AD ASTRA

Harnessing Degradation mechanisms to prescribe Accelerated Stress Tests for the Realization of SOC lifetime

Massimiliano Della Pietra, PhD

ENEA

www.ad-astra.eu

davide.pumiglia@enea.it

Clean Hydrogen Partnership

EUROPEAN PARTNERSHIP

Co-funded by the European Union

#EUResearchDays
#PRD2022
#CleanHydrogen

Project Overview

Call year: 2018

Call topic:
FCH-04-3-2018 - Accelerated Stress Testing (AST) protocols for Solid Oxide Cells (SOC)

AD ASTRA

Project dates:
1 January 2019 – 31 August 2022

Total project budget:
3,008,426.25 €

% stage of implementation 27/10/2022: 100%

Clean Hydrogen Partnership max. contribution: 3,008,426.25 €

Other financial contribution:////

European Hydrogen Week

Partners

sunfire

EIFER

DTU Danmarks Tekniske Universitet

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

DE LA RECHERCHE À L'INDUSTRIE cea

SOLID POWER

IEES

UNIVERSITÀ DEGLI STUDI DI GENOVA

ENEA

UNIVERSITÀ DEGLI STUDI DI SALERNO

Clean Hydrogen Partnership EUROPEAN PARTNERSHIP

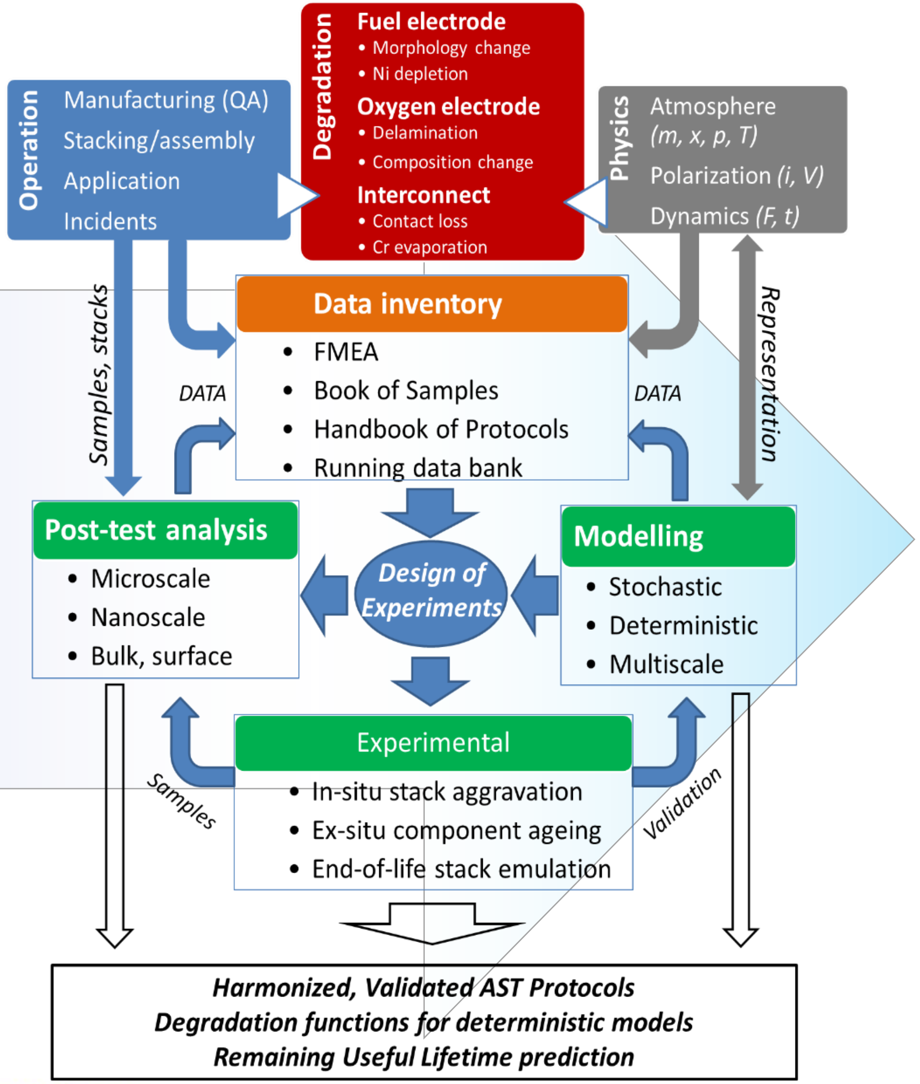
Co-funded by the European Union

European Hydrogen Week

Project summary

Global positioning vs SoA

- Useful lifetimes of >80kh expected/needed for commercial fuel cell stacks.
- No reliable degradation models currently available nor validated test procedures to predict durability in a practical timeframe.
- Resource- and time-consuming real-time durability tests required for verification of material/component modifications



Application and market area

- SOC Combined Heat & Power generators (CHP).
- SOC electrical energy storage into chemical energy (P2X).

Main Objectives

- Failure Mode and Effects Analysis (FMEA) for SOC stacks tested in the field.
- Prioritization of dependent and independent variables causing observed degradation.
- AST protocols that address realistic failure modes of fuel electrode, oxygen electrode and interconnect in P2X and CHP.
- Target AST durations < 3000 hours ←→ real-world stack < 40,000 h identifying transfer functions of degradation.
- Remaining Useful Life (RUL) prediction models based on operating profile.
- A *generalized methodology* for the definition of ASTs submitted for standardization to the International Electrotechnical Commission (IEC)

Clean Hydrogen Partnership
EUROPEAN PARTNERSHIP
Co-funded by the European Union

Progress/Actions - SOC ex situ and in situ AST

Achievement to M44

IN SITU AST — 7 different approaches

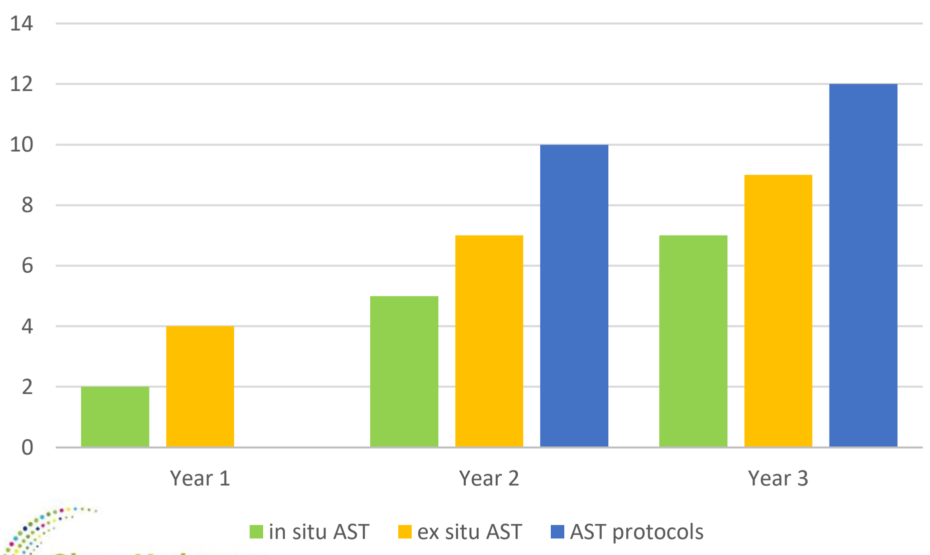
EX SITU AST — 9 different approaches

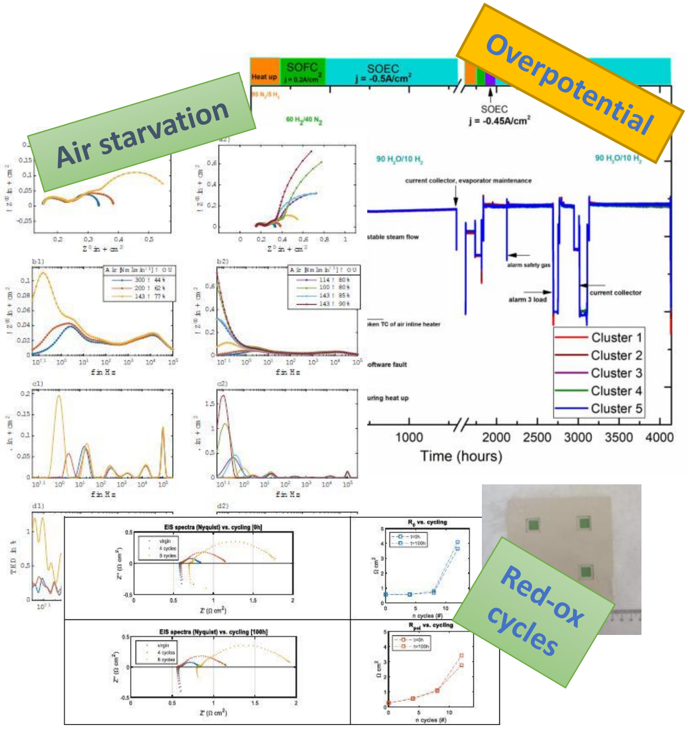
25% 50% 75%

Status at month 44 of a 44 months project at date 31/08/2022

Ex Situ
SOC components are aged out of the cell frame environment and reassembled in a SRU or Stack to check the degradation occurred in the ageing process

In Situ
Ageing strategies of single SOC components are implemented directly in SRUs or stacks





Clean Hydrogen Partnership

EUROPEAN PARTNERSHIP

Co-funded by the European Union

Progress/Actions SOC Degradation rate, CAPEX reduction

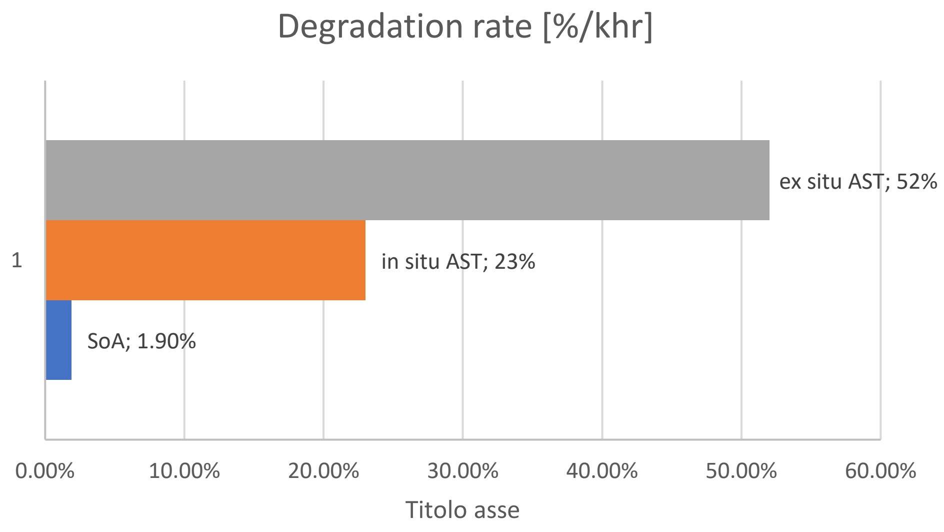
Achievement to M44

Degradation rate — SoA: 1,9% /khr

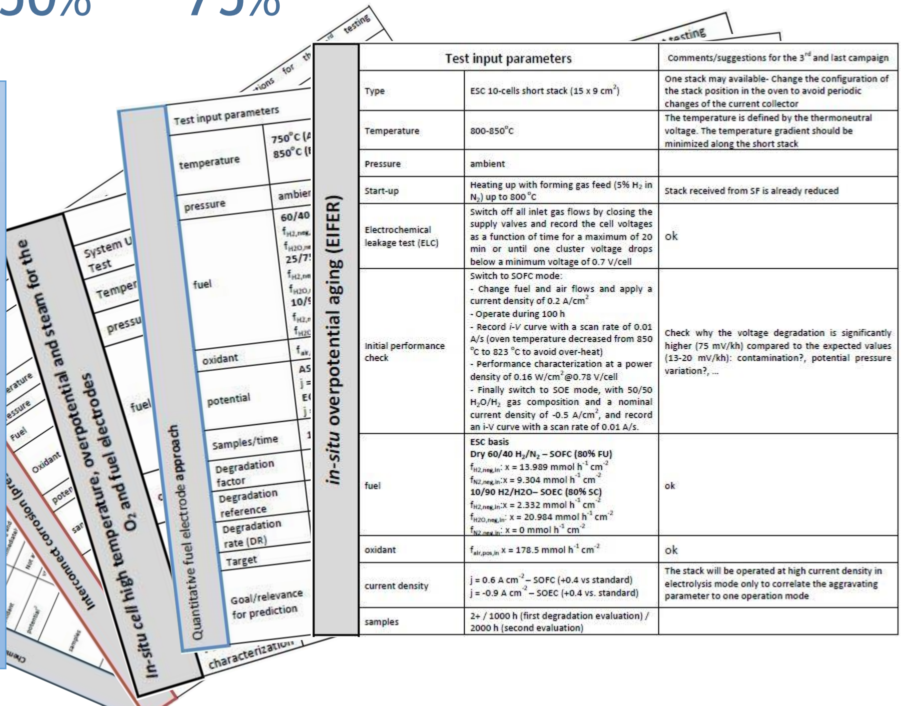
CAPEX reduction — SoA: 4k€/kW

25% 50% 75%

Status at month 44 of a 44 months project at date 31/08/2022



1000h stack test = approximately 10 k€ operational costs. Typical testing times are 15 kh for industry qualification. AD ASTRA protocols: aim reduce to 3kh and 120k€ can be saved per test.



in-situ overpotential aging (EIFER)

Test input parameters		Comments/suggestions for the 3rd and last campaign
Type	ESC 10-cells short stack (15 x 9 cm^2)	One stack may available- Change the configuration of the stack position in the oven to avoid periodic changes of the current collector
Temperature	800-850°C	The temperature is defined by the thermoneutral voltage. The temperature gradient should be minimized along the short stack
Pressure	ambient	
Start-up	Heating up with forming gas feed (5% H_2 in N_2) up to 800 °C	Stack received from SF is already reduced
Electrochemical leakage test (ELC)	Switch off all inlet gas flows by closing the supply valves and record the cell voltages as a function of time for a maximum of 20 min or until one cluster voltage drops below a minimum voltage of 0.7 V/cell	ok
Initial performance check	Switch to SOFC mode: - Change fuel and air flows and apply a current density of 0.2 A/cm^2 - Operate during 100 h - Record *i-V* curve with a scan rate of 0.01 A/s (oven temperature decreased from 850 °C to 823 °C to avoid over-heat) - Performance characterization at a power density of 0.16 W/cm^2@0.78 V/cell - Finally switch to SOE mode, with 50/50 H_2O/H_2 gas composition and a nominal current density of -0.5 A/cm^2, and record an i-V curve with a scan rate of 0.01 A/s.	Check why the voltage degradation is significantly higher (75 mV/kh) compared to the expected values (13-20 mV/kh): contamination?, potential pressure variation?, ...
fuel	**ESC basis** **Dry 60/40 H_2/N_2 – SOFC (80% FU)** $f_{H2,neg,in}$: x = 13.989 mmol h^{-1} cm^{-2} $f_{N2,neg,in}$: x = 9.304 mmol h^{-1} cm^{-2} **10/90 H2/H2O– SOEC (80% SC)** $f_{H2,neg,in}$: x = 2.332 mmol h^{-1} cm^{-2} $f_{H2O,neg,in}$: x = 20.984 mmol h^{-1} cm^{-2} $f_{N2,neg,in}$: x = 0 mmol h^{-1} cm^{-2}	ok
oxidant	$f_{air,pos,in}$ x = 178.5 mmol h^{-1} cm^{-2}	ok
current density	j = 0.6 A cm^{-2} – SOFC (+0.4 vs standard) j = -0.9 A cm^{-2} – SOEC (+0.4 vs. standard)	The stack will be operated at high current density in electrolysis mode only to correlate the aggravating parameter to one operation mode
samples	2+ / 1000 h (first degradation evaluation) / 2000 h (second evaluation)	

Progress/Actions - modeling

Achievement to M44

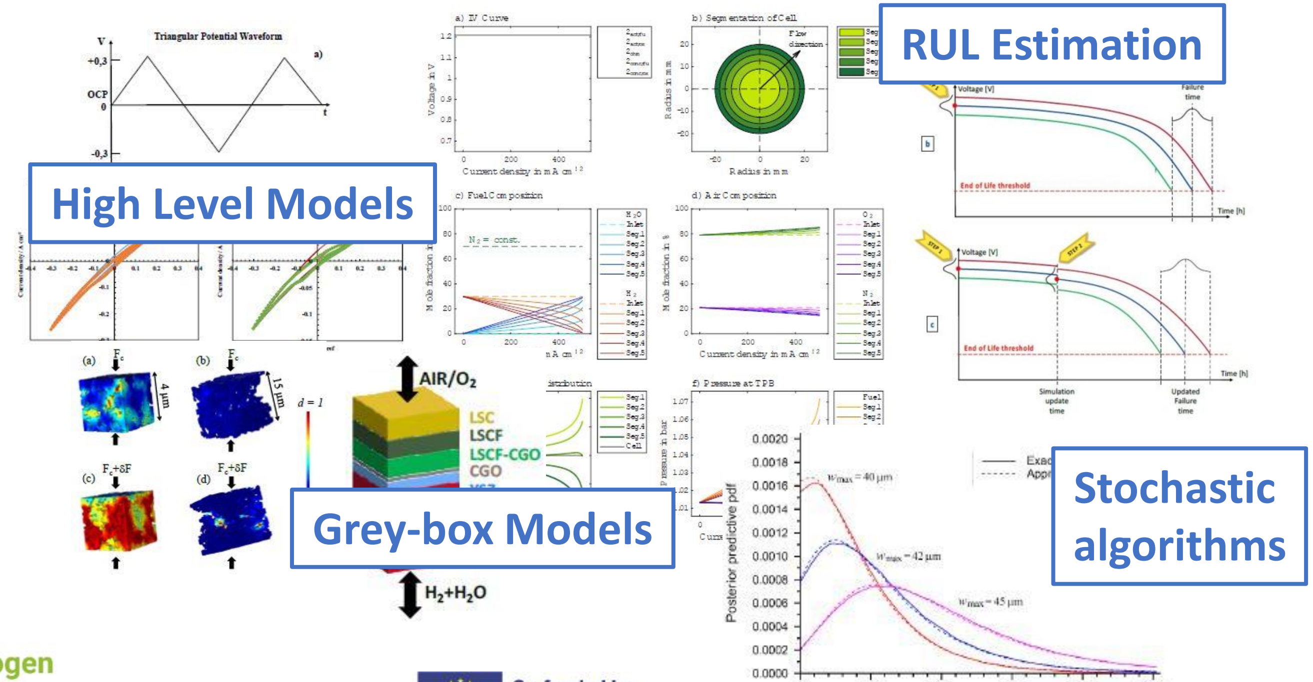
Local models
Multiscale models

25% 50% 75%

Ni-YSZ electrode
LSCF electrode
State-of-Health characterization
Degradation function
Degration rate evolution

Status at month 44 of a 44 months project at date 31/08/2022

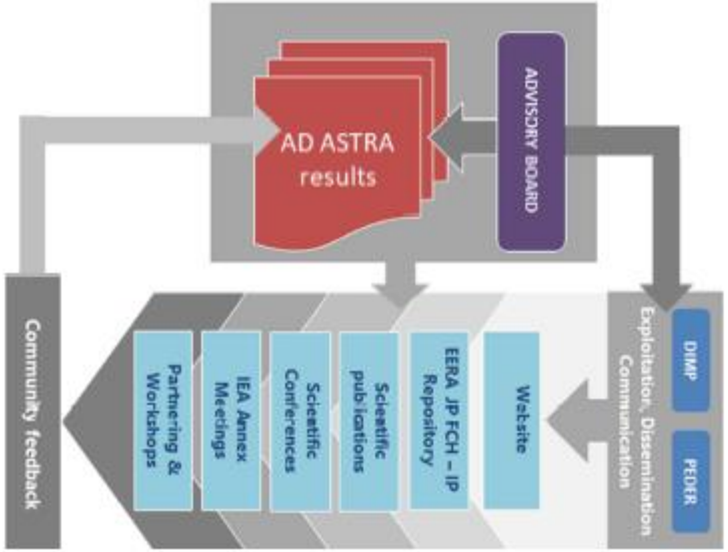
- Identification of the main degradation parameters from available data and high-level physical models.
- Development of grey-box (i.e. simplified) degradation models, describing the time evolution of degradation parameters.
- Stack performance and lifetime models, with embedded degradation mechanisms, simulated through parameter-based and statistical approaches.
- Association of suitable stochastic and signal treatment based algorithms to define uncertainties in high and low-level physical models in order to.
- Identification of statistical approaches allowing extrapolation of accelerated variables from high to low acceleration levels.



Exploitation Plan/Expected Impact

Exploitation

- 15+ open access scientific publications;
- 10+ experimental datasets available (and re-usable) on ZENODO;
- 1 dedicated Workshop jointly organized by AD ASTRA and Ruby projects (+ REACTT project participation)



Impact

Enhanced understanding of the correlation between user profile and degradation mechanisms on SOC interconnects, anodes and cathodes.

- Extraction of valuable information from previously performed studies and projects. It was gathered and summarized in the “ Review of SOC degradation mechanisms and modelling approaches”.
- Experimental data base beyond the SoA by the joined efforts of the industrial and research: post-mortem lab testing of samples prepared from field tested stacks up to 20000 h.

Correlation between AST results and lifetime in a user profile.

- Iteratively updated DoEs ultimately converging into validated ASTs, replicating the degradation effects seen in “real world” conditions for a particular user profile.
- Dual modelling approach, deterministic models with statistical and stochastic analysis, to capture the by nature probabilistic degradation processes.

Validation of the methodology.

- Benchmarking with significant numbers of field-tested samples and stacks, for each of the two operating profiles (P2X and CHP).
- Dedicated experiments, based on methodical design of experiments for maximization of statistical significance and model validation.
- Validation of the predicted remaining useful life (RUL) both in accelerated stress as in real-life conditions

Recommendations for international standardisation of AST with IEC TC105 which should lead to a New Working Item Proposal (NWIP).

This impact is on track and a first ad hoc working group on AST procedures (AHG11) has been instated in TC105 of the International Electrotechnical Commission.

EUROPEAN PARTNERSHIP
Co-funded by the European Union

Risks, Challenges and Lessons Learned

Description of risk (Low/Medium/High)	Proposed risk-mitigation measures	Lesson learned
Database not available or inaccessible (P=1, S=2, D=2: LOW)	The basic structure of the database comes straight out of ENDURANCE and will be hosted on IEES servers with linked copies placed with partners.	No mitigation measures were needed since the availability of the database has been guaranteed for the entire duration of the project
Inability to identify degradation mechanisms from “real world” agedstack components (P=1, S=3, D=3: LOW-MEDIUM)	AD ASTRA is nourished since the very beginning bythe output and know-how of other projects addressing this issue (WP2) therefore a large database will be available.	The huge know-how coming from other projects and collected in the AD ASTRA database was useful to integrate the information collected from the real world samples.
Inability to correlate “real life” degradation data with experimentaldegradation data (P==2, S=3, D=6: MEDIUM-HIGH)	Interaction with external advisors. Approximation ofeffects with higher-level (more macroscopic) parameters. Update and restriction of DoE to evaluate fewer mechanisms and gain more data.	The availability of the operational history of aged samples coming from real world environment is crucial for the correlation of degradation and AST
Inability to integrate *ex-situ* aged components in a new stack for *in-situ* verification (P=3, S=2, D=6: MEDIUM-HIGH)	Go/no-go milestone at M16 (MS8) after second experimental cycle. Focus on accelerated ageing for component evaluation & aggravated tests for stack evaluation. Validate models of long-term degradationwith ongoing field tests.	The samples aged via ex-situ ASTs were not usable in a stack environment after the ageing process. Therefore the in situ ASTs tests were very useful to complete the characterization of degradation mechanisms
Experimental facilities temporarilynot available (P=1, S=2, D=2: LOW)	All equipment is available and has been validated in previous projects. Buffering time allocated in eachexperimental cycle to allow partners to carry out unperformed tests.	No bottleneck occurred concerning availability of test benches
Slow test/modelling data feedback(P=2, S=1, D=2: LOW)	Interdependence between modelling and experimentation will be manageable. If experimental data is not yet available, models can be pre-validatedwith other models and/or external data.	The know how collected in the knowledge pool of the AD ASTRA database was very useful in terms of validation of modeling developed with experimental data
Failure of implementing models describing degradation mechanisms into performance models (P=2, S=2, D=4: MEDIUM)	Powerful statistical tools are available and being developed that need to dialogue with performanceand finite-element models. Separate models can be generated for each objective, that can be combined in an overarching interface.	Physics-based degradation functions have been introduced into performance models to predict the Remaining Useful Life (RUL). Moreover, degradation accelerating factors have been also correlated to cell operation through specific transfer functions.

European Hydrogen Week

Clean Hydrogen Partnership

EUROPEAN PARTNERSHIP

Co-funded by the European Union

#EUResearchDays
#PRD2022
#CleanHydrogen