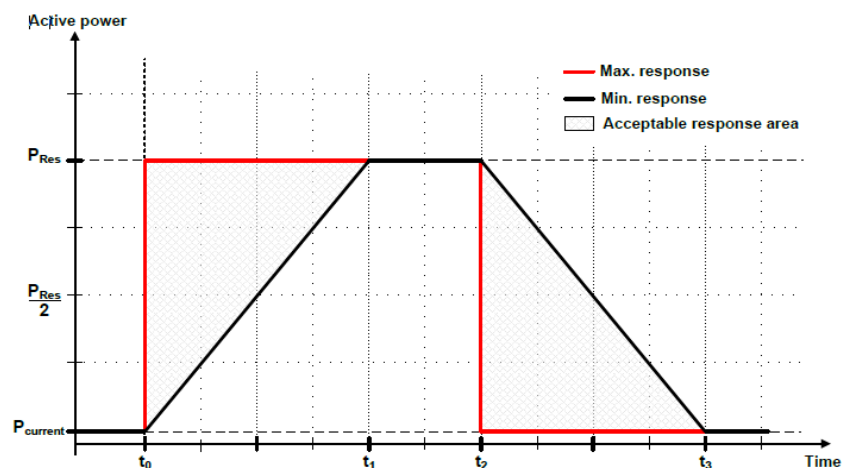


Figure 4: DC current of stack A and B and H₂ product flow during ramp-down.

It can be concluded that the electrolyser fulfills the conditions of grid service, showing a high reactivity and a good flexibility with ramp-up and ramp down time within seconds and the ability to realize load changes from 10% to 100%. Indeed to regulate the primary reserve (FCR), the TSO needs that the plant load is adjusted within 15 seconds per the protocol described in Figure 5.



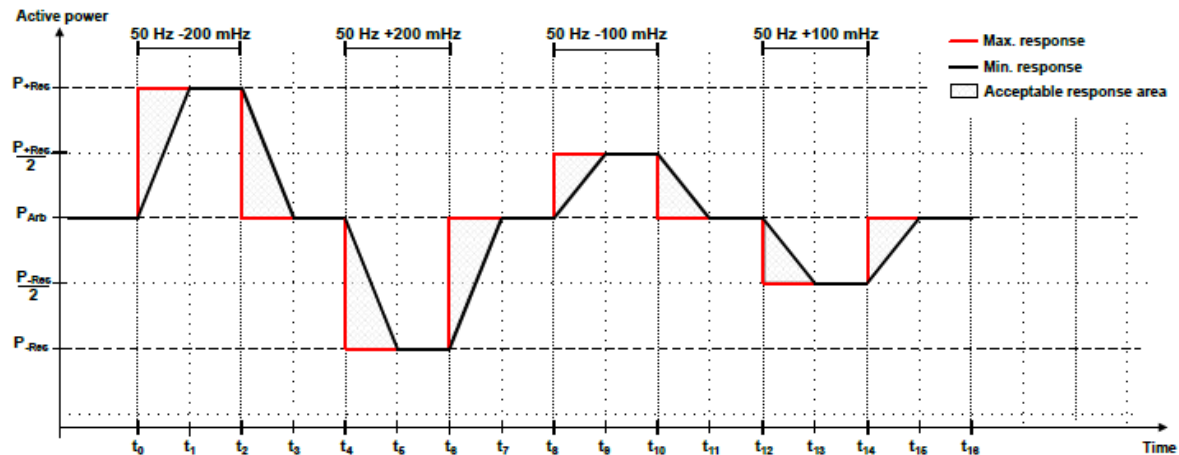


Figure 5 : Input power load profiles used for Hybalance homologation by TSO


Also it has been observed that it is preferable - and necessary to ensure customer demand - to keep a minimum baseload (~10%) to allow smooth ramp-up/down and avoid perturbations in the system when restarting from 0%.

The remaining capacities over the baseload are significant to participate in regulation power markets.

2.6 Ageing

The stack degradation is one important parameter giving insights into the activity loss with time leading to a higher specific energy consumption.

In dedicated tests within the period from January to June 2020 every month the performance at nominal load was tested over a period of 6 hours. The first results on cell degradation rate and expected lifetime are in line with the FCH 2 JU target for 2020. However, additional operating hours are necessary to validate these trends and publish the experimentation results.

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3. SUMMARY OF PERFORMANCE TESTS

First of all, there are the parameters describing the operating conditions: the pressure is equivalent to the benchmark case and the production capacity of 230 Nm³/h is higher than in current benchmark projects.

Then, there are several parameters describing the performance. The focus of the call was on high efficiency. In the first year of stack operation, the specific energy consumption is comparable with the benchmark, whereas room for improvement can be found in the stack capital cost, which has been slightly higher than the benchmark case. This is mostly explained by the fact that Hybalance was a pilot project and a single batch manufacturing system.

As can be seen, the HyBalance electrolyser reaches a high score in terms of hydrogen purity.


Overall HyBalance is producing high purity H₂ in the expected efficiency range at nominal volume flow and pressure.

Last but not least 2 parameters describe the ability to provide grid service: reactivity and flexibility. It could be shown that **ramp-up rates from 10% to 100% of 1 second** and ramp-down rates of a few seconds can be reached. The score for flexibility is slightly lower than in the benchmark, as in standard operation the current design allows down ramping to 10% and it is not optimized for down ramping to 5% or even 0%. With a **very high reactivity** the electrolyser fulfills the conditions of grid service at a low stack degradation rate which is completely according to expectations.

The spider diagram (Figure 4) shows the overall performance of the HyBalance plant in comparison to the benchmark defined in the Multi-Annual Work Plan 2014-2020 of the Fuel Cells and Hydrogen 2 Joint Undertaking and scientific literature. The evaluation criterion and ranking have been defined in table 3.

Criterion	Unit	Worst case	Reference Value	Best case
Stack Production Rate	[Nm ³ /h]	1	40	140
Pressure range	[bar]	atm	30	100
H2 purity at delivery	[xN]	3	4	5
Stack Capital Cost	[€/kW]	3000	1500	900
Specific Energy	[kWh/kg]	60	57.5	55
Reactivity (Hot ramp time)	[s]	60	10	2
Flexibility (Lower load limit)	(%)	10	5	0

Table 4: Criterion for the system evaluation in reference to 2017 state of the art for PEM electrolyser

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Parameters of overall 3 main categories are shown : operating conditions, technology performance and grid balancing capabilities.

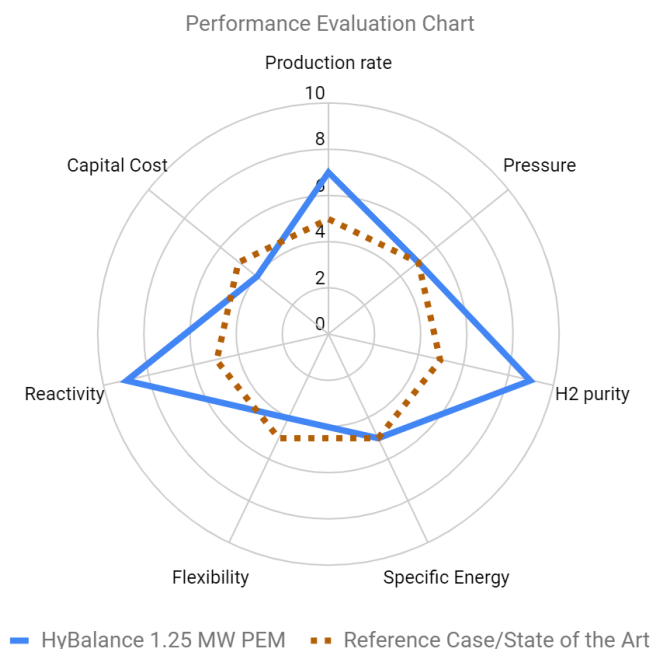


Figure 6: Summary of the HyBalance electrolyser plant performance evaluation

In terms of conclusions from an operating point of view, the project has demonstrated that :

- PEM electrolysis technology achieves a **high level of availability and efficiency** over a long period of usage - more than 3 years producing hydrogen and still in operation
- Hydrogen produced at Hybalance can serve **clean transport and industry markets** at required specifications in terms of H2 quality and supply chain management
- Power-to-Hydrogen is a viable way to **store energy** on a larger scale and support the increasing share of renewables in grid mix
- **High flexibility and short reaction-time** of PEM technology provide competitive advantages to balance the grid