



Key Factors for a High-Performance FC Stack

—
Efficiency & Robustness as Drivers
for Reliable Systems up to 500 kW

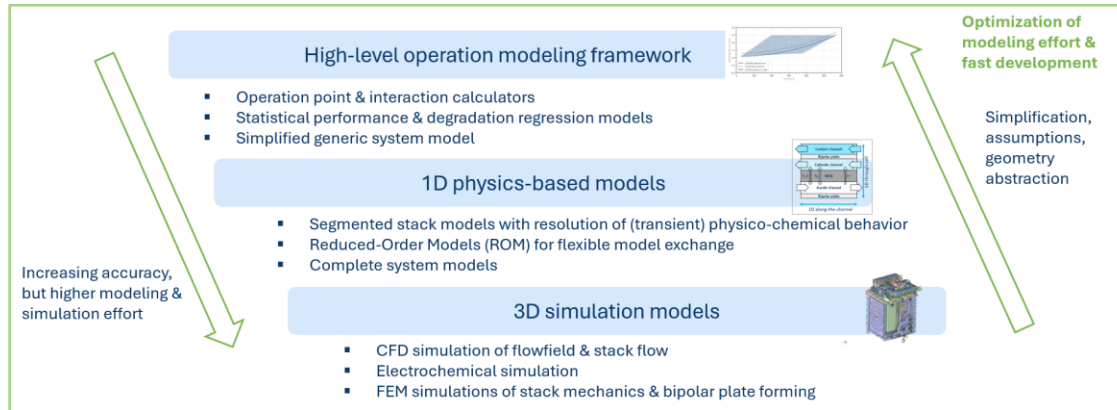
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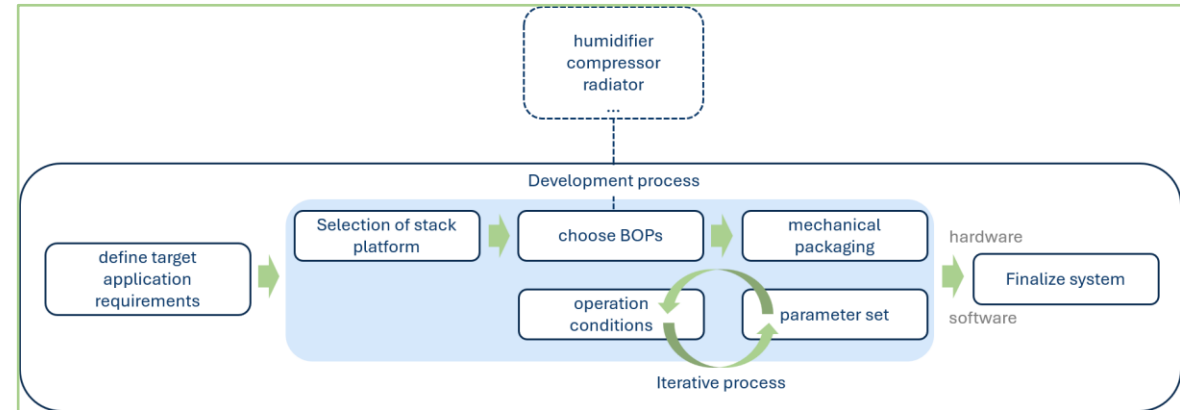
Key Factors for a High-Performance FC Stack

- **Last year:** Model-based fuel cell stack design and optimization
 - How do we develop a fuel cell stack without developing the fuel cell system?
 - How do we enable a broad range of use cases and system requirements while still having a main target application?

Modeling landscape



Approach

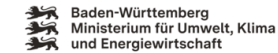
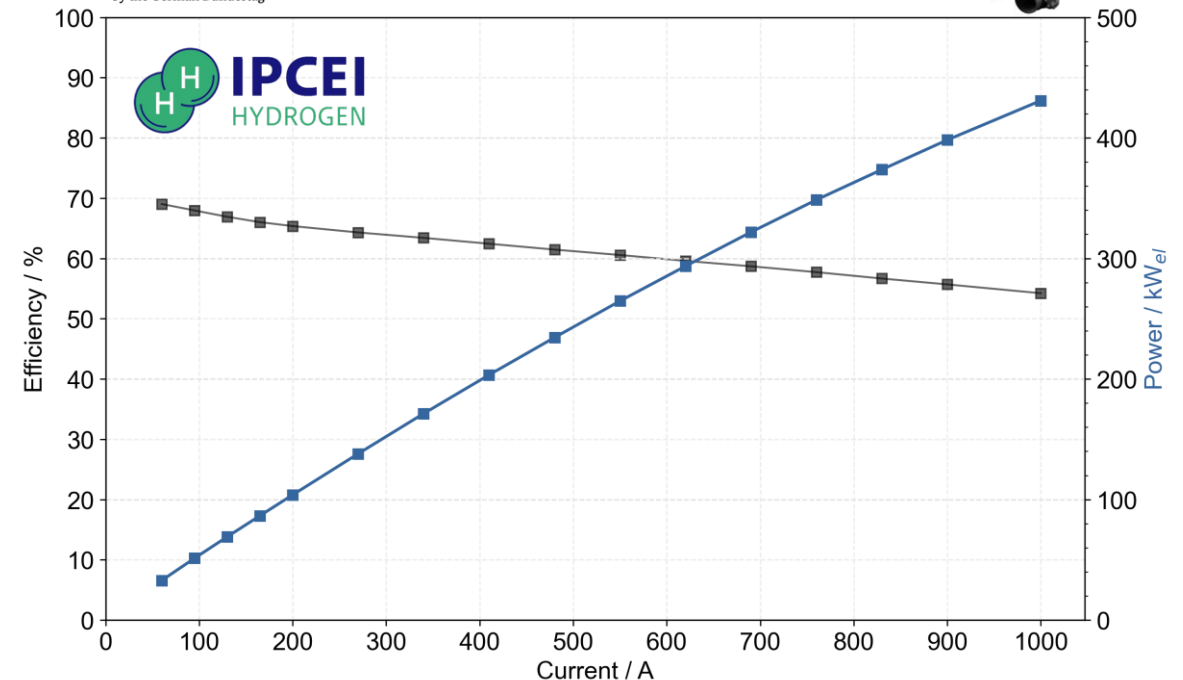


- **Today: Key factors for a high-performance FC stack**
 - NM20 DVP results & optimization
 - Exploring the operational boundaries & different applications
 - NM20 stack configurations towards high-efficiency MW systems

Standard Stack Module Specifications

- High efficiency & performance
 - Up to > **400 kW** begin of life
 - Stack full power typ. 340 ... 350 kW* (HD-truck)
 - to provide 300 kW* EOL power on system level
- Operation temperature **95°C** (max. 105°C)
- Operation pressure up to **3.5 bara**
- V/I-characteristics optimized for **800 V systems**
- Max. continuous current **1.000 A**
- Lifetime min. **25.000 hours**

Funded by:

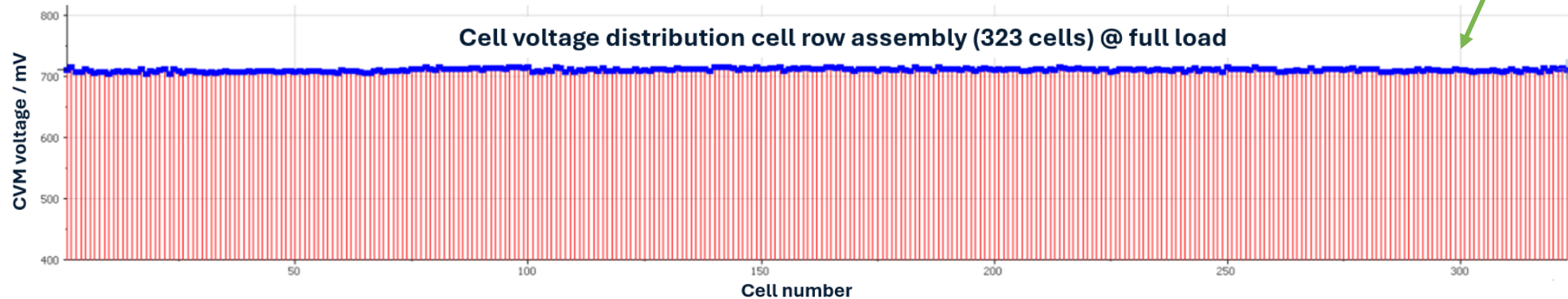
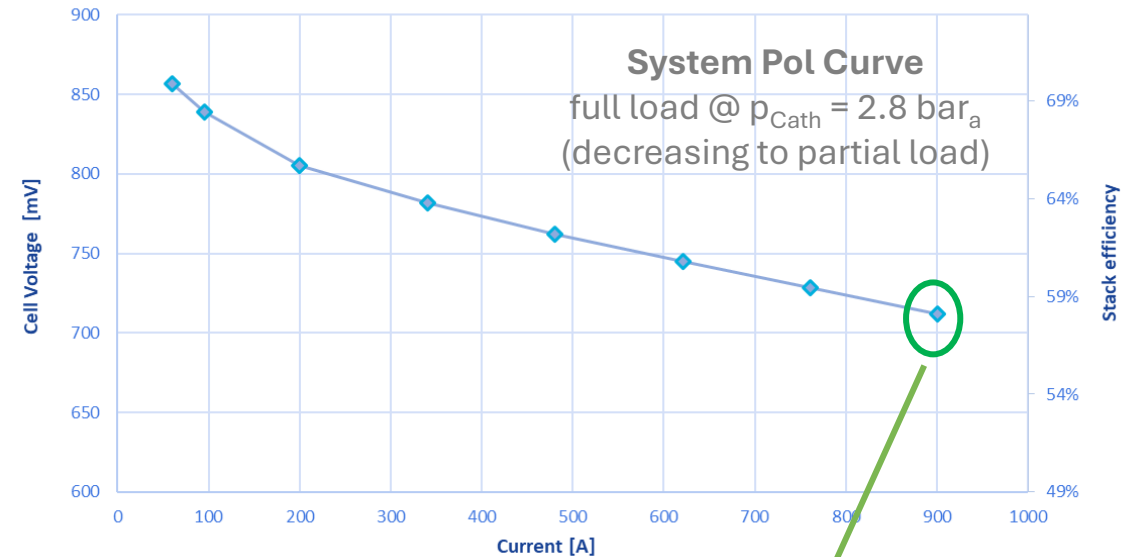
on the basis of a decision
by the German Bundestag

*Stack must provide > 340 kW to cover typ. requirements of 40 t HD truck (customer survey & drive cycle analysis)

- **NM20 - A HIGH-POWER STACK** enabling a single system/balance of plant package for maximum cost efficiency, tailored for HD integration as main application and scalable/modular for other applications

Begin-of-Life Performance

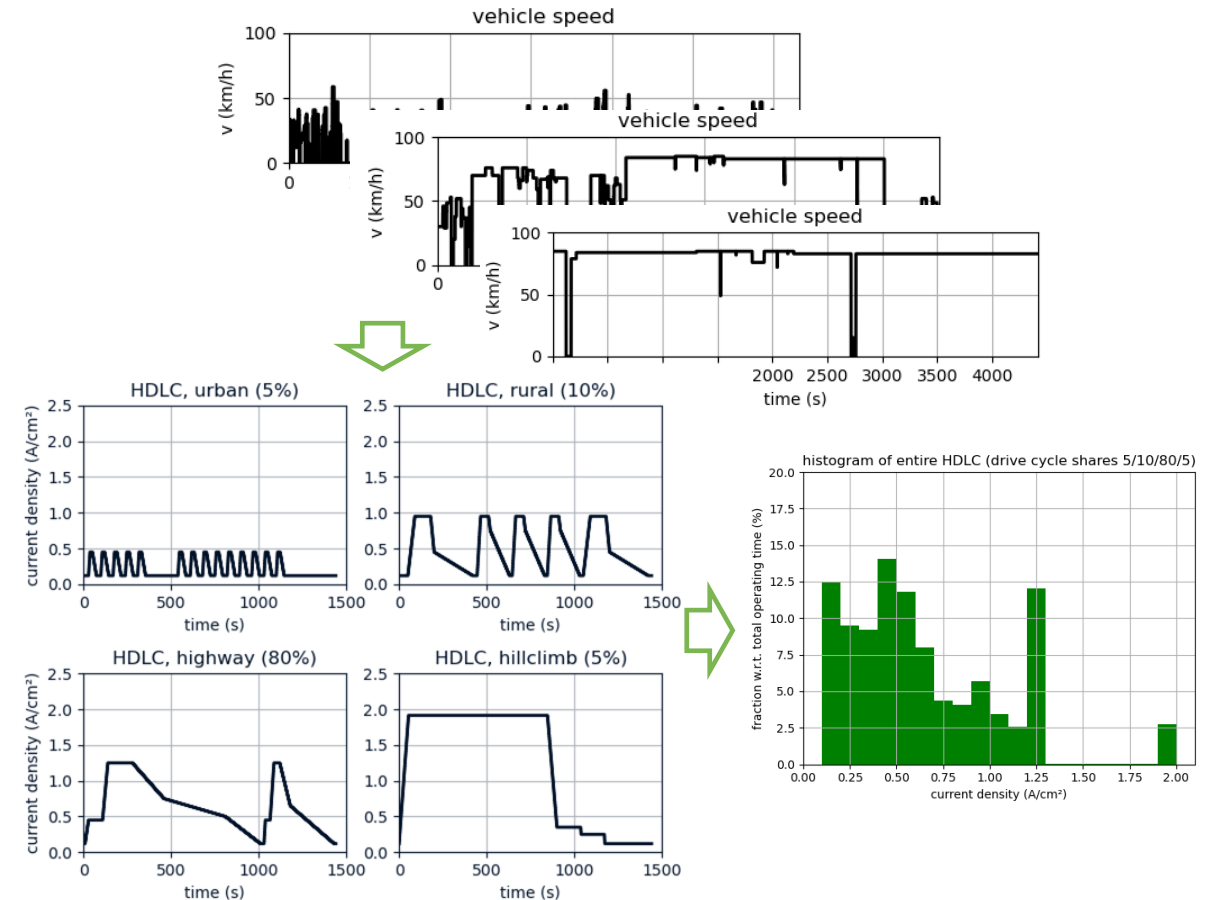
- Design point performance 900 A/2.5 bar_a/λ=1.7:
 - 694 mV , 56 % eff. (above A-sample target 0.69 V)
- Outstanding homogeneity ($U_{\text{avg}} - U_{\text{min}}$):
 - $\Delta U = 7 \text{ mV}$ @ full load
- Further increase by optimization on system level:
 - 414 kW @ 900 A, 2.8 bara, ($U_{\text{cell}} > 0.71 \text{ V}$)



- BoL performance targets reached in early A-sample stage
- Optimization in the system context mandatory to maximize performance and lifetime

Durability Testing – Heavy Duty Load Cycle (HDLC)

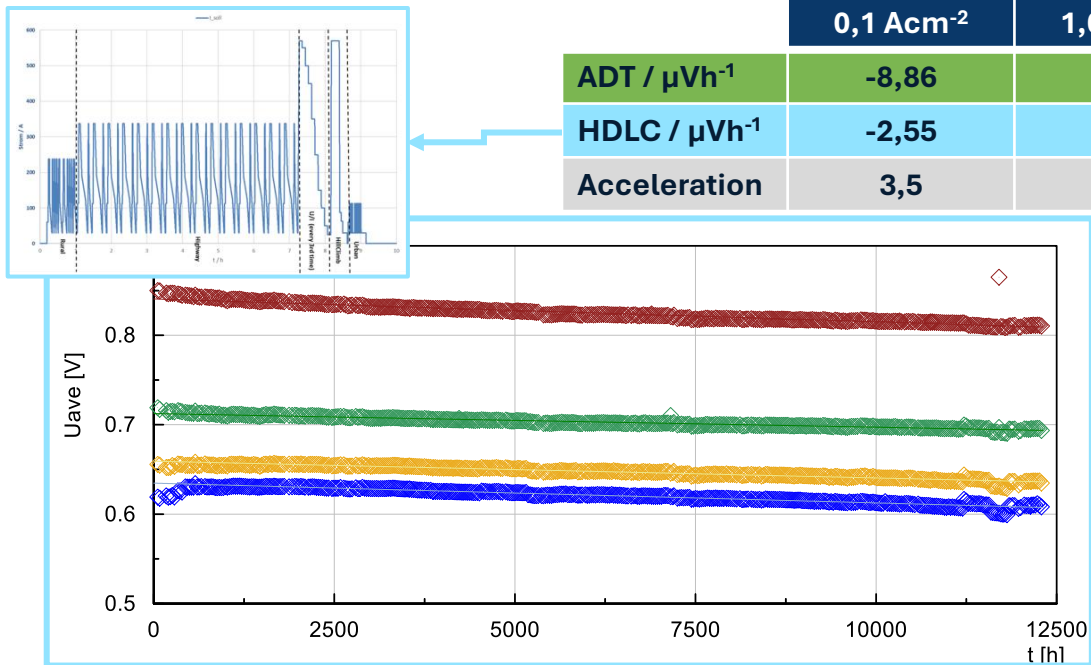
- **Load cycle testing** is essential for
 - Evaluation, verification and validation & requirement analysis and definition
- Load cycle definition based on
 - Vecto drive cycles for **city**, **rural** and **highway** case
 - Synthetic cycle added for **hill climb** (Brennerpass)
 - 40 t total mass, electric machines, battery size, simplified energy management system (EMS) etc.
- Test cycle has to be applicable in a test station setting and contain warm-up and SUS^{*}D phases and diagnostics
- Accelerated Durability Testing (ADT) under development for faster lifetime verification



- NM20 durability tested in Heavy Duty Load Cycle, ADT under development for faster lifetime verification
- Application-specific adjustments to test cycle and operating conditions

Accelerated Durability Testing (ADT)

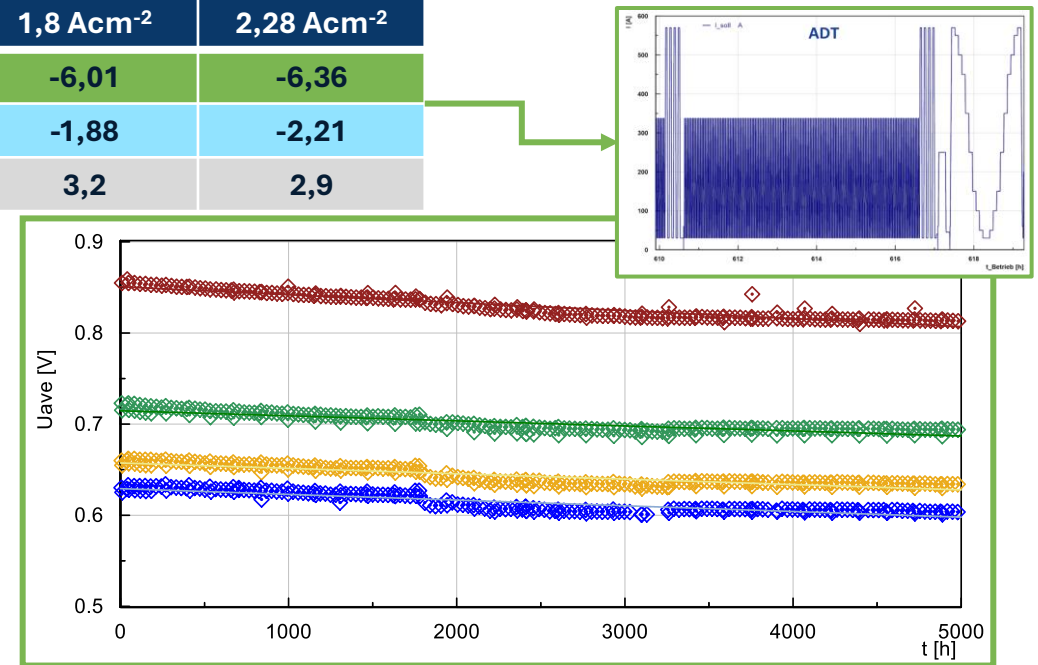
HDLC IN REFERENCE PLATFORM



- HDLC: realistic aging modes, but time-consuming

ADT IN REFERENCE PLATFORM

	0,1 Acm ⁻²	1,0 Acm ⁻²	1,8 Acm ⁻²	2,28 Acm ⁻²
ADT / μVh^{-1}	-8,86	-5,64	-6,01	-6,36
HDLC / μVh^{-1}	-2,55	-1,53	-1,88	-2,21
Acceleration	3,5	3,7	3,2	2,9

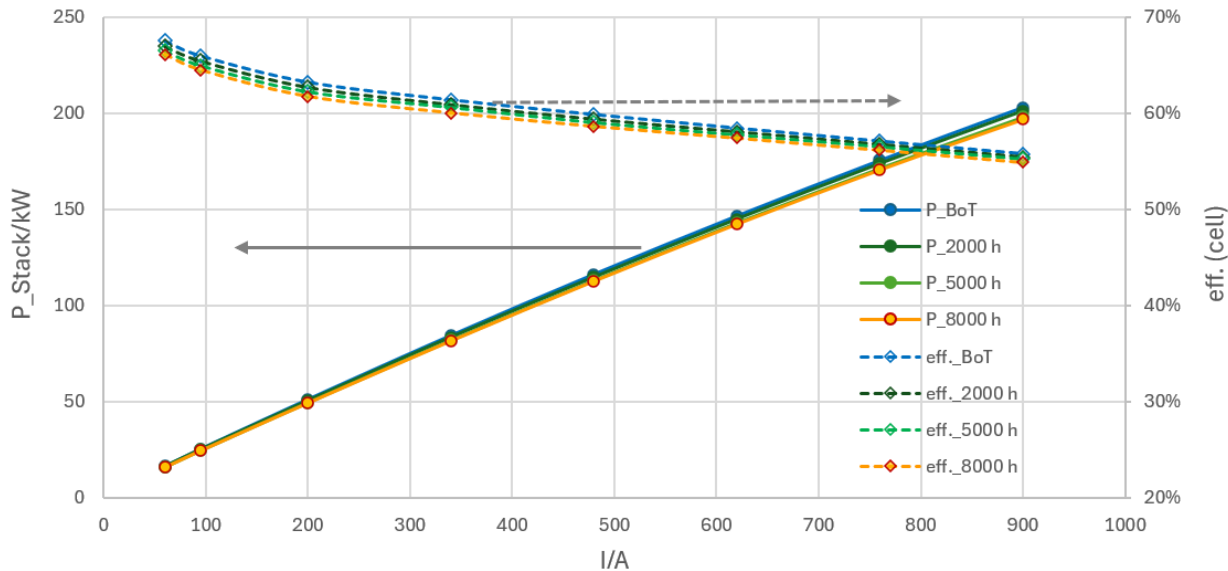


- ADT: simplified but realistic aging modes and less time-consuming
- Currently, 3 times higher degradation rates, still under development

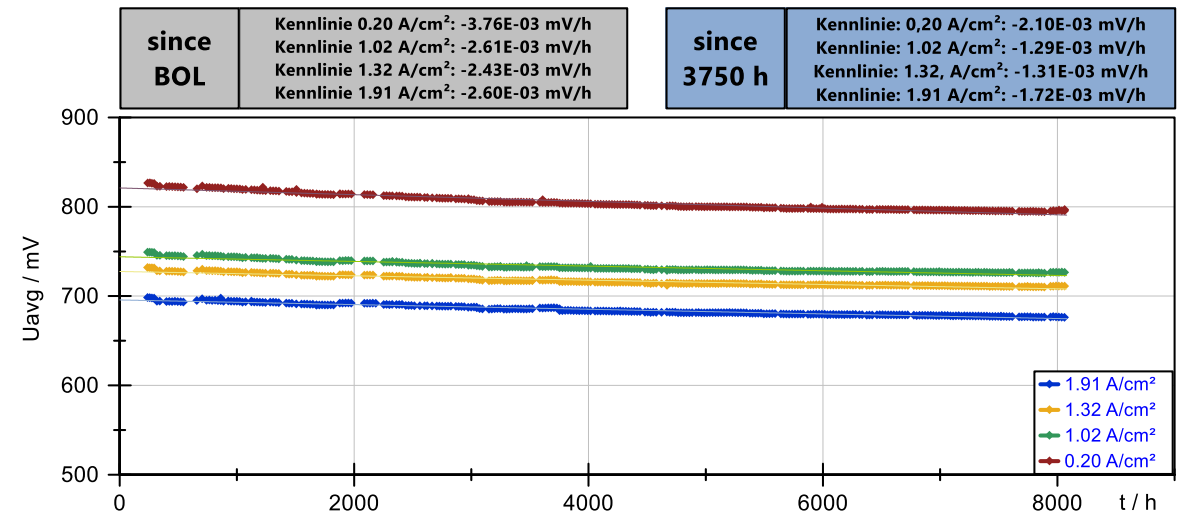
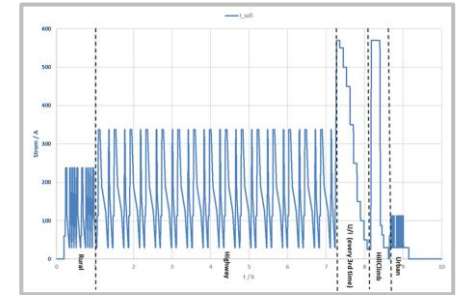
➤ Lifetime requirements > 15.000 h make testing expensive and time-consuming → ADT helps

Durability of NM20 CRA

Stack power & efficiency, full size CRA - 323 cells, 8000 h (test ongoing)
Cathode pressure 2,8 bara @ 900 A (decreasing towards partial load)

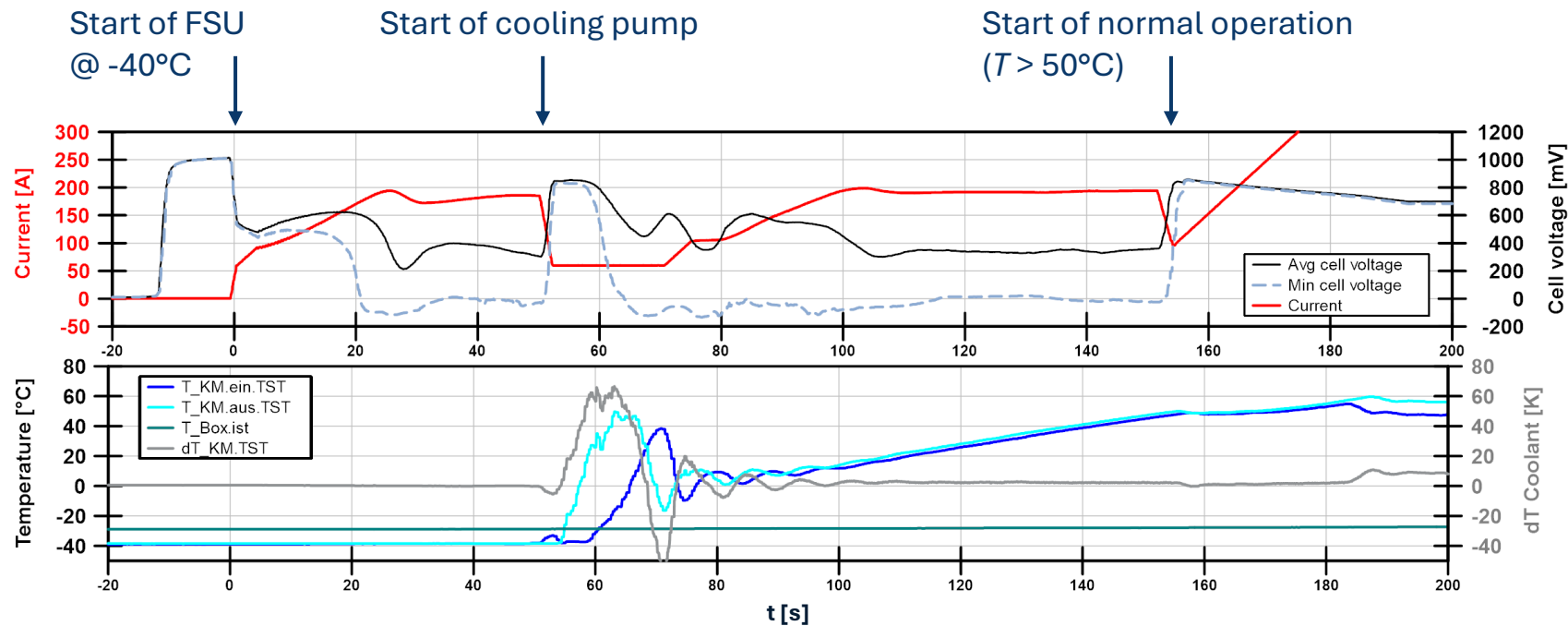


- Performance after > 8000 h: $678 \text{ mV} \cdot 900 \text{ A} \cdot 646 = 394 \text{ kW}$



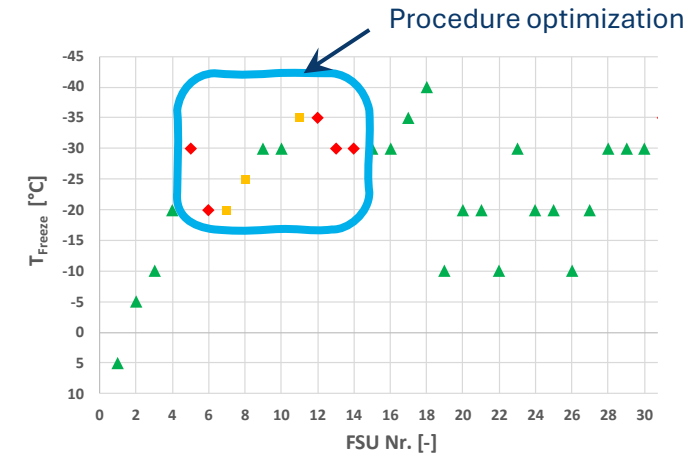
➤ Durability with 323-cells-stack shows low aging rate of -2 μV/h @900 A in HDLC after 8000 h

NM20 Freeze Start-Up



- Freeze start-up down to -40°C without external heating – System near design (small coolant loop)
- Warm-up 0.5 – 1 K/s depending on the start temperature

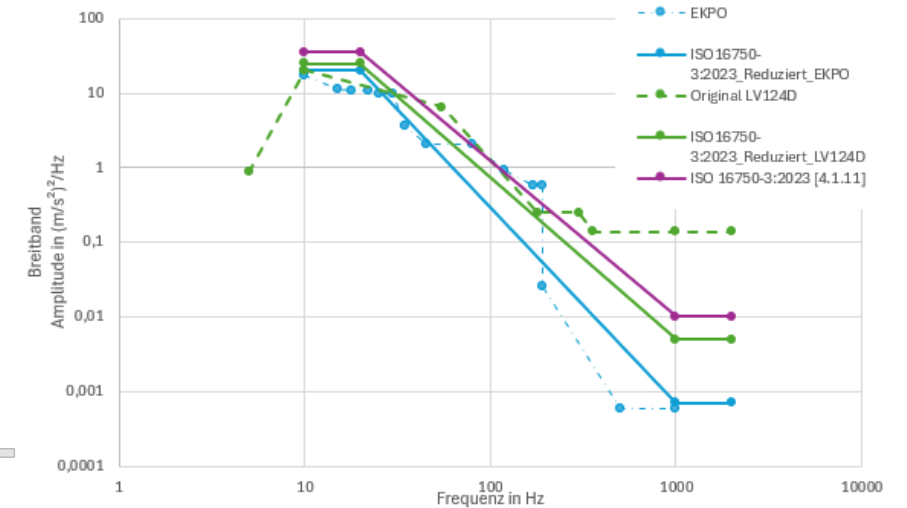
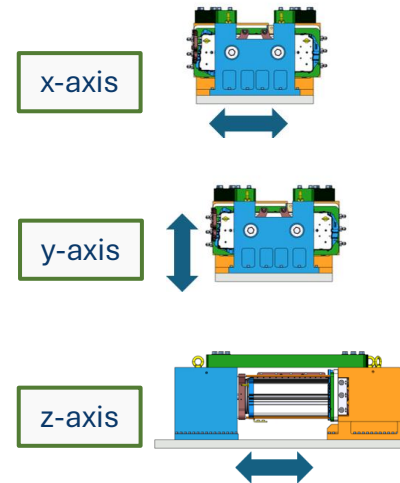
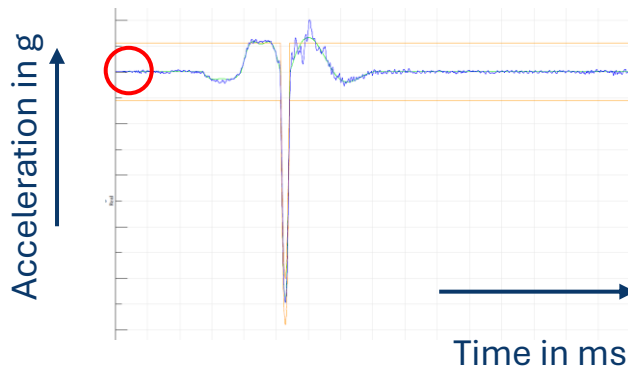
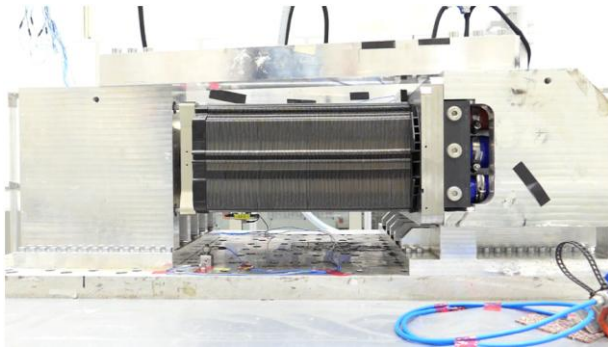
➤ Successful freeze start-up at temperatures down to -40°C



NM20 Shock and Vibration Testing

Early phase shaker testing to provide feedback

- A-sample function and safety
- B-sample design input



Test program according to different applications and their specific requirements ,
for each axis & different profiles (typ. $z \rightarrow x \rightarrow y$),
e.g. vibration ISO16750-3:2023, EN 60068-2-27
and shock up to 500 m/s^2 , 6 ms, 3x pos. + neg. axis

- Functional test
- Full and in-depth optical inspection with no/no-go-criteria & leak test

➤ CRA keeps **mechanical** integrity, no influence on core function

NM20 DVP – Summary of Results

- ✓ **BoL-Performance** at design point above design target (690 mV) at 900 A / 2.5 bara
- ✓ **Durability** with 323-cells-stack shows aging rates $< 3 \mu\text{V/h}$ @900 A in HDLC after 8000 h
- ✓ Successful **freeze start-up** at temperatures down to -40°C
- ✓ **Mechanical integrity / shock&vibration** testing successful
- ✓ Operation of NM20 module on 400 kW test bench with **inclination up to 30°** successful
- ✓ And many more...
 - ✓ Hydrogen protection time (> 25 h)
 - ✓ Max. operation pressure
 - ✓ Electrical tests (short circuit, dielectrical strength, ...)
 - ✓ Environmental tests (climatic storage, salt spray, ...)
 - ✓ ...

Twin stack inclination test



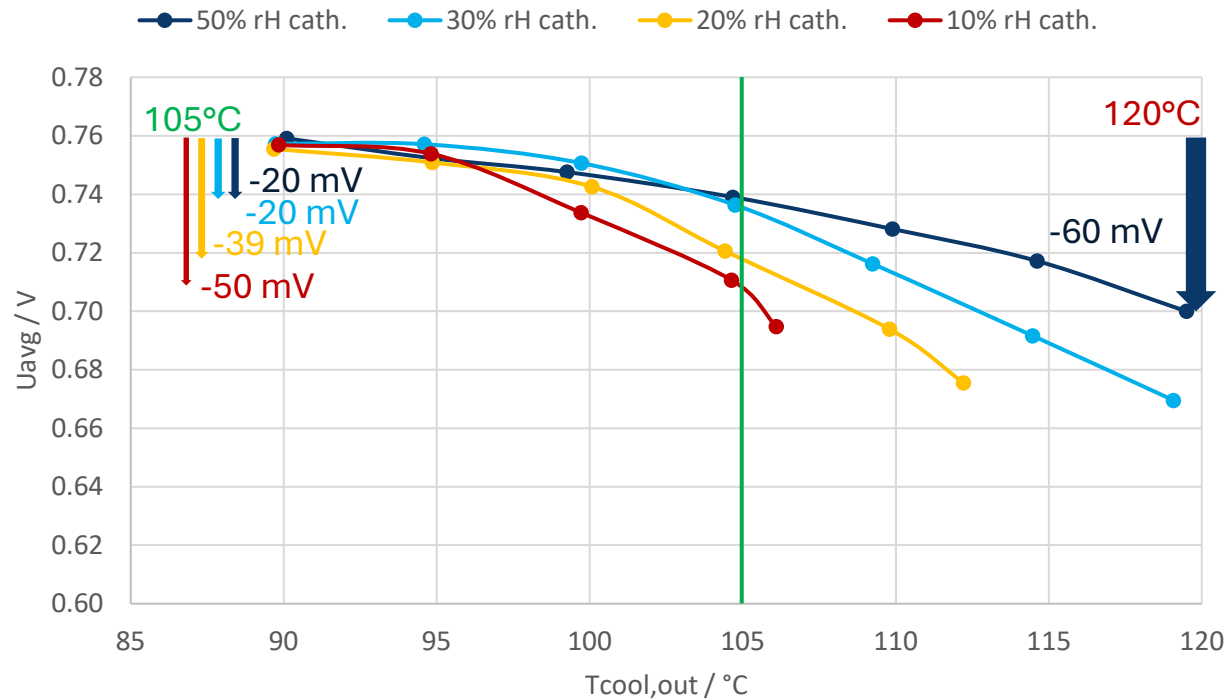
B-sample module test



- **Successful DVP → Approval of key features (e.g., performance, durability)**
- **Testing extended for other applications, e.g., extrema during operation (hot op., very high power, etc.)**

Boundary Testing: 120°C at 1.0 A/cm²

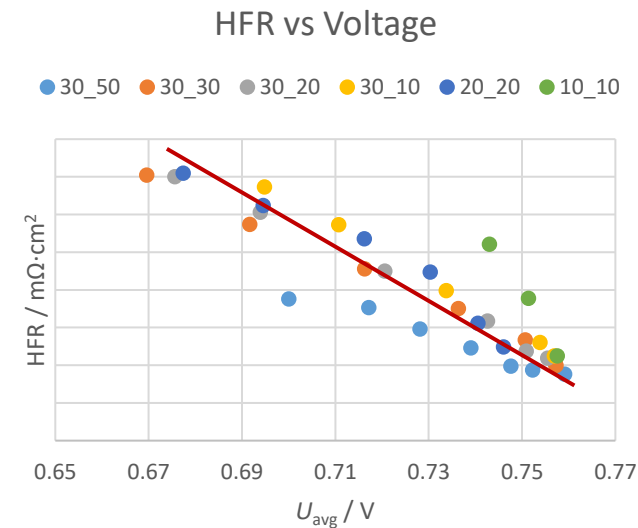
T & cathode RH depending performance at 1.0 A cm⁻², anode RH 40%



Criteria:

Stack was stopped when outlet *RH* < 40 % was measured

→ Critical limits resulting in major performance loss and stack damage



- Performance loss mainly caused by higher proton resistance due to lower *RH*
- No further negative effect of the higher temperature detected

- Operation at up to 120°C was possible; however, performance decreases
- Relevance of such extreme operation points depend on the use case

NM20 – Towards Different Applications

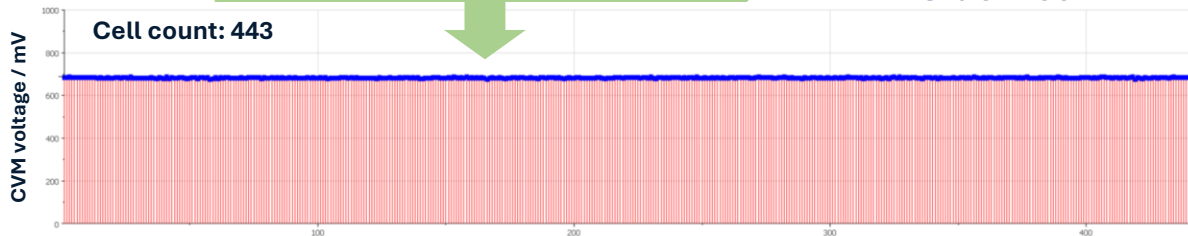
NM20 OPERATION AT VERY HIGH POWER OUTPUT

- High maximum pressure enables high power output, e.g., during take-off of plane
- High power output combined with good efficiency

P1 @ 1000 A

- $U_{\text{avg}} = 680 \text{ mV}$, $\eta_{\text{cell}} = 55 \%$
- $p_{\text{cat,in}} = 3.1 \text{ bar}_a$
- $\lambda_{\text{cat}} = 1.6$
- $T_{\text{cool,out}} = 100 \text{ }^\circ\text{C}$
- $dU = 6 \text{ mV}$

Single Stack: 301 kW
Twin Stack: 602 kW



NM20 OPERATION AT HIGH TEMPERATURE

- High-temperatures possible under various operating conditions
- Addresses limitations of coolant subsystem – increased dT to ambient
→ more compact and lighter coolant subsystem

P2 @ 800 A

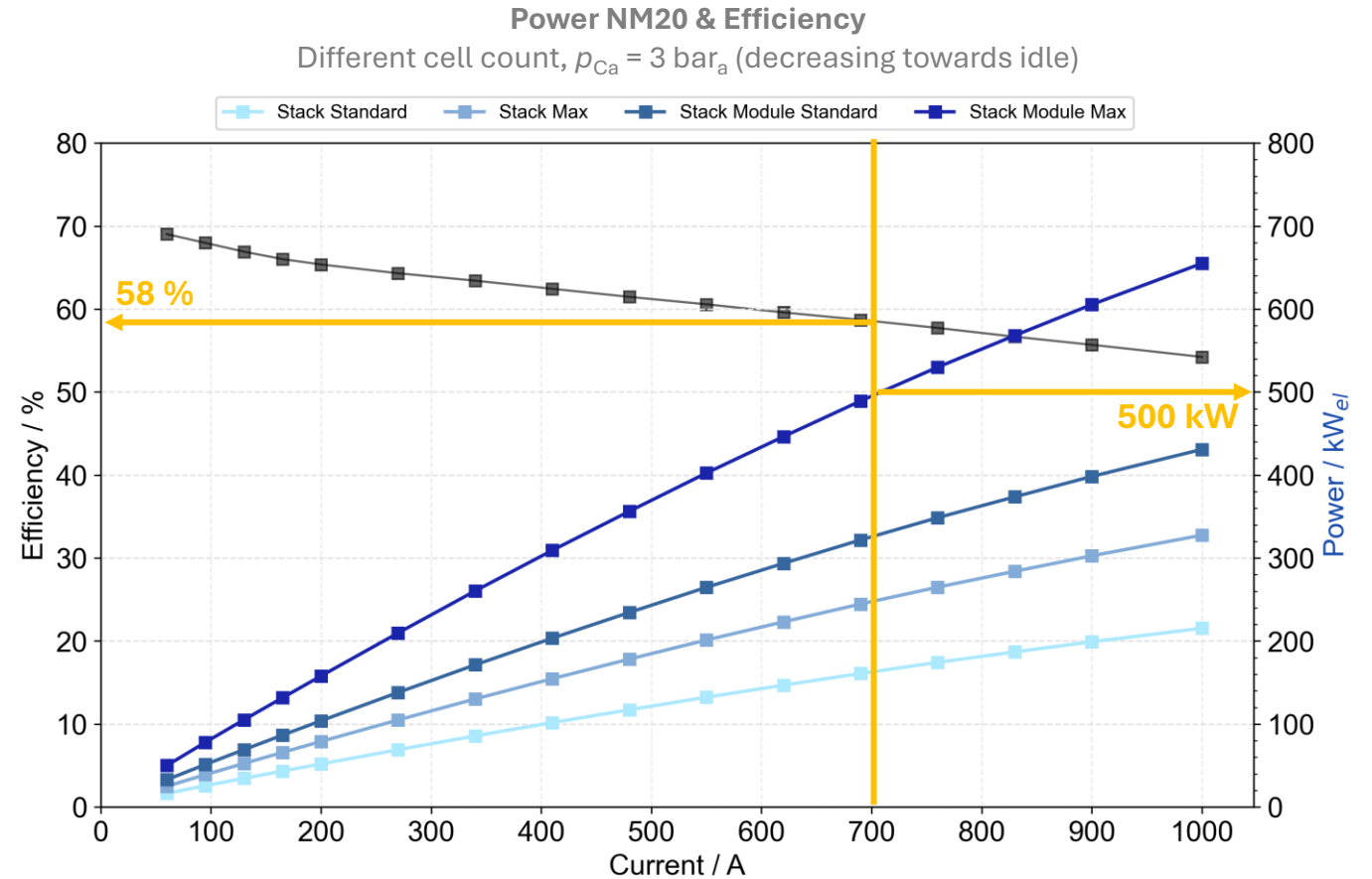
- $U_{\text{avg}} = 678 \text{ mV}$, $\eta_{\text{cell}} = 55 \%$
- $p_{\text{cat,in}} = 2.26 \text{ bar}_a$
- $\lambda_{\text{cat}} = 1.5$
- $T_{\text{cool,out}} = 104 \text{ }^\circ\text{C}$
- $dU = 7 \text{ mV}$

Single Stack: 240 kW
Twin Stack: 480 kW



➤ NM20 developed according to automotive process and quality standards – Provides a solid baseline for other specific developments, e.g., for aviation use cases (combined with light-weight solutions)

Stack Configurations



Modular approach for scalable applications

Easy integration and seamless scaling to highly efficient **Megawatt-Systems** that can be realized in setup with multiple twin stacks

Funded by:



Federal Ministry
of Transport



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NextGenerationEU



Baden-Württemberg
Ministerium für Umwelt, Klima
und Energiewirtschaft

on the basis of a decision
by the German Bundestag

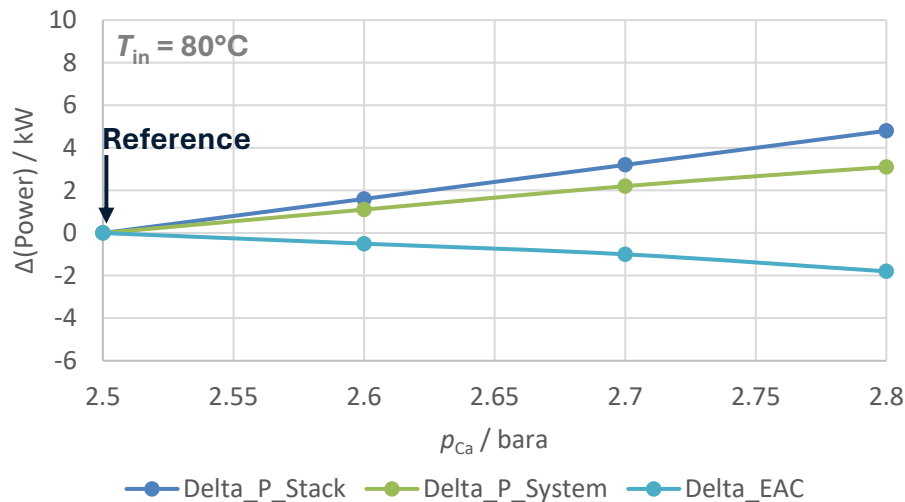
Thank you for your attention!

Contact: Dr.-Ing. Christophe Gerling
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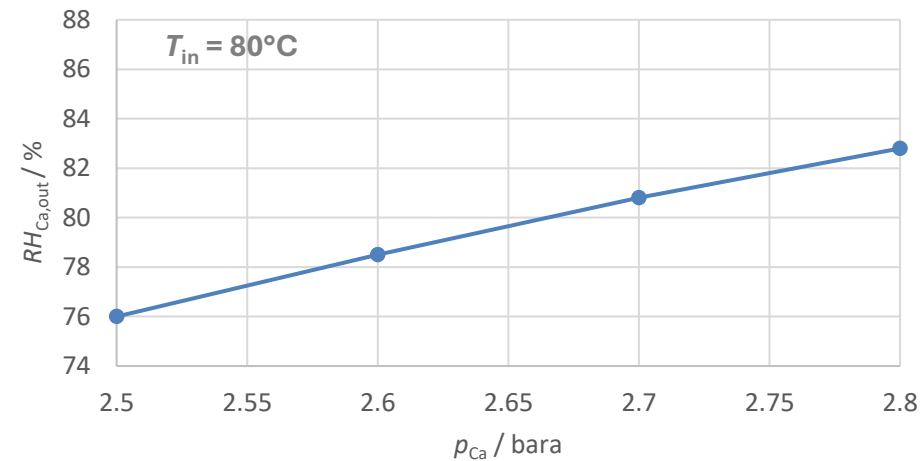
Model-Based Optimization of OpCons

OPTIMIZATION OF CATHODE PRESSURE @ INCREASED TEMPERATURE

Cathode pressure optimization @900 A - Power



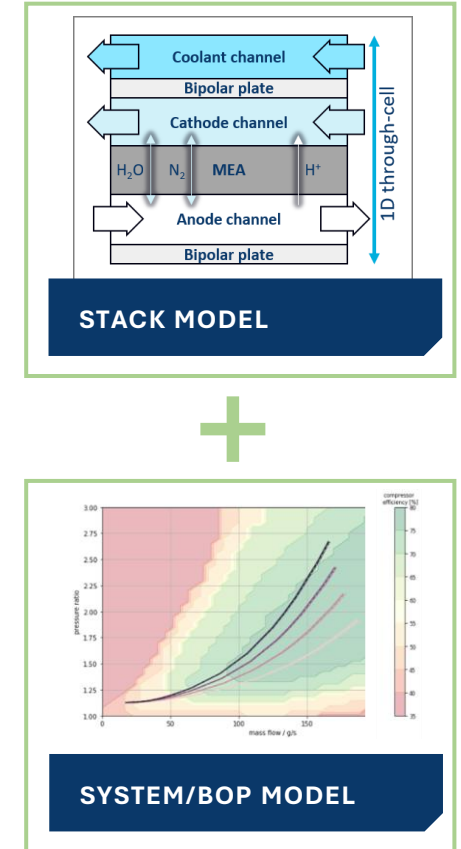
Cathode pressure optimization @900 A - RH



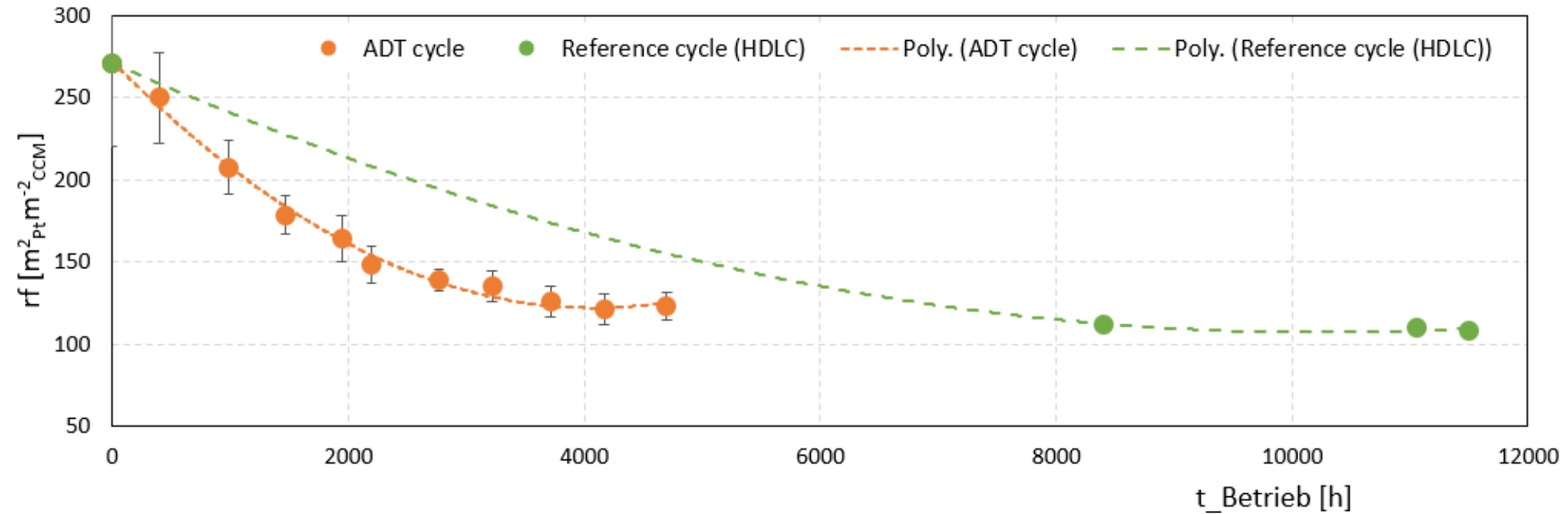
- Increasing the pressure leads to:
 - Slightly increasing system power
 - Increasing cathode outlet relative humidity (by 5 - 10 %) → beneficial for hum. performance & stack lifetime

➤ Optimization in the system context mandatory to maximize performance and lifetime; verification ongoing

Tools



RF Evolution During HDLC & ADT

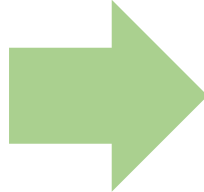


From A- to B-Sample – Optimization

A-SAMPLE



B-SAMPLE



DIM.	A-SAMPLE	B-SAMPLE	DIFFERENCE
X	683 mm	640 mm	-43 mm
Y	590 mm	509 mm	-81 mm
Z	682 mm	677 mm	-5 mm
Volume	275 l	221 l	-20 %



- Focus on performance of cell components
- Periphery: detail improvements without risk for function
- Target: Heavy Duty Application



- Focus on cost, space savings, durability & manufacturing
- Increased integration flexibility
- Target application full module (w/ MSA & Housing): Heavy Duty with maximized flexibility on CRA/Module level
- Stack and module solutions for Aviation, Rail and stationary Applications

➤ NM20 B-sample design achieves ~20% reduction in volume