ELY4OFF

PEM ELECTROLYSERS FOR OPERATION WITH OFFGRID RENEWABLE INSTALLATIONS

Analysis of demonstration phase Results

Deliverable D5.2

GRANT AGREEMENT
700359

D5.2 Analysis of demonstration period phase Results

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Author(s)	José Manuel Pérez (FHa), Pedro Casero (FHa)
Participant(s)	Sergio Ayuso (INYCOM), Guillermo Matute (INYCOM), Estanis Oyarbide (EPIC POWER, Ben Green (ITM)
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Executive Summary

This document shows the results obtained during the demonstration period, which run from March to September 2019 following the methodology established in the report D5.1 (Demonstration test programme). The demo-site is located in Huesca, in Aragon hydrogen Foundation premises.

This report presents the results achieved compared to the targets established in the Grant Agreement. As an overall conclusion it has to be announced that the performance of the system is satisfactory, it has been demonstrated that a strict off-grid electrolysis system can operate autonomously, safely, efficiently, and with a rapid response to the variable solar profile. The conclusion is that **the system works.** The accumulated hydrogen production during the period was 413 kg, being the most productive day 5th September with 5.9 kg.

For one hand it has to be remarked that the configuration tested was different from the one devised during engineering phase which consisted on a PV filed with 13 strings with one DC/DC converter per string, then the current splits part to the stack and the rest to the BoP where it is converted to AC to feed BoP consumers and store energy in batteries. However this arrangement could not be tested because the conversion to AC could not be properly tuned. So the alternative implemented was to use 3 of the strings directly to feed the BoP while the rest directly feed the stack.

The initial phases of the demo campaign were heavily affected by the immaturity of the control to handle off-grid conditions. This forced to do daily and frequent manual operations which led to leave the system shutdown outside the working journey. It meant that during weekends the system did not operate. This situation improved gradually and during a great part of the last month of the period the system was left unattended during weekends which made September to be the most productive month of the period. A chapter is devoted to present the main unavailability causes.

The system did not reach 100% of load (50 kW in stack), the maximum achieved was 82%. Certainly a greater PV field should be required which opens an interesting area of study because it is not evident the most advantageous ratio of PV field vs electrolyser capacity.

The report gives detailed description of the performance of the system regarding efficiencies, degradation, dynamic behaviour, and consumption of different sub-systems. In general many of the targets were fulfilled although some of them require further research. One of the conclusions reached is that off-grid systems differ much more from on-grid than expected.

In a final chapter a list of the main lessons learned is presented.

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1. INTRODUCTION AND PRESENTATION OF OVERALL RESULTS

The objective of this deliverable is to show the results that have been obtained during the demonstration period from March to September 2019. The aim of the demonstration is to test in real operating conditions the system that has been designed and built during WP2, WP3, and WP4 and established in the previous deliverable D5.1

A brief summary of the technical specifications established in previous deliverables (D2.4, D2.5, and D5.1) is given as the reference, together with analysis carried out from the data recorded in the SCADA system. The results provided are structured in a similar way as the KPIs values provided in the Annual Exercises (D1.2, D1.4).

A detailed demonstration plan (D5.1) was set up in order to ensure that the correct monitoring of objectives and expected operation of the off-grid system was correctly followed during the period and under variable conditions.

The system consists of 62 kWp solar field, 50 kW electrolyser stack and the BoP consumes around 7-8 kW base load, with peaks due to consumption of chillers, pumps, fans and rest of elements in the BoP. There are 13 strings in the PV field and there is one DC/DC converter per string; after conversion the current splits part to the stack and the rest to the BoP. As the elements in the BoP require AC, there is a commercial DC/DC followed by a typical installation used in photovoltaic for feeding consumers and storing energy in batteries. When there is no sun, the batteries supply the essentials (basically control system and frost protection) and in case of depletion a fuel cell enters into operation. This arrangement is the ideal one but could not be tested because we couldn't get the DC/DC and the inverter to work together. So the alternative implemented was to use 3 of the strings directly to feed the BoP while the rest directly feed the stack

It has been observed during the tests that the 100% load in the stack has never been reached. The maximum load reached in the stack was 82.44%, but it was not possible to have a larger solar field due to financing issues, as it was external to the project.

What we have learned from the results obtained is quite valuable to do a more appropriate sizing of the solar field, to improve the energy management of the system, and to increase the availability. The demonstration done is sufficient to conclude that the system works, it is robust, efficient and safe. However it's a fact that during the demo period the extreme weather conditions were not covered, which is an essential consideration to take into account. To fill this gap, the consortium has come to an agreement to follow the demonstration during some more time to gather information on the behaviour of the system also during winter time

During the early phases of the demonstration period there were many modifications in the control settings and the operation of the system was intermittent while they were being solved. This period required many manual interventions in the system. It should be noted that the system has a remote connection which allowed the partners (ITM, INYCOM and EPIC) to monitor the operation, while FHa did the modifications, adjustments or manoeuvres required in spite of that field engineers from all the partners worked on-site when required.

The initial phases of the demonstration were marked by a high consumption of auxiliaries during night period caused by lack of a proper de-energization of some elements of the BoP. This forced the system to be manually disabled during non-working hours, meaning that no hydrogen was produced during the weekends. Tis issue was solved in September and the system could be left unattended during the weekend

Regarding the use of hydrogen during the demonstration period, it was used for internal consumption at FHa as much as possible but unfortunately a great part of the hydrogen produced had to be vented. The production of hydrogen was analysed in detail from July onwards; from March to June the partners focused on improving aspects of control and individual elements. For this reason an exhaustive study of availability was conducted only from July until September.

In general during the demonstration period, more specifically during the months of July-August-September the weather was good with low amount of rainy or cloudy days. In fact only 11 days gave low hydrogen production due to the weather. The temperature during nights was not low enough to trigger the operation of the Fuel Cell system which takes over the essential consumers when batteries are depleted.

The main facts of the demonstration phase are as follows:

- The demonstration started on 13th March 2019.
- The demonstration ended on 30th September 2019.
- Thus, the demonstration phase consists of 201 days.
- During the development of the demonstration there has not been any incident affecting safety.
- Total hydrogen production during the demonstration period was 413 kg.
- The maximum production of hydrogen in one day has been: 5.88 kg on 5th September
- The maximum load reached in the stack was 82.44% on 10th September.
- Weekly production of H_2 was as follows:

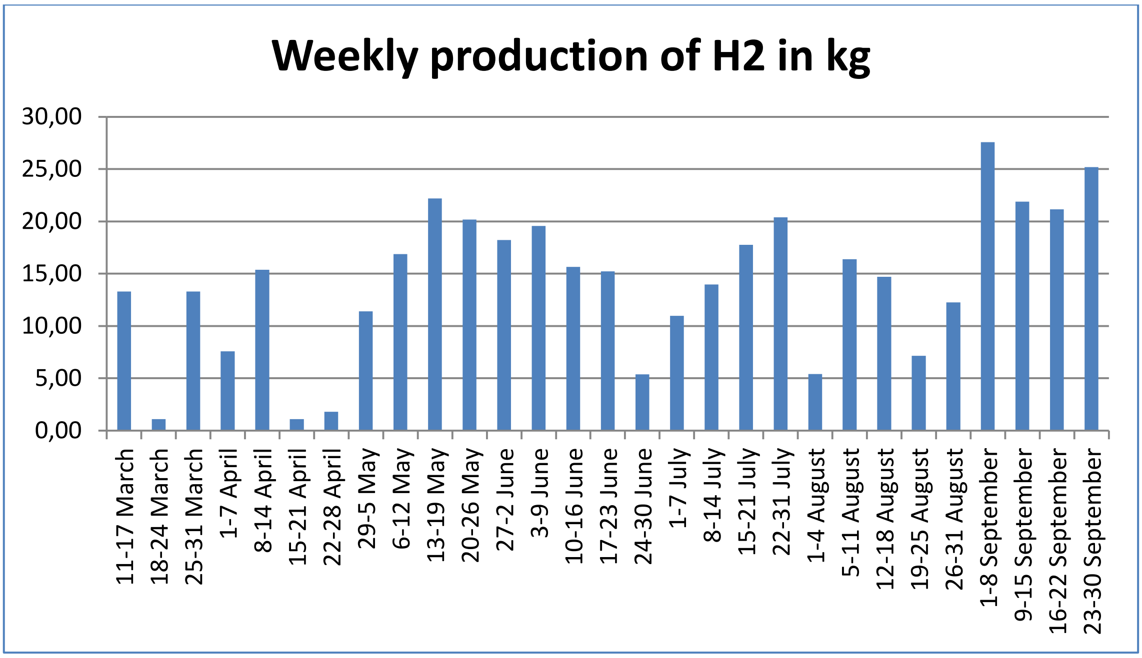

Figure 1-1. Weekly H2 production during demo period

The measurement of hydrogen production was initially made from the difference in pressure in the FHa's buffer over time. This method was improved in the last weeks of the demonstration period, allowing from that moment on to have an exact value, by means of a formula provided by ITM in which a value in kg/h is obtained from the voltage and the current to the stack for each second of data recording in the SCADA of INYCOM. An additional flowmeter was also installed in the final period.

Some examples of the operation of the system are presented. The first graphic (5 September 2019) shows the power to the stack (blue line) in a good weather day. The yellow line shows the operation of the batteries, and a negative value means that they are being charged. Finally the BoP consumption is depicted in black and the SOC of the batteries in red. We can see that there is a base load of around 6 kW, and peaks reaching 15 kW, derived from the intermittent operation of the H2 purification unit mainly and other elements.

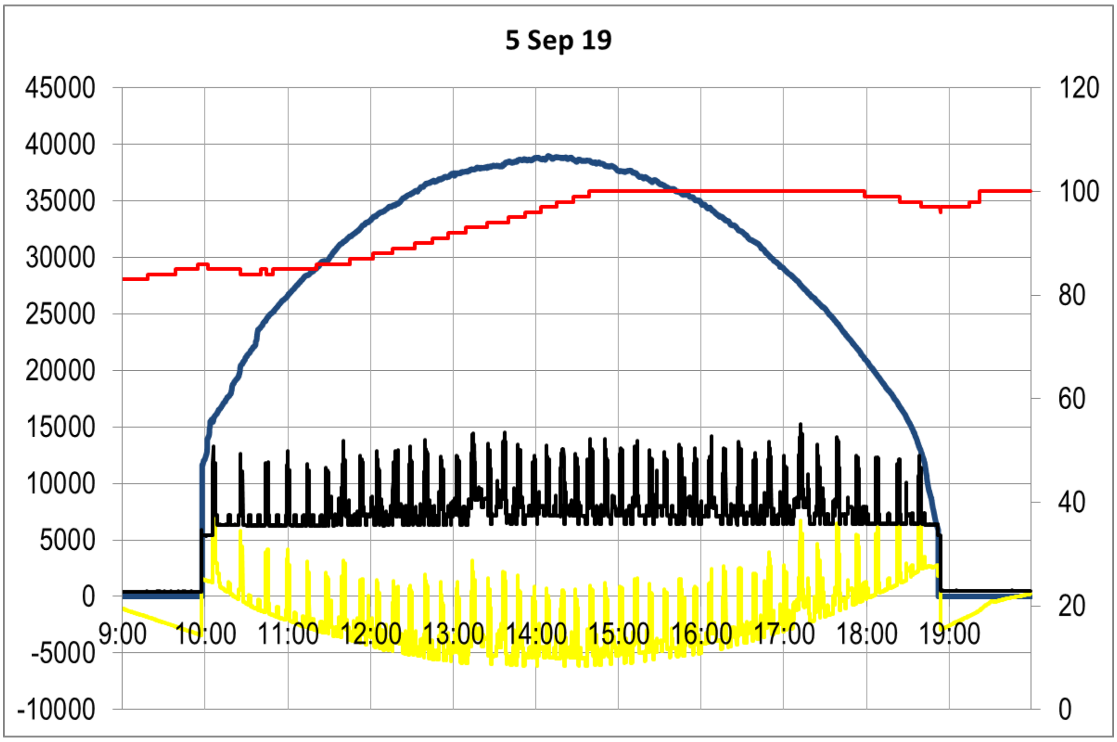

Figure 1-2. Example of operation in a good weather day

In contrast, the profile obtained for 10 September 2019 shows the operation in a bad weather day. The BoP load base remains at 6-7 kW, but the amount of peaks is lower. It can be seen also a moment at around 14:00 where the system stops and starts-up again automatically.

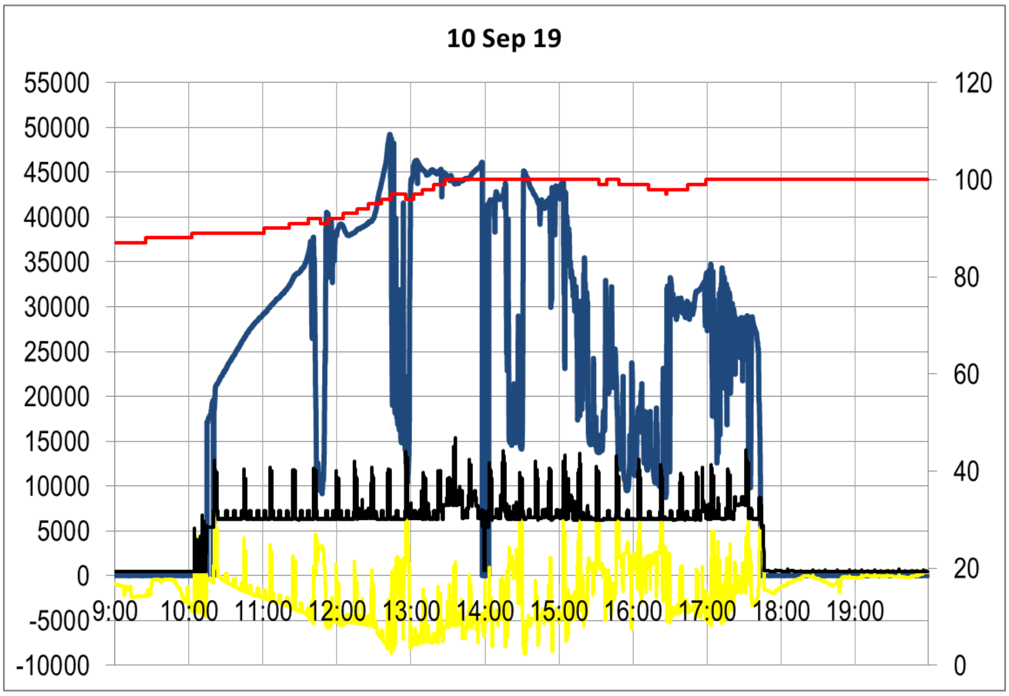

Figure 1-3. Example of operation in a bad weather day

The control system developed by INYCOM has a wser-friendly design which allows access to every subsystem to see status. Some screenshots are included below, showing the main screen, the interface developed for the DC/DC converters, and the graphic features.

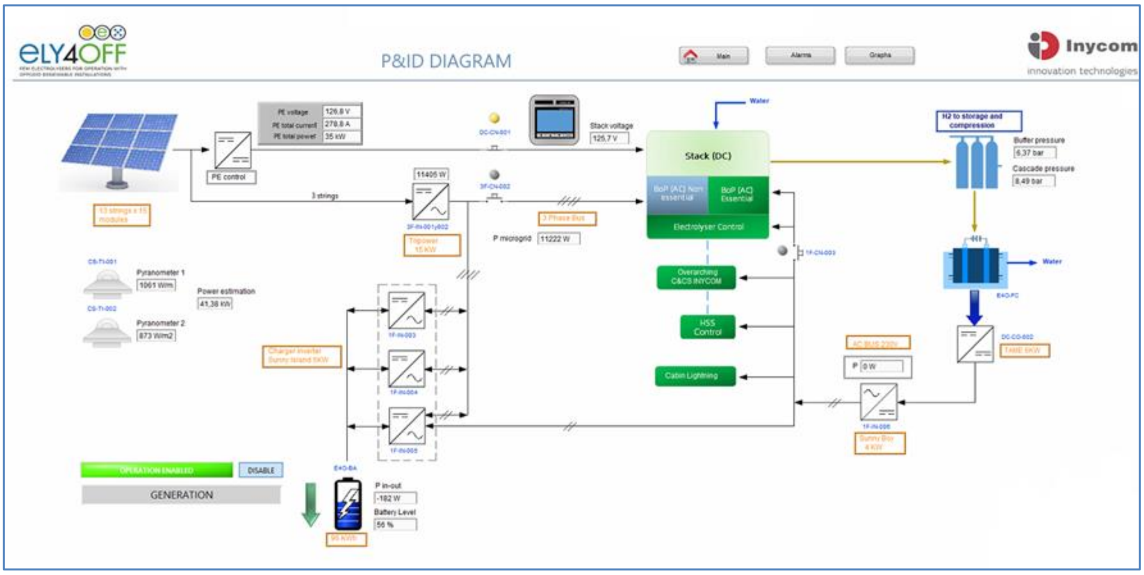

Figure 1-4. Overaching control system. Main screen

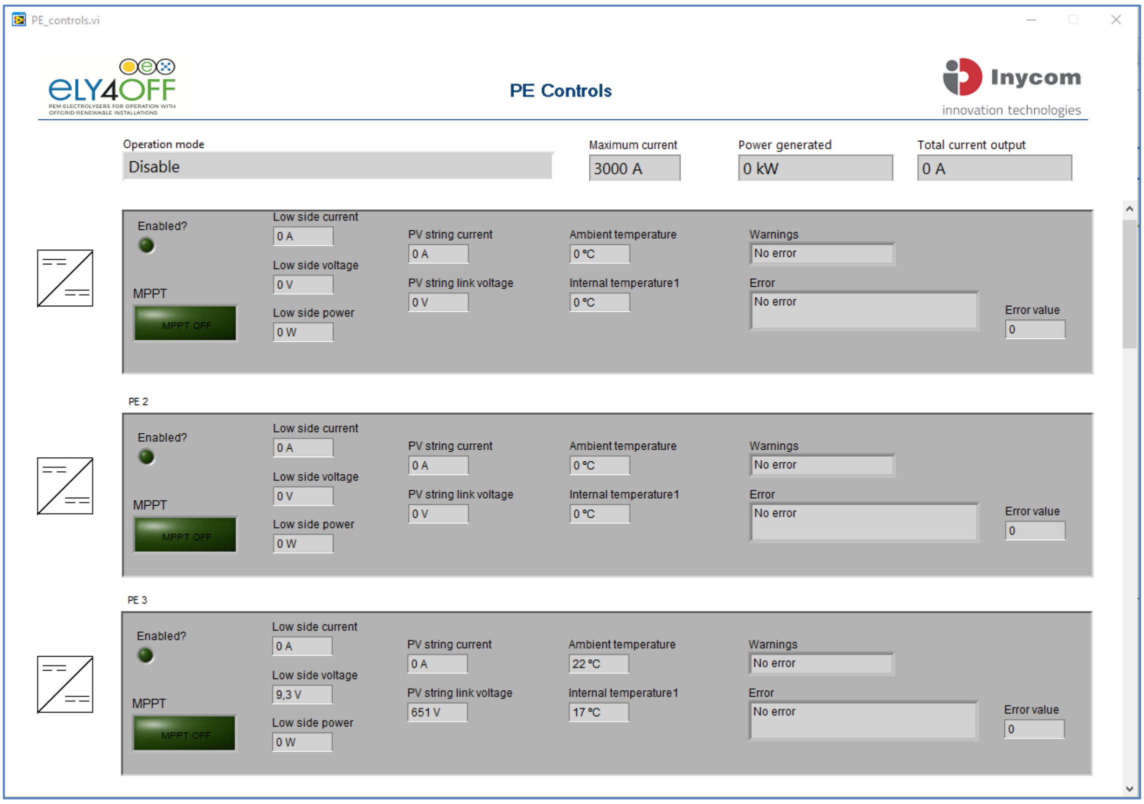

Figure 1-5. Overaching control system. DC/DC Converters interface

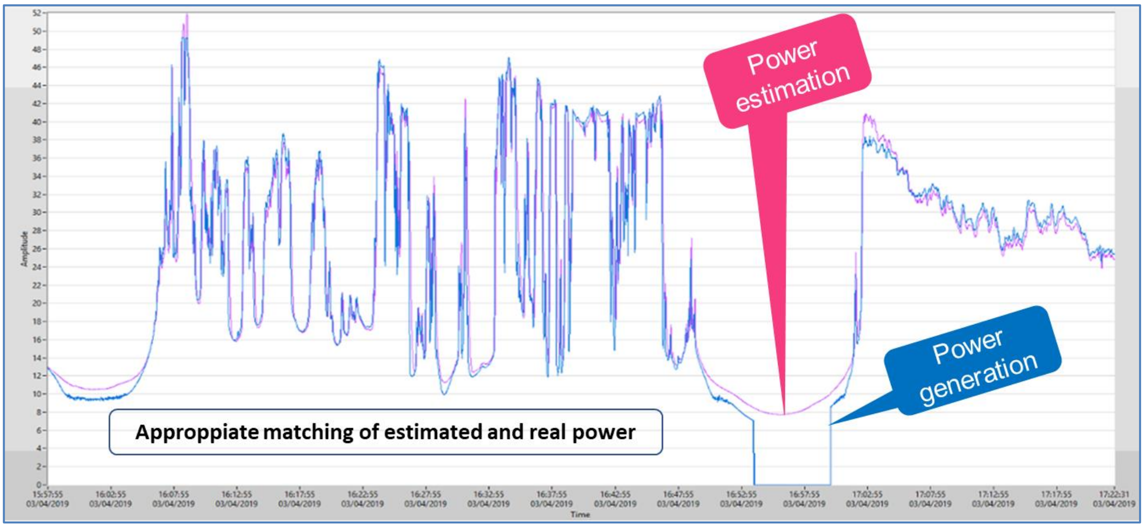

Figure 1-6. Overaching control system. Graphic features

On the other hand, FHa developed also a dedicated interface to manage the storage management system. Find below screenshots of the main sections:: main screen, battery monitor, settings, the fuel cell screen and graphic features.

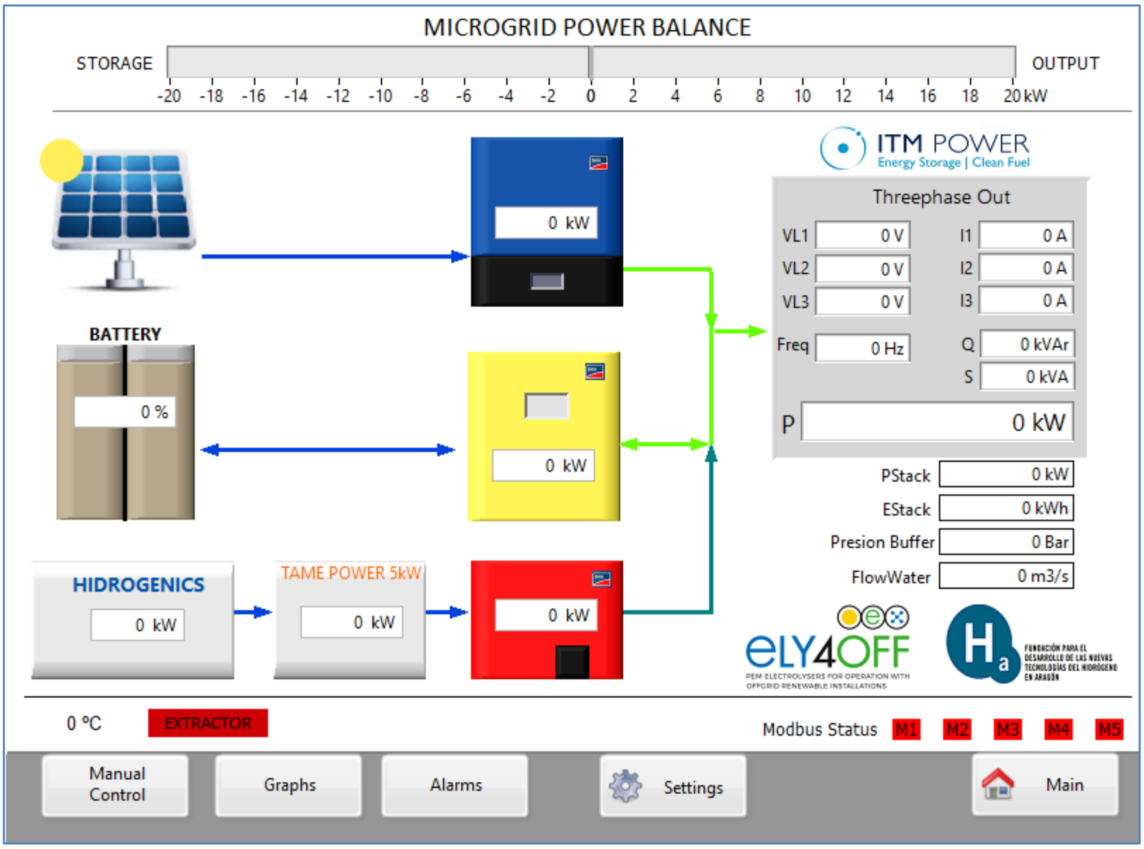

Figure 1-7. Energy management control. Main screen.

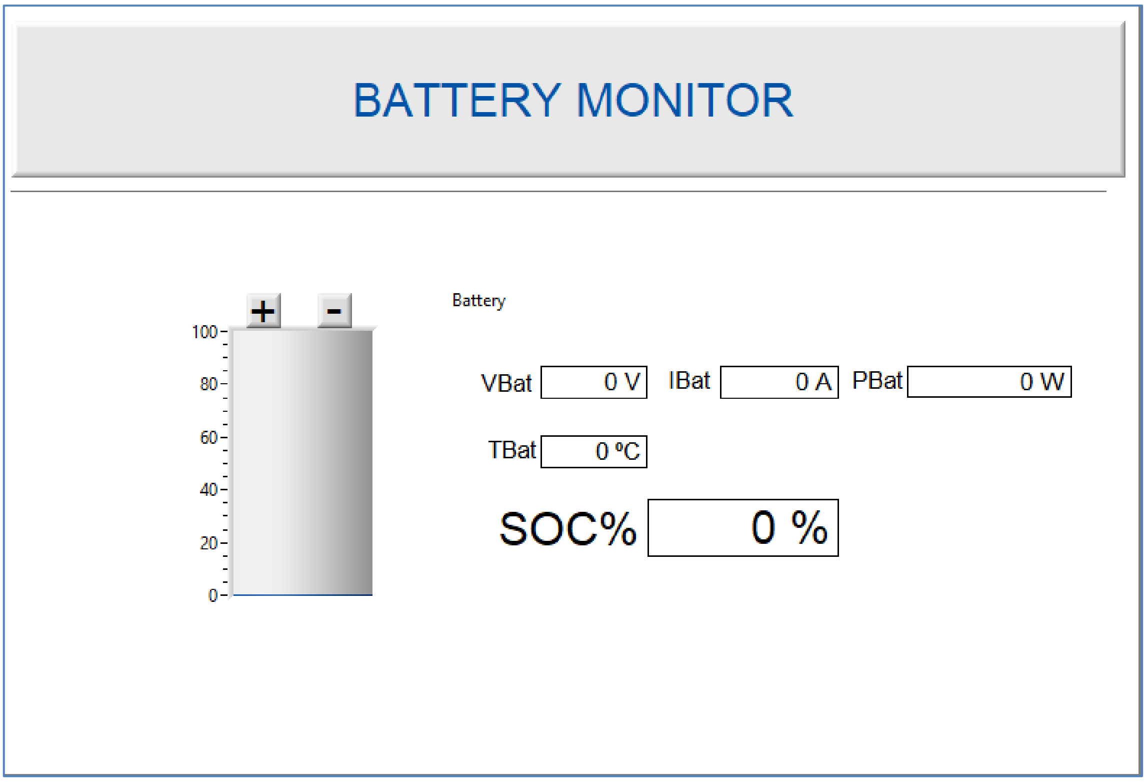

Figure 1-8. Energy management control. Battery monitor screen

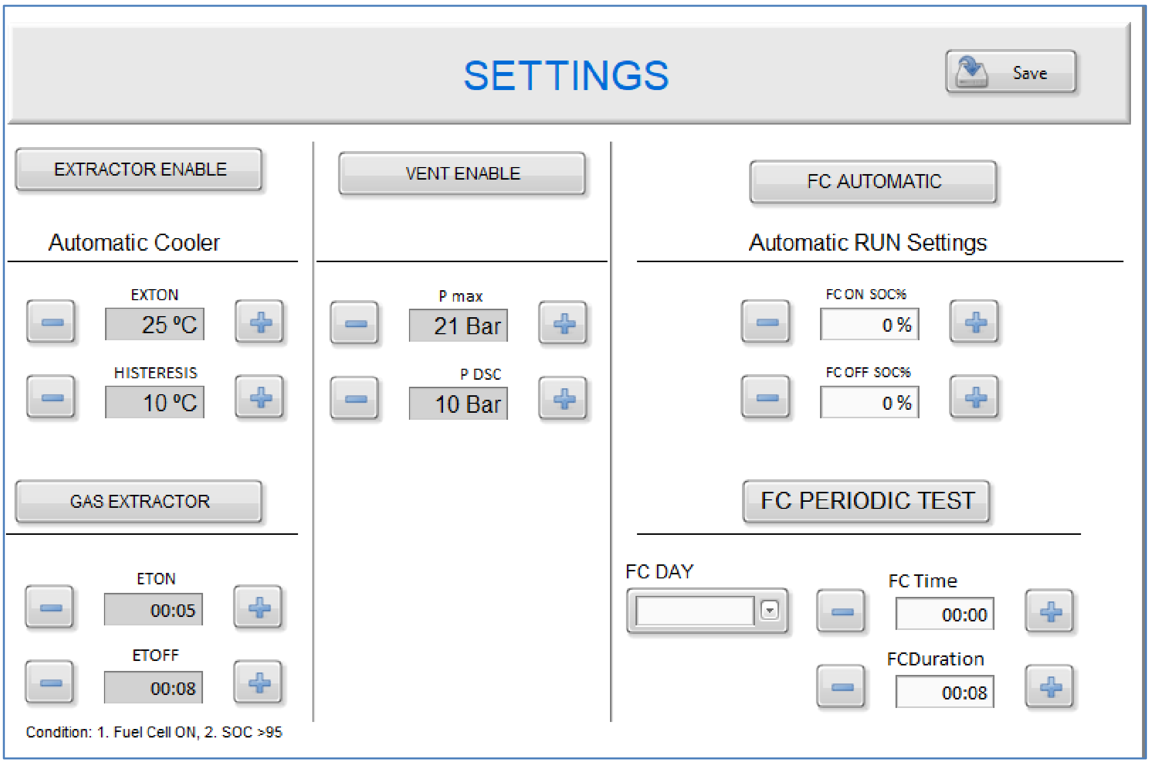

Figure 1-9. Energy management control. Main settings interface

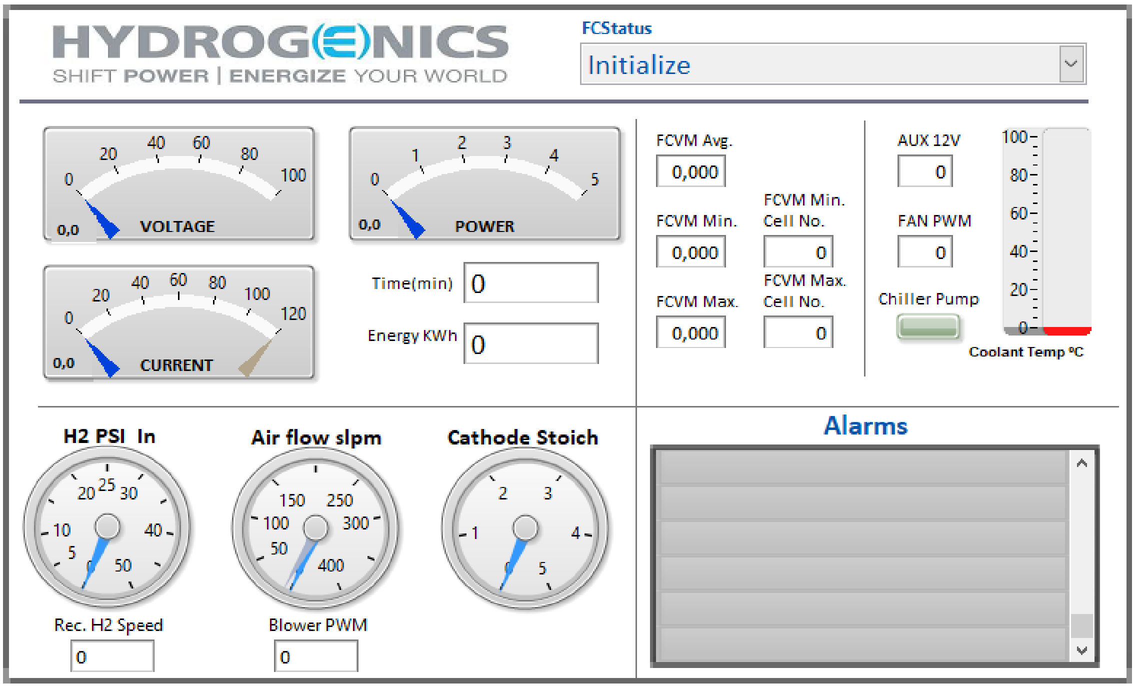

Figure 1-10. Energy management control. Fuel Cell interface

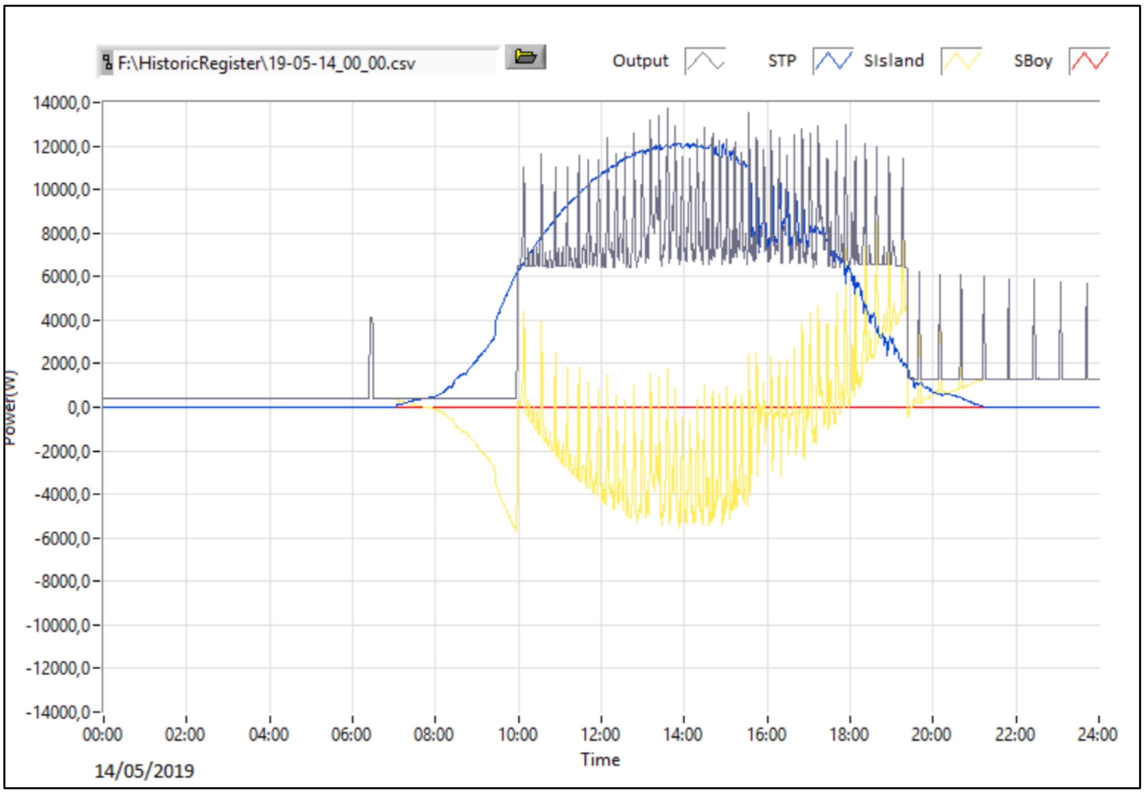

Figure 1-11. Energy management control. Graphic features.

2. ANALYSIS OF RESULTS

A specific testing plan to follow during the demonstration period was elaborated in the deliverable D5.1; it was aimed to gather data allowing knowing whether the main objectives of the project, both KPIs and others were achieved. The background of the objectives to achieve comprises the following documents, defined in the WP2:

- D2.4 Technoeconomic objectives
- D2.5 Indicators and test definition
- Modelling software Oddysey (WP2)
- Annual Exercise KPIs (done on a yearly basis)

From section 2.8 onwards, the parameters included are those that were already said not to be affected by the tests of the demonstration period and are included in the final table. For the sake of clarity, find below the parameters related to the design of the system:

Parameter	Id	Units	Target proposal	D2.4	Result
Stack size	KPI_12	kW	50	49.8	50
Stack capacity	KPI_13	Nm3/h H2	>13	14.2	14.2
		kg/d H2		27.9	27.9
Current density	KPI_14	A/cm2	1	1	1
Output pressure	KPI_15	bar	20	20	20
Operating temperature	KPI_16	ºC	60	55	54

Table 2-1. Main design parameters

Parameter	Units	Objectives (D2.4)	Result
Capacity of the system - rated	kW	56	62 rated – limited by PV
Footprint – hydrogen production unit	M2	4	<4
Volume	M3	8	<8
Nature of the electricity source	-	SOLAR	SOLAR
Fraction of renewable energy input	%	100	100
Quality required for water	µS	<1	~0.8µS
Purity of the hydrogen – rated	%	99.9995	>99.9995 (limit of detection)
Type of power converter	-	DC-DC	DC-DC
Input voltage	V	800	800
Electrical efficiency of the system (rated - HHV - AC current)	%	82	86
Cost - capital cost of the system (per ton/day) @ mass production (estimate)	M€/t/d	0.015	(see D2.6)

Table 2-2. Other design parameters

The parameters that were indicated to have a specific test in D5.1 are developed as follows.

2.1 Efficiency (KPI_1)

Units	Target in proposal	Target revision in D2.4	Specific test (D5.1)?	Result	Target achieved?
kWh/kg	System 50 (100% load)	<50	YES	56.33 @ 77.48% load	~~Yes / No/~~ partially
kWh/kg	Stack 42.4 (100% load)	<42.4	YES	46.30 @ 77.48% load	~~Yes / No/~~ partially

Table 2-3. Efficiency results

System efficiency definition: Best performance of the electrolyser system at maximum load, excluding compression (kWh/kg).

Stack efficiency definition: Best performance of the stack at maximum load, excluding compression (kWh/kg).

Description: The procedure for highest efficiency was as follows:

1) The maximum power of the stack of September 5 was monitored from 14:06 to 14:36 (the best half hour of irradiation of the day). The operation of the system during this day can be observed in the graph below.
2) From SCADA, the stack energy (19.91 kWh) and energy to feed BoP (4.31 kWh) was recorded during this defined time.
3) The hydrogen production during this defined time was 0.43 kg according to ITM´s hydrogen formula (see below)

$$H2\ production\left[\frac{mol}{s}\right] = \frac{[Coulomb] \times [Avogadro\ constant] \times [Stack\ Cell\ Count] \times [Faraday\ Efficiency] \times 0.01}{2 \times I\ [Current\ A]} = \frac{6.24 \times 10^{18} \times 6.02 \times 10^{23} \times 75 \times 100\% \times 0.01}{2 \times I\ [Current\ A]}$$

$$H2\ production\left[\frac{kg}{h}\right] = \left[\frac{mol\ H2}{s}\right] \times 2 \times 0.001 \times 3600 \times 24 = cte\ \times I[A] = 0.06717 \times I[A]$$

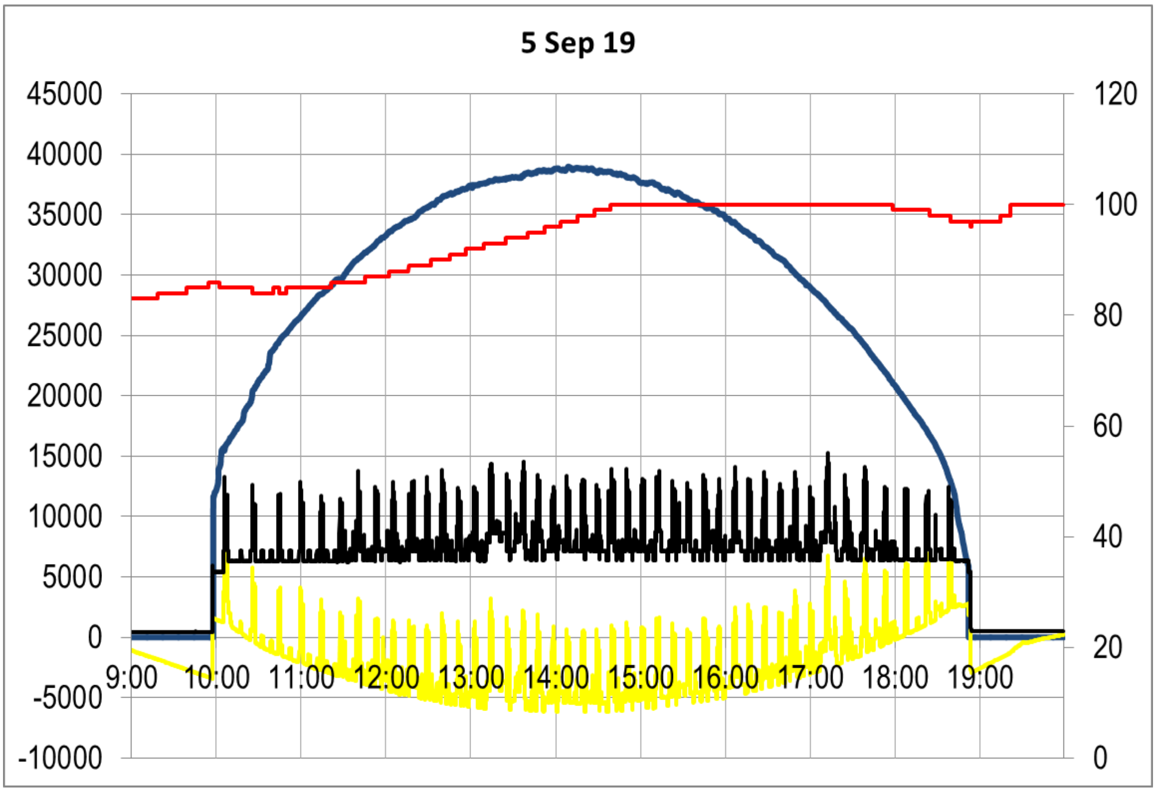

Figure 2-1. System operation during test

Remarks on efficiency at system level

Due to the final configuration of the Ely4off, the maximum load never can never reach 100% as only 10 of the 13 strings are directed to the stack. The maximum recorded load was 82.44% on September 9, 2019 with 41.22 kW at stack.

This parameter in an off-grid system is complicated to measure because the maximum load is reached only during short periods of the day. On the other hand, what really matters in off-grid conditions is a good efficiency in the whole spectrum of loads.

It should be noted that the size of the installation is relatively small and the consumption in the BoP is very large (average base load of around 8 kW) when the stack is generating. On the other hand the BoP doesn't grow in a linear way with electrolyser size. In this instance the BoP is around 17% of the total system power. If the system was increased to ~200kW the BoP would be ~5% of the total power based on ITM in-house data, which would give efficiency at system level much closer to the target.

Remarks on efficiency at stack level

This parameter was assessed during tests done at lab scale in ITM's facilities. As reported in D3.3, large-scale testing of the thin (50 μm, nominal) commercial MEA was conducted in a short PEMWE stack (3 cells), under steady-state conditions, at nominal operating temperature and pressure of the demonstration system (1 A/cm2 (100% load), 54 °C and 20 bar hydrogen pressure). The average cell voltage was measured at 1.68 V (88.1% efficiency vs HHV of Hydrogen), but unfortunately the

MEA did not have sufficient durability to withstand the cell environment. As there was not sufficient time in the project to redevelop the stack components, testing of an MEA made from a thicker membrane was chosen as the best option to enable the project to succeed. A commercial MEA made from a thicker membrane (125 µm, nominal) was selected. Increasing the thickness of the membrane by ~2.5 times resulted in a small penalty in efficiency (loss of ~1.6%), but led to a beneficial decrease in the amount of Hydrogen diffusing through the MEA. At 1 A/cm2, 60 ˚C and 20 bar Hydrogen pressure, the cell voltage measured 1.71 V (86.5% efficiency vs HHV of Hydrogen), showing an increment compared to the state of the art at December 2017 (84.5%). The following table shows these data in the units used in the target (kWh/kg):

Thickness MEA	Tests	Cell efficiency (% vs HHV H_2)	Cell efficiency (kWh/kg)
50 µm (3 cells)	Lab (100% load)	88.1%	44.7 kWh/kg
125 µm (3 cells)	Lab (100% load)	86.5 %	45.6 kWh/kg
125 µm (75 cells)	Demo-site (77% load)	85,2 %	46.3 kWh/kg

Table 2-4. Efficiency at stack level (lab and demo)

The small penalty in the efficiency compared to lab results can be explained due to the conditions found during the operation in the demo-site compared to the controlled boundaries in the lab. Considering this fact, the efficiency achieved is quite satisfactory.

Next it is shown a graph of the efficiency of the stack to different loads and it is observed as in spite of varying the load in different moments of the day or different days (red points), the efficiency is maintained quite constant (blue line). The efficiency of the stack from different days to different loads has been calculated as the integral through 30 minutes of the power recorded in the INYCOM software and divided by the production of hydrogen in kg during that period of time.

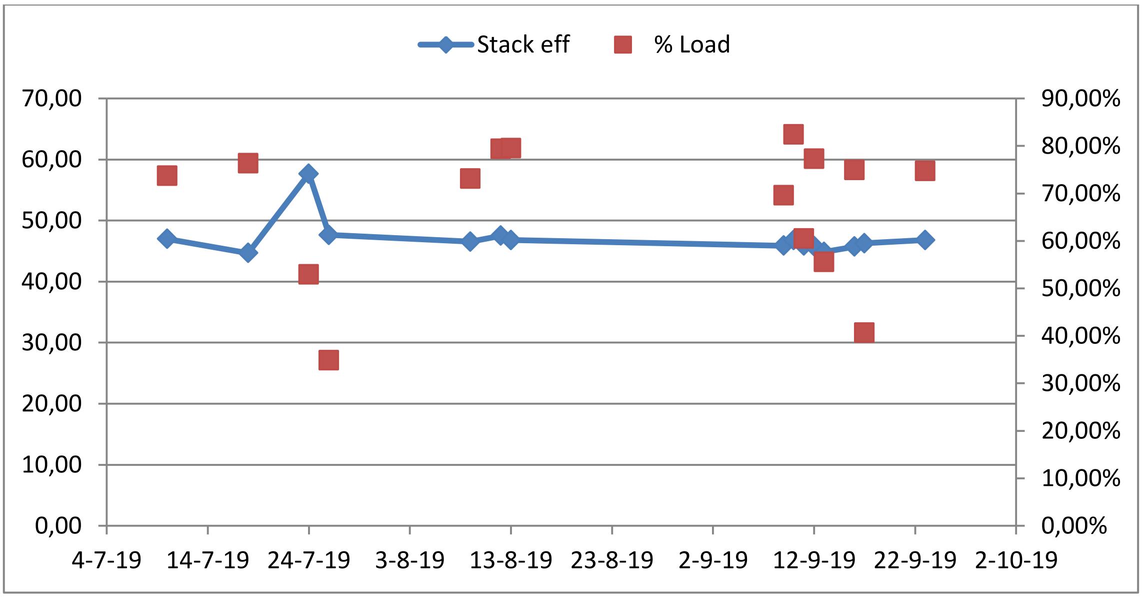

Figure 2-2. Evolution of efficiency at stack level during demo period

2.2 Efficiency degradation (KPI_7)

Units	Target in proposal	Target revision in D2.4	Specific test (D5.1)?	Result	Target achieved?
%/years 8000h	2	2	YES	1	Yes ~~/ No/ partially~~

Table 2-5. Efficiency degradation results

Efficiency degradation definition: Percentage of efficiency degradation per year assuming 8000h of operation.

Description: This is typically measured by looking at the system voltages at calculating µV/hour increases. Any increase in voltage means more energy is required per kg of hydrogen and is therefore a decrease in efficiency.

Remarks: As with stack lifetime it might be hard to analyse this in field conditions as very accurate input parameters are required (voltage and temperature mainly). In order to get the data to definitively prove this the system would need to return to Sheffield and a number of cells tested in ITM Labs. As the demonstration is continuing this isn't possible. The stack hardware is heavily based on ITM's commercial systems where ITM quotes 1% per year based on standard operating conditions and from the field data recorded during demonstration period this looks to be in line with that.

2.3 Hot idle ramp time (KPI_18)

Units	Target in proposal	Target revision in D2.4	Specific test (D5.1)?	Result	Target achieved?
Seconds	2	<30 (from idle) <3 (from standby)	YES	218 s (from idle) < 2 (from standby)	~~Yes / No/~~ partially

Table 2-6. Hot idle ramp time results

Hot idle ramp time definition: The time from hot idle to nominal power production, whereby hot idle means readiness of the system for immediate ramp-up.

Description: The procedure for hot idle ramp time was as follows:

1. The system was turned off once the system was already on generation mode, pressing disabled bottom. The DC/DC converters from the solar field to the stack were switched off. Was waited until the system was completely in IDLE mode.
2. "ENABLED" button was pressed and DC/DC converters were activated.
3. A time period of 218 seconds was recorded until hydrogen production was reached. This was checked on the product output line when the SV004 valve was active.

Remarks: The objective mentioned in D2.4 concerning the time to nominal hydrogen production is not met (<30 sec).. Ambient temperature during test: 27.9 °C. Power reached in the stack: 39 kW. Date of test: 24/09/2019.

The reason this KPI wasn't achieved isn't down to the electrolyser response time in terms of ability to absorb power. The safety system dictates that the unit must be kept at ambient pressure when not in use. The system reacted within the 2 second target but the pressurisation time added an extra time to pressurize the system again which depends heavily on the solar energy available (it can take between 30 seconds up to some minutes). There would be potential ways of reducing this time if a different safety philosophy was followed but that wasn't possible within the scope of this project as it was remotely deployed.

An example of the response from standby to generation is presented below. It related to 10 September operation, where a sudden blockage of solar power happened and the stack stop receiving energy (blue line). The situation lasted 31 seconds and the stack absorbed energy again in 1 second. This event was not planned, but was recorder by the SACADA system. The other line corresponds to the BoP consumption.

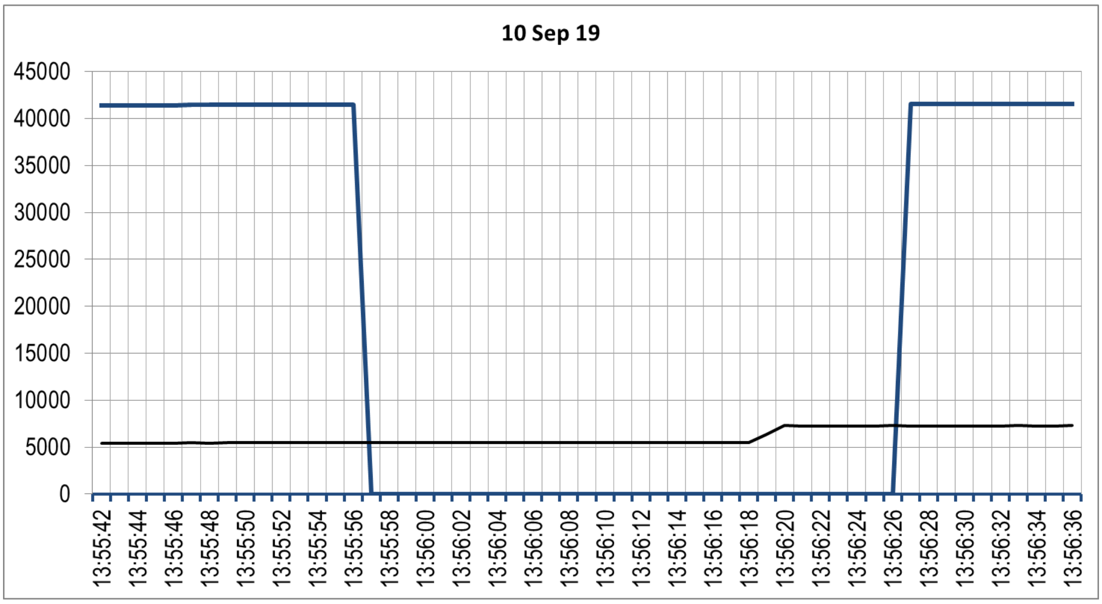

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Figure 2-3. Operation showing hot ramp up and down

2.4 Cold start ramp time (KPI_19)

Units	Target in proposal	Target revision in D2.4	Specific test (D5.1)?	Result	Target achieved?
Minutes	<5	<300 s (from idle) <30 s (from standby)	YES	210 s (from idle) -- (from standby)	Yes ~~/ No/ partially~~

Table 2-7. Cold start ramp time results

Cold start ramp time definition: Time required reaching nominal power when starting the electrolyser from a cold state (ambient temperature with no power input or output.

Description: The procedure for cold start ramp time was as follows:

1. The system was left off, without pressing enabled bottom until the system was at its time of day with greater irradiation in the solar field. The DC/DC converters from the solar field to the stack were switched off.
2. "ENABLED" button was pressed and DC/DC converters were activated.
3. A time period of 210 seconds was recorded until hydrogen production was reached. This was checked on the product output line when the SV004 valve was active.

Remarks: The objective mentioned in D2.4 concerning the time to nominal hydrogen production is met (<300 sec). The safety system dictates that the unit must be kept at ambient pressure when not in use so a specific test from standby cannot be done. Ambient temperature during test: 27.1 °C. Power reached in the stack: 39 kW. Date of test: 24/09/2019.

2.5 Ramp up (sec to full load) (KPI_21)

Units	Target in proposal	Target revision in D2.4	Specific test (D5.1)?	Result	Target achieved?
Secs to full load	2	1	YES	0.20 s	Yes ~~/ No/ partially~~

Table 2-8. Ramp up results

Ramp up definition: Average time to ramp up from 30% to 100% load at nominal power and operating temperature over the timeframe of this data collection exercise.

Description: The procedure for "ramp up" was as follows:

1. The system was running at 79% of nominal power to stack.
2. INYCOM disabled some DC/DC converter trough their SCADA, in order to get 22% of nominal power to stack.
3. INYCOM gave their order to enable again all DC/DC converters and time that takes to get the initial value was measured.

Remarks:. In the following graph is shown how the stack powers up from 11,015 W to 39,702 W in just 200 ms (0.2 sec). Date of test: 04/10/2019.

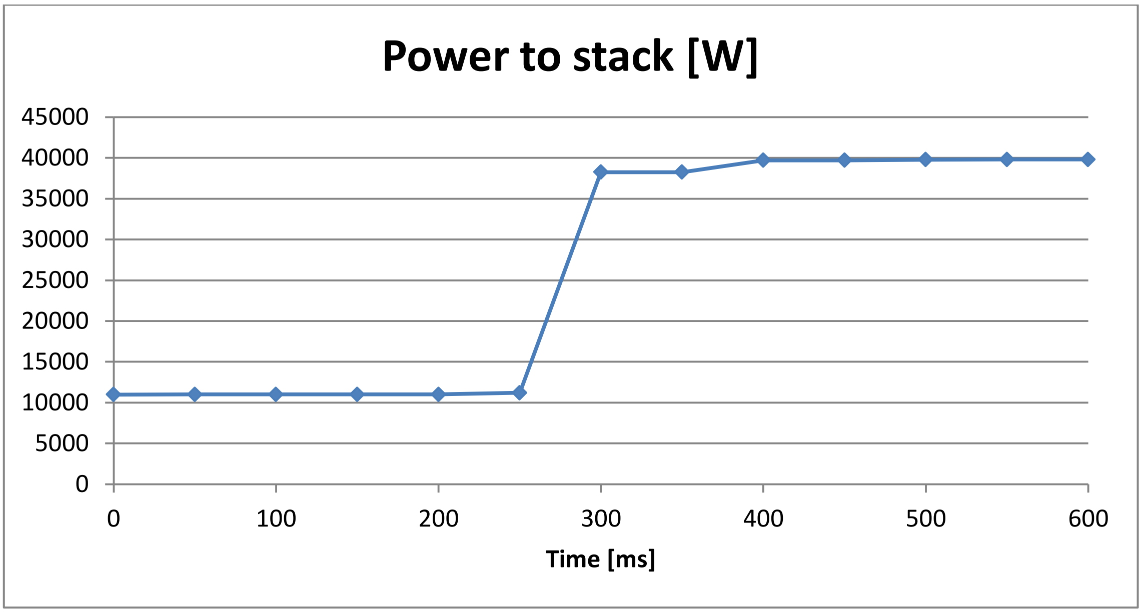

Figure 2-4. Stack power absorption during test

This response was also tested at laboratory level (ITM, see D3.3). Next graph shows the response at nominal operating temperature of a 3-cell stack containing the 125 μm (nominal) commercial MEA, to a change in load from 0 to 100%, before and after dynamic testing. It also shows that the target was also achieved at lab level.

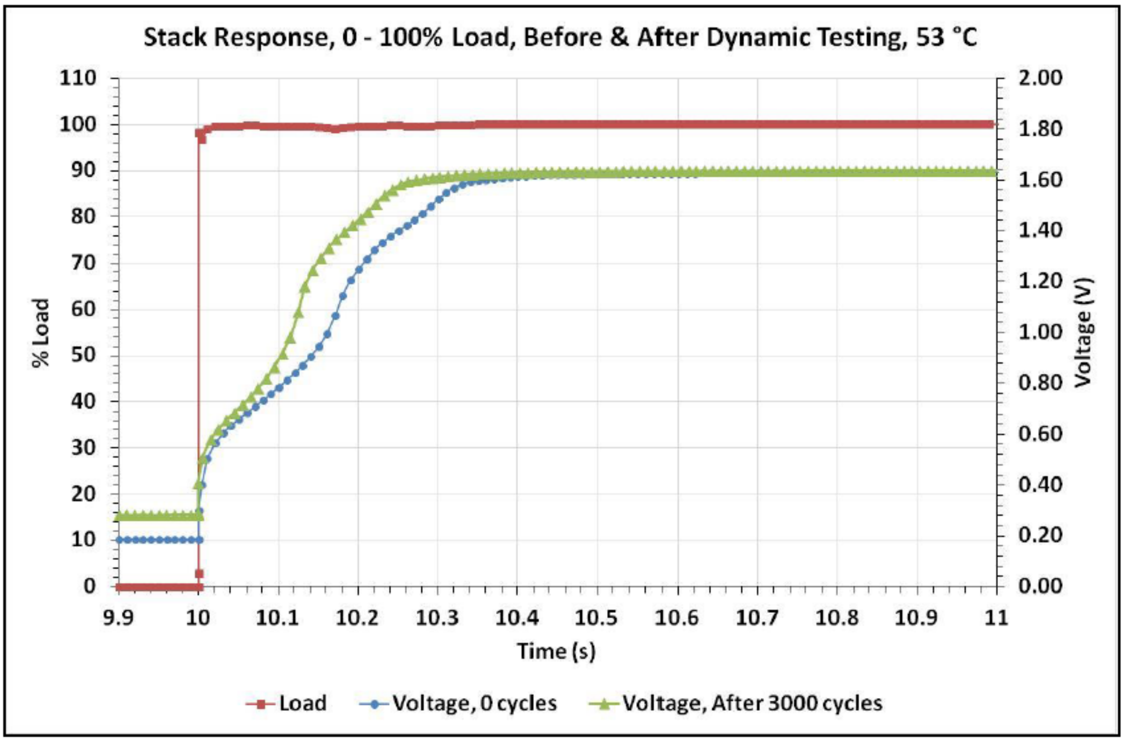

Figure 2-5. Stack response 0-100% during lab tests (ITM)

2.6 Efficiency of the PSU

Units	Target in proposal	Target revision in D2.4	Specific test (D5.1)?	Result	Target achieved?
%	-	>96	YES	97.4%	Yes ~~/ No/ partially~~

Table 2-9. Efficiency of PSU (DC(DC converters) results

Efficiency of the PSU definition: Performance of the power supply unit.

Description: input and output voltages and currents have been recorded during the test. As it has been mentioned three of the PV strings are dedicated to the BOP so there are 10 DC/DC converters to be analysed. Next figure shows the evolution of the data from converter number 10 during 10th September 2019. Using the voltage and current at each converter the input and output power can be computed, so the input and output energy can be easily obtained. This way it is possible to get the efficiency of each DC/DC converter.

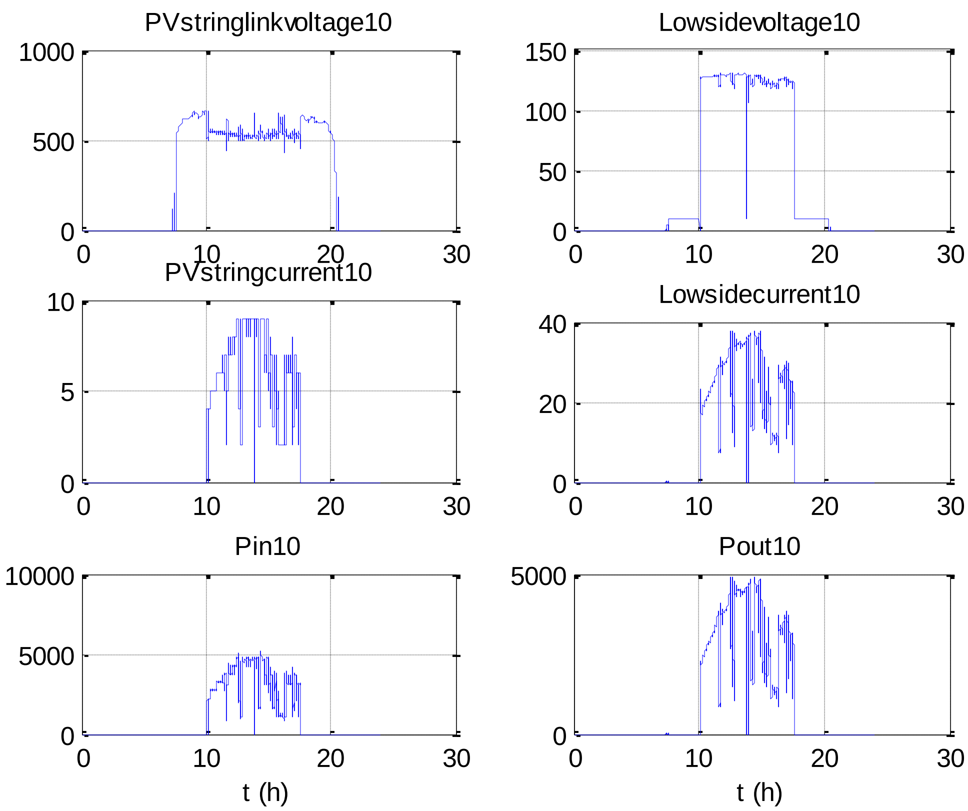

Figure 2-6. V, I and P in PV and downstream converters during test

Remarks: input and output voltages have been measured using standard voltage and current sensors included inside the DC/DC converters. These sensors have a measuring tolerance of +-1%. As there are 10 DC/DC converters operating in parallel and it is possible to consider that the measuring error will be statistically distributed and therefore the average of the efficiency of all the converters will be quite an accurate measure of the overall efficiency of the PSU. This way the computed overall efficiency is 97.4%, above the required 96%.

2.7 Power usage of auxiliary equipment – at nominal capacity.

Units	Target in proposal	Target revision in D2.4	Specific test (D5.1)?	Result	Target achieved?
kW	-	7 kW	YES	8.39	~~Yes / No/~~ partially

Table 2-10. Power usage of auxiliary equipment results

Power usage of auxiliary equipment definition: Power usage of the auxiliary equipment (e.g. heater/chiller, water ioniser, etc.) when the system is working at nominal production rate.

Description:

A day with high solar radiance was selected and during its best solar hours the average power consumed by the balance of plant is measured

Remarks: as the stack never reaches its rated power, the test was carried out taking into account only when the stack has more than 35 kW of power and reached a peak of 38 kW. The value of 8.39 kW comes from a calculation considering an average value of the power of the BOP from 12:30 to 16:00 of the 5th of September. The graph below shows that there is a power consumption base and there are some peaks, the base is less than 7 kW but the peaks in general the average value of power is a little higher. This has been a key learning point for us; whilst it has already been commented on in section 2.1 that ratio of BoP versus stack power is high due to the size of the demo plant the BoP consumption was higher than anticipated. We believe that the main issues are to do with the drying of the hydrogen where a large amount of heating and cooling power is required. The unit that was used to do this is typically used in an on-grid system where BoP power isn't monitored as closely as in this project. Ongoing work will be done to reduce this before this technology is ready for market.

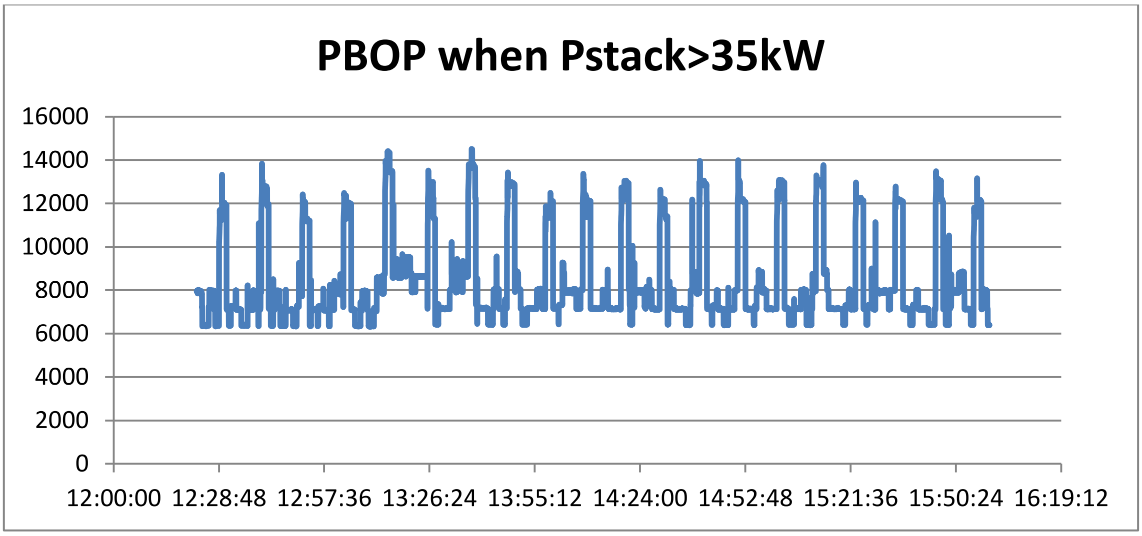

Figure 2-7. BoP consumption when power to stack is > 35 kW.

2.8 Power of the control system when off.

Units	Target in proposal	Target revision in D2.4	Specific test (D5.1)?	Result	Target achieved?
kW	-	<0.9	YES	0.485	Yes ~~/ No/ partially~~

Table 2-11. Power of the control system when off results

Description::

To select a day with high power to the stack (September 5, 2019) and during the time when the stack is not operating the average of the power to the control system is calculated.

Remarks: "Power of the control system when off" and "Power usage of auxiliary equipment - in idle" coincide because it has not been possible to prove in other situations, such as in winter, when the anti-freeze system works during nights or during cold days.

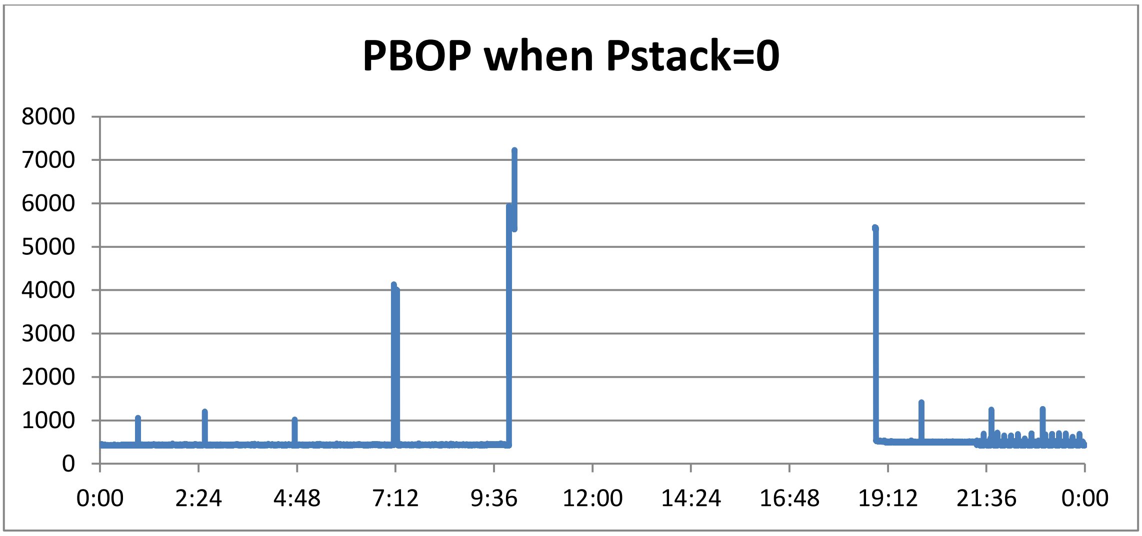

Figure 2-8. Consumption of BoP when electrolyser in idle status

2.9 Power usage of auxiliary equipment – in idle

Units	Target in proposal	Target revision in D2.4	Specific test (D5.1)?	Result	Target achieved?
kW	-	0.9	YES	0.485	Yes ~~/ No/ partially~~

Table 2-12. Power usage of auxiliary equipment results

Remarks: "Power of the control system when off" and "Power usage of auxiliary equipment - in idle" have coincided because it has not been possible to prove in other situations, such as in winter, that the anti-freeze system is working during night.

Not all the KPIs presented were monitored during the demo as it was exposed during demonstration plan in D5.1, as some of them are related to the design of the system more than coming from operation monitoring, while others are just a the summary of what happened during the operation.

The following parameters were not selected to a specific test and the following results were summary of what happened during operation:

2.10 Stack lifetime (KPI_3; KPI_4)

Units	Target in proposal	Target revision in D2.4	Specific test (D5.1)?	Result	Target achieved?
h	-	60000	NO	80000	Yes ~~/ No/ partially~~
Years	8	-	NO	9	Yes ~~/ No/ partially~~

Table 2-13. Stack lifetime results

Remarks: Whilst it is difficult to analyse the data with the accuracy required to calculate a µv/hour degradation which is the standard way ITM predicts life. In order to do this it would require the stack returning to ITM where a destructive test would be carried out in Lab conditions. It was agreed that it was in all the partners' best interests to continue the demonstration period of the project so the unit hasn't been decommissioned. The data looks consistent with commercial ITM systems at this point of life and lab based data from these systems indicates a life time of 80,000 hours would be achieved.

2.11 System lifetime (KPI_5; KPI_6)

Units	Target in proposal	Target revision in D2.4	Specific test (D5.1)?	Result	Target achieved?
h	-	160,000	NO	160,000	Yes ~~/ No/ partially~~
Years	20	-	NO	20	Yes ~~/ No/ partially~~

Table 2-14. System lifetime results

Remarks: Based on data gathered from all ITM systems currently in the field and accelerated testing ITM carry out in the labs we state that our systems have been designed to have a 20 year lifetime (which would include ELY4OFF) this is dependent on the maintenance intervals being adhered to.

2.12 Availability (KPI_8; KPI_9)

Units	Target in proposal	Target revision in D2.4	Specific test (D5.1)?	Result	Target achieved?
h/year	-	12	NO	n/a	~~Yes~~ / No/ ~~partially~~

Table 2-15. Availability results

Remarks: See section 3 where this parameter is discussed in detail.

The target value for this indicator was given by ITM during proposal phase. It refers to the maintenance time expected to be required when a commercial product was deployed. However this concept in a strict off-grid condition is more complex.

2.13 CAPEX (KPI_10; KPI_11)

Units	Target in proposal	Target revision in D2.4	Specific test (D5.1)?	Result	Target achieved?
M€/(t/d)	6	6	NO	(see D2.6)	Yes / No/ partially
€/kW	-	3360	NO	(see D2.6)	Yes / No/ partially

Table 2-16. CAPEX results

Remarks: The capex cost for €/kW is difficult to measure for a prototype project as the cost of the unit is typically higher than a commercial unit. Also the special circumstances of this project (direct connection to PV) means that the input power is very inconsistent. The figures quoted above are based on an ITM system of the same size operating at 100% output.

2.14 H2 production flexibility with a degradation <2% (KPI_17)

Units	Target in proposal	Target revision in D2.4	Specific test (D5.1)?	Result	Target achieved?
Load Spanning Range	5-150%	5-150	NO	5-150% (lab) 14–100% (demo)	Yes ~~/ No/~~ ~~partially~~

Table 2-17. H2 production flexibility results

Remarks: The target is achieved at stack level (see graph below, extracted from D3.3 - *Final results on characterisation and performance of membranes and stacks*, where a 3-cell stack was tested up to 1.5 A/cm2, equivalent to 150%) but not at system level because of limitation in PSU (EPIC) in upper limit. On low side, 5% limit is not recommended due to crossover issues and because it is not interesting at all in off-grid (more on this in the next parameter)

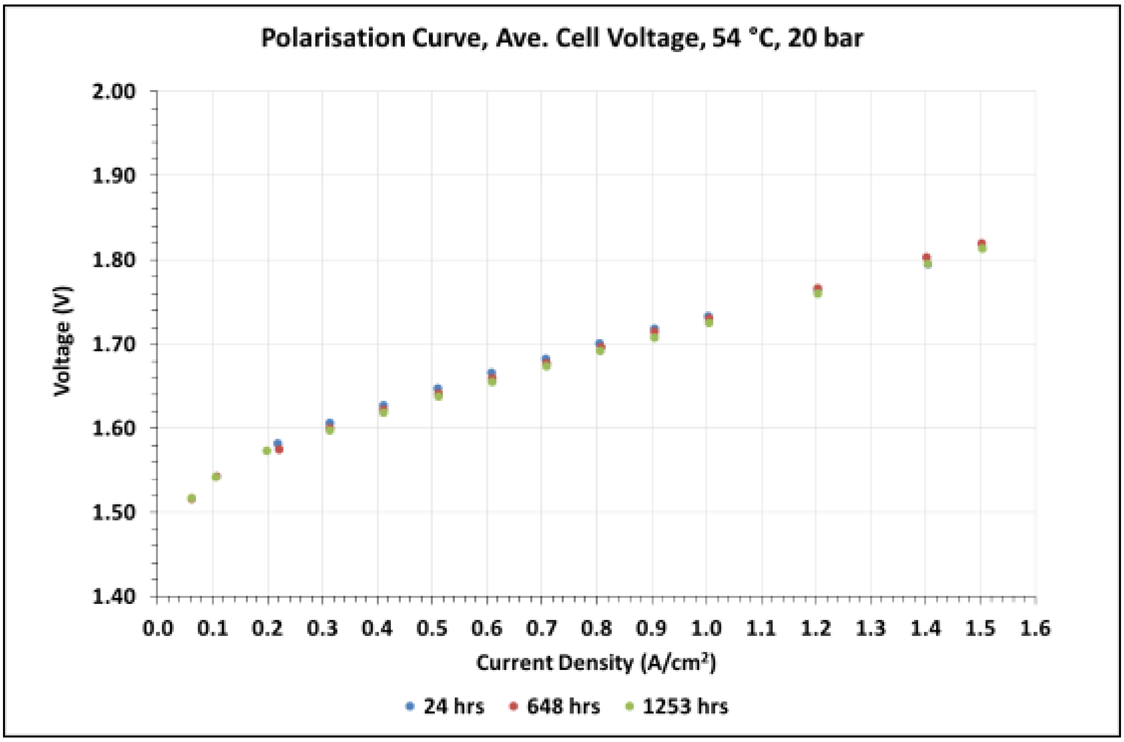

Figure 2-9. Flexibility of H2 production (lab tests at ITM)

2.15 Minimum part load (KPI_20)

Units	Target in proposal	Target revision in D2.4	Specific test (D5.1)?	Result	Target achieved?
%	10	10	NO	14	~~Yes / No/~~ partially

Table 2-18. Minimum part load results

Remarks: ITM work was done early in the project looking at low crossover membranes but as these was at an early development phase; whilst these could operate at low current density the decision was made to use commercial ones in the demo unit to ensure the success of the project (see D3.3). Due to this the plant isn't capable of working at loads lower than 14% due to the crossover rate resulting in the potential for a combustible mixture.

3. SYSTEM AVAILABILITY

It is worth noting the difficulty of the concept of availability. Throughout the demonstration period, an analysis of the causes of unavailability not caused by the lack of irradiation in the photovoltaic solar field was carried out simultaneously, with the purpose of increasing hydrogen production. The following conclusions were reached:

- **84%** of the time it was due to immaturity in the control system and chiller no automatic switched-off. This caused the electrolyser to be kept off on weekends, only taking advantage of the energy coming from the solar field to recharge batteries. As the chiller wasn´t automatically controlled and therefore it consumed much battery during the night so it was necessary to manually turned it off every day at the end. It is estimated that the weekly impact was about 30 hours each week. This cause of unavailability was corrected during the last part of the demonstration period leading to a positive impact on production hours.
- **4%** of the time was due to the fact that the system started to work with a delay with respect to the precise moment in which the solar radiation allowed the start of the operation in the stack. It is estimated that the weekly impact was about 1.5 hours each week.
- **10%** of the time was due to different INYCOM electrolyser alarms that required at best a manual reset and some other settings. It is estimated that the weekly impact was about 3.5 hours each week.
- **2%** of the time was due to due to other actions such as system shutdowns to recharge batteries, buffer checks and maintenance, hydrogen fuel cell testing, compressed air bottle changes, and so on. It is estimated that the weekly impact was about 0.7 hours each week.

Below is a detailed graph of the causes of unavailability by month.

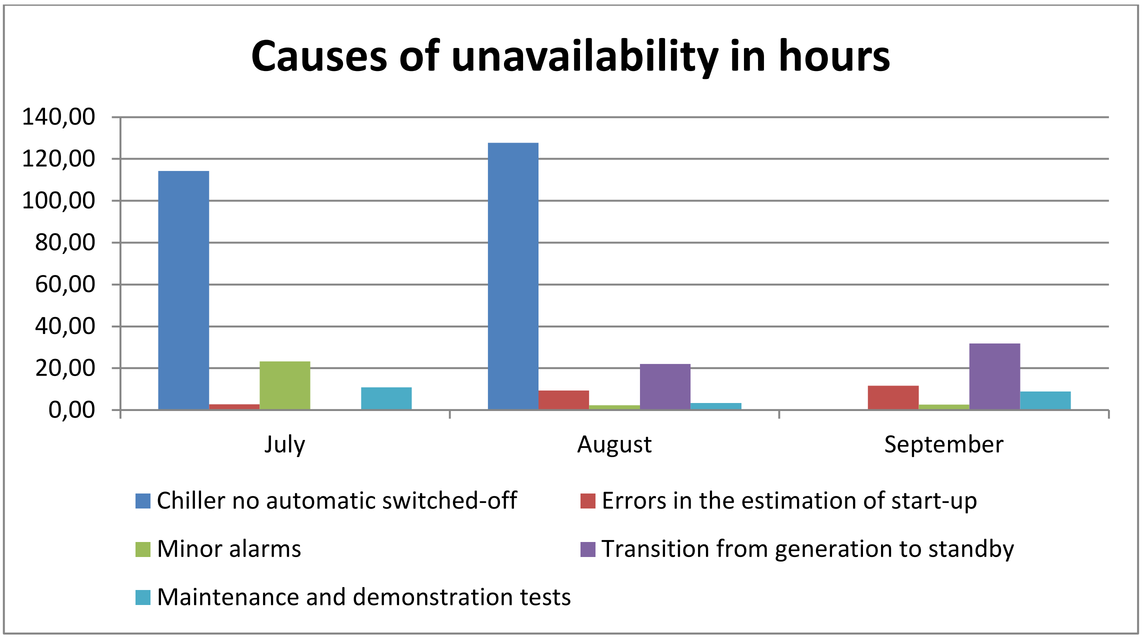

Figure 3-1. Causes of unavailability breakdown

This shows that during the last month of the demonstration period, unproductive hours have been significantly reduced, thus improving the amount of hydrogen produced.

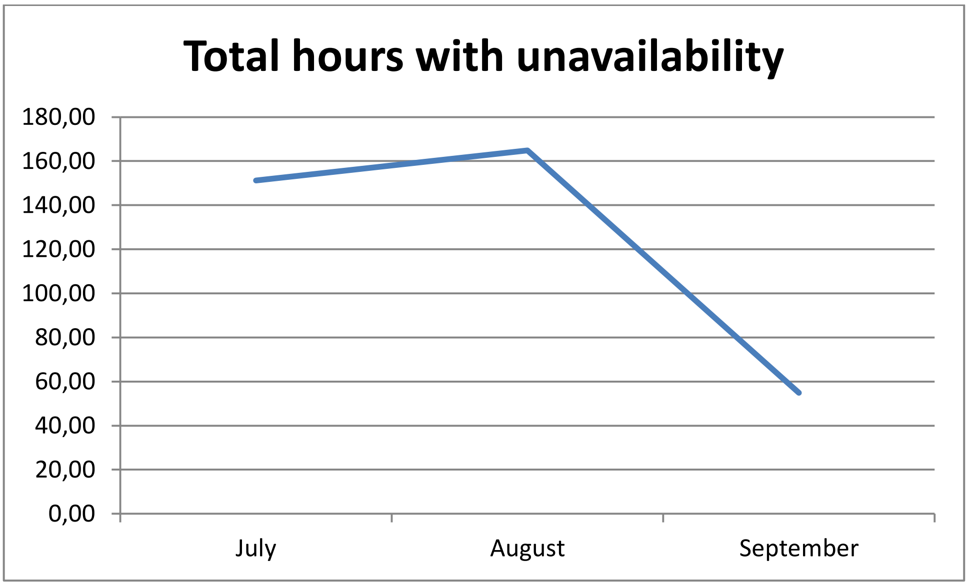

Figure 3-2. Evolution of unavailability during demo period

This concept is also reflected in the increase in **equivalent hours** in the system. For these purposes, the number of ***equivalent hours exploited*** is defined as the quotient between the energy that goes to the stack in kWh and the nominal power of the installation expressed in kW. And the number of ***equivalent hours on the solar field*** as the quotient between the energy reaching the solar field (and part of it may not have been taken advantage of) and the nominal power of the installation expressed in kW. This means In this case, the nominal power of the installation is determined by the electrolyser and is 50 kW.

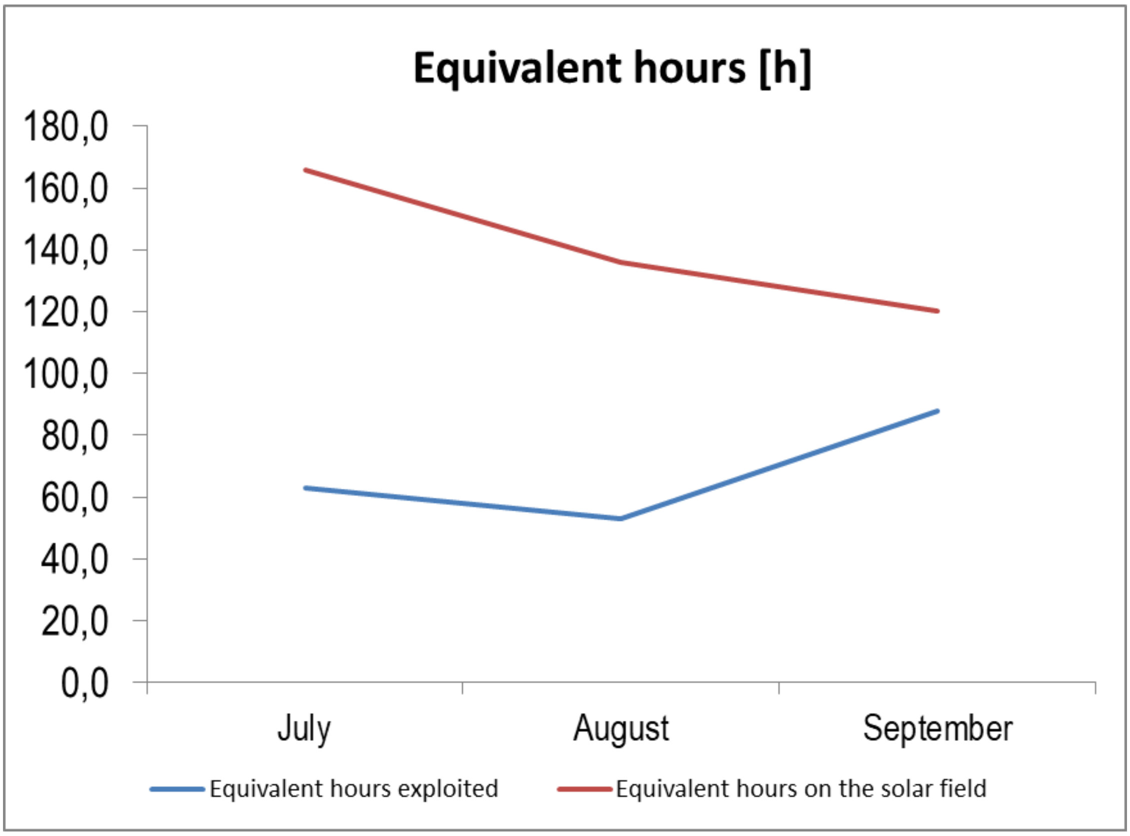

Figure 3-3. Equivalent hours evolution during demo period

As can be seen in the graph above, the difference between the hours exploited and the hours that energy reaches the solar field, is reduced as the demonstration period progresses. The cause of the big difference in July was mainly that the chiller was not automatic switched-off, also minor alarms due to the immaturity of the control system. In August, there were also many unused hours because the chiller was not automatic switched-off, but the alarms were reduced. In September finally, the main problem was solved as well as a maturity was acquired in the control, and simply the non-use was due to minor problems at the beginning of the day to start the H2 generation and some days when the system did not operate.

In summary, different actions were focused on increasing the productivity of the plant, especially in those where the percentage was higher. There were also lessons learned for future projects in all these availability studies.

4. TESTS WITH METAL HYDRIDES

4.1 Backgrounds

In the past, the feasibility of using hydrogen compressors using metal hydrides was analysed and a series of experiments were carried out with a test bench developed at the Foundation for the Development of Hydrogen in Aragon (FHA).

The assessment of the results obtained in test bench concluded that metal hydride compressors are not yet systems that will replace other technologies. But if aspects such as costs are adjusted and energy consumption is analysed for each specific case, they may become a technology that allows the introduction of hydrogen due to the ability to use thermal energy directly.

Therefore, in the search for solutions to achieve this objective, it was proposed during ELY4OFF to develop further the experiments to find ways of making the technology more competitive. The parameter that was identified to have the greatest effect on the cost is the compression capacity versus time, or in other words, the kinetics of the compressor. The specific proposal is to use the residual heat flows that can be tapped from the system and also de use of the hydrogen produced during the operation. However there is no physical link between electrolyser and the metal hydride test bench regarding heat flows, they have been mimicked thanks to the features of the installation.

4.2 Installation specifications

The installation existing in FHa's premises is shown in Figure 1. There are two circuits, the upper or hot circuit, and the lower, or cold circuit.

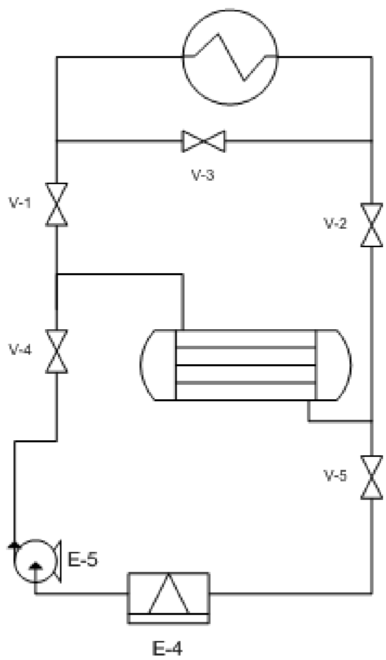

Figure 4-1. Design for the kinetic test bench.

The aim of this installation was to achieve a rapid heat exchange, i.e. to cause thermal inversions as quickly as possible. A 65 l/min pump was selected. The cold water circuit consists of the use of mains water directly at about 11 °C. The process of the complete installation is shown below:

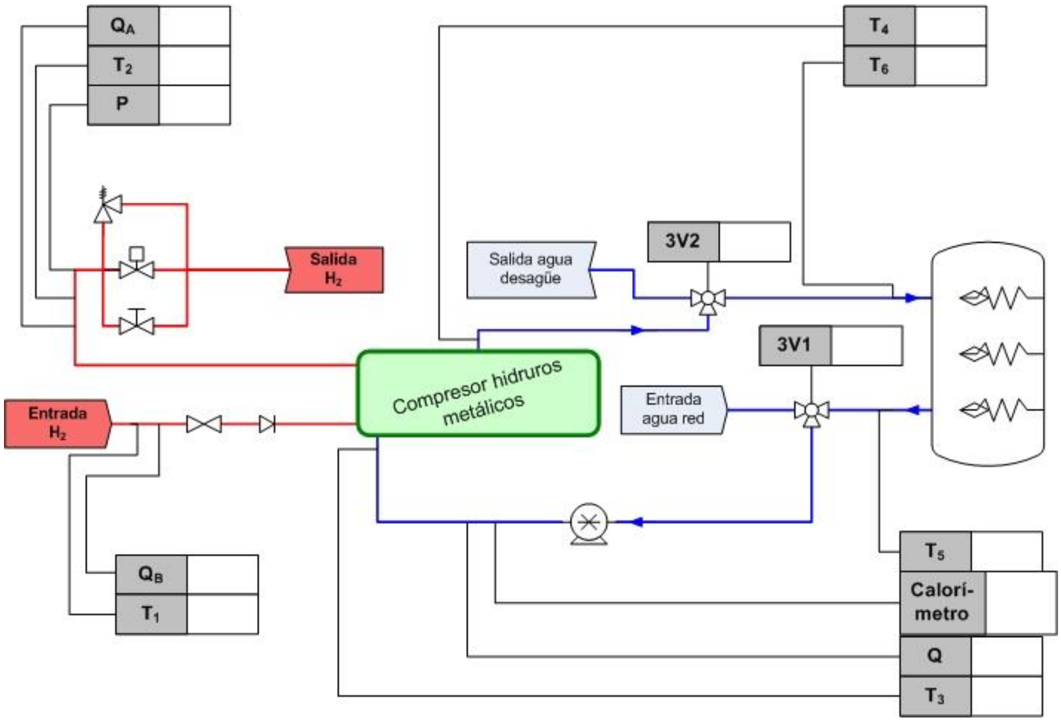

Figure 4-2. Design of the test bench for kinetics.

The sensor elements of the water circuit (T3, T4, T5, T6, Calorimeter and Q) were arranged as shown in Figure 2.

T1	Inlet Hydrogen Temperature	Sensor elements for hydrogen
T2	Outlet Hydrogen Temperature	
Qa	Output hydrogen flow rate	
Qb	Input hydrogen flow rate	
P	Hydrogen pressure	
T3	Water temperature at compressor inlet metal hydrides	Sensor elements of the water circuit
T4	Water temperature at the outlet of the compressor metal hydrides	
T5	Water temperature at the heater outlet	
T6	Water temperature at heater inlet	
Calorimeter	Compressor inlet calorimeter metal hydrides	
Q	Compressor inlet flow rate metal hydrides	
3V1	Water inlet valve	
3V2	Drainage water outlet valve	
Hydrogen valve	Hydrogen valve	

Table 4-1. Elements included in the metal hydrides test bench

4.3 Tests done in FHa prior to ELY4OFF

The tests carried out with this test bench years ago; allowed determining the kinetics of the process. Figure 3 shows the simulation of the pressure diagram of the compression of hydrogen charged at 10 bar, with a high thermal jump. In this case, the load was done at 20 °C and the compression at 150 °C, giving ΔT = 130 °C.

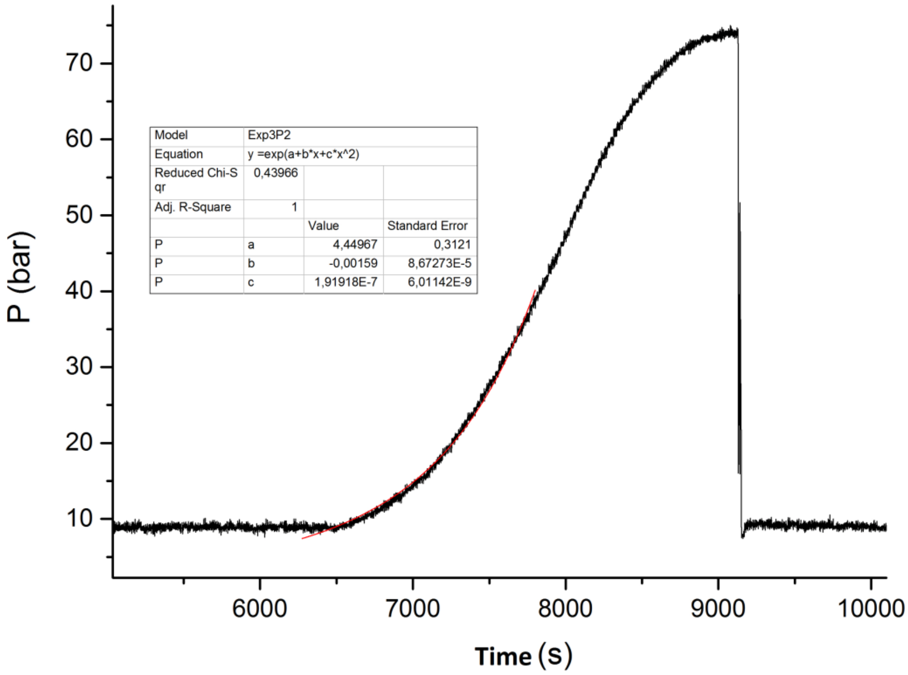

Figure 4-3. Heating diagram of the hydride loaded at 10 bar .

4.4 Tests done during ELY4OFF

The installation had to be repaired and commissioned again for this project due to the bad state by the disuse. Some of the actions undertaken were: revision of the instrumentation, repair of some sections of the piping circuit, and replacement of the pump. For the tests hydrogen produced during the demonstration phase was used, while the thermal flows were simulated; water was used as working fluid.

The first step was to find out the minimum temperature required by the hydrides to achieve some kind of reaction. After some tests it was found this value to be 80°C. This level of temperature entails a challenge because the waste heat available in the electrolyser is in the order of 60-65°C. Conceptually this gap can be solved using solar thermal energy, which fits with the system proposed in ELY4OFF. However, as was mentioned before, the heat flows are simulated in the hydrides test bench.

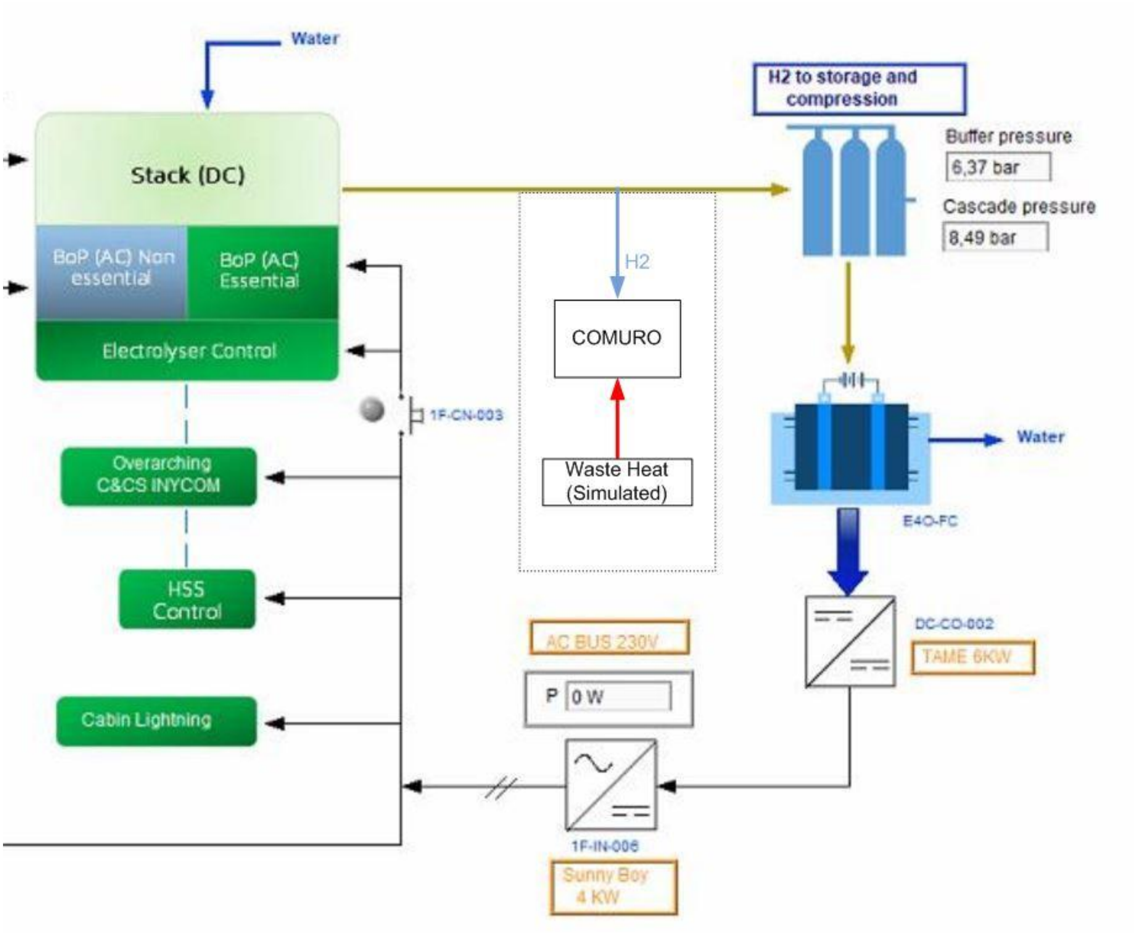

Figure 4-4. Integration of installation of metal hydrides within the Ely4off system.

The next step was to specify the conditions of the tests to execute. Considering a target of 80°C and cold temperature of 15°C, the tests were on using a ΔT = 65 °C,. The most important element during the execution of the tests was the variation (up and down) of the temperatures in the metal hydride reactor. For this purpose, the circuits are exchanged by mean of electro valves 3V1 and 3V2 in Figure 2. The temperature graphs at the reactor inlet (T3) and outlet (T4) are obtained, as shown in Figure 5.

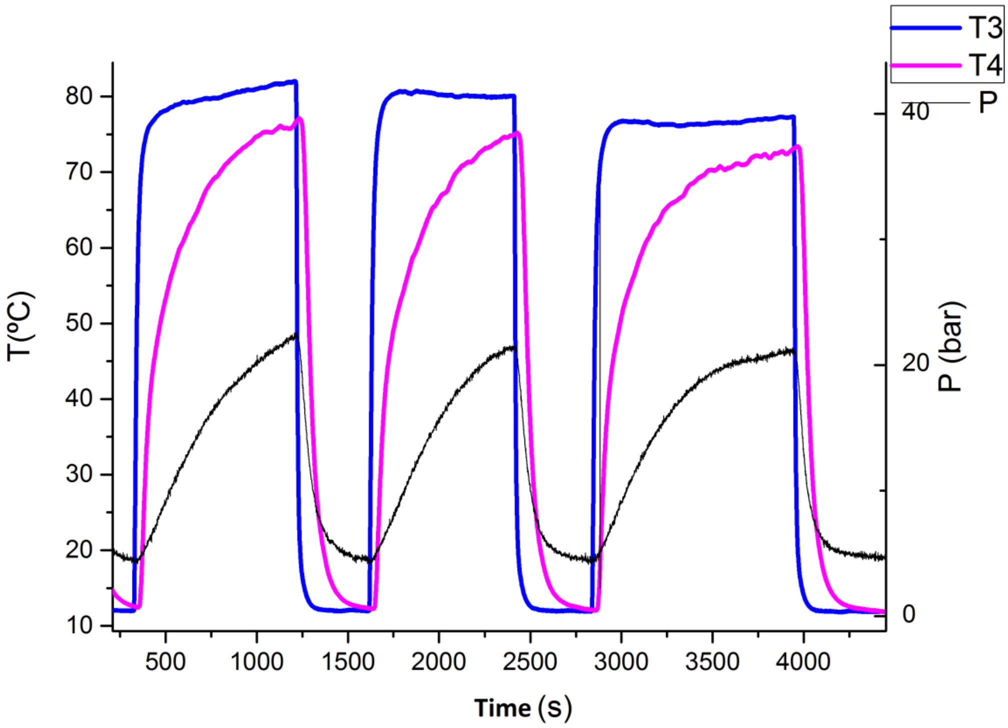

Figure 4-5. Evolution of inlet and outlet temperatures and gas pressure

As can be seen in the cooling and heating cycles, there is a certain delay between the reactor inlet and the reactor outlet, as expected for a tubular heat exchanger.

The change between cold water and hot water is made when the inlet and outlet temperatures coincide, in the case of cooling, or the difference is less than 5 °C, in the case of heating.

The following figure shows the flow rates of hydrogen, both for loading (Qb) and unloading (Qa).

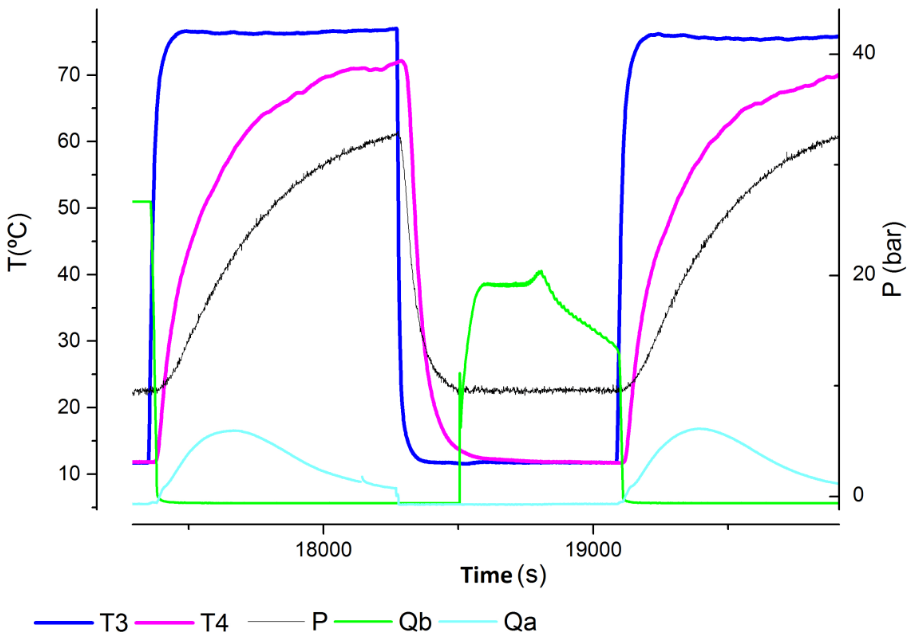

Figure 4-6. Evolution of compressor loading and unloading.

In general, hydride charging processes are carried out when pressure conditions permit them. In other words, until the system does not reach an equilibrium pressure lower than that provided by the source of hydrogen at low pressure, the system does not charge. But in order to reach this low equilibrium pressure, it is necessary to cool the system. And in this aspect the cooling of the system is done in less time than the heating.

The compression and subsequent discharge of the hydrogen at high pressure are carried out in the same process, in the heating of the system. Due to the fact that the system is not going to be discharged until high pressure has been reached, and once it has been reached, it has to be maintained to allow the desorption of hydrogen (endothermic process), the element that has the greatest effect on kinetics is the discharge process. The analysis of the compression curves obtained offers the following equation (adjusted to second order exponential):

$$P(bar) = e^{a+bt(s)+ct^2(s^2)}$$

The following table shows the results obtained in both cases:

			Value	Standard error
Previous to ELY4OFF	Test with ΔT = 130 °C, "slow"	a	4,44967	0,3121
		b	-0,00159	8,67E-05
		c	1,92E-07	6,01E-09
ELY4OFF tests	Test with ΔT = 65 °C, "fast"	a	3069,84125	100,27089
		b	-0,32268	0,01046
		c	8,49E-06	2,73E-07

Table 4-2. Comparison of tests

The obtained values for a, b and c are, in all cases higher in the "fast" test. This means that the system performs the cycles in less time if the temperature exchanges are faster, and without being affected by the different thermal jumps. But this adjustment can lead to confusion between the different factors in the equation. Therefore a fit of the curves by means of a linear equation is proposed.

For this, curves "fast" and "slow" are adjusted to the same origin and the equations of the straight lines of both elements are searched. Figure 7 shows the linear settings as well as the values of the equations.

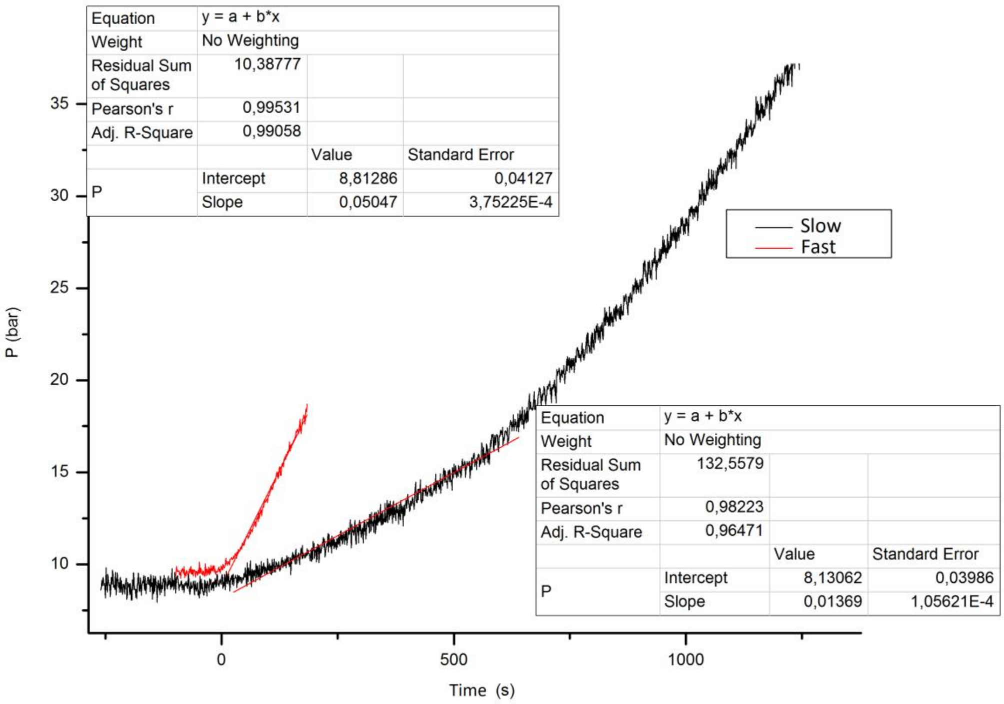

Figure 4-7. Linear fit graph of fast and slow curves.

It is proved in the previous comparison that in the tests with a ΔT = 130 °C (black curve) the compression step requires more time than with a ΔT = 65 °C (red curve) and "fast" slope..

To determine the cycle times, an average of all the cycles from the beginning of the hydride charge to the discharge of the compressed hydrogen is performed (absorption, heating and compression, and hydrogen discharge). This average value is 1385 s, which is equivalent to approximately 23 min. On the other hand, the integration of the values registered by the flowmeter during the load and discharge steps give the amount of hydrogen compressed, which was 110 standard litres.

4.5 Conclusions

The main conclusions obtained can be summarized as follows:

- The metal hydrides bench has shown a better performance (faster response) compared to the results obtained during tests executed before ELY4OFF.

- The minimum temperature required by the hydrides is 80°C, which is greater than the temperature that can be reached in the waste heat flows available in the electrolysis process.
- A solution could be to add solar thermal panels to the PV field that feeds the ELY4OFF system.
- However it may be wiser to store somehow such waste heats flows to be released wither to protect the system during nights or to speed the start-up of the system. More work on these aspects is proposed.

5. LEARNED LESSONS

- A great effort was done to adapt the **electrolyser BoP** to the variable solar profile. But it can be improved in many aspects, like the conversion of the entire consumers to work in DC.
- Unfortunately a **thin MEA** could not be finally tested due to time restrictions. But results were promising.
- Many modifications were applied to the ely's **control system**. Some others have been identified but could not be tested in the scope of the project. For example the transition between IDLE/STANDBY/OPERATION requires optimization.
- The **size of the system** (50 kW) makes that BoP consumption is disproportionately big. Further research for larger units (even up to 1 MW) should be pursued.
- The **DC/DC converters** have shown magnificent robustness and performance, exceeding the target efficiency. Even so, some aspects were identified to be further investigated.
- The **estimation of power available** for starting-up the system requires further refinement. It does not affect significantly on the amount of H2 produced but it is an area of improvement.
- With the experience gained with the **energy management configuration** tested (10 strings to stack, 3 strings to BoP), the original configuration (with all the strings connected) is considered to be a better solution. With the one tested during the demo there was energy wasted at some moments when the batteries were fully charged. This would be (probably) avoided in the other.
- The **storage of energy** in batteries tested does not allow feed the stack for bringing forward the hydrogen production in a day with good weather forecast. Such flexibility would provide helpful insights.
- The **availability** of the system improved as demonstration period progressed. The knowledge gained in several aspects of the control procedures, joined to the tuning of many parameters made that the amount of alarms causing shutdowns reduced dramatically. More modifications are identified that would increment even more the availability, which is an essential issue to consider in an off-grid system.
- It is of utmost interest to continue the demonstration during **extreme weather** conditions. It would allow stressing the system to limits that would offer valuable insights on consumption of the frost-protection system specially and would offer a robust support to deploy the system in other locations.
- The optimal **balance between the size of the PV field and the stack capacity** is not trivial. Considering the low CAPEX of PV technology it seems advisable to oversize it in order to bring the electrolyser to 100% load during a good period of the day. But the combination with electrochemical storage seems also reasonable and would allow even to keep the system operating continually.
- The ELY4OFF system ends in the production of H2 at 20 bar. Its **integration with other elements** (compression, storage, final application) would be an interesting challenge for the overarching control system.