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Experimental and simulative design of isothermal high temperature electrolyser controller for coupling with renewable energies

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DLR-TT-ESI - Electrochemical High Temperature Processes

Agenda

- H_2MARE
- Electrolysis technologies
- Solid Oxide Electrolysis (SOEL)
- Controller development framework
- Results
- Conclusions and Outlook

Introduction

Background

Methodology

Results

Outlook

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H_2MARE

- EU mandates 50 % Renewable Fuels as feedstock or energy carrier by 2040[1]
  - **H_2MARE** evaluates the production of H_2 and its derivatives offshore
  - Electrolysis is one of the most prominent way to achieve it
  - Production & transport of H_2 to shore has higher economic potential than HVDC[2]

- Electrolysis must operate with fluctuating energy sources

1: EU Parliament, Revision of the Renewable Energy Directive: Fit for 55 package

2: Hydrogen and syngas-production by Solid Oxide Electrolysis in off-shore PtX-applications, M.Metten et al., EFCF 2024

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Electrolysis technologies

- AEL
  - Single reactor size 5 MW[3]
  - Plant size 50-150 MW[4]
- PEMEL
  - Plant size up to 40 MW5
- SOEL
  - Plants in the 2-4 MW range implemented[6]
  - Production capacities in the GW range

	Op. Temperature / °C	Electrical efficency[6] $kWh/kg\ H_2$
AEL	70-120	50-78
PEMEL	70-120	50-83
SOEL	600-850	38-55

SOELs show high potential for coupling with renewable sources

AEL: Alkaline Electrolysis
PEMEL: Proton Exchange Membrane Electrolysis
SOEL: Solid Oxide Electrolysis
LCOH: Levelized Cost of Hydrogen

3: hydrogen.johncockerill.com/en/products/electrolysers
4: www.longi.com/en/cases/668/
5: hydrogen.johncockerill.com/en/markets/power-to-gas/
6: https://www.ir.plugpower.com/press-releases/news-details/2024/Plug-Delivers-and-Commissions-over-95-MW-of-Electrolyzer-Capacity-Globally/default.aspx

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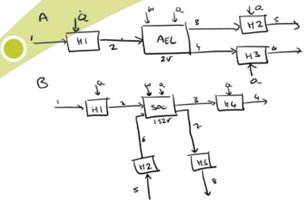
SOC System activities

High Temperature Process Group (EHT)

Research and Development of Solid Oxide Cell (SOC) systems

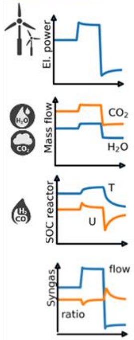
- Process engineering for bringing electrolysis (EC) and fuel cell (FC) systems into the GW range
- Linking large experiments with process system modelling
- From concept KPIs to operation strategies

Process system concepting



Experimental reactor investigations

Transient process system simulations



Process system experiments

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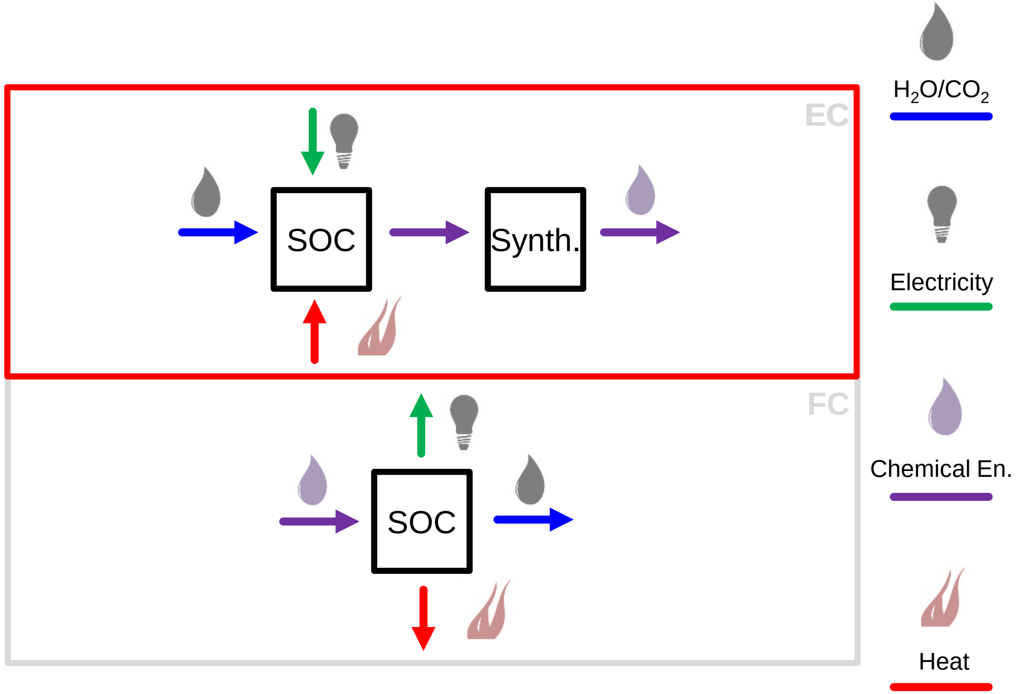
Solid Oxide Cells

Electrolysis (SOEL) → PtX for fuels

- $\eta_{LHV} > 80\%$
- H_2 from H_2O
- Syngas from H_2O+CO_2

Fuel Cell (SOFC) →Electricity production

- $\eta_{LHV} > 60\%$
- NG, LPG, Biogas, H_2



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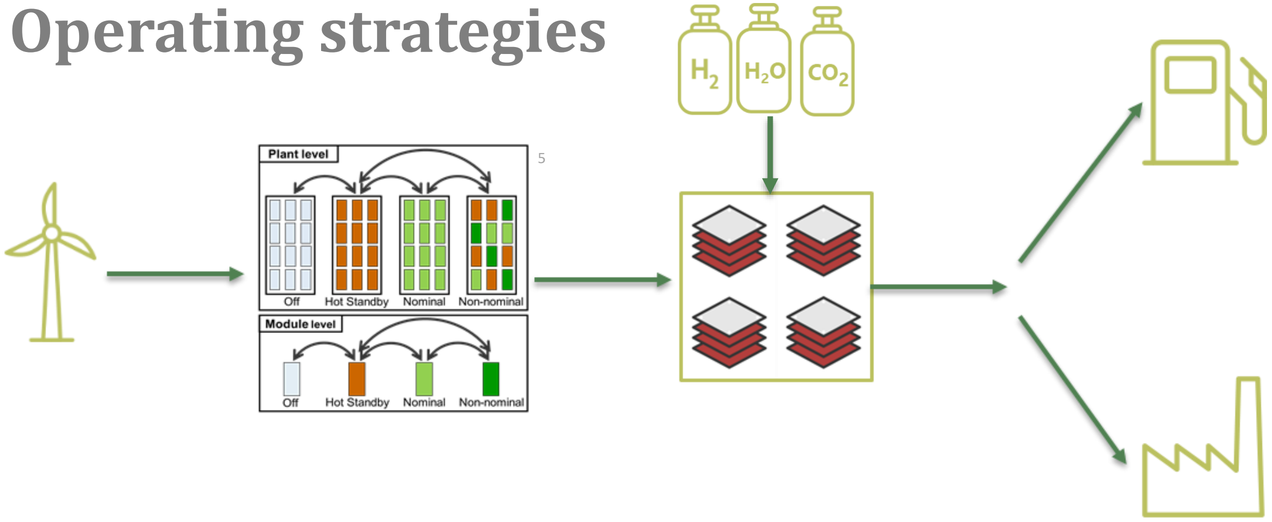
SOEL Operating strategies



- Energy input leads to temperature rise
- Fuel composition changes lead to to temperature decrease

Need to minimize T gradients by developing module-level control strategies

7: Transient Operating Strategies for Multi-MW Solid Oxide Electrolysis Systems Promoting Power-Following Operation, R.Lorenz et al., EFCF 2024

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EHT Tools

CELESTE – Conceptual design of ELectrochemical procEss SysTems with Exergy analysis
- Process system energy tool
- Python
- Assessment in system level
- Easy implementation

TEMPEST – Transient Electrochemical reactor Models for Process and Energy SysTems
- Transient simulations for SOCs
- Dymola/Modelica
- Cell & Module analysis
- Many levels of detail

HORST
- Pressurized short stack test rig
- $2kW_{el}$ power
- Up to 8bar
- No integration needed

GALACTICA
- Large module test rig
- $120kW_{el}$ power
- ~2.5kg/h H_2
- Avalaible for all modules

Combination of tools allows us to develop complex control strategies

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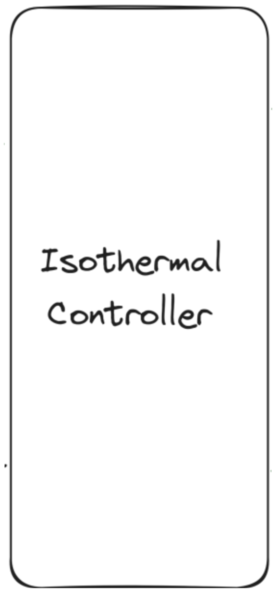
Controller Layout



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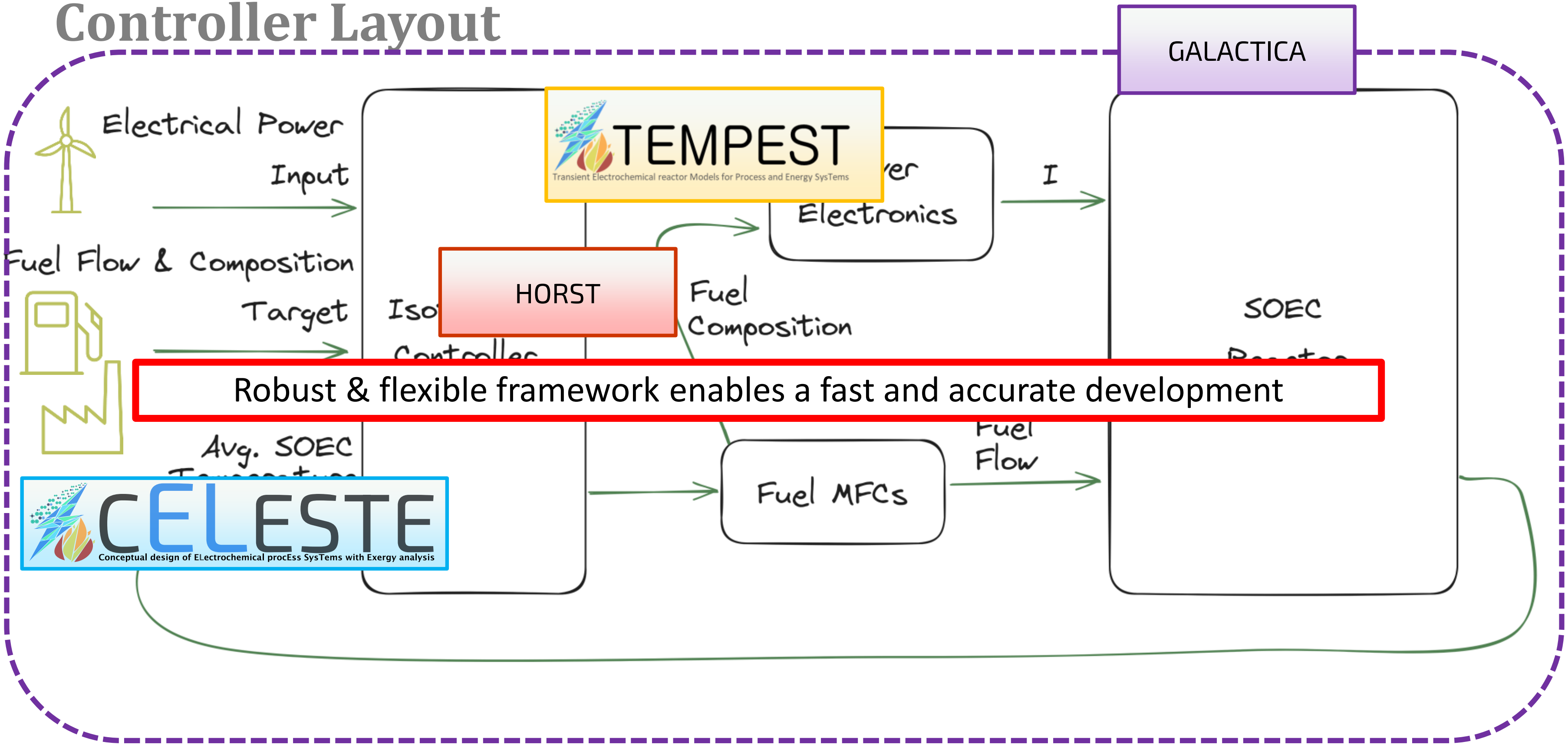
Controller Layout



Robust & flexible framework enables a fast and accurate development

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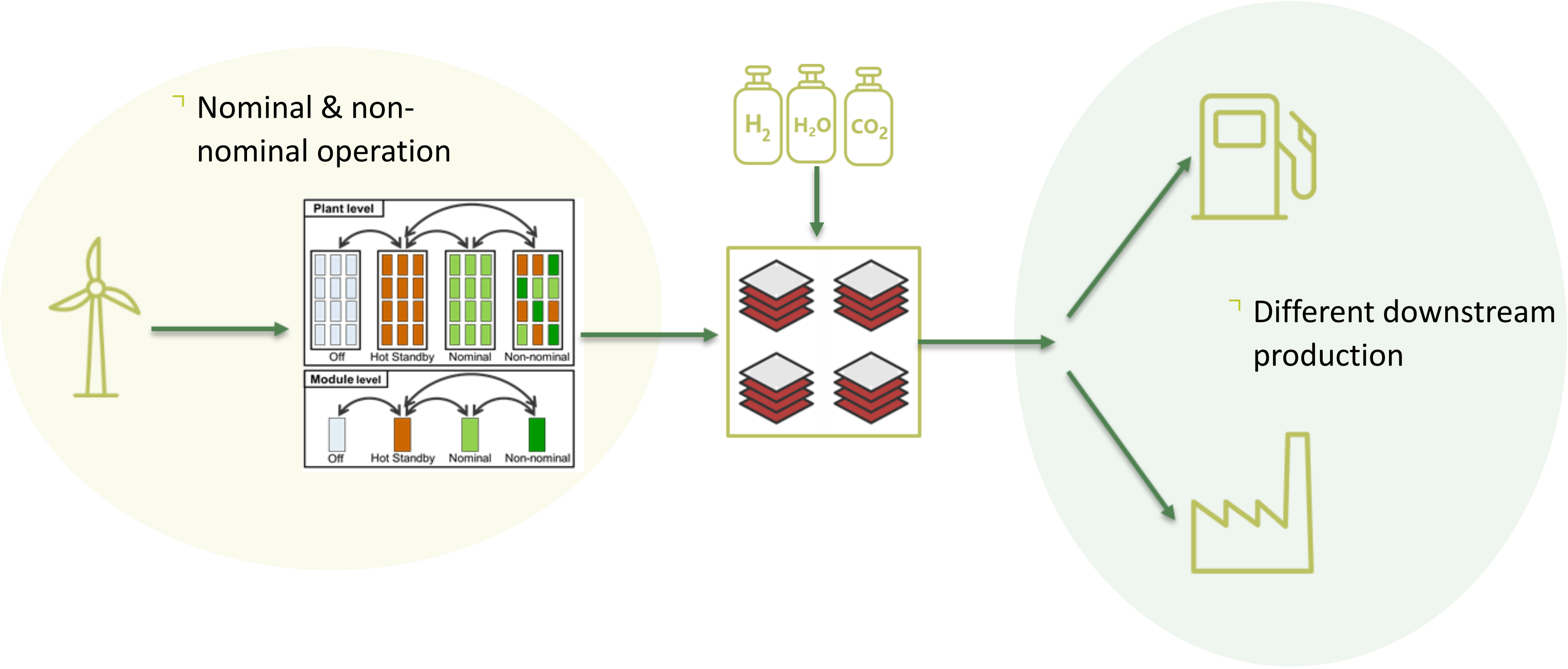
Controller testing



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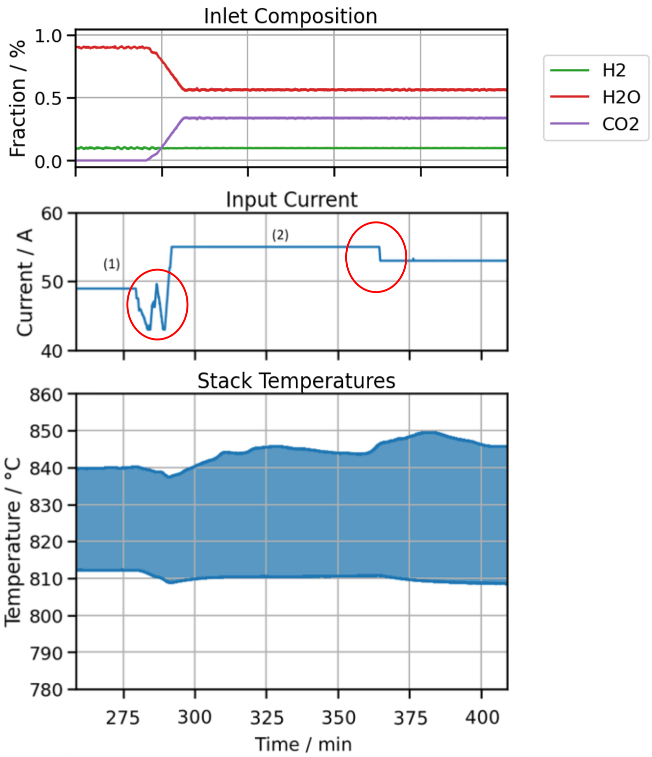
Non-nominal operating point



- Non-nominal operating point
- Transition from H_2 (1) to syngas production (2)
- Oscillation due to controller activation
- Control reaction to unexpected temperature increase

Isothermal operation is kept with expected and unexpected changes

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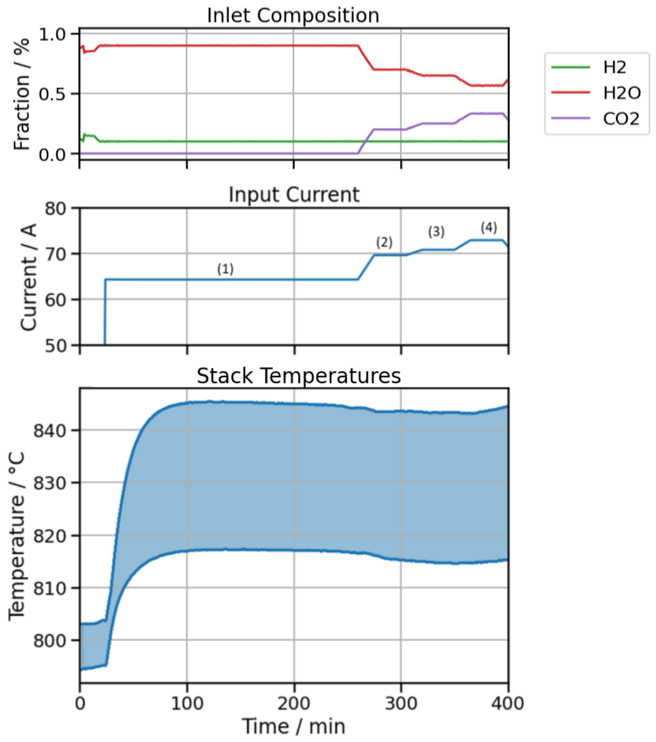
Nominal operating point



- Nominal operating point
- Inlet composition variation for pre-determined SGR

Operation	H_2O-CO_2 Inlet composition	H_2/CO Outlet Ratio	Application
(1) - H_2O-El.	90-0	N/A	H2 Production
(2) – Co-El.	70-20	~4	Research
(3) – Co-El.	65-25	~3	~Methanation
(4) – Co-El.	57-33	~2	Fischer Tropsch

Isothermal condition is kept for different process reactors

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Conclusions & Future Outlook

Conclusions

- Validation of temperature controller developed with in-house tools
- SOEC maintained in isothermal conditions for different operating points
- Base framework for experimental investigations in transient conditions
- SOEC can be controlled to meet transient demands

Future Outlook

- Development of more advanced control methods
- Plant-level operating strategies
- Coupling with real-life wind data

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Thank you!

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Flagship Project H_2Giga

Flagship Project H_2Mare

Flagship Project TransHyDE

Backup and additional information

Control Development

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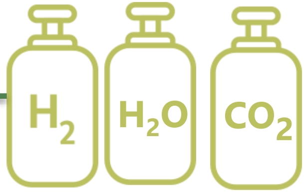
Methodology – Controller development

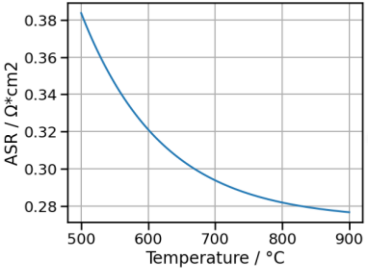


$$\alpha = \begin{cases} 1.0 \; if \; = full \; load \\ 0.7 \; if \; != part \; load \end{cases}$$

$$i = \alpha \cdot \left(\frac{\Delta V}{ASR} \cdot A_{cell} + \gamma \cdot PID(T_{cell;avg}; T_{inlet})\right)$$ [3]

SOC Reactor

$$ASR = y_0 + A \cdot \exp(B \cdot T)$$ [2]



2 Riedel et al., 2019

3 Tomberg et al., 2022

HORST

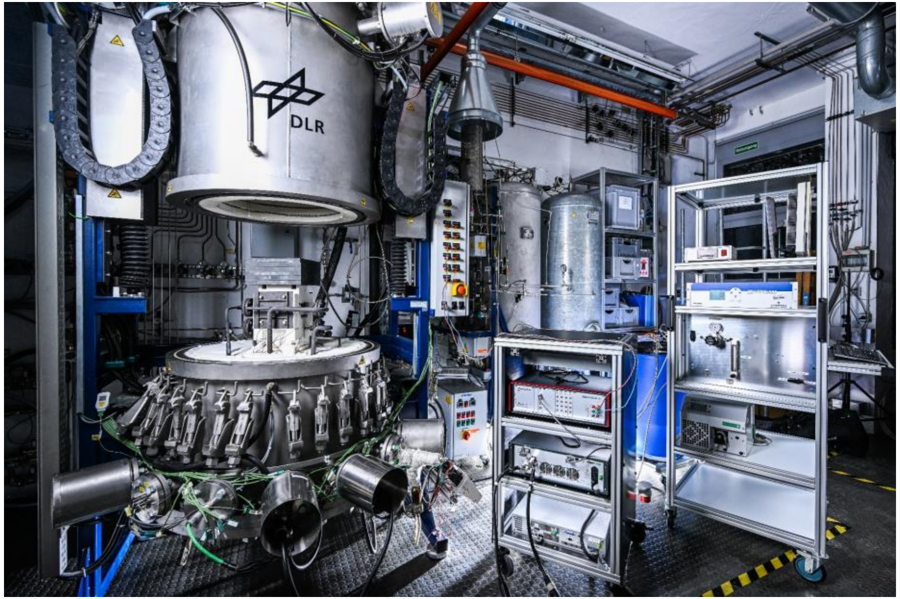
HORST: pressurized SOC short stack test rig

Technical specifications

- Pressure: 1.4 to 8 bar
- Operating temperature: 650 to 950 °C
- 0.5 kW FC; 2 kW EC

- Sensitive pressure control between gas compartments (<5 mbar)
- Fuel side: H_2, H_2O, N_2, CH_4, CO_2, CO
- Air side: air, O_2, N_2, He
- Stable steam supply up to 100 %

- *Operando* impedance measurements
- Online measuring of outlet gas composition
- Equipment for PMA available (SEM/EDX)



HORST: Pressurized short stack test bench

Technical specifications

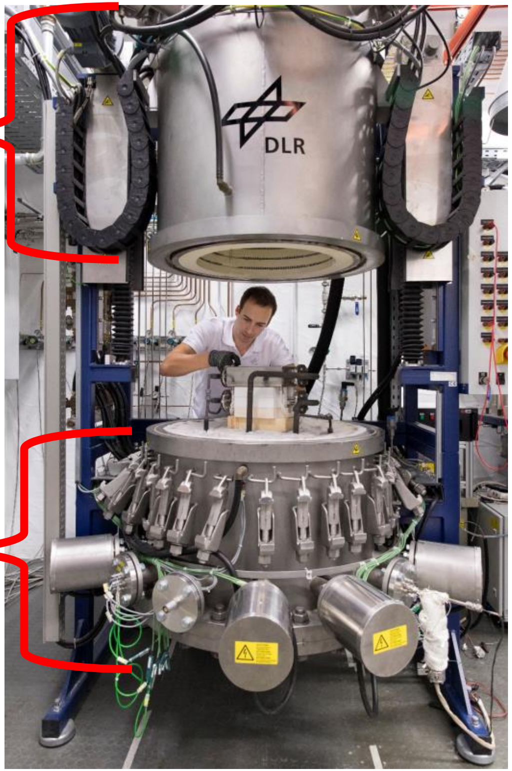
- *Operando* impedance measurements
- Online measuring of outlet gas composition
- Equipment for PMA available (REM/SEM/EDX)

Gas	Maximum capacity (slpm)
Air	140
N_2	20
O_2	15
5% H_2 in N_2	20
H_2	20
H_2O	13
CH_4	7.5
CO_2	9
CO	2.3

Upper Oven area
movable lid

ca. 710 mm Hub

Gas pre-heater
Installed as heater coil in the lower oven area



GALACTICA

GALACTICA

Test environment for SOC reactors with multiple stacks

- 40 kW_{el} in SOFC; 120 kW_{el} in SOEC
- Co-SOEC and rSOC also possible
- Temperature range 650 – 850 °C
- H_2, H_2O, CO_2, CO, N_2, CH_4, Air
- Steam supply up to 3.5 bar
- Production capacity ca. 2.3 kg H_2/h (85A) with 720 Cells reactor
- Electrochemical impedance analysis on SOC module level
- Online exhaust gas analysis
- Operation of stack modules with different cell concepts (ESC, CSC)

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GALACTICA

Gas Supply & Power Electronics

Fuel Type	Max Flow [kg/h]	Max.Flow [nlpm]	Tested Max.Flow [nlpm]	Capacity [kg]	Capacity [h]	Quality
H_2	7.0	1400	1400	200	26	N/A
CO	34.9	500	200	218	6	2.0
CO_2	44.1	400	350	900	20	4.5
CH_4	4.8	120	120	19.6	3.5	3.5
N_2	105	1500	1200	N/A	N/A	N/A
H_2O	50	1060	870	∞	∞	Purified
Air	500	7500	7000	∞	∞	Filtered

ID	Amount	Type	Max.Voltage [V]	Max.Current [A]	Max.Power [kW]
A	3	Bi-Directional	750	120	30
B	4	Bi-Directional	200	420	30
C	6	Thermal	500	150	7.2

TEMPEST

Modelling Framework TEMPEST

Modelling Depth and Examples

Reactor	Stack model	Loss mechanism model
Includes all stacks, manifolds and insulation	Detailed 1D+1D	Ionic conductivities, Butler-Volmer-equation, dusty gas model
Assumes all cells/stacks have the same boundary conditions	Simplified 1D+1D	Lumped ASR approach
Lumped reactors	0D/1D	

Plant simulations	SOC system simulations Focus: plant and control	SOC system simulations Focus: reactor and operation	SOC stack simulations	AEL system simulations

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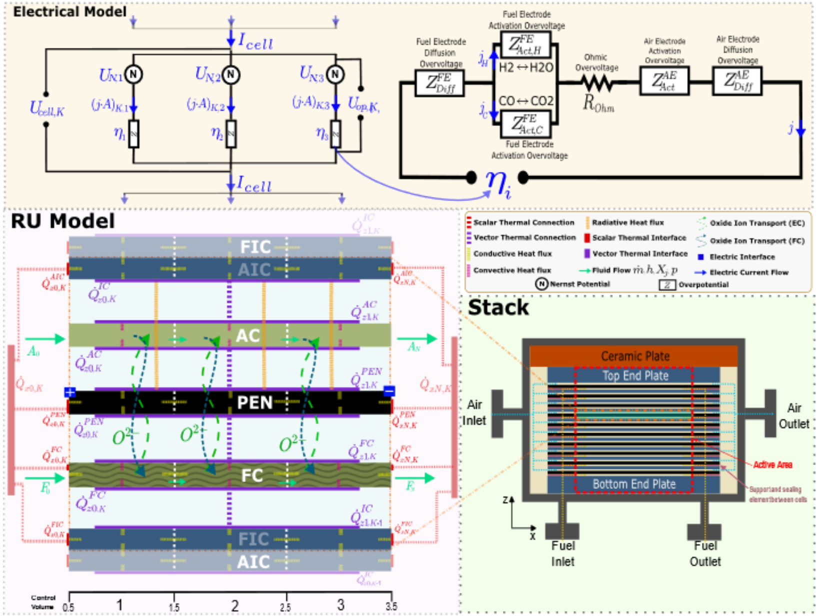
Modelling SOC Reactors

Detailed Model

- 1D+1D Transient model of SOC reactor
- Considers the main phenomena within cell
  - Heat & mass transfer, Electro- & thermo-kinetics
- Based on in-house and opensource libraries for reusable models
- Estimate behaviour with very fast solving speed
- Can include different numerical methods and accuracies (FVM, DG, flux functions …)
- Can be adapted for different cell designs



System of DAEs:

$$
\begin{cases}
\Delta x_i A \frac{d\bar{u}_i}{dt} = \dot{\boldsymbol{F}}_{i-\frac{1}{2}} A - \dot{\boldsymbol{F}}_{i+\frac{1}{2}} A + \dot{\boldsymbol{S}}_i \\
\dot{\boldsymbol{S}} = g(\boldsymbol{u}, t, \boldsymbol{\alpha}) \\
\dot{\boldsymbol{F}} = f(\{\boldsymbol{u}_i\}, \boldsymbol{\beta})
\end{cases}
$$

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Transient process system simulations

Example: Operation strategies for SOC reactors

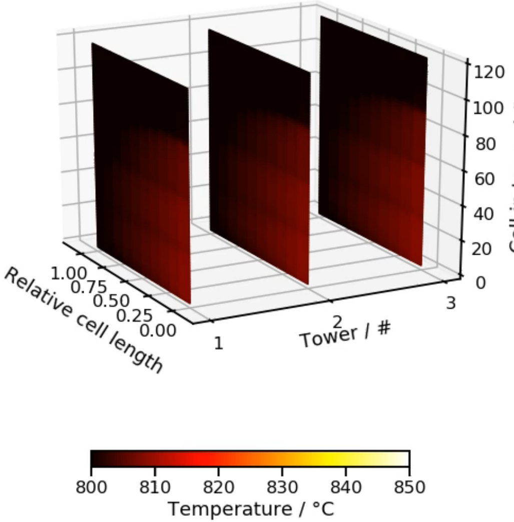
Development of operation and control strategies for H_2O- and co-electrolysis

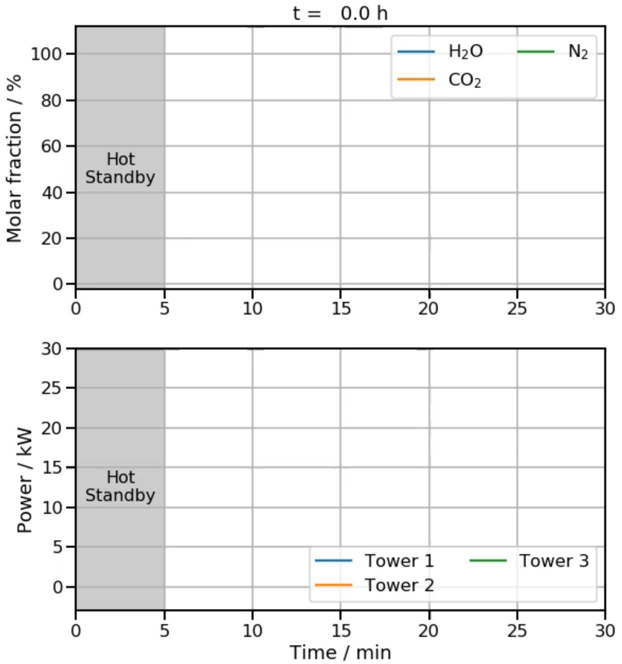
General goals

- Efficiency and robustness

Specific goals (examples)

- Fast and safe transients
- Reactions to incidents
- Outlet composition





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TEMPEST Use Cases

SOC

- Reactor-level
  - Cell technologies + operation mode
    - SOEL/SOFC/co-electrolysis/CO2-electrolysis
- System level
  - Operation and Control strategies
  - Interaction with BoPs (also for heat integration)
- Reactor and System
  - Safe scale-up considering thermophysical behaviour
  - Synergies with synthesis process (e.g. pressurised + recirculation)
  - Coupling with renewables
  - Powering electric drivetrains (ships, planes etc.)

AEL

- Reactor level
  - Hot spot prediction
- System level
  - Impurities management
  - Coupling with renewables
  - Thermal management
  - Field management(ships, planes etc.)

CELESTE

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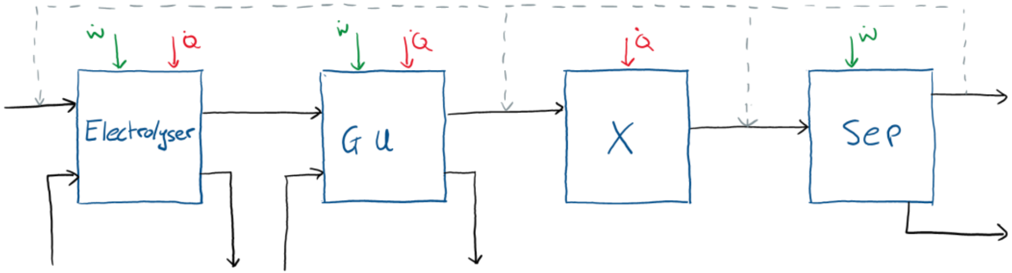
CELESTE

Conceptual System Design With Electrochemical Reactors

- PtX Systems have many configurations
  - Need a fast way to evaluate relevant scope



Conceptual design of Power ↔ X systems

- Create stationary process system models
- Analyse KPIs e.g. efficiency, yield, exergy

Tool: CELESTE

- Component oriented concepting framework written in Python
- Modular and integrable with other libraries

Use cases

Determine mass and energy balances

Harmful product formation study (i.e. carbon)

Exergy analysis

Off-gas recirculation studies

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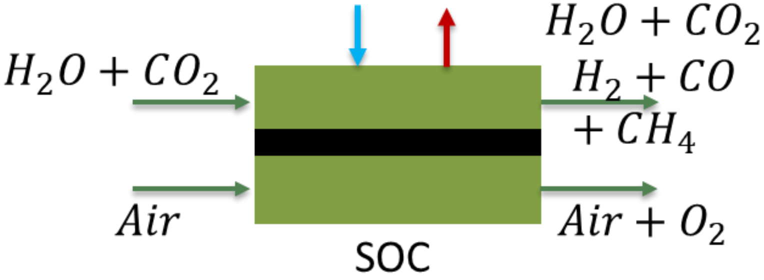
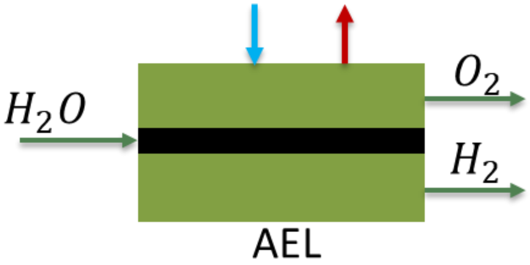
CELESTE

Stationary Electrolyser Models

- 0D Models
- Balance equations considering mass transfer and reactions + thermodynamics
- ASR model for voltage loss (experimentally derived)
- Additional models for heat losses can be added on top





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System Modelling Example

Basic Concept for >100MW Plant

- Simplified model for hybrid SOC-AEL H_2synthesis for NH_3 production
- Simplified air separation model (exergy based)
- Kinetic HB reactor model

- Optimiser used to solve inverse problem to find feed considions to meet desired operating point