HORIZON-JTI-CLEANH2-2024

GA No. 101192342

Direct seawater electrolysis technology for distributed hydrogen production

SWEETHY

SWEETHY - Deliverable report

D7.1 – Single-cell test specification

Clean Hydrogen Partnership

Co-funded by the European Union

Deliverable No.	D7.1	
Related WP	WP 7	
Deliverable Title	Single-cell test specification	
Deliverable Date	2025-11-30	
Deliverable Type	DEM	
Dissemination level	Public (PU)	
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Approved by	Live Mölmen (RISE)	2025-11-27
Status	Final	2025-11-27

Document History

Version	Date	Editing done by	Remarks
V1.0	13.10.2025	Norbert Kazamer	Initial Version
V1.1	15.10.2025	Jeffrey Roth	Major revisions in all chapters
V2.0	17.11.2025	Norbert Kazamer	Final Draft
V3.0	25.11.2025	Francisco Alcaide	Reviewed
FINAL	25.11.2025	Live Mölmen	Approved
Updated	30.01.2026	Live Mölmen	Update of PTL in table 2

Project Summary

SWEETHY will develop an advanced technology for direct seawater electrolysis that will be able to produce H_2 and O_2 under intermittent conditions accounting for the coupling to renewable power sources (especially wind and PV). The electrolyser will be based on an anion exchange membrane (AEM) operating in natural or alkaline seawater, and the SWEETHY technology will be developed along three dimensions:

a) Materials optimisation. To meet the specific requirement of seawater environment the project will focus on corrosion resistance and selective PGM-free electrocatalysts for hydrogen and oxygen evolution reactions, on AEM with high selectivity for transporting hydroxide anions and anti-fouling properties as well as on novel anti-corrosion coatings for bipolar plates and porous transport layers prepared by plasma spraying and electrodeposition.

b) Electrolyser stack prototyping. The project will exploit a novel stack architecture, which uses hydraulic cell compression to host the advanced materials and to produce H_2 at high pressure. Beneficial functions of the targeted unique stack are related to scalability, reliability and maintainability that will be tremendously improved in comparison to conventional AEMWE stacks.

c) Sustainability analysis. The project will conduct studies (life-cycle assessment (LCA), techno-economic analysis (TEA)) to evaluate circularity of the electrolyser system and its integration into renewable-power systems and to explore an efficient by-product utilisation way through industrial symbioses. These studies will feed back to materials optimisation and stack development. Complementing LCA, social LCA and techno-economic analyses/optimisation by qualitative work ensures both environmental, economic, and social sustainability.

Combining these three dimensions, SWEETHY will utilise Mediterranean seawater from the coast of Messina, Italy, to test its electrolyser with the goal withstand more than 2000 h of operation to produce 20 g_{H2}/h with a degradation rate lower than 1%/100h. In addition, SWEETHY will demonstrate how the operation of the electrolyser can ensure an optimised revenue concerning by-products and grid services.

Public summary

SWEETHY single cell test harmonisation defines standardised procedures for preparing synthetic seawater and describes the benchmarking test cell and sample properties for testing anion exchange membrane water electrolyser (AEMWE) cells in the SWEETHY project. Finally, it sets the test conditions for activation, polarisation and degradation testing. This harmonised approach supports SWEETHY's goals and proposes a public reference of testing procedure for direct seawater operation with reliable and comparable performance results.

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Abbreviations & Definitions

Abbreviation	Meaning
AEM	Anion exchange membrane
AEMWE	Anion exchange membrane water electrolysis
EIS	Electrochemical impedance spectroscopy
JRC	Joint Research Centre
PEEK	Polyether ether ketone
PP	Pole plate
PTL	Porous transport layer

1 Introduction

The transition toward clean and secure energy systems calls for innovative pathways to produce green hydrogen from abundant resources. The SWEETHY project addresses this challenge by developing advanced direct seawater electrolysis technology capable of operating efficiently under realistic marine conditions and variable renewable power input. Within this framework, harmonised and reliable single-cell testing is essential to ensure that new materials and cell components can be evaluated consistently across all research partners.

This deliverable defines the standardised procedures, reference materials, and in-situ operating conditions for the assessment of anion exchange membrane water electrolysis (AEMWE) single cells in the SWEETHY project. By establishing a common methodology for synthetic seawater preparation, cell assembly, break-in processes, and performance and durability characterisation, it enables:

- Consistent and comparable results across different laboratories
- Improved interpretation and traceability of component performance
- Effective knowledge transfer to broader scientific and industrial communities
- Strengthened exploitation potential of the developed technologies

The harmonised testing protocol outlined in this document supports the systematic screening and optimisation of SWEETHY materials and feeds directly into the development of a scalable and durable seawater electrolyser system. Moreover, this document can serve as a guideline for in-situ seawater electrolysis investigations.

2 Materials and methods

2.1 Background

In the following subchapters, detailed technical information is provided on testing feed solutions, components and hardware, as well as testing conditions. These parameters will serve as baseline and may be adapted where necessary to suit the specific characteristics of the materials under investigation.

2.2 Testing feed solutions, components and hardware

2.2.1 Synthetic seawater and alkaline seawater composition

Testing of the final SWEETHY prototype in M31-48 of the project will be conducted with natural seawater in Messina, Italy. However, during the earlier stages of the project, most of the partners will also need to conduct single-cell and short-stack testing with seawater, but not everyone has access to natural seawater. Moreover, the composition of natural seawater varies between the locations, that is why synthetic seawater will be used at early stages of the SWEETHY project.

Preparation of synthetic seawater will follow a standard SWEETHY recipe, which is a modified ASTM D1141-98(2021)[1] standard. For the preparation of 1 L of synthetic seawater, salts in accordance with Table 1. will be dissolved in 0.8 L of deionised (DI) water. After full dissolution of salts, the solution will be diluted to 1 L and the pH will be adjusted to 8.2 with 0.1 M NaOH solution.

Table 1: Dry salt composition of synthetic seawater

Compound	Weight / g	Comment
NaCl	24.53	
$MgCl_2 \bullet 6\ H_2O$	11.10	Anhydrous salt may be used if the weight is recalculated
Na_2SO_4 (anhydrous)	4.09	Hydrated salt may be used if the weight is recalculated
$CaCl_2$ (anhydrous)	1.16	Hydrated salt may be used if the weight is recalculated
KCl	0.695	
$NaHCO_3$	0.201	
KBr	0.101	

For the preparation of synthetic alkaline seawater, or 1 M KOH in seawater, salts with weights according to Table 1 will be dissolved in 0.8 L of DI water. To this solution, 0.2 L of a 5 M KOH solution in DI water will be slowly added under stirring. After 1 hour of stirring, the solution will be filtered to ensure that no solid particles remain in the filtrate.

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[1] ASTM International, D19 Committee, ATSM D1141-98 Practice for the Preparation of Substitute Ocean Water, (2021). https://doi.org/10.1520/D1141-98R21.

2.2.2 Reference components

For each cell component, a state-of-the-art benchmark material has been chosen, as shown in Table 2. Test samples must be prepared either for testing in 4 cm^2 or 25 cm^2 format to fit into the provided ProPuls test systems (single-cells and short-stacks).

Table 2: Benchmark components

Component	Electrode	Benchmark material
Pole plate (PP)	Anode	Platinum coated titanium, 0.5 mm (Titan Grade 1 / 3.7025), Resilion™ Pt coating by James Cropper Advanced Materials (former TFP (P-TECH 0102))
Porous transport layer (PTL)	Anode	Platinum coated titanium, 3x Bekaert 0,5 mm (Type Currento® PTL Ti-56/500 PT200 (215 x 280 mm))
Catalyst	Anode	Cobalt(II,III)oxide applied on Ni felt anode PTL (Bekaert) at 2.5 mg cm^{-2} with PiperION ionomer
Membrane		PiperION®, non-reinforced, 40 µm
Catalyst	Cathode	Freudenberg E20 with 0.4 mg cm^{-2} Pt coating
Porous transport layer (PTL)	Cathode	AvCarb MGL2000LD
Pole plate (PP)	Cathode	Nickel, 0.5 (Type Ni201 / 2.4068)

Table 3: Cathode electrode coating ingredients

Component	Specification	Obtaining example
Pt catalyst	40 wt. % Pt/C	Thermoscientific (Article 047308.06)
PiperION solution	5 wt. %	Fuel Cell Store
Deionised water	below 0.5 µS cm^{-1}	
2-propanol	99.9 %	ROTISOLV 99.9% HPLC by CarlRoth

To prepare the catalyst layers, C, the PiperIon ionomer, I, content should be adjusted to 10 wt. % on a dry basis, defined as $I / (I + C)$. The losses caused by the spraying process must be considered to achieve the required 0.4 mg_{Pt} cm^{-2} in the catalyst layer.

2.2.3 Component dimensions

The materials suitable for direct seawater electrolysis developed in the project will be in-situ assessed using the ProPuls GmbH single-cell test system. To enable uniform testing and reliable comparison with benchmark materials, samples must be produced in identical dimensions to the reference components to fit in the reference test system. For each side of the test cell the electrode (which will be a combination of PTL and catalyst or of GDL and catalyst), the combined thickness in compressed state should be 1.3 mm to 1.5 mm. The outer dimensions of all the components, except pole plates, must be 19.8 x 21.8 mm (4.0 cm^2 samples) and 51.8 x 51.8 mm (25 cm^2 samples), see Figure 1. Further changes in dimensions should be discussed with ProPuls before testing.

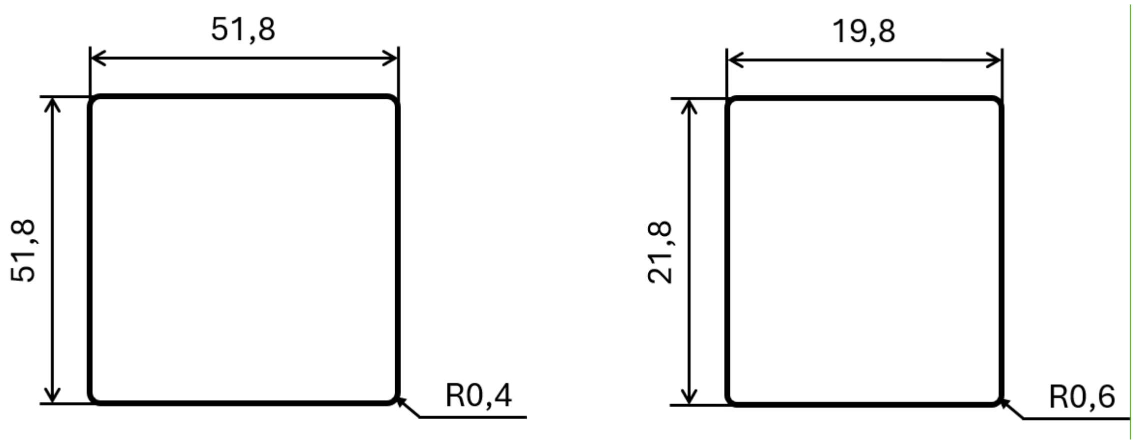

Figure 1: PTL and electrode dimensions (in mm) for test cell

PP materials should have a thickness between 0.1 and 0.5 mm and outer dimensions of 61.8 x 61.8 mm (Figure 2) .

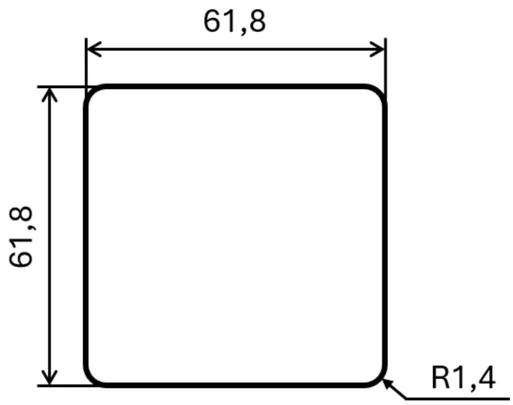

Figure 2. Pole plate dimensions for a ProPuls test cell of 25 cm^2

2.2.4 Test cell assembly

To ensure comparable measurements within the project, the SWEETHY partners are equipped with single-cell test systems from ProPuls based on hydraulic cell compression (see Figure 3). The applied hydraulic pressure ensured uniform mechanical compression and minimized contact resistances, thereby providing reliable electrical connectivity across all cell components throughout operation.

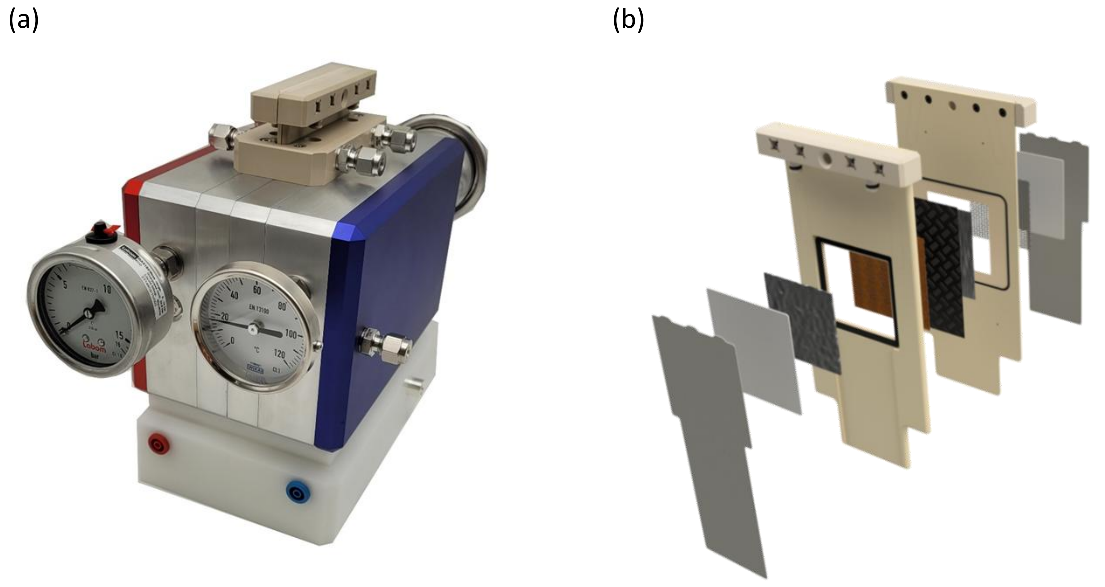

Figure 3: (a) Single-cell test system with an active area of 4 cm² or 25 cm², and (b) exploded view of the ProPuls test cell

The test system contains a test cell that is assembled with the test components. The cell can be equipped with active materials of area either 4 cm² or 25 cm². The testing cell consists of (from left to right in 3b):

- Cathode contact plate (silver/gold coated copper)
- Cathode PP
- Cathode PTL
- Cathode cell frame (with gaskets) made of PEEK
- Cathode electrode
- Membrane
- Anode electrode
- Anode cell frame (with gaskets) made of PEEK
- Anode PTL
- Anode PP
- Anode contact plate (silver/gold coated copper)

For sample preparation, each side is assembled first by its own. The two cell frames are placed separately on a clean surface with the side facing the membrane downwards, and the components are inserted starting from the PTL towards the pole plate and contacting plate in the half cell frame. Both frames are assembled separately. Subsequently, one of the cell halves is turned around facing the inside up, a membrane is placed on it. Then, the other half-cell is placed on top of the half-cell with a membrane. The full cell is then carefully mounted in the test system. Detailed mounting instructions and videos will be provided by ProPuls GmbH.

2.3 Test Conditions

2.3.1 General single-cell testing conditions

As decided by the consortium, all the cells will be tested under the following conditions to ensure comparable results.

- Test temperature
    - Test system temperature 50°C, regulated by separate heat circuit.
    - Process media supplied at 50°C KOH is supplied only to the anode, while a mixture of KOH and seawater is fed to the cathode.
- Cell compression 8 bar
- Gas evolution at ambient pressure
    - Process media pressure inlet max. 1 bar
- Electrolyte feed:
    - Composition:
        - 1 M potassium hydroxide, KOH, dissolved in DI water (> 1 MΩ cm) as anolyte.
        - 1 M potassium hydroxide, KOH, dissolved in seawater as catholyte. The pH will be adjusted to pH = 14 with KOH if it lowers due to precipitation of salts. Any formed solid precipitates will be removed by suitable methods (*e.g.* sedimentation, filtration, or centrifugation)
    - Physical properties (Based on the JRC protocol for water electrolysis)
        - minimum 4 ml min^{-1} (4 cm^2 cell type)
        - minimum 25 ml min^{-1} (25 cm^2 cell type)
        - **maximum inlet pressure 1 bar**

2.3.2 Break-in protocol

The break-in protocol is an important step in the commissioning of AEM electrolyser cells to prevent material damage and ensure stable and long-lasting cell function. Without this process, performance losses could occur, and the life of the cell could be significantly reduced.

After setting the general test conditions mentioned above, all the cells will be subjected to a break-in procedure as shown in Figure 4.

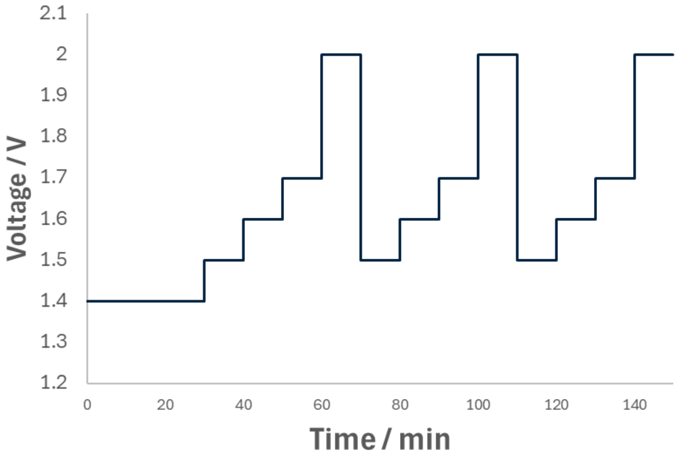

Figure 4: Schematic break-in procedure for the test cells

The testing procedure will start with lowest possible loading or 0.025 A cm^{-2} for 30 minutes, followed by steps, specified in Table 4, with fixed potential for 10 min until current stabilisation.

Table 4: Break-in procedure steps

Step	Loading	Type	Time
1	0.025 A cm^{-2}	Fixed current	30 min
2	1.5 V	Fixed potential	10 min
3	1.6 V	Fixed potential	10 min
4	1.7 V	Fixed potential	10 min
5	2.0 V	Fixed potential	10 min
6	Repeat Step 2 to 5 two times or until current values are stable during the fixed potential setting		

2.3.3 Polarisation curves: test cell performance characterisation

Polarisation curves will be recorded according to the harmonised protocol for low temperature electrolysis testing of the Joint Research Centre (JRC)[2]. Due to fact the AEM technology has improved since this protocol was published, the recommended measuring steps for AEMWE as described in the abovementioned protocol, are not usable for the SWEETHY project. Therefore, step recordings will be realised according to the protocol for proton exchange membrane water electrolysis.

After break-in (subchapter 3.3.2), the cell will be kept at 0.1 A cm^{-2} for 5 minutes, before starting to record the polarisation curves. Polarisation curves will be measured by galvanostatic control, stepwise increasing the current from 0.001 A cm^{-2} to a maximum of 2.0 A cm^{-2}, in steps defined by the JRC protocols[2] and shown in Table 5. At each set point, the dwell time should be chosen in a way that the potential is +/- 5 mV over a period of 30 s, followed by 30 s acquisition time, where voltage and current are recorded. A cut-off voltage of 2.0 V will be used. If the voltage reaches this value during a measurement, no further set points will be set even if the maximum current density has not been reached.

Table 5: Polarisation curve setpoints for the test cells

Set point	Current density / A cm^{-2}	Set point	Current density / A cm^{-2}
1	0.001	16	0.600
2	0.005	17	0.700
3	0.010	18	0.800
4	0.025	19	0.900
5	0.050	20	1.000
6	0.075	21	1.100
7	0.100	22	1.200
8	0.150	23	1.300
9	0.200	24	1.400
10	0.250	25	1.500
11	0.300	26	1.600
12	0.350	27	1.700
13	0.400	28	1.800
14	0.450	29	1.900
15	0.500	30	2.000

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[2] Malkow, T., Pilenga, A., Tsotridis, G. and De Marco, G., EU harmonised polarisation curve test method for low-temperature water electrolysis, EUR 29182 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-81993-3 (online),978-92-79-81992-6 (print), doi:10.2760/179509 (online),10.2760/324006 (print), JRC104045.

2.3.4 Electrochemical Impedance Spectroscopy (EIS)

Electrochemical Impedance Spectroscopy (EIS) will be used as a diagnostic tool to assess the electrochemical behaviour and degradation of test cells both before and after durability testing. The measurements will follow the approach recommended by the Joint Research Centre (JRC) in the harmonised protocol, with adaptations as needed based on cell configuration and partner feedback.

EIS measurements will be conducted in both galvanostatic and potentiostatic modes. In galvanostatic mode, impedance spectra will be recorded at three reference current density levels:

- Low current: $j \leq 0.03$ A·cm^{-2}
- Nominal current: $j = 0.5$ A·cm^{-2}
- High current: $j = 1.0$ A·cm^{-2}

These levels will serve as standard reference points for comparison between partners. Additional points may be added as needed, based on the results obtained during testing or to capture specific electrochemical behaviours. The amplitude of the current perturbation will be set within the range of 0.5% to 5% of the DC **current**, in line with the JRC recommendation, to ensure linear response and measurement accuracy.

In potentiostatic mode, impedance will be measured at fixed cell voltages of:

- 1.5 V, 1.8 V, and 2.0 V

The perturbation will consist of a sinusoidal voltage signal, typically 5–10 mV**,** as recommended in the JRC protocol for maintaining signal integrity while avoiding nonlinear behaviour. The recommended frequency range for all EIS scans is 10^{-2} Hz to 10^{6} Hz. If instrumentation does not allow measurements up to 1 MHz, the maximum available frequency should be used and clearly documented. Measurements will be performed under steady-state operating conditions, with stable temperature, pressure, flow rates, and DC current or voltage, to ensure reliable and reproducible results.

The analysis of EIS spectra will focus on extracting key parameters that provide insight into device behaviour and degradation processes:

- Ohmic resistance (R_{Ω}): derived from the high-frequency intercept on the real axis of the Nyquist plot, representing mainly membrane and contact resistances.
- Polarisation resistance (R_{p}): determined as the difference between the low- and high-frequency intercepts, reflecting interfacial charge transfer resistance.

In addition, where relevant, the following spectral features may be analysed:

- Inductive behaviour at high frequencies, which may indicate transient processes or effects from wiring, gas evolution, or current collectors.
- Diffusion-related impedance, typically observed as a low-frequency tail or inclined line in Nyquist plots, suggesting mass transport limitations within porous electrodes or gas diffusion layers.

Visual tools such as Nyquist and Bode plots will support the qualitative interpretation. Quantitative fitting will be carried out using equivalent circuit models, including resistive and capacitive elements, constant phase elements (CPEs), or inductors, depending on the shape of the spectrum and the operating conditions.

Where applicable, Kramers–Kronig (KK) validation will be performed to verify that the data comply with the fundamental assumptions of EIS (linearity, causality, stability), in line with the JRC guidelines.

This analysis protocol aims to ensure consistency across laboratories and enable meaningful comparison of data, while supporting a deeper understanding of degradation phenomena in both low- and high-temperature electrolysis systems.

2.3.5 Polarisation curves: test cell durability characterisation

To test as many samples as possible in the available work package time, the durability characterisation must be reduced to a minimum to achieve comparable results.

For the characterisation the cell will be set in galvanostatic mode depending on the performance of the cell at the performance characterisation. Setpoint is chosen by the current density of 0.5 A cm^{-2} , to ensure good comparability with the project key performance indicators. Testing conditions stay as described in subchapter 2.3 at least 100-h. Maximum voltage should be kept below the cut-off voltage of 2.0 V. At the End of the 100-h durability test a final polarisation curve as described in subchapter 3.3.3 should be performed.

2.4 Shut-down, cell disassembly and component storage

At the end of the test runs, each cell must be removed from the test system and the components disassembled for further analysis.

- Test cell disassembly

The electrolyte feed must be stopped before removing the applied cell compression. Then, compression is set to 0 bar and the test cell can be removed from the test system (Beware: it may still be hot!). The test cell is placed on a clean surface and disassembled in reverse order of the assembling process of subchapter 3.2.4. Table 6 describes the nomenclature for the component types.

- Component handling
    - PPs and PTLs should be cleaned under ultrapure water and dried to prevent any redox processes on the component.
    - Membranes should be stored with some droplets of 1 M KOH solution to prevent them from drying.
    - All samples should be stored in separate zip bags which are labelled as described in Table 6.

Table 6: Nomenclature of component types

Component type (C)	Description of a component
01	Anode PP
02	Anode PTL
03	Anode electrode
04	Membrane
05	Cathode electrode
06	Cathode PTL
07	Cathode PP
08	Anolyte sample
09	Catholyte sample
09	Other

The sample names should be in the following form:
SWEETHY – Acronym of institute – Sample number – Component type – Test date (JJMMDD)

Example:
SWEETHY, ProPuls, Sample 3, cathode PTL, Test started at 31. October 2025
SWEETHY-PP-S03-C06-251031

Additional descriptions defined by the partners' institutions are acceptable, they may be placed on the sample bags below the SWEETHY-nomenclature. It is recommended to print the labels.

- All components in the separate sample bags and labeled should be stored in a lightproof, robust box for later documentation or further analysis.

2.5 Data Analysis

Measured data must be stored and handled in accordance with the Data Management Plan (DMP) of the SWEETHY project (see Deliverable D1.1).

The main criteria for the evaluation of the different experiments with the test cells are the polarisation curves recorded and the results of the durability tests (degradation). The specified data points according to JRC protocol must be stored. Uncertainties caused by the measurement setup must be documented and be available for following data processing.

For data analysis the following data points are mandatory:

- Timestamp (e.g. YYYY-MM-DD hh:mm:ss)
- Cell potential [V]
- Current / current density [A, A cm^{-2}]
- Temperature [°C] (anode electrolyte feed inlet, cathode electrolyte feed inlet, or at least test system temperature)
- Cell compression [bar]
- Back pressure anode and cathode electrolyte feed [mbar]
- Electrolyte feeds [ml min^{-1}]

Further information must be provided about:

- Cell size
- Material setup
- Electrolyte feed composition

For EIS measurements also parameters like:

- Galvanostatic or potentiostatic
- Frequency [Hz] / Time [s] / Real [Ω, Ω cm^2] / Imaginary [Ω, Ω cm^2] (for all frequencies)

3 Contribution to project

This report on single cell test harmonisation will contribute to the project's targets SO1 "Develop high performance, cost-effective and durable materials for the direct seawater AEMWE Components" (DoA Part B, Page 5/6) as all in-situ tests should be performed in the same type of test cell and testing conditions. In this way, aberrations can be detected at an early stage. Also, the results of the individual project partners can be better aligned for their respective developments.

In addition, the development of the SO2 "Develop and test an energy-efficient and stable 0.5 kW AEMWE short stack with direct seawater feed" (DoA Part B, Page 5/6) will be addressed, as the results generated in the previous work packages will directly lead to the development of the scalable electrolyser, which should be operated by preserving the cell conditions.

4 Conclusion and Recommendation

The harmonised single cell testing protocol developed within the SWEETHY project establishes a unified framework for evaluating anion exchange membrane water electrolysers (AEMWEs) under synthetic seawater conditions. By defining standardised procedures for seawater preparation, cell assembly, and performance characterisation, the methodology ensures that results obtained across different laboratories and partners are directly comparable and reproducible.

The implementation of this protocol supports SWEETHY’s broader objective of enabling efficient and sustainable hydrogen production from seawater. The defined operating and characterisation procedures facilitate identification of performance-limiting factors, support component benchmarking, and enhance confidence in data consistency across the consortium.

It is recommended that future work focus on extending this harmonisation effort to include stacks, long-term durability assessment under realistic seawater compositions, and the evaluation of potential degradation mechanisms specific to marine-derived electrolytes. Furthermore, publishing this protocol as a reference testing guideline will strengthen transparency and foster alignment with other international initiatives on seawater electrolysis exploration.

5 Acknowledgement

The author(s) would like to thank the partners in the project for their valuable comments on previous drafts and for performing the review.

Project partners:

#	Partner short name	Partner Full Name
1	RISE	RISE RESEARCH INSTITUTES OF SWEDEN AB
2	CNR	CONSIGLIO NAZIONALE DELLE RICERCHE
3	CIDETEC	FUNDACION CIDETEC
4	DLR	DEUTSCHES ZENTRUM FUR LUFT- UND RAUMFAHRT EV
5	IC	INSTITUT DE LA CORROSION SASU
6	SINTEF	SINTEF AS
7	PROPULS	PROPULS GmbH
8	CENMAT	CUTTING-EDGE NANOMATERIALS CENMAT UG HAFTUNGSBESCHRANKT
9	UNR	UNIRESEARCH BV

Disclaimer/ Acknowledgment

The project is supported by the Clean Hydrogen Partnership and its members.
Co-funded by the European Union under Grant Agreement No. 101192342. The views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the Clean Hydrogen Partnership. Neither the European Union nor the granting authority can be held responsible for them.

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Co-funded by the European Union