Towards Robust PEM Electrolyzer Operation

Utilizing Physical-Empirical Degradation Models

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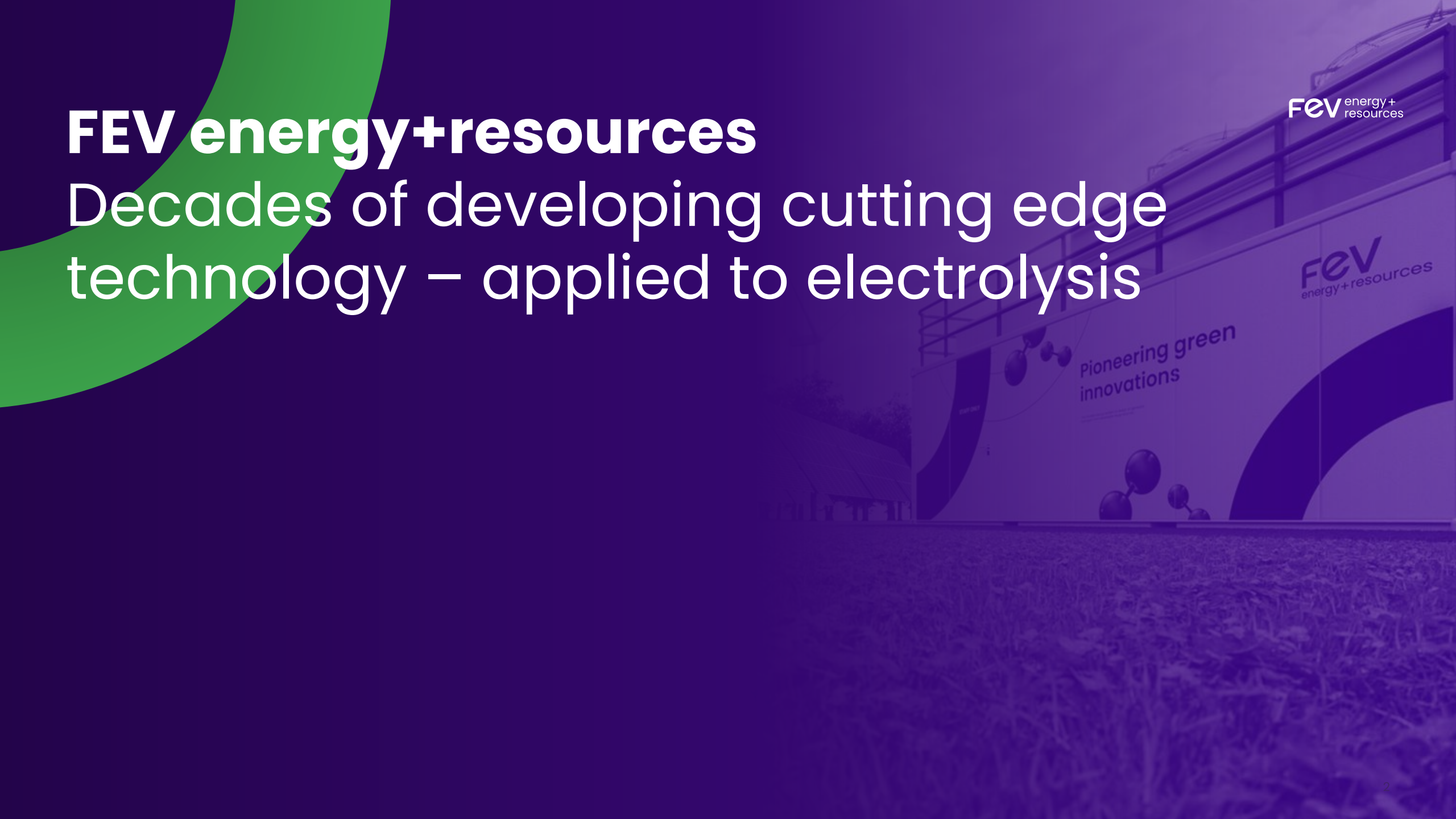
FEV energy+resources

Decades of developing cutting edge technology – applied to electrolysis



Offering 360° engineering and consultancy services for electrolyzer prototypes and series developments

Customer

Single Cell and Stack Characteri-zation | System Benchmark | Design / CAD / FEA | Virtual Testing / Optimization / CAE | PnID/ Thermal Manage-ment | E/E Design / Cabinet Planning

Grid-connection, power electronics & rectifier optimization

Project Management

Requirements & Systems Engineering

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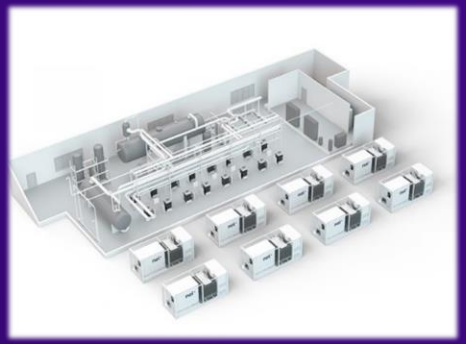
360° ELECTROLYSIS SOLUTIONS

Cost & Value Engineering / Supply Chain Management

Standards / HV / Hydrogen / Functional Safety / Cyber Security



Production planning | Prototype Building | Hardware Testing & Validation | ELYCU Verification & Validation | Control Unit & Automation System | Controller Implemen-tation

SOP

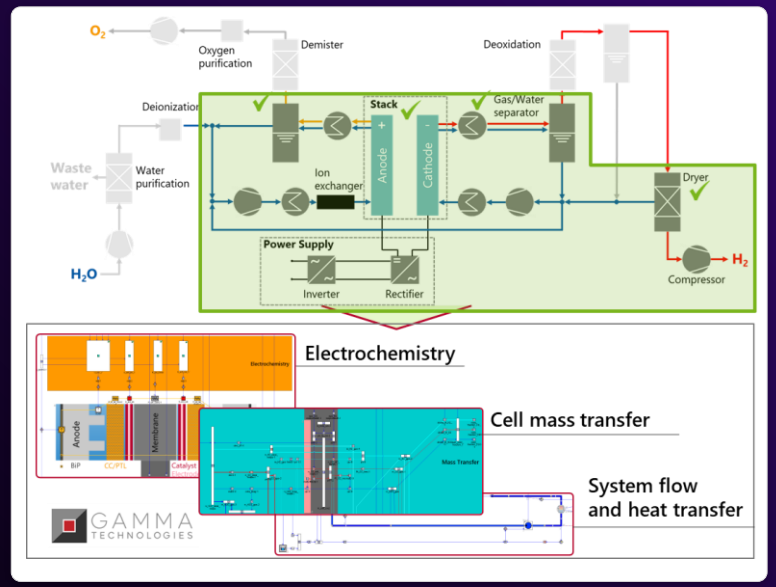
Troubleshooting, Second Opinion & Field Fixing

Source: FEV

Excerpt of the electrolysis tool & method landscape @ FEV

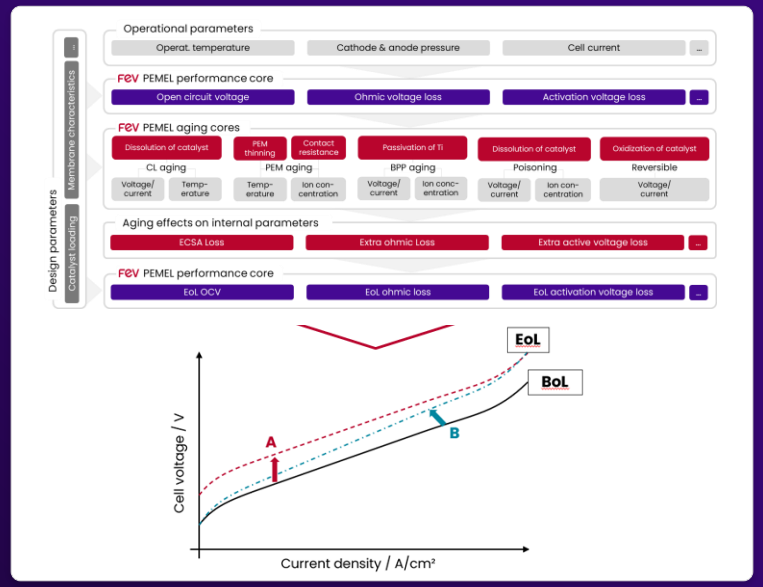
From detailed and physical modeling to empiric and big picture toolset

0D/1D-SYSTEM/PLANT SIMULATION MODELs



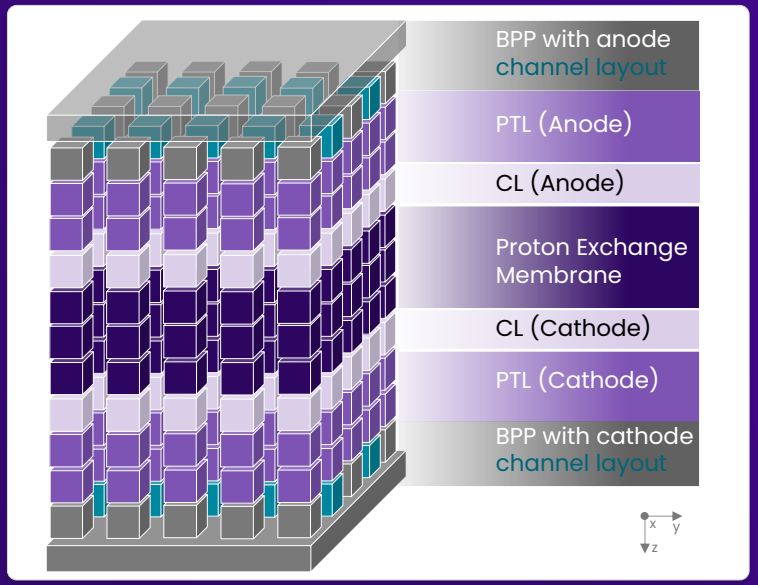
Dynamic & flexible simulation tool to calculate mass and energy flows, production / investment costs as well as optimize operation

PHYSICAL-EMPIRICAL DEGRADATION MODEL



Simulation model for degradation effects on the polarization curve and individual ageing effects as well as aging and lifetime predictions

3D SEGMENTED MULTI-PHYSICS CELL SIMULATION MODEL

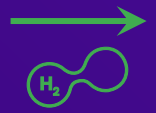


Simulation framework for assessing influence of process parameters on system efficiency, two-phase flow behavior and conductivity under varying conditions

Source: FEV

Various use-cases to be considered
Defining boundary conditions and real-world operating profiles

Use cases & boundary conditions from a down-stream perspective considering hydrogen usage



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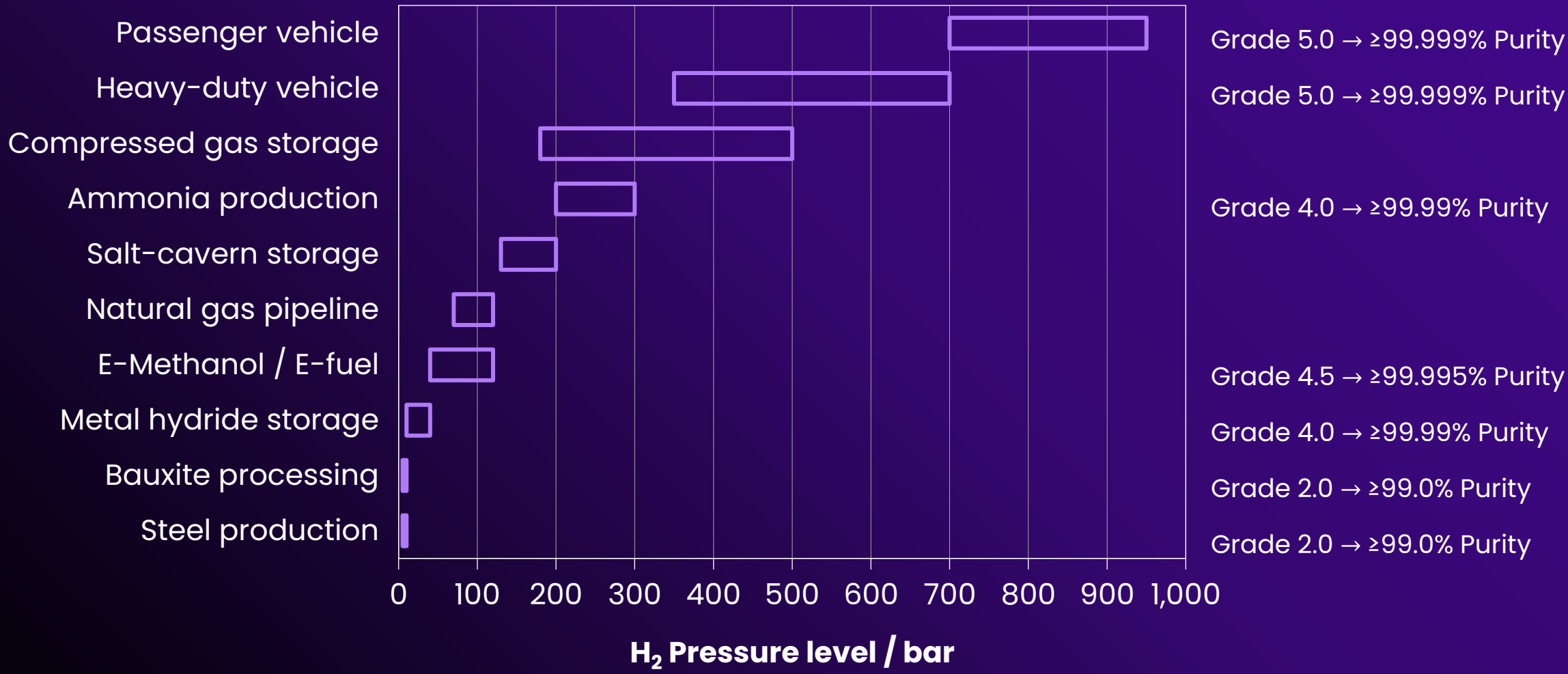
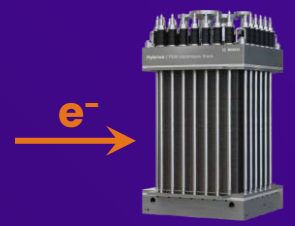
CHARACTERISTICS OF DIFFERENT HYDROGEN END-USE APPLICATIONS



Source: Hancke et al. (2022), ISO 14687, PhD Defense Kexel (2025)

Use cases & boundary conditions from an up-stream perspective considering renewable electricity



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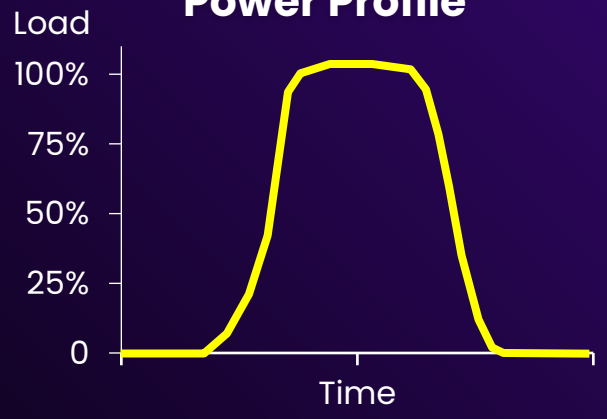
CHARACTERISTICS OF DIFFERENT RENEWABLE ENERGY PROFILES

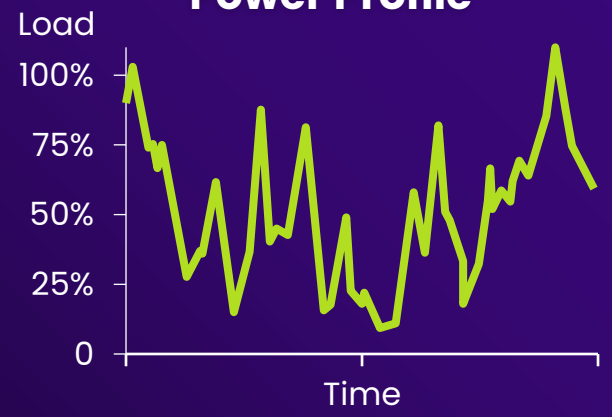
Solar
Power Profile



Characteristics

- Day/night cycle
- Local weather dependency
- Summer/winter variation
- Needs buffering

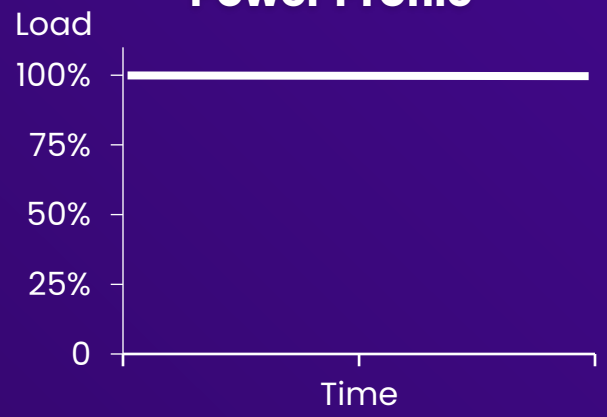
Wind
Power Profile



Characteristics

- High variability
- Local weather-driven
- Offshore potential
- Seasonal complementarity

Geothermal, Biomass & Hydro
Power Profile



Characteristics

- Steady output
- Limited potential
- Heat integration potential
- Supports baseload

Source: FEV, PhD Defense Kexel (2025)

Understanding Degradation
Key Stressors, mechanisms, and measurable effects

PEM electrolyzer require noble materials and operate under harsher conditions – making degradation more critical compared to fuel cell

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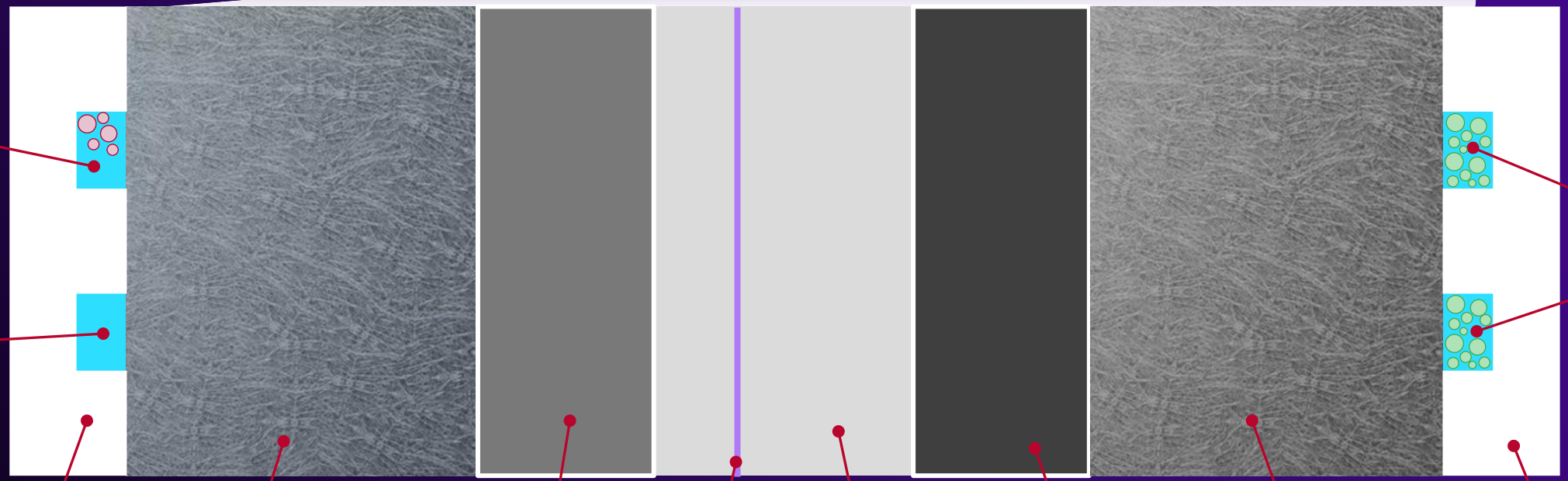
ANODE

CATHODE



H_2O/O_2 2-Phase Out

H_2O Inlet

$H_2/(H_2O)$ 2-Phase Out

BPP Bipolar Plate (Ti w/ Pt coating)

aPTL Anode Porous Transport Layer (Ti)

aCL Anode Catalyst (Ir on TiO_2)

RCL Recombination Catalyst Layer (Pt)

PEM Membrane (PFSA)

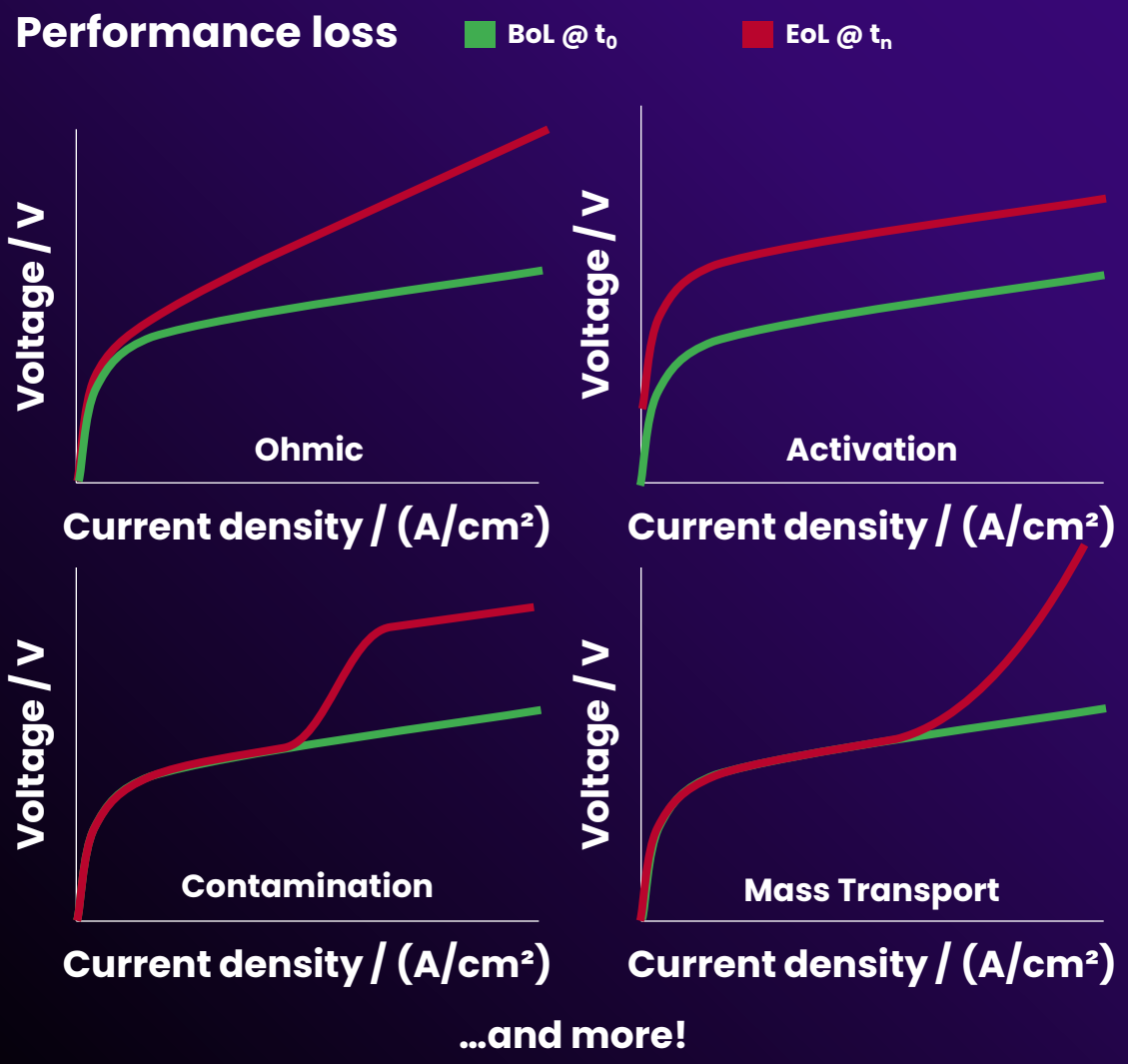
cCL Cathode Catalyst (Pt on C)

cPTL Cathode Porous Transport Layer (Ti/C)

BPP Bipolar Plate (Ti)

Source: Hydrogen Shot (2024); NREL (2024), Smolinka & Garche (2021), Godula-Jopek (2015), PTL (2025), PhD Defense Kexel (2025)

Overview of typical aging and degradation behaviors of PEM electrolysis, which need to be captured within the degradation model



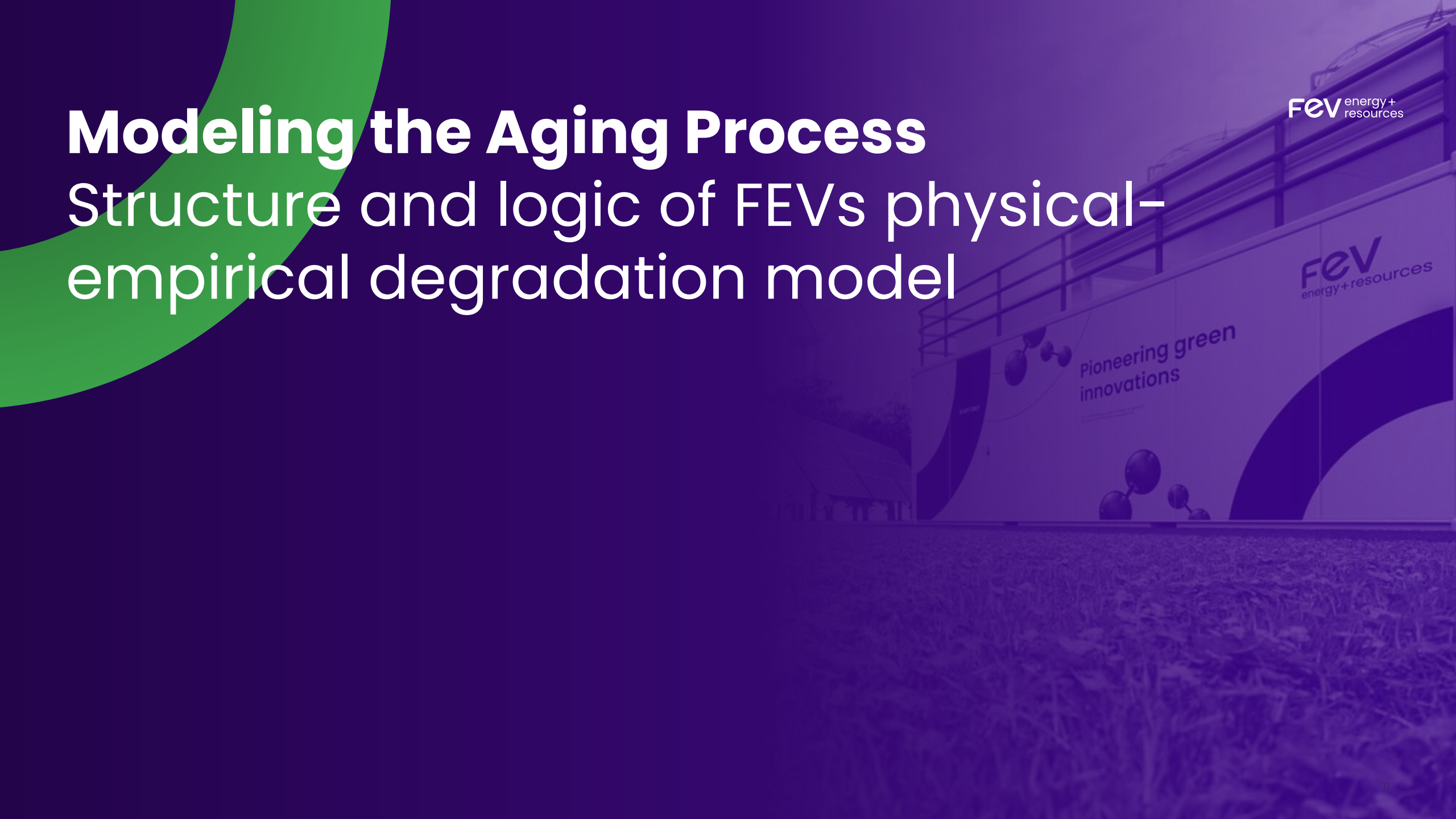
Degradation mechanisms are based on different cell components

1. Catalysts degradation (Anode & Cathode)
   - Particle growth (e.g. Ostwald-ripening)
   - Catalyst particle detachment and washout
   - Catalyst carrier corrosion (mainly Ti as catalyst carrier)
   - Foreign ion poisoning , e.g. iron and sulfur
2. Membrane degradation (PEM)
   - Membrane thinning and membrane swelling
   - Foreign ion poisoning
3. Mechanical degradation (End plates & GDL)
   - Loss of clamping force of the cell/stack on every contact area and thus increasing ohmic overpotential
4. Surface passivation (BPPs & PTL)
   - Superficial titanium oxide formation

Source: FEV, Adapted based on Bosch Thin Metal Technologies @ Aachen Hydrogen Colloquium 2025

Modeling the Aging Process

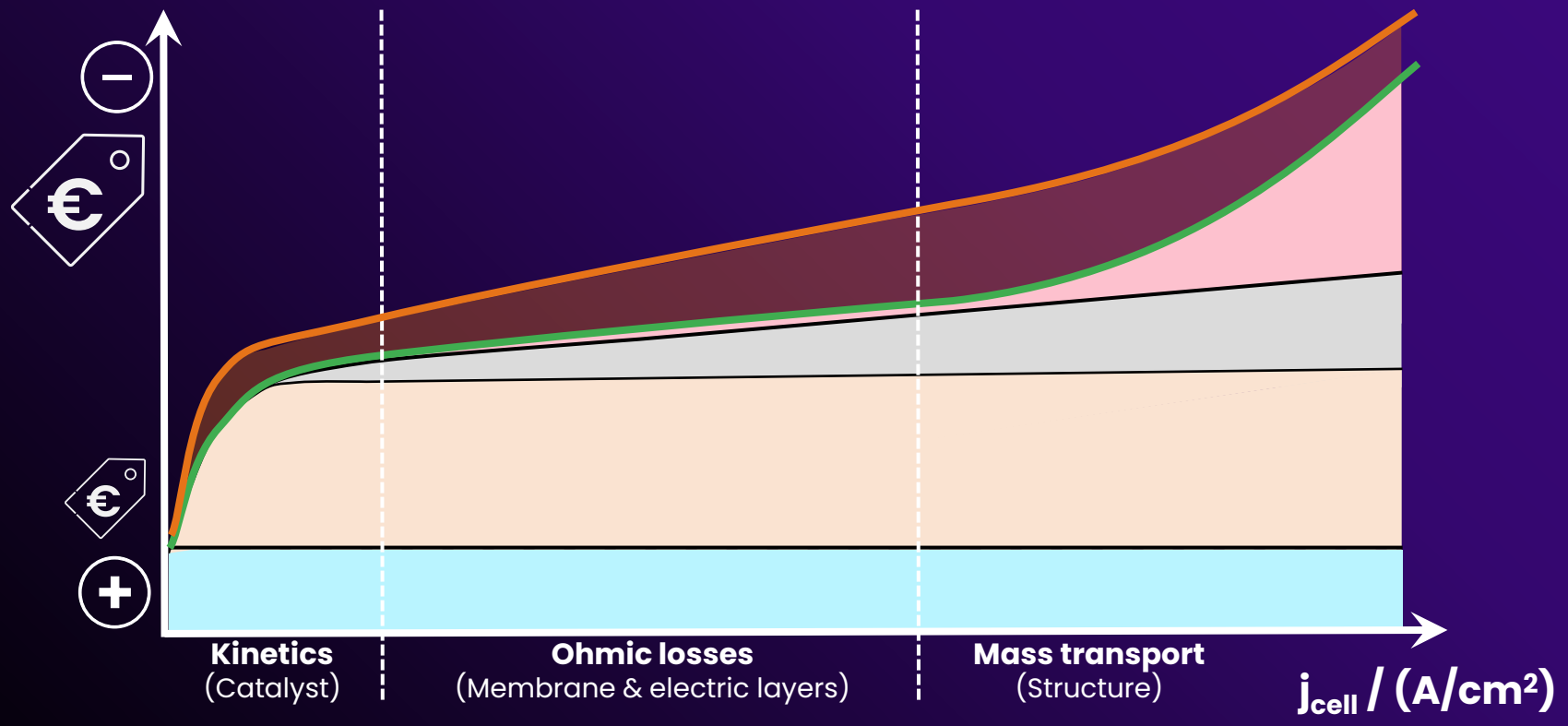
Structure and logic of FEVs physical-empirical degradation model



Polarization behavior of electrochemical cells — influence of cell-specific design parameters and degradation over lifetime

Polarization curve Pristine / Degradation

$$U_{cell} = E_{rev} + \eta_{act,A} + \eta_{act,C} + R_\Omega \cdot j + \eta_{mt,A} + \eta_{mt,C} [+\eta_{mix}]$$



Concentration overpotential

$$\eta_{mt,A/C} = \frac{RT}{n_{A\backslash C} F} \ln\left(\frac{c_{bulk,A\backslash C}}{c_{surf,A\backslash C}}\right)$$
$$with\ n_A = 4, n_C = 2$$

Ohmic overpotential

$$R_\Omega = \frac{\delta_M}{\underbrace{\sigma_m(T,\lambda)}_{R_{mem}}} + R_{el} + R_{contact}$$

Activation overpotential (Tafel)

$$\eta_{act,A/C} \approx \frac{RT}{\alpha_{A\backslash C} F} \ln\left(\frac{j}{i_{0,A\backslash C}\ (T)}\right)$$

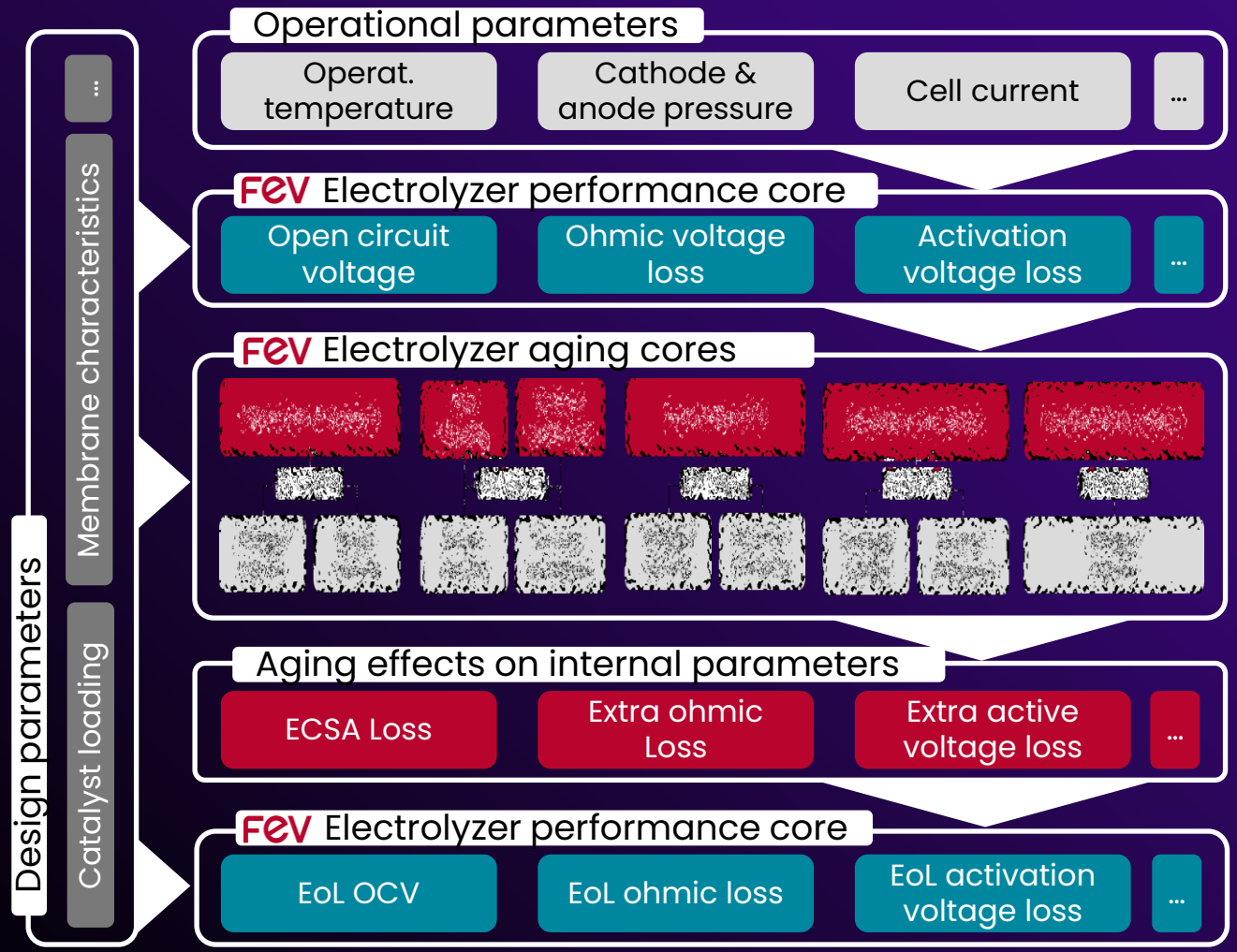
Reversible Voltage (Nernst)

$$E_{rev} = E^0_{rev}(T) + \frac{RT}{2F} \ln\left[\left(\frac{P_{H_2}}{p^0}\right)\left(\frac{P_{O_2}}{p^0}\right)^{0.5}\right]$$

Variable Definitions:
U_{cell} – Cell voltage (V); E_{rev} –Reversible voltage (Nernst potential, V); $E^0_{rev}(T)$ –Standard potential at temperature T (V); $\eta_{act,A/C}$ –Activation overpotential (anode/cathode, V); $\eta_{mt,A/C}$ –Concentration or mass transport overpotential (V); η_{mix} –Mixed overpotential (e.g. gas bubbles, V); R_Ω –Total ohmic resistance (Ω cm²); R_{el} –Electronic resistance outside membrane (Ω cm²); $R_{contact}$ –Contact resistance (Ω cm²); δ_M –Membrane thickness (m); $\sigma_m(T, \lambda)$ –Proton conductivity of membrane (S m⁻¹); j_{cell} or j – Current density (A cm⁻²); $i_{0,A/C}$ –Exchange current density (A cm⁻²); $\alpha_{A/C}$ –Charge transfer coefficient (–); R– Universal gas constant (8.314 J mol⁻¹ K⁻¹); T– Temperature (K); F– Faraday constant (96 485 C mol⁻¹); p_{H_2}, p_{O_2} –Partial pressures of H_2 and O_2 (bar); p^0 –Standard pressure (1 bar); $c_{bulk,A/C}$ –Bulk concentration (mol m⁻³); $c_{surf,A/C}$ –Surface concentration (mol m⁻³); $n_{A/C}$ –Number of electrons transferred (–); λ– Membrane hydration level (–).

Source: Smolinka & Garche (2021), Godula-Jopek (2015), Hermauer et al. (2023), PhD Defense Kexel (2025)

FEV's patented model predicts electrolyzer performance loss time-resolved based on design parameters and operating conditions



Design & Operating strategy

Begin of life performance

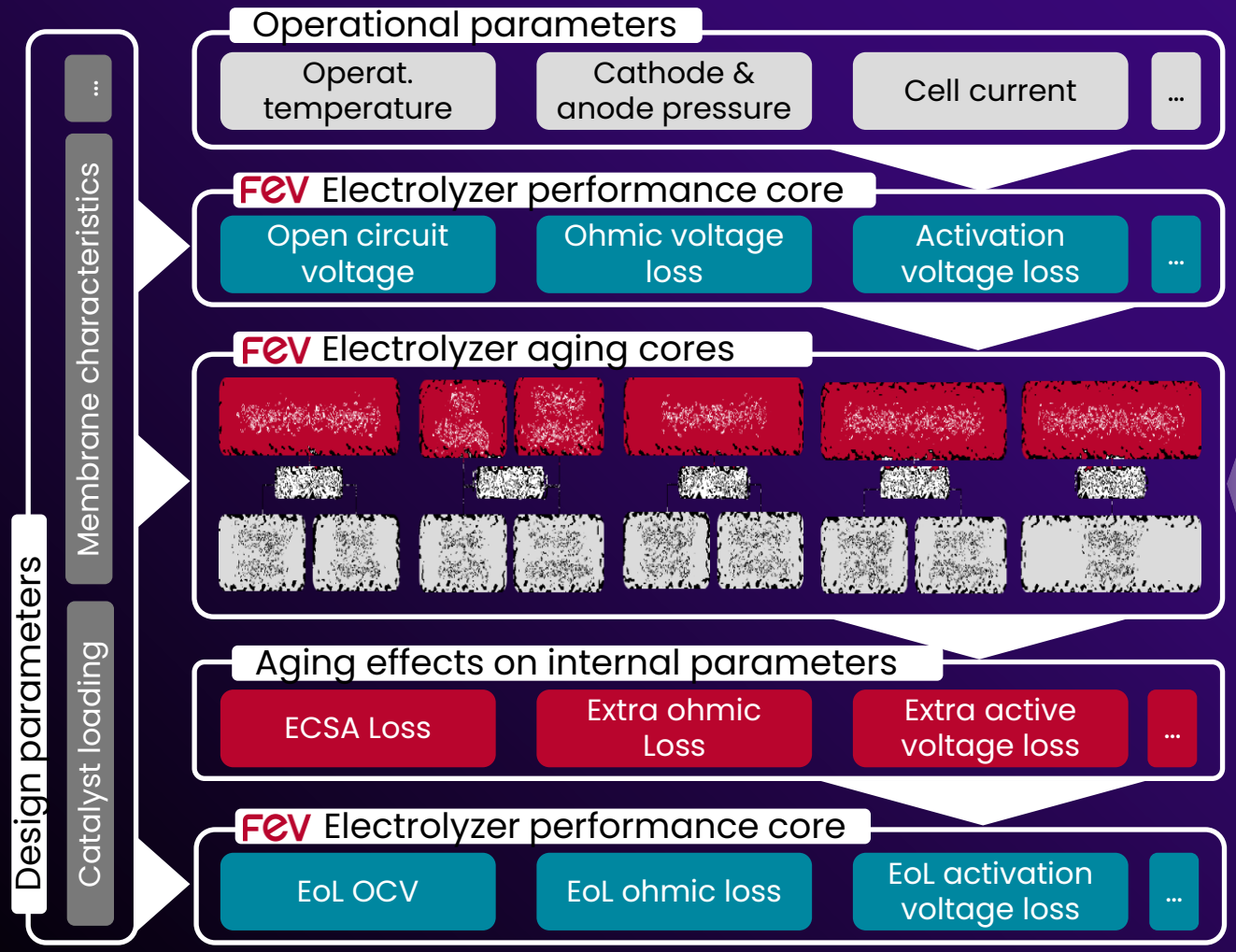
Aging & degradation mechanisms

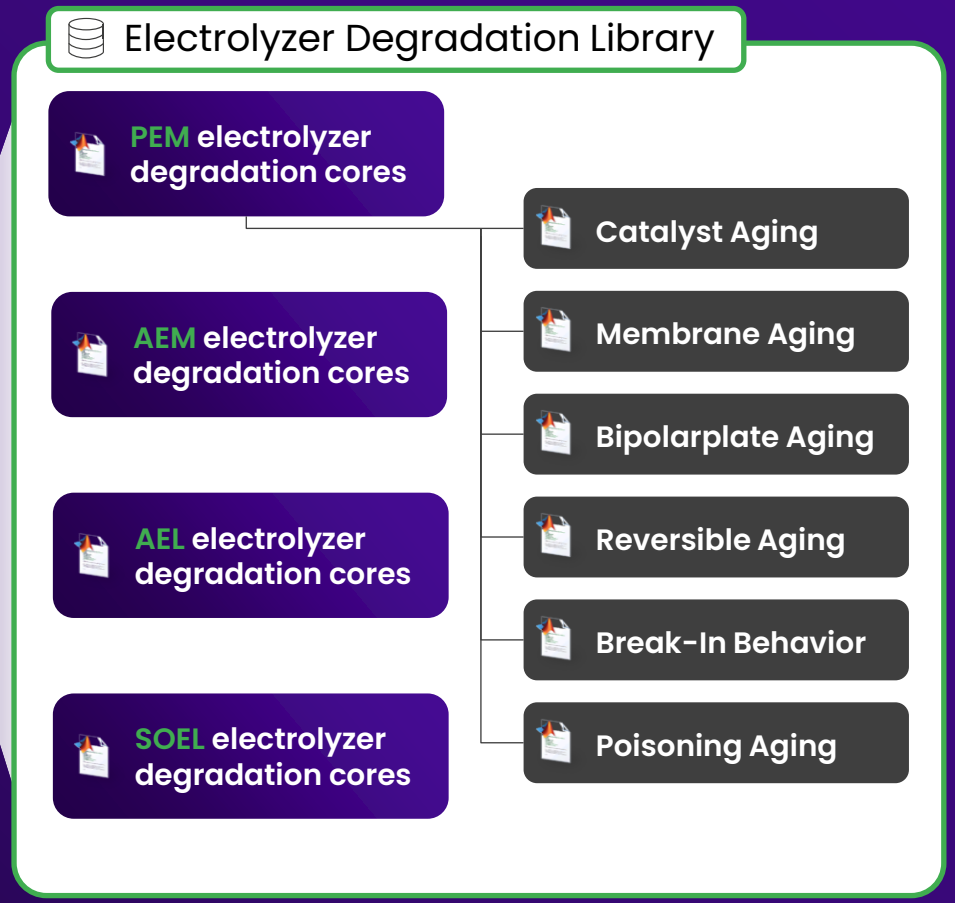
Impact on physical properties

Current performance

Source: FEV, MODELL ZUM BESTIMMEN EINER DEGRADATION EINER POLYMERMEMBRAN-ELEKTROLYSEZELLE

FEV's modular and white box available electrolyzer performance, degradation, and state of health monitoring & simulation platform





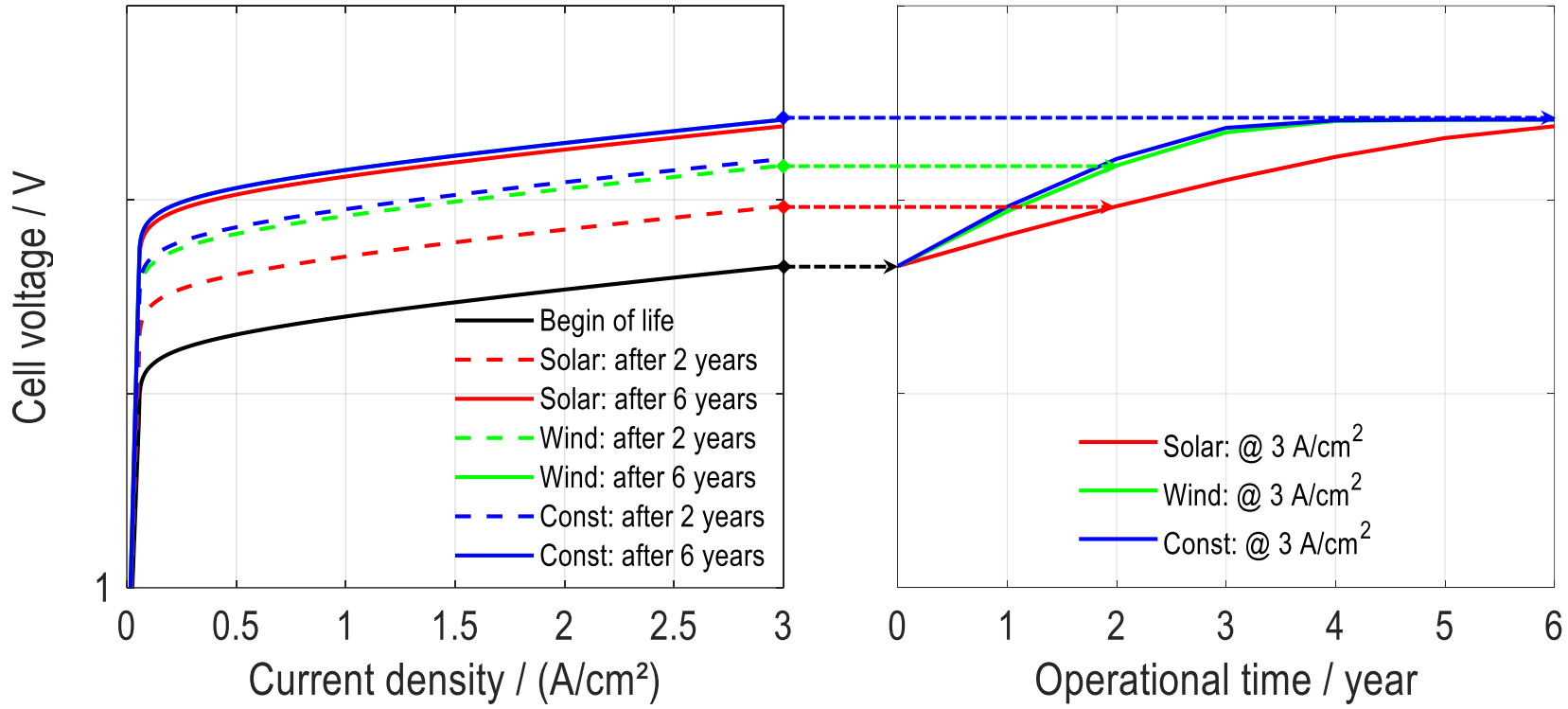
Source: FEV, MODELL ZUM BESTIMMEN EINER DEGRADATION EINER POLYMERMEMBRAN-ELEKTROLYSEZELLE

Enabling Robust Applications
Predicting performance loss & lifetime extrapolation

Without any constraints for original yearly operating profiles, the predicted degradation shows a similar voltage increase after 6 years – why is that the case?

Original Annual Profiles

Polarization Curves & Long-Term Time-Based Degradation

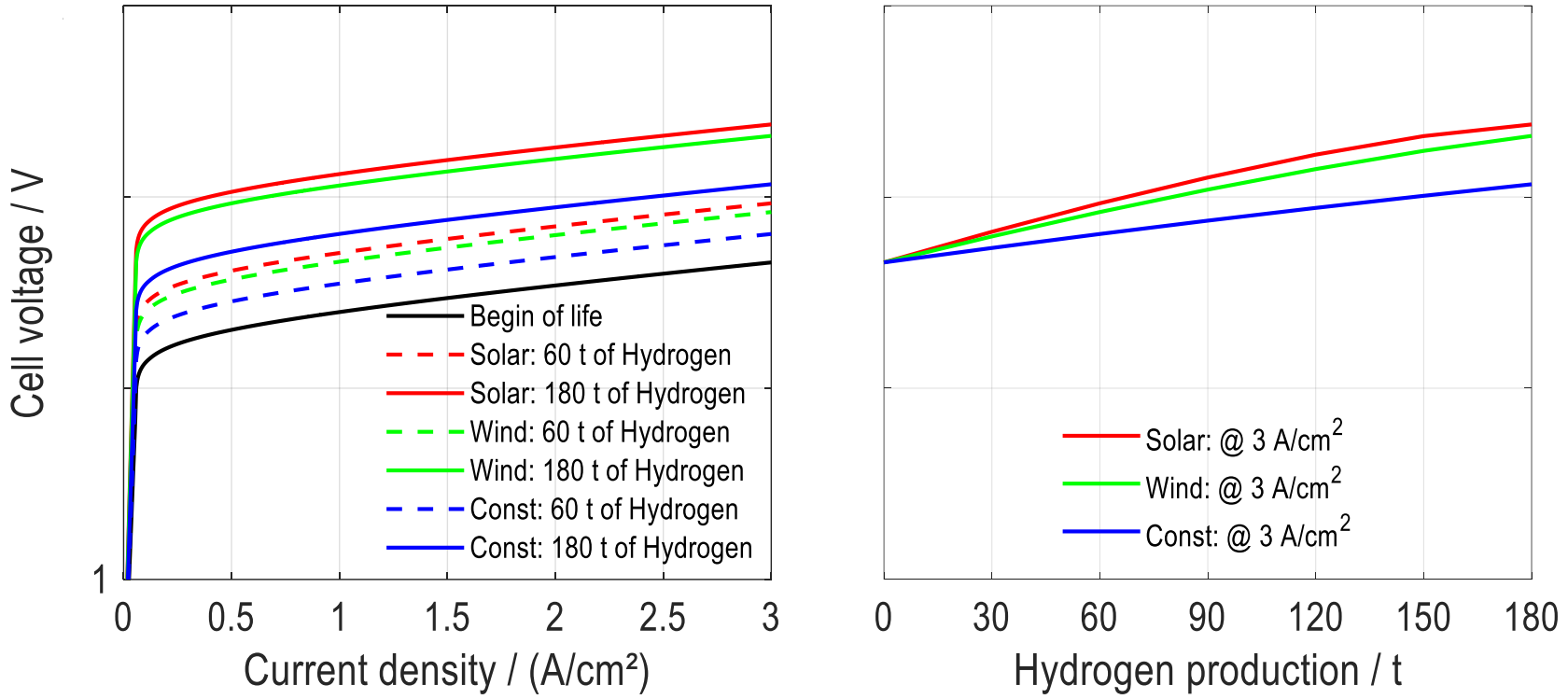


Operating hours vary significantly between use cases due to the different load profiles and operating behavior

Normed to comparable hydrogen output, constant operation shows the smallest aging behavior – but why is PV worse compared to wind input?

Normed Hydrogen Output

Polarization Curves & Long-Term Hydrogen-Output-Based Degradation

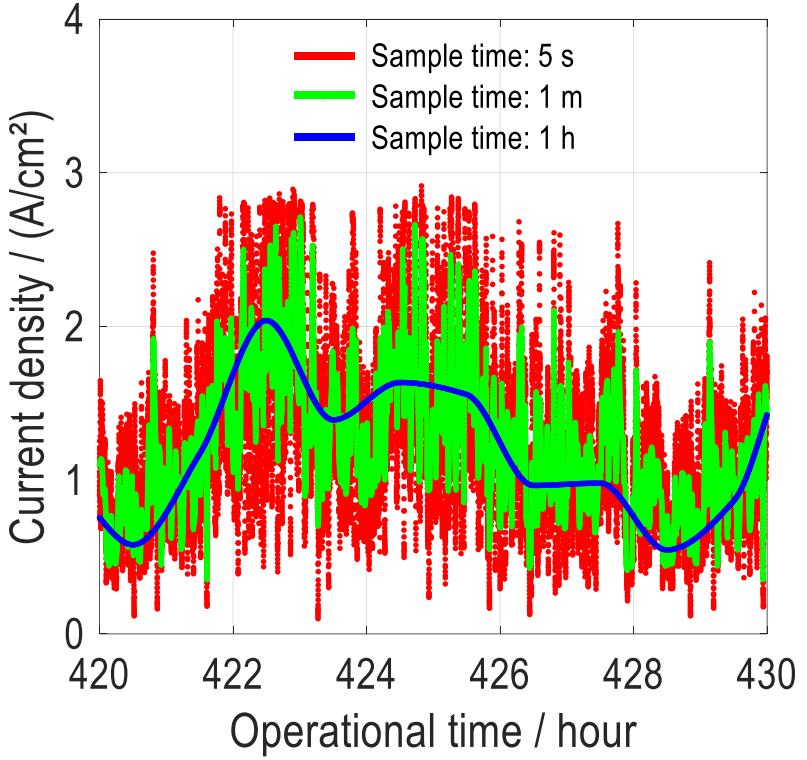


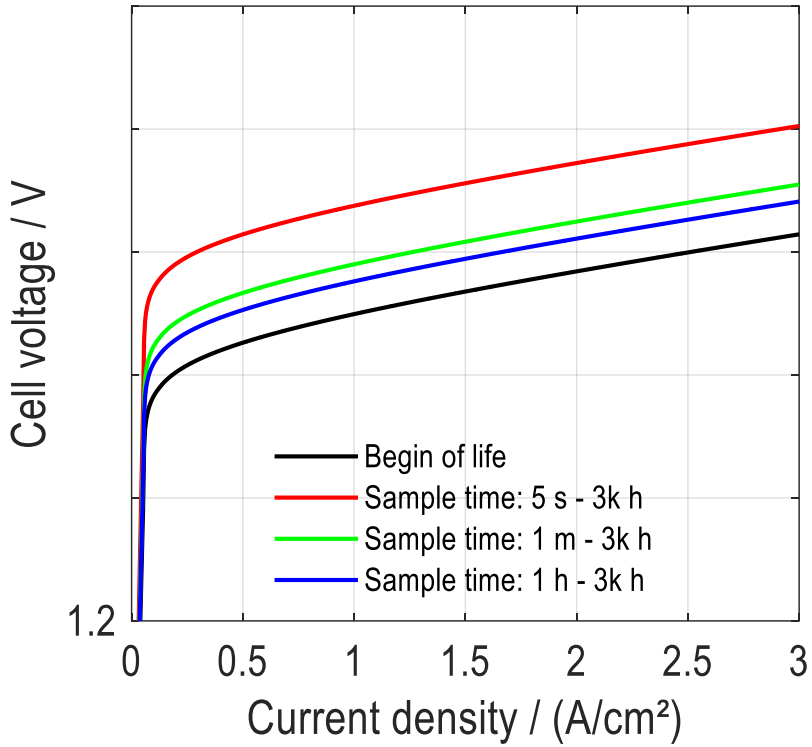
Average current of PV is smaller, which leads to longer time for comparable H_2-amount and thus to higher degradation

Sensitivity analysis of the exemplary wind power input shows… …significantly different degradation regarding the dynamics of the renewable energy profile

Sensitivity Analysis: Dynamics of Load Profiles

Exemplary Section of Operational Data & Polarization Curves





Be careful when comparing degradation results and consider the results as implication for reasonable buffers

Remark: Theoretical example, fluid-dynamics of BoP neglected.

Implications & outlook

Key takeaways

Degradation Modeling as a Strategic Enabler

- Pre-development and AST, Online monitoring and predictive maintenance, Optimization of operating strategies under real-world conditions.

Operating Profiles Matter

- Load dynamics and sampling rates significantly affect degradation behavior.
- Constant operation leads to lower aging compared to volatile profiles (e.g., PV-based input).
- Threshold-based operation (cutting off low-load phases) can reduce degradation with minimal impact on hydrogen yield.

Real-World Use Cases Show Divergence

- Use cases like North Sea wind vs. Spanish PV demonstrate how location-specific conditions (e.g., full-load hours, electricity cost) influence both degradation and Levelized Cost of Hydrogen (LCOH).
- Despite different conditions, durability and efficiency remain key levers for LCOH reduction.

Material and Design Optimization

- Degradation mechanisms span across catalysts, membranes, mechanical components, and surface passivation.
- Innovations in material selection (e.g., reduced catalyst loading, optimized BPP design) and stack architecture can significantly reduce CAPEX and extend lifetime.

Implications for Scaling and Bankability

- The model supports standardization and compliance with emerging regulatory frameworks.
- It enhances bankability by enabling transparent, data-driven evaluation of electrolyzer performance over time.
- Field data integration will be crucial for continuous model refinement and scaling of hydrogen infrastructure.

NEXT GEN ELECTROLYZER TESTING

PEM & AEM Testbench

Building on decades of testing expertise, FEV is taking electrolysis testing to the next level. Combining high-precision data acquisition with fully automated analysis workflows—enabling reliable performance and durability insights under real-world conditions.

Performance / Durability Testing / Advanced Measurement Devices

Testbench Specifications

Technology	**PEM & AEM**
P / U / I scale	<10 kW / <20 V / <500 A
Cell areas	1-150 cm²
Number of Cells	1-10
Pressure Range	**0-50 bar(g)**
Temperature Range	Up to 90°C
Test capabilities	**Durability Testing** # Durability with realistic load profiles # Voltage Cycling / Current Cycling # Stand-by-Start Testing # Rainbow-Stack Testing **Performance Testing** # Temperature variation # Back pressure # Hydrogen pressure
Measurement features	Cell voltages; Temperatures; Pressures; EIS; LSV; CV; Process water conductivity measurements; Fluoride concentration measurement (Ion chromatography) H2/O2 & O2/H2 cross over / Permeation

Source: FEV

Electrochemical Impedance Spectroscopy (EIS); Linear sweep voltammetry (LSV); Cyclic voltammetry (CV)

Thank you for your kind attention!

›What's your take?

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Let's stay connected!