Transient Operation Strategies for a 10 kW Steam Electrolysis Module Operated at up to 20 bar

Matthias Riegraf, Faisal Sedeqi, Anis Taissir, Florian Stährfeldt, Matthias Metten, Christian Schnegelberger, René Lorenz, Jan Hollmann, Santiago Salas Ventura, Marc Heddrich, Asif Ansar

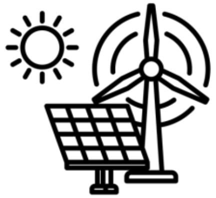
German Aerospace Center (DLR)
Institute of Engineering Thermodynamics
Energy System Integration Department

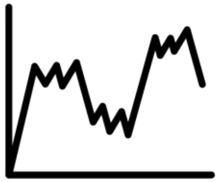
July 2, 2026

The Problem: Transient pressurized operation

1. Pressurization

- ❖ Higher system efficiency
- ❖ Easier system integration





2. Transient operation

- ❖ Coupling with fluctuating RES power
- ❖ Thermal stresses cause degradation

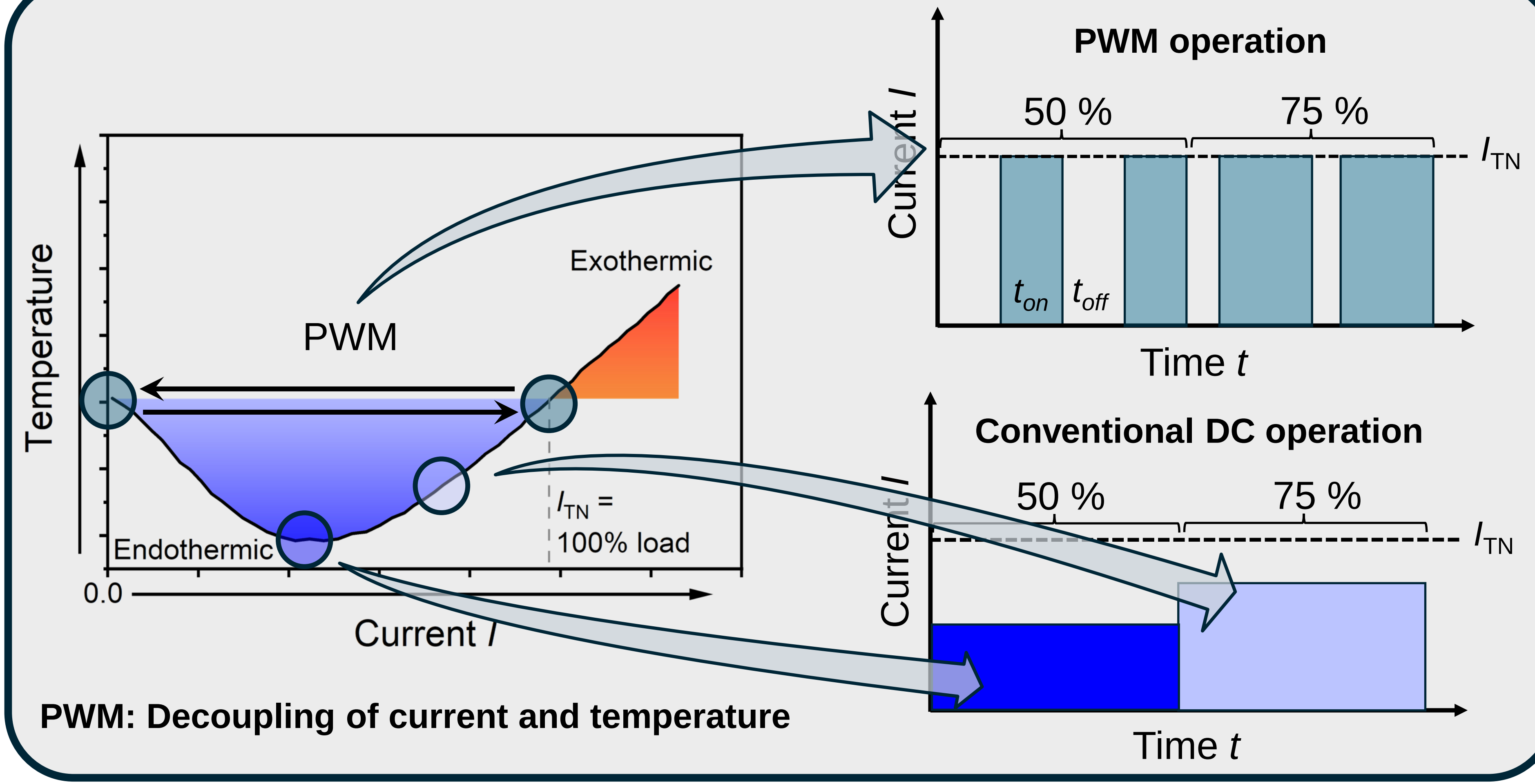
German PtX@Sea project:

- **Offshore demonstration on floating P2X platform**
- **Containerized SOEC system**

Goals

- Transient module operation with low temperature gradients
- Mitigation of differential pressures

Approach: Pulse-width modulation (PWM) for operational flexibility



PWM: Decoupling of current and temperature

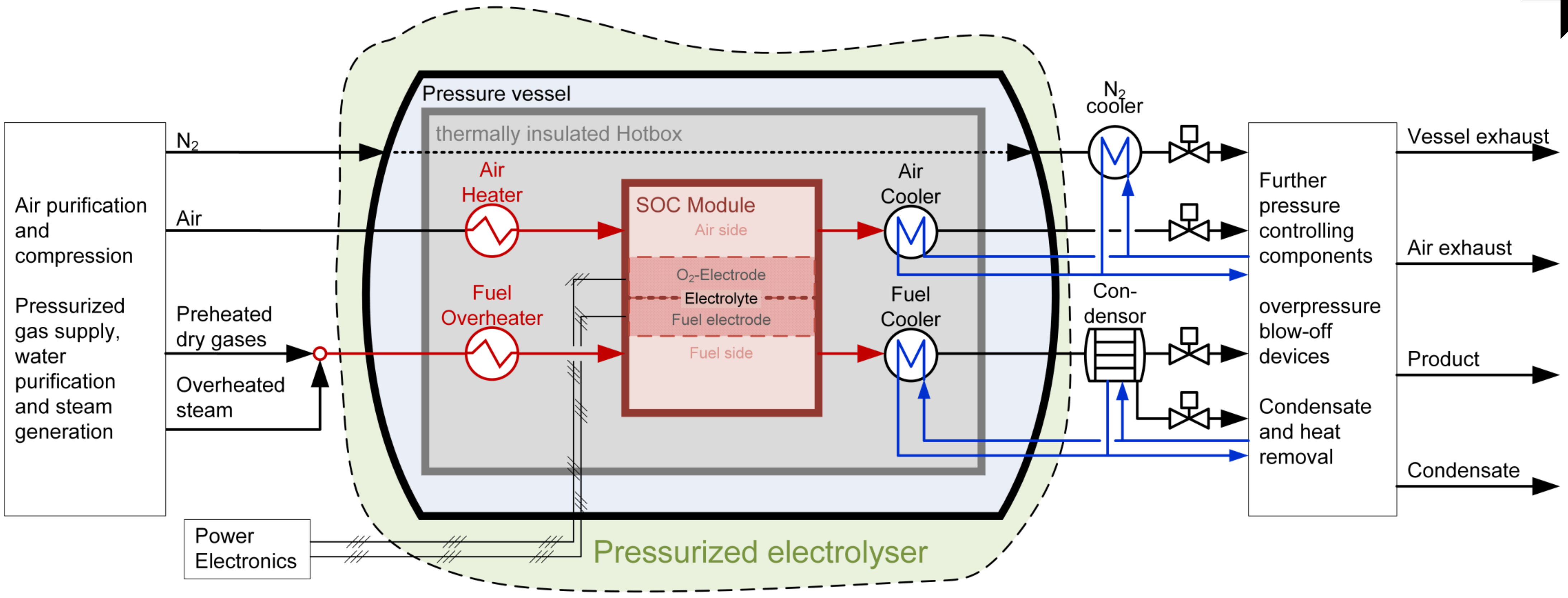
- Steam generation cannot follow minute-scale pulsing
→ low reactant conversion (RC)

- Fast pulsing exploits slow gas transport dynamics

Research questions

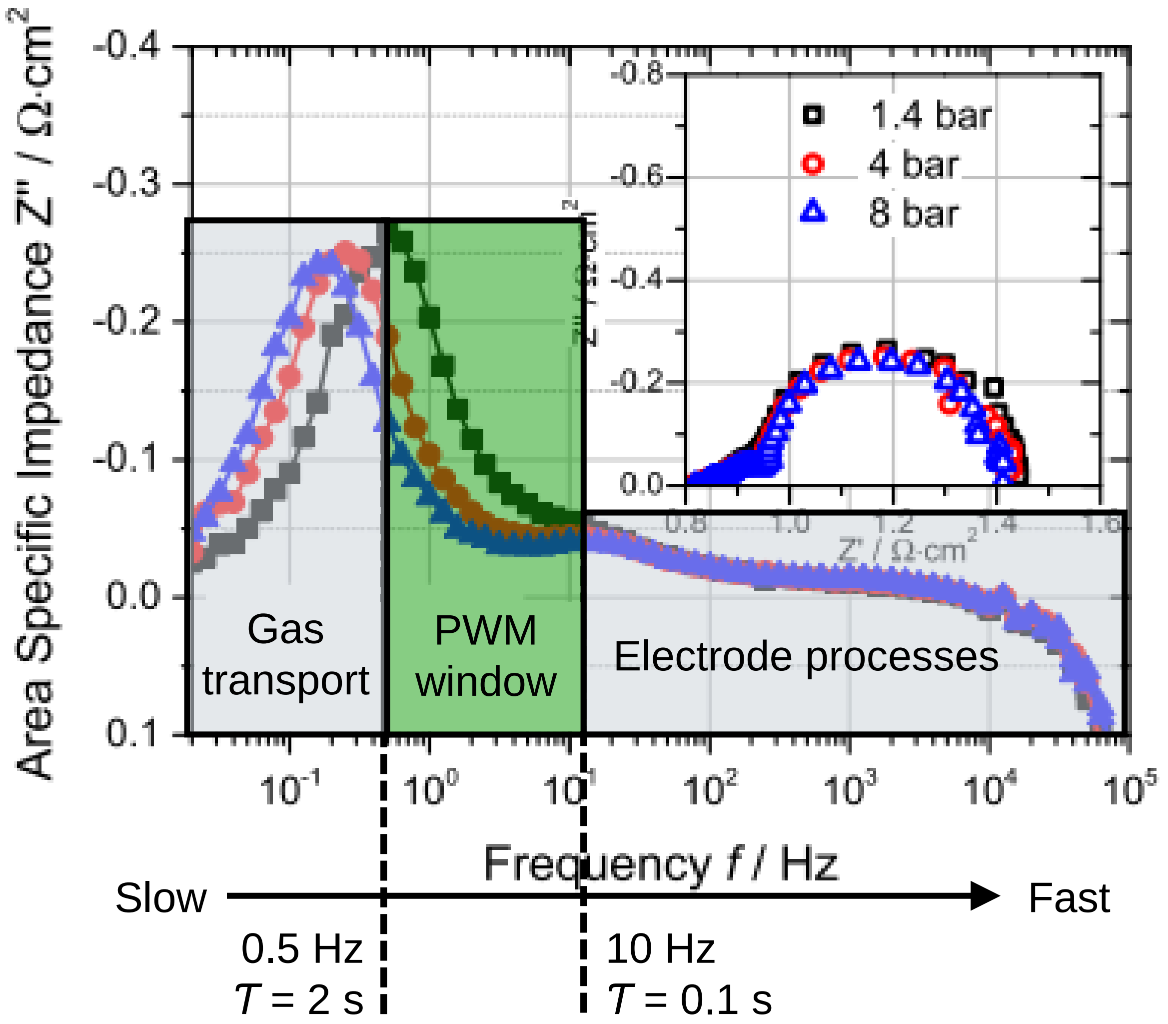
- Investigate thermal gradients in multi-stack modules
- Define pulse duration-dependent operating window

Pressurized module test rig



- 10 kW SOEC module from Sunfire in pressure vessel with 9-25 bar thermally insulated hotbox
- Air and fuel side heated via electrical heaters, no recuperators
- Differential pressures control between vessel, fuel- and air-side via valves to stay below 10 mbar

Pulsing frequency must be higher than gas transport dynamics



Sunfire ESC technology[1-3]:

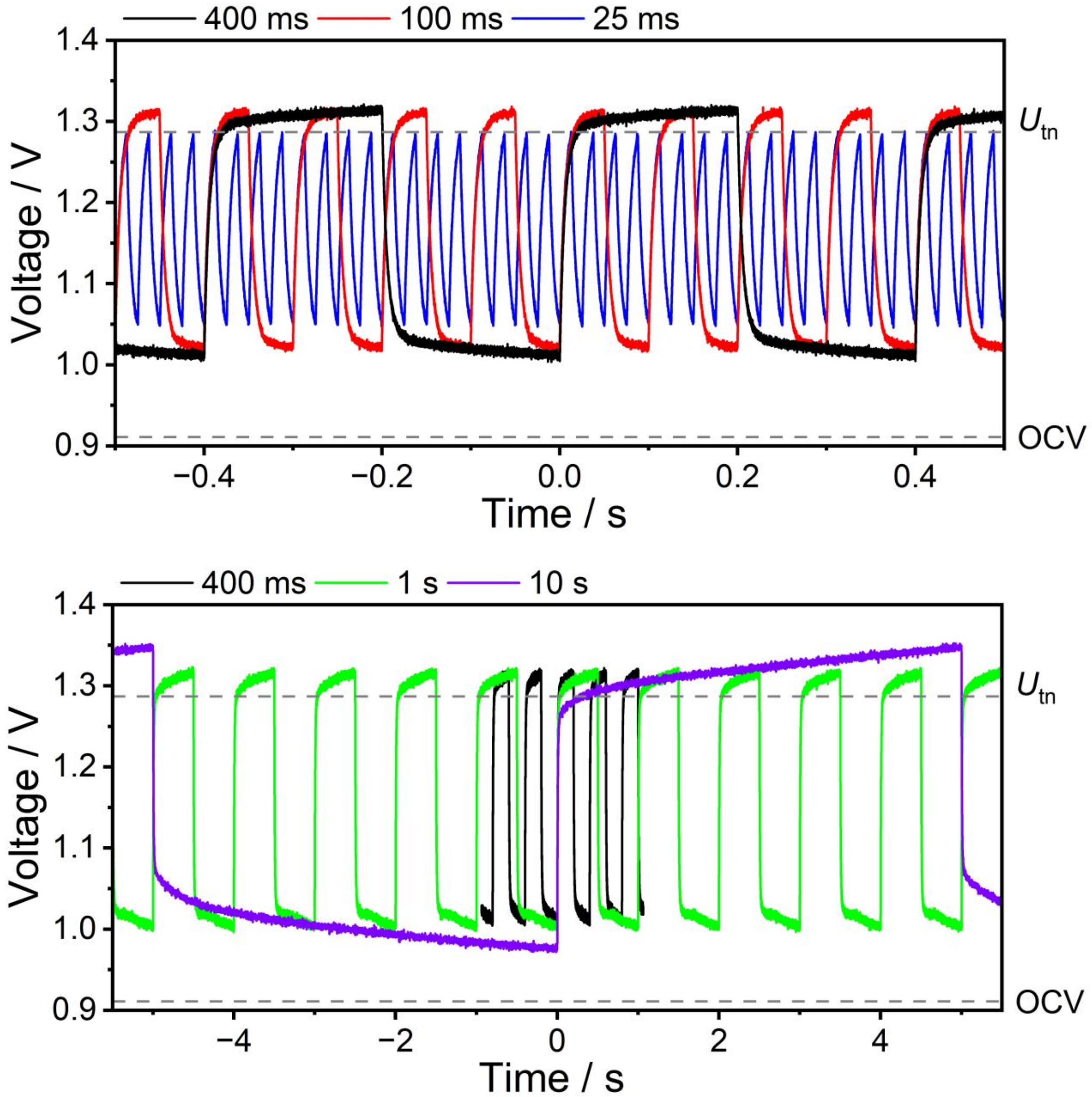
- Gas conversion below 1 Hz
- Negligible diffusion losses
- Fuel electrode process above ~10 Hz

PWM window:

- High frequency to maintain high RC_{avg}
- Temporary RC values >100%
- Not fast enough to interfere with electrode processes

[1]Riedel et al., *Int. J. Hydr. Ener.*, 2019
[2]Riegraf et al., *Chem. Eng. J.*, 2024
[3]Grosselindemann et al., *J. Electrochem. Soc.*, 2021

Voltage response at different pulse duration



Operating conditions

• Pressure	15 bar
• Duty cycle (‚on‘ time)	50%
• RC_{avg}	58 %
• Temperature	~800°C

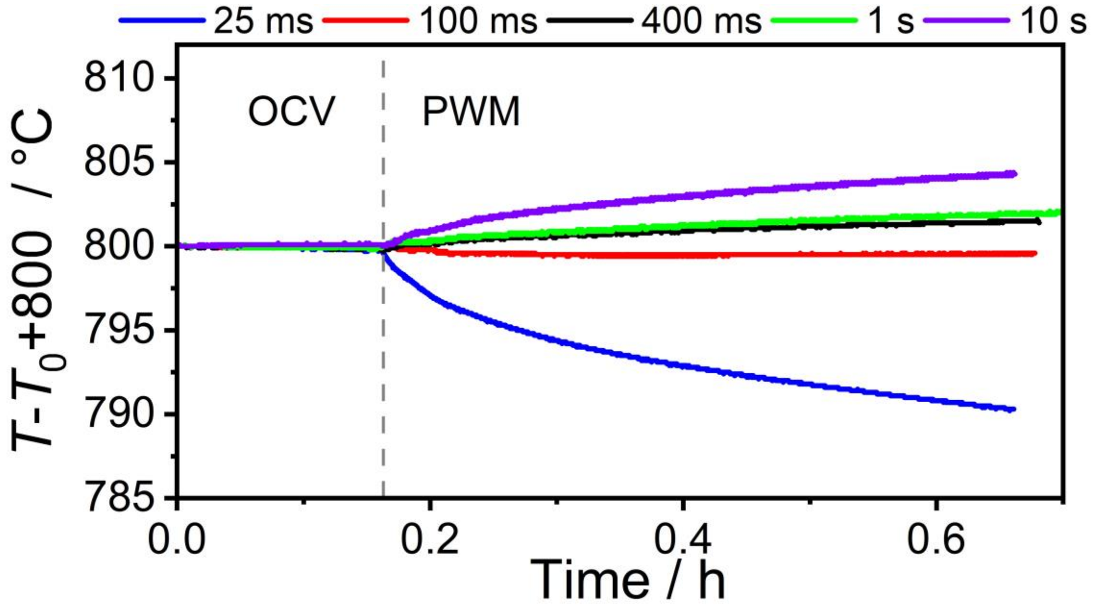
Physical interpretation

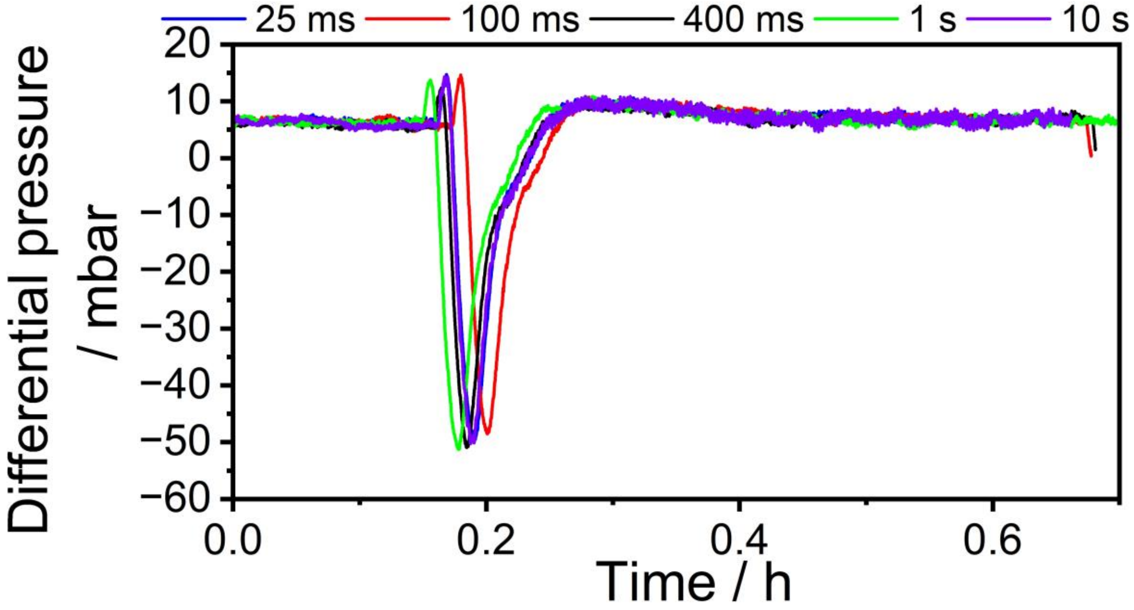
a) Initial voltage step: Ohmic resistance

b) Exponential relaxation (~25 ms):
   - Double-layer capacitance (Ni/CGO fuel electrode)
   - Non-ideal square-wave current

c) Slow drift (s range):
   Mass transport limitations

Small temperature changes at 0.1-1 s pulse duration





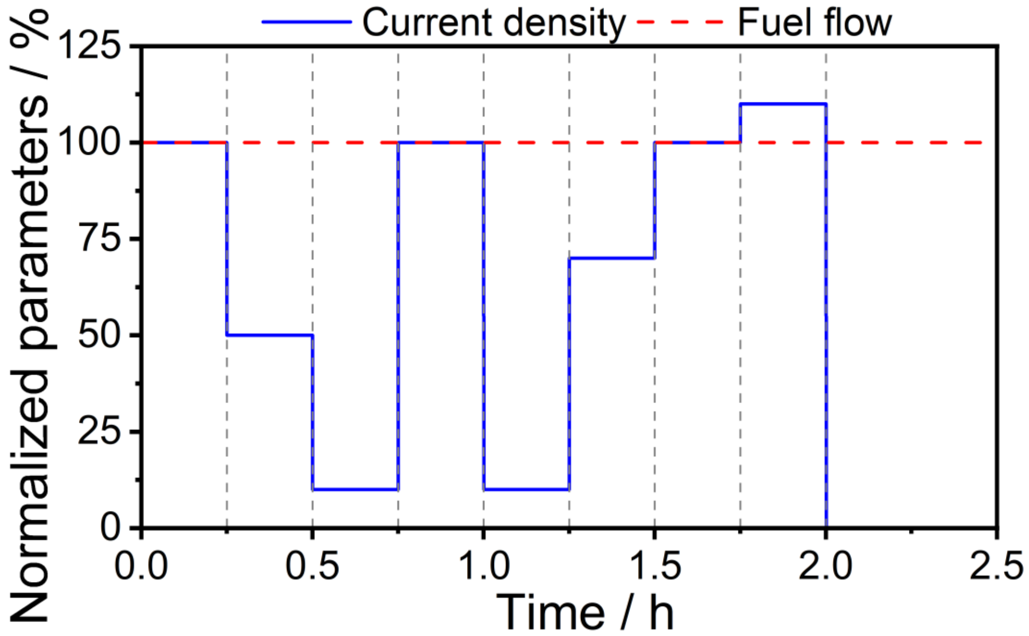
<u>Operating conditions</u>

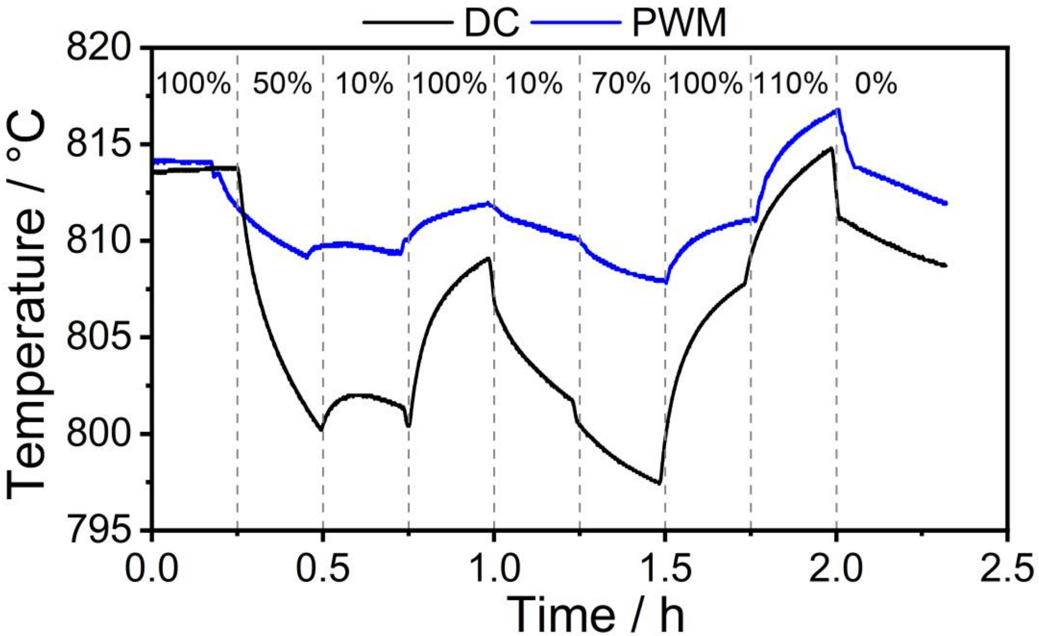
• Pressure	15 bar
• Duty cycle (‚on‘ time)	50%
• RC_{avg}	58 %
• Temperature	~800°C

- Temperature changes with pulse duration
- ‚Ideal pulse duration‘ at 50%: 0.1-1 s
- No differential pressure spikes during PWM

→ Continuous mass flow

PWM: Lower thermal gradients than DC operation



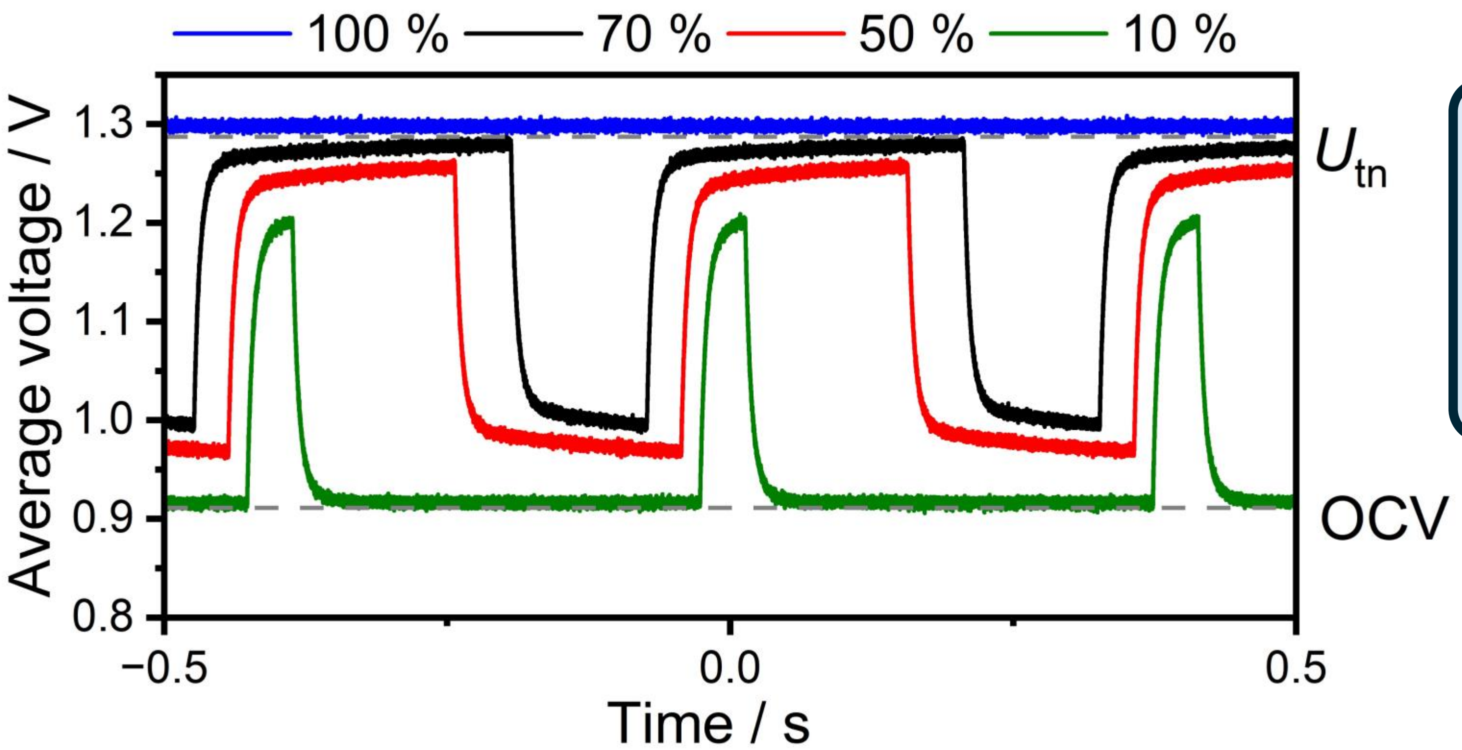


Operating conditions

- Pressure 15 bar
- Pulse duration 400 ms
- RC 7-70 %
- Temperature ~800°C

- Dynamic load profile with 15 min intervals
- Including steps from 10% to 100%
- Max. temperature changes:
  - DC: 17 K
  - PWM: 8 K

Lower duty cycles decrease voltage and temperature



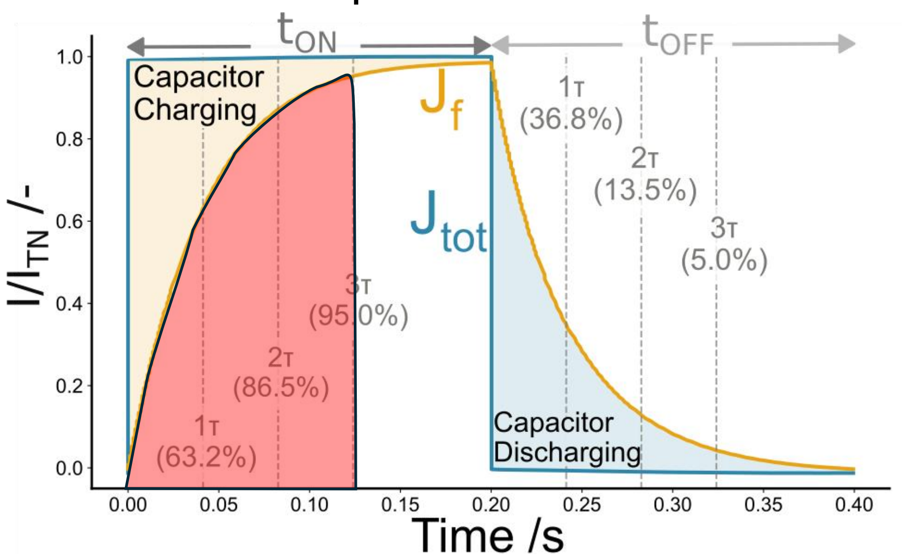
Operating conditions

- Pressure 15 bar
- Pulse duration 400 ms
- RC 7-70 %
- Temperature ~800°C
- Current density 0 → 0.22 A cm^{-2}

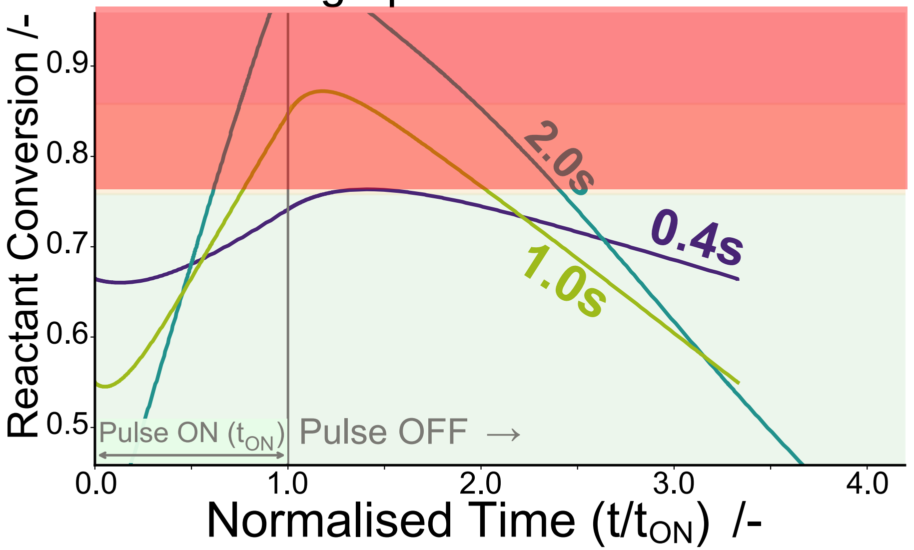
- Lower duty cycles decreases average voltage
- 10%: Low pulse time during ‚on‘ phase (40 ms)→ Cooling

Operating window: Restricted by capacitance and mass transport

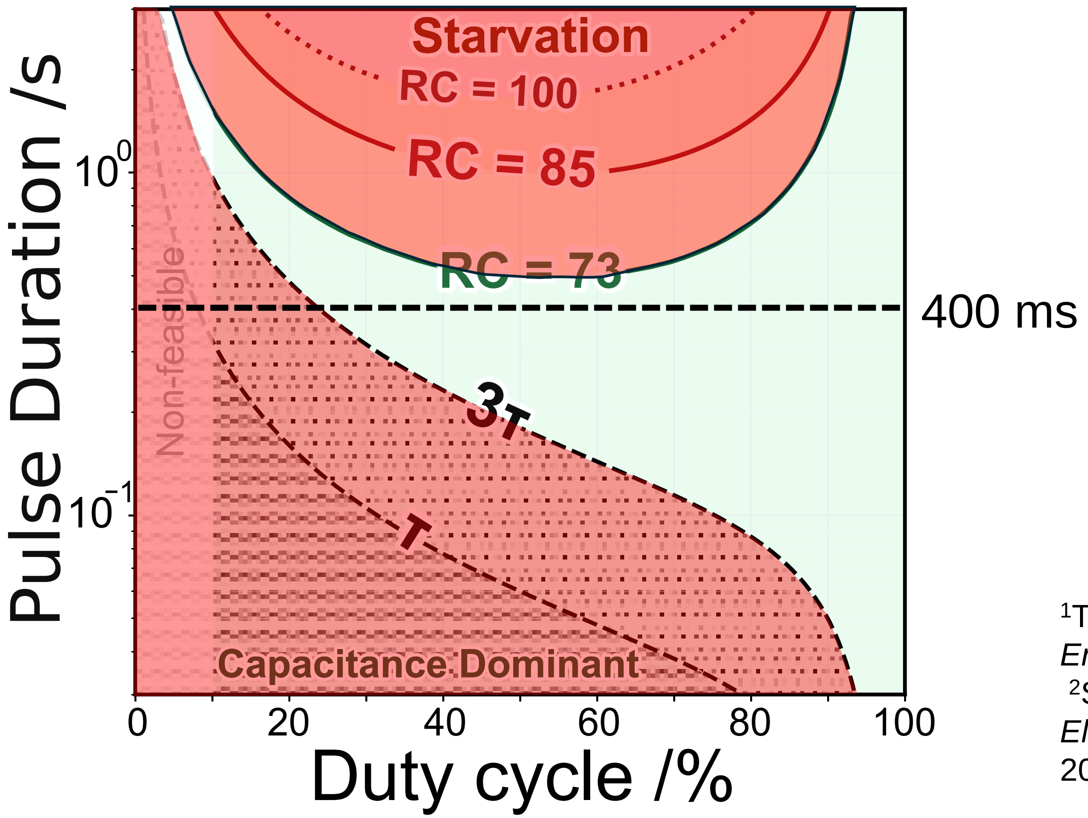
Low pulse duration



High pulse duration



- Simulations based on validated transient model[1,2]
- Capacitance behavior fitted with RC element
- Operating map based on variation of pulse duration and duty cycle



[1]Tomberg et al., *Sust. Ener. Fuels*., 2023;
[2]Sedeqi et al., *J. Electrochem. Soc.*, 2024

Conclusions

- Demonstration of PWM for transient SOEC operation at 15 bar
- Careful choice of pulse duration required
- Dependent on power electronics, stack architecture and operating conditions

Thank you for your attention

DLR

Offshore campaign

Helgoland, North Sea
November 2025

Financially supported by:

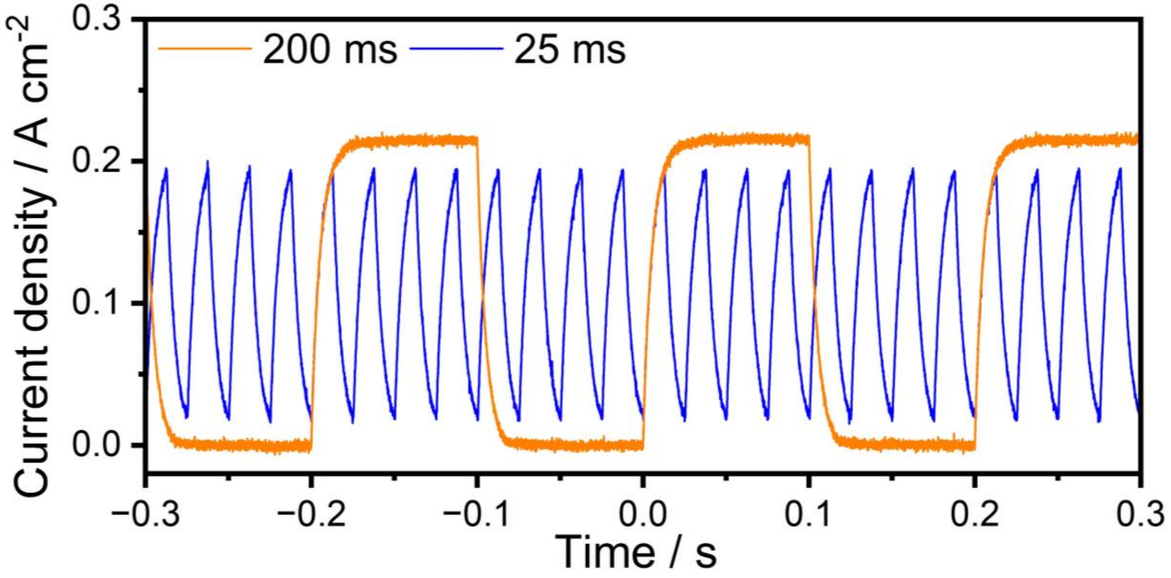
“H2mare” project of the German Federal Ministry of Research, Technology and Space (BMFTR, grant number 03HY302F).

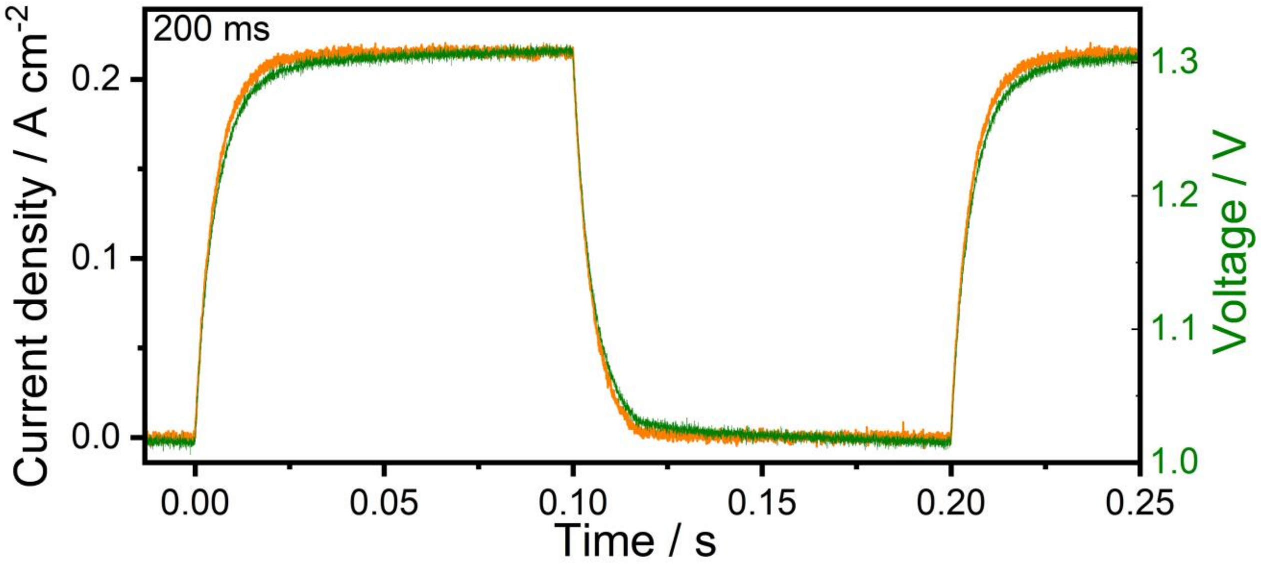
With funding from the:
Federal Ministry of Research, Technology and Space

“PtX@Sea” project of the German Federal Ministry of Research, Technology and Space (BMFTR, grant number 03SF0799B).

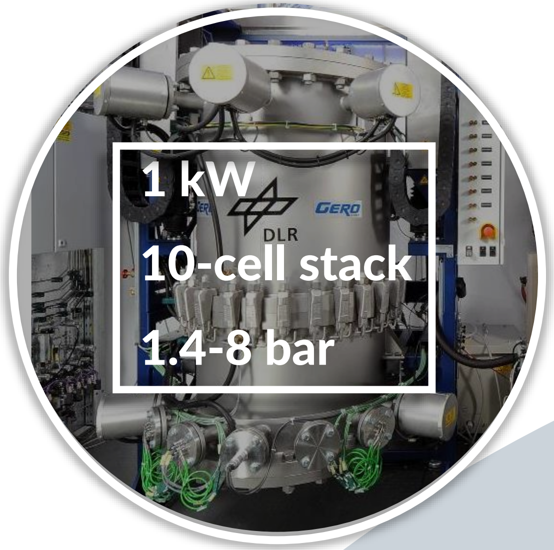
With funding from the:
Federal Ministry of Research, Technology and Space

Current input signal



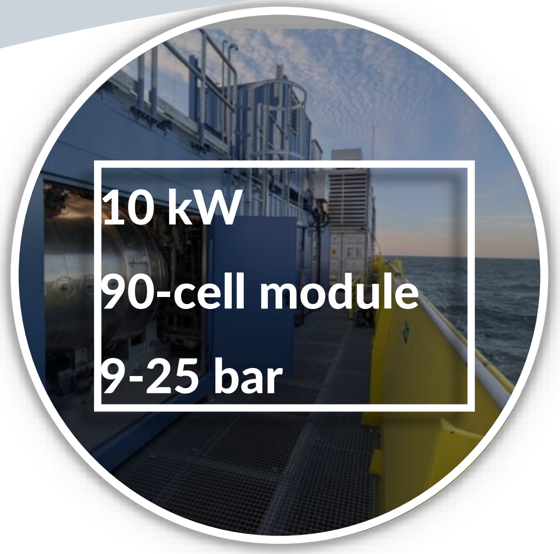


Dynamic investigations at different scales provide different benefits

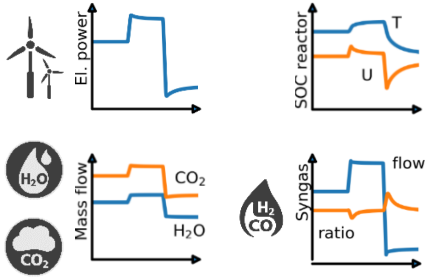


- Impedance spectroscopy

- High pressure range
- Module environment
- Temperature effects
- Oscilloscope



Transient simulations



- Validated transient model
- Physico-chemical processes implemented