



**Enhanced performance and cost-effective materials for long-term operation of PEM water electrolyzers coupled to renewable power sources**

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**DELIVERABLE REPORT**

**D.2.2 – PROTOCOLS FOR STACK AND SYSTEM CHARACTERISATION**

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**NATURE OF THE DELIVERABLE**

<b>R</b>	Report	<b>X</b>
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<b>P</b>	<i>Prototype</i>	
<b>D</b>	<i>Demonstrator</i>	
<b>O</b>	<i>Other</i>	

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## **SUMMARY**

### **Keywords**

*Electrolysis, stack, system, Characterisation, Procedures, Protocols*

### **Abstract**

The objective of this deliverable is to define characterisation and test protocols for the assessment of performance, efficiency and durability of a PEM water electrolyser (PEMWE) stack. It does not purport to address the performance or durability of the balance of plant required to operate the stack. Balance of plants already available at the partners laboratories will be used for interfacing PEMWE stacks to RES.

The procedures and methods defined within are a set of protocols for the electrochemical characterization under the specific operating conditions applicable to interfacing with renewable power sources.

The protocols use electrochemical polarization (voltage vs. current density or j-V) curve beginning of test (BoT) and end of test (EoT) to determine important parameters such as performance, efficiency and voltage decay (performance loss). The suggested tests include constant load (current) operation, and dynamic load operation with a specific current profile to simulate at various steps the behaviour of a renewable power source.

Electrochemical impedance spectroscopy (EIS), gas cross-over and water analysis can be used for in-situ MEA diagnostics and EoT characterisation. However, it is expected that ex-situ tests, performed after stack disassembly will be used to assess degradation mechanism(s).

Protocols for non active components assessment are also defined. The stability of bipolar plates is checked after prolonged operation by measuring contact resistance measurements. Where appropriate post-mortem analysis (SEM, TEM, EDX, XPS, etc) can be used in order to select the most useful materials and configuration for the stacks.

## D.2.2 – PROTOCOLS FOR STACK AND SYSTEM CHARACTERISATION

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### 1. INTRODUCTION

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The aim of this deliverable is to describe a set of protocols to measure performance, efficiency and durability of the PEM electrolyser stack developed as part of the ElectroHyPEM project. In addition this report aims to describe specific procedures for the stack evaluation in relation to the duty cycle experiments associated with connection to intermittent renewable power sources (specifically wind).

The set of protocols are organised as follows:

*1) Protocols for assessment of the stability of non active components:*

These mainly concern with bipolar plates, backing layers and current collectors of PEM electrolyser stack housing. Essentially, these consist in measuring changes in contact resistance before and after duty cycle testing.

*2) Definition of protocols and procedures for the stack concerning with performance and durability assessment.*

These are similar to the MEA testing protocols already defined as part of this project and concern with durability tests, using polarisation as a key indicator of performance loss.

Durability is assessed by investigation of voltage increase at constant current operation under specific conditions of temperature and pressure.

*3) Protocol for stack failure analysis and aspects related to safety issues*

Diagnostic procedures regarding the determination of important parameters. These essentially use ac-impedance measurements, cyclic voltammetry of single cells within the stack and ex-situ, analysis of the water and cross-over measurements. Physico-chemical analysis of the active components is also to be performed post-operation.

*4) Tests and protocols for duty cycles and direct coupling with renewable energy sources (RES)*

The effects caused by intermittent operation of RES on the performance decay of the electrolyser stack are investigated. These protocols concern with load and on-off cycles, using current profiles simulating the behaviour of wind based renewable power sources.

## 2. PROTOCOLS

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### 2.1 Protocols for the assessment of the stability of non active components

A procedure involving post-operation physico-chemical analysis is carried out on non-active components to assess any degradation effects related with operation under practical stack configuration.

Pre- and post-operation physico-chemical analyses of specific pieces of components will be carried out by XRD (structural), XRF (elemental), TEM and SEM-EDX (morphological), XPS (surface analysis). Bipolar plates and current collectors/backing layers, sealing gaskets forming the stack housing, are subjected to physico-chemical studies after prolonged operation in short-stacks in order to down-select the most appropriate materials and configurations for the full stack used as proof-of-concept.

Electronic conductivity of bipolar plates and current collectors before and after the stack testing are determined by measuring the difference in resistance between a four-point probe method and a two point contact method.

The procedures for physico-chemical experiments are the conventional ones; thus, such protocols have not been detailed here.

Conductivity test protocols are defined in the following.

### 2.1.1 Measurement of in-Plane Conductivity

#### Summary

The measurement of in plane conductivity is performed using controlled current electrochemical impedance spectroscopy (EIS). Low frequency measurement is not necessary and measurements can be carried out from the maximum frequency ( 50 kHz down to 1 Hz with data log 5 points per decade).

### Measurement of In-Plane Conductivity

#### Protocol and Metrics

<b>Pre-conditioning</b>	No specific procedures	
<b>Operating conditions:</b>		
<b>Measurement technique</b>	Potentiostatic Electrochemical Impedance Spectroscopy (EIS)	
<b>Component size</b>	As appropriate (but must be recorded)	
<b>Technique</b>	Four point probe/two point probe	
<b>Frequency range</b>	50 kHz to 1 Hz (5 steps/decade)	
<b>DC current</b>	no DC current	
<b>AC voltage</b>	10 mV	
<b>Analysis</b>	<ul style="list-style-type: none"> <li>• Plot each result in standard Nyquist form</li> <li>• Where the signal first crosses the real axis is the series resistance (high frequency resistance)</li> <li>• Contact resistance is <math>\frac{1}{2}</math> the difference between the two point resistance and the four point resistance (voltage probes must be at same point, thickness and under the same applied pressure.</li> </ul>	
<b>METRIC</b>	<b>FREQUENCY</b>	<b>TARGET</b>
<b><i>Nyquist plot</i></b>	Start and end of any test plus as required	
<b><i>Electronic conductivity</i></b>	As required	No target for monitoring

## **2.2 Definition of protocols and procedures for measuring the performance and durability assessment of the stack.**

The stack containing components developed as part of this project are validated in terms of performance and stability in short stack and full stack.

The nominal rated hydrogen production capacity is planned in  $1 \text{ Nm}^3 \text{ h}^{-1}$ .

The planned stack active area should preferably range from  $100 \text{ cm}^2$  to  $300 \text{ cm}^2$  and the number of cells should be sufficient to reach the nominal capacity. Other configurations may be planned according to the results obtained in WP5.

The active area will results from an analysis of the benefits in reducing capital costs and the need to reduce mechanical stresses for high pressure operation as well as temperature gradients at high currents.

Stack testing is carried out under controlled conditions in designed test stations available in the partners laboratories operating at specific temperatures and pressures.

Particular attention is addressed to analyze the flow regime in the compartment anode and cathode especially with reference to the occurrence of slug and annular flows under various operating current densities by using CFD analysis of some selected stack designs.

## 2.2.1 Measurement of Stack Current-Voltage Polarization Curve

### Summary

This is a measure of the stack voltage as a function of the applied current. The current is raised and then lowered to measure any hysteresis. The results are analysed to determine energy consumption of the stack and efficiency at the nominal capacity. Energy consumption will be reported in terms of kWh/Nm<sup>3</sup> H<sub>2</sub>; beside this, the average cell voltage at a specific current density of 0.5 -1 A cm<sup>-2</sup> will provide a comparison of stack performance (WP6) with single cell MEA testing in WP5.

## **IV Curve**

### **Protocol and Metrics**

<b>Pre-conditioning</b>	Stack MEAs must be hydrated prior to measurement It is recommended that stack run for at least 24 hours to ensure the MEA has reached a steady state	
<b>Operating conditions:</b>		
<b>Control</b>	Chronopotentiometric (current controlled; voltage recorded)	
<b>Cell size/number of cells/ series connection</b>	As appropriate	
<b>Water temperature</b>	Recorded on both exits and reported with IV curve	
<b>Pressure</b>	Pressure must remain at atmospheric pressure for currents less than 0.4 A·cm <sup>-2</sup> . Higher pressures can be used above this current density but must be recorded and reported.	
<b>Current Density range</b>	1 mA·cm <sup>-2</sup> to 2 A·cm <sup>-2</sup> (and reversed)	
<b>Step size</b>	Smaller at low currents such that the change in voltage between step size is < 30 mV/cell (see example below)	
<b>Voltage monitoring</b>	Monitoring of terminal stack voltage and each single cell voltage	
<b>Technique</b>	<ul style="list-style-type: none"> <li>• Hold current at 100 mA·cm<sup>-2</sup> for 5 minutes to ensure catalysts are in the correct oxidation state</li> <li>• Step current to 1 mA·cm<sup>-2</sup></li> <li>• Record voltage after 1 min (Note: if dV/dt &gt; 1 mV·cell<sup>-1</sup>·cm<sup>-2</sup>·s<sup>-1</sup> then must wait until dV/dt &lt; 1 mV·cell<sup>-1</sup>·cm<sup>-2</sup>·s<sup>-1</sup> before recording voltage)</li> <li>• Step to next current and repeat .</li> </ul>	
<b>Single cell voltage cut off</b>	2.2 V /cell	
<b>METRIC</b>	<b>FREQUENCY</b>	<b>TARGET</b>
<b>I-V curve</b>	Start and end of any test plus as required	
<b>Energy consumption (pseudo steady state test)</b>	<b>&lt; 4 kWh/Nm<sup>3</sup> H<sub>2</sub> at 1 Nm<sup>3</sup> h<sup>-1</sup></b>	
<b>Efficiency (pseudo steady state test)</b>	<b>&gt; 80% vs. LHV of H<sub>2</sub></b>	

ElectroHyPEM Stack Specifications and Procedures

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

Current Density [A·cm <sup>-2</sup> ]	Terminal stack Voltage [V]	Average Cell Voltage [V/cell]		Current Density [A·cm <sup>-2</sup> ]	Cell Voltage [V]	Average Cell Voltage [V/cell]
0.002				0.6		
0.01				0.8		
0.06				1.2		
0.1				1.4		
0.2				1.6		
0.3				1.8		
0.4				2		

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

## 2.2.2 Stack steady-State Test at 1.0 A/cm<sup>2</sup> and determination of the stack voltage and efficiency at the nominal capacity

### Summary

Stack is tested under constant load, temperature and pressure, to measure the decay rate at 0.5 A/cm<sup>2</sup>.

### Stack steady-State Test at 0.5 A/cm<sup>2</sup>

#### Protocol and Metrics

<b>Stack Conditioning</b>	Refer to MEA conditioning Procedure
<b>Test Conditions</b>	Stack of nominal capacity <ol style="list-style-type: none"> <li>1. Before starting test, operate for 24 hrs at steady-state, 1.0 A/cm<sup>2</sup>.</li> <li>2. Measure an IV curve as detailed in the Measurement of Current-Voltage Curve Procedure (Current Range: 1 mA/cm<sup>2</sup> – 1 A/cm<sup>2</sup>).</li> <li>3. Operate the stack at a steady-state 1.0 A/cm<sup>2</sup>.</li> <li>4. At the end of the test, measure an IV curve as detailed in the Measurement of Current-Voltage Curve Procedure (Current Range: 1 mA/cm<sup>2</sup> – 1 A/cm<sup>2</sup>).</li> </ol>
<b>Total Time</b>	1000 hrs after measurement of the first IV curve
<b>Temperature</b>	Set as required, must be recorded and reported
<b>Pressure</b>	Set as required, must be recorded and reported

METRIC	FREQUENCY	TARGET
<b>F<sup>-</sup> release or equivalent for non-fluorine membranes</b>	Every 100hrs of steady-state operation from the beginning of the test.	No target for monitoring
<b>Metallic ions release / increase of water conductivity at stack outlet</b>	After 100 hrs of steady-state operation from the beginning of the test.	No target for monitoring
<b>Hydrogen Cross-over</b>	Continuously monitored. Systems should be put in place to shut down should the levels go above ½ the flammability limit.	H <sub>2</sub> concentration in the oxygen stream <2 vol.% at specific pressure and current
<b>Voltage Degradation</b>	1000 hrs of operation after first IV curve.	≤ 15 μV/hr degradation in operating voltage using line of best fit.
<b>IV Curve</b>	BoT and EoT	No target for monitoring
<b>Determine hydrogen flow rate after cryogenic removal of water</b>	Every 100hrs	< 4 kWh/Nm <sup>3</sup> H <sub>2</sub> at 1 Nm <sup>3</sup> h <sup>-1</sup>
Energy consumption or		
Efficiency		> 80% vs. LHV of H <sub>2</sub> at 1 Nm <sup>3</sup> h <sup>-1</sup>

## 2.3 Protocol for stack failure analysis and aspects related to safety issues

Electrochemical diagnostics such as in-situ cyclic voltammetry and ac-impedance analyses are used to determine voltammetric charge, series resistance, polarization resistance and double layer capacitance for different cells in the stack. By using proper electrochemical set-up for diagnostic purposes, these techniques may be applied also with large surface area MEAs in the stack. These methodologies will allow to monitor the eventual differences in the operating behaviour of the different MEAs of the stack during operation.

AC-impedance is carried out in potentiostatic mode or under galvanostatic mode according to the procedure described for the MEA in D2.1. Ohmic resistance is determined from series resistance in the AC-impedance spectra (high frequency intercept in the Nyquist plot), whereas polarization resistance is determined from the low frequency intercept. In the potentiostatic mode the cell voltage is fixed at 1.5 V/cell in order to compare the data-set to those obtained in single cell MEA testing. However for large area cells, if the current will exceed 20 A at his potential, the galvanostatic operating mode will be selected with DC current of 10 A and oscillation 1 A. The frequency range should be as close as possible to the one selected for single cell MEA testing (D2.1).

Reference cyclic voltammetry will be carried out according to the procedures defined in D2.1 in the potential range 0-1.2 V RHE for the cathode and 0-1.4 V RHE for the anode with a sweep rate in the range 20-150 mV s<sup>-1</sup>. The proper sweep rate will be selected to avoid current overload depending on the active cell area in the stack. Determination of ECSA for the cathode is made by integration of H adsorption (theoretically 0.210 mC/real cm<sup>2</sup>) peaks (0.02-0.4 V RHE) after subtraction of double layer charging at 0.4 V RHE; whereas for the anode, active area expressed as specific charge q\* is obtained from integration of the anodic region in the entire potential window.

Protocols for *in-situ* cross-over measurements of gases under practical operation include sensor methods and electrochemical methods (H<sub>2</sub>). Details of these operating procedures are reported in D2.1.

A post-operation physico-chemical analysis will be carried out on active (membrane, catalysts, MEAs) to individuate any degradation effect related with operation under practical stack configuration with respect to the single cell MEA testing. Pre- and post-operation physico-chemical analyses of active components will be carried out by XRD (structural), XRF (elemental), TEM and SEM-EDX (morphological), XPS (surface analysis).

Hydrogen is a highly flammable gas that has been associated with several high profile disasters. Ensuring the electrolytic generation of hydrogen is performed safely is critical to the successful implementation of electrochemical hydrogen production. A short overview of the most important safety aspects that need to be considered when developing a PEM electrolyser is given below. This is in no way all encompassing but is rather intended as an introduction. Further information should be sought from such references as the British Standard BS ISO 22734-1, <http://h2bestpractices.org/>, and <http://www.hydrogensafety.info/>.

Being such a small molecule, hydrogen is prone to leaking. Combining with its low-energy ignition, wide range of combustible fuel-air mixtures and its ability to embrittle metals means extra caution needs to be taken and the environment monitored at all times. Plastic or elastomeric materials used within classified areas must not be allowed to build up static charge. All classified areas should have both low and high oxygen sensors and hydrogen sensors.

All materials used in the construction of an electrolyser must be suitable for the range of temperatures and pressures to which the electrolyser is subjected to. The reaction between hydrogen and/or oxygen with all materials used in the construction of the electrolyser must be very slow. In addition, the materials used must resist degradation due to the chemical and physical action of fluids within the electrolyser. When selecting materials due consideration must also be given to wear resistance, and galvanic corrosion.

The nature of electrolyser development is such that sampling of liquids or gases is often necessary. Precautions need to be taken in the design of the take-off points, and these points should be marked appropriately.

Pressure relief valves must be used on pressurized systems to prevent over-pressurization. In the event of the release of hydrogen through a pressure relief valve, the electrolyser system must automatically shut down, and the relieved gas(es) must be vented into a classified area.

The lower explosive limit of hydrogen in oxygen or air is 4% (by volume). However, gas mixtures must remain below 1% volume fraction of hydrogen in air within the hydrogen generator. Both passive and active means can be used to ensure this protective level is adhered to.

The polymeric electrolyte used within PEM electrolysers must be chemically stable over the operating conditions of the electrolyser. It must not release any chemicals nor catalyse any parasitic reactions that can contaminate the product gases of hydrogen or oxygen. Membrane failure can result in an explosive mixture of gases, therefore all electrolyser devices need to incorporate monitoring devices to monitor the effects of membrane instability.

The oxygen evolution reaction has its own demands on the system. When pressurised oxygen is used, some materials can have a dramatically lowered auto-ignition temperature. Any materials in contact with oxygen should have an auto-ignition temperature at least 50°C above the maximum operating temperature the material will see.

Hydrogen electrolysis has the potential to make a large positive impact on the environment. Unsafe practices can set this back, often years. Education of hydrogen safety is critical to making hydrogen a consumer used fuel that is used safely and responsibly.

## 2.4 Tests and protocols for duty cycles and direct coupling with renewable energy sources (RES)

Procedures are here defined to examine and assess the stability of the components under randomly occurring harsh conditions such as high cell potentials, load cycles, load on-off, these effects are quantified in terms of performance decay.

### 2.4.1 Stack Cycling Test

#### Summary

Stack is tested under a load cycle at constant temperature and pressure to test degradation mechanisms occurring under a dynamic load.

#### Stack Cycling Test Protocol and Metrics

<b>Stack Conditioning</b>	Refer to MEA Hydration Procedure in D2.1	
<b>Test Conditions</b>	Stack of nominal capacity	
	<ol style="list-style-type: none"> <li>1. Before starting test operate for 24 hrs at steady-state, 0.5 A/cm<sup>2</sup>.</li> <li>2. Measure an IV curve as detailed in the Measurement of Current-Voltage Curve Procedure (Current Range: 0.5 mA/cm<sup>2</sup> – 1 A/cm<sup>2</sup>).</li> <li>3. Followed by a 4 step cycle: <ul style="list-style-type: none"> <li>• Step 1: 1 min at 0.5 A/cm<sup>2</sup></li> <li>• Step 2: 1 min at 1 A/cm<sup>2</sup></li> <li>• Step 3: 1 min at 0.5 A/cm<sup>2</sup></li> <li>• Step 4: 1 min at 0 A/cm<sup>2</sup></li> </ul> </li> <li>4. At the end of the test, measure an IV curve as detailed in the Measurement of Current-Voltage Curve Procedure (Current Range: 0.5 mA/cm<sup>2</sup> – 1 A/cm<sup>2</sup>).</li> </ol>	
<b>Number of Cycles</b>	100	
<b>Temperature</b>	Set as required, must be recorded and reported	
<b>Pressure</b>	Set as required, must be recorded and reported	
METRIC	FREQUENCY	TARGET
<b>F<sup>-</sup> release or equivalent for non-fluorine membranes</b>	BoT and EoT	No target for monitoring
<b>Hydrogen Cross-over</b>	BoT Following 100 cycles	H <sub>2</sub> concentration in the oxygen stream <1-2 vol.% at recorded pressures and current
<b>IV Curve</b>	BoT Following 100 cycles	Low voltage decay in line with steady state tests

The same procedure may be repeated by increasing the maximum current density to 2 A cm<sup>-2</sup>.

## 2.4.2 Stack operation under duty cycles simulating RES

### Summary

Stack is tested in the presence of duty cycles simulating RES to test stability for coupling with intermittent renewable energy sources. A micro wind turbine is identified; this is developed by a Consortium partner for micro-distributed energy generation. However, depending on the availability of data from a photovoltaic plant, the same protocol can be adapted also to this field.

### Stack operation under duty cycles simulating RES

#### Protocol and Metrics

<b>Test bench preparation</b>	<ul style="list-style-type: none"> <li>Determine the current profile from the renewable energy source under consideration (wind microturbine 1.5 kW) on a time basis of 24 h for low (~7 m/s), moderate (~13 m/s) and high (~18 m/s) speed wind.</li> <li>Transfer this profile to the function generator set-up of the electronic load</li> </ul>
<b>Stack Conditioning</b>	Refer to MEA Hydration Procedure in D2.1
<b>Test Conditions</b>	<p>Stack of nominal capacity</p> <ol style="list-style-type: none"> <li>Before starting test operate for 24 hrs at steady-state, 0.5 A/cm<sup>2</sup>.</li> <li>Measure an IV curve as detailed in the Measurement of Current-Voltage Curve Procedure (Current Range: 0.5 mA/cm<sup>2</sup> – 1 A/cm<sup>2</sup>).</li> <li>Followed by a duty cycle: <ul style="list-style-type: none"> <li>Apply the low speed-current profile to the stack</li> </ul> </li> <li>At the end of the test, measure an IV curve as detailed in the Measurement of Current-Voltage Curve Procedure (Current Range: 0.5 mA/cm<sup>2</sup> – 1 A/cm<sup>2</sup>).</li> <li>Repeat steps 3 and 4 for the intermediate speed profile</li> <li>Repeat steps 3 and 4 for the high speed profile</li> </ol>
<b>Number of Cycles</b>	5
<b>Temperature</b>	Set as required, must be recorded and reported
<b>Pressure</b>	Set as required, must be recorded and reported

METRIC	FREQUENCY	TARGET
F release or equivalent for non-fluorine membranes	BoT and EoT	No target for monitoring
Hydrogen Cross-over	BoT Following 5 cycles	H <sub>2</sub> concentration in the oxygen stream <1-2 vol.% at recorded pressures and current
IV Curve	BoT After specific steps Following 5 cycles	Low voltage decay in line with steady-state tests

### **2.4.3 Direct coupling of PEM electrolyser system with RES**

#### **Summary**

The activity next to stack testing concerns with implementation of a balance of plant (BoP) around the stack for the direct coupling with RES and testing under simulated RES current profiles as well as under practical conditions.

Beside the stack, the system concerns, with water and electrical supply, water drain, hydrogen and oxygen separation from water, hydrogen purification section including cooling, desiccant bed - drying units, sensors, power management, safety and control system integrated into a single and compact device for RES applications.

If necessary, the BoP already developed in the consortium laboratories can be further implemented for operation with RES. This implementation may concern with the hydraulic circuit and AC/DC converters, DC/DC step-down or step-up converters, power tracking electronics.

In the system, the actual capacity is regulated by an electronic control system as well as by the pressure on the output tubes.

Special care is addressed to the optimization of the on-line ion exchange cartridges to reduce the trace of metal ions that can be present in the water circuit that may derive from degradation of novel hardware components and the H<sub>2</sub>-water separation. Separate studies carried out at short stack level concerning with the effects of water contaminants will form the basis for the optimization of the ion exchange cartridges for the system.

The BoP behaviour is first analysed in the presence of current profiles (waveforms) simulating intermittent conditions to assess the capability of the new components to operate under direct coupling with renewable power sources.

The aim is also to show that this system can be matched directly to a renewable energy source with moderate use of power tracking electronics.

The protocols are addressed to validate the system characteristics in order to allow time-response of less than a second for a change from 5 to 100% of full operational capacity and to increase the coupling efficiency of the PEM electrolyser/RES combination to above 93%. Such dynamic range of operational capacity will allow an appropriate coupling of the system with a large variation of input power or gas output requirements as it occurs with wind, solar energy.

Procedures aimed to evaluate the effect of the effect of ripple current can be identified successively experimentation.

## Direct coupling of PEM electrolyser system with RES

### Protocol and Metrics

<b>BoP impementation</b>	BoP developed around a nominal capacity stack or short stack with capacity compatible with the selected RES. BoP equipped with proper AC/DC and DC/DC step-down converters depending on the specific characteristics of the RES.
<b>Test Conditions</b>	<ol style="list-style-type: none"> <li>1. Before starting test operate the system for 24 hrs at steady-state, 0.5 A/cm<sup>2</sup>.</li> <li>2. Determine power consumption for the system at different stack hydrogen production capacity, temperature and pressure conditions as defined in previous tests.</li> <li>3. Connect the electrolyser system to the RES for 8 hrs.</li> <li>4. Monitor voltage-current profile from the RES</li> <li>5. Register system performance in terms of hydrogen production capacity as function of the input profile from the RES.</li> <li>6. At the end of the test, determine power consumption for the system at different stack hydrogen production capacity, temperature and pressure conditions as defined in previous tests.</li> <li>7. Repeat steps 2 - 6 under different RES operating conditions</li> </ol>
<b>Number of Cycles</b>	3
<b>Temperature</b>	Set as required, must be recorded and reported
<b>Pressure</b>	Set as required, must be recorded and reported

<b>METRIC</b>	<b>FREQUENCY</b>	<b>TARGET</b>
<b>F<sup>-</sup> release or equivalent for non-fluorine membranes</b>	BoT and EoT	No target for monitoring
<b>Hydrogen Cross-over</b>	BoT Following 5 cycles	H <sub>2</sub> concentration in the oxygen stream <1-2 vol.% at recorded pressures and current
<b>IV Curve</b>	BoT After specific steps Following 3 cycles	Low voltage decay in line with steady-state stack tests

#### **2.4.4 Numerical simulation of current and voltage time series generated by a small wind turbine**

The small wind turbine behaviour is typically unsteady because of the wind condition in which the machine operates. Wind speed mean values over a period of 1 to 10 minute and turbulence intensity are the parameters that define the operational condition of the wind turbine.

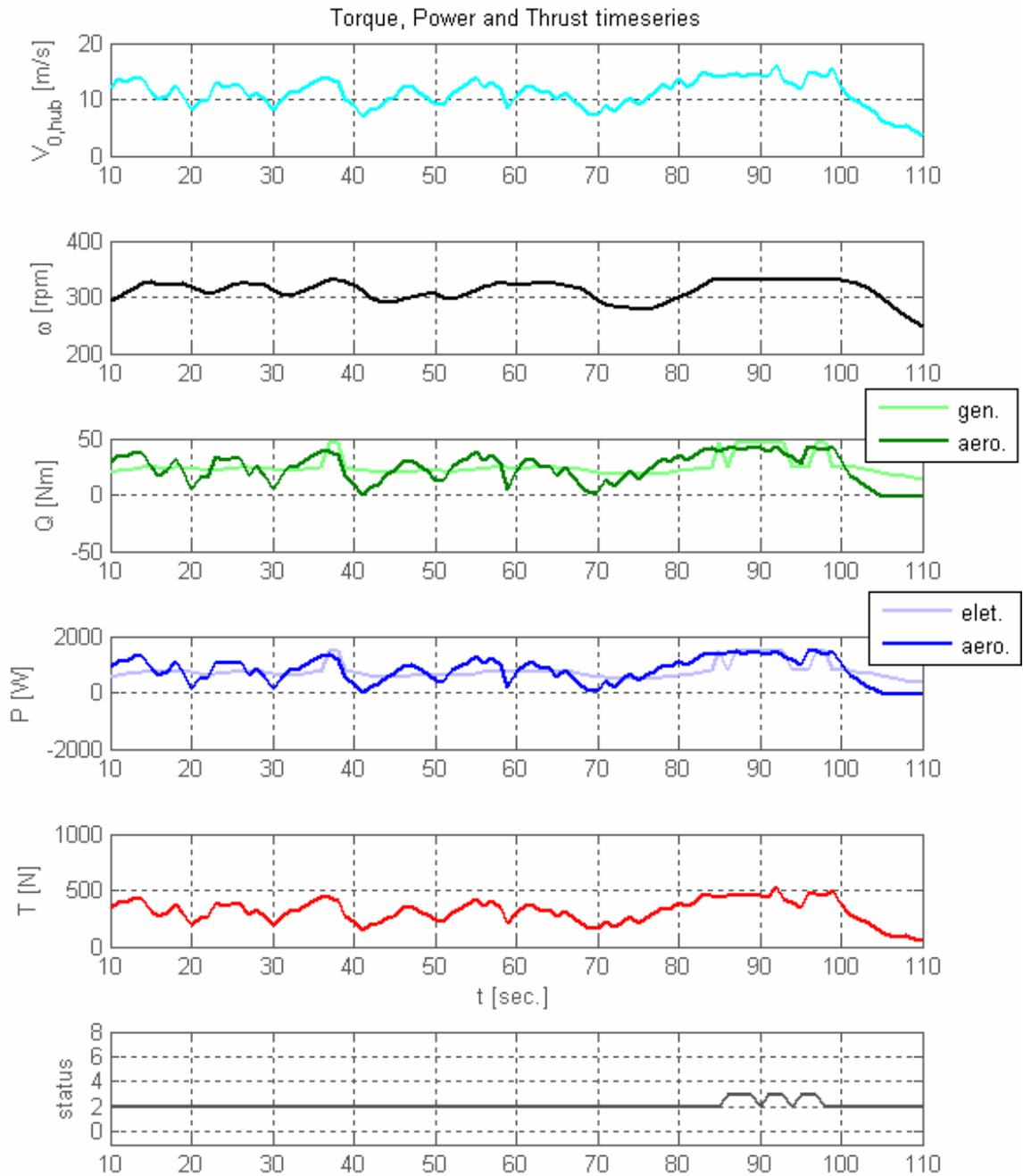
The aim is to develop a numerical model that simulates the wind turbine operational behaviour: the model output will be current and voltage time series values. Such data represents the input data for the electrolyser stack operational model. Due to the frequency distribution of wind speed over the time (yearly) the model allows to weigh properly each operational condition (bin) the system will be asked to operate.

Two possible system configuration are evaluated:

1. the electrolyser stack does not influences the behaviour of the wind turbine (wind turbine control system independent);
2. the electrolyser stack influences the behaviour of the wind turbine (wind turbine control system dependent on the load status of the stack);

Several scenarios for possible control logic are considered.

Wind turbine operational model is based on Blade Element Momentum theory. The aerodynamic performance of the rotor are calculated with reference to the wind turbine operational parameters. By means of an electro-mechanical train model, values of mechanical and electrical torque are calculated. Simplified equations lead to voltage and current values for every cycle of calculation. The model generates time series over 10 min with data at 10 Hz as shown in the following graphics:



In order to transfer the 10 min time series to the real condition (site condition) the model allows to weigh the time series values over the wind distribution (resource) at site (weibull distribution) as shown in the following table:

**SITE VARIABLES**

k	2.00	[-]
V <sub>m</sub>	7.50	[m/s]
IT <sub>15</sub>	18.00%	[-]
a	2.0	[-]
c	8.4628	[m/s]
V <sub>m3</sub>	9.3053	[m/s]

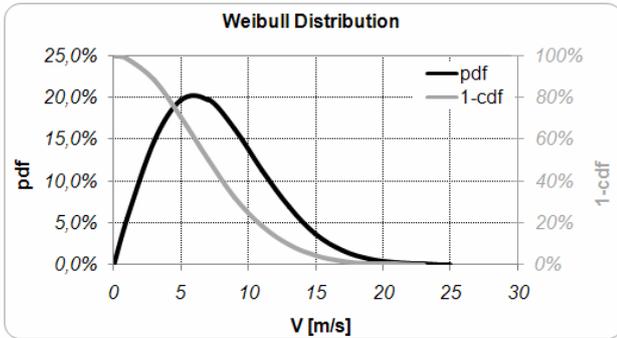
**LIFETIME VARIABLES**

years	20.0	[-]
h <sub>fault/year</sub>	24.0	[hours]
N <sub>subset,prod&amp;idling</sub>	3	[-]
N <sub>subset,fault</sub>	1	[-]
h <sub>tot,prod&amp;fault</sub>	165030	[hours]

**Auxiliary Cells**

(1+1/k)	1.50	[-]
Γ(1+1/k)	0.8862	[-]
(1+2/k)	2.00	[-]
Γ(1+2/k)	1.0000	[-]
(1+3/k)	2.50	[-]
Γ <sup>1/3</sup> (1+3/k)	1.0995	[-]

j	V <sub>min,bin</sub> [m/s]	V <sub>max,bin</sub> [m/s]	V <sub>ave,bin</sub> [m/s]	σ [m/s]	IT [-]	flag	pdf [-]	1-cdf [-]	Δ(cdf) [-]	h <sub>bin</sub> [hours]	h <sub>prod</sub> [hours]	h <sub>idling</sub> [hours]	h <sub>fault</sub> [hours]	h <sub>prod,subset</sub> [hours]	h <sub>idling,subset</sub> [hours]	h <sub>fault,subset</sub> [hours]
1	0.0	2.0	1.0	1.0	102.0%	0	5.51%	98.61%	5.43%	9517		9517			3173	
2	2.0	4.0	3.0	1.3	42.0%	1	14.78%	88.19%	14.59%	25560	25485	0	75	8495	0	75
3	4.0	6.0	5.0	1.5	30.0%	1	19.70%	70.53%	19.49%	34142	34042	0	100	11348	0	100
4	6.0	8.0	7.0	1.7	24.9%	1	19.72%	50.45%	19.57%	34295	34195	0	100	11399	0	100
5	8.0	10.0	9.0	2.0	22.0%	1	16.22%	32.27%	16.17%	28323	28240	0	83	9414	0	83
6	10.0	12.0	11.0	2.2	20.2%	1	11.34%	18.46%	11.36%	19906	19848	0	58	6616	0	58
7	12.0	14.0	13.0	2.5	18.9%	1	6.86%	9.44%	6.91%	12110	12074	0	36	4025	0	36
8	14.0	16.0	15.0	2.7	18.0%	1	3.62%	4.32%	3.68%	6440	6421	0	19	2141	0	19
9	16.0	18.0	17.0	2.9	17.3%	1	1.68%	1.77%	1.72%	3011	3002	0	9	1001	0	9
10	18.0	20.0	19.0	3.2	16.7%	1	0.69%	0.65%	0.71%	1243	1239	0	4	413	0	4
11	20.0	22.0	21.0	3.4	16.3%	0	0.25%	0.21%	0.26%	455	0	455	0	0	152	0
12	22.0	24.0	23.0	3.7	15.9%	0	0.08%	0.06%	0.08%	148	0	148	0	0	50	0
13	24.0	26.0	25.0	3.9	15.6%	0	0.02%	0.02%	0.02%	43	0	43	0	0	15	0
14	26.0	28.0	27.0	4.1	15.3%	0	0.01%	0.00%	0.01%	11	0	11	0	0	4	0
15	28.0	30.0	29.0	4.4	15.1%	0	0.00%	0.00%	0.00%	3	0	3	0	0	1	0
tot →							100.47%		100.00%	175207	164546	10177	484	54852	3395	484



Sensitive analysis and studies of different operational scenarios is considered.

### 3 CONCLUSIONS

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The protocols and procedures defined in this deliverable are intended as means of verification to assess the achievements of target efficiency in the specific range of operating temperature and pressure.

The aim is also to compare stack performance with single cell performance at specific current densities and to determine energy consumption at the nominal production capacity.

Moreover, the objective is to determine a protocol for assessing performance degradation in terms of a terminal voltage increase in steady-state tests and duty cycle experiments.

These protocols are developed with the aim to propose harmonized testing for PEM electrolyzers establishing agreed and shared operation procedures among different partners involved in this project and to provide a basis for comparison to research performing entities outside Electrohypem.