H2AEOLUS

DELIVERABLE D8.1

PUBLIC

Protocols for demonstration of energy-storage strategy

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Project acronym:	HAEOLUS
Project title:	Hydrogen-Aeolic Energy with Optimised eLectrolysers Upstream of Substation
Project number:	779469
Call:	H2020-JTI-FCH-2017-1
Topic:	FCH-02-4-2017
Document date:	April 30, 2020
Due date:	2019/06/30

Keywords: Test protocols, test cases, energy-storage use case, electrolyser, hydrogen storage

Abstract: This document defines the suite of test protocols that will be used to assess the performances of the HAELOLUS system when configured for operations in the energy-storage use case that specifically aims at improving the grid integration of wind farms providing energy in the optimal conditions. For that purpose, on-site test protocols for the electrolyser and the fuel cell, on-site test protocols for the three use cases of the energy-storage use case, and on-site demonstration protocols for three use cases of the energy-storage use cases are defined.

Revision History

Date	Description	Author
2019/05/15	Description of what was done and systems information required	Iker Marino (TECNALIA)
2019/07/15	Preliminary version	Iker Marion (TECNALIA)
2019/08/08	Additional information and internal revision	Maider Santos (TECNALIA) Eduardo García (TECNALIA)
2019/08/30	Version be distributed for gathering some minor systems information	Iker Marino (TECNALIA)
2019/09/12	Version v2.4 sent to Dr Valerio Mariani (UNISANNIO) for quality revision (QR)	Eduardo García (TECNALIA)
2019/09/30	Version v2.5 sent to Dr Valerio Mariani and updated with the QR comments	Eduardo García (TECNALIA)
2019/10/09	Version v2.6 sent to Dr Valerio Mariani updated with his QR comment to v2.5	Eduardo García (TECNALIA)
2019/10/17	Version v2.7, updated with the QR comments from v2.6, and sent to Dr Valerio Mariani and Federico Zenith as D8.1 final version	Eduardo García (TECNALIA)
2020/04/27	Version v3.0, updated with the corrections defined from the revision of the project officer [Ref. Ares (2020)2201545 - 23/04/2020]	Eduardo García (TECNALIA)

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme *under grant agreement No 779469*

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1 Acronyms and glossary of terms

aFRR: Automatic Frequency Restoration Reserve

AGC: Automatic Generation Control

CAPEX: Capital expenditures

ELY: Electrolyser

EU: European Union

FC: Fuel cell

WF: wind farm

H_2: Hydrogen

H_2 System: set of H_2 production, storage and consumption equipment jointly operated

LCOE: Levelized cost of Energy

LCOS: Levelized cost of storage

LCOH2: Levelized cost of hydrogen

M€: Million (10^6) euros

Nm^3: Normal cubic meter

MTBF: Mean Time Between Failure

MTTR: Mean Time To Repair

NPV: Net present value

OPEX: Operational expenditures

P: Active Power

PCC: Power Connection Point (refer to the Hydrogen system)

P_n: Rated Power or nominal Power

PEM: Proton Exchange Membrane

PV: Present value

Q: Reactive Power

RES: Renewable energy system

ROI: Remaining useful life

TBD: To be defined

TOT: Time of Test or Test duration

WF: Wind Farm

2 Introduction

2.1 HAEOLUs project

HAEOLUS [1] is an EU co-funded project which aim is the integration of a new-generation 2.5 MW PEM electrolyser in a 45 MW wind farm. The project will demonstrate different control strategies to enhance the techno-economic performance of the system.

The Raggovidda wind farm is located in a remote area of Norway, the Varanger peninsula, at approximately 400 m above sea level and 30 km south of Berlevåg. The Raggovidda wind farm owner, Varanger Kraft, has a granted concession of 200 MW, but only 45 MW of capacity have been built due to limitations in the grid export capacity. Steady winds result in high capacity factors of about 50% that built capacity. Raggovidda wind farm produced just short of 200 GWh in 2015.

One of the most relevant activities that has to be carried out as part of the development of the HAEOLUS project is the validation and demonstration of the wind-electrolyser facility, which should produce 120 tons of H_2 during a 2.5 years demonstration period according to the project commitments. To this aim three different use cases are considered (HAEOLUS Grant Agreement, task 6.2):

- Energy-storage to improve the integration of Raggovidda wind farm with the utility grid:
  This use case consists on the operation of an electrolyser and in some cases also a fuel cell to improve the integration of variable energy sources as a wind farm. This use case may include specific operation strategies as price arbitrage or frequency regulation among others;

- Hydrogen production:
  This use case basically consists on the production of hydrogen through electrolysis within the wind farm, as a fuel for other uses out of the wind farm as transportation or industrial applications;

- Mini-grid:
  This use case is related on the operation of a hydrogen system to support isolated or weak connected grids, as for example in islands.

The HAEOLUS project impact is expected to be relevant for the following aspects:

- The wind farm is in a sub-grid with limited export capacity (95 MW at Varanger) compared to its full concession of 200 MW;
- Storing excess energy as hydrogen will help reduce uncertainty in wind power production, which is much larger than total consumption in the Varanger peninsula (relatively small uncertainties can destabilise the grid);
- In the long term, Varanger Kraft is strategically interested in exploiting their full wind power potential by producing and exporting hydrogen in large scale.

2.2 Test protocols

In order to provide a guideline for field test and demonstration of the operation of a 2.5 MW PEM electrolyser in coordination with the Raggovidda wind farm, test protocols for each of the aforementioned corresponding use cases will be developed. Particularly, in this document the test protocols for the energy-storage use case are reported.

The test protocols shall not be used to provide a detailed characterization, evaluation or factory acceptance tests of the electrolyser but to assess the performance of a wind-electrolyser facility operated under different control strategies. Moreover, their final implementation may slightly vary during the demonstration project phase according to the final operating conditions (room conditions, components setup, etc.), local H_2 consumption profiles or H_2 vending possibilities, among other aspects. Any deviation with respect to what stated in the present document will be reported in the deliverable D8.5 along with the test and demonstration results.

This set of protocols in D8.1 will be completed with D8.2 [7] and D8.3 [8] that will specify the test protocols for the demonstration of the other two use cases, the Mini-grid and the Fuel-production use cases respectively.

2.3 Energy-storage Use Case

The energy-storage use case is related to the operation of the hydrogen system for improving the grid integration of the Raggovidda wind farm [14] within the grid. To this aim, the electrolyser intends to produce H_2 at the lowest possible cost according to a certain demand.

The energy-storage use case is very relevant to the industry because while in general electrolysers are designed to operate continuously at their nominal capacity, in HAEOLUS the electrolyser will operate at variable power according to the wind farm integration requirements and the several energy markets signals.

As it has been reported in D5.1 [2], the following three operation strategies are considered under the so-called energy-storage use case, namely *congestion management*, *price arbitrage* and *frequency regulation*.

Congestion management

This operation strategy basically consists in producing hydrogen when the wind farm generation exceeds the power limit at the connection point, due to either administrative or physical constraints. Thus, the electrolyser would produce hydrogen with the energy surplus generated in the wind farm, energy that, otherwise, would be wasted. In case the hydrogen system includes also a fuel cell, the hydrogen can be re-electrified whenever the wind farm power generation is below the export limit. The main technical requirements to be met in order to achieve the congestion management operation strategy are reported in Table 1.

Table 1. Congestion management operation strategy. Technical requirements.

Congestion Management technical requirements			
Response time	**Ramp rate**	**Duration**	**Market schedule**
< 1 min	Not relevant	1 hour	According to daily (Day D-1) and intraday markets

Price arbitrage

This operation strategy consists in storing energy as hydrogen when the energy market price is low and in the subsequent re-electrification when the energy market price is high. In case the system only includes an electrolyser, as analysed in D5.1, the aim of this operation strategy would be the production of hydrogen at the minimum possible cost. Table 2 shows the main technical requirements needed for achieving price arbitraging.

Table 2. Price arbitrage operation strategy. Technical requirements.

Price arbitrage technical requirements			
Response time	**Ramp rate**	**Duration**	**Market schedule**
Minutes (*)	Not relevant	1-4 hours (typical 1-hour signal prices)	According to daily and intraday markets

(*) As the electrolyser is operated within the wind farm, depending on the specific market or product the electrolyser may have to compensate the fluctuations of the wind farm, thus the required response time is much lower than if the electrolyser is directly operated in the spot market as a demand response asset.

Frequency regulation

Frequency regulation is related to active power regulation (up/down) for balancing the system frequency, which can vary due to the generation and consumption conditions of the energy resources connected to the grid. Frequency regulation is usually organized in several levels of power regulation at different time-scales. Within the scope of the HAEOLUS project (D5.2, D5.3 and demonstration activities), the frequency regulation operation strategy is related to the FCR (Frequency Containment Reserves, also called primary regulation) and FFR-a (Frequency Restoration Reserves, also called secondary regulation), which are the levels that are generally more attractive for storage and demand response assets. Figure 1 shows the different frequency regulation levels with the corresponding time-scale where they are achieved.

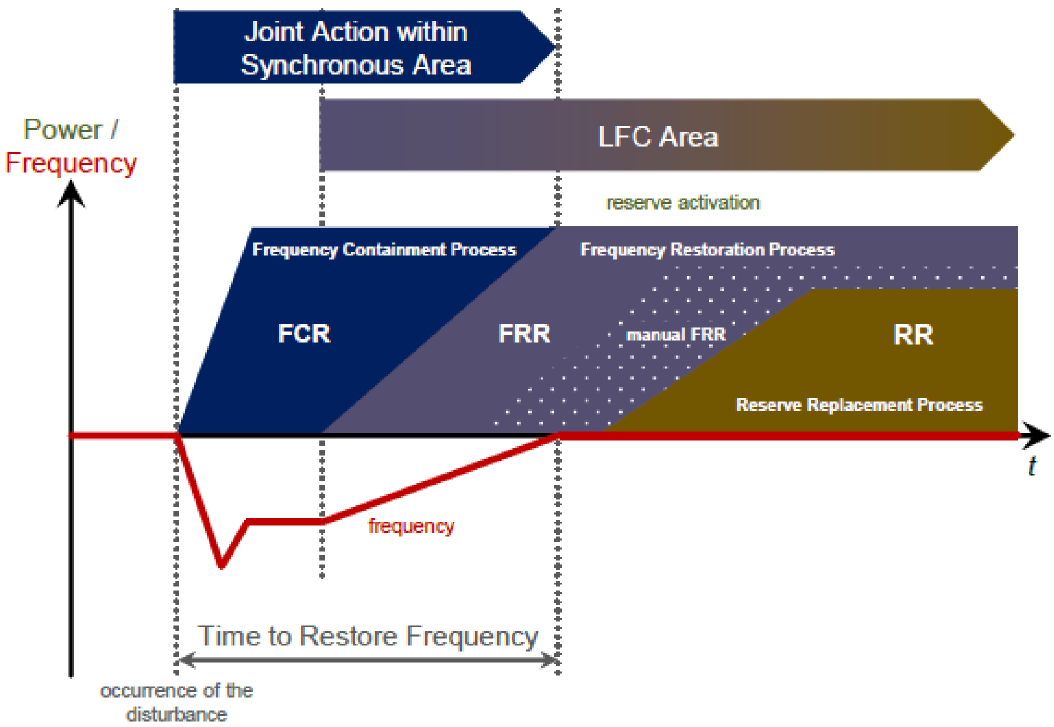

Figure 1. Dynamic hierarchy of Load-Frequency Control processes [3].

The report "D1.1 Electrical Grid Service Catalogue for Water Electrolyser" [4] from QualyGrids H2020 funded project, reviews the requirements for frequency regulation and balancing services in different countries, including Norway and Spain that are also considered in D5.1 and D5.2. Table 3 shows the main technical requirements for operations according to this strategy.

Table 3. Frequency regulation operation strategy. Technical requirements.

Frequency regulation				
Service	**Response time**	**Ramp rate**	**Duration**	**Market schedule**
aFRR Norway	120-210 s	Set-point in 120s (or 210s)	≤30min	Weekly auction
aFRR Spain	≤100s	Set-point in100 s	≤ 15 min (1)	Day D-1 for the 24 hours of day D

(1) In practice 1 hour of duration which is the minimum bidding time could be required

It is important to highlight that the requirements reported in Table 3 and the related market rules may change from one country to another. With respect this issue, the new 2019/943 Regulation of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity [9] has to be considered in the near future with respect the European energy market harmonization. This regulation establishes the new rules the member states should apply for the energy market, including the daily and intraday markets and balancing services among others. This regulation paves the way for the participation of energy storage systems in the energy market which provides a relevant business opportunity to the HAEOLUS energy-storage use case in this regulation market.

2.4 Structure of the document

Following the previous brief introduction to the HAOELUS project and description of the considered use cases, this report is organized as follows:

- Chapter 3 describes the Raggovidda wind-hydrogen system and the identification of the main parameters and variables.
- Chapter 4 includes the tests protocols, namely:
    - On-site tests protocol for the electrolyser and the fuel cell.
    - On-site test protocols for the three operation strategies of the energy-storage use case.
    - On-site demonstration protocols for three operation strategies.
- Chapter 5 provides some risk considerations related to the defined tests.

The document ends with the references used in chapter 6 and the Annex 1 including the parameter calculations to be applied in the tests.

3 Raggovidda wind-hydrogen facility description:

Figure 2 depicts the layout of the Raggovidda wind-hydrogen system along with its main components. The Raggovidda wind-hydrogen system will be realized by adding to the current 45 MW Raggovidda wind farm a 2.5 MW PEM electrolyser, a 120 kW PEM fuel cell (limited to 100 kW due to regulatory limitations in the PCC) and a stain steel storage tank of 65 m^3.

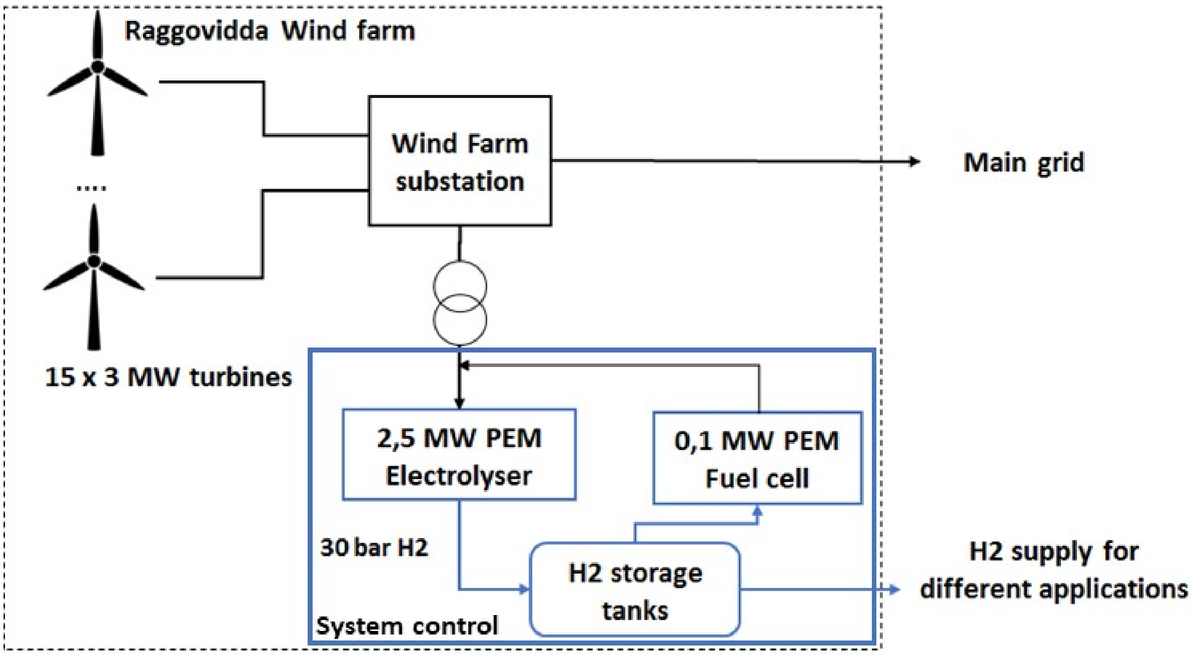

Figure 2. Conceptual layout of the Raggovidda wind-hydrogen system.

The electrolyser will generate hydrogen according to the different three uses cases introduced in Section 2.1. However, the use and exploitation of the hydrogen produced in Raggovidda beyond the project is currently under analysis as part of WP3 of the HAEOLUS project.

The PEM fuel cell will be used to re-electrify the produced hydrogen while other local markets for hydrogen are developed. This fuel cell was manufactured by HYDROGENICS as part of INGRID (www.ingridproject.eu) EU cofounded project. The fuel cell will also be used for testing some of the mentioned use cases and their possible operation strategies.

The stain steel storage tank can withstand input hydrogen flows at 30 bars. This facility does not include any hydrogen compressor.

A control framework will be provided for the monitoring and operation the hydrogen system connected to the wind farm at both levels, globally and at each of the hydrogen system components.

Due to logistic aspects the electrolyser and the fuel cell will be installed in the harbour of the nearby village of Berlevåg, along with the deployment of a power link that directly connects with the wind farm.

In case of the energy-storage use case, the hydrogen system could have two possible configurations:

- Wind farm with the electrolyser operated under a demand response scheme. The hydrogen would be intended for other uses out of the wind farm. These are the main reference configuration and operation strategy that will be tested under HAEOLUS project with the 2.5 MW PEM electrolyser.
- Wind farm with the electrolyser and the fuel cell. In this case the produced hydrogen could also be used for re-electrifications by means of the fuel cell. As the fuel cell power (100 kW) is well below the electrolyser one (2.5 MW), the operation strategies with this architecture will be evaluated in a limited way. Additionally, re-electrification of hydrogen is only economically justified for few niche applications, due to the low cycle efficiency of the hydrogen storage system.

The following sections provide specific information of the Raggovidda facility which are relevant for the definition of the test protocols. This information by components is structured, when relevant, into the component characteristics (Table 4, Table 6 and Table 8), the reference to check the behaviour of the component (Figure 3 and Figure 4) and the component parameters to be monitored (Table 5, Table 7, Table 9, Table 10 and Table 11).

3.1 Raggovidda Wind Farm

Table 4 summarises the global parameter values regarding the Raggovidda wind farm as provided by Varanger Kraft [2].

Table 4. General information regarding the wind farm.

Raggovidda Wind Farm	
Parameter	**Value**
Nominal power	45 MW
Number of wind turbines	15
Turbine nominal power	3 MW
Connection point export power	45 MW
CAPEX	900 €/kW
OPEX	40 €/kW per year

It is important to highlight that the wind farm CAPEX and OPEX reported in Table 4 are just estimates depending on the current technology state-of-the-art and on the available market data.

Table 5. Wind Farm monitorable parameters and variables.

Variable	Units	Measurement devices
Instant Active Power	MW	Power analyser
Mean, Median, Mode Active Power (P)	MW	Power analyser
Instant Reactive Power	MVAr	Power analyser
Mean, Median, Mode Reactive Power (Q)	MVAr	Power analyser
Energy produced by the wind farm	MWh	Power analyser
Energy fed to the grid by the wind farm	MWh	Power analyser
Wind farm status: Connected/Disconnected	----	WF SCADA

3.2 2.5 MW PEM electrolyser

Table 6. 2.5MW Hydrogenic electrolyser PEM data.

2.5 MW PEM Electrolyser	
Parameter	**Value**
Nominal Power	2.5 MW
Minimum Power	0.3 MW
Maximum Power	3.25 MW
Efficiency	see Figure 3
Efficiency degradation at rated power and considering 8000 h operations / year	2 %/year
Hydrogen delivery pressure	30 bar
Hydrogen production rate	45 kg/hour
Start-up time (cold start)	1,200 seconds
Response time (warm start)	30 seconds
Shut down time	1 seconds
Ramp rate up/down	60 MW/min
Standby consumption	1 kW
Calendar life	20 Years
Cycle life	5,000 on/off cycles
	40,000 operation hours
CAPEX-electrolyser	1328 €/kW
OPEX per installed MW	60 €/MW year
Overhaul costs (*)	354 €/kW

(*) Overhaul cost are mainly related to the stack replacement.

Figure 3 will be taken as the reference for the definition of the electrolyser efficiency parameters.

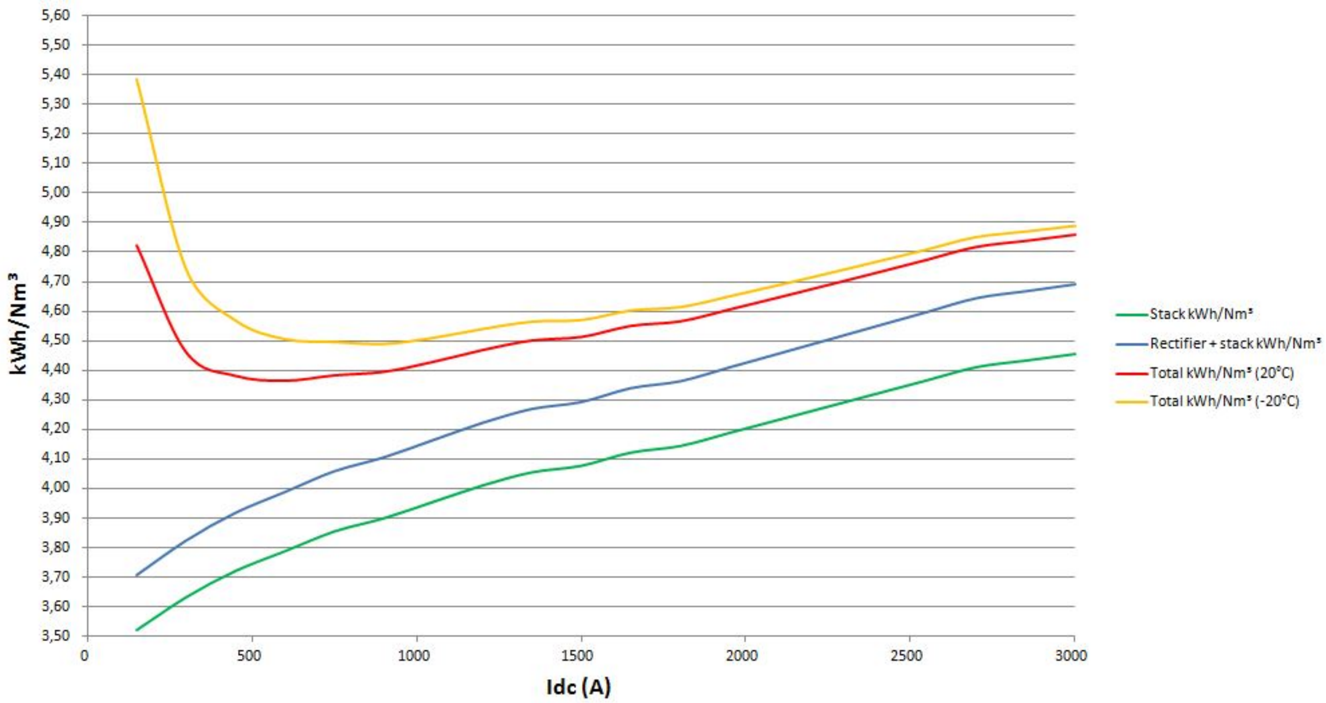

Figure 3. Electrolyser efficiency curves.

Table 7. Electrolyser monitorable parameters and variables.

2.5 MW Electrolyser parameters and variables		
Variable	**Units**	**Measurement devices**
Instant Active Power	MW	ELY / Power analyser
Mean, Median, Mode Active Power (P)	MW	ELY / Calculation
Instant Reactive Power	MVAr	ELY / Power analyser
Mean, Median, Mode Reactive Power (Q)	MVAr	ELY / Calculation
Instant Active Power Auxiliaries	MW	Power analyser
Energy consumed by the electrolyser	MWh	ELY / Calculation
Energy consumption in Standby	MWh	ELY / Calculation
Instant Power consumed by auxiliaries	MW	ELY & Power Analyser
Energy consumption by auxiliaries	MWh	P Analyser / Calculation
Water consumed by the electrolyser	Litres	ELY
H_2 production flow	kg/h	ELY
H_2 produced	Kg	ELY / Calculation
Efficiency curve for the production range	%	Calculation
Mean H_2 production efficiency	%	Calculation
Operating pressure	bar	ELY
Operating temperature	C	TBD
Total number of working hours	Hours	ELY
Hours OFF	Hours	ELY
Hours ON	Hours	ELY
Hours STANDBY	Hours	ELY
Remaining useful life (ROI)	Hours	Calculation
Number of OFF/ON transitions or cold starts	number	ELY

2.5 MW Electrolyser parameters and variables		
Variable	**Units**	**Measurement devices**
Number of STANBY/ON transitions or hot starts	number	ELY
H_2 purity (TBD how to measure it)	%	ELY
Other consumables (filters, etc)	---	---
Alarms	---	ELY

3.3 Fuel cell

In Table 8 the relevant parameter regarding the 120 kW PEM fuel cell by Hydrogenics are reported.

Table 8. Hydrogenics 120 kW PEM fuel cell data.

120 kW PEM Fuel Cell	
Parameter	**Value**
Nominal Power	120 kW (limited to 100 kW)
Minimum Power	12 kW (10%)
Maximum Power	132 kW (limited to 100 kW)
Efficiency	See graph
Peak Efficiency	50 %
Hydrogen consumption rate	9 kg/hour
Response time (warm start)	300 seconds
Warms start time	<5 seconds
Ramp rate up/down	<3 seconds to full power

In order to provide a comprehensive picture of the relevant parameters of the fuel cell provided by Hydrogenics, in Figure 3 are reported the fuel cell efficiency curves with respect to voltages and net currents.

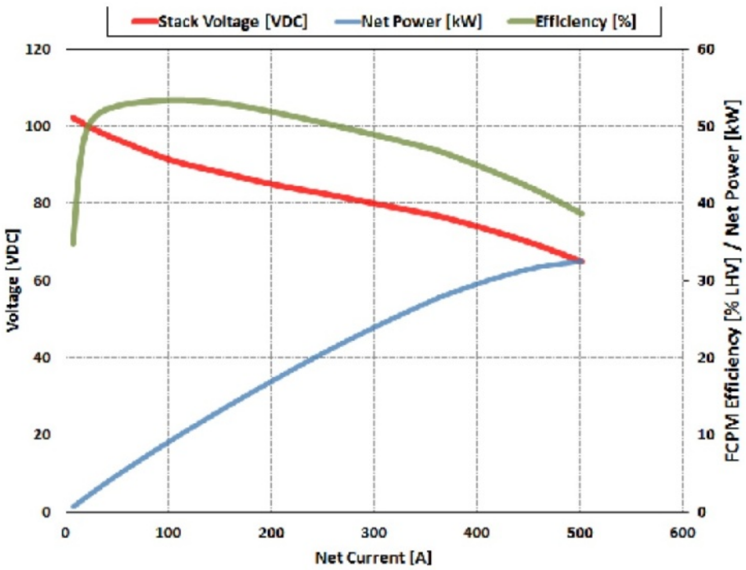

Figure 4. Fuel cell efficiency curves.

Table 9. Fuel cell monitorable parameters and variables.

Fuel cell parameters and variables		
Variable	**Units**	**Measurement devices**
Instant Active Power	MW	FC / Power analyser
Mean, Median, Mode Active Power (P)	MW	FC / Calculation
Instant Reactive Power	MVAr	FC
Mean, Median, Mode Reactive Power (Q)	MVAr	FC / Calculation
Energy produced by the FC	MWh	FC / Calculation
Energy Consumption in Standby	MWh	FC / Calculation
Auxiliaries energy consumption	MWh	FC
H_2 consumption flow	kg/h	FC
H_2 consumed	kg	FC / Calculation
Efficiency curve for the power range	%	Calculation
Mean power production efficiency	%	Calculation
Operating temperature	C	FC
Total number of working hours	Hours	FC
Hours OFF	Hours	FC
Hours ON	Hours	FC
Hours STANDBY	Hours	FC
Remaining useful life (ROI)	hours	Calculation
Number of OFF/ON transitions or cold starts	Number	FC
Number of STANBY/ON transitions or hot starts	Number	FC
Other consumables (filters, etc)	---	
Alarms	---	FC

3.4 Hydrogen storage tank

Table 10. Hydrogen tank monitorable parameters and variables.

Hydrogen storage tank variables and parameters		
Variable	**Units**	**Measurement devices**
H_2 in flow	kg/h	Tank flow meter
H_2 out flow to Fuel cell	kg/h	Tank flow meter
H_2 out flow to other uses	kg/h	Tank flow meter
H_2 out flow vented	kg/h	Tank flow meter
Tank Instant Pressure	Bar	Tank pressure meter
Mean, Median, Mode tanks pressure	Bar	Calculation
Tank temperature	C	Tank temperature meter
Alarms	---	TBD

3.5 Overall facility and controller

Finally, the following in Table 11 gathers those observable parameters related to the Control System, the power connection taken to power the system and the site conditions.

Table 11. Overall system and controller monitorable parameters and variables.

Overall facility and controller		
Variable	**Units**	**Measurement devices**
Electrolyser Active Power setpoint	MW	Controller
Electrolyser Reactive Power setpoint	MVA	Controller
ELY status setpoint (OFF, ON, STANDBY)	---	Controller
FC Active Power setpoint	MW	Controller
FC Reactive Power setpoint	MVA	Controller
FC status setpoint (OFF, ON, STANDBY)	---	Controller
Room Temperature setpoint (if any)	C	Controller
Voltage at connection point	V	Power Analyser
Frequency at connection point	Hz	Power Analyser
Room temperature	C	TBD
Auxiliaries consumption	MW	Power Analyser
Alarms	---	TBD

4 Test protocols

4.1 Functional test of the main controller

In this section the operational features of the main controller that must be verified before starting the test and demonstration activity are defined.

Table 12 shows the items to be verified on the Systems Controller.

Table 12. Test T1: Systems Controller functional tests.

Test T1: Systems Controller functional tests	
Objective: To test the communication links between the main controller, the SCADA and the elements.	
Item to verify	**State**
Communication with the electrolyser: • Parameters monitoring • State control (ON, OFF, STANDBY) • Power set point	OK/NOK
Communication with the fuel cell: • Parameters monitoring • State control (ON, OFF, STANDBY) • Power set point	OK/NOK
Communication with the hydrogen storage tank controller • Parameters monitoring	OK/NOK
Communication with the wind farm: • Parameters monitoring	OK/NOK
Communication with the TSO or price and balancing signal provider	OK/NOK
Communication with BOP controller (if any)	OK/NOK
Communication with the SCADA	OK/NOK
Monitored data storage	OK/NOK
Cycle time (including control and communications)	Seconds

4.2 On-site functional test of the electrolyser

The following tests shall be used to characterize on-site functional operations of the electrolyser and for crosschecking the obtained results with the electrolyser theoretical characteristics stated in the data sheet. The obtained results should be considered for tuning the controller.

4.2.1 ELY on-site nominal production capacity and efficiency

This test is intended to validate the electrolyser on-site production capacity and efficiency under stationary working conditions and is reported in Table 13.

Table 13. Test T2: ELY on-site nominal production capacity and efficiency.

Test T2: ELY on-site nominal production capacity and efficiency	
Objective: Calculate the ELY onsite efficiency for the whole production range.	
Test Pre-conditions:	
Electrolyser	- OFF

	- Stack temperature at room temperature
Fuel cell	- Not used for this test (OFF)
Tank	- Not relevant, the hydrogen produced during this test maybe either stored or vented
Room temperature	- TBD (within the temperature range of the ELY operation)
Test sequence	
- Start the system (1200 seconds). - Run the electrolyser at 0.3 MW (minimum power) for 1 hour (or the time required to reach the working temperature). - Run the electrolyser from 10 % (minimum is 12%) to 100 % of P_n in steps of 10% for 1 hour (after reaching required power) at each production ratio. - Run the electrolyser from 100% to 10 % of P_n in steps of 10% for 1 hour at each production ratio. - Electrolyser in Standby for 1 hour.	
Test duration:	Start process time (1200 s) + heating (1h) + 9 hours (Production increase) + 9 hours (Production decrease) +

Required Data Recording

Variable	Sampling	Variable	Sampling
ELY Power set point	1 seconds	H_2 quality	10 seconds
ELY Active Power	1 seconds	H_2 flow (Or H_2 production rate)	1 seconds
Auxiliaries consumption (if not considered in the ELY P)	1 seconds	Tank pressure	1 seconds
ELY Reactive Power	1 seconds	Room temperature	1 minute
ELY Stack nominal temperature	1 minute		

Required Calculations

Parameter	Description
ELY capacity	Electrolyser onsite nominal production capacity (H_2 kg/h).
ELY efficiency (curve)	Electrolyser onsite efficiency calculated as the mean efficiency at each power step.
Controller accuracy	Calculated as root-mean-square error between actual response and command for each power step.

4.2.2 ELY on-site hot and cold start

Table 14. Test T3: ELY on-site hot and cold start.

Test T3: ELY on-site hot and cold start			
Objective: Verify ELY cold and hot start duration and consumption.			
Test Pre-conditions:			
Electrolyser	- OFF - Stack temperature at room temperature		
Fuel cell	- Not used for this test (OFF)		
Tank	- Not relevant (store or vend the produced hydrogen)		
Room temperature	- TBD (within the temperature range of the ELY operation)		
Test sequence			
- Start the ELY (1200 seconds) and bring it to Full Power. - Keep the ELY 1 hour in Full Power. - Switch ELY from Full Power to Standby. - Keep the ELY 1 hour in Standby. - Switch ELY from Standby to Full Power. - Keep the ELY 1 hour in Full Power. - Switch ELY from Full Power to OFF.			
Test duration	approximately 3 hours and 20 minutes		
Required Data Recording			
Variable	**Sampling**	**Variable**	**Sampling**
ELY State	1 second	H_2 quality	10 seconds
ELY Power Set point	1 seconds	H_2 flow (Or H_2 production rate)	1 seconds
ELY Active Power	1 seconds	Tank pressure	1 seconds
Auxiliaries consumption	1 seconds	Room temperature	1 minute
P onsite (Overall H_2 system consumption)	1 seconds		
Required Calculations			
Parameter	**Description**		
Cold Start up time	Time to start hydrogen production from OFF.		
Time from Cold Start to Full Power	Time to bring the ELY from OFF to Full Power.		
Time from Full Power to Standby	Time to stop hydrogen production and bring ELY to Standby (If this state transition is faster than 1 second, the time will be fixed to 1 second).		
Hot Start up time	Time to start hydrogen production from Standby.		
Time from Hot Start to Full Power	Time to bring the ELY from Standby to Full Power.		
Time from Full Power to OFF	Time to bring the ELY from Full Power to OFF		

4.2.3 ELY on-site dynamic response

Table 15. Test T4: ELY on-site dynamic response.

Test T4: ELY on-site dynamic response			
Objective: Verify ELY dynamic response to P/Q setpoint, verify the ramp rates and electrolyser control accuracy.			
Test Pre-conditions			
Electrolyser	- Standby - Operate the ELY at 0,3 MW for 1 hour to bring the ELY to nominal operation conditions (stack working temperature)		
Fuel Cell	- Not used for this test (OFF)		
Tank	- Not relevant (store, extract or vent the produced hydrogen)		
Room temperature	- TBD (within the temperature range of the ELY operation)		
Test sequence			
Start: - Electrolyser working at minimum power (0,3 MW) for 1 hour. Test 4.1 - Power Step-change from 12% to 50% of P_n (from 0.3 MW to 1.25 MW). - Power Step-change from 50% to 100% of P_n (from 1.25 MW to 2.5 MW). - Power Step-change from 100% to 50% of P_n (from 2.5 MW to 1.25 MW). - Power Step-change from 50% to 12% of P_n (from 1.25 MW to 0.3 MW). Test 4.2 - Power Step-change from 12% to 100% of P_n (from 0.3 MW to 2.5 MW). - Power Step-change from 100% to 12% of P_n (from 2.5 MW to 0.3 MW). - Put the electrolyser in Standby. Test 4.3 - Power Step-change from Standby to 100 % of P_n (from Standby to 2.5 MW). - Power Step-change from 100 % to 0% of P_n (from 2.5 MW to Standby). General considerations: - Keep the electrolyser working at each set a minimum of 300 seconds or until the error is below ±1 %. - As the electrolyser will be operated as an electric grid asset the set point are provided in power rather than in hydrogen production.			
Test duration	Not relevant (estimated less than 1 hour)		
Required Data Recording			
Variable	**Sampling**	**Variable**	**Sampling**
ELY Active Power Set point	100 ms	ELY Reactive Power set point	100 ms
ELY Active Power	100 ms	ELY Reactive Power	100 ms
Alarms	1 s		
Required Calculations			
Parameter	**Description**		

Response accuracy	Calculated as root-mean-square error between actual response and command.
t_p	Peak power time for each power step change.
t_s	Setting time (time to reach a stable answer with an error below ±1 %).

In order to assess the dynamic response of the electrolyser, the typical parameters of the response of a second-order system will be considered, see Figure 5. Particularly, the active and reactive power P/Q time evolutions following a load transient will be assessed for each one of the use cases reported in Section 2.1 as each one has different dynamic requirements.

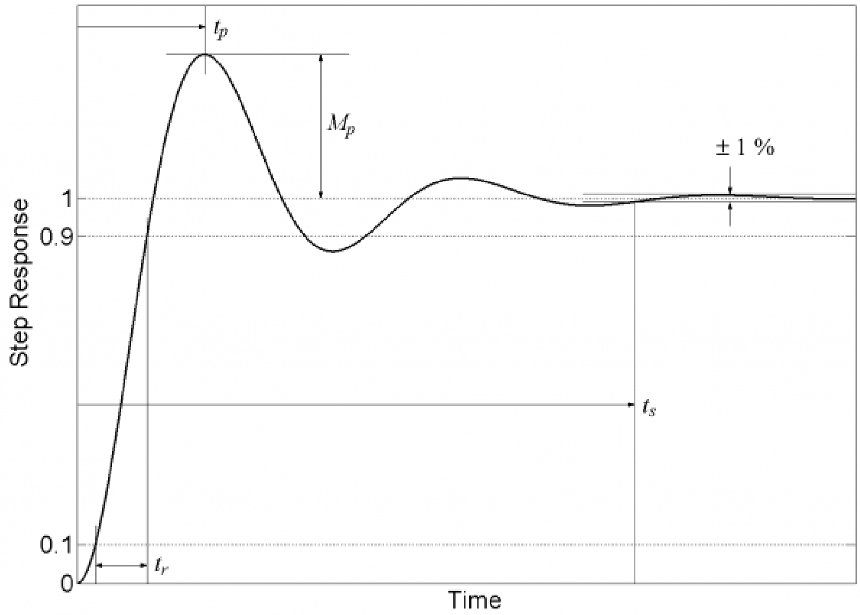

Figure 5. Second order system typical response (just as reference for parameters definition).

4.3 On-site functional test of the fuel cell

These tests are intended to characterize the fuel cell on-site functional operations by crosschecking the obtained results with the theoretical characteristics. The obtained results should be considered for controller tuning.

It must be taken into account that the fuel cell is not a core component of the wind-hydrogen system developed in HAEOLUS and that the fuel cell has been already used in a previous European project (INGRID - http://www.ingridproject.eu/). Moreover, as also reported in Section 3, the fuel cell conversion rate is very small in comparison of that of the electrolyser, resulting in a bottleneck in the energy-hydrogen-energy conversion process, so that the use cases with both elements jointly operated are limited by this factor.

4.3.1 FC on-site nominal production capacity and efficiency

Table 16. Test T5: FC on-site nominal production capacity and efficiency.

Test T5:FC on-site nominal production capacity and efficiency			
Objective: Calculate the FC onsite efficiency for the power range. Carry out the test at the beginning and end of the demonstration tests.			
Test Pre-conditions			
Electrolyser	- Not used for this test (OFF)		
Fuel cell	- OFF		
Tank	- Tank at 30 bar (to be able to run the FC continuously during the test)		
Room temperature	- TBD (within the temperature range of the FC operation)		
Test sequence			
- Start the system (300 seconds). - Run the fuel cell at 12 kW (minimum power) for 1 hour (the time required to reach working temperature). - Run the fuel cell from 10 % (minimum is 12 %) to 100 % of maximum power (120 kW) in steps of 10 kW (12, 20...,120 kW) for 1 hour (after reaching required power) at each power ratio. - Run the fuel cell from 100 % to 10 % of P_n in steps of 10 % for 1 hour at each power ratio.			
Test duration	Start process time (300 s) + heating (1h) +11 hours (Up) + 11 hours (Down)		
Required Data Recording			
Variable	**Sampling**	**Variable**	**Sampling**
FC Active Power	10 seconds	Room temperature	1 minute
Auxiliaries Consumption	10 seconds	Tank pressure	1 seconds
P onsite (Overall consumption)	10 seconds	FC H_2 consumption flow	1 seconds
Required Calculations			
Parameter	**Description**		
FC efficiency (curve)	Fuel cell onsite efficiency calculated as the mean efficiency at each power step.		
Controller accuracy	Calculated as root-mean-square error between actual response and command for each power step.		

4.3.2 FC on-site hot and cold start

Table 17. Test T6: FC on-site hot and cold start.

<table>
<tr><th colspan="4">Test T6: FC on-site hot and cold start</th></tr>
<tr><td colspan="4">Objective: Verify FC cold and hot start duration and consumption.</td></tr>
<tr><td colspan="4">Test Pre-conditions</td></tr>
<tr><td>Electrolyser</td><td colspan="3">- Not used for this test (OFF)</td></tr>
<tr><td>Fuel cell</td><td colspan="3">- OFF (Condition before test start)</td></tr>
<tr><td>Tank</td><td colspan="3">- Tank above 50 % (to be able to run the FC for the test)</td></tr>
<tr><td>Room temperature</td><td colspan="3">- TBD (within the temperature range of the FC operation)</td></tr>
<tr><td colspan="4">Test sequence</td></tr>
<tr><td colspan="4">Cold Start:
- Switch ON the FC and bring it to 100 kW.
- Keep the electrolyser at 100 kW until reaching stack operational temperature.
- Shift from 100 kW power to Standby.
Hot start:
- Shift from Standby to 100 kW.
- Switch OFF the FC.</td></tr>
<tr><td>Test duration:</td><td colspan="3">Non relevant (less than 1 hour)</td></tr>
<tr><td colspan="4">Required Data Recording</td></tr>
<tr><td>Variable</td><td>Sampling</td><td>Variable</td><td>Sampling</td></tr>
<tr><td>FC Active Power</td><td>10 seconds</td><td>Room temperature</td><td>1 minute</td></tr>
<tr><td>Auxiliaries Consumption</td><td>10 seconds</td><td>Tank pressure</td><td>1 seconds</td></tr>
<tr><td>Onsite Active Power (Overall consumption)</td><td>10 seconds</td><td>FC H_2 consumption flow</td><td>1 seconds</td></tr>
<tr><td colspan="4">Required Calculations</td></tr>
<tr><td>Parameter</td><td colspan="3">Description</td></tr>
<tr><td>Cold Start up time</td><td colspan="3">Time to start power production from OFF.</td></tr>
<tr><td>Time to 100kW from Cold Start</td><td colspan="3">Time to bring the FC to 100kW from OFF.</td></tr>
<tr><td>Cold Start Auxiliary consumption</td><td colspan="3">External energy consumed during cold start.</td></tr>
<tr><td>Hot Start up time</td><td colspan="3">Time to start power production from Standby.</td></tr>
<tr><td>Time to 100 kW from Hot Start</td><td colspan="3">Time to bring the FC to 100 kW from Standby.</td></tr>
<tr><td>Hot Start Auxiliary consumption</td><td colspan="3">External energy consumed during hold start.</td></tr>
</table>

4.3.3 FC on-site dynamic response

Table 18. Test T7: FC on-site dynamic response.

Test T7: FC on-site dynamic response			
Objective: Verify FC dynamic response to P/Q setpoint.			
Test Pre-conditions			
Electrolyser	- Not used for this test (OFF)		
Fuel Cell	- Operate the Fc at 12 kW for 1 hour to bring the FC to nominal operation conditions		
Tank	- Tank above 50 % (to be able to run the FC for the test)		
Room temperature	- TBD (within the temperature range of the FC operation)		
Test sequence			
- Fuel cell working at minimum power (12 kW) for 1 hour Test 7.1 - Power Step-change from 12 kW to 50 kW. - Power Step-change from 50 kW to 100 kW. - Power Step-change from 100 kW to 50 kW. - Power Step-change from 50 kW to 12 kW. Test 7.2 - Power Step-change from 12 kW to 100 kW. - Power Step-change from 100 kW to 12 kW. - Put the FC in Standby. Test 7.3 - Power Step-change from Standby to 83 % of P_n (from Standby to 100 kW). - Power Step-change from 83 % to 0% of P_n (from 100 kW to Standby). General considerations: - Keep the electrolyser working at each set a minimum of 300 seconds or until the error is below ±1 %.			
Test duration:	Not relevant (FC power must be stable before applying any power step)		
Required Data Recording			
Variable	**Sampling**	**Variable**	**Sampling**
FC Active Power Set point	1 second	FC Reactive Power set point	1 second
FC Active Power	1 second	FC Reactive Power	1 second
Alarms	1 second		
Required Calculations			
Parameter	**Description**		
Response accuracy	Calculated as root-mean-square error between actual response and command.		
t_p	Peak power time for each power step change.		
t_s	Setting time (time to reach a stable answer with an error below ±1 %).		

With the obtained results it must be verified that the dynamic response of the fuel cell fits with that required in the relevant uses cases (i.e., price arbitrage and congestion management).

4.4 Field test protocols

This set of protocols is intended to verify the correct operation of the electrolyser for each of the three operation strategies defined for the energy-storage use case. The protocols refer to two main stages that are the test stage and the demonstration stage. The test stage is intended to validate the correct operation of the control algorithms and the hydrogen installation, while demonstration stage is intended to evaluate the techno-economic performance of the energy-storage use case throughout a long period of time. Please note that these tests shall not be used in order to analyse the control algorithms in depth (i.e. the detailed tests on the software development) but in order to evaluate their performance with respect to the defined economic expectation [5] [6].

Table 19. Test T8: Energy-storage Use case – Price Arbitrage.

Test T8: Energy-storage Use case – Price Arbitrage	
Objective: Verify the correct operation of the hydrogen system under price arbitrage use case	
Test Pre-conditions	
Electrolyser	- OFF
Fuel Cell	- OFF
Tank	- Empty Tank
Room temperature	- TBD (within the temperature range of the hydrogen system operation)
Test sequence	
T8.1: H_2 systems constituted only by the electrolyser: - Previously required test: T1, T2, T3 and T4 (Price arbitrage algorithms should be tuned according to test results). - Verify main aspect of the price arbitrage algorithm: o There is access to Wind farm and PCC Power measurements. o There is access to energy price signals for the next hours (either via communication with the TSO or through a database). o Verify that price thresholds for electrolyser activation are defined and that it will be activated unless for 1 hour. - Run the test for 24 hours period. - Switch OFF the electrolyser after the test. - Electrolyser Reactive Power Set Point will be kept at zero during the whole test duration. - The fuel cell will be kept in OFF state during the whole test duration. T8.2: H_2 systems constituted only by the electrolyser: - Previously required test: T1, T2, T3, T4, T5, T6, T7 and T8 (Price arbitrage algorithms should be tuned according to test results). - Verify main aspect of the price arbitrage algorithm: o There is access to Wind farm and PCC Power measurements. o There is access to energy price signals for the next hours (either via communication with the TSO or through a database). o Verify that price thresholds for electrolyser activation are defined and that it will be activated unless for 1 hour. o Verify that price thresholds for fuel cell activation are defined and that it will be activated unless for 1 hour (the activation of the fuel cell should be after the activation of the electrolyser so that there is hydrogen in the tank). - Run the test for 24 hours period.	

- Switch OFF the electrolyser and the fuel cell after the test.
- Electrolyser and Fuel Cell Reactive Power Set Point will be kept at zero during the whole test duration.

Test duration	24 hours (shorter periods are also possible)

Required Data Recording

Variable	Sampling	Variable	Sampling
ELY State	10 seconds	ELY Reactive Power	10 seconds
ELY Active Power Set point	10 seconds	H_2 quality	10 seconds
ELY Active Power	10 seconds	ELY H_2 flow	10 seconds
ELY Reactive Power Set point	10 seconds	ELY Alarms	1 second
FC state	10 seconds	FC Reactive Power	10 seconds
FC Active Power Set point	10 seconds	FC H_2 consumption flow	10 seconds
FC Active Power	10 seconds	FC Alarms	1 second
FC Reactive Power set point	10 seconds		
Tanks pressure	10 seconds	Room temperature	10 seconds
Active Power in the PCC	10 seconds	WF active Power	10 seconds

Required Calculations

Parameter	Parameter
Total Energy consumed by ELY	H_2 Consumed by FC
Cost of Energy consumed by ELY	Total Energy consumed by Auxiliaries
Hydrogen Produced by ELY	Total Energy produced by the WF
Total Energy produced by FC	Total Energy exchanged in the PCC
Income of Energy produced by FC	

Required Verifications

Verify that the total Energy exchanged in the PCC is the sum of FC, ELY and auxiliaries' total energy.
Verify that that the Sum of Wind Power and Power in the PCC is never negative, this means that there is no net power consumption
Verify that the hydrogen tank pressure is in accordance with ELY and FC hydrogen production and consumption.
Verify that the ELY was activated at the lowest price hours.
Verify that the FC was activated at the highest price hours.

Table 20. Test T9: Energy-storage Use case – Congestions Management.

Test T9: Energy-storage Use case – Congestions Management			
Objective: Verify the correct operation of the hydrogen system under congestion management use case.			
Test Pre-conditions			
Electrolyser	- OFF		
Fuel Cell	- OFF		
Tank	- Empty Tank		
Room temperature	- TBD (within the temperature range of the hydrogen system operation)		
Test sequence			
T9.1: H_2 systems constituted only by the electrolyser: - Previously required test: T1, T2, T3 and T4 (Congestion Management algorithm should be tuned according to test results). - Verify main aspect of the congestion management algorithm: o There is access to Wind farm and PCC Power measurements. o A power production limit has been defined (virtual limit as now a days there is not a real limit). - Run the test for 24 hours period, assuring that the wind power overpasses the selected limited. - Switch OFF the electrolyser after the test. - Electrolyser Reactive Power Set Point will be kept at zero during the whole test duration. - The fuel cell will be kept in OFF state during the whole test duration. T9.2: H_2 systems constituted only by the electrolyser: - Previously required test: T1, T2, T3, T4, T5, T6, T7 and T8 (Congestion Management algorithm should be tuned according to test results). - Verify main aspect of the congestion management algorithm: o There is access to Wind farm and PCC Power measurements. o A power production limit has been defined (virtual limit as now a days there is not a real limit). - Run the test for 24 hours period, assuring that the wind power overpasses the selected limited. - Switch OFF the electrolyser and the fuel cell after the test. - Electrolyser and Fuel Cell Reactive Power Set Point will be kept at zero during the whole test duration..			
Test duration	24 hours (shorter periods are also possible)		
Required Data Recording			
Variable	**Sampling**	**Variable**	**Sampling**
ELY State	10 seconds	ELY Reactive Power	10 seconds
ELY Active Power Set point	10 seconds	H_2 quality	10 seconds
ELY Active Power	10 seconds	ELY H_2 flow	10 seconds
ELY Reactive Power Set point	10 seconds	ELY Alarms	1 second
FC state	10 seconds	FC Reactive Power	10 seconds
FC Active Power Set point	10 seconds	FC H_2 consumption flow	10 seconds
FC Active Power	10 seconds	FC Alarms	1 second

FC Reactive Power set point	10 seconds		
Tanks pressure	10 second	Room temperature	10 second
Active Power in the PCC	10 seconds	WF active Power	10 seconds
Required Calculations			
Parameter		**Parameter**	
Total Energy consumed by ELY		H_2 Consumed by FC	
Cost of Energy consumed by ELY		Total Energy consumed by Auxiliaries	
Hydrogen Produced by ELY		Total Energy produced by the Wind Farm	
Total Energy produced by FC		Total Energy exchanged in the PCC	
Income of Energy produced by FC			
Required Verifications			
Verify that the total Energy exchanged in the PCC is the sum of FC, ELY and auxiliaries' total energy.			
Verify that that the Sum of Wind Power and Power in the PCC is never negative and is never above the established export limit.			
Verify that the H_2 tank pressure is in accordance with ELY and FC H_2 production and consumption.			
Verify that the ELY was only activated when the Wind Farm was above the limit.			
Verify that the FC was only activated when the Wind Farm was below the limit.			

Table 21. Test T10: Energy-storage Use case – Frequency Regulation.

Test T10: Energy-storage Use case – Frequency Regulation			
Objective: Verify the correct operation of the hydrogen system under frequency regulation use case.			
Test Pre-conditions			
Electrolyser	- Standby		
Fuel Cell	- OFF (not used in this use case)		
Tank	- Empty Tank		
Room temperature	- TBD (within the temperature range of the hydrogen system operation)		
Test sequence			
- Previously required test: T1, T2, T3 and T4 (Frequency regulation algorithms should be tuned according to test results). - Verify main aspect of the frequency regulation algorithm: o There is access to Wind farm and PCC Power measurements. o There is access to AGC or frequency signals. o A Power/frequency curve or answer to AGC signal algorithm has been defined. o If there is no access to the frequency signal is to create a 24 hours power profile typical of frequency regulation services. See also for example the prequalification profiles identified in [4]. - Run the test for the test period (24 hours or less depending on the selected profile). - Electrolyser Reactive Power Set Point will be kept at zero during the whole test duration - The fuel cell will be kept in OFF state during the whole test duration.			
Test duration	24 hours (shorter periods are also possible)		
equired Data Recording			
Variable	**Sampling**	**Variable**	**Sampling**
ELY State	1 second	ELY Reactive Power	1 second
ELY Active Power Set point	1 second	H_2 quality	1 second
ELY Active Power	1 second	ELY H_2 flow	1 second
ELY Reactive Power Set point	1 second	ELY Alarms	1 second
Tanks pressure	1 second	AGC or frequency signal	1 second
Active Power in the PCC	1 second	Room temperature	1 second
WF Active Power	1 second		
Required Calculations			
Parameter		**Parameter**	
Total Energy consumed by ELY		ELY Answer Instant Error (1s)	
Total Energy consumed by Auxiliaries		Total Energy produced by the Wind Farm	
H_2 Produced by ELY		Total Energy exchanged in the PCC	
Required Verifications			
Verify that the total Energy exchanged in the PCC is the sum of ELY and auxiliaries' total energy.			
Verify that the electrolyser active power varies with the frequency signal.			
Verify that that ELY instant error is below the maximum allowable error.			

4.5 Field demonstration protocols

As commented before, the demonstration protocols are intended to evaluate the operation of the hydrogen system for an extended period. Some of the use cases may not make sense currently at demonstration stage. For example there are not congestions in the wind farm, or it will probably not be possible to participate into the frequency regulation markets. In any case, demonstration protocols are provided for the three uses cases.

Table 22. Demonstration Test T11: Energy-storage Use case – Price Arbitrage.

Demonstration Test T11: Energy-storage Use case – Price Arbitrage			
Objective: Verify the correct operation of the hydrogen system under price arbitrage use case.			
Test Pre-conditions			
Electrolyser	- OFF		
Fuel Cell	- OFF.		
Tank	- Empty Tank		
Test sequence			
T11.1: H_2 systems constituted only by the electrolyser: - Previously required test: T8.1. - Before starting this demonstration test, carry out Test T2 to assess electrolyser efficiency. - Run the system for XX months (2.5 years of whole demonstration phase duration). - After the end of the demonstration phase or periodically carry out again test T2 to assess the ELY efficiency degradation. - Electrolyser Reactive Power Set Point will be kept at zero during the whole test duration. - The fuel cell will be kept in OFF state during the whole test duration. T11.2: H_2 systems constituted only by the electrolyser: - Previously required test: T8.2. - Before starting this demonstration test, carry out Test T2 and T5 to assess electrolyser and fuel cell efficiency. - Run the system for XX months (2.5 years of whole demonstration phase duration). - After the end of the demonstration phase or periodically carry out again tests T2 and T5 to assess ELY and FC efficiency degradation. - Electrolyser and fuel cell Reactive Power Set Point will be kept at zero during the whole test duration.			
Test duration	>xx months		
Required Data Recording			
Variable	**Sampling**	**Variable**	**Sampling**
ELY State	10 seconds	ELY Reactive Power	10 seconds
ELY Active Power Set point	10 seconds	H_2 quality	10 seconds
ELY Active Power	10 seconds	ELY H_2 flow	10 seconds
ELY Reactive Power Set point	10 seconds	ELY Alarms	1 second
FC state	10 seconds	FC Reactive Power	10 seconds
FC Active Power Set point	10 seconds	FC H_2 consumption flow	10 seconds
FC Active Power	10 seconds	FC Alarms	1 second
FC Reactive Power set point	10 seconds		
Tanks pressure	10 seconds	Room temperature	10 seconds

Active Power in the PCC	10 seconds	WF Active Power	10 seconds
Required Calculations			
Parameter		**Parameter**	
Total Energy consumed by ELY		Total Energy produced by FC	
Cost of Energy consumed by ELY		Income for Energy produced by FC	
Total hydrogen Produced by ELY		Total hydrogen Consumed by FC	
ELY Mean, Median, Mode Active Power		FC Mean, Median, Mode Active Power	
ELY mean hydrogen production rate		FC mean hydrogen consumption rate	
Ely mean H_2 quality		FCY efficiency degradation	
ELY efficiency degradation		FC total number of working hours	
ELY total number of working hours		FC OPEX during the demonstration	
ELY OPEX during the demonstration		FC ROI	
ELY ROI		FC MTBF	
ELY MTBF		Water consumption	
Total Energy exchanged in the PCC		Total Energy produced by the WF	
Total Energy consumed by Auxiliaries		Total Income for the Energy of the WF	
NPV of the H_2system		LCOH2	

Table 23. Demonstration Test T12: Energy-storage Use case - Congestions Management.

Demonstration Test T12: Energy-storage Use case - Congestions Management			
Objective: Verify the correct operation of the hydrogen system under congestion management use case.			
Test Pre-conditions			
Electrolyser	- OFF		
Fuel Cell	- OFF		
Tank	- Empty Tank		
Test sequence			
T12.1: H_2 systems constituted only by the electrolyser: - Previously required test: T9.1. - Before starting the demonstration, phase carry out Test T2 to assess electrolyser efficiency. - Run the system for XX months (2.5 years of whole demonstration phase duration). - After the end of the demonstration phase or periodically carry out again test T2 to assess the ELY efficiency degradation. - Electrolyser Reactive Power Set Point will be kept at zero during the whole test duration. - The fuel cell will be kept in OFF state during the whole test duration. T12.2: H_2 systems constituted only by the electrolyser: - Previously required test: T9.2. - Before starting the demonstration, phase carry out Test T2 and T5 to assess electrolyser and fuel cell efficiency. - Run the system for XX months (2.5 years of whole demonstration phase duration). - After the end of the demonstration phase or periodically carry out again tests T2 and T5 to assess ELY and FC efficiency degradation. - Electrolyser and fuel cell Reactive Power Set Points will be kept at zero during the whole test duration.			
Test duration	>xx months		
Required Data Recording			
Variable	**Sampling**	**Variable**	**Sampling**
ELY State	10 seconds	ELY Reactive Power	10 seconds
ELY Active Power Set point	10 seconds	H_2 quality	10 seconds
ELY Active Power	10 seconds	ELY H_2 flow	10 seconds
ELY Reactive Power Set point	10 seconds	ELY Alarms	1 second
FC state	10 seconds	FC Reactive Power set point	10 seconds
FC Active Power Set point	10 seconds	FC Reactive Power	10 seconds
FC Active Power	10 seconds	FC Alarms	1 second
Tanks pressure	10 seconds	Room temperature	10 seconds
Active Power in the PCC	10 seconds	WF Active Power	10 seconds
Required Calculations			
Parameter		**Parameter**	
Total Energy consumed by ELY		Total Energy produced by FC	
Cost of Energy consumed by ELY		Income for Energy produced by FC	
Total hydrogen Produced by ELY		Total hydrogen Consumed by FC	
ELY Mean, Median, Mode Active Power		FC Mean, Median, Mode Active Power	

ELY mean hydrogen production rate	FC mean hydrogen consumption rate
Ely mean H_2 quality	FCY efficiency degradation
ELY efficiency degradation	FC total number of working hours
ELY total number of working hours	FC OPEX during the demonstration
ELY OPEX during the demonstration	FC ROI
ELY ROI	FC MTBF
ELY MTBF	Water consumption
Total Energy exchanged in the PCC	Total Energy produced by the WF
Total Energy consumed by Auxiliaries	Total Income for the Energy of the WF
NPV of the H_2system	LCOH2

Table 24. Demonstration Test T13: Energy-storage Use case – Frequency Regulation.

Demonstration Test T13: Energy-storage Use case – Frequency Regulation			
Objective: Demonstrate the correct operation of the hydrogen system under frequency regulation use case.			
Test Pre-conditions			
Electrolyser	- OFF		
Fuel Cell	- OFF (not used in this use case)		
Tank	- Empty Tank		
Test sequence			
- Previously required test: T10. - Before starting the demonstration, phase carry out Test T2 to assess electrolyser efficiency. - Run the system for XX months (2.5 years of whole demonstration phase duration). - After the end of the demonstration phase or periodically carry out again test T2 to assess the ELY efficiency degradation. General considerations: - Electrolyser Reactive Power Set Point will be kept at zero during the whole test duration. - The fuel cell will be kept in OFF state during the whole test duration.			
Test duration	>xx months		
Required Data Recording			
Variable	**Sampling**	**Variable**	**Sampling**
ELY State	1 seconds	ELY Reactive Power	1 seconds
ELY Active Power Set point	1 seconds	H_2 quality	1 seconds
ELY Active Power	1 seconds	ELY H_2 flow	1 seconds
ELY Reactive Power Set point	1 seconds	ELY Alarms	1 second
Tanks pressure	1 second	Room temperature	1 second
Active Power in the PCC	1 seconds	AGC or frequency signal	1 second
Required Calculations			
Parameter		**Parameter**	
Total Energy consumed by ELY		ELY mean H_2 production rate	
Cost of Energy consumed by ELY		Ely mean H_2 quality	
Total H_2 Produced by ELY		ELY efficiency degradation	
ELY mean, Median, Mode Active Power		ELY MTBF	
ELY total number of working hours		ELY ROI	
ELY Instant Answer Error (1s)		ELY OPEX during the demonstration	
ELY mean, median, mode answer error		Water consumption	
Total Energy exchanged in the PCC		Total Energy produced by the WF	
Total Energy consumed by Auxiliaries		Total Income for the Energy of the WF	
Total Income for frequency regulation service		Total income for the wind H_2 system	
NPV of the H_2system		LCOH2	

5 Risk Analysis

Safety aspects related to hydrogen leakage and accumulation, ignition sources and protection against fire and explosions are covered at element and system level and are not part of the scope of this study. This assessment is intended to analyse and control risk at test and demonstration level and more specifically at dispatching and system control level, which indeed do not cover safety functionalities.

A classic risk management methodology has been used. Each of the identified risks related to the test activity has been scored using the product of probability (P) and impact (I) as depicted in Table 25.

Table 25. Risk management scoring reference

Risk (R)		Probability (L)		
		Low	Medium	High
Impact (I)	High	3	6	9
	Medium	2	4	6
	Low	1	2	3

- Green indicates that the project is on track. The identified risks are not expected to impact the other project metrics or overall business outcomes.
- Yellow indicates that some course correction may be required.
- Red indicates that significant course correction may be required. One or more identified risks may impact the other project metrics or overall business outcomes and significant course correction may be required.

Table 26. Preliminary identification and characterization of test contingencies.

N	Description	Prob.	Impact	Score	Test
1	No communication with the control system	Low	Medium	**2**	All
	Contingency Plan				
	• Repair the communication link between the control system and the electrolyser on the meanwhile the electrolyser could be operated by means of the ELY own SCADA system.				

N	Description	Prob.	Impact	Score	Test
2	Electrolyser does not work	Low	High	**3**	T1, T2, T3, T4, T8, T9, T11, T12, T13
	Contingency Plan				
	• Complete the electrolyser maintenance planning to avoid undesired damages. • Review the electrolyser if any underperformance is detected on that to avoid higher damages. • If the electrolyser fails and does not work, repair it as soon as possible as no test can be carried out without it. In this case, re-plan the demonstration activity to complete the requested.				

N	Description	Prob.	Impact	Score	Test
3	Fuel cell does not work	Low	Low	**1**	T1, T5, T6, T7, T8, T9, T11, T12
	Contingency Plan				

N	Description	Prob.	Impact	Score	Test
	• Complete the electrolyser maintenance planning to avoid undesired damages. • If the fuel cell fails and does not work, repair the fuel cell if possible. If it is permanently damaged apply demonstration protocols without fuel cell.				

N	Description	Prob.	Impact	Score	Test
4	Electrolyser under performance	Low	Low	**1**	T1, T2, T3, T4, T8, T9, T11, T12, T13
	Contingency Plan				
	• Review the electrolyser to check any potential source of the underperformance. • Repeat test T2 and report the results and the continue test activity taking the updated efficiency curve as reference.				

N	Description	Prob.	Impact	Score	Test
6	Hydrogen leakage	Low	High	**3**	All
	Contingency Plan				
	• Stop test and demonstration activity. • Review the installation, detect the leakage source and repair it before resuming test activity.				

N	Description	Prob.	Impact	Score	Test
7	Not enough hydrogen storage capacity	Medium	Low	**2**	All
	Contingency Plan				
	• If there is no market for the produced hydrogen and the fuel cell may not be able to consume all the produced hydrogen, this should be vented in a controlled way so that to assure that the electrolyser demonstration activity does not stop.				

N	Description	Prob.	Impact	Score	Test
8	Problem with data recording and monitoring	Low	Medium	**2**	All
	Contingency Plan				
	• Provide several systems for data recording, for example at local and remote level, so that to avoid losing test results. • Solve data recording or communication problems without stopping the test activity.				

6 References

[1] HAEOLUS project website. www.haeolus.eu.

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[5] D3.2 Preliminary exploitation plan. HAEOLUS H2020 FCHU EU funded project. www.haeolus.eu

[6] D5.3 Techno-economic analysis of wind-hydrogen integration. HAEOLUS H2020 FCHU EU funded project. www.haeolus.eu.

[7] D8.2 Protocols for demonstration of mini-grid strategy.

[8] D8.3 Protocols for demonstration of fuel-production strategy.

[9] Regulation (EU) 2019/941 of the European Parliament and of the Council of 5 June 2019 on risk-preparedness in the electricity sector and repealing Directive 2005/89/EC (Text with EEA relevance.). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32019R0941.

[10] Raggovidda Vindkraftverk - Varanger Kraft n.d. www.varanger-kraft.no/raggovidda-vindkraftverk/category2592.html.

Next documents have also been consulted for the preparation of this report:

[11] D1.2 Protocols for experiments and validation activities. GIANTLEAP H2020 FCHU EU funded project.

[12] D2.1 Protocols for characterisation of system components and electrolysis system assessment. HPEM2GAS H2020 FCHU EU funded project deliverable.

[13] Impact of Electrolysers on the Network. Part of the Aberdeen Hydrogen Project, Scottish and Southern Electricity Networks.

[14] Task 24 Wind Energy & Hydrogen Inegration Final Report. http://ieahydrogen.org/Activities/Task-24.aspx. This Final Report was presented for approval at the 68th IEA HIA Executive Committee Meeting March 13-14, 2013 in Paris, France.

Annex 1: Parameters calculations

Electrolyser efficiency:

The electrolyser mean efficiency for a certain production rate and period of time must be evaluated according to the following formula:

$$\eta_{ELY}\ (\%) = \frac{HHV\left(\frac{kWh}{kg}\right) \cdot Produced\ \mathrm{H_2}(kg)}{Consumed\ energy\ (kWh)} \cdot 100$$

Fuel cell efficiency:

The fuel cell men efficiency for a certain power rate and period of time must be evaluated according to the following formula:

$$\eta_{\ FC}(\%) = \frac{Produced\ energy\ (kWh)}{HHV\left(\frac{kWh}{kg}\right) \cdot Produced\ \mathrm{H_2}(kg)} \cdot 100$$

Levelized cost of the produced H_2 (LCOH2)

This parameter is a version of the Levelized Cost of Energy (LCOE), which is commonly-used metric to compare the costs of electricity from different energy sources. In this case the LCOH2 is an estimation of H_2 production costs.

The LCOH2 can be also calculated through the traditional LCOS formula adapted to the case of H_2:

$$\mathrm{LCOH_2}\left(\frac{€}{\mathrm{kg}}\right) = \frac{\sum_{i=0}^{n}\left[\mathrm{CAPEX}_i \cdot \left(\frac{1}{1+d}\right)^i + \mathrm{OPEX}_i \cdot \left(\frac{1+e}{1+d}\right)^i + \mathrm{EnergyCost}_i \cdot \left(\frac{1+e}{1+d}\right)^i\right]}{\sum_{i=1}^{n} \mathrm{H_2\ production}_i \cdot \left(\frac{1+e}{1+d}\right)^i}$$

Equation 1

Where:

- **CAPEX:** electrolyser capital costs, including debt cost.
- **OPEX:** electrolyser operation and maintenance costs.
- **H_2 production:** is the amount H_2 produced per year.
- **EnergyCost:** is the cost of the energy consumed for producing H_2. In practice, as the electrolyser will be installed inside the wind farm, it is not a direct cost but a loss of income as the energy consumed for H_2 productions is not fed to the grid.
- **I:** year.
- **d**: discount rate.
- **e:** inflation.

MTBF: Mean Time Between Failure

This parameter is the predicted elapsed time between inherent failures of an element, in this case of the electrolyser and the fuel cell. MTBF can be calculated as the arithmetic average time between failures.

$$MTBF(hours) = \frac{\sum_{i=1}^{n} Hours\ the\ Electrolyser\ is\ on\ service}{Number\ of\ failures}$$