DELIVERABLE D8.2

PUBLIC

Protocols for demonstration of mini-grid 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: 2019/12/31

Keywords: Demonstration test protocols, demonstration test cases, mini-grid use case, electrolyser, hydrogen storage, fuel cell, wind farm

Abstract: This document defines the suite of test protocols that will be used to assess the demonstration performance of the HAELOLUS system when configured for operations in the mini-grid use case. Mini-grid use case covers both options of the combination of the wind-hydrogen systems supplying electricity to the load in two modes: islanded and weakly connected to the main grid. These demonstration test protocols are related to the control algorithms defined by US and SINTEF for the mini-grid use case (D6.3 [8]). These protocols shall ensure that all relevant aspects of that control algorithms shall be tested during demonstration. For that purpose, on-site test protocols for the electrolyser and the fuel cell, on-site test protocols for the defined strategies of the mini-grid use case, and on-site demonstration protocols for defined strategies of the mini-grid use case are defined in this document. Some of these protocols were already defined in D8.1 [9] but are also adapted and included here to ensure the completeness and self-consistency of this document.

Revision History

Date	Description	Author
2019/10/15	Draft definition of D8.2 index and preliminary content description	Eduardo García (TECNALIA)
2020/01/07	Draft version distributed to partners involved in D6.3	Eduardo García (TECNALIA)
2020/02/09	Version 0.1d distributed for quality revision (Valerio Mariani – UNISANNIO)	Eduardo García (TECNALIA)
2020/02/21	Version 0.1e including the update on the comments of the UNISANNIO's QR	Eduardo García (TECNALIA)
2020/02/27	Version 1.0 including the update on the final comments of QR (Valerio Mariani - UNISANNIO)	Eduardo García (TECNALIA)
2020/02/27	Version v2.0, updated with the corrections defined from the revision of the project officer.	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*

Table of Contents

List of Figures

List of Tables

Acronyms and glossary of terms

aFRR: Automatic Frequency Restoration Reserve

AGC: Automatic Generation Control

BOP: Balance of Plant

CAPEX: Capital expenditures

DSO: Distributed System Operator

ELY: Electrolyser

ESS: Energy Store System

EU: European Union

FC: Fuel Cell

H_2: Hydrogen

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

HLC: High Level Control

IEA: International Energy Agency

LCOE: Levelized cost of Energy

LCOS: Levelized cost of storage

LCOH2: Levelized cost of hydrogen

LLC: Low Level Control

M€: Million (10^6) euros

MPC: Model Predictive Control

MTBF: Mean Time Between Failure

MTTR: Mean Time To Repair

Nm^3: Normal cubic meter

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

1 Introduction

The objective of this deliverable is the specification of the test protocols that will ensure that all relevant features of the control algorithms specifically defined for the mini-grid use case shall be tested during demonstration.

Additionally, a risk analysis will be carried out to be performed for each set of controllers in terms of plant reliability and safety.

1.1 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 resulting wind-hydrogen system will be used, in different operating modes and use cases, to both smoothen the power output (e.g. in mini-grid use case) and to provide grid services (more relevant for energy-storage and fuel production use cases). For that, the planned Haeolus plant will have a 100 kW fuel cell (FC) to re-electrify part of the hydrogen, which is essential to those mentioned mini-grid and energy storage use cases.

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-hydrogen 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 use case 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 (FC) 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 use case:
  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 use case:
  This use case is the focus of the demonstrations test cases defined in this document. The mini-grid 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.

1.2 Demonstration test protocols approach

In order to achieve a first guideline for field tests 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 use cases will be developed.

Particularly, in this document, the test protocols for the **mini-grid** use case are reported.

These test protocols shall not be used to provide a detailed characterization, evaluation or factory acceptance tests of the electrolyser and the FC, but to assess the performance of a wind-hydrogen facility and the corresponding controller operated in the mini-grid use case. 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 D8.6 [10] along with the test and demonstration results.

On the other hand, the defined demonstration test cases are focused on the verification, at the demonstration stage, of the proper operation and performance of the specific functionalities of the control system specified in D6.3 [8] for the mini-grid use case. The verification of other grid-related issues (i.e. frequency and voltage regulation or overload handling,) is not object of the present test protocols assuming that these issues are managed by other elements in the demonstration site (the inverters with corresponding low level controllers, for instance).

With respect the implementation of the system control under test, the verification of its internal functionalities, interfaces or components is not object of the demonstration tests. It is assumed that this kind of verification has been carried out at the unit and component test phases during the control system development process.

1.3 Structure of the document

Following the previous introductory sections, this report is organized as follows:

- Chapter 2 describes the Raggovidda wind-hydrogen system configuration and the identification of the main related parameters and variables.
- Chapter 3 includes some considerations relevant for the definition of the demonstration test protocols in the mini-grid use case and required for assessing the operation strategies of the corresponding control algorithms.
- Chapter 4 includes:
    - The on-site test protocols for the electrolyser and the fuel cell.
    - The on-site test protocols for the mini-grid operation strategies.
    - The on-site demonstration protocols for the mini-grid operation strategies.
- Chapter 5 provides some risk considerations related to the defined tests with respect to the demonstrations plant reliability and safety.

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

2 Raggovidda wind-hydrogen facility description:

Figure 4 depicts the layout of the Raggovidda wind-hydrogen system, according to [8], along with its main components.

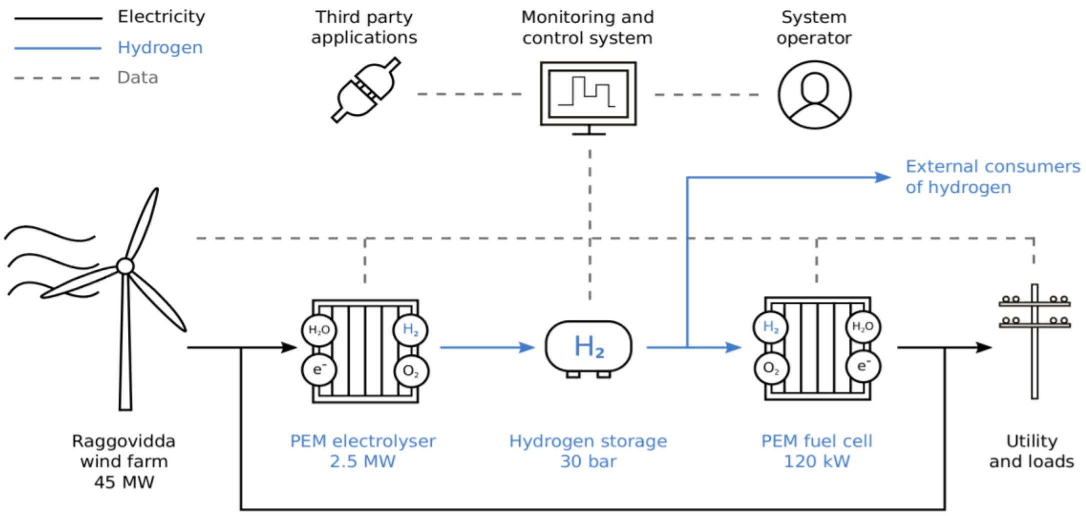

Figure 1. Raggovidda wind-hydrogen system components scheme.

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.

The electrolyser will generate hydrogen according to the three different use cases targeted in the HAEOLUS project (energy-storage, mini-grid and hydrogen production). 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 FC will be used to re-electrify the produced hydrogen while other local markets for hydrogen are developed. This FC was manufactured by HYDROGENICS as part of INGRID (www.ingridproject.eu) EU cofounded project. The FC 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 300 bars from a 30/300 bar compressor connected to the electrolyser hydrogen output. This is an updated configuration with respect D8.1 [9] where a 30 bars hydrogen tank was initially considered. This issue does not impact the specification of the demonstration test protocols.

A control framework will be provided for the monitoring and operation of 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 FC 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.

The following sections provide specific information of the Raggovidda facility which are relevant for the definition of the test protocols. This information is structured, when relevant, into the component characteristics (Table 1, Table 3 and Table 5), the reference to check the behaviour of the component (Figure 2 and Figure 3) and the component parameters to be monitored (Table 2, Table 4, Table 6, Table 7 and Table 8).

2.1 Raggovidda Wind Farm

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.

Table 1 summarises the global parameter values regarding the Raggovidda wind farm as provided by Varanger Kraft [2].

Table 1. 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 1 are just estimates depending on the current technology state-of-the-art and on the available market data.

The variables related to the observation of the wind farm are listed in the following Table 2.

Table 2. 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

2.2 2.5 MW PEM electrolyser

The following Table 3 shows the electrolyser data relevant for the definition of the demonstration test cases.

Table 3. 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 2
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.

The following Figure 2 and Table 4 will be taken as the reference for the definition of the electrolyser efficiency parameters.

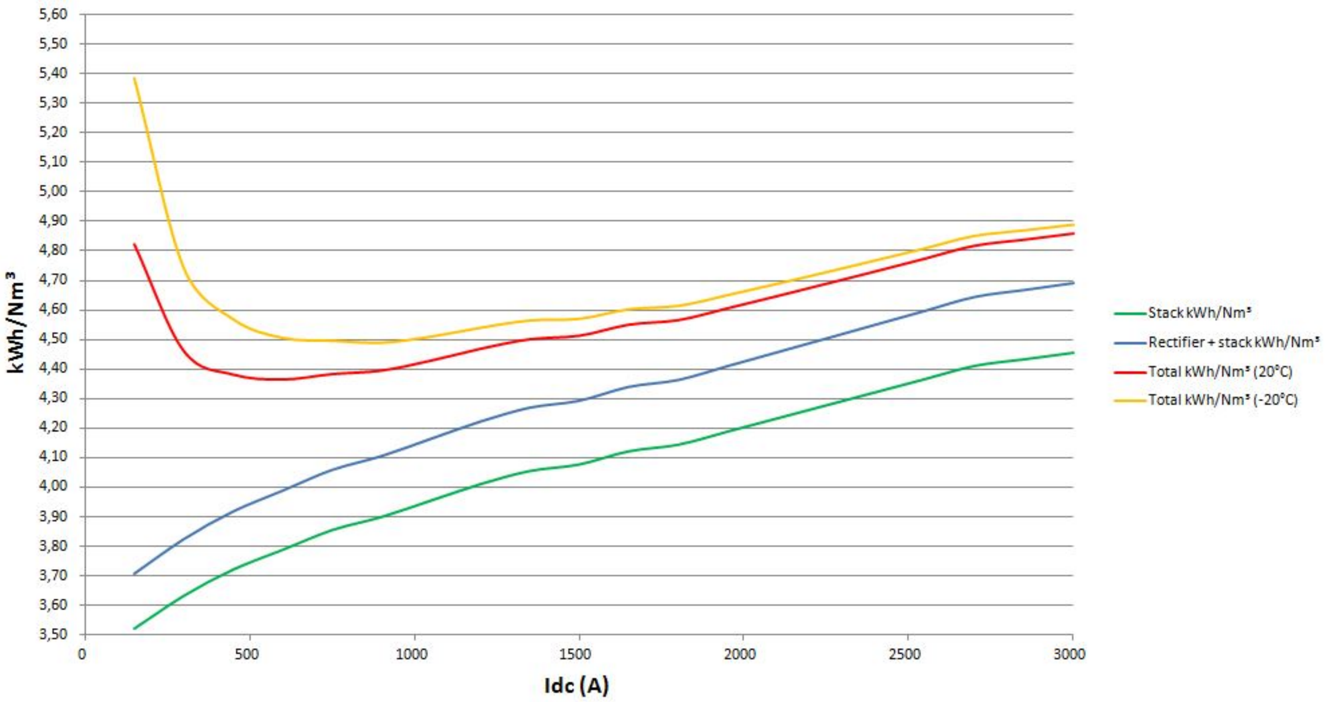

Figure 2. Electrolyser efficiency curves.

Table 4. 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

2.3 Fuel cell

In Table 5, the relevant parameters regarding the 120 kW PEM FC, provided by Hydrogenics, are reported.

Table 5. 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 FC, Figure 2 reports the corresponfing efficiency curves with respect to voltages and net currents.

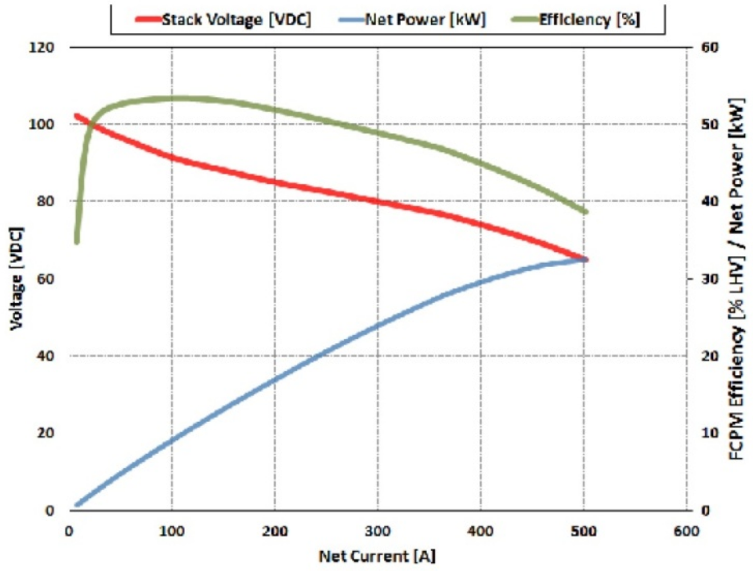

Figure 3. Fuel cell efficiency curves.

Completing that information, the Table 6 below presents the values of the parameters and variables related to the monitoring of the FC.

Table 6. 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

2.4 Hydrogen storage tank

The following Table 7 presents the hydrogen tank variables and parameters relevant for the observation of the execution and results of the demonstration test cases.

Table 7. 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
H_2 level inside the tank	kg	Calculation
Mean, Median, Mode tanks pressure	Bar	Calculation
Tank temperature	C	Tank temperature meter
Alarms	---	TBD

2.5 Overall facility and controller

Finally, the following Table 8 gathers those observable parameters related to the Control System, the power connection taken to power the system and the site conditions.

Table 8. 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

3 The Mini-grid Use Case

According to the International Energy Agency [3], the mini-grids category refers to fully or partially islanded systems that include wind energy and typically other (decentralised) power generation, like the hydrogen based one in the HAEOLUS project.

Two alternatives are considered with respect the mini-grid connection to the main electricity grid [3]:

- **Weakly connected (or partially islanded as named in [3]) mini-grid,** with significant constraints with respect to their link to the main grid. In this case, the main purpose of hydrogen production is the storage of temporary surpluses of energy from renewables, the provision of a demand side management solution for energy supply (the electrolyser serving as a controllable / dispatchable load) and the contribution to the frequency and voltage stability of the grid. In this last case, the hydrogen system should work in the "Grid Following" mode. Its main aim would be to support (droop control) in regulating the amplitude and frequency of the AC grid voltage by controlling the active and reactive power supplied to the grid. The following Figure 4 depicts the components layout for this weakly connected mode.

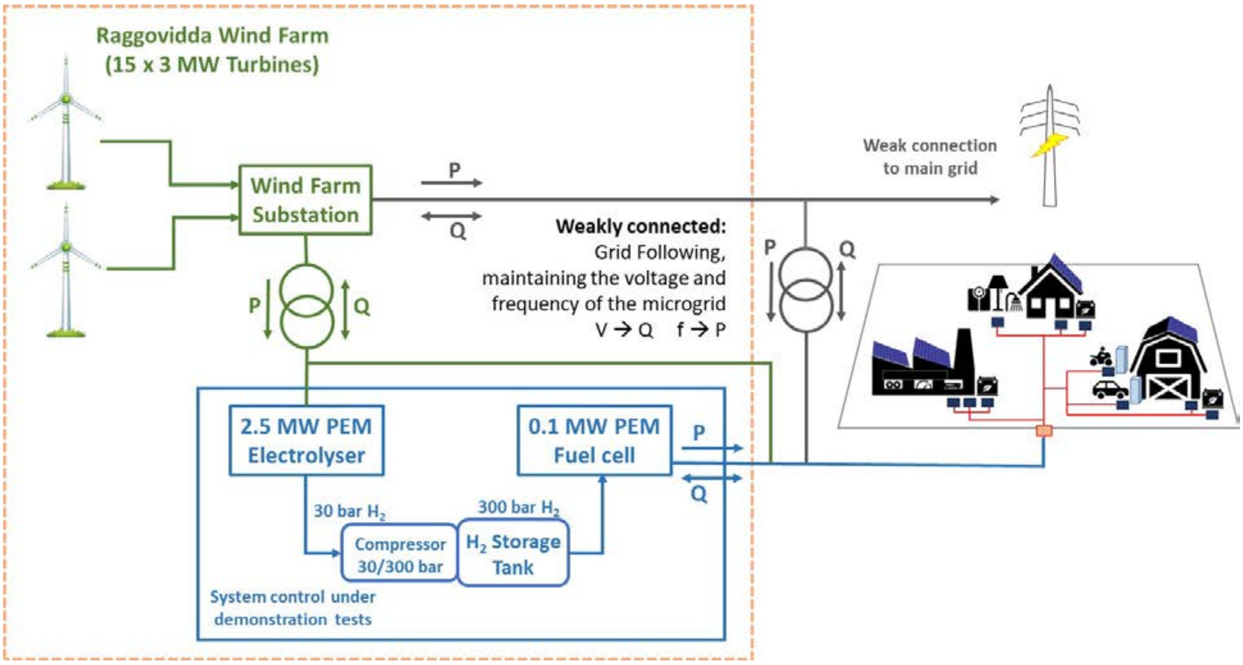

Figure 4. Conceptual layout of the Raggovidda wind-hydrogen system for the weakly connected mini-grid use case.

- **Fully islanded mini-grid** in which, without any connection to the main grid, the load is only fed by the wind-hydrogen system with the main constraints related to the provision of the required energy with proper quality and stability levels. Therefore, the main purpose is maintaining the power balance between generation and demand without the grid support. In this case, the hydrogen system should work in the "Grid Forming" mode regulating the voltage and frequency of the mini-grid in prevision of no energy generation from the wind system. Next Figure 5 shows the wind-hydrogen system components architecture and their interconnection for the islanded mode.

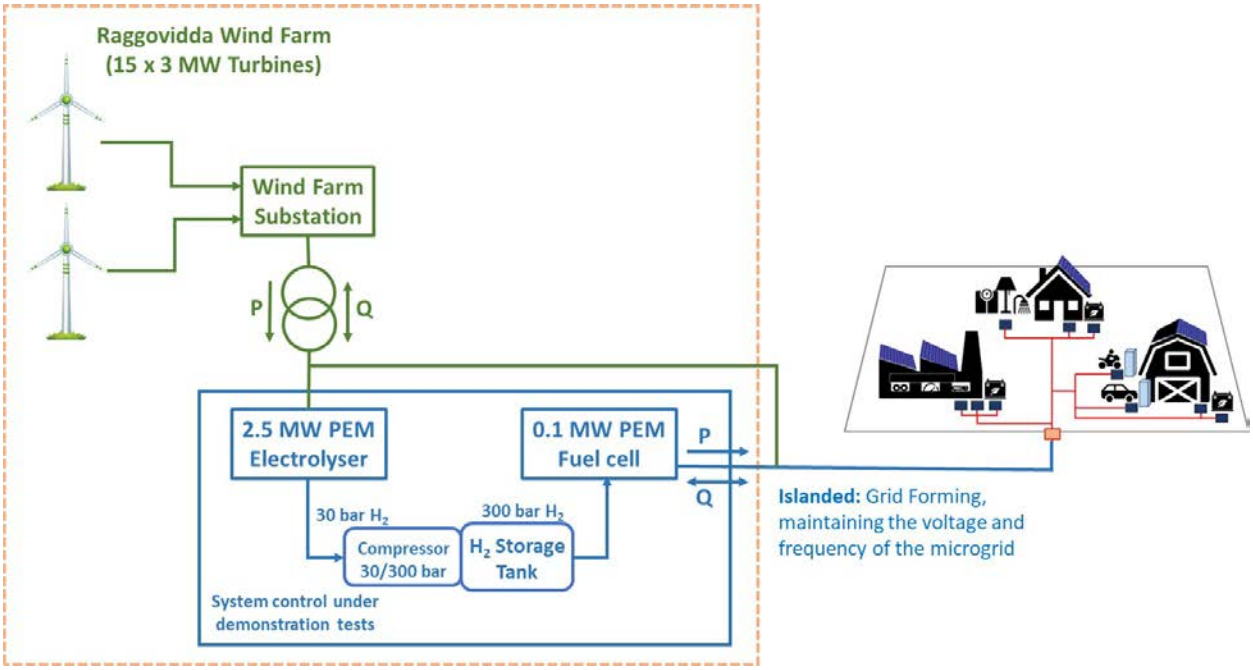

Figure 5. Conceptual layout of the Raggovidda wind-hydrogen system for the islanded mini-grid use case.

Additionally, some mini-grids constraints are already anticipated in HAEOLUS project Grant Agreement and D6.3 [8] that are also considered for this use case:

- No or limited ability to import or export power
- Instantaneous power output according to the energy demand
- To reach the MAWP 2020 KPI's targets, in particular:
    - Energy consumption at rated power below 52 kWh/kg;
    - A hot start from min to max power in less than 2 sec;
    - A cold start in less than 30 sec;
    - An efficiency degradation @ rated power below 1.5 % per year (8000 operating hours).
    - Hot and cold start are not met with present technology, either alkaline or PEM. These KPIs are however indicated as optional in the MAWP [2, p. 31], to be fulfilled according to their value proposition. Task 6.2 will consider control strategies to increase this response time, also suggesting components and plant modifications, in particular for the case of mini-grid operation (D6.3 [8]) where response time is mission-critical.

All these considerations are taken into account for the specification of the mini-grid use case control system, provided in D6.3 [8], that is presented in brief in the next section 3.1.

3.1 Characteristics of the control system for the mini-grid use case

The defined mini-grid use case control system covers both the islanded and the connected modes.

In islanded mode the electrolyser and the fuel cell will be operated in order to meet the load demand as required. In turn, the load demand tracking is achieved at two different time-scales, that are handled by the proposed algorithm. For the scenario under investigation, a larger time-scale involves load demand tracking with 1 hour sampling time while a shorter time-scale, that will be referred by the term real-time, involves load demand tracking with 1 minute sampling time. As a consequence, two level controller architecture is proposed, each level dealing with strategies to be implemented in one corresponding time-scale.

In weakly connected mode, the additional participation to the electricity market will be also managed covering both day-ahead and intraday market time-scales. In this mode, the load is still present and its forecasted demands have to be met, in this weakly connected mode a very wide and complex variety of possible operating strategies for the electrolyser and the fuel cell may be achieved. So, in principle, also in this mode two different time-scales have to be managed by the controller. However, since for the project scenario no real-time market is actually available, the low-level controller just implements on the shorter time-scale what scheduled by the high-level controller. This also allows to consistently keep the previously mentioned two level architecture across the two different modes, islanded and weakly connected.

The load demand tracking of a hydrogen-based Energy Store System (ESS) is developed, solved, and experimentally validated under a complete 24-h test for both intraday and real time energy markets by using sample times of Ts = 1 hour and Ts = 1 min, respectively.

Additionally, in connected mode, the participation to the electricity market will also be managed with a very wide and complex variety of possible operating strategies for the electrolyser and the fuel cell that may be achieved in principle. In this case, two different time-scales (day-ahead and intra-day) have to be managed by the controller thus allowing to consistently keep the previously mentioned two level architecture across the two different modes: Islanded with the two time-scales for the load demand, and Connected with the two time-scales for the day-ahead and intraday markets.

The following Figure 6 shows the abovementioned multi-level approach featuring Model Predictive Control (MPC) schemes being used in the design and development of the mini-grid system control as defined in D6.3 [8].

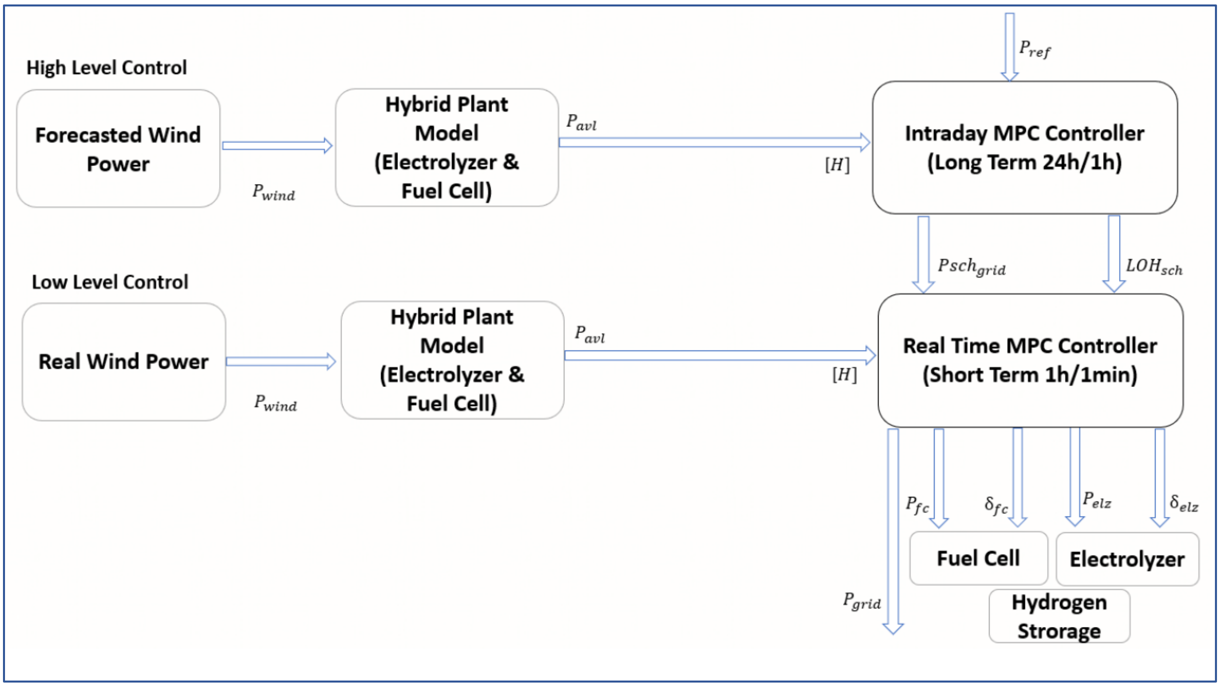

Figure 6. Block scheme of the multilevel cascade Model Predictive Control (MCP)applied to the mini-grid system control [8].

This multi-level MPC approach is that it gives a freedom degree in the controller allowing to correct deficit scenario with exceeding scenario in comparison with the forecast carried out at the day-ahead energy market or load demand.

However, from the demonstration tests point of view, it is a question of the implementation of the control system if both controlling levels, High Level Control (HLL) and Low Level Control (LLC), run as two controllable and observable processes or run together as an unique process that is only controllable and observable as a whole. Considering the high level approach of the hydrogen demonstration campaign, the demonstration test cases proposed in this deliverable will consider preliminarily both HLL and LLC levels as a unique process taking into account the input and output variables of the joint HLC-LLC ensemble and not the internal interfaces between these two levels. This monolithic approach will be reviewed once the implementation of the system control algorithms is available proposing the required update of the demonstration tests cases if required.

As derived from D6.3 [8], the algorithms of the mini-grid use case control system will work at high-level with the purpose of delivering ON/OFF commands to the devices, managing the cold and warm starts, for the energy management and the HAEOLUS system supervision and control. The controller also provides the amount of hydrogen to be produced or re-electrified. With the results of that reasoning, the logic commands enable/disable the electrolyser and the fuel cell operations according to the scheduled policy. The way the exceeding power from the wind farm is redirected to the electrolyser or the way the fuel cell inject power needed is out of concern of our controller. In fact, it assumes the electrolyser and the fuel cell are smart enough, i.e. they have local control loops and converters/inverters, to properly generate voltages/currents when required by the scheduled policy. At the best of our knowledge regulation services are usually achieved at lower levels, where faster control loops are implemented also enabling to handle faster dynamics. Regarding congestion management, also we know that its purpose is to increase the share of renewables in the grid i.e., with multiple generation units, but for HAEOLUS plant we have only one generation unit (wind generator) which control is not in the scope of WP6 (and probably of the project).

The following variables and parameters are identified from D6.3 [8] as relevant for the purpose of launching the test cases and observing their results.

- Main algorithm parameters relevant to the demonstration tests:
    - P_{maxe} *Maximum power level of the electrolyzer [kW]*
    - P_{mine} *Minimum power level of the electrolyzer [kW]*
    - P_{STBe} *Standby power of the electrolyzer [kW]*
    - P_{CLDe} *Standby power of the electrolyzer [kW]*
    - P_{WRMe} *Standby power of the electrolyzer [kW]*
    - P_{maxf} *Maximum power level of the fuel cell [kW]*
    - P_{minf} *Minimum power level of the fuel cell [kW]*
    - P_{STBf} *Standby power of the fuel cell [kW]*
    - P_{CLDe} *Standby power of the fuel cell [kW]*
    - P_{WRMe} *Standby power of the fuel cell [kW]*
    - NH_e *Number of life hours of the electrolyser [h]*
    - R_e *Ramp limit of the electrolyser [kW/s]*
    - R_f *Ramp limit of the fuel cell [kW/s]*
    - Γ *Energy price [€]*

- As forecast parameters:
    - P_W *Wind power production [kW] → Power production profile with 1hour (HLC) and 1min (LLC) precision*
    - P_{ref} *Electrical load demand [kW] → Power demand profile with 1hour precision*

- As variables:
    - P_e *Electrical power of the electrolyser [kW]*
    - P_f *Electrical power of the fuel cell [kW]*
    - P_{avl} *Available system electrical power [kW]*
    - P^{dump} *Dumped electrical power [kW]*
    - P_{grid} *Grid power [kW]*
    - P_{grid}^{sch} *Scheduled grid power [kW]*

3.2 Demonstration operation strategies to be tested

Considering the mini-grid control system characteristics described in the previous section 3.1, some assumptions are made in the following about the control system implementation that are relevant for the identification and definition of the demonstration test cases:

a. The control system will be considered as a monolithic development. Some of the functionalities specified in D6.3 [8] (i.e. the interface between the two, HLC and LLC control levels or the operational, maintenance or degradation costs functions) are basically internal to the control system and not accessible for independent running at the demonstration stage. The verification of these functionalities is assumed to have been carried out at the unit and integration tests phases during the development process. However, depending of the specific implementation, some development resources like log, tracking or configuration files could be considered in the demonstration tests to check different cost profiles and their corresponding effect in the control.

b. With this "black-box" approach mentioned in the previous point, the LLC schedule control horizon (of 1h and a Ts =1 minute), and not the HLC's one, would be considered as the reference for the test cases definition that would imply time

c. The main information to be taken as the reference for the govern and verification of the system control behaviour:
    - the forecast of local demand. Input information
    - the contracted grid power (sale and purchase) from the corresponding market. Input information
    - the energy price profile from the corresponding market as input information
    - the variation of the level of Hydrogen (LoH) as an evidence from the evolution of the corresponding control algorithm during the optimisation stage and a measurement that is performed every cycle. Output information

Additionally, it is important to remark that these operation strategies, and their corresponding demonstration test cases, are proposed taking into account the specification of the mini-grid use case control system [8] being its implementation not available yet. Therefore, these demonstration test cases will be reviewed, and updated if it is the case, with the reference of that implementation and the final characteristics of the HAEOLUS system demonstration installation.

Considering the previous assumptions, the following operation strategies for each of the connection modes (weakly connected and islanded) are considered under the so-called mini-grid use case:

a) Weakly connected mini-grid mode:

1. Generation and local load matching, observing the real-time (related to the LLC although the HLC is internally processing the 1h tracking) measurements of generation and consumption to calculate the real time market available power to feed the local load. Hydrogen system has to complete the energy generated by the wind farm and coming from the main grid when required. Table 9shows the main technical requirements needed for achieving this local load matching.

Table 9: Generation and local load matching operation strategy. Technical requirements.

Generation and local load matching			
Response time	**Ramp rate**	**Duration**	**Market schedule**
< 1 min	Depending on load, wind generation and grid supply profile ramp rate	2 hours (*)	According to daily (Day D-1) and intraday markets

(*) At least, two hours in order to verify properly the two HLC and LLC control levels

2. Real-time energy profile matching within the intra-day market. The outputs of the controller should be the reference power values for the ESS, for each hour of the day according to the committed energy profile to be supply or bought to the market. Considering the HLC and LLC monolithic approach, the sample period used for this control level would be T_s = 1min, with a scheduled horizon of 1h discretized in periods of 60min. Table 10 shows the main technical requirements needed for achieving this market profile matching.

Table 10. Market profile matching operation strategy. Technical requirements.

Market profile matching			
Response time	**Ramp rate**	**Duration**	**Market schedule**
< 1 min	Depending on the market and wind generation profiles ramp rate	2 hours	According to daily (Day D-1) and intraday markets

3. Energy price arbitrage (checking the Grid Cost Function). Power sale and purchase at real-time energy market with the grid according to the balance of the energy price with respect the cost of the own generated energy (real-time market energy price profile and the tracking deviation of power exchange with the grid and the contracted scheduled grid power). This operation strategy is related to the Grid Cost Function (D6.3 [8]) and consists of 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 11 shows the main technical requirements needed for achieving price arbitraging.

Table 11. Energy price arbitrage operation strategy. Technical requirements.

Energy price arbitrage			
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

4. Store surplus energy through storage of hydrogen. 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 surplus energy storing operation strategy are reported in Table 12

Table 12. Store surplus energy operation strategy. Technical requirements.

Store surplus energy			
Response time	**Ramp rate**	**Duration**	**Market schedule**
< 1 min	Not relevant	2 hours	According to daily (Day D-1) and intraday markets

5. Respond to demand response (DR) programs in a cost-optimized, environment friendly, and customer satisfying solution, and generally acting as the controllable load from the grid point of view. In this operation strategy, electrolyser would be the relevant hydrogen related element to be controlled according to the demand response program to be processed. The main technical requirements to be met in order to achieve the demand response operation strategy are reported in Table 13

Table 13. Demand response energy operation strategy. Technical requirements.

Demand Response operation strategy			
Response time	**Ramp rate**	**Duration**	**Market schedule**
< 1 min	Demand response program ramp rates	2 hours	According to daily (Day D-1) and intraday markets

b) Islanded mini-grid mode:

1. Contribution to the supply of energy demanded by the local load maintaining the power balance between generation and demand without the main grid support. This operation strategy is similar than the local load matching in the grid connected mode but without the participation of the main grid in the supply of energy to the load. The electrolyser and the fuel cell will be operated in order to complete the wind farm production meeting together the load demand. The load demand is considered in the control reasoning by means of two different forecasts at to different time scales, at 1 hour and at 1 minute sampling time respectively. Considering the defined variables, the load demand P_{ref} is met with the system available power P_{avl} only with no external exchange of energy sale or purchase, i.e. in this mode $P_{grid} = 0$. Table 14 shows the main technical requirements needed for achieving this local load matching.

Table 14. Generation and local load matching operation strategy in islanded mini-grid mode. Technical requirements.

Generation and local load matching in islanded muni-grid mode			
Response time	**Ramp rate**	**Duration**	**Market schedule**
< 1 min	Depending on load and wind generation profiles ramp rate	2 hours (*)	According to daily (Day D-1) and intraday markets

4 Test protocols

The present chapter includes the identification and specification of the test cases to be carried out for the demonstration stage at both its initial start and during the demonstration period.

The defined test cases cover the following demonstration objectives:

a) The verification of the proper and independent functioning of the main components previously to its integration in the demonstration facility and at the demonstration site. These components are:
   1. The own control system under demonstration test in section 4.1
   2. The electrolyser in section 4.2
   3. The FC in section 4.3

b) The verification of the operations strategies defined in the section 3.2 at the beginning of the demonstration phase, identified as field test protocols in section 4.4

c) As an extension of the previous tests, the verification of the operation strategies defined in the section 3.2 during the complete demonstration campaign, identified as field demonstration protocols in section 4.5.

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 15 shows the items to be verified on the Systems Controller.

Table 15. 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: 1. Parameters monitoring 2. State control (ON, OFF, STANDBY) 3. Power set point	OK/NOK
Communication with the fuel cell: 4. Parameters monitoring 5. State control (ON, OFF, STANDBY) 6. Power set point	OK/NOK
Communication with the hydrogen storage tank controller 7. Parameters monitoring	OK/NOK
Communication with the wind farm: 8. Parameters monitoring	OK/NOK
Communication with the TSO or price and balancing signal provider	OK/NOK
Communication with Balance of Plant (BOP) controller (if any)	OK/NOK
Communication with Dumped electrical power (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 datasheet. 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 16.

Table 16. 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

Both the electrolyser and the FC have different state transition models for the HLC and the LLC. However, in the LLC modelling, the short time features of both devices imply tighter and shorter time restrictions for these transitions.

The actual observable states of the electrolyser and the FC correspond to the states transition scheme of the HLC modelling, shown in the following Figure 7.

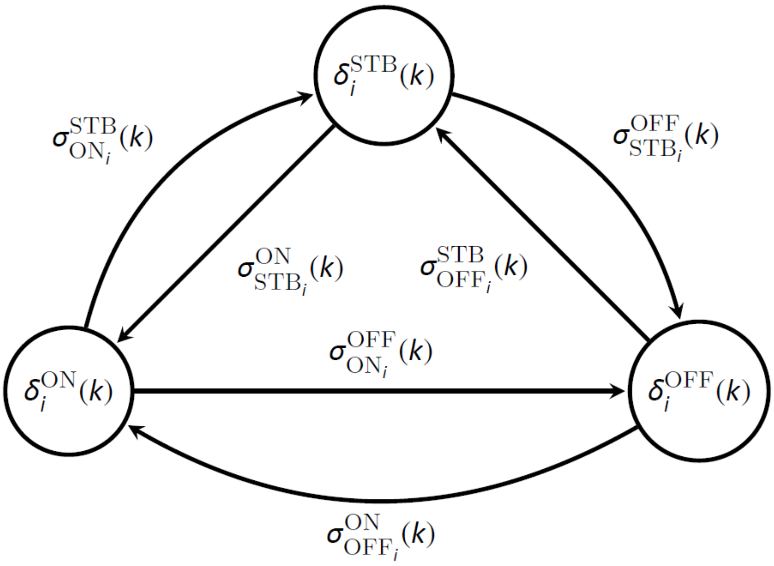

Figure 7: Automata of the electrolyser (i = e) and of the fuel cell (i = f).

These three states are, in consequence, verified at the demonstration phase with the main objective of measuring the transition time between states in order to check that the transition logic programmed in the control is adequate.

Table 17. 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 STB. - 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. - Switch ELY from OFF to STB states - Keep ELY 1 hour in STB - Switch ELY from STB to OFF			
Test duration	approximately 4 hours and 30 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. In Standby state, devices warm start is achieved with a trade-off of delivering a constant power of 1kW to keep the devices stack warm.		
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		
Time from OFF to Standby	Time to bring the ELY from OFF to Standby.		
Time from Standby to OFF	Time to bring the ELY from Standby to OFF.		

4.2.3 ELY on-site dynamic response

Table 18. Test T4: ELY on-site dynamic response.

<table>
<tr><th colspan="4">Test T4: ELY on-site dynamic response</th></tr>
<tr><td colspan="4">Objective: Verify ELY dynamic response to P/Q setpoint, verify the ramp rates and electrolyser control accuracy.</td></tr>
<tr><td colspan="4">Test Pre-conditions</td></tr>
<tr><td>Electrolyser</td><td colspan="3">- Standby
- Operate the ELY at 0,3 MW for 1 hour to bring the ELY to nominal operation conditions (stack working temperature)</td></tr>
<tr><td>Fuel Cell</td><td colspan="3">- Not used for this test (OFF)</td></tr>
<tr><td>Tank</td><td colspan="3">- Not relevant (store, extract or vent the produced hydrogen)</td></tr>
<tr><td>Room temperature</td><td colspan="3">- TBD (within the temperature range of the ELY operation)</td></tr>
<tr><td colspan="4">Test sequence</td></tr>
<tr><td colspan="4">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.</td></tr>
<tr><td>Test duration</td><td colspan="3">Not relevant (estimated 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>ELY Active Power Set point</td><td>100 ms</td><td>ELY Reactive Power set point</td><td>100 ms</td></tr>
<tr><td>ELY Active Power</td><td>100 ms</td><td>ELY Reactive Power</td><td>100 ms</td></tr>
<tr><td>Alarms</td><td>1 s</td><td></td><td></td></tr>
<tr><td colspan="4">Required Calculations</td></tr>
<tr><td>Parameter</td><td colspan="3">Description</td></tr>
<tr><td>Response accuracy</td><td colspan="3">Calculated as root-mean-square error between actual response and command.</td></tr>
<tr><td>t_p</td><td colspan="3">Peak power time for each power step change.</td></tr>
<tr><td>t_s</td><td colspan="3">Setting time (time to reach a stable answer with an error below ±1 %).</td></tr>
</table>

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 8. Particularly, the active and reactive power P/Q time evolutions, following a load transient, a demand response or an energy market profile to be matched, will be assessed for each one of the operation strategies reported in Section 3.2 as each one has different dynamic requirements.

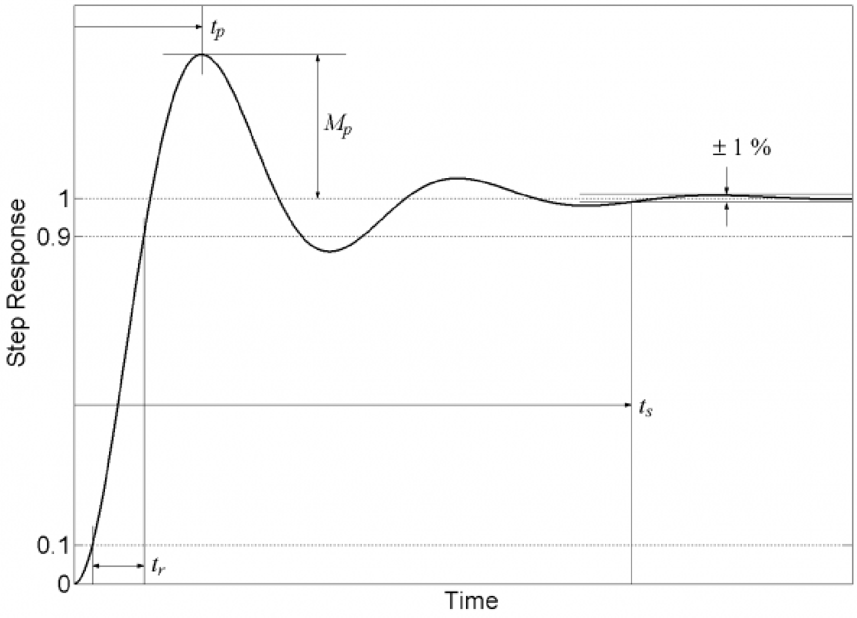

Figure 8. Second order system typical response (just as reference for parameters definition).

4.3 On-site functional test of the fuel cell

These tests are intended to characterize the FC 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 FC is not a core component of the wind-hydrogen system developed in HAEOLUS and that the FC has been already used in a previous European project (INGRID - http://www.ingridproject.eu/). Moreover, as also reported in Section 2.3, the FC 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 19. 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	300 bar tank to provide hydrogen at the input pressure of the FC 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 20. 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 % or, at least, enough 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 FC at 100 kW until reaching stack operational temperature.
- Shift from 100 kW power to Standby.
- Switch the FC from Standby to OFF
Hot start:
- Switch the FC from OFF to Standby
- 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. In Standby state, devices warm start is achieved with a trade-off of delivering a constant power of 1kW to keep the devices stack warm.</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>
<tr><td>Time from OFF to Standby</td><td colspan="3">Time to bring the FC from OFF to Standby.</td></tr>
<tr><td>Time from Standby to OFF</td><td colspan="3">Time to bring the FC from Standby to OFF.</td></tr>
</table>

4.3.3 FC on-site dynamic response

Table 21. 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 % or, at least, enough 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 FC fits that required in the relevant operation strategies defined in section 3.2.

4.4 Field test protocols

This set of protocols is intended to verify the correct operation of the electrolyser for each of the operation strategies defined in section 3.2 for the mini-grid use case, namely:

a) Weakly connected mini-grid mode:
  1. Generation and local load matching
  2. Real-time energy profile matching within the intra-day market
  3. Energy price arbitrage
  4. Store surplus energy through storage of hydrogen
  5. Respond to demand response (DR) programs

b) Islanded mini-grid mode:
  1. Contribution to the supply of energy demanded by the local load

The protocols refer to two main stages that are the test stage, previously to start the demonstration period, and during the demonstration campaign. 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 [6] [7].

Table 22. Field Test T8: Weakly Connected Mini-grid use case. A1-Generation and local load matching.

Field Test T8: Weakly Connected Mini-grid use case. A1-Generation and local load matching	
Objective: Verify the correct operation of the hydrogen system collaborating with the wind farm and the main grid in the supply of the energy demanded by the local load, basically completing the active power required. Due to the weak grid connection, it is assumed that the power available in the grid is limited and not enough for the load energy demanded, therefore the required participation of the hydrogen system.	
Test Pre-conditions	
ELY	- OFF or Standby if it is going to be operated to generate the hydrogen required by the FC to generate energy
FC	- Standby
Tank	- ELY OFF: Full enough to support the FC during the test execution - ELY Standby/ON: Could be empty depending on the balance between the hydrogen produced by the ELY and consumed by the FC
Room temperature	- TBD (within the temperature range of the hydrogen system operation)
Test sequence	

- Previously required test: T1, T5, T6 and T7 (Local load supply algorithms should be tuned according to test results).
- Verify main aspect of the local load supply algorithm:
    - There is access to Wind farm and PCC Power measurements.
    - Access to the limited grid power profile.
    - There is access to the local load power signal.
    - A local demand forecast curve has been defined.
    - If there is no access to the local load power signal it is necessary to create a 24 hours local load power profile.
- Run the test for the test period (24 hours or less depending on the selected profile).
- FC 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**
FC State	1 second	FC Reactive Power	1 second
FC Active Power Set point	1 second	H_2 quality	1 second
FC Active Power	1 second	FC H_2 flow	1 second
FC Reactive Power Set point	1 second	FC Alarms	1 second
Tanks pressure	1 second	Local Load power profile (P_{avl}, P_{ref})	1 second
Active Power in the PCC	1 second	Grid power (P_{gridl})	1 second
WF Active Power	1 second	Wind farm power (P_W)	1 second
		Room temperature	1 second
Required Calculations			
Parameter		**Parameter**	
Total Energy generated by the FC		Total energy supplied to the local load	
Total Energy consumed by the ELY		Total Energy produced by the Wind Farm	
Total Energy consumed by Auxiliaries		Total Energy exchanged in the PCC (P_{fc}-P_{ez})	
H_2 consumed by the FC		Total energy received from the grid (P_{grid})	
FC Answer Instant Error (1s)			
Required Verifications			
Verify that the total Energy exchanged in the PCC is the sum of ELY, FC and auxiliaries' total energy.			
Verify the matching of generation and load within times ranges of order of minutes.			
Verify that the FC active power varies according to the local load profile completing, when required, the supply of the wind farm and the limited grid connection.			
Verify that that FC instant error is below the maximum allowable error.			

Table 23. Field Test T9: Weakly Connected Mini-grid use case. A2- Real-time energy profile matching within the intra-day market.

Field Test T9: Weakly Connected Mini-grid use case. A2- Real-time energy profile matching within the intra-day market.			
Objective: This test is similar to the previous T8 but, in this case, the reference to be followed is the committed energy profile to be supply to the market. So, the objective is to verify the correct operation of the hydrogen system collaborating with the wind farm in the supply of the energy profile offered to the market, basically completing the active power required.			
Test Pre-conditions			
ELY	- OFF or Standby if it is going to be operated to generate the hydrogen required by the FC to generate energy		
FC	- Standby		
Tank	- ELY OFF: Full enough to support the FC during the test execution - ELY Standby/ON: Could be empty depending on the balance between the hydrogen produced by the ELY and consumed by the FC		
Room temperature	- TBD (within the temperature range of the hydrogen system operation)		
Test sequence			
- Previously required test: T1, T5, T6 and T7 (real time market energy supply algorithms should be tuned according to test results). - Verify main aspect of the real time market energy supply algorithm: o There is access to Wind farm and PCC Power measurements. o Access to the grid. o The energy profile committed to the market. o The forecast of the wind farm power generation for the period. - Run the test for the test period (24 hours or less depending on the selected profile). - FC 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**
FC State	1 second	FC Reactive Power	1 second
FC Active Power Set point	1 second	H_2 quality	1 second
FC Active Power	1 second	FC H_2 flow	1 second
FC Reactive Power Set point	1 second	FC Alarms	1 second
Tanks pressure	1 second	Power delivered to the market	1 second
Active Power in the PCC	1 second	Wind farm power (P_W)	1 second
WF Active Power	1 second	Room temperature	1 second
Required Calculations			
Parameter		**Parameter**	
Total Energy generated by the FC		Total energy supplied to the local load	

Total Energy consumed by the ELY	Total Energy produced by the Wind Farm
Total Energy consumed by Auxiliaries	Total Energy exchanged in the PCC (P_{fc}-P_{ez})
H_2 consumed by the FC	Total energy received from the grid (P_{grid})
FC Answer Instant Error (1s)	
Required Verifications	
Verify that the total Energy exchanged in the PCC is the sum of ELY, FC and auxiliaries' total energy.	
Verify the matching of generation and committed energy to the market within times ranges of order of minutes.	
Verify that the FC active power varies according to that energy profile committed to the grid, completing, when required, the supply of the wind farm.	
Verify that FC instant error is below the maximum allowable error.	

Table 24. Field Test T10: Weakly Connected Mini-grid use case. A3-Energy Price Arbitrage.

<table>
<tr><th colspan="4">Field Test T10: Weakly Connected Mini-grid use case. A3-Energy Price Arbitrage</th></tr>
<tr><td colspan="4">**Objective:** Verify the correct operation of the hydrogen system under the energy price reference storing energy as hydrogen when the energy market price is low and in the subsequent re-electrification when the energy market price is high</td></tr>
<tr><td colspan="4">**Test Pre-conditions**</td></tr>
<tr><td>ELY</td><td colspan="3">- OFF</td></tr>
<tr><td>FC</td><td colspan="3">- OFF</td></tr>
<tr><td>Tank</td><td colspan="3">- Empty Tank</td></tr>
<tr><td>Room temperature</td><td colspan="3">- TBD (within the temperature range of the hydrogen system operation)</td></tr>
<tr><td colspan="4">**Test sequence**</td></tr>
<tr><td colspan="4">T10.1: H_2 systems constituted only by the ELY:
- Previously required test: T1, T2, T3 and T4 (energy 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 ELY activation are defined and that it will be activated unless for 1 hour.
- Run the test for 24 hours period.
- Switch OFF the ELY after the test.
- ELY Reactive Power Set Point will be kept at zero during the whole test duration.
- The FC will be kept in OFF state during the whole test duration.

T10.2: H_2 systems constituted by the ELY and the FC:
- Previously required test: T1, T2, T3, T4, T5, T6, T7 and T10.1 (energy 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 ELY activation are defined and that it will be activated unless for 1 hour.
o Verify that price thresholds for FC activation are defined and that it will be activated unless for 1 hour (the activation of the FC should be after the activation of the ELY so that there is hydrogen in the tank).
- Run the test for 24 hours period.
- Switch OFF the ELY and the FC after the test.
- ELY and FC Reactive Power Set Point will be kept at zero during the whole test duration.</td></tr>
<tr><td>**Test duration**</td><td colspan="3">24 hours (shorter periods are also possible)</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>ELY State</td><td>10 seconds</td><td>ELY Reactive Power</td><td>10 seconds</td></tr>
<tr><td>ELY Active Power Set point</td><td>10 seconds</td><td>H_2 quality</td><td>10 seconds</td></tr>
<tr><td>ELY Active Power</td><td>10 seconds</td><td>ELY H_2 flow</td><td>10 seconds</td></tr>
</table>

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 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 according to the defined thresholds.			
Verify that the FC was activated at the highest price hours according to the defined thresholds.			

Table 25. Field Test T11: Weakly Connected Mini-grid Use case. A4-Store surplus energy through storage of hydrogen.

Field Test T11: Weakly Connected Mini-grid Use Case. A4-Store surplus energy through storage of hydrogen

Objective: Verify the correct operation of the hydrogen system under store surplus operation strategy producing hydrogen when the wind farm generation exceeds the power limit at the connection point. The ELY would produce hydrogen with the energy surplus generated in the wind farm. The FC will re-electrify the hydrogen whenever the wind farm power generation is below the export limit

Test Pre-conditions

ELY	-	OFF
FC	-	OFF
Tank	-	Empty Tank
Room temperature	-	TBD (within the temperature range of the hydrogen system operation)

Test sequence

T11.1: H_2 systems constituted only by the electrolyser:

- Previously required test: T1, T2, T3 and T4 (Store Surplus Energy algorithms should be tuned according to test results).
- Verify main aspect of the Store Surplus Energy algorithms:
    - There is access to wind farm and PCC Power measurements.
    - A wind farm power production limit for hydrogen generation 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 ELY after the test.
- ELY Reactive Power Set Point will be kept at zero during the whole test duration.
- The FC will be kept in OFF state during the whole test duration.

T11.2: H_2 systems constituted by the ELY and the FC:

- Previously required test: T1, T2, T3, T4, T5, T6, T7 and T11.1 (Store Surplus Energy algorithms should be tuned according to test results).
- Verify main aspects of the Store Surplus Energy algorithms:
    - There is access to Wind farm and PCC Power measurements.
    - A wind farm power production limit for hydrogen re-electrification 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 ELY and the FC after the test.
- ELY and FC 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 power was above the limit.
Verify that the FC was only activated when the Wind Farm power was below the limit.

Table 26. Field Test T12: Weakly Connected Mini-grid Use case. A5-Respond to DR programs.

Field Test T12: Weakly Connected Mini-grid Use case. A5-Respond to DR programs			
Objective: Verify the correct operation of the hydrogen system as a manageable load able to follow Demand Response programs, mainly through the power consumed by the ELY in a controlled way.			
Test Pre-conditions			
ELY	- Standby		
FCl	- 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 (Demand Respond program algorithms should be tuned according to test results). - Verify main aspect of the Demand Respond algorithm: o There is access to Wind farm and PCC Power measurements. o There is access to the Demand Response program to be fulfilled according to market or DSO signals o If there is no access to the DR signal, it could be created a 24 hours DR profile typical of DR-based flexibility services. o The inputs to the controller are load demand (P_{ref}), power generation (P_w), and initial conditions of devices states, powers and level of hydrogen in the storage tank - Run the test for the test period (24 hours or less depending on the selected profile). - ELY Reactive Power Set Point will be kept at zero during the whole test duration - The FC will be kept in OFF state during the whole test duration.			
Test duration	24 hours (shorter periods are also possible)		
Required 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	DR signal applied	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 ELY active power varies accordingly to the DR profile established.			
Verify that that ELY instant error is below the maximum allowable error.			

Table 27. Field Test T13: Islanded Mini-grid Use case. B1-Contribution to the supply of energy demanded by the local load.

Field Test T13: Islanded Mini-grid use case. B1- Contribution to the supply of energy demanded by the local load	
Objective: This is a similar test than T8 but for the islanded mode of the mini-grid. The objective is to verify the correct operation of the hydrogen system collaborating with the wind farm but, in this case, without the connection to the main grid, in the supply of the energy demanded by the local load, basically completing the active power required.	
Test Pre-conditions	
ELY	- OFF or Standby if it is going to be operated to generate the hydrogen required by the FC to generate energy
FC	- Standby
Tank	- ELY OFF: Full enough to support the FC during the test execution - ELY Standby/ON: Could be empty depending on the balance between the hydrogen produced by the ELY and consumed by the FC
Connections	- Wind farm, hydrogen system and its system, and the load connected between them but disconnected from the main grid setting an islanded mini-grid
Room temperature	- TBD (within the temperature range of the hydrogen system operation)
Test sequence	
- Previously required test: T1, T5, T6 and T7 (Local load supply algorithms should be tuned according to test results). - Verify main aspect of the local load supply algorithm: o There is access to Wind farm and PCC Power measurements. o There is access to the local load power signal. o A local demand forecast curve has been defined. o If there is no access to the local load power signal it is necessary to create a 24 hours local load power profile. - Run the test for the test period (24 hours or less depending on the selected profile). - FC 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**
FC State	1 second	FC Reactive Power	1 second
FC Active Power Set point	1 second	H_2 quality	1 second
FC Active Power	1 second	FC H_2 flow	1 second
FC Reactive Power Set point	1 second	FC Alarms	1 second
Tanks pressure	1 second	Local Load power profile (P_{avl}, P_{ref})	1 second
Active Power in the PCC	1 second	Local load power forecasts	1 second
WF Active Power	1 second	Wind farm power (P_W)	1 second
		Room temperature	1 second

Required Calculations	
Parameter	**Parameter**
Total Energy generated by the FC	Total energy supplied to the local load
Total Energy consumed by the ELY	Total Energy produced by the Wind Farm
Total Energy consumed by Auxiliaries	Total Energy exchanged in the PCC (P_{fc}-P_{ez})
H_2 consumed by the FC	FC Answer Instant Error (1s)
Required Verifications	
Verify that the total Energy exchanged in the PCC is the sum of ELY, FC and auxiliaries' total energy.	
Verify the matching of generation and load within times ranges of order of minutes.	
Verify that the FC active power varies according to the local load profile completing, when required, the supply of the wind farm.	
Verify that that FC 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 of time. Some of the operation strategies may not make sense currently at demonstration stage. For example, it seems to be not feasible to achieve an islanded mini-grid topology disconnecting the wind farm from the main grid, or to receive demand response profiles for the corresponding aggregator (market related issues) or DSO (grid related issues). However, all operation strategies are considered here just in the case it would be possible to set up the demonstration scenarios corresponding to the considered operation strategies.

Table 28. Demonstration Field Test T14: Weakly Connected Mini-grid use case. A1-Generation and local load matching.

Demonstration Field Test T14: Weakly Connected Mini-grid use case. A1-Generation and local load matching			
Objective: Demonstrate the correct operation of the hydrogen system providing the required energy to the local load in collaboration to the wind farm and a weak connection to the grid with limited power available.			
Test Pre-conditions			
ELY	- OFF		
FC	- OFF (not used in this use case)		
Tank	- Empty Tank		
Test sequence			
- Previously required test: T8. - Before starting the demonstration, phase carry out Test 5 to assess the FC efficiency. - The profile reference for the wind farm power, weak grid power, local load forecast and local load power measured should be the actual ones. - 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 T5 to assess the FC efficiency degradation. General considerations: - FC 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**
FC State	1 second	FC Reactive Power	1 second
FC Active Power Set point	1 second	H_2 quality	1 second
FC Active Power	1 second	FC H_2 flow	1 second
FC Reactive Power Set point	1 second	FC Alarms	1 second
Tanks pressure	1 second	Local Load power profile (P_{avl}, P_{ref})	1 second
Active Power in the PCC	1 second	Local load power forecasts	1 second
WF Active Power	1 second	Grid power (P_{gridl})	1 second
Room temperature	1 second	Wind farm power (P_W)	1 second
Required Calculations			

Parameter	Parameter
Total Energy consumed by FC	FC mean H_2 production rate
Cost of Energy consumed by FC	FC mean H_2 quality
Total H_2 Produced by FC	FC efficiency degradation
FC mean, Median, Mode Active Power	FC MTBF
FC total number of working hours	FC ROI
FC Instant Answer Error (1s)	FC OPEX during the demonstration
FC 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 the wind H_2 system
NPV of the H_2system	LCOH2

Table 29. Demonstration Field Test T15: Weakly Connected Mini-grid use case. A2- Real-time energy profile matching within the intra-day market.

Demonstration Field Test T15: Weakly Connected Mini-grid use case. A2- Real-time energy profile matching within the intra-day market			
Objective: Demonstrate the correct operation of the hydrogen system providing the required energy to the market according to the committed energy profile in collaboration to the wind farm.			
Test Pre-conditions			
ELY	- OFF		
FC	- OFF (not used in this use case)		
Tank	- Empty Tank		
Test sequence			
- Previously required test: T9. - Before starting the demonstration, phase carry out Test 5 to assess the FC efficiency. - The profile reference for the wind farm power and the intraday energy profile to be delivered to the market should be the actual ones. - 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 T5 to assess the FC efficiency degradation. General considerations: - EY 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**
FC State	1 second	FC Reactive Power	1 second
FC Active Power Set point	1 second	H_2 quality	1 second
FC Active Power	1 second	FC H_2 flow	1 second
FC Reactive Power Set point	1 second	FC Alarms	1 second
Tanks pressure	1 second	Power delivered to the market	1 second
Active Power in the PCC	1 second	Grid power (P_{gridl})	1 second
WF Active Power	1 second	Wind farm power (P_W)	1 second
Room temperature	1 second		
Required Calculations			
Parameter		**Parameter**	
Total Energy consumed by FC		FC mean H_2 production rate	
Cost of Energy consumed by FC		FC mean H_2 quality	
Total H_2 Produced by FC		FC efficiency degradation	
FC mean, Median, Mode Active Power		FC MTBF	
FC total number of working hours		FC ROI	
FC Instant Answer Error (1s)		FC OPEX during the demonstration	
FC 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 the wind H_2 system	
NPV of the H_2system		LCOH2	

Table 30. Demonstration Field Test T16: Weakly Connected Mini-grid Use case. A3-Energy Price Arbitrage.

Demonstration Field Test T16: Weakly Connected Mini-grid Use case. A3-Energy Price Arbitrage
Objective: Verify, during the considered demonstration period, the correct operation of the hydrogen system under the energy price reference storing energy as hydrogen when the energy market price is low and in the subsequent re-electrification when the energy market price is high.

Test Pre-conditions

ELY	- OFF
FC	- OFF.
Tank	- Empty Tank

Test sequence

T16.1: H_2 systems constituted only by the ELY:

- Previously required test: T10.1.
- Before starting this demonstration test, carry out Test T2 to assess ELY 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 FC will be kept in OFF state during the whole test duration.

T16.2: H_2 systems constituted by the ELY and the FC:

- Previously required test: T10.2.
- Before starting this demonstration test, carry out Test T2 and T5 to assess ELY and FC 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.
- ELY and FC 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 31. Demonstration Test T17: Weakly Connected Mini-grid Use case. A4-Store surplus energy through storage of hydrogen.

Demonstration Field Test T17: Weakly Connected Mini-grid Use case. A4-Store surplus energy through storage of hydrogen			
Objective: Verify during the considered demonstration period the correct operation of the hydrogen system under store surplus operation strategy producing hydrogen when the wind farm generation exceeds the power limit at the connection point. The ELY would produce hydrogen with the energy surplus generated in the wind farm. The FC will re-electrify the hydrogen whenever the wind farm power generation is below the export limit			
Test Pre-conditions			
Electrolyser	- OFF		
Fuel Cell	- OFF		
Tank	- Empty Tank		
Test sequence			
T17.1: H_2 systems constituted only by the ELY: - Previously required test: T11.1. - Before starting the demonstration, phase carry out Test T2 to assess ELY 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. T17.2: H_2 systems constituted by the ELY and the FC: - Previously required test: T11.2. - 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 32. Demonstration Field Test T18: Weakly Connected Mini-grid Use Case. A5-Respond to DR programs.

Demonstration Field Test T18: Weakly Connected Mini-grid Use Case. A5-Respond to DR programs

Objective: Verify during the considered demonstration period the correct operation of the hydrogen system as a manageable load able to follow Demand Response programs, mainly through the power consumed by the ELY in a controlled way

Test Pre-conditions

ELY	- OFF
FC	- OFF (not used in this use case)
Tank	- Empty Tank

Test sequence

- Previously required test: T12.
- Before starting the demonstration, phase carry out Test T2 to assess electrolyser efficiency.
- A reference DR profile, actual or emulated, should be continuously available for the demand response algorithm.
- 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:

- ELY 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	DR effect achieved	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 DR regulation service	Total income for the wind H_2 system
NPV of the H_2system	LCOH2

Table 33. Demonstration Field Test T19: Islanded Mini-grid Use Case. B1-Contribution to the supply of energy demanded by the local load.

<table>
<tr><th colspan="4">Demonstration Field Test T19: Islanded Mini-grid Use Case. B1-Contribution to the supply of energy demanded by the local load</th></tr>
<tr><td colspan="4">Objective: Demonstrate during the corresponding demonstration period the correct operation of the hydrogen system providing the required energy to the local load in collaboration to the wind farm and without any connection to the grid.</td></tr>
<tr><td colspan="4">Test Pre-conditions</td></tr>
<tr><td>ELY</td><td colspan="3">- OFF</td></tr>
<tr><td>FC</td><td colspan="3">- OFF (not used in this use case)</td></tr>
<tr><td>Tank</td><td colspan="3">- Empty Tank</td></tr>
<tr><td colspan="4">Test sequence</td></tr>
<tr><td colspan="4">- Previously required test: T13.
- Before starting the demonstration, phase carry out Test 5 to assess the FC efficiency.
- The profile reference for the wind farm power, the local load forecast and local load power measured should be the actual ones.
- 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 T5 to assess the FC efficiency degradation.
General considerations:
- FC 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.</td></tr>
<tr><td>Test duration</td><td colspan="3">>xx months</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 State</td><td>1 second</td><td>FC Reactive Power</td><td>1 second</td></tr>
<tr><td>FC Active Power Set point</td><td>1 second</td><td>H_2 quality</td><td>1 second</td></tr>
<tr><td>FC Active Power</td><td>1 second</td><td>FC H_2 flow</td><td>1 second</td></tr>
<tr><td>FC Reactive Power Set point</td><td>1 second</td><td>FC Alarms</td><td>1 second</td></tr>
<tr><td>Tanks pressure</td><td>1 second</td><td>Local Load power profile (P_{avl}, P_{ref})</td><td>1 second</td></tr>
<tr><td>Active Power in the PCC</td><td>1 second</td><td>Local load power forecasts</td><td>1 second</td></tr>
<tr><td>WF Active Power</td><td>1 second</td><td>Wind farm power (P_W)</td><td>1 second</td></tr>
<tr><td>Room temperature</td><td>1 second</td><td>Room temperature</td><td>1 second</td></tr>
<tr><td colspan="4">Required Calculations</td></tr>
<tr><td colspan="2">Parameter</td><td colspan="2">Parameter</td></tr>
<tr><td colspan="2">Total Energy consumed by FC</td><td colspan="2">FC mean H_2 production rate</td></tr>
<tr><td colspan="2">Cost of Energy consumed by FC</td><td colspan="2">FC mean H_2 quality</td></tr>
<tr><td colspan="2">Total H_2 Produced by FC</td><td colspan="2">FC efficiency degradation</td></tr>
<tr><td colspan="2">FC mean, Median, Mode Active Power</td><td colspan="2">FC MTBF</td></tr>
<tr><td colspan="2">FC total number of working hours</td><td colspan="2">FC ROI</td></tr>
<tr><td colspan="2">FC Instant Answer Error (1s)</td><td colspan="2">FC OPEX during the demonstration</td></tr>
<tr><td colspan="2">FC mean, median, mode answer error</td><td colspan="2">Water consumption</td></tr>
<tr><td colspan="2">Total Energy exchanged in the PCC</td><td colspan="2">Total Energy produced by the WF</td></tr>
<tr><td colspan="2">Total Energy consumed by Auxiliaries</td><td colspan="2">Total Income for the Energy of the WF</td></tr>
<tr><td colspan="2"></td><td colspan="2">Total income for the wind H_2 system</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td colspan="2">NPV of the H_2system</td><td colspan="2">LCOH2</td></tr>
</table>

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 34.

Table 34. 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 35. 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	**3**	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
5	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
6	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
7	Problem with data recording and monitoring	Low	Medium	**4**	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.

[2] D5.1 Energy analysis of the Raggovidda integrated system. HAEOLUS H2020 FCHU EU funded project. www.haeolus.eu.

[3] Aaron Hoskin, Allan Schrøder Pedersen, Elli Varkaraki, Francisco Javier Pino, Ismael Aso, Jesús Simón, Jochen Lehmann, Jörg Linnemann, Klaus Stolzenburg, Lorenzo Castrillo, Milagros Rey, Pablo Fontela, Raquel Garde, Raymond Schmid, Rita Mubbala, Rupert Gammon, Salvador Suarez, Stein Trygve Briskeby, and Stian Nygaard. *Task 24: Wind Energy and Hydrogen Integration—Final report. Tech. rep. International Energy Agengy - Hydrogen Implementing Agreement, 2013*. url: http://ieahia.org/pdfs/Task_24_final_report.aspx.

[4] Supporting Document for the Network Code on Load Frequency Control and Reserves. 2013. ENTSO-E.

[5] D1.1 Electrical Grid Service Catalogue for Water Electrolyser. QualyGrids H2020 FCHU EU funded project. www.qualygrids.eu.

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

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

[8] D6.3 Control system for mini-grid use case. www.haeolus.eu.

[9] D8.1 Protocols for demonstration of energy-storage strategy. www.haeolus.eu.

[10] D8.6 Field demonstration results with mini-grid strategy. www.haeolus.eu.

[11] 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.

[12] 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:

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

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

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

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.

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