Indicators and test definition

Deliverable 2.5

GRANT AGREEMENT
700359

D2.5 Indicators and test definition

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Author(s)	Pedro Casero (FHA), Lorién Gracia (FHA)
Participant(s)	Nick van Dijk (ITM), Logan López (EPIC), Rubén Gálvez (EPIC)
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Executive summary

The report is one of the deliverables foreseen in the ELY4OFF project. It is part of the Work Package 2, whose aim to provide a clear definition of technical, regulatory and safety aspects for an electrolysis system as a solution for completely off-grid areas in stand-alone operation.

The content presented in this report is based on a previous work presented in D2.4 "*Objectives at system and subsystem level*" (published in October 2017 and available in the project's website) where the consortium defined a set of objectives to be met by the system to be developed and commissioning.

The report is composed of three sections. One covers a discussion on the main indicators of the project, developing in more extent the targets identified in the proposal and giving explanations about their meaning and their relationship with the operational indicators that has to be communicated to the FCH JU within the annual exercise. As a summary, it can be said that essentially after 14 months of progress in the project, there are no relevant changes with respect to the targets presented in the proposal.

Another section presents the ex-situ tests that two of the partners of the project have scheduled to perform to their respective supplies.

The power electronics (PE) developed by EPIC to directly couple the PEMWE to the photovoltaic will be tested to verify the following parameters: input and output voltage, efficiency, operating temperature, storage temperature, control capabilities, stand-by consumption, and communication.

The PEMWE is supplied by ITM and the testing procedures of the Membrane Electrode Assembly (MEA) consist of the following: MEA hydration, water analysis, measurement of Polarisation Curves (gives insights into both the membrane resistance and the catalytic activity), measurement of Hydrogen Crossover through an MEA, steady-state operation durability, and Accelerated Stress Test (where 1000 On/Off Cycles offers information of the stability of the cathode catalyst). After the execution of these procedures, a characterisation assessment is performed to the MEA; thickness analysis, Ion-exchange Capacity Measurement, and Post-operation Analysis of MEA Contaminants.

In the final section, a preliminary identification of the kind of tests to run during the demonstrative period in the demo-site (FHA facilities located in Huesca) is presented. The demonstrative period is the Working Package 5 and it is foreseen from August 2018 until end of project, in March 2019.

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1. Compliance with the objectives

This chapter develops in more extent the ELY4OFF targets for 2018 already presented in the proposal, linking it to the techno-economic objectives listed in D2.4 "*Objectives at system and subsystem level*" (public deliverable), and also the operational indicators requested for the annual exercise (TRUST platform). The indicators are split in 6 main categories:

i) Efficiency, lifetime and voltage degradation
ii) Capital cost
iii) Stack
iv) Operating conditions
v) Dynamic and flexible operation
vi) Others

Efficiency, lifetime and voltage degradation					
Parameter	*ID*	*Units*	Ely4off target (proposal)	Objectives (D2.4)	Order TRUST Operational
Efficiency	***KPI_1***	*kWh/kg*	System 50 Stack 42.4 92.5% *at 100% load*	< 50 < 42 92,5%	*25* *23 and 24*
	KPI_2	*kWh/Nm³*	4		
Stack lifetime	***KPI_3***	*h*		60000	
	KPI_4	*years*	8		
System lifetime	***KPI_5***	*h*		160000	
	KPI_6	*years*	20		*4 and 6*
Efficiency degradation	***KPI_7***	*%/year 8000h*	2	2	*20, 21 and 22*
Availability	***KPI_8***	*h/year*		12	*18*
	KPI_9	*%*			*19*

Some discussion on each one of these indicators is provided below:

ID	**Parameter**	**Discussion**
KPI_1	Efficiency (kWh/kg)	Targets included in proposal and objectives in D2.4D2.4 are based on values rated by supplier (ITM). Those values refer to best performance at maximum load, which will be achieved very briefly as the energy source is solar PV. There are 3 indicators included in TRUST: 23, 24 and 25
KPI_2	Efficiency (kWh/Nm³)	It is the same as 1, with different units
KPI_3	Stack lifetime (h)	It has been decided to include the stack lifetime in hours instead of years because in an off-grid situation, the unit of years is not valid as compared with an on-grid situation.
KPI_4	Stack lifetime (y)	See previous parameter. There is not any direct indicator included in TRUST platform referred to this one, but there are two that cover somehow this concept: 4 and 6.
KPI_5	System lifetime (h)	Same argument as for n°3 and n°4, hours seems to be a better unit for comparison purposes.
KPI_6	System lifetime (y)	The same two indicators used for n°4 in TRUST are valid also here.
KPI_7	Efficiency Degradation (*%/year 8000h*)	The value is provided by ITM. In TRUST, indicators number 20, 21 and 22 refer to the efficiency degradation in different units.
KPI_8	Availability (h/year)	In D2.4D2.4 a value for this indicator is given by ITM. It refers to the maintenance time expected to be required. In any case, this concept is quite broad, especially in an off-grid case with an electrolyser fed with solar PV. This indicator has

		sense when the operating time of the electrolizer (or system) is referred to the total amount of hours when the solar resource is available, which is a small fraction of the number of hours in a year.
KPI_9	Availability (%)	Is the same indicator as n° 8 but in other units

As summary, the following indicators included in the operational section of the TRUST template will be considered:

Order	Name	Definition	Units
4	Hours of operation - cumulative	Total number of hours of operation (excluding downtime) over the electrolyser's entire lifetime (until the end date of this data collection exercise)	h
6	Days of operation - cumulative	Total number of days of operation (excluding downtime) over the electrolyser's entire lifetime (until the end date of this data collection exercise)	days
18	Duration of planned maintenance	Total duration of planned maintenance leading to system downtime during the timeframe of this data collection exercise	h/year
19	Availability	Percent amount of time that the electrolyser was able to operate versus the overall time that it was intended to operate over the timeframe of this data collection exercise	%
20	Efficiency degradation per 1000 h	System efficiency degradation in percentage per 1000 h of operation within the timeframe of this data collection exercise. If the system has operated for less than 1000 h, please extrapolate and indicate the extrapolation methodology used in the comment field	%/y
21	Degradation rate in µV/h	Measured degradation - in microvoltage loss per hour	µV/h
22	Degradation rate in %/kh	Measured degradation - in percentage voltage per 1000 hours	%/1000h
23	Stack electrical efficiency (observed - HHV - DC current)	Electrical efficiency of the stack(s), higher heating value value vs. direct current input - as actually measured - average for all stacks - within the timeframe of this data collection exercise. Please indicate relevant current density in the comment field.	%
24	System electrical efficiency (observed - HHV - AC current)	System electrical efficiency, higher heating value vs. alternating current input - as actually measured - average within the timeframe of this data collection exercise. Please indicate relevant current density in the comment field.	%
25	Energy consumption for hydrogen production	Energy consumption per kg of hydrogen produced, excluding compression	kWh/kg

Capital cost

Parameter	ID	Units	Ely4off target (proposal)	Objectives (D2.4)	Order TRUST Operational
CAPEX	*KPI_10*	*M€/(t/d)*	6	6*	*30*
	KPI_11	*EUR/kW*		3360**	*28*

*In D2.4 there was a mistake: it appears a value of 0.1 M€/(t/d), but the right value is 6.

**In D2.4 there was a mistake: it appears a value of 6000 €/kW but should be 3360

Some discussion on each one of these indicators is provided below:

ID	Parameter	Discussion
KPI_10	CAPEX (M€/(t/d)	Targets included in proposal and objectives in D2.4 are based on values rated by supplier (ITM).
KPI_11	CAPEX (eur/kW)	It is the same as 10, but based on the power of the electrolyser instead of the production of hydrogen.

As summary, the following indicators included in the operational section of the TRUST template will be considered.

Order	Name	Definition	Units
28	Price/cost of electricity	Average price paid for the consumed electricity - or electricity cost (for electrolysers coupled to their own renewable energy installation), over the timeframe of this data collection exercise.	EURc/kWh
29	OPEX - Operational and maintenance costs	Operational and maintenance costs per unit hydrogen ouput, including electricity, insurances, running costs, maintenance, repairs. Taxes excluded.	EUR/kg
30	Cost of the hydrogen produced	Average cost of the hydrogen produced, including OPEX and CAPEX, over the timeframe of this data collection exercise	EUR/kg

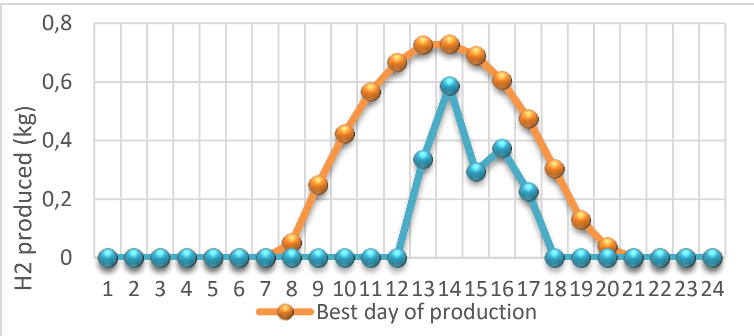
Stack

Parameter	ID	Units	Ely4off target (proposal)	Objectives (D2.4)	Order TRUST Operational
Stack size	***KPI_12***	*kW*	50	49.8	
Stack capacity	***KPI_13***	*Nm^3/h H_2*	>13	14.2	
		kg/d H2		27.9	*16*

Some discussion on each one of these indicators is provided below:

ID	Parameter	Discussion
KPI_12	Stack size (kW)	The value refers to the capacity of the stack rated. Is the power it can consume under nominal conditions.
KPI_13	Stack capacity (Nm3/h H2 and kg/d)	There is one indicator included in TRUST: 16, though in reality it represents the accumulated H2 production. The value included in objectives (D2.4) refers to best performance at maximum load and during 24 hours. As the source of energy is solar PV, 24 hours will never be achieved. In the table below two examples of what is expected in a summer day and in a winter day is presented.

	Kg/d	Operating time/ d	Nm^3/h
Best day in summer	5,65	13	4,86
Random day in winter	1,81	5	4,05



Thereby, the production hydrogen will vary through the year from 0 kg to ≈ 6 kg,

As summary, the following indicators included in the operational section of the TRUST template will be considered:

Order	Name	Definition	Units
16	Quantity of hydrogen produced	Total amount of hydrogen produced over the timeframe of this data collection exercise	t

Operating conditions

Parameter	ID	Units	Ely4off target (proposal)	Objectives (D2.4)	Order TRUST Operational
Current density	***KPI_14***	*A/cm²*	1	1	
Output pressure	***KPI_15***	*bar*	20	20	
Operating temperature	***KPI_16***	*°C*	60	55	

Some discussion on each one of these indicators is provided below:

ID	**Parameter**	**Discussion**
KPI_14	Current density (A/cm2)	This is the nominal production rate of hydrogen (in electric terms); this value is used to calculate other KPI's. The system is capable of going from 5% to 150% (dependent on power electronics capability) (see KPI 17).
KPI_15	Output pressure (bar)	Pressure value of hydrogen that will be store in the buffer, before the compressor and the pressurized vessels.
KPI_16	Operating temperature (°C)	Value provided by ITM, temperature in which the stack can be in standby and nominal conditions.

Dynamic and flexible operation

Parameter	*ID*	*Units*	Ely4off target (proposal)	Objectives (D2.4)	Order TRUST Operational
H_2 production flexibility with a degradation < 2%	***KPI_17***	*Load Spanning Range (%)*	5 – 150%	5 150	
Hot start (min to max power)	***KPI_18***	*seconds*	2	<30 (from standby) <3 (from operation)	*8* *9*
Cold start (min to max power)	***KPI_19***	***minutes***	<5	<5 min (from off) <30 s (from standby)	*10* *11*
Minimum part load	***KPI_20***	*%*	10	10	*12*
Ramp up (sec to full load)	***KPI_21***	*% full load/s*	2	100%	*7*

Some discussion on each one of these indicators is provided below:

ID	**Parameter**	**Discussion**
KPI_17	H2 production flexibility with a degradation <2% (load spanning range, %)	This is the range in which the electrolyser can operate which compromising safety or degradation. The stack and system should be able to operate between 5% and 150% of nominal power (KPI14); however this dependent on power electronics capability.
KPI_18	Hot start (min to max power) (seconds)	This value refers to the start of operation from the standby mode to the nominal power. Objectives mentioned in D2.4 refer to time until reaching hydrogen production (<30s), and nominal power (<3s) , from standby and with pumps off. TRUST correspondence is n° 8 and 9 respectively.
KPI_19	Cold start (min to max power) (minutes)	This value refers to the start of operation from shutdown mode to the nominal power. Objectives mentioned in D2.4 refer to time until nominal hydrogen production (<300s) and until nominal power (<30s). These values include safety checks to assure no leaks during turning on.
KPI_20	Minimum part load (%)	Whilst nominally the same as KPI 17, the value is different because of the limitation of the power electronics.
KPI_21	Ramp up (sec to	Is the average time to increase load per second at

	full load) (% full load/s)	nominal power. No objectives indicated in D2.4. This is similar objective to KPI 18. The electrolyser is capable of going from 5% to 100% in less than one second but is dependent of ability of subsystems. One indicator (number 7) exists in TRUST.

As summary, the following indicators included in the operational section of the TRUST template will be considered:

Order	Name	Definition	Units
8	Time from standby to nominal capacity	Time required to reach the nominal hydrogen output rate operating capacity when starting the electrolyser from stand-by mode (system already at operating temperature)	s
9	Time from standby to nominal power	Time required to reach the nominal power when starting the electrolyser from stand-by mode (system already at operating temperature)	s
10	Time for cold start to nominal capacity	Time required to reach the nominal hydrogen output rate operating capacity when starting the electrolyser from shut-down mode	s
11	Time for cold start to nominal power	Time required to reach the nominal power when starting the electrolyser from shut-down mode	s
12	Part-load operation - minimum - observed	Minimum part-load operation achieved in the timeframe of this data collection exercise, as a percentage of nominal capacity, in terms of power input	%
7	Transient response time	Average time to ramp up from 30% to 100% load at nominal power and operating temperature over the timeframe of this data collection exercise	s

Others

This category collects other parameters not directly presented in the KPI table of the proposal, but that has been included in report D2.4, and/or in TRUST template under the category of "operational". They will be taken into account during the demo period.

Parameter	Units	Objectives (D2.4)	Order TRUST Operational
Capacity of the system - rated	kW	56	
Efficiency of the PSU	%	>96	13, 15
Power of the control system when off	kW	<0.9	
Footprint - hydrogen production unit	M2	4	
Volume	M3	8	
Nature of the electricity source		SOLAR	
Fraction of renewable energy input	%	100	14
Quality required for water	µS	<1	
Purity of the produced hydrogen - rated	%	99.9995	
Type of power converter		DC-DC	
Input voltage	V	800	
Power usage of auxiliary equipment - idle	kW	0.9	
Power usage of auxiliary equipment - max production	kW	7	
Electrical efficiency of the system (rated - HHV - AC current)	%	82	
Cost - capital cost of the system (per ton/day) @ mass production (estimate)	M€/t/d	0.015	
Start date for reporting			1
End date for reporting			2
Number of safety incidents - total			27
Electricity consumed			17
Energy consumption for hydrogen compression			26
Hours of operation			3
Days of operation			5

2. Prototypes ex-situ test methodology

This section presents which tests and indicators will be used within the prototype developments. The prototypes that are being developed are: DC/DC converters (from EPIC Power) and the membranes of the stack (from ITM). There are other prototypes to be developed in the project, like the Hybrid Storage System, and a compressor prototype using hydrides (FHA), but they do not require the same thorough methodology as the other mentioned above since they based on already existing components, so it is mainly its integration with the other elements what has to be tested during the first stages of the commissioning of the system

Ex-situ testing and characterisation that has been developed by the partners is briefly summarized, according to previous experience and literature data (some information has been already provided by ITM in the Deliverable 3.1 about the membranes).

2.1 Power Electronics test and definitions

2.1.1 Input and output current-voltage characteristics

As the overall conversion will be provided by a set of Power Electronic units operating in parallel, it is considered enough to perform two tests:

- Test of a single Power Electronic Unit: using programmable DC-sources it is possible to emulate the behaviour of an array of photovoltaic panels. A programmable DC charge will emulate a fraction of the consumption of the stack. Each Power Electronic Unit converts only part of the overall power, therefore only a fraction of the current characteristic of the stack impedance must be emulated. Example given, if there are 18 photovoltaic arrays with 18 power electronic units, only 1/18 of the current of the stack will be fed by each power electronic unit.
- A test with a minimum of three Power Electronic Units in parallel must be performed in order to assure the absence of cross influence that can lead to instabilities.

Indicator: full power conversion will be available at any of the possible input-output voltage combinations.

2.1.2 Efficiency

Considering that the entire Power Electronic device operates thanks to several Power Electronic Units working in parallel, the overall conversion efficiency is equal to the particular efficiency of each parallelized unit. Therefore, the efficiency of one Power Electronic Unit will be measured. This test will be performed using the above mentioned programmable DC source and programmable DC charge. Input and output powers will be measured through accurate laboratory current and voltage probes.

Indicator: efficiency > 90% in any case

2.1.3 Operating ambient temperature (inside the container)

Using a climatic chamber one Power Electronic Unit will be tested at 0°C and 40°C. These tests will be carried out during 16h according to the strongest photovoltaic power production profiles (a long summer day) in order to test that the Power Electronic Unit withstands these conditions. Thermocouples will be used in order to measure temperatures at significant points and a thermal camera will help to identify any unpredicted hot-point at the power electronics unit.

Indicators:

- Semiconductors: case temperature < maximum case temperature of the device
- Magnetics:
  - nucleus temperature < 110 °C
  - copper temperature < 110 °C
- Hot spot: temperatures at the PCB < 130°C and temperatures at any component other than semiconductors and magnetics will be checked.

2.1.4 Storage temperature

The Power Electronic Unit will be kept at -20°C during 3 days and will be then tested at 0°C and 40°C at full power (16 hours at full power).

Indicator:
Similar behaviour than in *2.1.3 Operating ambient temperature (inside the container)*

2.1.5 Control capabilities

Each Power Electronic unit must be able to perform the next control tasks:

- During Standby
  - Measure voltage at the input terminals if string voltage > 300 V
  - Communicate the input voltage to the System Control if string voltage > 300 V
  - Receive start-of conversion command from the System Control and start the conversion
- During conversion
  - Perform MPPT algorithm to achieve maximum power conversion from the Photovoltaic Array
  - Monitor input and output voltages and currents and operating temperature
  - Safely stop conversion and disconnect in case of an internal or external failure
  - Communicate to the System Control measured variables and operation status
  - Receive stop of conversion command from the System Control and stop to operate safely

Considering the extremely low dynamics of the photovoltaic panels and the electrolyser stack, there is not any particular dynamic requirement

Indicator: Functional tests will be performed with the control system. The power supply and DC load used in 2.1.1 will be required.

2.1.6 Standby power consumption

This power will be measured at voltage input boundaries.
Indicator: Total stand-by power lower than 100 W.

2.1.7 Communications

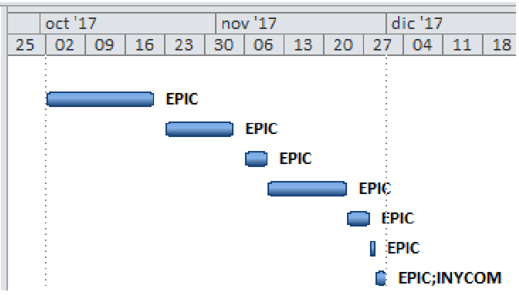
Communications will be performed through a CAN link. The exchanged data is:

- Transmitted:
  - Input voltage
  - Input current
  - Output voltage
  - Output current
  - Temperature of the Power Electronic Unit
  - If failure, failure and type of failure
- Received
  - Start of conversion
  - Stop of conversion

Indicator: Functional tests will be performed with the control system. The power supply and DC load used in 2.1.1 can be used.

2.1.8 Planning

Nombre de tarea	Duración
Input and output current-voltage characteristics	15 días
Efficiency	10 días
Operating ambient temperature (inside the container)	4 días
Storage temperature	10 días
Control capabilities	2 días
Stand-by power consumption	1 día
Communications	2 días



2.2 Membrane Electrode Assembly (MEA) Testing Procedures

The following summarises the procedures developed to characterise the MEAs developed during the ELY4OFF project at the single cell and stack scales.

2.2.1 MEA Hydration Procedure

This procedure should be followed prior to testing MEAs to ensure that the MEA is well hydrated.

Procedure		
MEA Conditioning	Hydrate the MEA in Type 2 deionised water for 24 hrs at the operating temperature of the intended test	
Volume of water	Minimum of 2 ml of Type 2 water per cm^2 of membrane	
Method of water testing	Refer to the Water Analysis procedure	
Outcome - Pass	If the water passes the targets, the MEA is ready to be used	
Outcome - Fail	If the water does not pass the targets, discard the water; continue rinsing the MEA as appropriate before repeating the procedure above.	
METRIC	**FREQUENCY**	**TARGET**
TOC	24hr until it passes	<0.3ppm
pH	24hr until it passes	Between 5 and 7
Conductivity	24hr until it passes	<1.5μS/cm
Fluoride	24hr until it passes	<0.1ppm
ICPMS	24hr until it passes	<100μg/L for all elements apart from Si which is <500μg/L

2.2.2 Water Analysis Procedure

This is a general procedure for the analysis of water.

Procedure	
Where to take samples during an electrolyser cell test	Take water samples from the anode and cathode process lines and deionised water top-up stream
Sampling for TOC, pH, Conductivity and Fluoride Analysis	100ml in a glass bottle
Sampling for ICPMS	10ml in a 15ml plastic centrifuge tube
Equipment for TOC analysis	OI Analytics 1030W or equivalent system
Equipment for pH, conductivity and fluoride analysis	Mantech Titrasip System with conductivity probe, pH probe and fluoride ISE or equivalent system
Equipment for ICPMS analysis	Agilent 7500cx ICPMS or equivalent system
Method for TOC analysis	Wet (persulfate) oxidation TOC and TIC measurement (averaged over 3 repeats)

Method for pH, conductivity and fluoride analysis	Single Conductivity and pH measurement, averaged fluoride measurement (3 repeats)	
Method for ICPMS analysis	Acidification with Traceselect Ultra Nitric acid to ~5%. Quantitative measurement of the following elements; Na, Mg, Al, Si, S, K, Ca, Ti, Cr, Mn, Fe, Ni, Cu, Zn, Zr, Mo, Ru Ce, Ta, Ir, Pt, Pb.	
METRIC	**FREQUENCY**	**TARGET**
TOC	As required	As appropriate to the test being analysed
pH	As required	Between 4 and 7
Conductivity	As required	As appropriate to the test being analysed
Fluoride	As required	As appropriate to the test being analysed
ICPMS	As required	As appropriate to the test being analysed

2.2.3 Measurement of Polarisation Curves

This is a measure of the MEA performance and can give insights into both the membrane resistance and the catalytic activity. It is a measure of the cell voltage as a function of the applied current density. Variation of current density is carried out as reported below. When operating at pressure and low current densities, care must be taken to ensure that the percentage of hydrogen in oxygen remains below the lower flammability limit.

Procedure	
Pre-conditioning	It is recommended that test cells are operated for at least 24 hours to ensure the MEA has reached a steady state
Operating conditions:	
Control	Chronopotentiometric (current controlled; voltage recorded)
Cell size	As appropriate (but must be recorded)
Water Inlet temperature	Recorded and reported with the polarisation curve
Pressure	Recorded and reported with the polarisation curve.
Current range	0.05 A/cm² to 1.5 A/cm²
Step size	Smaller at low currents such that the change in voltage between step size is < 30 mV (see example below)
Direction of the change in current	Ascending and/or descending, must be reported.
Technique	• Hold current at 1.5 A/cm² for 10 minutes to ensure MEA is in a steady state • Step current to 1.4 A/cm²

	• Record voltage after 1 minute. • Step to next current density and repeat.	
METRIC	**FREQUENCY**	**TARGET**
Polarisation curve	Start and end of any test plus as required	
Voltage at 1 A/cm²		1.6 V

Example of applied current densities against which voltage should be recorded:

Current Density [A/cm²]	Cell Voltage [V]
0.05	
0.06	
0.08	
0.10	
0.15	
0.2	
0.4	
0.6	
0.8	
1.0	
1.2	
1.4	
1.5	

Note: water temperature and pressure should be controlled and recorded.

2.2.4 Measurement of Hydrogen Crossover through an MEA

Hydrogen crossover through the MEA is measured whilst the electrolyser is operating by placing a sensor in-line in the oxygen gas flow.

Procedure	
Assembly	MEAs in a stack or single electrolysis cell with water flowing through the anode process line
Sensor	E.g. HY-OPTIMA in-line in gas flow on oxygen vent line, calibrated
MEA thickness	Measure the thickness of the MEA prior to cell/stack assembly, must be reported
Inlet Water Temperature	Set as required, must be recorded and reported
Pressure	Between balanced pressure and 2MPa delta P (pressurised hydrogen), must be recorded and reported
Current Density	0.5 A/cm² – In a single cell, active area 8 cm² 0.5 A/cm², 0.2 A/cm², 0.1 A/cm² and 0.05 A/cm² – In a

	short stack, active area ≥130 cm^2	
METRIC	**FREQUENCY**	**TARGET**
%H2 in O2	Steady state measurement	<1%

2.2.5 Steady-State Operation Durability Test of an MEA

MEAs are tested under constant load, temperature and pressure, to measure the rate of MEA degradation during operation at steady-state.

Procedure		
MEA Conditioning	Refer to MEA Hydration Procedure	
Test Conditions	1. Before starting test, operate for 24 hrs at steady-state, 1 A/cm^2. 2. Measure a polarisation curve as detailed in the Measurement of Polarisation Curve Procedure (Current Range: 0.05 mA/cm^2 – 1.5 A/cm^2). 3. Operate the cell at a steady-state, 1 A/cm^2. 4. At the end of the test, measure a polarisation curve as detailed in the Measurement of Polarisation Curve Procedure (Current Range: 0.05 mA/cm^2 – 1.5 A/cm^2).	
Total Time	1000 hrs after measurement of the first polarisation curve	
Temperature	Set as required, must be recorded and reported	
Pressure	Set as required, must be recorded and reported	
METRIC	**FREQUENCY**	**TARGET**
F^- release	After 24 hrs of steady-state operation at the beginning of the test. Every 100 hrs after the first polarisation curve.	No target for monitoring
Hydrogen Cross-over	After 24 hrs of steady-state operation at the beginning of the test. Following 1000 hrs of operation	≤1%
Operating Voltage	Continuous	≤1.6 V
Voltage Degradation	Between 100 hrs and 1000 hrs of operation. If a stoppage occurs during this time period then data collected between the restart and 100 hrs after the restart should not be included.	≤ 10 μV/hr degradation in operating voltage using line of best fit
Polarisation Curve	After 24 hrs of steady-state operation at the beginning of the test. Before stopping the test.	≤1.6 V at 1 A/cm^2

2.2.6 1000 On/Off Cycle Accelerated Stress Test

This test is indicative of the stability of the cathode catalyst. A small-scale test cell (8 cm^2 active area) developed in partnership with the National Physical Laboratory (NPL) is used for this test. The cell is able to differentiate the potentials of the anode and cathode. Determination of electrochemical surface area (ECSA) of the cathode catalyst is made by integration of hydrogen adsorption (theoretically 0.210 mC/real cm^2) peaks (0.02-0.4 V RHE) after subtraction of double layer charging at 0.4 V RHE.

Procedure			
MEA Conditioning	Refer to MEA Hydration Procedure		
Test Conditions	1. Operate the cell at a steady-state 1 A/cm^2 for 1 hr. 2. Measure a polarisation curve as detailed in the Measurement of Polarisation Curve Procedure (Current Range: 0.01 mA/cm^2 – 1 A/cm^2). 3. Operate the cell at a steady-state 1 A/cm^2 for 10 mins. 4. Carry out cyclic voltammetry of the cathode in the potential range 0-0.6 V (vs Reference hydrogen electrode (RHE)) , sweep rate of 20 mV s^{-1}. 5. Cycle the cell voltage between 1.65-0V, 1000 times, with each potential held for 30 seconds per cycle. 6. At the end of the test, repeat steps 1 - 4		
Temperature	Set as required, must be recorded and reported		
Pressure	Set as required, must be recorded and reported		
METRIC	**FREQUENCY**	**Measurement**	**TARGET**
Polarisation Curves (Full cell, anode and cathode)	Before and after cycling	Voltage (V)	Cell voltage ≤1.6 V at 1 A/cm^2
Electro Catalytic Surface Area (ESCA)	Before and after cycling	Electrochemical surface area (ECSA) (C)	No target for monitoring
Cell Operating Voltage at 1 A/cm^2	Before and after cycling	Voltage (V)	≤1.6 V
Voltage Change After Cycling	After cycling	Voltage change (ΔV)	No target for monitoring

2.3 Membrane Electrode Assembly (MEA) Ex-situ Characterisation

2.3.1 Post-operation MEA Thickness Analysis

Analysis of the MEA before and after any steady-state and cycling tests will be carried out using SEM-EDX to assess changes in the thickness of the different layers of the MEA (membrane and catalyst) and precipitation of precious metals within the membrane.

2.3.2 Post-operation MEA Ion-exchange Capacity Measurement

This measurement provides an indication as to whether chemical degradation of the membrane in the MEA has taken place. A base titration is used to measure the number of equivalents of sulfonic acid groups within the MEA and the measurements used to calculate the ion-exchange capacity and equivalent weight of the MEA.

Procedure

1. Treat sample of MEA with 0.1M sulfuric acid for 1 hour.
2. Rinse the sample thoroughly with deionised water.
3. Dry the sample in a vacuum oven at 50 °C for a minimum of 4 hours.
4. Weigh the dried MEA sample and record the mass to 4 dp.
5. Place the MEA sample into 0.01M sodium hydroxide (aq) solution and leave to soak for a minimum of 16 hrs, at room temperature.
6. Titrate the sodium hydroxide soak solution against 0.01M hydrochloric acid and record the volume of hydrochloric acid required to neutralize the sodium hydroxide soak solution.
7. Calculate the concentration of the sodium hydroxide soak solution following contact with the MEA.
8. Calculate the difference between the concentrations of the sodium hydroxide solution before and after contact with the MEA, to obtain the equivalent number of moles of sulfonic acid groups in the MEA.
9. Using the number of moles of sulfonic acid groups in the MEA and the mass of the dry MEA, calculate the ion-exchange capacity and equivalent weight of the MEA.

METRIC	FREQUENCY	TARGET
Ion-exchange Capacity	End of Test	No target for monitoring
Equivalent Weight	End of Test	No target for monitoring

2.3.3 Post-operation Analysis of MEA Contaminants

Soaking a sample of MEA in a fixed volume of dilute nitric acid, of known concentration and then analysing the solution by ICP-MS, enables any ionic contaminants of the MEA to be identified.

Procedure

1. Treat a sample of MEA with 5% Trace SELECT Ultra Nitric Acid solution.
2. Leave the vial in a 60 °C oven for 18 hours.
3. Sample solution for ICPMS, 10ml in a 15ml plastic centrifuge tube.

Equipment for ICPMS analysis	Agilent 7500cx ICPMS or equivalent system	
METRIC	**FREQUENCY**	**TARGET**
ICP-MS	End of Test	No target for monitoring

2.3.4 Planning

Tests and characterisation of MEAs at both single cell and short stack scale will be conducted as and when required during Work Package 3 – Designing, Engineering and Validation of Electrolysis System, between M7 - M21 (October 2016 – November 2017).

3. Demonstrative period. Testing plan

WP5 covers all the activities related to the demonstration of the system developed in ELY4OFF. There are two main activities, described below. In this chapter, a preliminary identification of the kind of tests to run during the demonstrative period is presented.

The objective of Task 5.1 (*Erection, commissioning and start-up tests, March 18 – June 18*) is to reach a successful commissioning and start-up of the systems developed, ensuring that the subsequent demonstration period is run safely and under the technical specifications (WP2). This task is essential to smoothly integrate the subsystems developed in separate facilities (electrolysis system at ITM premises, power electronics at EP premises, pre-existent PV installation at FHA premises).

After a commissioning is accomplished, a detailed demonstration plan will be set up to check and show the performance of the system against objectives established in WP2.

The tests, programmed according to a defined demonstration plan are formally executed in Task 5.2 (*Demonstration, July 18 – March 19*), and will be designed to cover the potential operation of the electrolysis in the off-grid installation. The results obtained during the demonstrative tests will be compared with the objectives and KPIs agreed in the project in WP2.

Following figure shows the Gantt Chart. The demonstrative period (WP5) starts in March 2018 with the integration of all the elements of the system and the commissioning. The testing period is foreseen from August 2018 until end of project (March 2019).

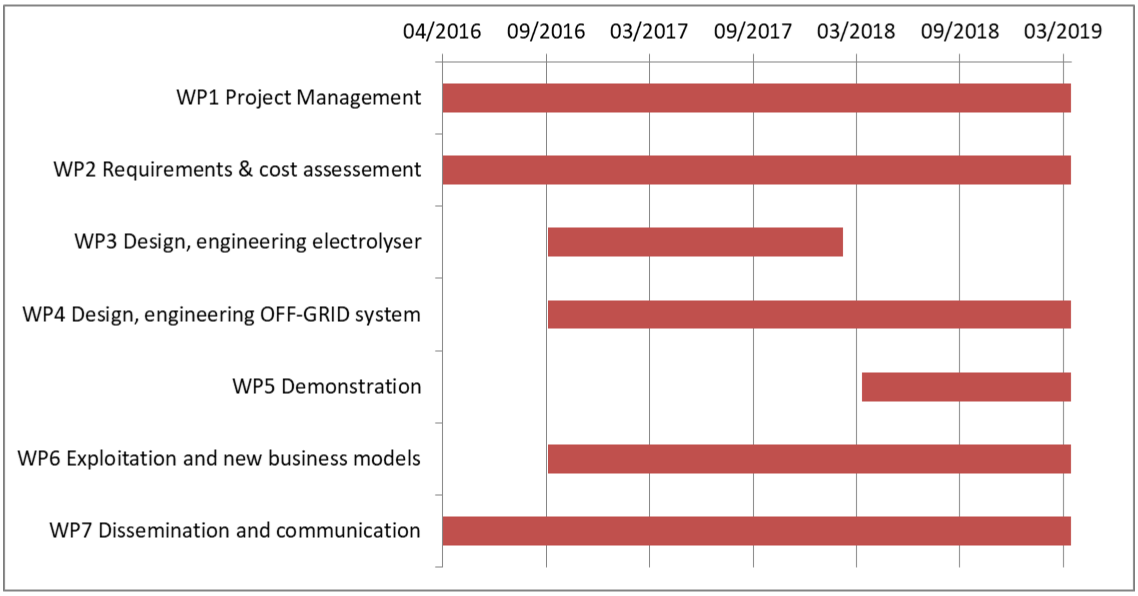


Figure 1. ELY4OFF Gantt Chart

During the demonstration dates, the solar radiation expected to be available in the demo site will be as follows:

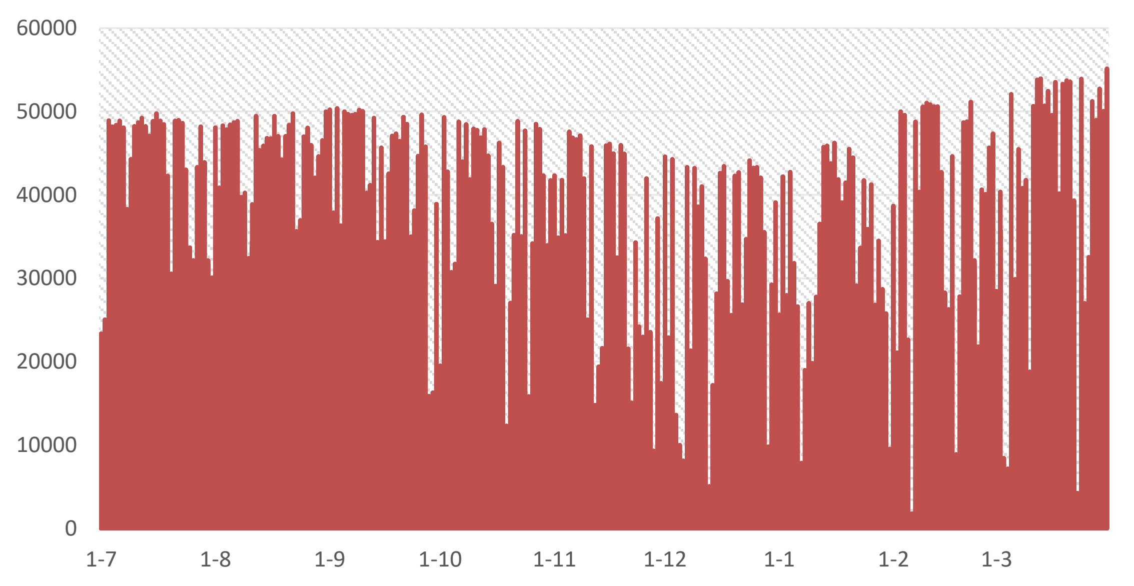


Figure 2. Hourly radiation (Wh/m^2) in Huesca during the demonstration date (source: PVWATTS)

3.1 Parameters proposed to test during demonstrative period

The model developed using Odyssey (software tool developed by CEA and described in D2.7 "*First assessment on monitor and model: alignment with requirements and objectives*") allows to assess the effect of the different boundaries and assumptions used as reference. Every element on the system, such as the stack, the fuel cell, batteries, etc., should be tested in order to find the influence over the final hydrogen production as well as the behaviour of the whole system.

The scope of the testing plan proposed includes variations (up and down usually) of a set of parameters aiming to obtain its sensitivity on the performance of a specific component and in the whole system. These variations have already been simulated in Odyssey so the expected impact in the main indicators is already available. This assessment has been used by now to select some of the characteristics of the components of the system (like the capacity of the batteries, or the fuel cell power).

In Table 1 the list of parameters and the range of variation that have been simulated is presented. Some of these parameters will not be able to be modified in the real tests, but the robust knowledge acquired about their effect on the system will allow drawing rigorous conclusions on the performance of the system, that is why they are included in the table.

Element	Parameter	Range of variation	Test
Electrolyser	Efficiency	60 - 62%	Variation of the efficiency
Electrolyser	Auxiliary System power (BoP)	5 - 30%	Variation of the power
Compressor	Isentropic efficiency	72 - 82%	Variation of the efficiency
Fuel Cell	Power	2 - 3,5 kW	Variation of the power
Fuel Cell	Efficiency	50 - 65 %	Variation of the efficiency
Batteries	Capacity (kWh)	5 - 36 kWh	
DC Converters	Efficiency Curve	0.64-0.99	Variation of the curve
DC Converters	Efficiency	70-100%	Variation of the efficiency
Consecutive days without sun	Days in summer	1,2,3...	See the influence in the system if there are more than one day without sun

Table 1. Parameters simulated in Odyssey

Figure 3 illustrates the results obtained with Odyssey of the variations of the parameters listed in the table, with regard to the net amount of H2 produced in the system (the H2 used in the FC for vital support of the electrolyser has been therefore taken into account). The figure shows the sensitivity (positive or negative of ΔH_2 in kg) of the variation of each parameter (Δ%).

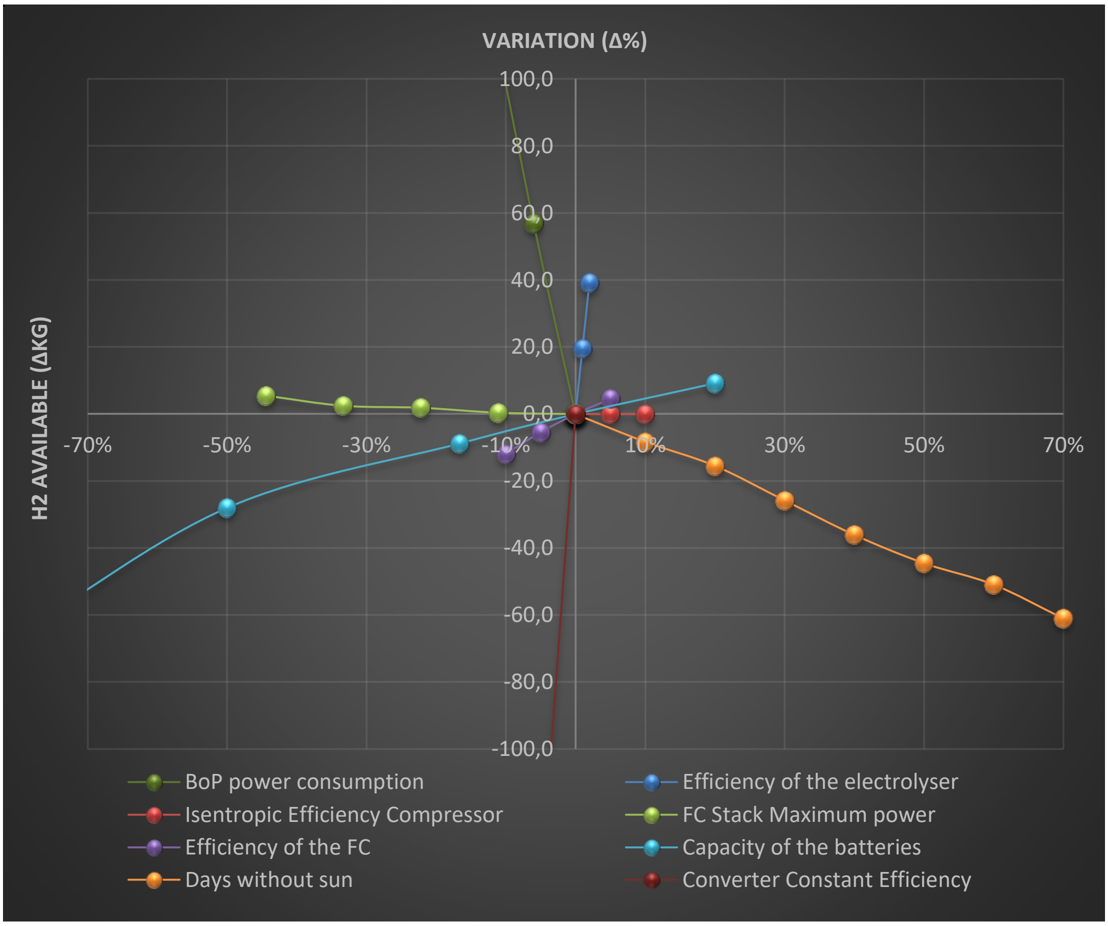


Figure 3. Influence of several parameters on the amount of hydrogen produced

3.2 Different strategies to test

There is an important aspect detected during the work done during the first stages of the project, related to the strategy in the use of the energy. There are two possibilities of using the only source of energy available (solar PV): 1) to prioritize H2 production, or 2) to prioritize electrical storage. In addition, other aspects like when triggering the operation of the FC, and whether using the batteries to produce H2 in certain situations has sense.

Following table shows these simulated indicators that have allowed defining the testing plan boundaries:

Strategy	Description	
Operation of the FC	SOC of battery: Turn On when SOC 0,2-0,4	
Produce H2 with batteries	Can be interesting in summer when certainty about good radiation during the day	
H2 storage priority	If excess of PV power:	- PV power produce hydrogen
		- Storage in the battery
	If deficit of PV power:	- Battery supply the electrical load
		- SOC <= 0,25 to > 0,35 the FC actuates
Electrical storage priority	If excess of PV power:	- PV power charge the battery
		- If SOC =1 PV power produces hydrogen
		- PV power supply the electrical load
	If deficit of PV power:	- Battery supply the electrical load
		- SOC <= 0,3 to > 0,4 the FC actuates

Table 2. Strategies to test during demonstrative period