SWITCH

The core of SWITCH system : challenges, performance and perspective.

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Zacharie Wuillemin & Florian Waeber

SolydEra

zacharie.wuillemin@solydera.com / florian.waeber@solydera.com

The core of SWITCH system.
Agenda

Introduction : Where we started …

- Context of the SOFC industry.

Challenges : What we achieved !

- Our first Stack scale-up and BoP development (design and construction).

- Automation (control and safety).

Performance : Proof of concept !

- Integration and testing (simulation, lab, real).

- Results and data worth sharing.

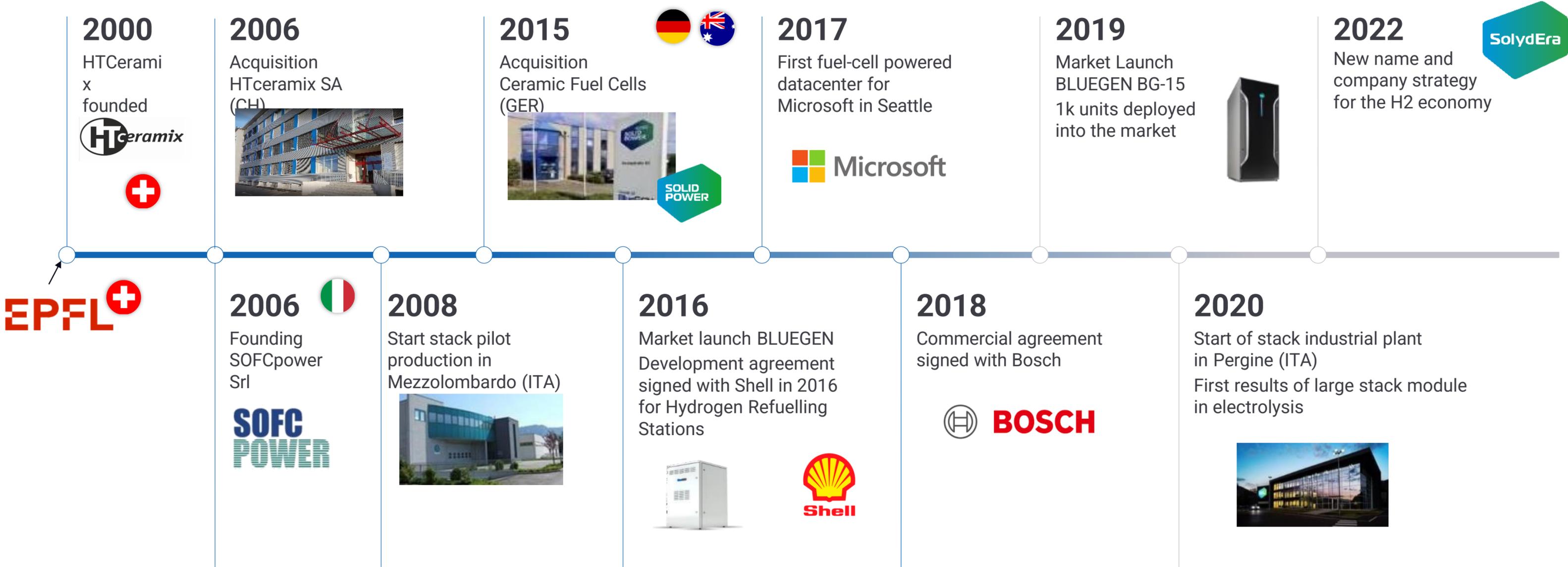Perspective : What's next ?

- *More insight during round table !*

Introduction

Where we started ...

SolydEra - More than 20 years of experience in SOC technology

2000
HTCeramix founded

2006
Acquisition HTceramix SA (CH)

2015
Acquisition Ceramic Fuel Cells (GER)

2017
First fuel-cell powered datacenter for Microsoft in Seattle

2019
Market Launch BLUEGEN BG-15
1k units deployed into the market

2022
New name and company strategy for the H2 economy

2006
Founding SOFCpower Srl

2008
Start stack pilot production in Mezzolombardo (ITA)

2016
Market launch BLUEGEN
Development agreement signed with Shell in 2016 for Hydrogen Refuelling Stations

2018
Commercial agreement signed with Bosch

2020
Start of stack industrial plant in Pergine (ITA)
First results of large stack module in electrolysis

SolydEra at a glance

Products

vertically integrated end-to-end fuel cell technology provider
ready to enter green hydrogen production

Stack → Stack Module → Fuel Cell module → System

Partners & Affiliations

BOSCH

Shell

Hydrogen Europe

Microsoft

EQUINIX

COGEN EUROPE

H2IT
ASSOCIAZIONE ITALIANA IDROGENO

Group structure

MEZZOLOMBARDO **ITALY**

R&D, Pilot Production

PERGINE VALSUGANA **ITALY**

Stack Manufacturing, Head Quarters

YVERDON **SWITZERLAND**

R&D Center

MELBOURNE **AUSTRALIA**

R&D Center

Facts & figures

3,000 units installed

Products sales in **22** countries

250+ customers

75M hours of operation

90 GWh energy produced

SolydEra's technology addresses both power generation & hydrogen production

GAS-TO-POWER

Highest efficiency of power and heat production using multiple fuels: natural gas, biogas, ammonia, LPG*, H_2 and H_2/ gas blends

POWER-TO-GAS

Highest efficiency in conversion of steam into H_2 using electricity for hard-to-abate industrial sectors and heavy-duty transportation
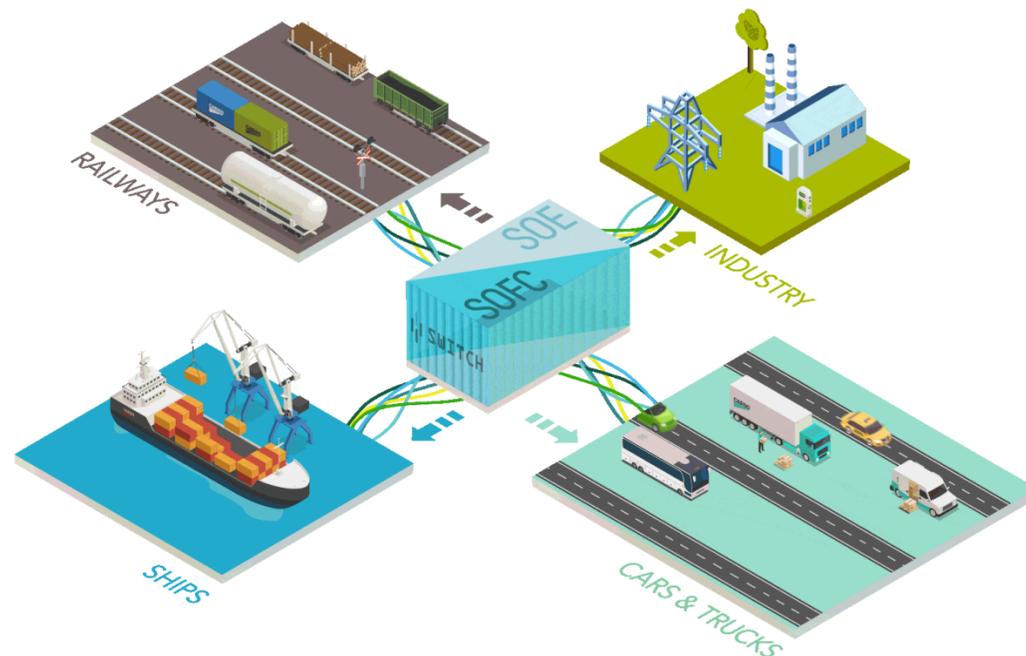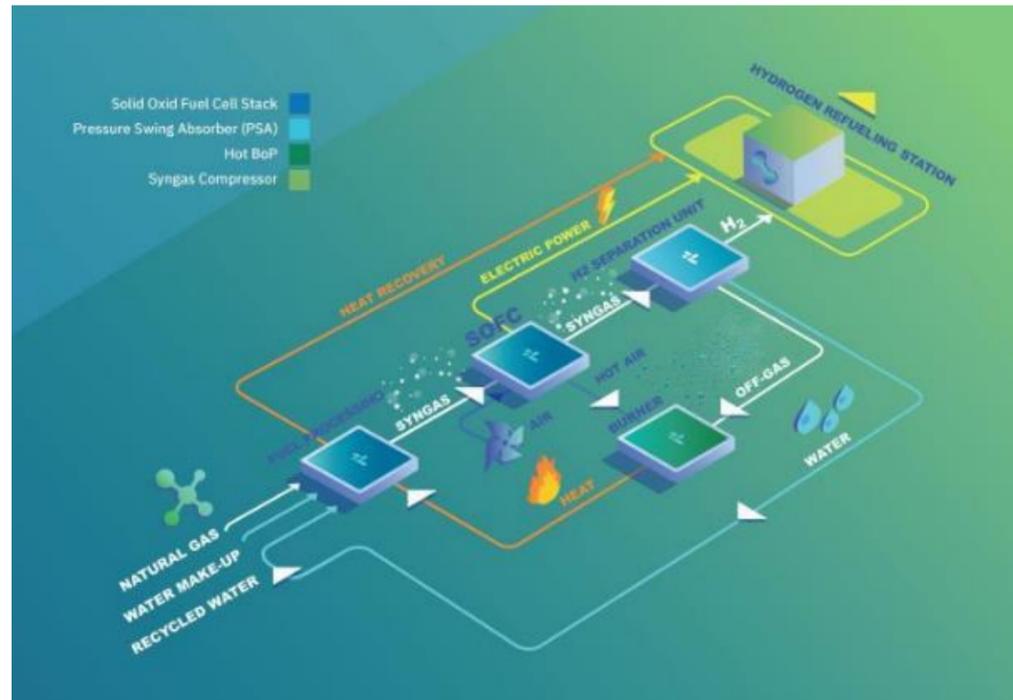
H_2

* LPG - Liquefied Petroleum Gas

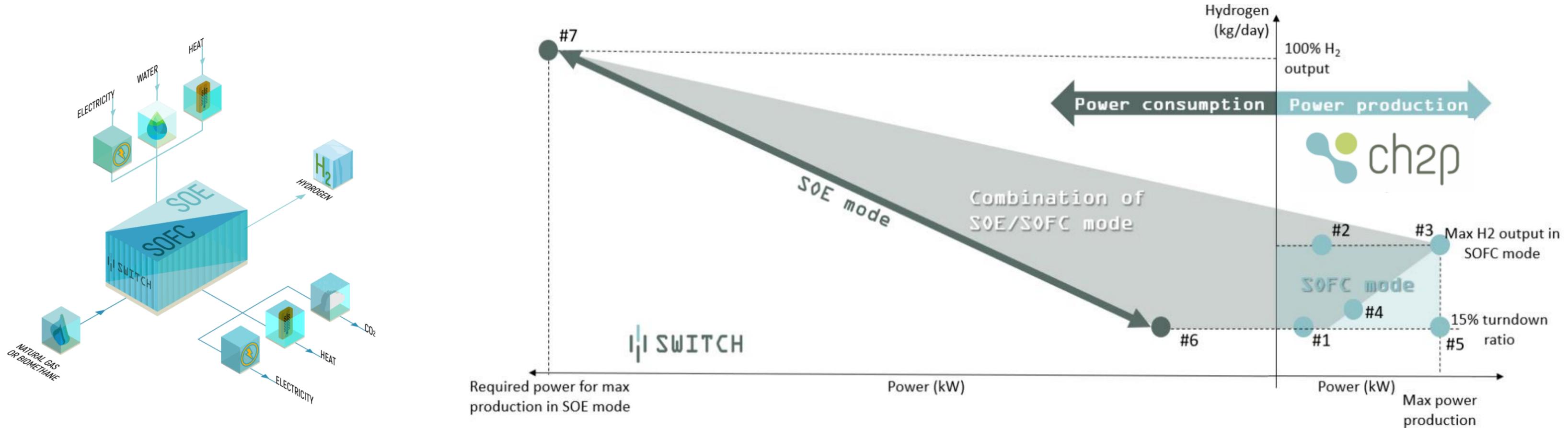# The SWITCH project

Challenge accepted!

Decentralized, reversible Hydrogen (Co-)Generation

- **Project targets**
- Original application: H2 refuelling stations
- Operation modes:
  - Hydrogen co-generation from NG/Biogas (CH2P)
  - Steam Electrolysis   (SWITCH)
- Technology: coupling of a (reversible) SOFC system with a PSA unit for gas cleaning
- Module specifications
  - **One single module** for 2 operation modes
  - **Hydrogen co-generation mode (CH2P):** production of 20kg H2/day + 25kWel
  - **SOE mode (SWITCH project):** min 50kg H2/day

Decentralized, reversible Hydrogen (Co-)Generation

- Module specifications
  - **One single module** for 2 operation modes
  - **CH2P mode:** production of 20kh H2/day + 25kWel
  - **SOE mode (SWITCH project):** min 50kg H2/day
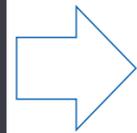
Challenges

What we achieved ...

Challenges
First challenge : the G8X stack

- **Scale-up of the G8 stack technology**
  - Same patented interconnect technology, but scaled up
  - Same cells
  - Same contact layers, etc.

    =

  - Same quality of fuel distribution and performance
  - Low cost scale-up (no additionnal manufacturing quality requirements)

- **Designed for tight integration in multi-stack systems**

G8 stack core

G8X stack core

Challenges
2nd challenge : the Large stack module (LSM) Generation 1&2

Large Stack Module
32 kW$_e$ SOFC/100 kW$_e$ SOE

LSM-32

G8X stack
(8 kW)

LSM – SOE Hydrogen Production Performance

Generation 1 :
→ **25kW SOFC / 75kW SOE**
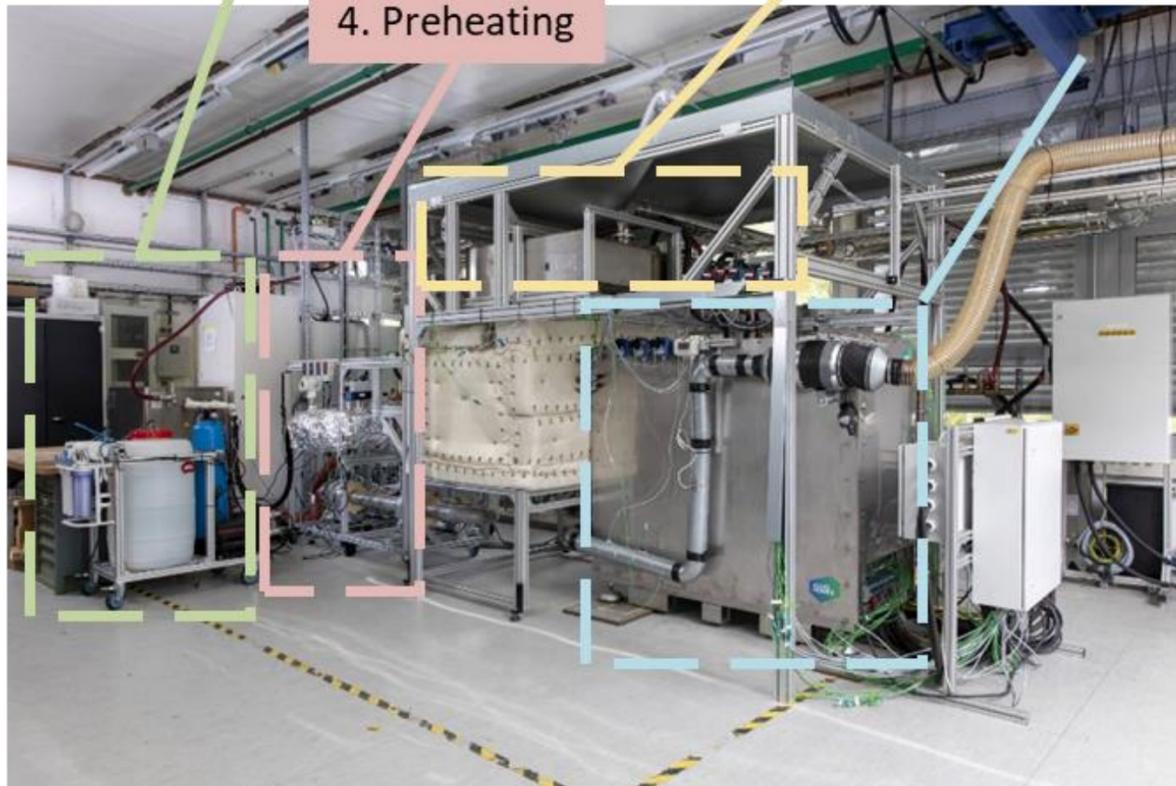
Generation 2 :
→ **32kW SOFC / 100kW SOE**

2ⁿᵈ challenge : the Large stack module (LSM) Generation 1&2

1.,2.,3. Air, gas, steam supply
4. Preheating
6. Cooling and exhaust

DLR

Galactica test station @ DLR

LSM – SOFC & SOE testing at DLR Stuttgart

Test campaigns

- Initial test campaign for design validation

- Second test campaign to investigate reversible operation
  - 100 days of testing
  - SOFC mode operation H2/N2
  - SOE testing
  - SOFC mode operation SMR (simulated)
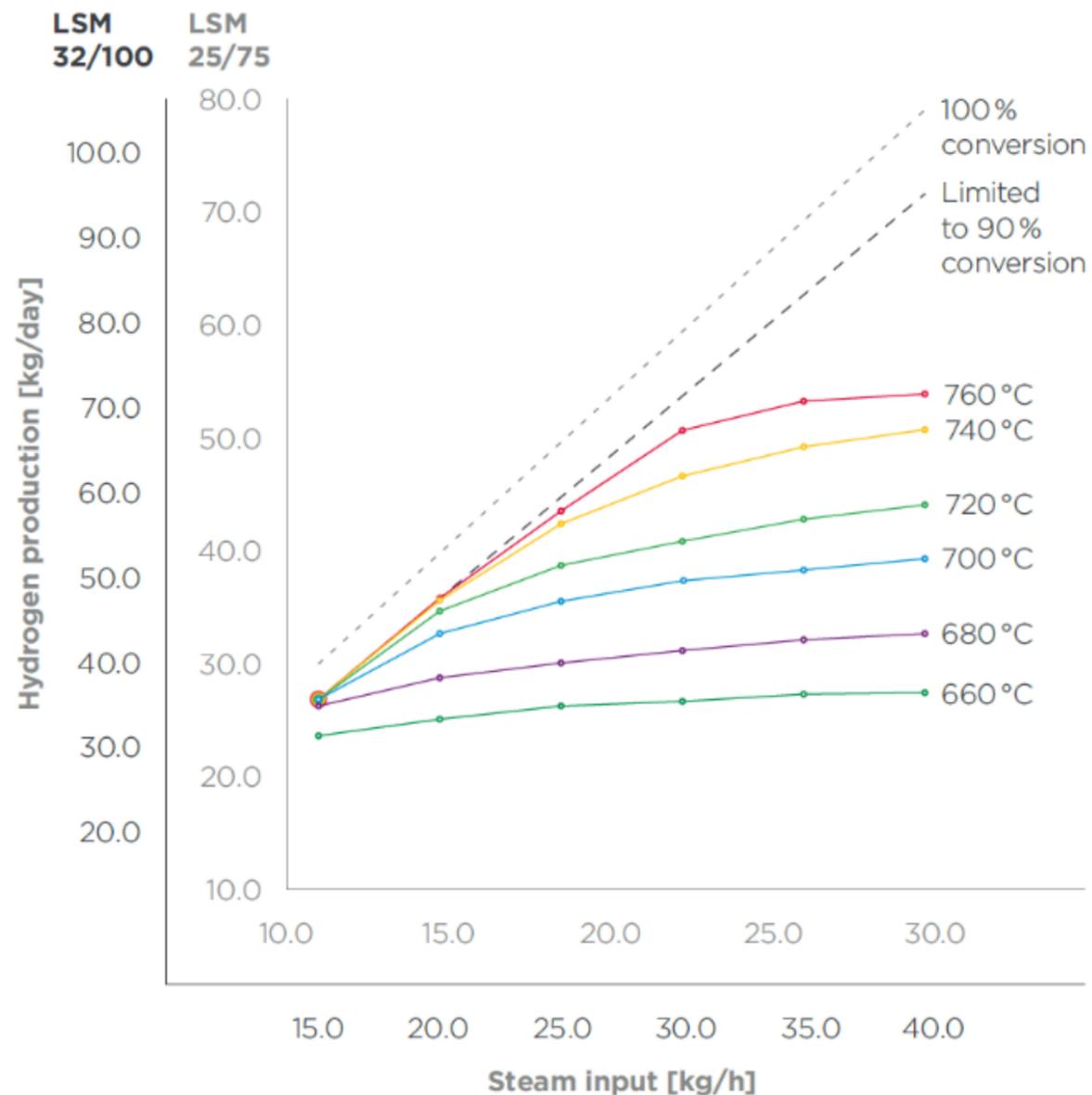 - CH2P mode testing (hydrogen co-generation)

ch2p   SWITCH

2nd challenge : the Large stack module (LSM) Generation 1&2

LSM – SOE Hydrogen Production Performance

Experimental data of H₂ production output of a 25/75 kW LSM and corresponding extrapolated data of a 32/100 kW LSM in SOE vs steam input.

Data Courtesy of DLR (Stuttgart, GER)

SOE Performance Map

- H2 production tested as function of steam flow and temperature

- Artificial limitation at 90% steam conversion

- Operation at thermoneutral voltage unless reaching the 90% steam conversion limit

- Maximum hydrogen production 53kg/day @ 76.8kW
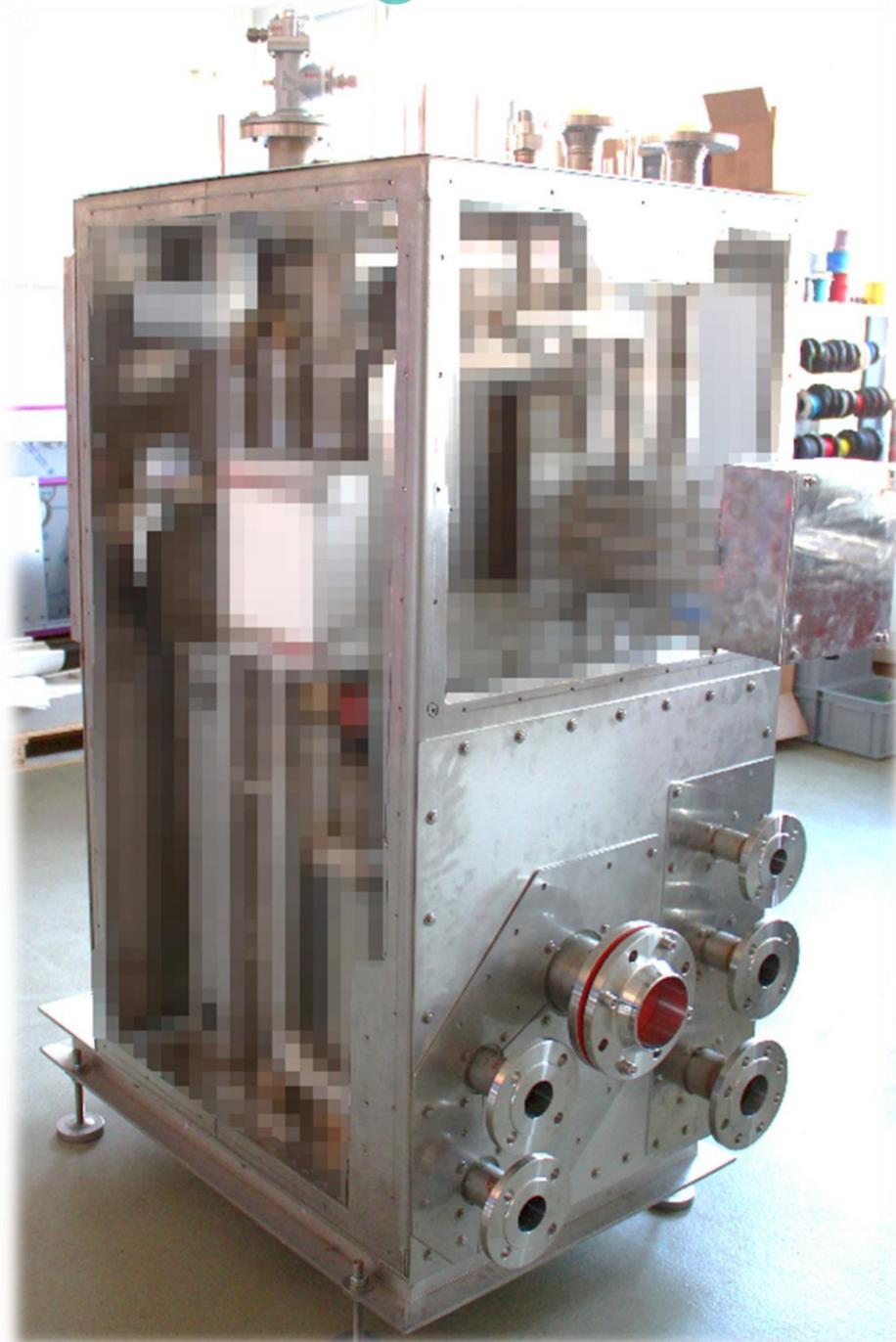
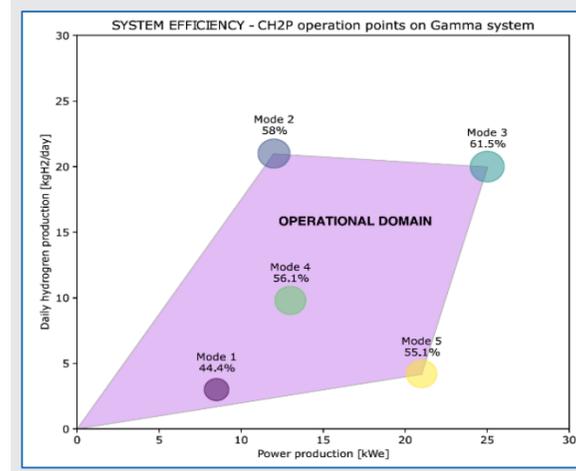- > 65kg H2/day expected with an LSM32/100

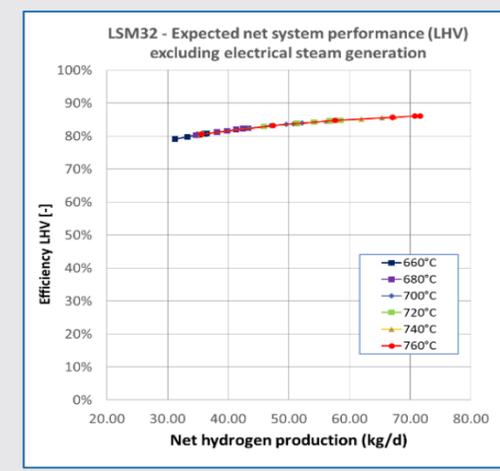60-layers stacks (now 80)

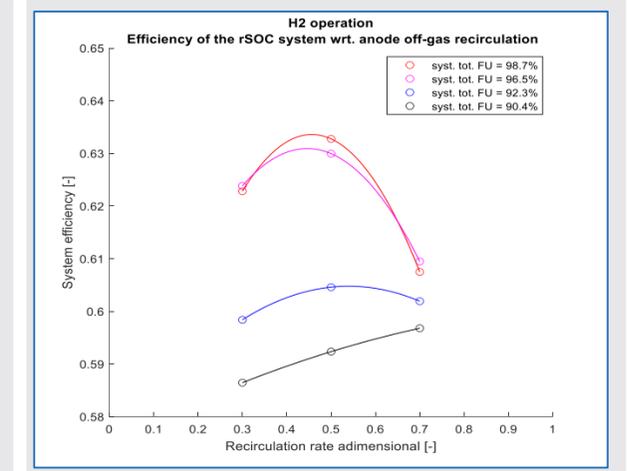# 3rd challenge : the Hot Balance-of-Plant (HotBoP)

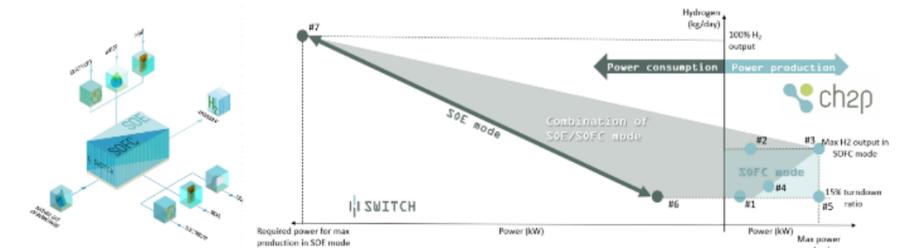Hydrogen co-generation using NG/Biogas

Steam electrolysis

Power generation with H2

Multi-purpose BoP

- High efficiency recuperator

- Controllable reformer

- Controllable WGS

- Afterburner and electrical heater (SOE)

- 4 operation modes
    Power generation H2
    Power generation NG
    Hydrogen co-generation
    SOE

4th challenge : automation and safety

- Full safety analysis (HAZOP/FMEA/LOPA) was performed.
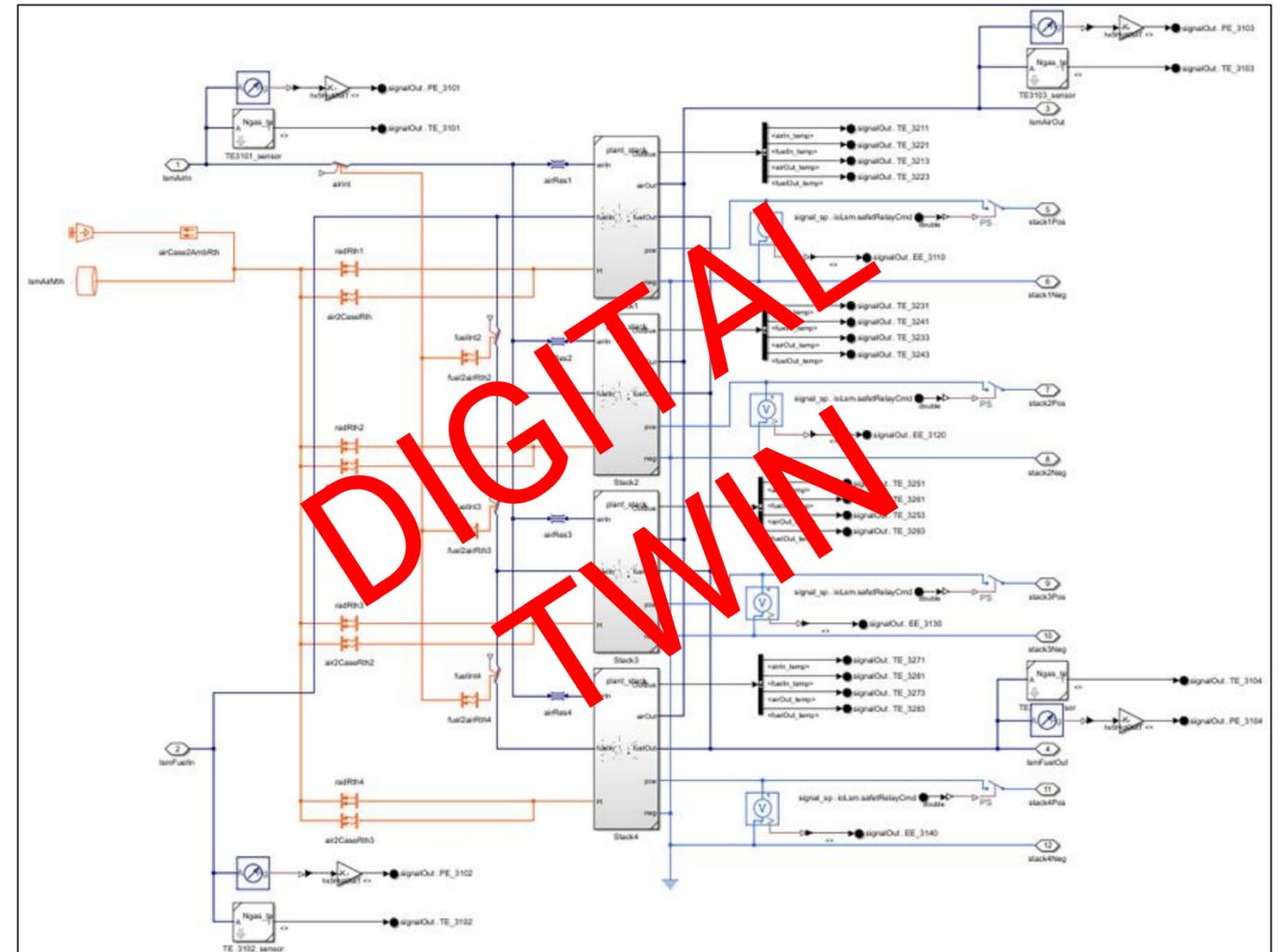- Recommendations identified. -> How to put them in place?

- How to test fault detection functions?
- How to train supervisory staff / operators?
- How to test system behaviour in dangerous situations?

- Development of a digital twin
- Training of control system using dynamic model
  - Pre-validate safety functions ✅
  - Pre-validate BPCS ✅

DIGITAL TWIN

5ᵗʰ challenge : process integration with Compression + PSA
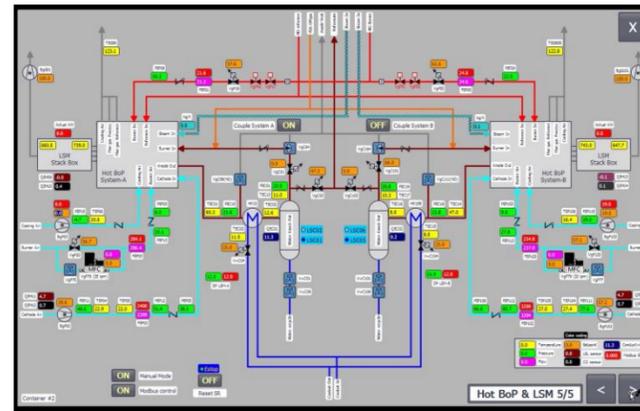
Process integration challenges

- Control software and state machines

- Safety concepts and systems

- Intricate perimeters due to initial project definition

- Compression
  - Two types of compressors
  - Intake pressure control
  - Fuel cell back-pressure control

- PSA
  - Purification at variable loads and with different mixtures
  - Yield optimization
  - Composition optimization

- PSA return to afterburners

- Auxiliary systems

- Power distribution

Container integration
On site installation
IO checks
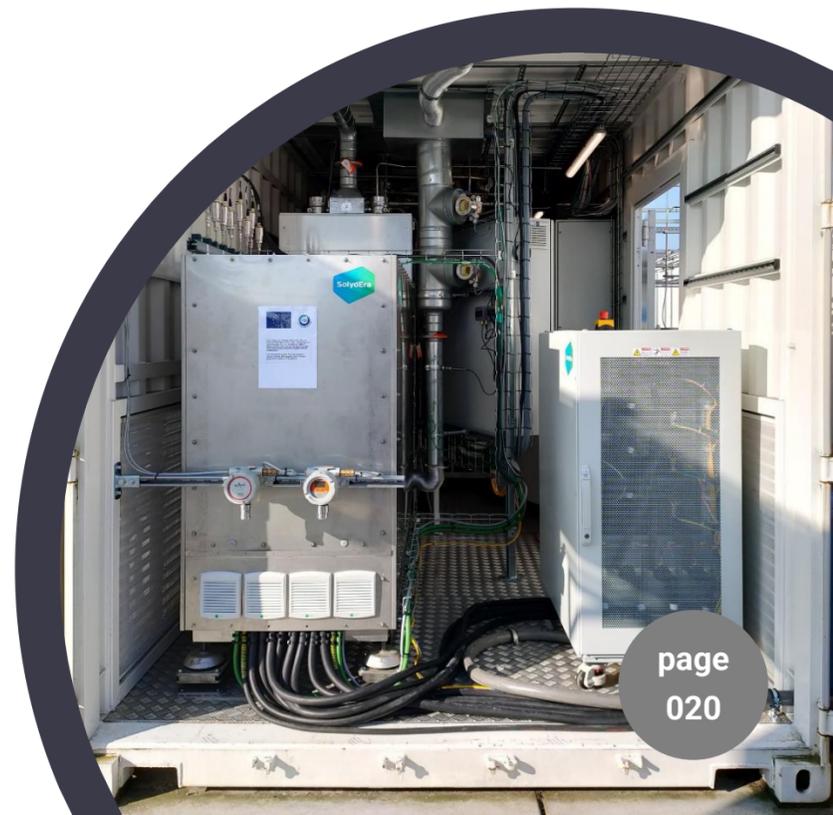
Results

Prototype testing and validation

SWITCH Module – Reversible Power & Electrolysis Testing (SolydEra labs)

Lab testing at SolydEra

LSM – SOE Hydrogen Production Performance

Experimental data of H₂ production output of a 25/75 kW LSM and corresponding extrapolated data of a 32/100 kW LSM in SOE vs steam input.

Data Courtesy of DLR (Stuttgart, GER)
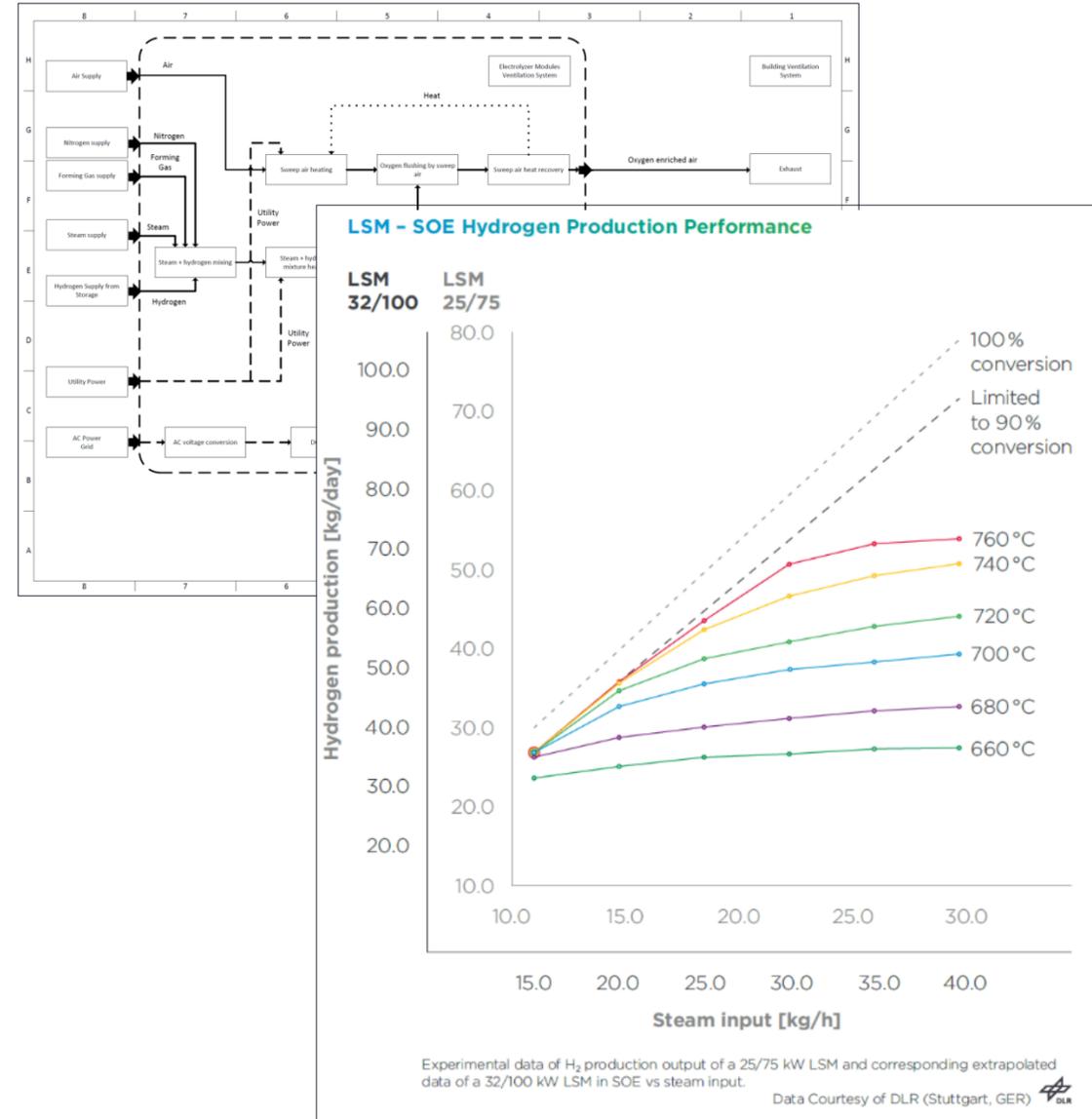
- Validations tests ongoing
  - System
  - Control
  - Stacks
  - Safety
  - Compression/purification integration
- Operation modes
  - SOE
  - SOFC-H2
  - SOFC-NG
  - H2 co-generation
- Detailed investigations
  - Operation above 90% steam conversion
  - High fuel-utilization in SOFC mode
  - Transient behavior
- System deployment and integration
  - 2 systems at Hygear (NL)
  - *PRHYSM project*
  - *GreenHub project*
  - *24/7 ZEN project*

SWITCH Module – Reversible Power & Electrolysis Testing (SolydEra labs)

Stack Electrical Efficiency (LHV) - H_2
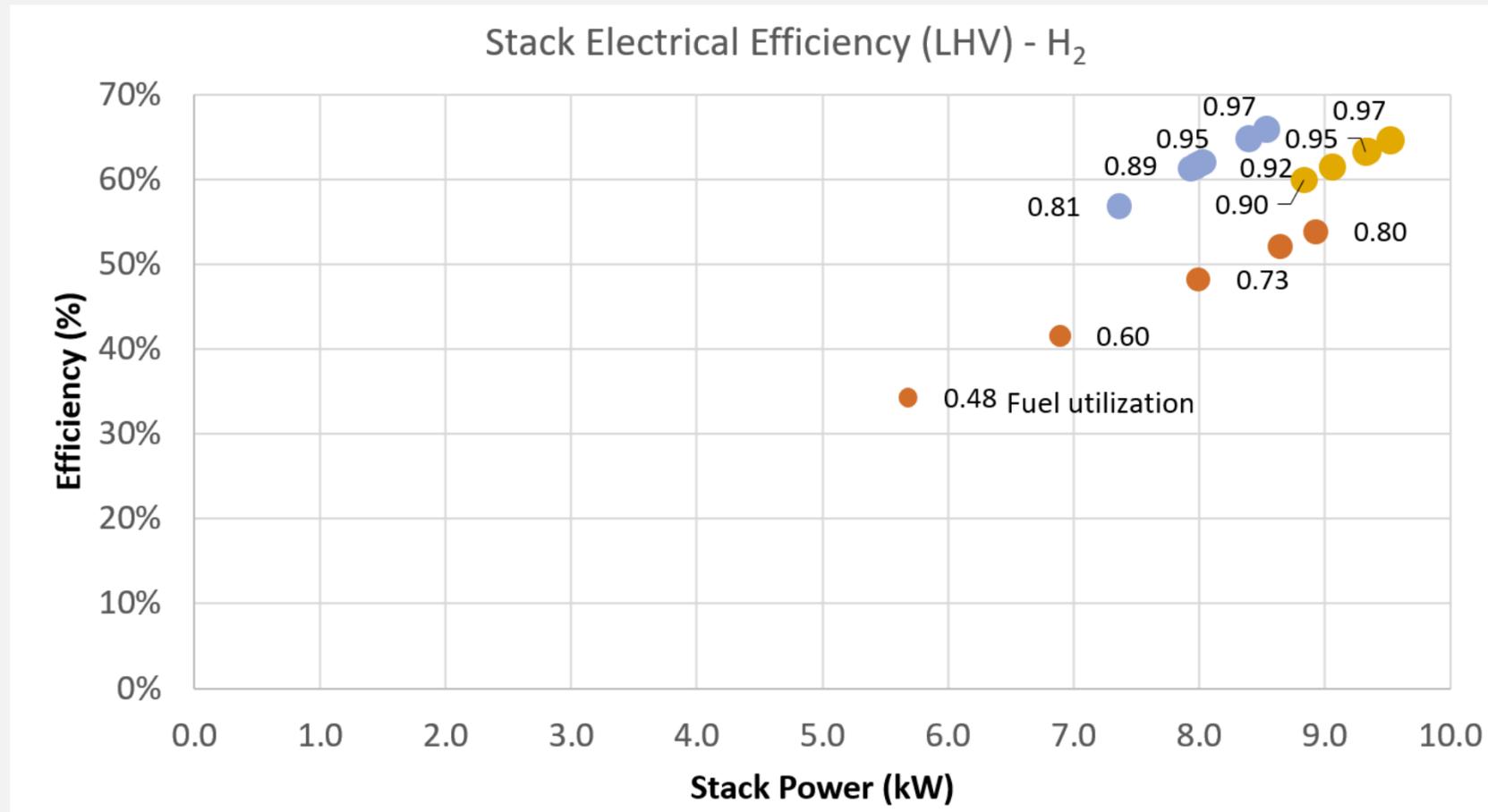
Power generation with H2: optimization of efficiency and benchmarking

High-performance power generation

Goal:
- Maximize electrical efficiency with H2 as fuel
- System benchmark
- Stack benchmark
- Reduction process air flow

Experimental setting
- SolydEra Labs (CH)
- rEMX-NG module
- H2 operation with recirculation
- G8X stack (80 layers)

Results
- Electrical efficiency (process) up to 67%
- Fuel conversion up to 97%
- Increased power from nominal 8kW to 9.5kW

SWITCH unit : Full Prototype Testing at Hygear

After years of team work…
…Successfully Started!

System testing

- Plant integration and automation
  - Testing of automation & safety
  - SOFC and PSA automation & synchronisation
  - IO checks
  - PID tuning

- PSA
  - Compressor tests
  - Coupling tests
  - Optimization of purification and yield

- Operation modes
  - SOE tests (full load, part load, dynamics)
  - Power generation (natural gas)
  - Hydrogen co-generation

- Overall commisionning time: 3 weeks

SWITCH unit - Testing phases - overview
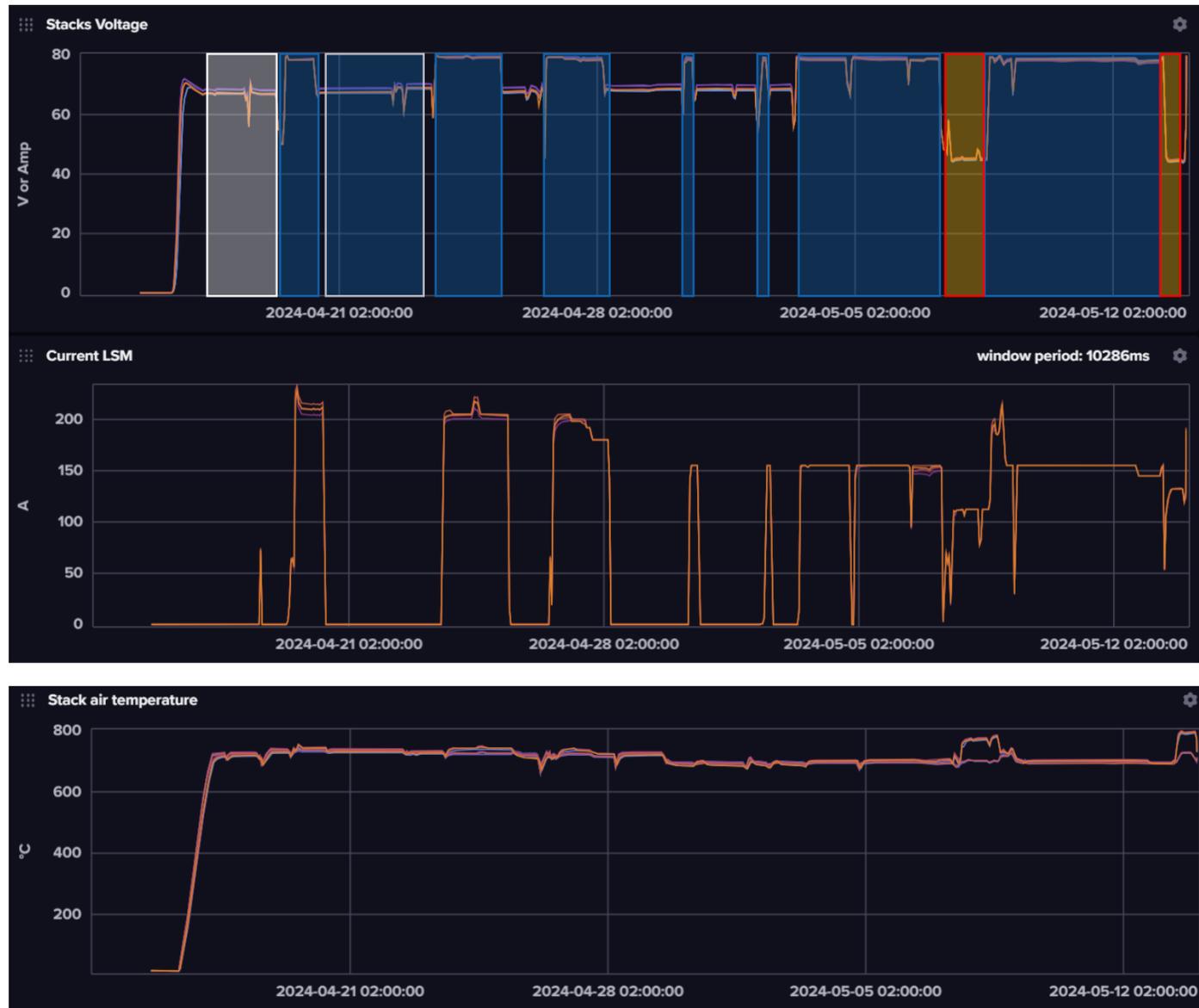

System testing

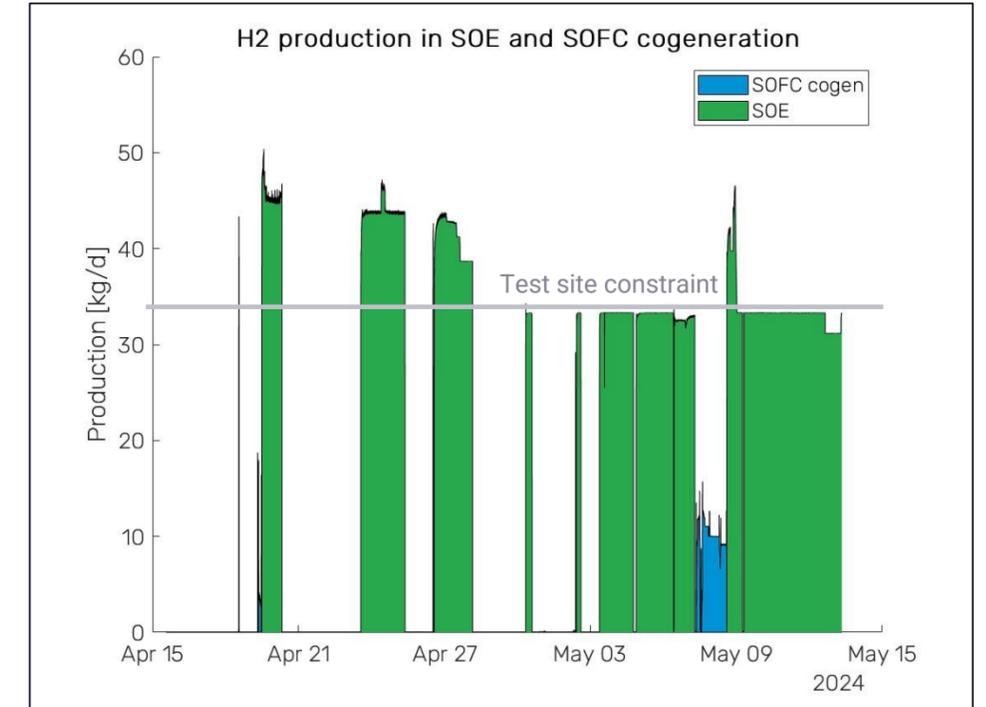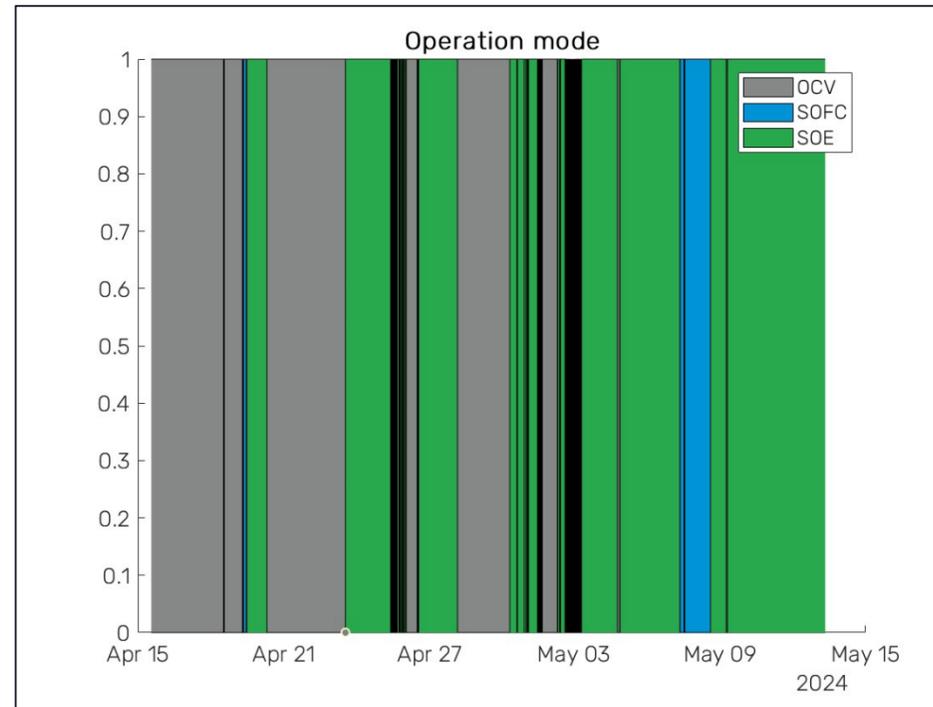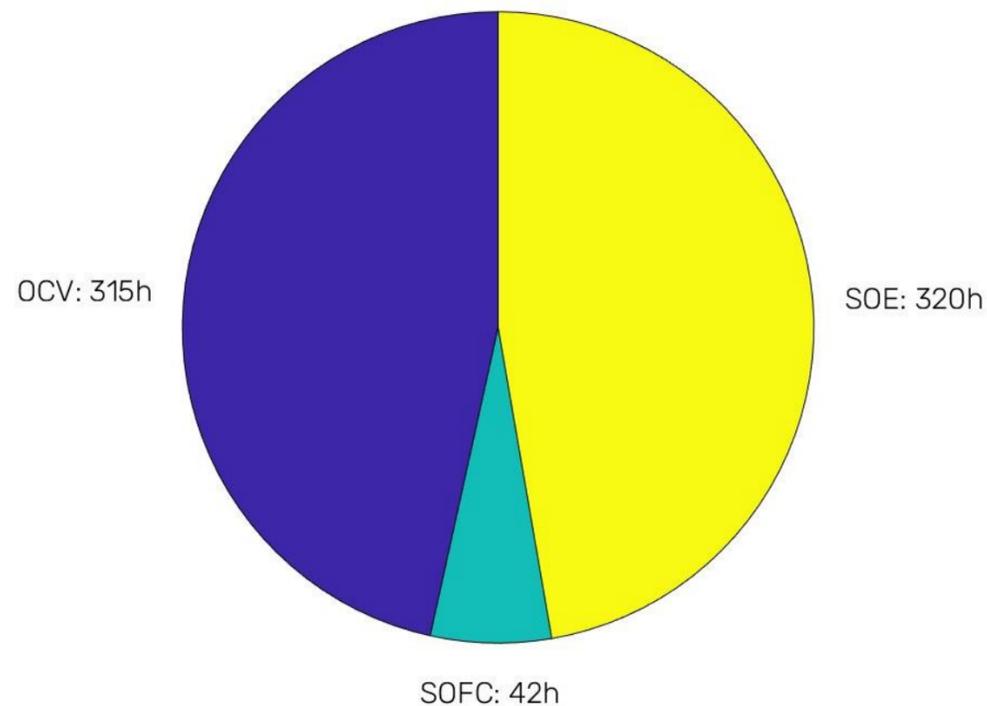- Plant integration and automation
  - Testing of automation & safety
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- PSA
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- Operation modes
  - SOE tests (full load, part load, dynamics)
  - Power generation (natural gas)
  - Hydrogen co-generation

- Overall commissioning time: 3 weeks

Results – Testing campaign in industrial setup @HyGear

OCV: 315h

SOE: 320h

SOFC: 42h

Operation mode

OCV / SOFC / SOE

H2 production in SOE and SOFC cogeneration

SOFC cogen / SOE

Production [kg/d]

Test site constraint

- From mid-April to mid-May 2024
- Industrial setup: HyGear premises
- 1 month operation
- *Continuous operation limited at 50kW max (infrastructure)*

H2 produced during the tests:

- ~300 kg H2 produced in SOE
- ~7.5 kg H2 produced in COGEN

SWITCH unit – Full Power SOE

Full power SOE

- 1st Generation LSM (4 stacks of 60 layers, GEN1)

- Target max power reached: 75kW @ thermoneutral voltage

- H_2 production 2.08kg/h

- Production deviation among stacks < 1.5% at full load

- Efficiency : less than 40kWh/kg H_2 at the nominal production level

- Performance in line with models and expectation

- Validation for next-generation EMX module
  - similar auxiliary losses for 66% more production
  - 37-39kWh/kg target
  - concept validation

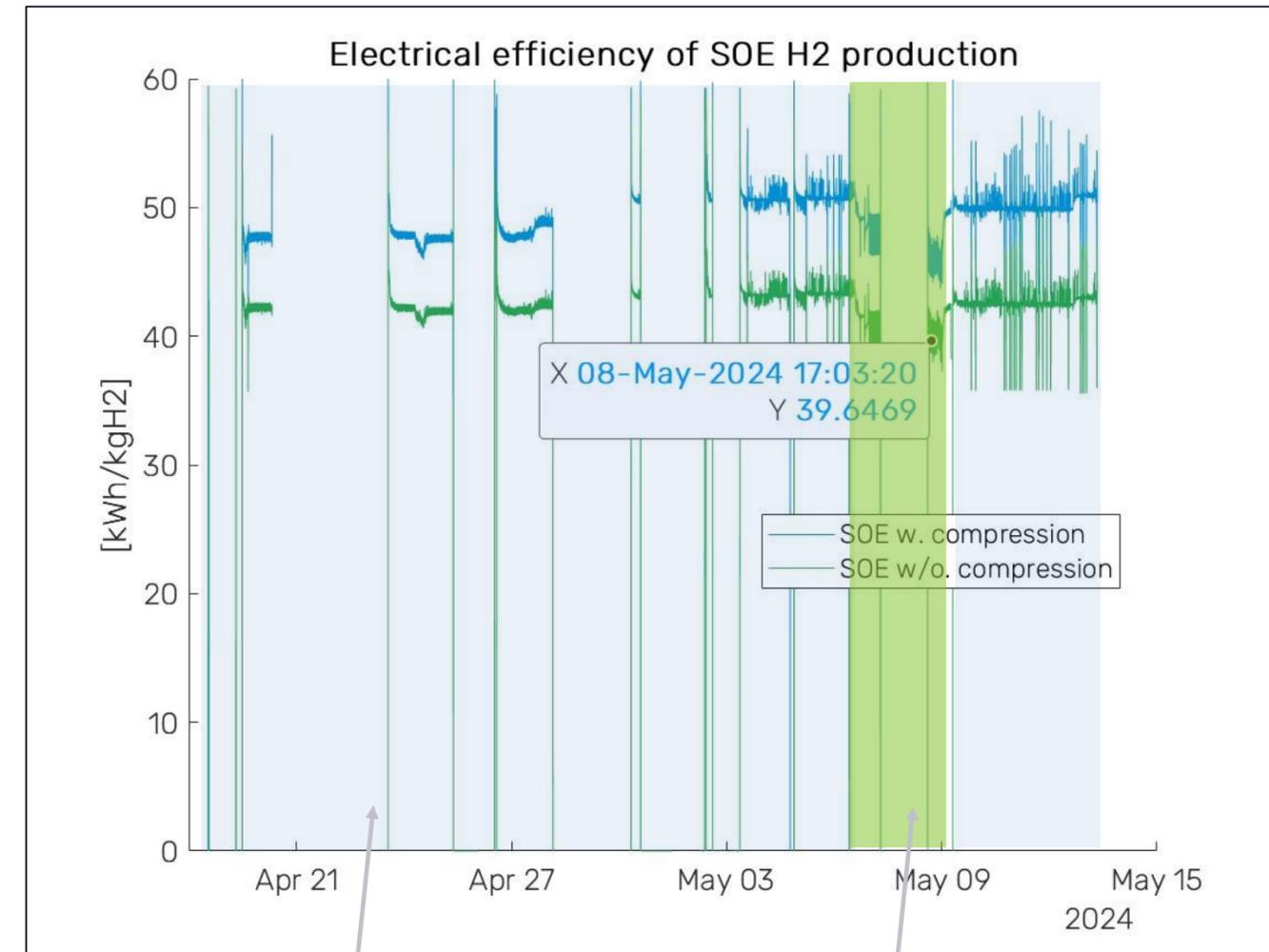# Results − Hydrogen (co-)generation
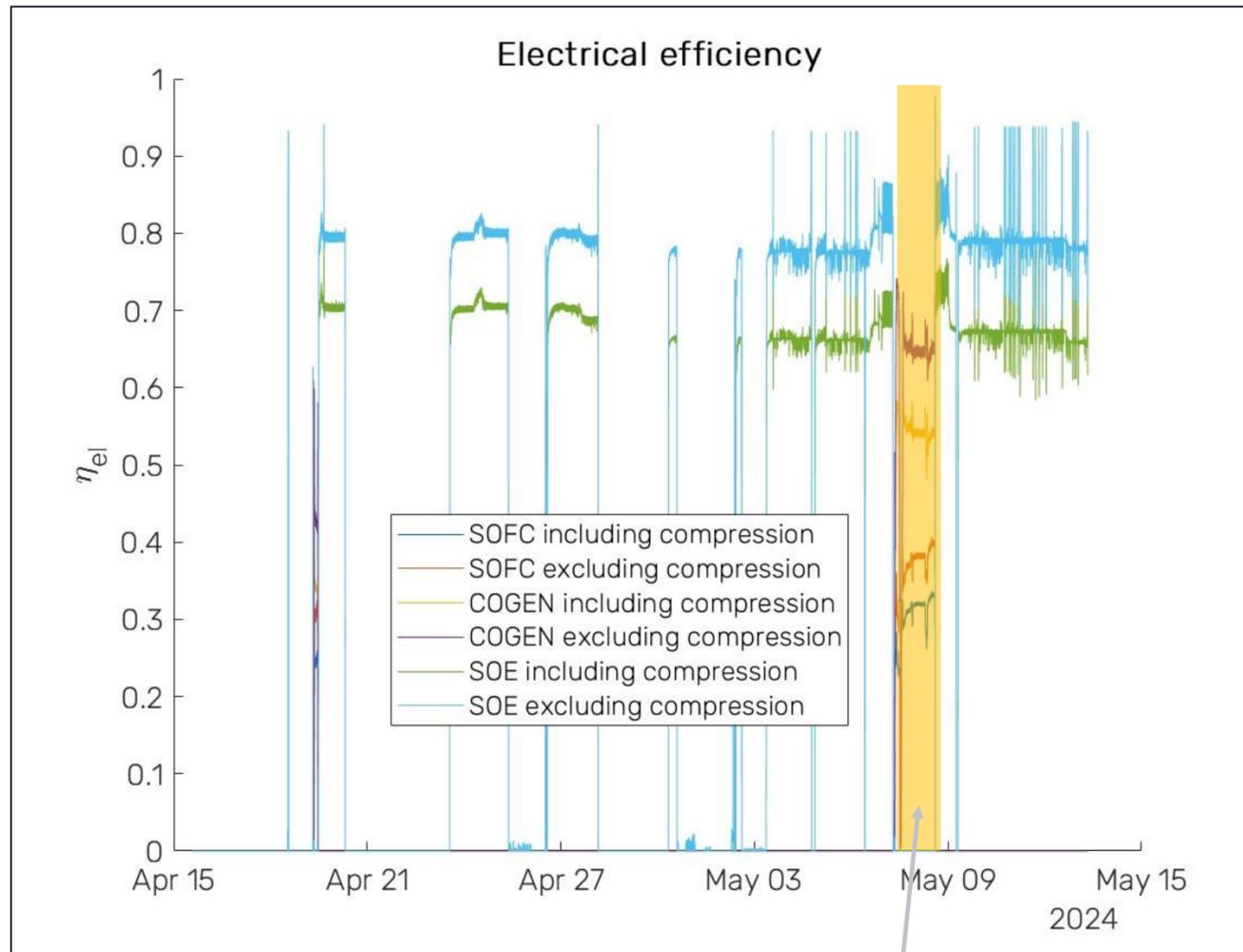
Hydrogen Cogeneration @ 20kW

Cogeneration efficiency > 60%

Targets reached for 75kW LSM
Higher efficiency
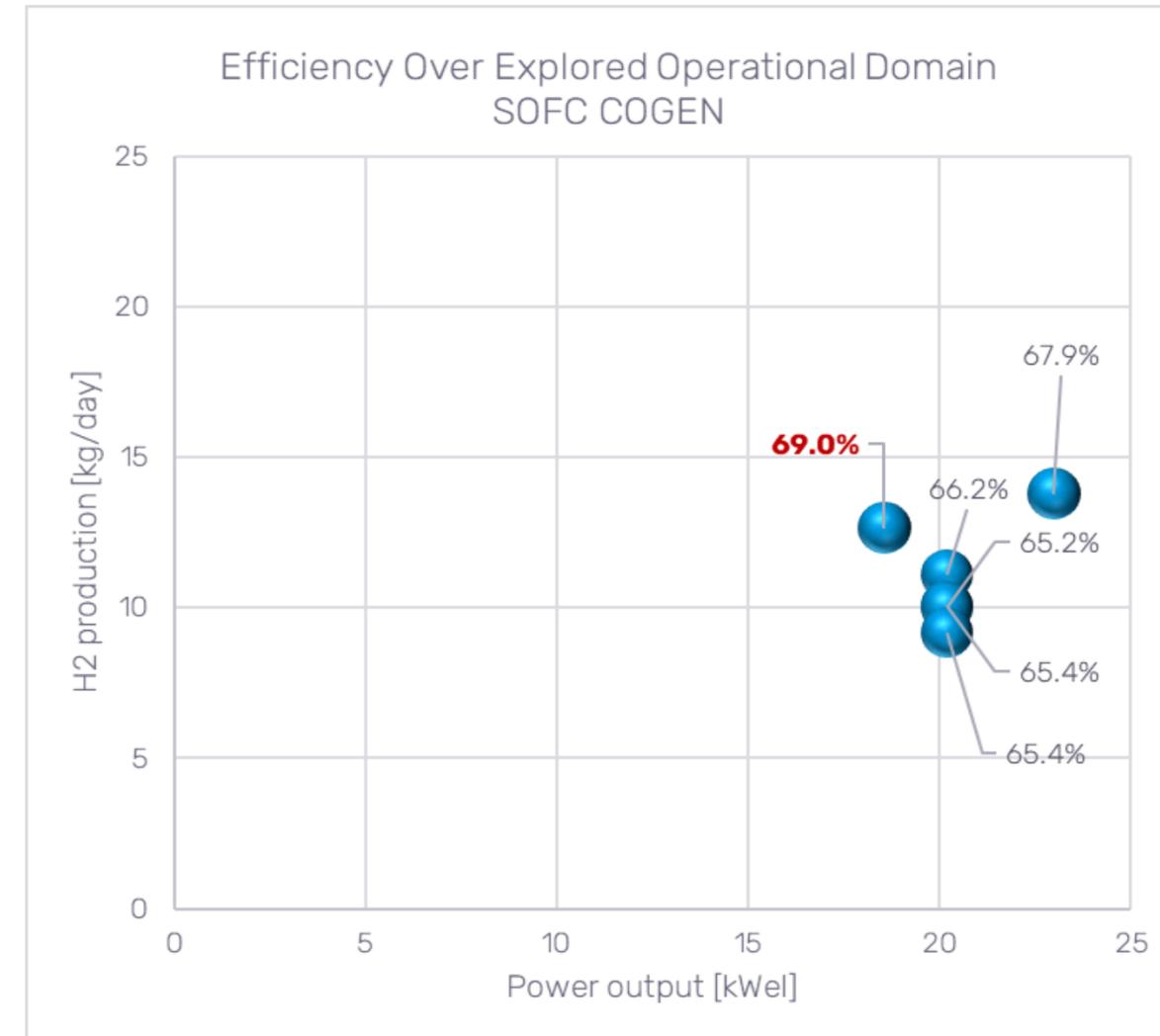
SOE part load

SOE full load

Specific power
- <40kWh/kg SOE
- <50kWh/kg purified
  and compressed

Results – Hydrogen (co-)generation

Operation map
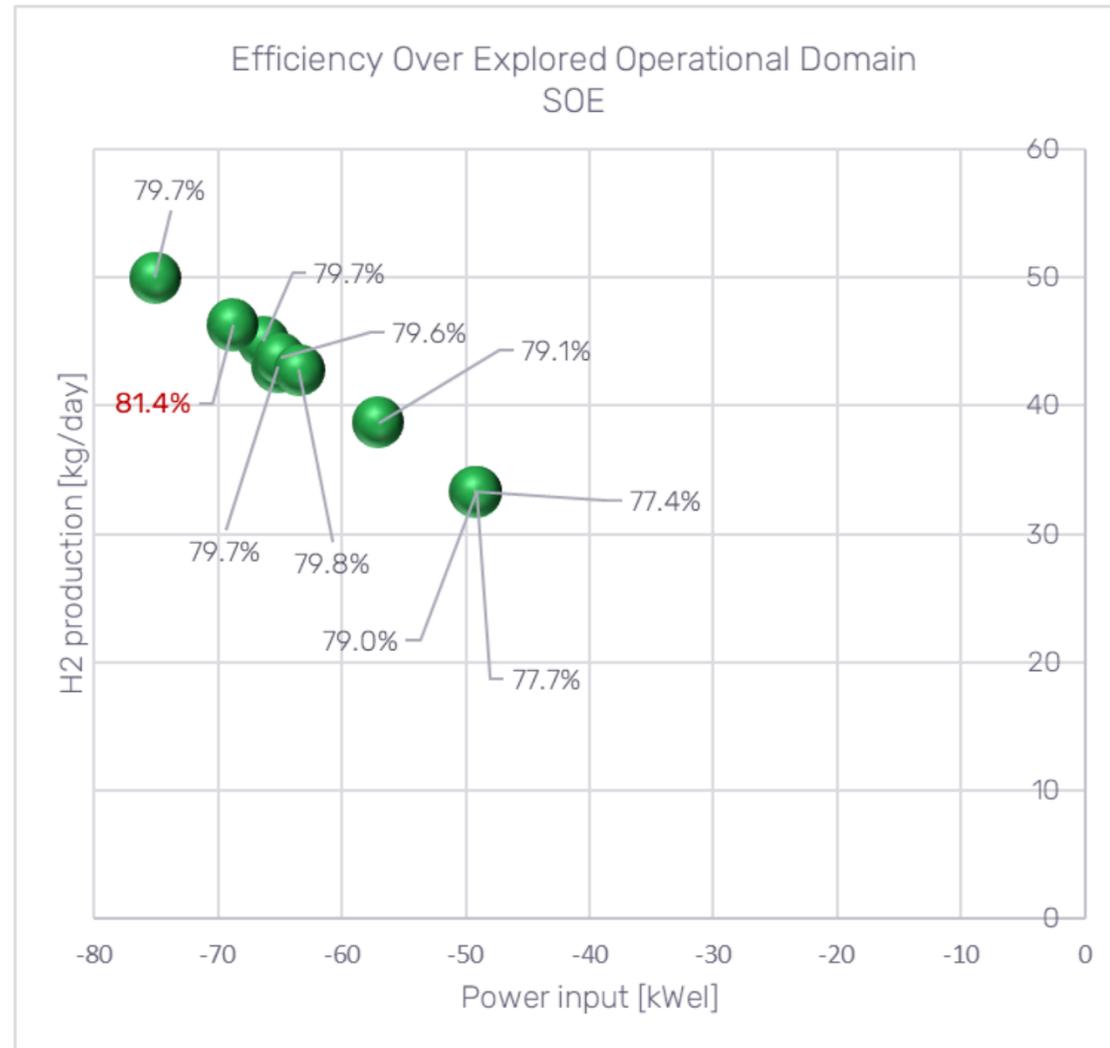
SWITCH unit - Fast switching tests (Power Generation to SOE)

Fast switching

- Fast switching from power generation (natural gas) to SOE

- Overall switching time < 16 minutes

- SOE production ramp-up:
  - < 1 minute to thermoneutral voltage and initial production level
  - Final ramp-up to full production (increase of steam feed), here within 7 minutes

- Smooth thermal gradients in stack

SWITCH unit - Modulation Strategies – Fast modulation
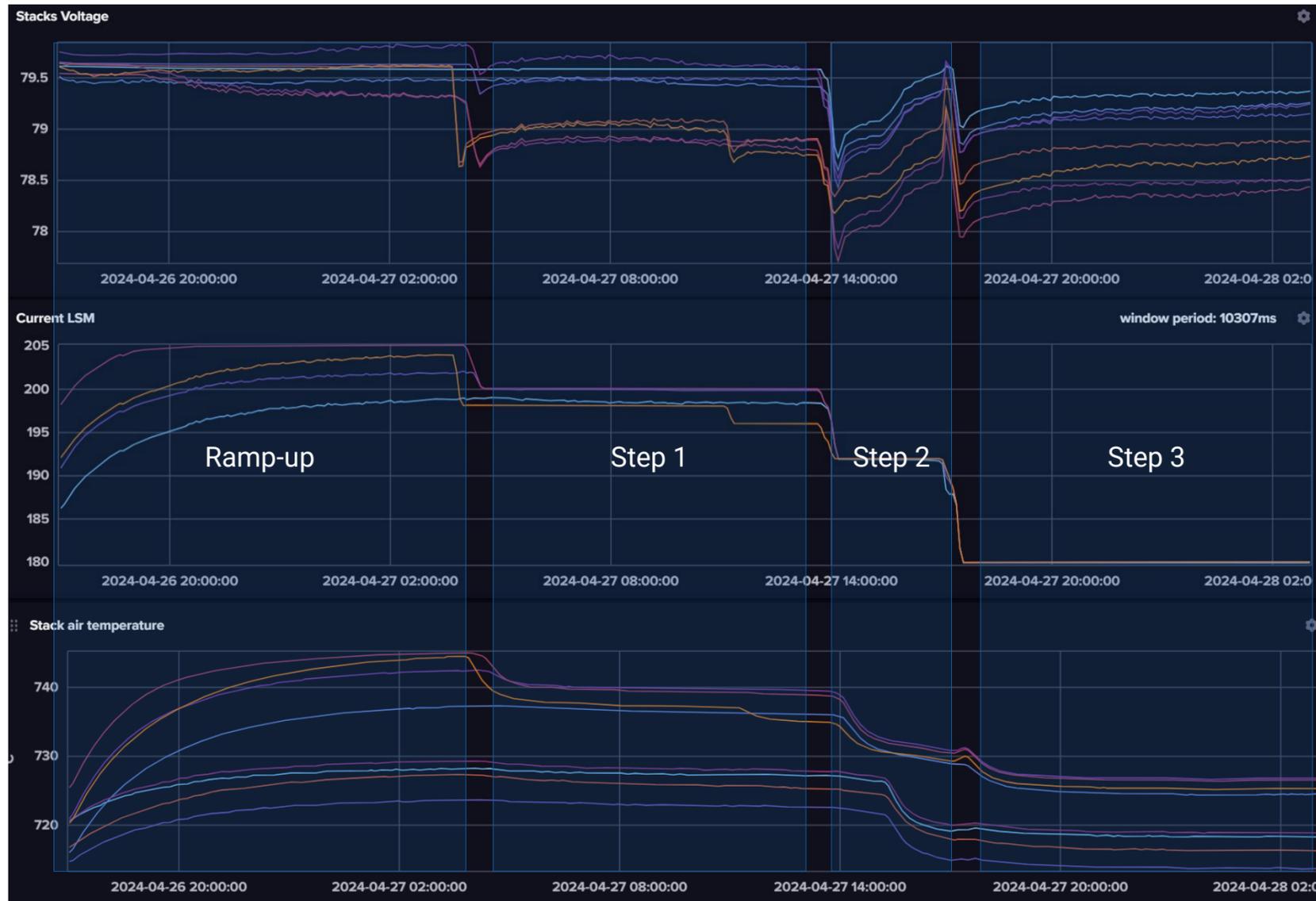

Module Enabling / Disabling

- Fast power modulation at Array level (module ON/Stdby)

- All stacks synchronized

- Rampup/down < 1 minute, coupled to compressor

- Steam-limiting ramp-down at thermoneutral voltage

SWITCH unit - Modulation Strategies – Slow modulation

Auto-balancing control

- Current-limit control method

- Current step-down
  - Initial voltage drop to endothermal operation (eff > 100%)
  - Induced stack cool-down
  - Voltage increases automatically back to thermoneutral
  - Temperature stabilization

- Ramp-up
  - Current goes immediately to point defined by voltage, tempeature and steam flow
  - Current ramp-up controlled by steam supply and temperature
  - Moderate exothermal operation speeds-up the production increase
  - System stabilizes at temperature dictated by desired current

SWITCH unit - Product quality & delivery pressure

- ## Purity

  - N2<50ppm

  - CO below detection limit

  - O2 below detection limit

  - No water

  - Yield SOE mode > 80% (PSA)

  - Product pressure: up to 8barg
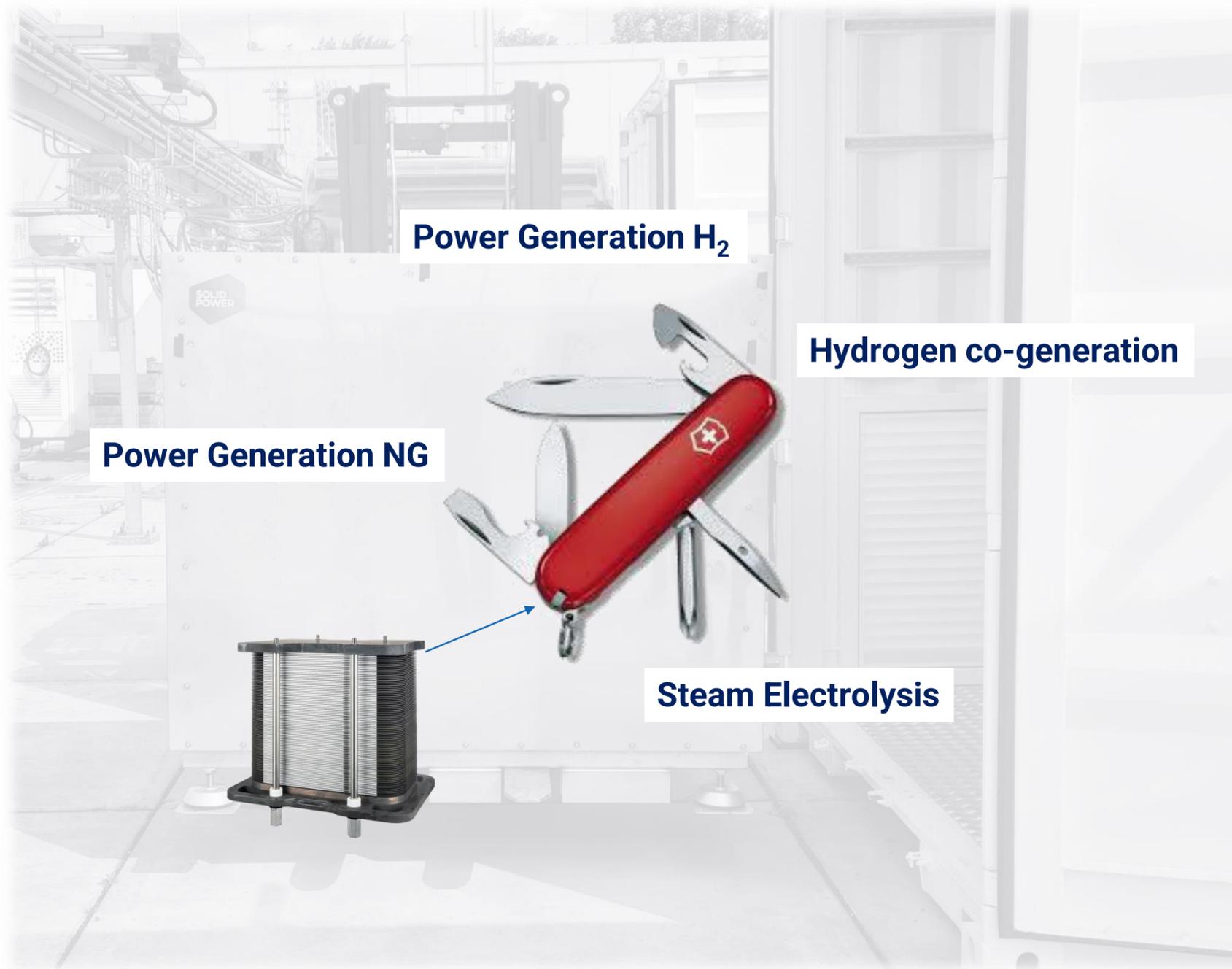
Conclusion

and outlook

Decentralized, reversible Hydrogen (Co-)Generation

Power Generation H$_2$

Hydrogen co-generation

Power Generation NG

Steam Electrolysis

- **Project achievements**
- New stack platform for industrial applications
- Full-reversible system with **4 operation** modes
    - Power generation H2
    - Power generation NG
    - Hydrogen co-generation
    - SOE
- Successful integration in compression + purification system
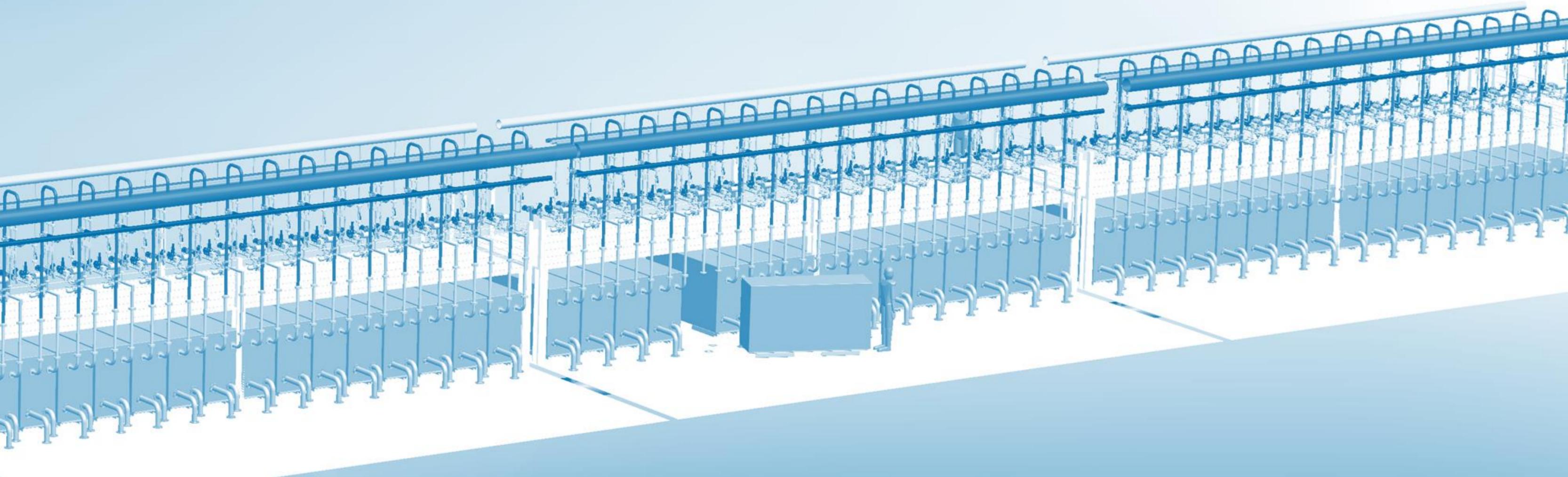
From SWITCH...

to the future....

SolydEra EMX arrays − SOE only or reversible

MW scale arrays for industrial applications

Serviceable, robust, process integrated, optimized control

thank you.