DELIVERABLE D8.3

***PUBLIC***

# Protocols for demonstration of fuel-production strategy

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**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 fuel-production use case. Fuel-production use case covers the option of the combination of the wind-hydrogen systems that maximise the production of hydrogen by the electrolyser feed by the energy coming from the wind farm. The fuel production has the priority and the wind farm should produce as much hydrogen as required but also feeding a local load and selling to the electric market the extra hydrogen. These demonstration test protocols are related to the control algorithms defined by UNISANNIO and SINTEF for the fuel-production use case (D6.4 [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 fuel-production use case, and on-site demonstration protocols for defined strategies of the fuel-production use case are defined in this document. Some of these testing protocols were already defined and included in D8.1 [9] and D8.2 [10] but are also adapted and included here to ensure the completeness and self-consistency of this document.

## Revision History

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# 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

PCP: 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 fuel-production 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) or just a clean way of producing green-hydrogen that is the specific purpose of this fuel-production use case. 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 and some of the operation modes of the fuel-production case.

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;

- Mini-grid use case:
  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.

- Hydrogen fuel-production use case:
  This use case is the focus of the demonstrations test cases defined in this document. 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;

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, demonstration test protocols for each of the aforementioned use cases will be developed. Particularly, in this document, the test protocols for the **fuel-production** use case demonstration 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 fuel-production 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 hydrogen consumption profiles or hydrogen sale possibilities, among other aspects. Any deviation with respect to what stated in this document will be reported in the deliverable D8.6 [11] 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 D6.4 [8] for the fuel-production use case. The verification of other grid- or energy market-related issues (i.e. frequency and voltage regulation, overload handling or market participation through hydrogen re-electrification) is not object of the present demonstration 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 control system 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 fuel-production use case and required for assessing the operation strategies of the corresponding control algorithms.
- Chapter 4 includes:
    - The on-site test protocols for the verification of the proper operation of the electrolyser and the fuel cell previously to the demonstration tests.
    - The on-site test protocols for the fuel-production operation strategies to check out the correct operations of the control system prior to start the demonstration campaign.
    - The on-site demonstration protocols for the fuel-production operation strategies during the demonstration campaign.
- Chapter 5 provides some risk considerations related to the defined demonstration tests with respect to the demonstration 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 1 bellow depicts the layout of the Raggovidda wind-hydrogen system, according to [8], along with its main components.

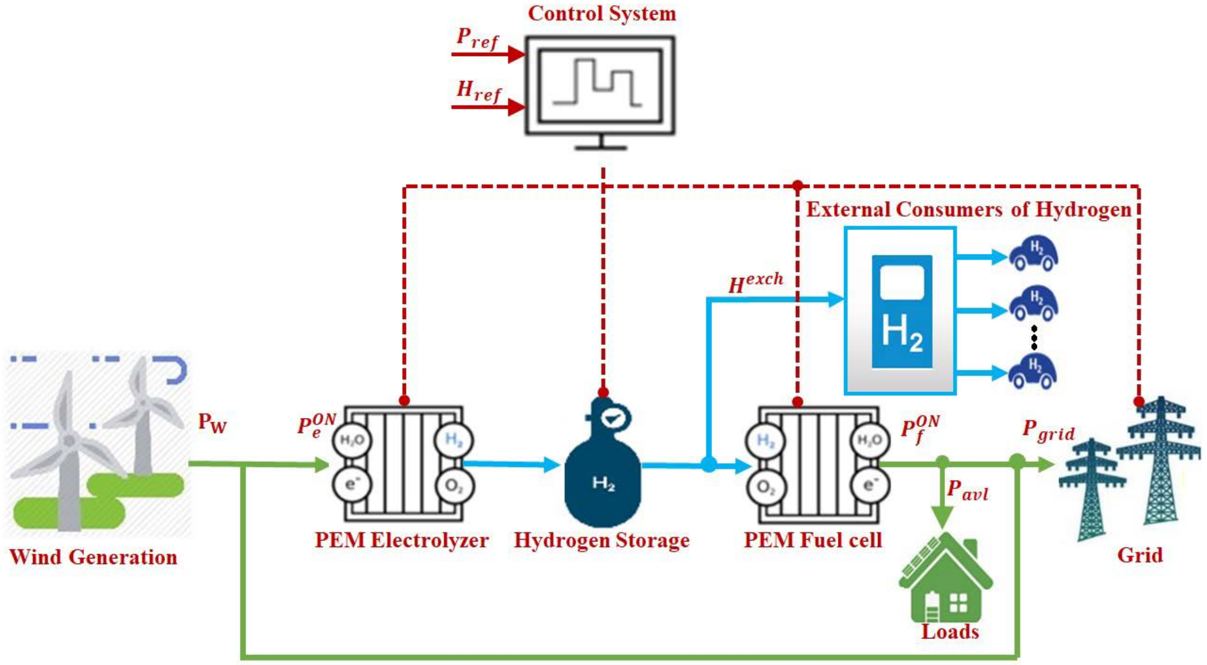

*Figure 1. System architecture for the fuel-production use case according to D6.4 [8]*

The Raggovidda wind-hydrogen system will be realized by adding 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 hydrogen storage tank of 65 m$^3$ to the current 45 MW Raggovidda wind farm.

The electrolyser will generate hydrogen according to the three different use cases targeted in the HAEOLUS project (energy-storage, mini-grid and hydrogen production). 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% of 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.

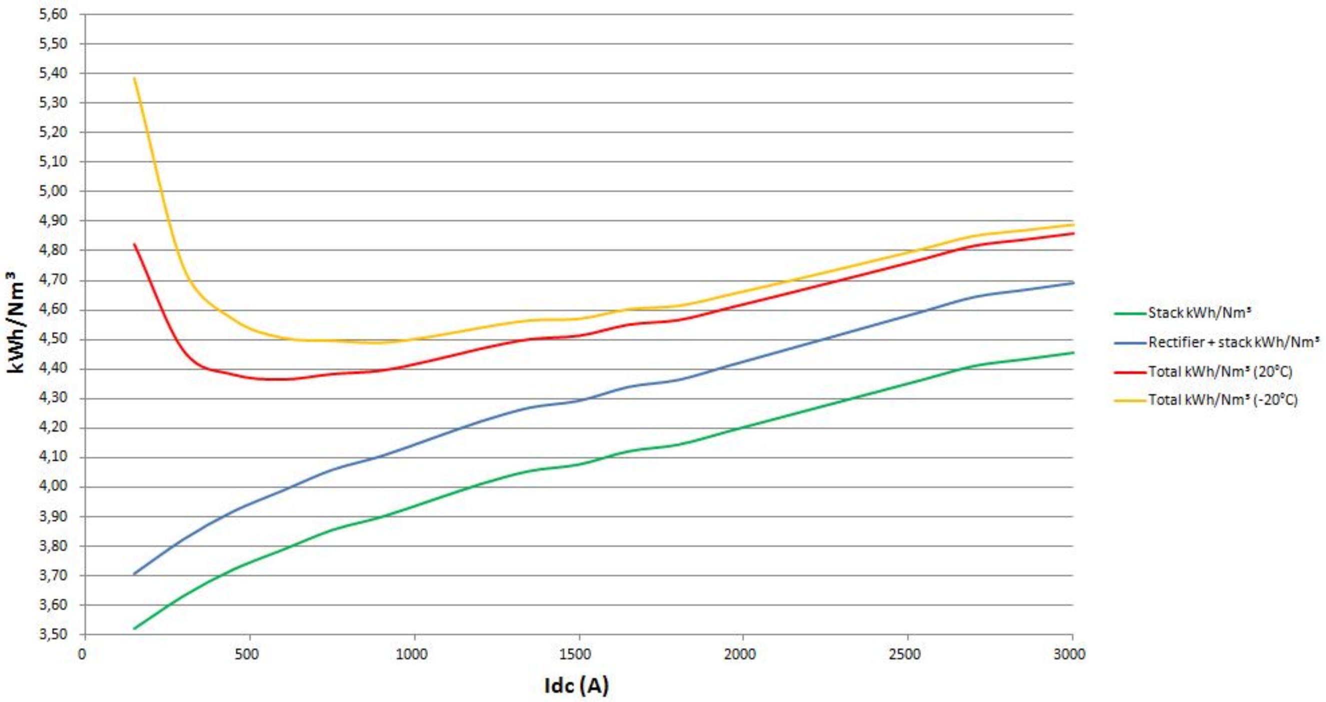

*Figure 2. Electrolyser efficiency curves.*

*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.

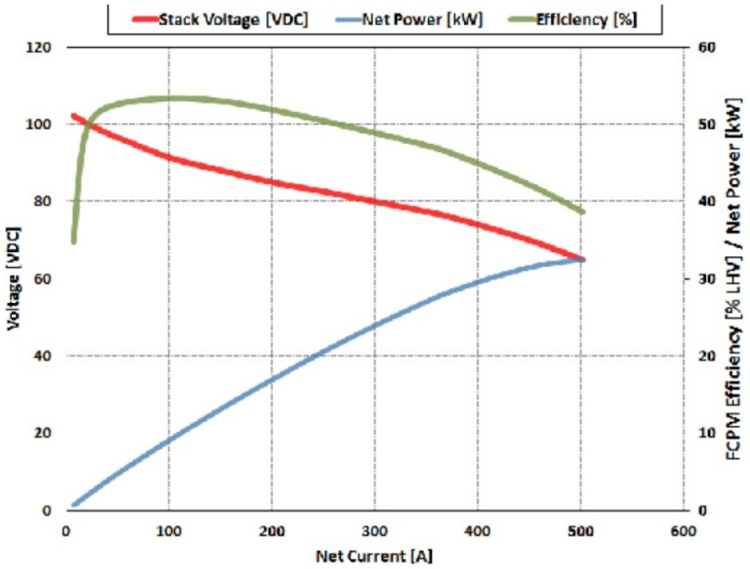

*Figure 3. Fuel cell efficiency curves.*

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 variables and parameters.*

| **Hydrogen storage tank variables and parameters** | | |
|---|---|---|
| **Variable/Parameter** | **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, and according to [8], the following Table 8 gathers those observable variables and 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 / Parameters** | **Units** | **Measurement devices** |
| ELY Active Power setpoint | MW | Controller |
| ELY Reactive Power setpoint | MVA | Controller |
| ELY status setpoint (OFF, ON, STANDBY) | --- | Controller |
| ELY: Electrical power | kW | Controller |
| FC Active Power setpoint | MW | Controller |
| FC Reactive Power setpoint | MVA | Controller |
| FC status setpoint (OFF, ON, STANDBY) | --- | Controller |
| FC: Electrical power | kW | Controller |
| Tank: Maximum level of the hydrogen storage unit | kg | Controller |
| Tank: Minimum level of the hydrogen storage unit | kg | Controller |
| Tank: Stored level of the hydrogen | kg | Controller/ Tank display |
| 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 |
| Grid: Available power delivered to the grid | kW | Controller/ meter |
| Grid power | kW | Controller/ meter |

# 3 The fuel-production Use Case

According to the International Energy Agency (IEA) [3], the main purpose of facilities conceived for fuel production is to supply hydrogen fuel to (road) vehicles. The simplest mode of electrolysis operation would be to produce and store hydrogen continuously on a 24 hours-a-day / 7 days-per-week basis to satisfy the average fuel demand. However, this plays no role in the management of wind power, as it does not respond to the variable output of either local or distant wind turbines, like the hydrogen-based one in the HAEOLUS project.

This study of the IEA [3] also considers advantageous a mixed approach that incorporates both re-electrification and fuel production.

Additionally, some fuel-production constraints are already anticipated in HAEOLUS project Grant Agreement that are also considered for this use case. This Grant Agreement states that the cases of electricity production and fuel production targets mainly set up real-time optimization problems on the energy flows. In this way, according to the profiles of electricity and hydrogen demand and the prices of the related energy, the wind production forecast and the operating constraints listed above, the controller will optimize on-line the power flow and, consequently, provide the optimal commitments profile of all the units

Those mentioned above approaches are being adopted in D6.4 [8] for the control algorithms specified for the fuel-production use case. According to [8], the fuel production has the priority for the Haeolus control system with the main aim for the wind farm to produce as much hydrogen as required.

It is assumed existing fuel cell vehicles using such generated hydrogen. That usage is modelled as a hydrogen demand profile to be tracked as the key reference for the reasoning of the Haeolus system control. This hydrogen load profile is basically a forecast on what will happen at long-term, e.g., tomorrow, according to the timing criteria adopted in the present control system design.

This approach is basically adopted to conform to the fuel production use case as considered in [3]. However, in order to have a meaningful control problem, it is assumed an existing local load to be fed and the possibility of selling electricity to the electric market with the extra hydrogen.

Therefore, the control system priorities are as follows:

1. To fulfil the defined hydrogen demand profile for a due period. For that purpose, the required energy coming from the wind farm will be used to feed the electrolyser which will produce the demanded hydrogen that will be stored in the hydrogen tank. The fill level of the tank would be the main parameter that would represent the hydrogen demand profile to be covered. This has the highest, unconditional priority.
2. Other option is to solve the market participation according to the committed energy profile.
3. Finally, the third option is to feed the local load by tracking as close as possible its corresponding energy profile.

The priority of the second and third options, market participation and local load feeding, is configurable in the control system by tuning the corresponding weights according to possible user-defined criteria (electricity price in the market or in the local community, energy use, etc.). Thus, the control system reasoning forces unconditionally the highest priority to the hydrogen demand tracking (with the sequential optimization) while the other two objectives can be mixed with configurable weights so that to achieve the wanted prioritization.

That is, the prioritization of the available energy generated by the Haeolus hybrid system is achieved solving the optimization in a sequential fashion. Firstly, the track of the hydrogen demand is made coming up with the optimal amount of hydrogen that has to be stored in the tank. This amount is used as a constraint in the second stage where the electricity market and the local load are addressed with configurable priorities according to the local load demand tracking and the maximization of profits by selling energy to the market.

All these considerations are taken into account for the specification of the fuel-production use case control system, provided in D6.4 [8], that is presented in brief in the next section 3.1.

## 3.1 Characteristics of the control system for the fuel-production use case

The following Figure 4 shows the multi-level approach featuring Model Predictive Control (MPC) schemes being used in the design and development of the fuel-production system control as defined in D6.4 [8].

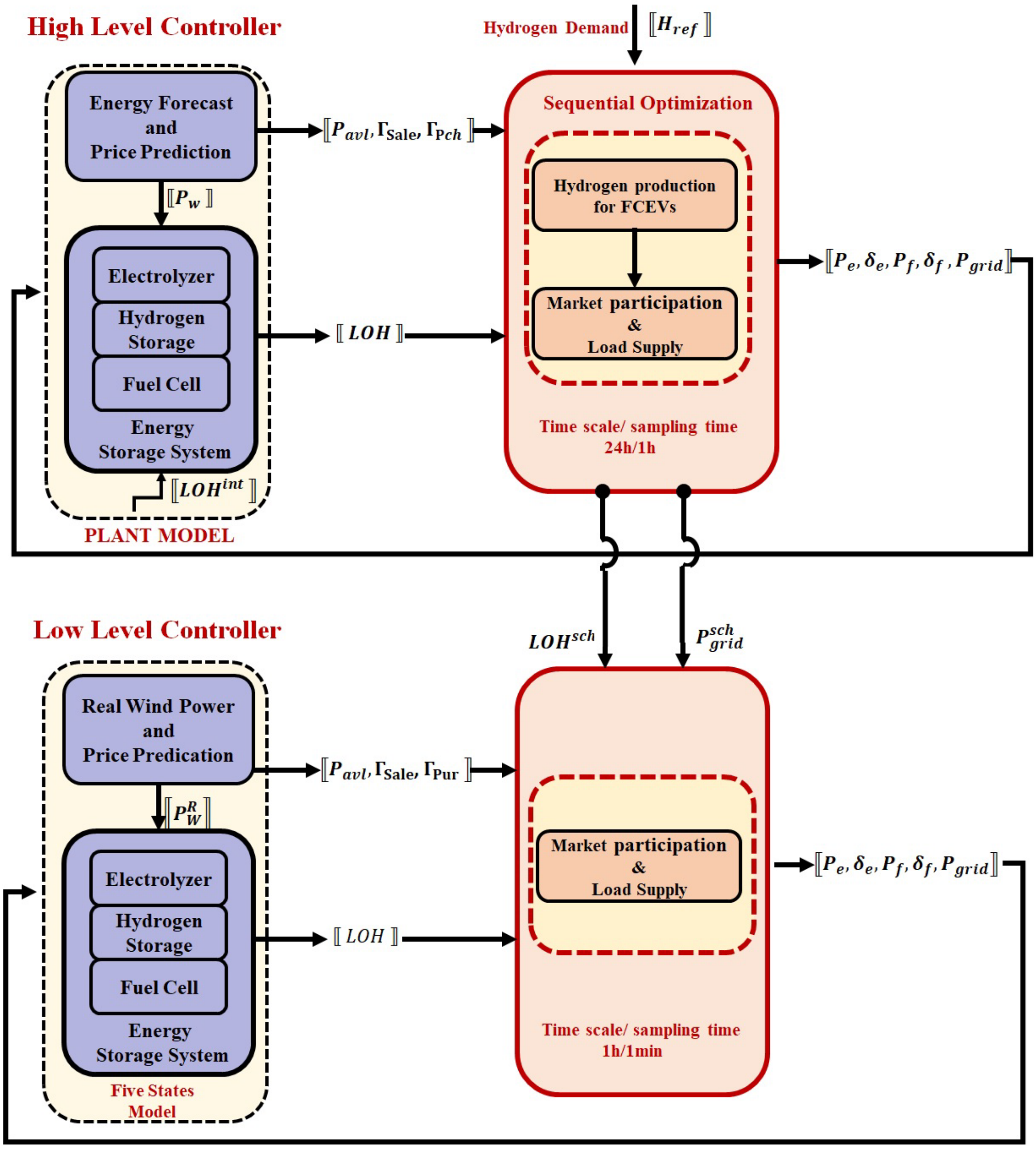

*Figure 4. Control design for the fuel-production system control according to D6.4 [8]*

This multi-level MPC approach is that it gives a freedom degree in the controller allowing to correct deficit scenario with exceeding scenario for both hydrogen and electricity production in comparison with the forecasts regarding the day-ahead energy market and local 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 (HLC) 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.

The following variables and parameters are identified from D6.4 [8] as relevant for the purpose of configuring the control system, launching the test cases and observing their results.

I. Main algorithm parameters relevant to the demonstration tests:

| | |
|---|---|
| $H^{max}$ | *Maximum Level of the hydrogen storage unit [Nm$^{3}$]* |
| $H^{min}$ | *Minimum Level of the hydrogen storage unit [Nm$^{3}$]* |
| $P_e^{max}$ | *Maximum power level of the electrolyser [kW]* |
| $P_e^{min}$ | *Minimum power level of the electrolyser [kW]* |
| $P_e^{CLD}$ | *Power required by the electrolyser for cold starts [kW]* |
| $P_e^{STB}$ | *Power required by the electrolyser in standby [kW]* |
| $P_e^{WRM}$ | *Power required by the electrolyser for warm starts [kW]* |
| $P_f^{max}$ | *Maximum power level of the fuel cell [kW]* |
| $P_f^{min}$ | *Minimum power level of the fuel cell [kW]* |
| $P_f^{CLD}$ | *Power required by the fuel cell for cold starts [kW]* |
| $P_f^{STB}$ | *Power required by the fuel cell in standby [kW]* |
| $P_f^{WRM}$ | *Power required by the fuel cell for warm starts [kW]* |
| $\eta_e$ | *Efficiency for the electrolyser* |
| $\eta_f$ | *Efficiency for the fuel cell* |
| *Cycles* | *Number of life cycles* |
| *NHe* | *Number of life hours of the electrolyser [h]* |
| *NHf* | *Number of life hours of the fuel cell [h]* |
| *HYe* | *Number of per year life hours of the electrolyser [h]* |
| *HYf* | *Number of per year life hours of the fuel cell [h]* |
| *Srep,e* | *Electrolyser stack replacement cost [AC/kW]* |
| *Srep,f* | *Fuel cell stack replacement cost [AC/kW]* |
| *Ts* | *Sampling period [h]* |
| *T* | *Simulation horizon [h]* |
| $\Gamma^{sale}$ | *Selling energy price [AC/kW h]* |

II. As forecast parameters:

| | |
|---|---|
| $P_w$ | *Wind power production [kW]* |
| $H_{ref}$ | *Hydrogen reference demand [kg]* |

III. The following variables are considered as relevant to the demonstration purposes:

| | |
|---|---|
| $H$ | *Stored level of the hydrogen [kg]* |
| $P_e$ | *Electrical power of the electrolyser [kW]* |
| $P_f$ | *Electrical power of the fuel cell [kW]* |
| $P_{avl}$ | *Available power delivered to the grid [kW]* |
| $P_{grid}$ | *Grid power [kW]* |

Other sort of information that could be relevant for the control system operation as references for the demonstration tests:

- Hydrogen demand profile forecasted [kg or Nm$^{3}$]
- Hydrogen demand price forecasted [€/kg or €/Nm$^{3}$]
- Local load demand profile forecasted [kW]
- Energy price of the local market related to the local load [€/kWh]
- Electricity market price forecasted [€/kWh].

## 3.2 Operation strategies to be tested in the demonstration campaign

Considering the fuel-production 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 D6.4 [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. Considering the three uses of the energy in this use case (fuel production, energy market and local load), the main control information to be taken as the reference for the govern and verification of the system control behaviour:
    - the forecast of hydrogen demand. Input information that would be translated into the required fill level of the hydrogen tank.
    - 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
    - the energy price profile from the corresponding market as input information for decision
    - the committed energy profile to be delivered to the energy market as input information to be tracked.
    - the forecast of local demand. Input information to be tracked when possible.

Additionally, it is important to remark that these operation strategies defined below, and their corresponding demonstration test cases, are proposed taking into account the specification of the fuel-production 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, it could be considered a unique operation strategy that is:

***To produce, always, the defined hydrogen demand profile with the existing energy produced by the wind farm***

However, some kind of secondary operation strategies could be considered when the energy available from the wind farm is bigger than required for the specific use considered and taking into account that only this wind energy will be used for the generation of hydrogen.

With this criterion, the following possibilities are considered that would be translated into the corresponding demonstration test cases:

a) While the hydrogen level ($H$) is under the hydrogen demand level ($H_{ref}$) the fuel cell will be off, And the wind power production ($P_w$) is under the maximum power level of the electrolyser ($P_e^{max}$), all the wind power will be used for feeding the electrolyser ($P_e$) at its highest power level with a limit at $P_e^{max}$.

b) While the hydrogen level ($H$) is over the hydrogen demand level ($H_{ref}$), perhaps with a specific margin, the wind power production will be used, depending on the level, to market participation and local load feeding. Additionally, the excess of the stored hydrogen ($H - H_{ref}$) will be re-electrified through the fuel cell to contribute, jointly the wind farm, to that market participation and local load feeding according to the configured weights of these two options in the control system. The possible surplus of combined wind-hydrogen electricity generation could be used to feed the electrolyser to produce additional hydrogen till the maximum capacity of the hydrogen tank ($H^{max}$).

That operation strategy stated above is described in more detail in the following based on the following operation modes according to each of the three uses being attended:

I. Hydrogen production mode. This operation mode is always active while the stored hydrogen level in the tank is under the reference hydrogen demand profile. It basically consists in producing hydrogen according to a specific hydrogen demand profile with the wind farm generation. Thus, the electrolyser would produce hydrogen using the required energy at each moment from that one generated in the wind farm. The hydrogen level dynamics is managed basically by the High Level Control (HLC) with a tracking lapse of time of 1 h. Those main technical requirements to be met in order to achieve the surplus energy storing operation strategy are reported in Table 9

*Table 9. Hydrogen production operation mode. Technical requirements.*

| **Hydrogen demand profile matching** | | | |
|---|---|---|---|
| **Response time** | **Ramp rate** | **Duration** | **Market schedule** |
| 1 hour | Depending on the hydrogen demand profile and wind generation profiles ramp rate | 24 hours (*) | According to 24h/1h basis for the production of hydrogen for transport |

(*) At least, 24 hours in order to verify properly the HLC control level

II. Re-electrification and real-time energy profile matching within the intra-day market. This operation mode occurs once covered the hydrogen demand profile providing energy to the market from the wind production surplus and the re-electrification of the exceeding hydrogen when the market-local load weight parameter is properly configured, in this case, giving priority to the market. Table 11 shows the main technical requirements needed for achieving this electricity market matching. 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 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 (2h are considered for proper verification) 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 mode. Technical requirements.

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

(*) At least, 2 hours in order to verify properly the HLC and LLC control levels

III. Re-electrification and local load matching, once covered the (instantly) hydrogen load profile and the market-local load weight parameter is configured as prioritising the local load, , the exceeding hydrogen is re-electrified to feed the local load according to its profile defined, observing the real-time (related to the LLC although the HLC is internally processing the 1h tracking) measurements of generation and load consumption to calculate available power to feed that local load. Hydrogen system should complete the energy generated by the wind farm and coming from the main grid when required. Table 11 shows the main technical requirements needed for achieving this local load matching.

Table 11. Local load matching operation strategy. Technical requirements.

| **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, 2 hours in order to verify properly the HLC and LLC control levels

# 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 4.1.2
   3. The FC in section 4.1.3

b) The verification, at the beginning of the demonstration phase, of the operation strategies defined in the section 3.2, identified as initial **field test protocols** in section 4.2.1

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 4.2.2.

## 4.1 Preliminary system components verification

### 4.1.1 Functional test of the own control system

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

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

*Table 12. Test T1: Systems Controller functional tests.*

| **Test T1: Systems Controller functional tests** | |
|---|---|
| **Objective:** To test the communication links between the main controller, the SCADA and the elements. | |
| **Item to verify** | **State** |
| Communication with the electrolyser:<br>1. Parameters monitoring (see ELY-related parameters in section 3.1)<br>2. State control (ON, OFF, STANDBY)<br>3. Power set point | OK/NOK |
| Communication with the fuel cell:<br>4. Parameters monitoring (see FC-related parameters in section 3.1)<br>5. State control (ON, OFF, STANDBY)<br>6. Power set point | OK/NOK |
| Communication with the hydrogen storage tank controller<br>7. Parameters monitoring (see hydrogen tank-related parameters in section 3.1) | OK/NOK |
| Communication with the wind farm:<br>8. Parameters monitoring (see wind farm-related parameters in section 3.1) | 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 |

### 4.1.2 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.

#### *4.1.2.1 ELY on-site nominal production capacity and efficiency*

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

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

| **Test T2: ELY on-site nominal production capacity and efficiency** | | | |
|---|---|---|---|
| **Objective:** Calculate the ELY onsite efficiency for the whole production range. | | | |
| **Test Pre-conditions:** | | | |
| Electrolyser | - OFF<br>- 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).<br>- Run the electrolyser at 0.3 MW (minimum power) for 1 hour (or the time required to reach the working temperature).<br>- 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.<br>- Run the electrolyser from 100% to 10 % of $P_n$ in steps of 10% for 1 hour at each production ratio.<br>- 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 Power) | 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. | | |

#### 4.1.2.2 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 correspond to the states transition scheme of the HLC modelling, relevant for the fuel production mode, shown in the following Figure 5 as is described in [8].

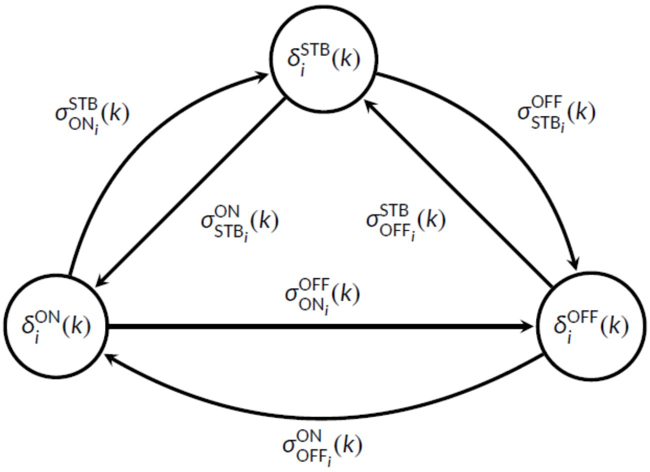

*Figure 5: Automata of the electrolyser (i = e) for the HLC.*

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. The Table 14 reflects these mentioned tests.

*Table 14. Test T3: ELY on-site hot and cold start (i=e)*

| **Test T3: ELY on-site hot and cold start** | |
|---|---|
| **Objective:** Verify ELY cold and hot start duration and consumption. | |
| **Test Pre-conditions:** | |
| Electrolyser | - OFF<br>- 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.<br>- Keep the ELY 1 hour in Full Power.<br>- Switch ELY from Full Power to STB.<br>- Keep the ELY 1 hour in Standby.<br>- Switch ELY from Standby to Full Power. | |

| | | | |
|---|---|---|---|
| - Keep the ELY 1 hour in Full Power.<br>- Switch ELY from Full Power to OFF.<br>- Switch ELY from OFF to STB states<br>- Keep ELY 1 hour in STB<br>- 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. | | |

#### *4.1.2.3 ELY on-site dynamic response*

*Table 15. 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"><b>Objective:</b> Verify ELY dynamic response to P/Q setpoint, verify the ramp rates and the electrolyser control accuracy.</td></tr>
<tr><td colspan="4"><b>Test Pre-conditions</b></td></tr>
<tr><td>Electrolyser</td><td colspan="3">- Standby<br>- 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"><b>Test sequence</b></td></tr>
<tr><td colspan="4">Start:<br>- Electrolyser working at minimum power (0,3 MW) for 1 hour.<br>Test 4.1<br>- Power Step-change from 12% to 50% of $P_n$ (from 0.3 MW to 1.25 MW).<br>- Power Step-change from 50% to 100% of $P_n$ (from 1.25 MW to 2.5 MW).<br>- Power Step-change from 100% to 50% of $P_n$ (from 2.5 MW to 1.25 MW).<br>- Power Step-change from 50% to 12% of $P_n$ (from 1.25 MW to 0.3 MW).<br>Test 4.2<br>- Power Step-change from 12% to 100% of $P_n$ (from 0.3 MW to 2.5 MW).<br>- Power Step-change from 100% to 12% of $P_n$ (from 2.5 MW to 0.3 MW).<br>- Put the electrolyser in Standby.<br>Test 4.3<br>- Power Step-change from Standby to 100 % of $P_n$ (from Standby to 2.5 MW).<br>- Power Step-change from 100 % to 0% of $P_n$ (from 2.5 MW to Standby).<br><br>General considerations:<br>- Keep the electrolyser working at each set a minimum of 300 seconds or until the error is below ±1 %.<br>- 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><b>Test duration</b></td><td colspan="3">Not relevant (estimated less than 1 hour)</td></tr>
<tr><td colspan="4"><b>Required Data Recording</b></td></tr>
<tr><td><b>Variable</b></td><td><b>Sampling</b></td><td><b>Variable</b></td><td><b>Sampling</b></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"><b>Required Calculations</b></td></tr>
<tr><td><b>Parameter</b></td><td colspan="3"><b>Description</b></td></tr>
<tr><td>Response accuracy</td><td colspan="3">Calculated as root-mean-square error between actual response and command.</td></tr>
</table>

| | |
|---|---|
| $t_p$ | Peak power time for each power step change. |
| $t_s$ | Setting time (time to reach a stable answer with an error below ±1 %). |

In order to assess the dynamic response of the electrolyser, the typical parameters of the response of a second-order system will be considered, see Figure 6. 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.

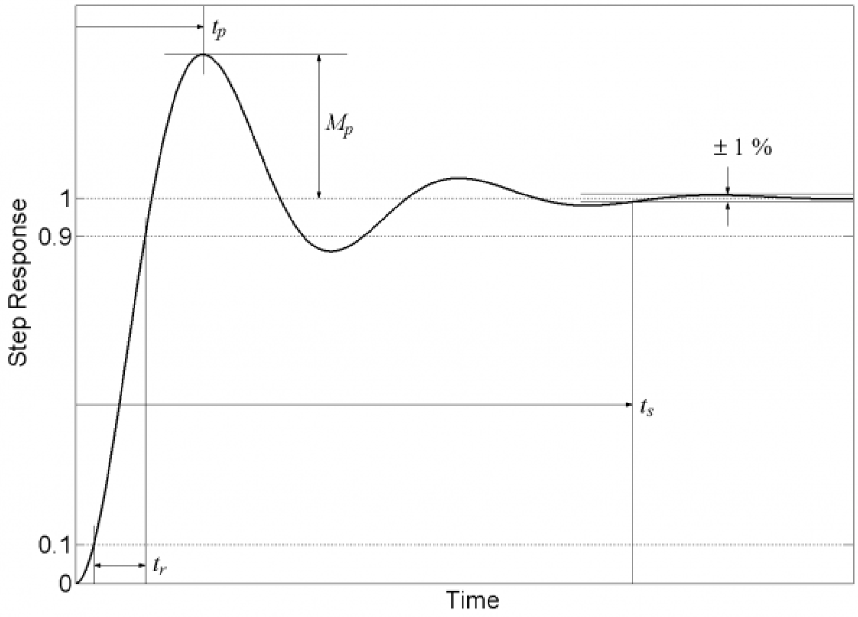

*Figure 6. Second order system typical response (just as reference for parameters definition).*

### 4.1.3 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.

### 4.1.3.1 FC on-site nominal production capacity and efficiency

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

| **Test T5:FC on-site nominal production capacity and efficiency** | | | |
|---|---|---|---|
| **Objective:** Calculate the FC onsite efficiency for the power range. Carry out the test at the beginning and end of the demonstration tests. | | | |
| **Test Pre-conditions** | | | |
| Electrolyser | Not used for this test (OFF) | | |
| Fuel cell | OFF (condition before test start) | | |
| 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).<br>- Run the fuel cell at 12 kW (minimum power) for 1 hour (the time required to reach working temperature).<br>- 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.<br>- 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. | | |

### 4.1.3.2 FC on-site hot and cold start

In a similar way to what described for the electrolyser in section 4.1.2.2, the FC have different state transition models for the HLC and the LLC. However, the LLC modelling is the one relevant for the eventual hydrogen re-electrification for feeding the local load and for the participation in the energy market, the short time features for the FC 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 previously in the Figure 5.

However, the more demanding state transition for the FC is related to the LLC, with the scheme of state transition depicted in the following Figure 7 the as defined in [8].

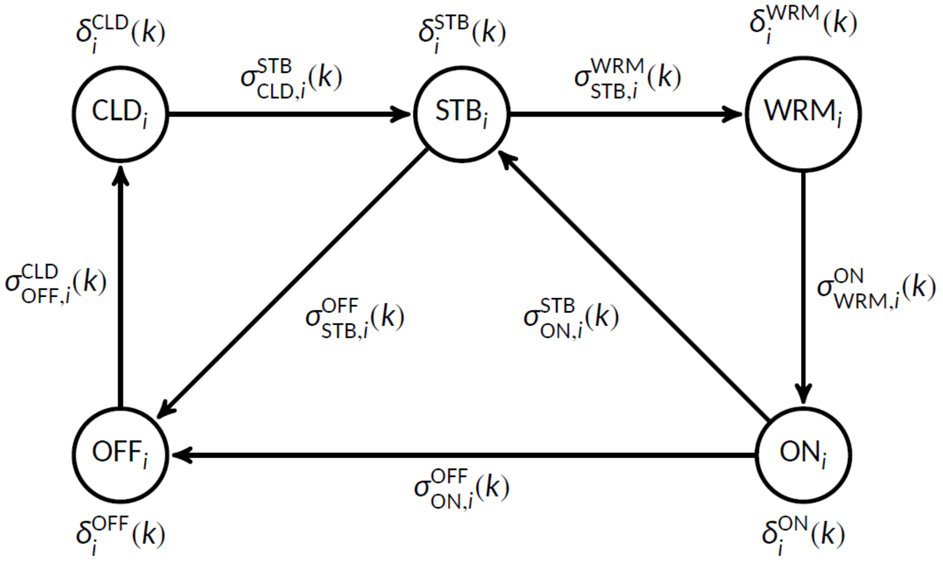

*Figure 7: Automata of the electrolyser (i = e) and of the fuel cell (i = f).*

These three states are verified at the demonstration phase according to test T6 in Table 17 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 T6: FC on-site hot and cold start.*

| **Test T6: FC on-site hot and cold start** | | | |
|---|---|---|---|
| **Objective:** Verify FC cold and hot start duration and consumption. | | | |
| **Test Pre-conditions** | | | |
| Electrolyser | - Not used for this test (OFF) | | |
| Fuel cell | - OFF (Condition before test start) | | |
| 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** | | | |
| **Cold Start:**<br>- Switch ON the FC and bring it to 100 kW.<br>- Keep the FC at 100 kW until reaching stack operational temperature.<br>- Shift from 100 kW power to Standby.<br>- Switch the FC from Standby to OFF<br>**Hot start:**<br>- Switch the FC from OFF to Standby<br>- Shift from Standby to 100 kW.<br>- Switch OFF the FC. | | | |
| **Test duration:** | Non relevant (less than 1 hour) | | |
| **Required Data Recording** | | | |
| **Variable** | **Sampling** | **Variable** | **Sampling** |
| FC Active Power | 10 seconds | Room temperature | 1 minute |
| Auxiliaries Consumption | 10 seconds | Tank pressure | 1 seconds |

|  |  |  |  |
|---|---|---|---|
| Onsite Active Power (Overall consumption) | 10 seconds | FC $H_2$ consumption flow | 1 seconds |
| **Required Calculations** |  |  |  |
| **Parameter** | **Description** |  |  |
| Cold Start up time | Time to start power production from OFF. |  |  |
| Time to 100kW from Cold Start | Time to bring the FC to 100kW from OFF. |  |  |
| Cold Start Auxiliary consumption | External energy consumed during cold start. |  |  |
| Hot Start up time | 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. |  |  |
| Time to 100 kW from Hot Start | Time to bring the FC to 100 kW from Standby. |  |  |
| Hot Start Auxiliary consumption | External energy consumed during hold start. |  |  |
| Time from OFF to Standby | Time to bring the FC from OFF to Standby. |  |  |
| Time from Standby to OFF | Time to bring the FC from Standby to OFF. |  |  |

### 4.1.3.3 FC on-site dynamic response

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

| **Test T7: FC on-site dynamic response** | | | |
|---|---|---|---|
| **Objective:** Verify FC dynamic response to P/Q setpoint: verify the ramp rates and the fuel cell control accuracy | | | |
| **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<br>Test 7.1<br>- Power Step-change from 12 kW to 50 kW.<br>- Power Step-change from 50 kW to 100 kW.<br>- Power Step-change from 100 kW to 50 kW.<br>- Power Step-change from 50 kW to 12 kW.<br>Test 7.2<br>- Power Step-change from 12 kW to 100 kW.<br>- Power Step-change from 100 kW to 12 kW.<br>- Put the FC in Standby.<br>Test 7.3<br>- Power Step-change from Standby to 83 % of $P_n$ (from Standby to 100 kW).<br>- Power Step-change from 83 % to 0% of $P_n$ (from 100 kW to Standby).<br>General considerations:<br>- 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 specially related to matching the electricity profile committed the electric market and, the local load profile.

## 4.2 Field test protocols

This set of protocols is intended to verify the correct operation of the electrolyser for each of the operation modes identified for the unique operation strategy considered that is the production of hydrogen according to a defined hydrogen demand profile. These operation modes identified in section 3.2 for the fuel-production use case are the following:

1. Hydrogen demand profile matching mode, active while the hydrogen fill level in the tank is lower than level representative of the hydrogen demand profile being tracked.
2. Hydrogen re-electrification and real-time energy profile matching within the intra-day market, mode that is always activated when:
    a. the hydrogen fill level in the tank is higher than the level representative of the hydrogen demand profile being tracked or
    b. the power generated in the wind farm is higher than the maximum operation power of the electrolyser when that hydrogen fill level in the tank is lower than the level representative of the hydrogen demand profile being tracked
3. Hydrogen re-electrification and local load matching mode, that would be active once the committed electricity profile to be delivered to the marker is covered.

The field protocols refer to two main stages, namely:

I. The test stage, previously to start the demonstration period, which is intended to validate the correct operation of the control algorithms and the hydrogen installation. These tests are defined in the following section 4.2.1
II. During the demonstration campaign., which is intended to evaluate the techno-economic performance of the energy-storage use case throughout a long period of time. These demonstration tests are defined in section 4.2.2.

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, defined in [6] and [7].

### 4.2.1 Initial field test protocols

*Table 19. Field Test T8: Production of hydrogen.*

| **Field Test T8: Production of hydrogen** | |
|---|---|
| **Objective:** Verify the correct operation of the hydrogen system under the **hydrogen demand profile matching mode** when the fill level of the hydrogen tank ($H$) is under the reference level ($H_{ref}$) representative of the hydrogen demand profile being matched. Being the fuel production the unique priority, the FC would be permanently OFF during the test.<br>Wind farm production is not especially relevant in this case, assuming that it is enough to generate the required amount of hydrogen, and apart from checking the matching accuracy between the generation of hydrogen and the reference hydrogen demand profile. In that sense, perhaps a complementary management would be needed on the $H_{ref}$ to maximize a tighter matching between the hydrogen generation, the hydrogen demand profile and the energy available from the wind farm | |
| **Test Pre-conditions** | |
| ELY | - OFF |
| FC | - OFF |
| 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 (fuel-production algorithms should be tuned according to test results).
- Verify main aspects of the fuel-production algorithms:
  - There is access to wind farm and PCC Power measurements.
  - A hydrogen reference demand ($H_{ref}$.) profile has been defined according to the pursued hydrogen demand profile.
- Run the test for 24 hours period, assuring that the stored level of the hydrogen (H) is always under the hydrogen reference demand ($H_{ref}$).
- Run additional tests, about alt least one hour, with the condition of the stored level of the hydrogen (H) being over and down the hydrogen reference demand ($H_{ref}$.) in order to check that, when down, the ELY stops producing hydrogen. Turning periods of 15’ over and 15’ down are enough for that checking.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.

| | |
|---|---|
| **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 |
| | | | |
| Hydrogen tank fill level ($H$) | 10 seconds | Wind power production ($P_w$) | 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 | Total Energy consumed by Auxiliaries |
| Cost of Energy consumed by ELY | Total Energy produced by the Wind Farm |
| Hydrogen Produced by ELY | Total Energy exchanged in the PCC |
| Deviations between $H$ and $H_{ref}$ | |
| | |
| | |

**Required Verifications**

| |
|---|
| Verify that the total Energy exchanged in the PCC is the sum of 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 hydrogen production. |
| Verify that the ELY was only activated when the Wind Farm power was above the limit. |
| Verify that the hydrogen generated by the ELY follows properly the hydrogen demand ($H_{ref}$) |
| Verify that, in the case of the generated hydrogen level ($H$) is over demanded hydrogen ($H_{ref}$), the ELY stops producing hydrogen |

*Table 20. Field Test T9: Hydrogen re-electrification and real-time energy profile matching within the intra-day market.*

<table>
<tr><th colspan="2">Field Test T9: Hydrogen re-electrification and real-time energy profile matching within the intra-day market.</th></tr>
<tr><td colspan="2"><b>Objective:</b> This test is similar to the previous T8 but, in this case, the reference to be followed is the committed energy profile to be supplied 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.<br>This mode will occur when the hydrogen demand is already covered ($H > H_{ref}$), independently of the wind power available or when that wind power available is higher than the power required by the ELY, and when the weight of market-local load is set to “market” at 100%.<br>In the case of ($H > H_{ref}$), that exceeding hydrogen is re-electrified by the FC to contribute, jointly the wind farm, to generate the electricity committed to the market.<br>In any case, the objective of this test is to verify the proper matching of that intra-day market independently if there is generation of hydrogen or not.</td></tr>
<tr><td colspan="2"><b>Test Pre-conditions</b></td></tr>
<tr><td>ELY</td><td>- OFF when ($H > H_{ref}$) or Standby if it is going to be operated to generate the hydrogen ($H < H_{ref}$)</td></tr>
<tr><td>FC</td><td>- Standby when ($H > H_{ref}$). OFF when ($H < H_{ref}$) considering that the ELY will generate hydrogen to cover the hydrogen demand</td></tr>
<tr><td>Tank</td><td>- ELY OFF: Full enough to support the FC during the test execution<br>- ELY Standby/ON: Could be empty depending on the balance between the hydrogen produced by the ELY and consumed by the FC<br>- Possible venting of hydrogen to get ($H < H_{ref}$) in order to check that FC stops re-electrifying hydrogen and the ELY starts generating hydrogen</td></tr>
<tr><td>Control system</td><td>- Market-local load weight configuration set to “market” at 100%</td></tr>
<tr><td>Wind power available</td><td>- Designed to make possible to attend the market even when producing hydrogen ($P_w > P_e^{max}$)</td></tr>
<tr><td>Intra-day market profile</td><td>- Designed to make possible occasionally the local load to be fed when already covered the intra-day market ($P_f > P_{grid}$)</td></tr>
<tr><td>Room temperature</td><td>- TBD (within the temperature range of the hydrogen system operation)</td></tr>
<tr><td colspan="2"><b>Test sequence</b></td></tr>
<tr><td colspan="2">- Previously required test: T1, T5, T6 and T7 (real time market energy supply algorithms should be tuned according to test results).<br>- Verify main aspects of the real time market energy supply algorithm:<br>o There is access to Wind farm and PCC Power measurements.<br>o There is access to the grid.<br>o The energy profile committed to the market.<br>o The forecast of the wind farm power generation for the period.<br>- Run the test for the test period (24 hours or less depending on the selected profiles) applying the profiles of the wind power available, the intraday market and hydrogen demand (this one in case to check ($H > H_{ref}$) and [($H < H_{ref}$) + ($P_w > P_e^{max}$)] cases.<br>- Induce in several controllable periods of time (e.g. by means of venting hydrogen) that ($H < H_{ref}$) in order to verify that FC stops re-electrifying hydrogen and the ELY starts generating hydrogen.<br>- FC Reactive Power Set Point will be kept at zero during the whole test duration.</td></tr>
</table>

| **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 | 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 produced by the Wind Farm | |
| Total Energy consumed by the ELY | | Total Energy exchanged in the PCC ($P_{fc}$-$P_{ez}$) | |
| Total Energy consumed by Auxiliaries | | Total energy delivered to the grid ($P_{avl}$) | |
| $H_2$ consumed by the FC | | Total energy supplied to the local load | |
| 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 FC instant error is below the maximum allowable error. | | | |
| 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 that provision of energy to the intra-market is made according to the defined conditions of ($H > H_{ref}$) and [($H < H_{ref}$) + ($P_w > P_e^{max}$)] | | | |
| Verify that FC stops re-electrifying hydrogen and the ELY starts generating hydrogen in those periods of time when $H < H_{ref}$ | | | |

*Table 21. Field Test T10: Hydrogen re-electrification and local load matching.*

<table>
<tr><th colspan="2">Field Test T10: Hydrogen re-electrification and local load matching</th></tr>
<tr><td colspan="2"><b>Objective:</b> Similar to the previous T9 with respect the re-electrification, in this case, the reference to be followed is the local load consumption profile to be supplied to the local loads connected to the wind-hydrogen system. 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 local load, basically completing the active power required.<br>This mode will occur when the hydrogen demand is already covered ($H > H_{ref}$), independently of the wind power available or when that wind power available is higher than the power required by the ELY, and when the weight of market-local load is set to “local load” at 100%.<br>In the case of ($H > H_{ref}$), that exceeding hydrogen is re-electrified by the FC to contribute, jointly the wind farm, to generate the electricity committed to the local load.<br>In any case, the objective of this test is to verify the proper matching of that local load profile independently if there is generation of hydrogen or not.</td></tr>
<tr><td colspan="2"><b>Test Pre-conditions</b></td></tr>
<tr><td>ELY</td><td>- OFF when ($H > H_{ref}$) or Standby if it is going to be operated to generate the hydrogen ($H < H_{ref}$)</td></tr>
<tr><td>FC</td><td>- Standby when ($H > H_{ref}$). OFF when ($H < H_{ref}$) considering that the ELY will generate hydrogen to cover the hydrogen demand</td></tr>
<tr><td>Tank</td><td>- ELY OFF: Full enough to support the FC during the test execution<br>- ELY Standby/ON: Could be empty depending on the balance between the hydrogen produced by the ELY and consumed by the FC<br>- Possible venting of hydrogen to get ($H < H_{ref}$) in order to check that FC stops re-electrifying hydrogen and the ELY starts generating hydrogen</td></tr>
<tr><td>Control system</td><td>- Market-local load weight configuration set to “local load” at 100%</td></tr>
<tr><td>Wind power available</td><td>- Designed to make possible to feed the local load even when producing hydrogen ($P_w > P_e^{max}$)</td></tr>
<tr><td>Local load profile</td><td>- Designed to make possible occasionally the market to be feed when already covered the local load ($P_f > P_{avl}$)</td></tr>
<tr><td>Room temperature</td><td>- TBD (within the temperature range of the hydrogen system operation)</td></tr>
<tr><td colspan="2"><b>Test sequence</b></td></tr>
<tr><td colspan="2">- Previously required test: T1, T5, T6 and T7 (local load market energy supply algorithms should be tuned according to test results).<br>- Verify main aspects of the local load energy supply algorithm:<br>o There is access to Wind farm and PCC Power measurements.<br>o Access to the local load.<br>o The energy profile committed to the local load.<br>o The forecast of the wind farm power generation for the period.<br>- Run the test for the test period (24 hours or less depending on the selected profiles) applying the profiles of the wind power available, the local load and hydrogen demand (this one in case to check ($H > H_{ref}$) and [($H < H_{ref}$) + ($P_w > P_e^{max}$)] cases.<br>- Induce in several controllable periods of time (e.g. by means of venting hydrogen) that ($H < H_{ref}$) in order to verify that FC stops re-electrifying hydrogen and the ELY starts generating hydrogen.<br>- FC Reactive Power Set Point will be kept at zero during the whole test duration.</td></tr>
<tr><td><b>Test duration</b></td><td>24 hours (shorter periods are also possible)</td></tr>
</table>

| **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 | 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 committed energy to the local load within times ranges of order of minutes. |
| Verify that FC instant error is below the maximum allowable error. |
| Verify that the FC active power varies according to that committed local load energy profile, completing, when required, the supply of the wind farm. |
| Verify that that provision of energy to the local load is made according to the defined conditions of ($H > H_{ref}$) and [($H < H_{ref}$) + ($P_w > P_e^{max}$)] |
| Verify that FC stops re-electrifying hydrogen and the ELY starts generating hydrogen in those periods of time when $H < H_{ref}$ |

*Table 22. Field Test T11: Hydrogen re-electrification according to market-local load weight configuration.*

<table>
<tr><th colspan="3">Field Test T11: Hydrogen re-electrification according to market-local load weight configuration</th></tr>
<tr><td colspan="3"><b>Objective:</b> Combination of the previous T9 and T10 test cases with respect the re-electrification. In this case, the references to be followed are both, the market local and the load consumption profiles to be supplied connected both to the wind-hydrogen system. So, the objective is to verify the correct operation of the hydrogen system, collaborating with the wind farm in the supply of the energy profiles offered to market and the local load, basically completing the active power required, and according to the market-local load weight parameter setting.<br>This mode occurs when hydrogen demand is already covered ($H > H_{ref}$), independently of the wind power available or when that wind power available is higher than the power required by the ELY.<br>In that case of ($H > H_{ref}$), that exceeding hydrogen is re-electrified by the FC to contribute, jointly the wind farm, to generate the electricity committed to the market and to the local load according to the configured weight.<br>Therefore, the objective of this test is to verify the proper supply of energy to both the intra-day market and the local load in a proportion according to the configured market-local load weight parameter.<br>The tests will verify market-local load % ratios of 100-0, 75-25, 50-50, 25-75 and 0-100.</td></tr>
<tr><td colspan="3"><b>Test Pre-conditions</b></td></tr>
<tr><td>ELY</td><td>-</td><td>OFF when ($H > H_{ref}$) or Standby if it is going to be operated to generate the hydrogen ($H < H_{ref}$)</td></tr>
<tr><td>FC</td><td>-</td><td>Standby when ($H > H_{ref}$). OFF when ($H < H_{ref}$) considering that the ELY will generate hydrogen to cover the hydrogen demand</td></tr>
<tr><td>Tank</td><td>-<br>-</td><td>ELY OFF: Full enough to support the FC during the test execution<br>ELY Standby/ON: Could be empty depending on the balance between the hydrogen produced by the ELY and consumed by the FC</td></tr>
<tr><td>Control system</td><td>-</td><td>Market-local load weight configuration set initially to “market” al 100%.</td></tr>
<tr><td>Wind power available</td><td>-</td><td>Designed to make possible to feed the market or/and local load even when producing hydrogen ($P_w > P_e^{max}$)</td></tr>
<tr><td>Intra-day market profile</td><td>-</td><td>Designed to make possible occasionally the local load to be fed when already covered the intra-day market ($P_f > P_{grid}$)</td></tr>
<tr><td>Local load profile</td><td>-</td><td>Designed to make possible occasionally the market to be feed when already covered the local load ($P_f > P_{avl}$)</td></tr>
<tr><td>Room temperature</td><td>-</td><td>TBD (within the temperature range of the hydrogen system operation)</td></tr>
</table>

| **Test sequence** | | | |
|---|---|---|---|
| - Previously required test: T1, T5, T6 and T7 (intra-day market and local load market energy supply algorithms should be tuned according to test results).<br>- Verify main aspects of the real time market and local load energy supply algorithms:<br>o There is access to Wind farm and PCC Power measurements.<br>o Access to the grid.<br>o The energy profile committed to the market.<br>o Access to the local load.<br>o The energy profile committed to the local load.<br>o The forecast of the wind farm power generation for the period.<br>- Run the test for the test period 20 hours applying the profiles of the wind power available, real-time market, the local load and hydrogen demand (this one in case to check ($H > H_{ref}$) and [($H < H_{ref}$) + ($P_w > P_e^{max}$)] and setting in a cycling way during one hour the following sequence of the configuration of the market-local load weight:<br>o Market: 100% - Local load: 0%<br>o Market: 75% - Local load: 25%<br>o Market: 50% - Local load: 50%<br>o Market: 25% - Local load: 75%<br>o Market: 0% - Local load: 100%<br>- Induce in several controllable periods of time (e.g. by means of venting hydrogen) that ($H < H_{ref}$) in order to verify that FC stops re-electrifying hydrogen and the ELY starts generating hydrogen.<br>- 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 | 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 real-time market |
| Total Energy consumed by the ELY | Total energy supplied to the local load |
| Total Energy consumed by Auxiliaries | Total Energy produced by the Wind Farm |
| $H_2$ consumed by the FC | Total Energy exchanged in the PCC ($P_{fc}$-$P_{ez}$) |
| FC Answer Instant Error (1s) | Total energy received from the grid ($P_{grid}$) |

| **Required Verifications** |
|---|
| Verify that the total Energy exchanged in the PCC is the sum of ELY, FC and auxiliaries' total energy. |
| Verify that the distribution of the FC active power between market and local load varies according to the configured market-local load weight trying to match the respective market and local load energy profiles, completing, when required, the supply of the wind farm. |
| Verify the matching of generation and committed energy to the market and local load within times ranges of order of minutes. |
| Verify that FC instant error is below the maximum allowable error. |
| Verify that that provision of energy to the market and the local load is made according to the defined conditions of ($H > H_{ref}$) and [($H < H_{ref}$) + ($P_w > P_e^{max}$)] |
| Verify that FC stops re-electrifying hydrogen and the ELY starts generating hydrogen in those periods of time when $H < H_{ref}$ |

### 4.2.2 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.

The Haeolus hybrid wind-hydrogen system will operate in the regular environment connected to the main grid and the local load. Its main aim is to produce hydrogen to cover the existing hydrogen demand and then to participate to the electricity market and to feed the local load re-electrifying the surplus of hydrogen.

During the demonstration period, the hydrogen demand profile, the energy profile to be sold to the market and the local load profile will be whatever and the system control should switch between the three operation modes according to these reference profiles, the energy generated by the wind farm and the hydrogen level in the tank at any time.

Additionally, during the demonstration campaign the hydrogen re-electrification will be distributed between the market and the local load according to the configuration of the market-local load weight parameters. These parameters could vary during the demonstration campaign according the priority of each electricity use in every time.

Basically, the demonstration test case would be the verification of the proper switching between modes checking for each sampling the combination of the input reference profile values and the related reference outputs of the Haeolus hybrid wind-hydrogen system. These outputs are basically the hydrogen produced (related to the hydrogen level in the hydrogen tank), the hydrogen re-electrified in the FC and how this electrification is distributed between the market and the local load.

*Table 23. Demonstration Field Test T12: Prioritization of hydrogen production with possible real-time market participation and local load feeding.*

| **Demonstration Field Test T12 Prioritization of hydrogen production with possible real-time market participation and local load feeding** | |
|---|---|
| **Objective:**. | |
| **Test Pre-conditions** | |
| ELY | - OFF |
| FC | - 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, T4, T5, T6 and T9 (fuel-production, intra-day market and local load feeding algorithms should be tuned according to test results).
- Verify main aspects of the hydrogen production intra-day market and local load feeding algorithms:
  - There is access to wind farm and PCC Power measurements.
  - There is access to the grid
  - There is access to the local load
  - A hydrogen reference demand ($H_{ref}$.) profile has been defined according to the pursued hydrogen demand profile.
- The profile references for the wind farm power, the hydrogen demand, the intra-day market and the local load consumption should be the actual ones.
- The market-local load weigh parameter set at any time to the corresponding value depending on the priority given to each use.
- Run the system during the demonstration campaign period monitoring and gathering the corresponding output variables that represents the proper operation of the system, namely:
  - The fulfilling of the hydrogen demand profile
  - The re-electrification of hydrogen when ($H > H_{ref}$)
  - The use of that re-electrification between the intra-day market and local load according to the given weight at any moment.
- After the end of the demonstration phase, or periodically if observed unexpected behaviour, carry out again test T2, T3 and T4 to assess the ELY efficiency degradation and T5, T6 and T7 to assess the FC efficiency degradation.

| **Test duration** | Demonstration campaign |
|---|---|

**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 | 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 ($P_{grid\downarrow}$) | 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 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 $H_2$system | LCOH2 |
| | |

# 5 Risk Analysis

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

A classic risk management methodology has been used. Each of the identified risks related to the test activity has been scored using the product of probability (P) and impact (I) as depicted in Table 24.

*Table 24. 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 25. 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, T10, T11, T12 |
| | **Contingency Plan** | | | | |
| | • Complete the electrolyser maintenance planning to avoid undesired damages.<br>• Review the electrolyser if any underperformance is detected on that to avoid higher damages.<br>• 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, T9, T10, T11, T12 |
| | **Contingency Plan** | | | | |
| | • Complete the electrolyser maintenance planning to avoid undesired damages.<br>• 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, T10, T11, T12 |
| | **Contingency Plan** | | | | |
| | • Review the electrolyser to check any potential source of the underperformance.<br>• 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.<br>• 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.<br>• Solve data recording or communication problems without stopping the test activity. | | | | |

# 6 References

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[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.

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

[10] D8.2 Protocols for demonstration of mini-grid strategy. www.haeolus.eu.

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

[12] 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.

[13] 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:

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

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

[16] 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 $H_2$:

$$\mathrm{LCOH}_2\left(\frac{€}{\mathrm{kg}}\right) = \frac{\sum_{i=0}^{n}\left[\mathrm{CAPEX}_i \cdot \left(\frac{1}{1+d}\right)^i + \mathrm{OPEX}_i \cdot \left(\frac{1+e}{1+d}\right)^i + \mathrm{EnergyCost}_i \cdot \left(\frac{1+e}{1+d}\right)^i\right]}{\sum_{i=1}^{n} \mathrm{H}_2\ \mathrm{production}_i \cdot \left(\frac{1+e}{1+d}\right)^i}$$

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 electrolyser and fuel cell. MTBF can be calculated as the arithmetic average time between failures:

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