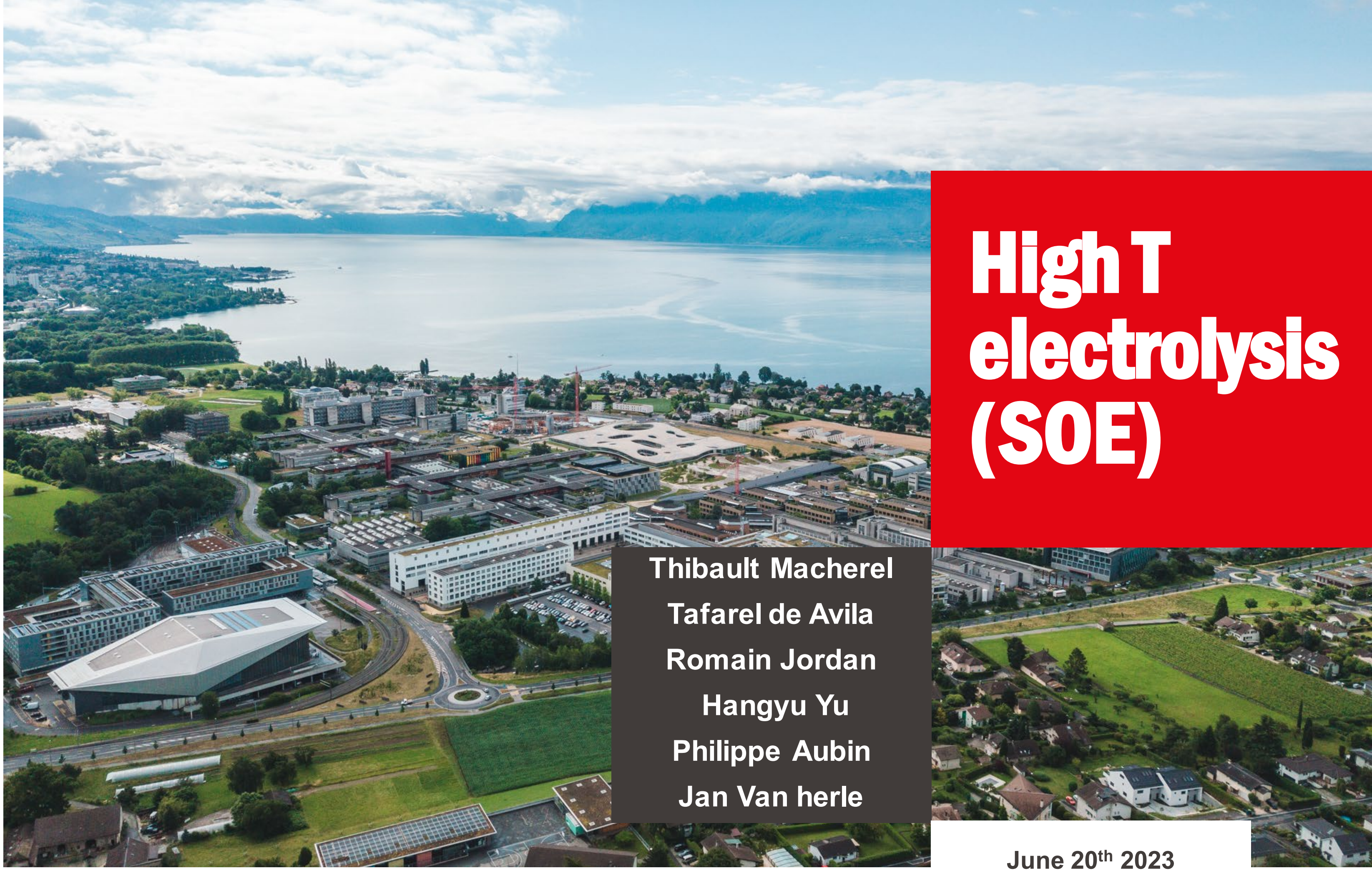


High T electrolysis (SOE)

Thibault Macherel
Tafarel de Avila
Romain Jordan
Hangyu Yu
Philippe Aubin
Jan Van herle

June 20th 2023

École polytechnique fédérale de Lausanne

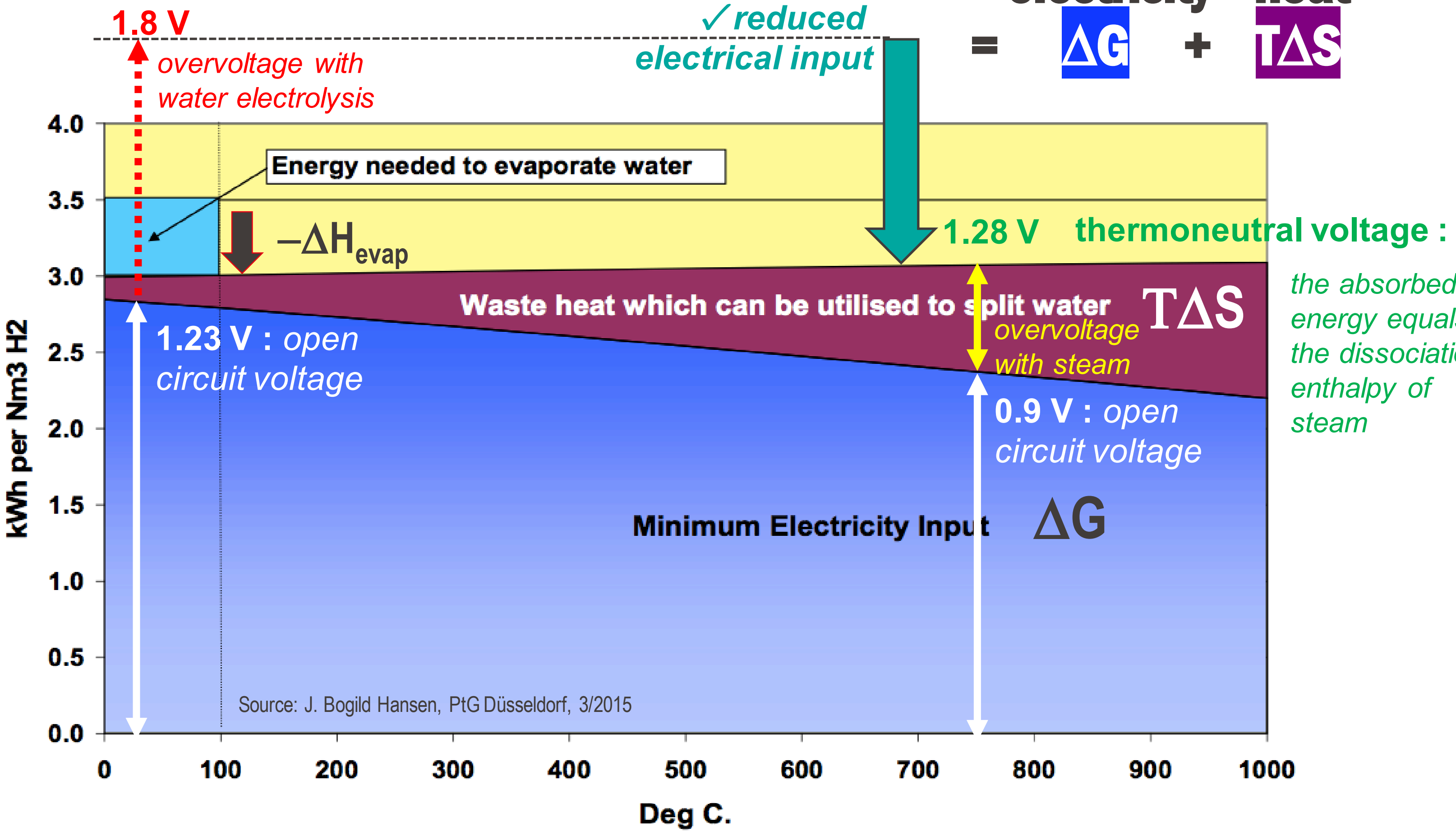
Steam electrolysis unit (SOE) in HEPP

Jan Van Herle

1. Key of steam electrolysis : reduce electrical input need to split H_2O
2. Endo / exo / thermoneutral H_2O splitting
3. SOE tests at OST
4. Stacks 1801 / 1803 from SolydEra
   - Performance (IV and efficiencies)
   - Impact of the coupling of electrolysis + methanation
5. System integration perspectives
   - Co-electrolysis of steam + CO_2
   - Internal methanation
6. Conclusions and outlook

Why *steam* electrolysis?

ΔH = total energy
= electricity + heat
= ΔG + $T\Delta S$



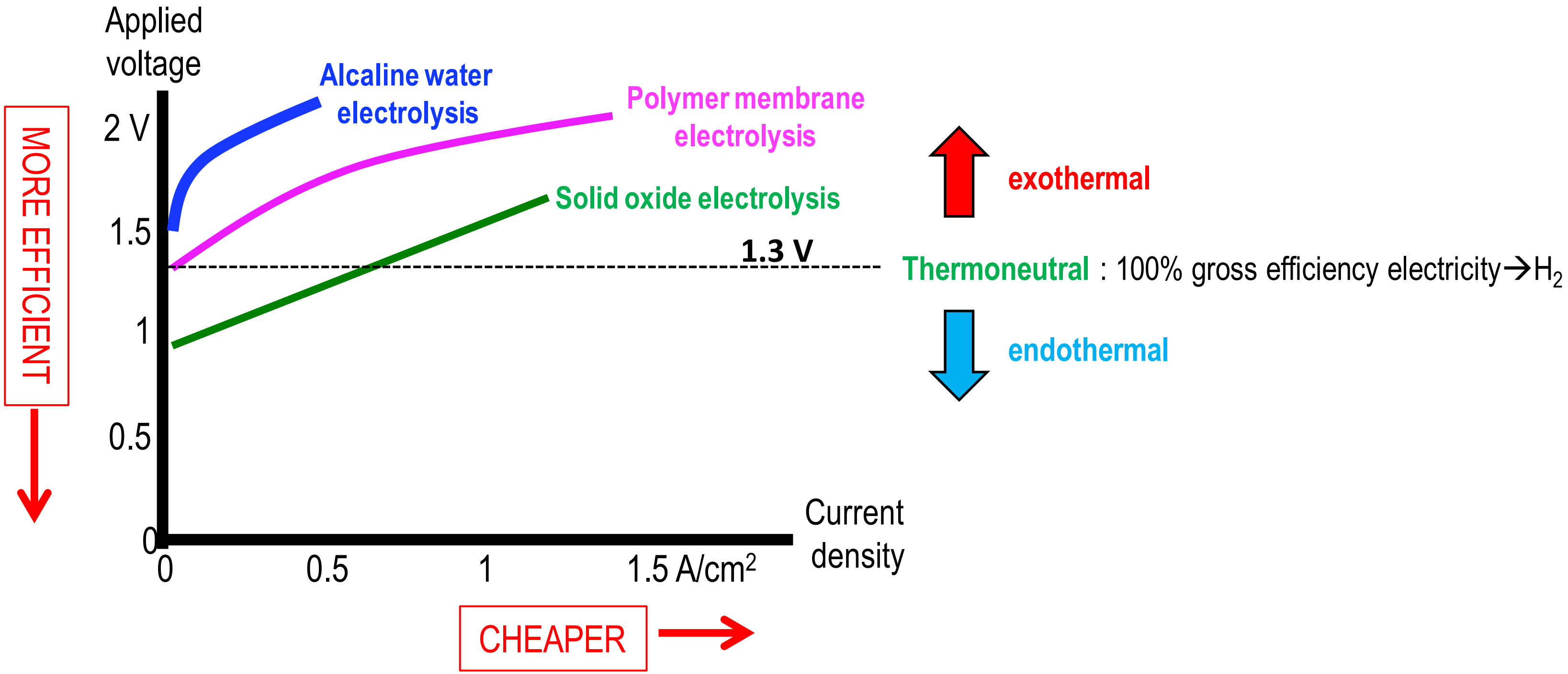
the absorbed energy equals the dissociation enthalpy of steam

Jan Van herle / gem.epfl.ch

EPFL

Steam vs water electrolysis

Jan Van herle / gem.epfl.ch



GEM

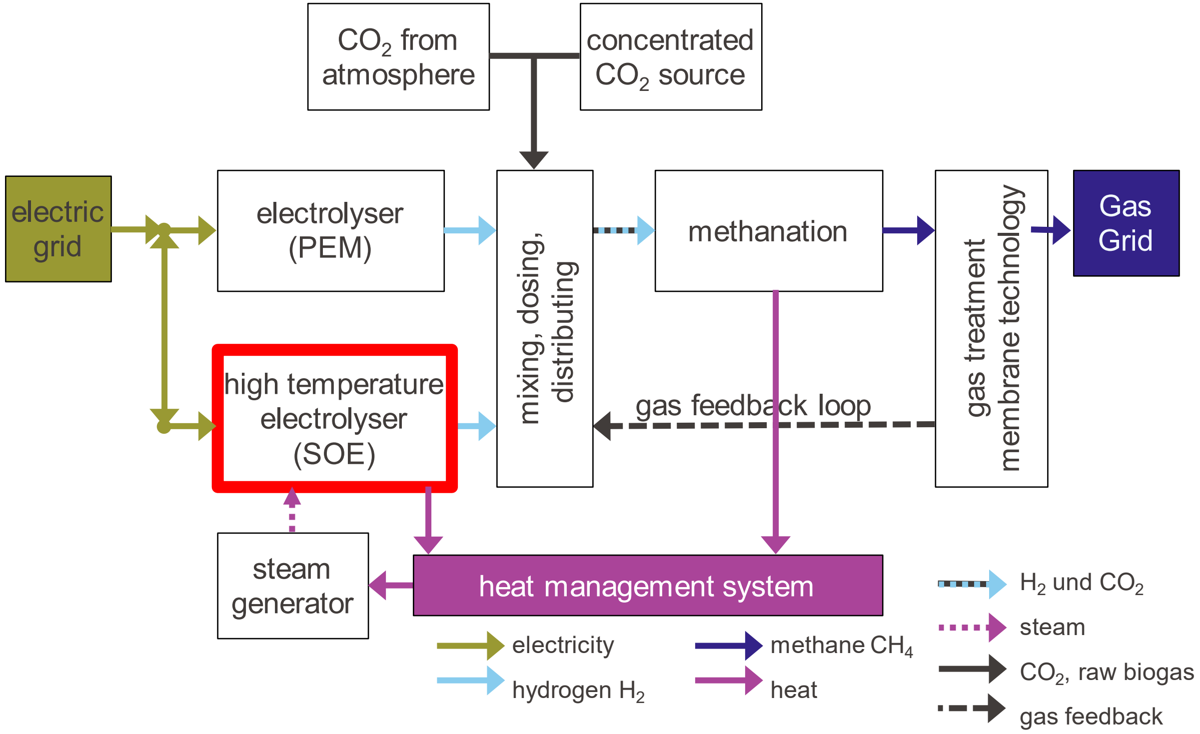
SOE context and PtG

- SOE: ***steam*** input need (= the bottleneck)
- Solution: use waste heat sources and/or heat integration with downstream exothermal fuel synthesis (=> CH_4, CH_3OH, …)

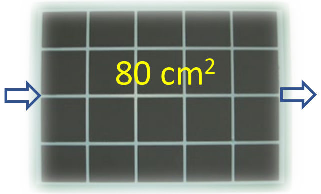
In addition:

- SOE is reversible (=> SOFC fuel cell for power generation):
  - → flexibility of operation
  - → lower CAPEX (1 installation for both modes)
  - → lower OPEX (high efficiency in both modes PtG, GtP)

SOE in the HEPP project

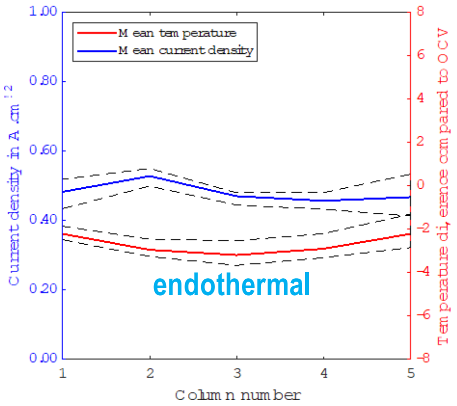


Measured temperature map in a running SOE

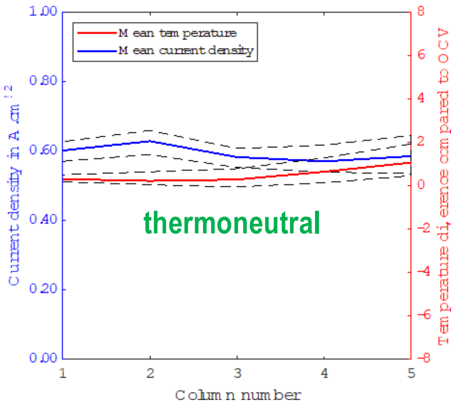


J Van herle / EPFL / GEM

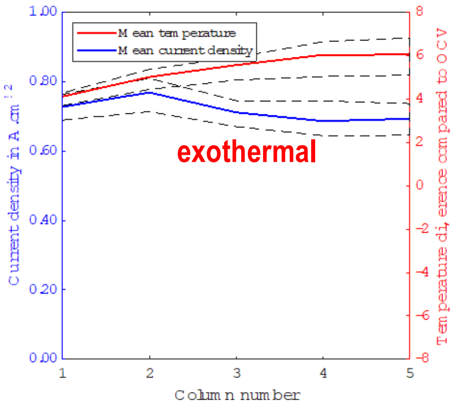
$H_2O:H_2$ = 90:10
8 NmL/min/cm²
@756°C



1.2 V
34 A
SC: 37%



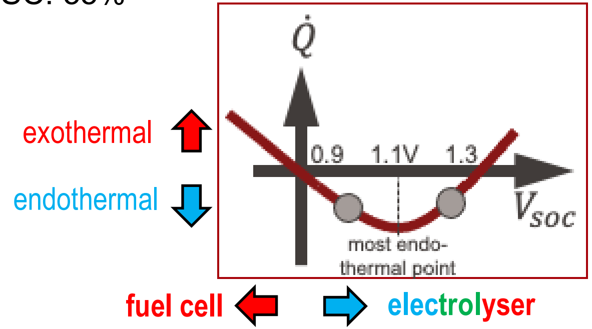
1.3 V
42 A
SC: 46%



1.4 V
51 A
SC: 55%

$$\dot{Q}_{rx} = j\left[\frac{-\Delta_r h}{zF} - \left(\frac{\Delta_r g}{zF} - \eta\right)\right] = j[V_{tn} - V_{SOC}]$$

☑ 1.3 V is indeed the most homogeneous point of operation



SOE tests at OST

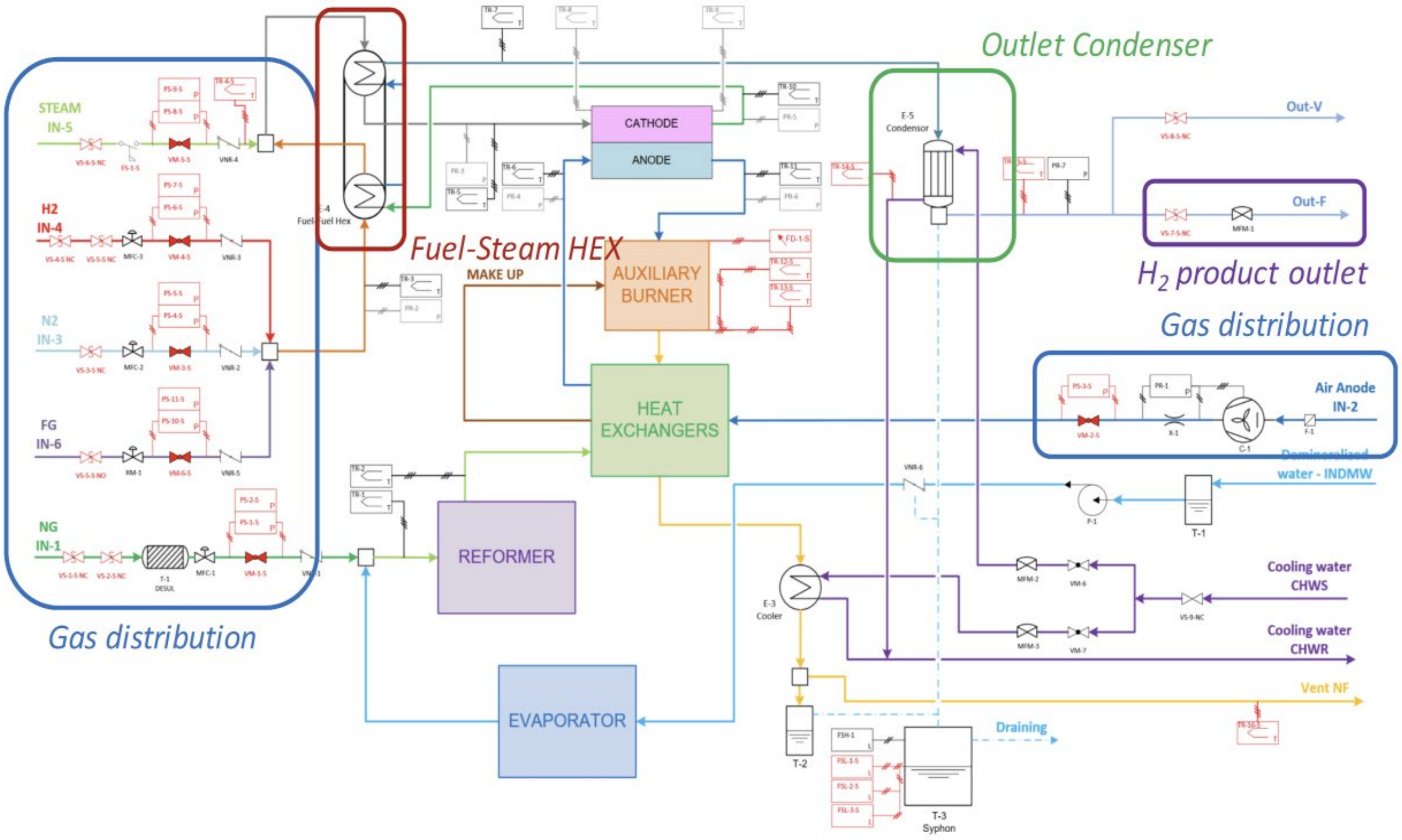
SOE 5 kWe prototype unit

- Gas distribution panel :
  H_2, steam, CH_4, formgas H_2/N_2, N_2 , Air
- Hot BoP to preheat the gases before entering the electrolyser stack
- Insulated box containing SolydEra G80 stack (70 cells, 80 cm^2) => **90 V** thermoneutral
- Cooling and condensing panel to remove remaining water in the exhaust gas (=> H_2)
- Junction box for electrical connections
- Control rack

The entire unit is enclosed in a ventilated closet equipped with H_2 detectors.

SolydEra

SOE system layout



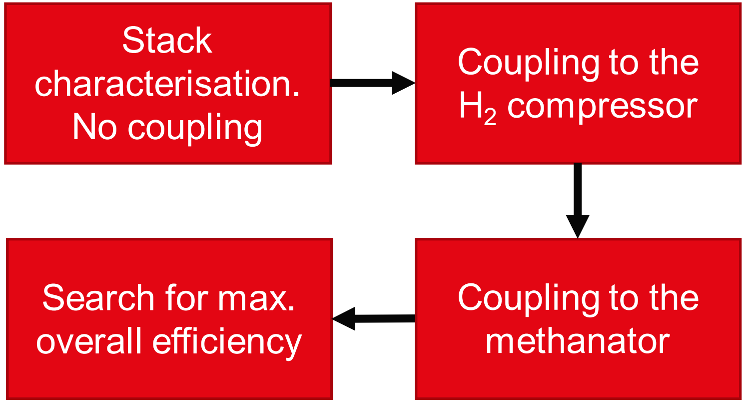
EPFL

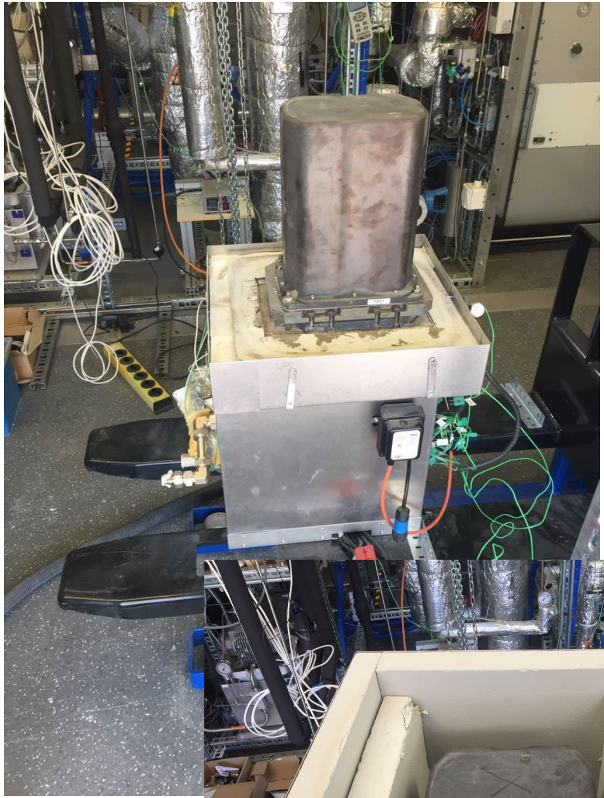
SOE tests

Two 5 kWe G80 stacks from SolydEra have been tested (so far) :

- Stack #1801 : used stack. Tested 9-11/2022.
- Stack #1803 : pristine stack. Tested 2-3/2023.

General structure of the testing :





SolydEra

Challenges and limitations

- Distance Rapperswil ←→ Sion does not allow continuous / frequent work
- For safety reasons, someone from EPFL must be on-site when the SOE is running, also overnight
- At least 3 people from EPFL needed on-site during testing weeks to carry out 3 x 8 hours shifts

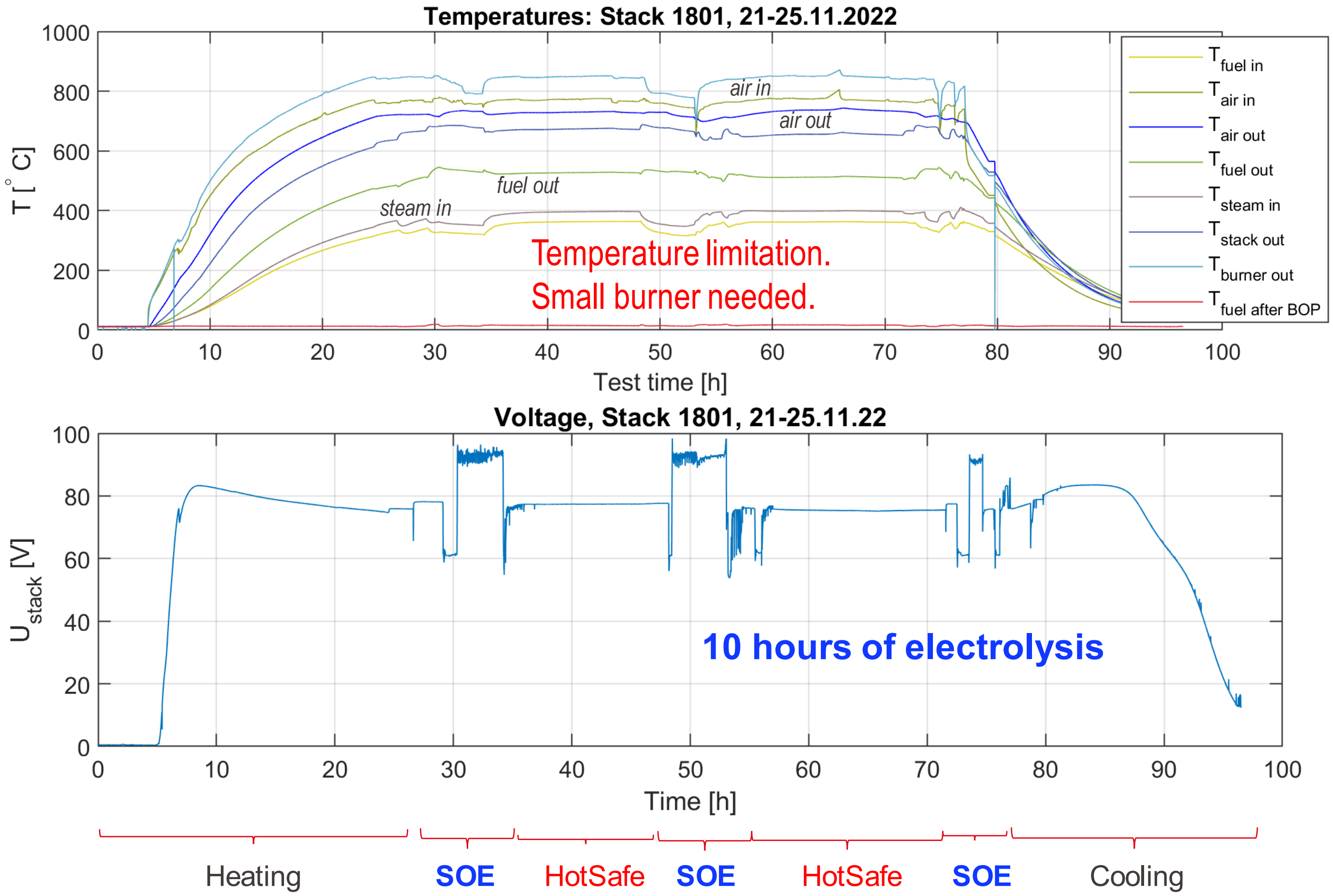
→ Cost for travel, hotel, salaries

Limited duration of the experiments (1 week continuous)

Results

EPFL

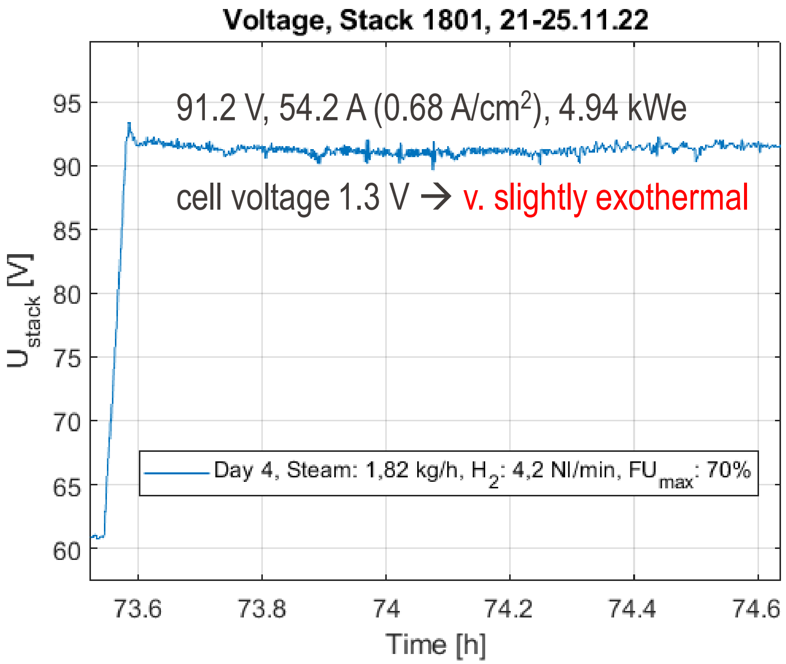
Stack #1801 (5 kWe) : T, V evolution

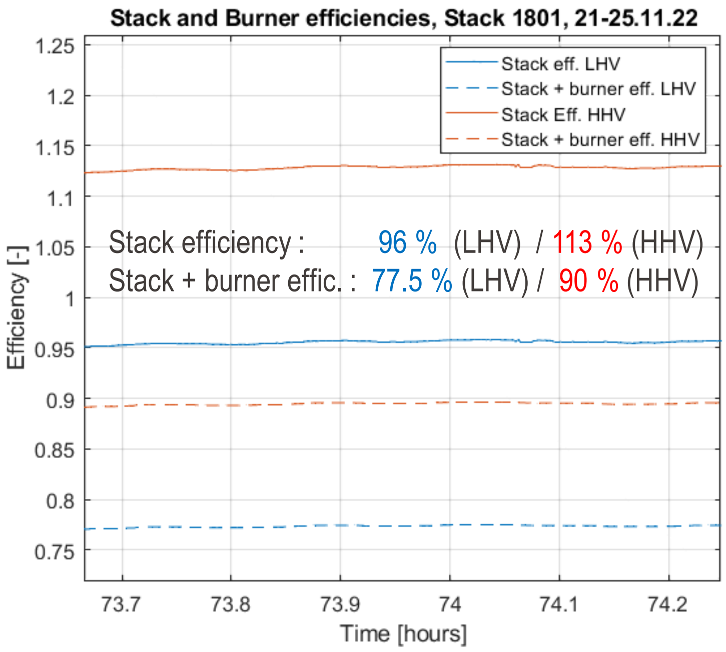


Jan Van Herle

Stack #1801: performance

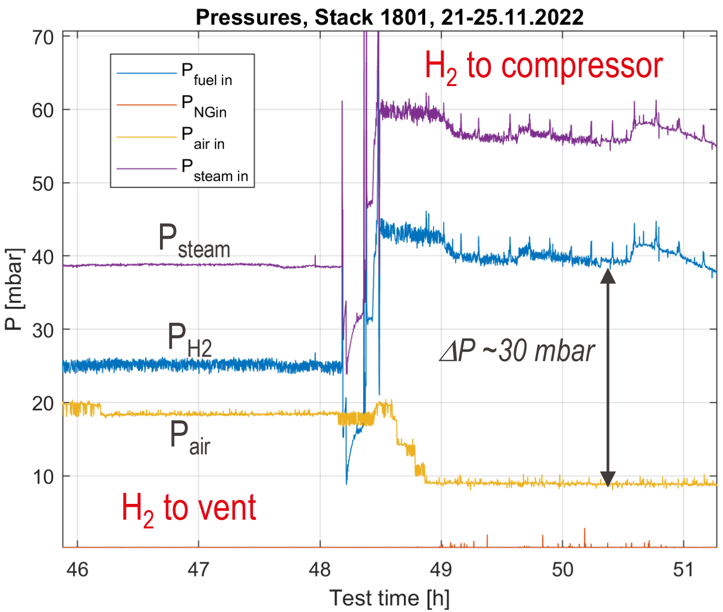
Jan Van Herle

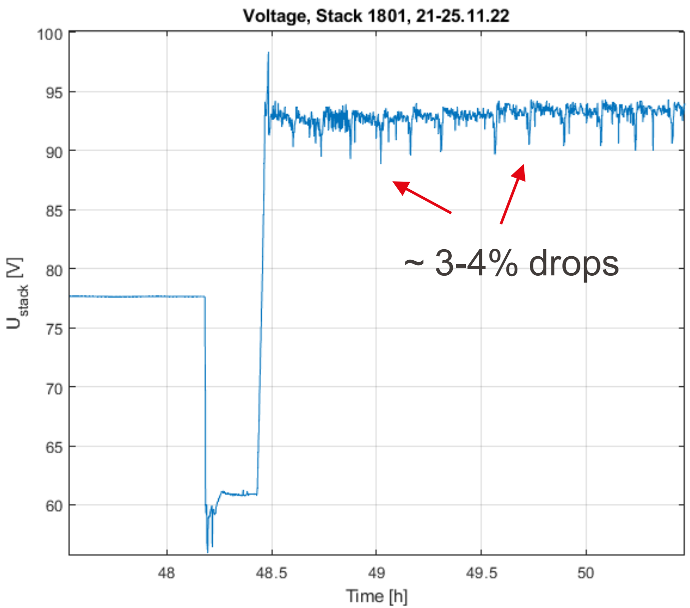




Jan Van Herle

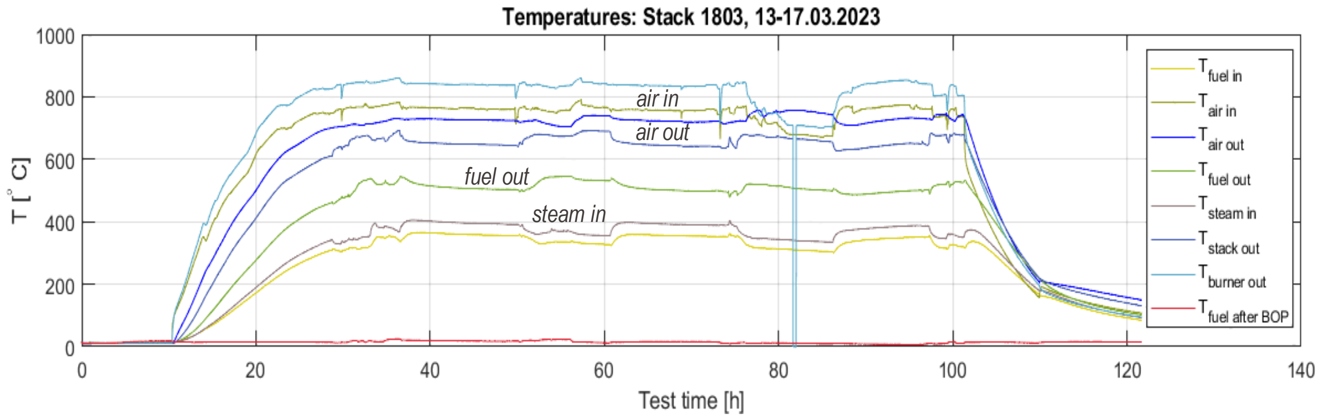
Stack #1801 (P_{atm}): coupling with the H_2-compressor and methanator (10 bar)

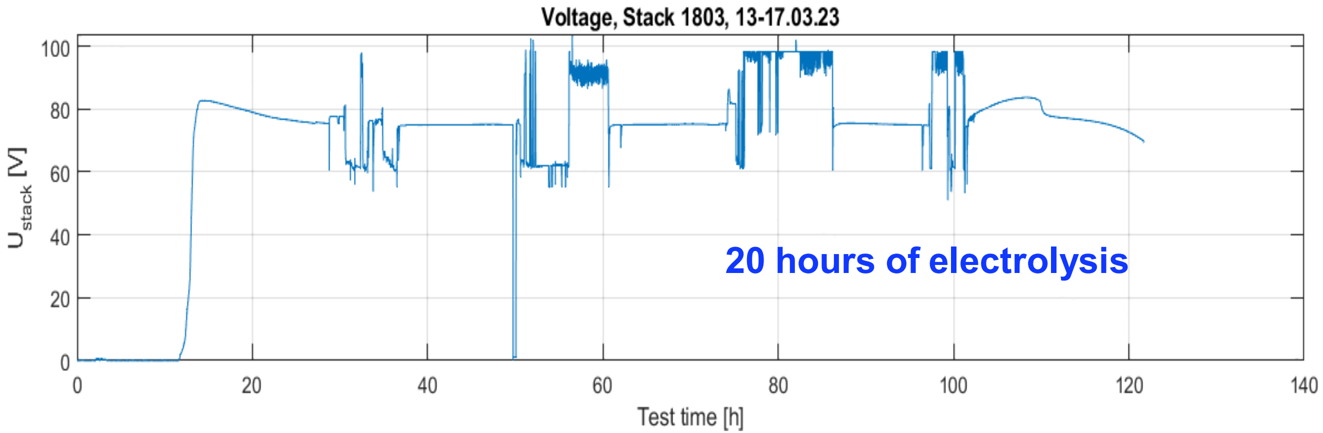




The fuel pressure increases when the SOE is coupled to the compressor/methanator.
This increase (and the ΔP between air and fuel side) must be minimized and controlled.
The voltage fluctuates during the coupling.

Stack #1803: T, V evolution

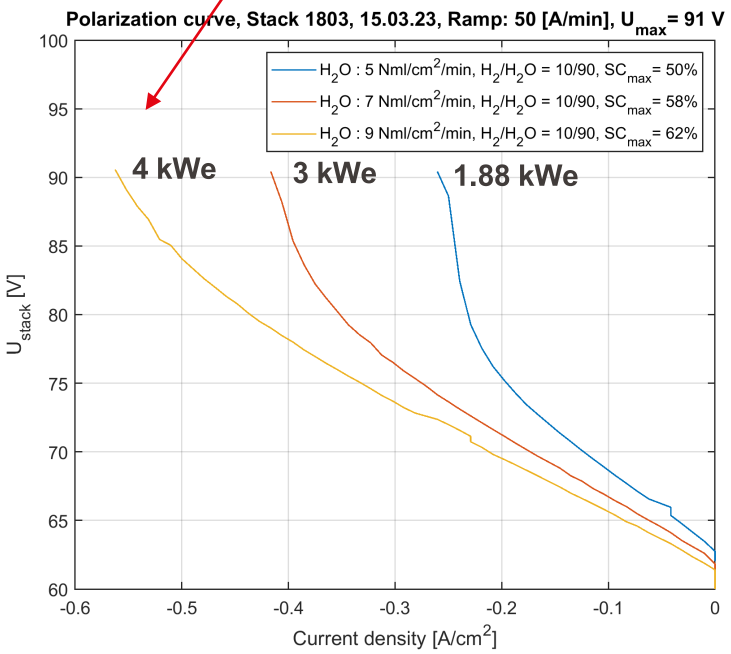


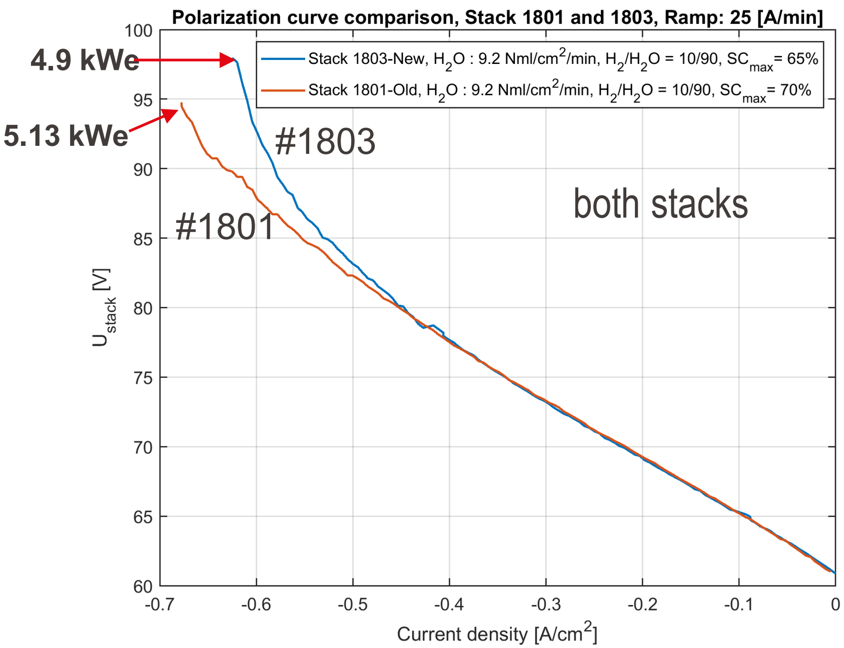


Heating **SOE** HotSafe **SOE** HotSafe **SOE** HotSafe **SOE** Cooling

EPFL

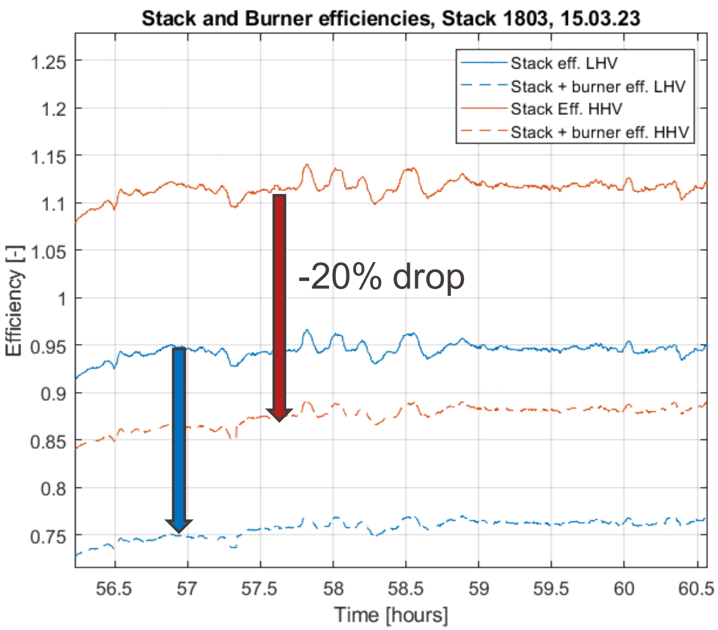
Stacks #1803, #1801: i-V

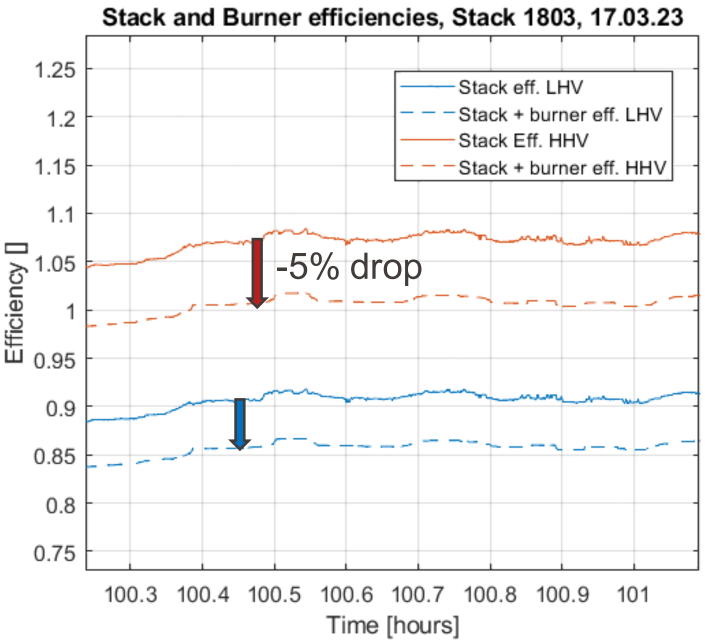




Stack 1803 shows a fast voltage increase at relatively low steam conversion (SC).
⇒ leakage between stack and hot BoP
⇒ stack lacks steam supply and reaches steam starvation

Stack #1803: efficiency





91.5 V, 50 A (0.625 A/cm^2), 4.57 kWe
Cell voltage 1.307 V → v. slightly exothermal
Stack efficiency: 95 % (LHV) / 112 % (HHV)
Stack + burner efficiency: 76.4 % (LHV) / 89 % (HHV)

decrease burner by 75 %

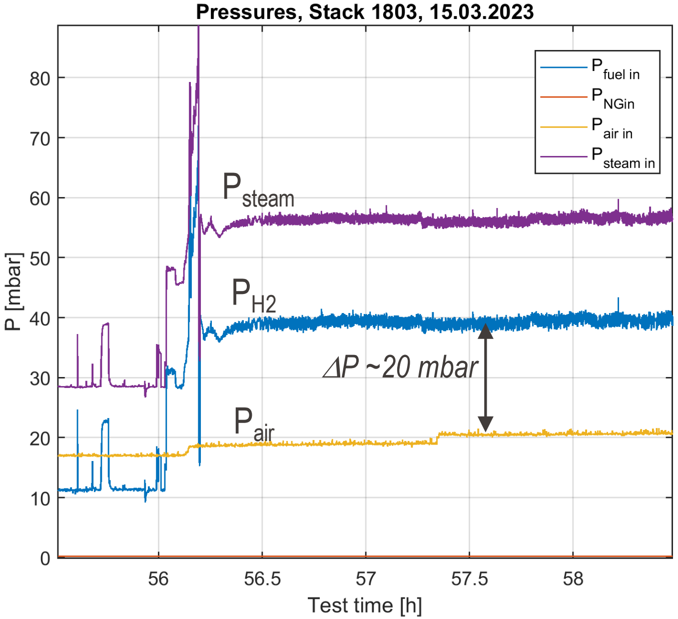
96 V, 60 A (0.75 A/cm^2), 5.76 kWe
Cell voltage **1.37 V** → exothermal conditions
Stack efficiency: 91 % (LHV) / 107.5 % (HHV)
Stack + burner efficiency: 86 % (LHV) / 101.5 % (HHV)

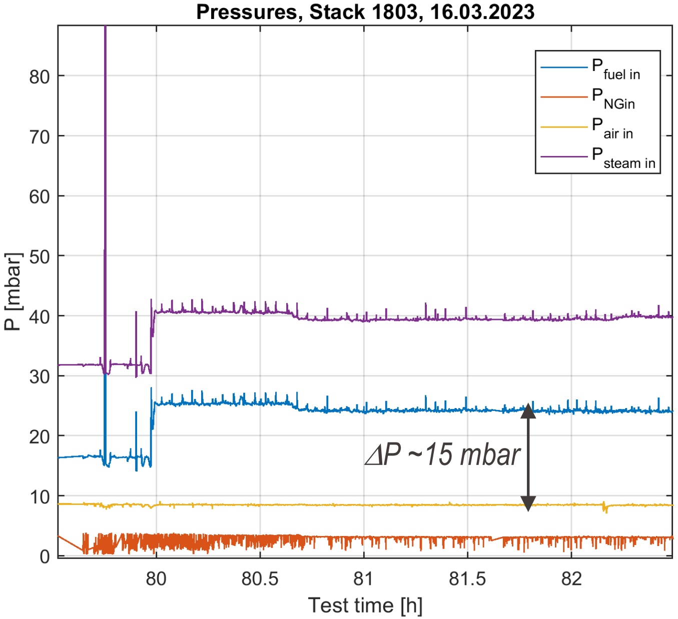
Stack 1803 : coupling

Jan Van Herle

Improvement of the coupling methodology (less fluctuations)

(more details in Christoph's presentation)



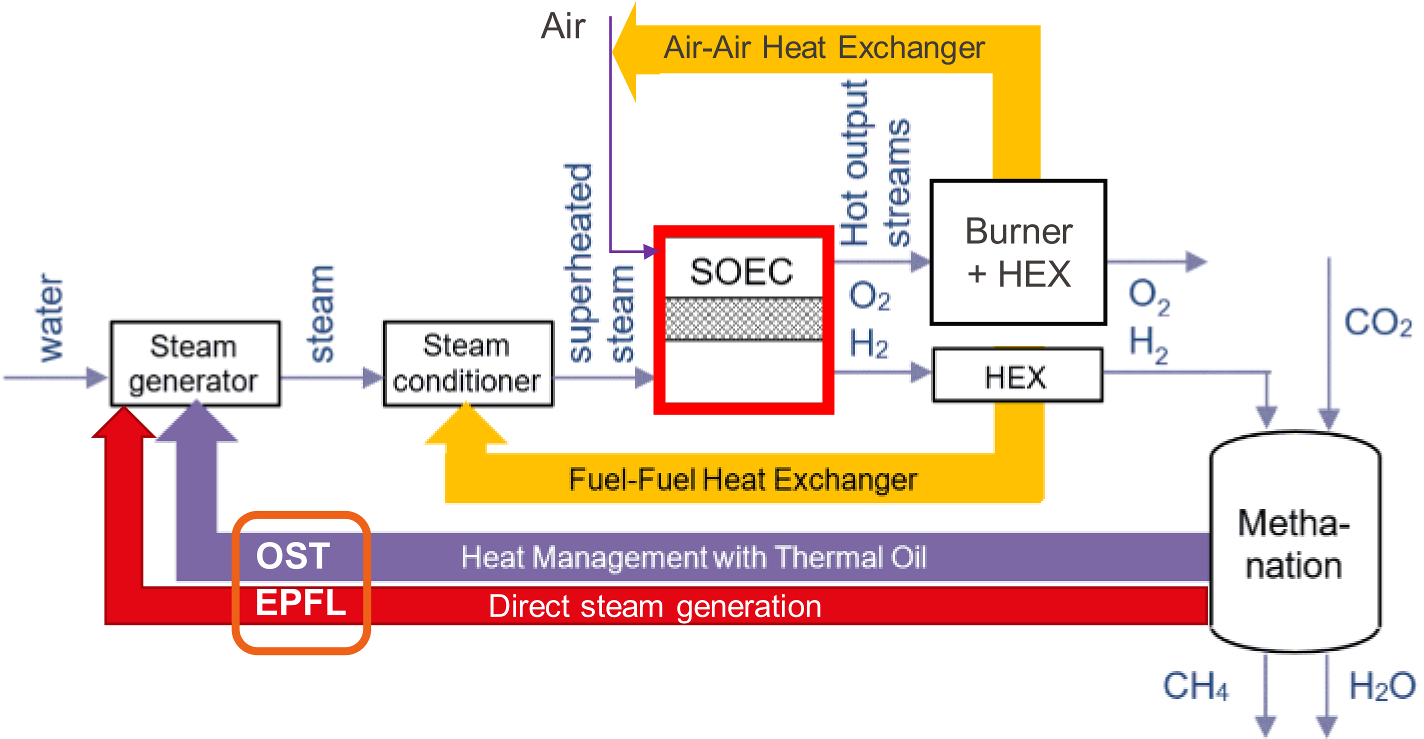


Methanation @EPFL

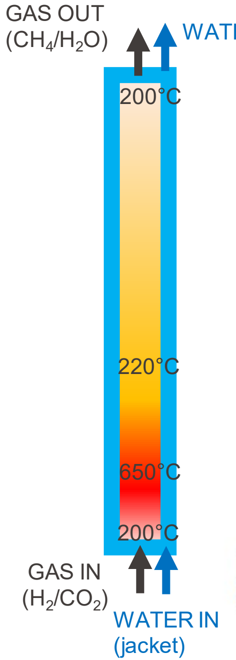
EPFL

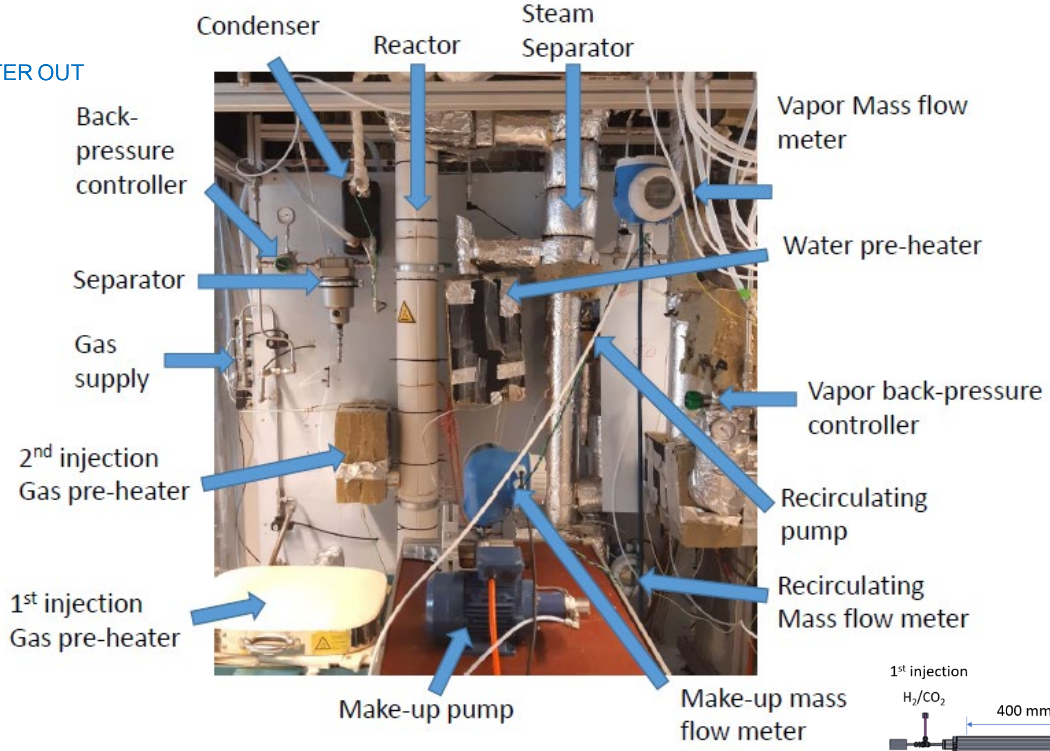
Thermal coupling methanator => steam generation

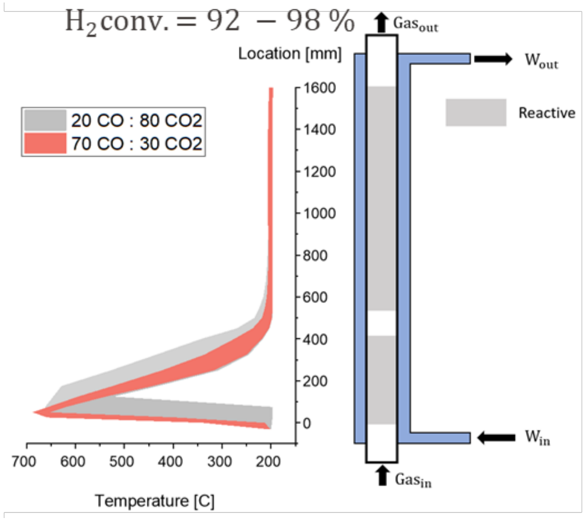
- ➤ indirect
- ➤ direct

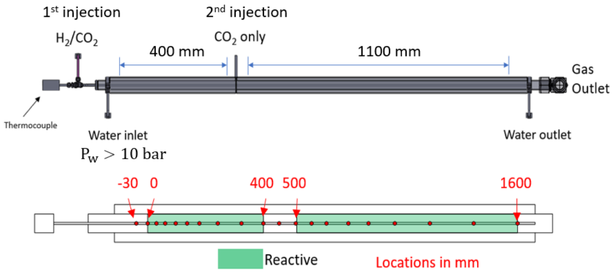


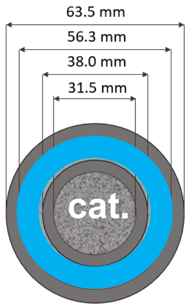
EPFL methanator (10 kW) => direct steam prod.











EPFL

Methanation results @ EPFL

- ✓ 98.5% H_2-conversion achieved
- ✓ both CO_2 and CO/CO_2-methanation successful (CO more exothermal)
- ✓ reactor cooled with pressurised water (15 bar, 200°C)
- ✓ heat exchange efficiency 80-91%
- ✓ methanation heat generates 87-113% of the steam required by the steam electrolyser

Publications

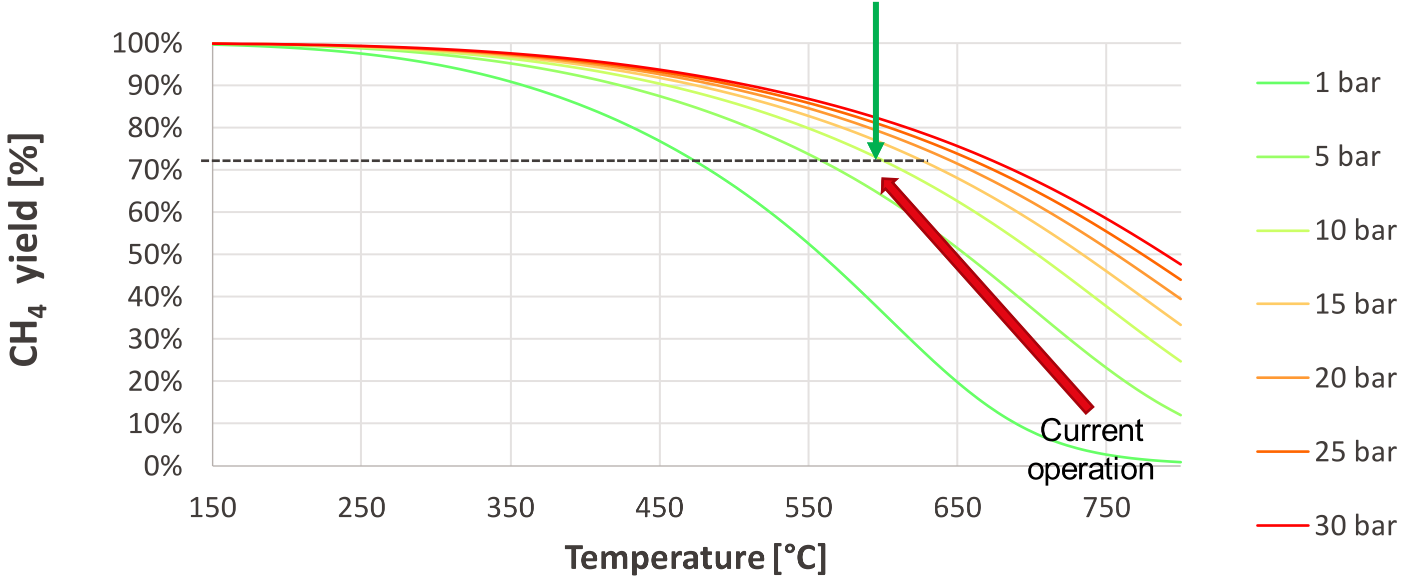
- P. Aubin, L. Wang, and J. Van herle, “Evaporating water-cooled methanation reactor for solid-oxide stack- based power-to-methane systems: design, experiment and modeling,” *Chemical Engineering Journal*, **456**, 140256, 2023.
- P. Aubin, L. Wang, and J. Van herle, “SOE-methanation PtM system simulation: a case study with real reactor results,” [submitted]
- P. Aubin, L. Wang, and J. Van herle, “SOE-methanation PtM system under steam and CO_2 co-electrolysis: reactor operation and system simulation,” [prepared]
- P. Aubin, and J. Van herle, “Thermosyphon operation of the cooling system of a methanation reactor: an experimental assessment,” [submitted]

Perspectives

Stack-internal methanation

coupled

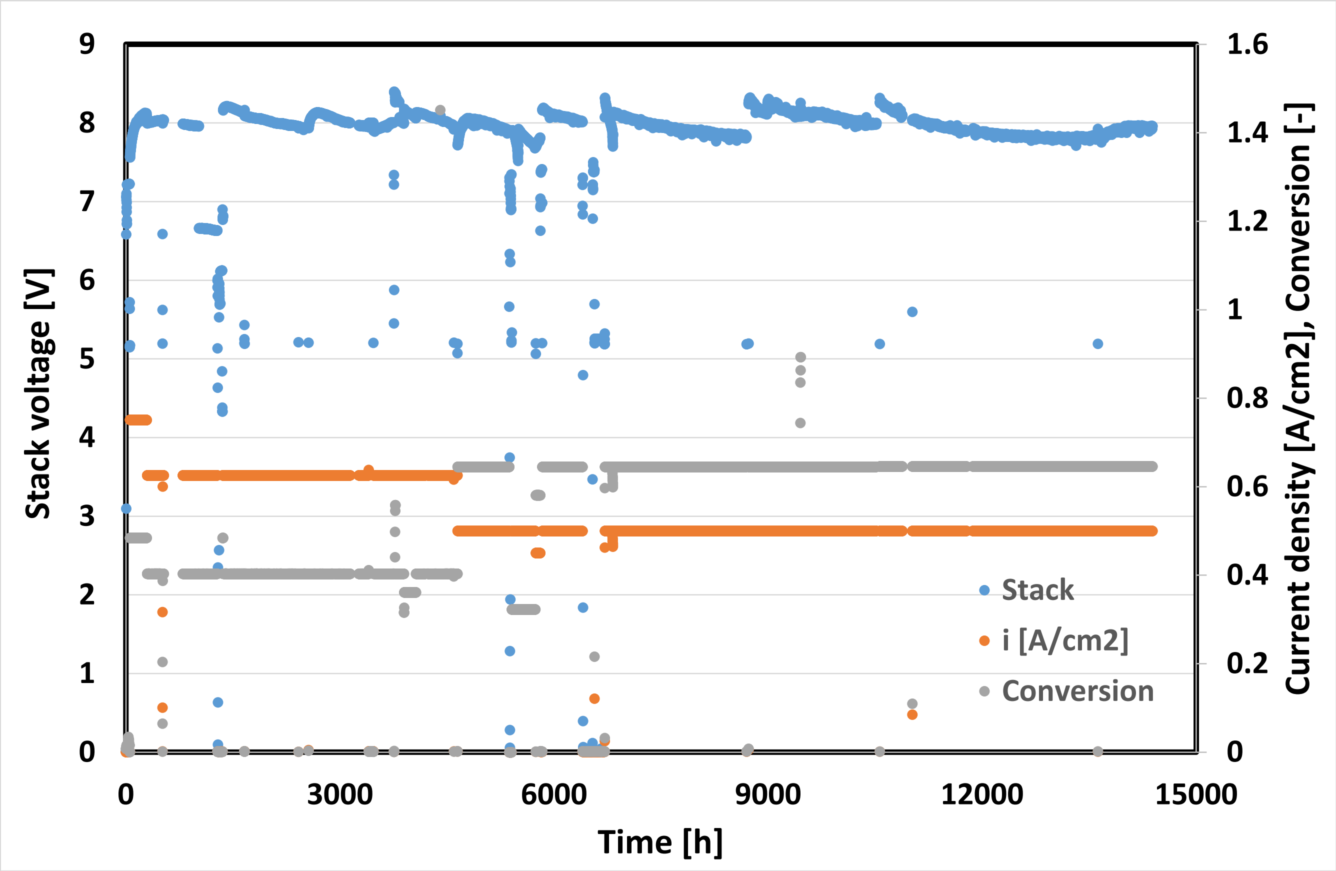
Steam + CO_2 **co-electrolysis**
under higher **pressure** (10 bar), lower temperature (600°C)
=> methane production in the stack => smaller methanator (10 bar)



EPFL

Co-electrolysis already validated 16'000h ✓

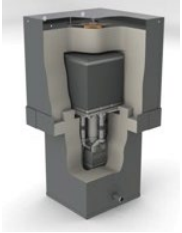
Short stack (6-cells); 65% steam, 25% CO_2, 10% H_2

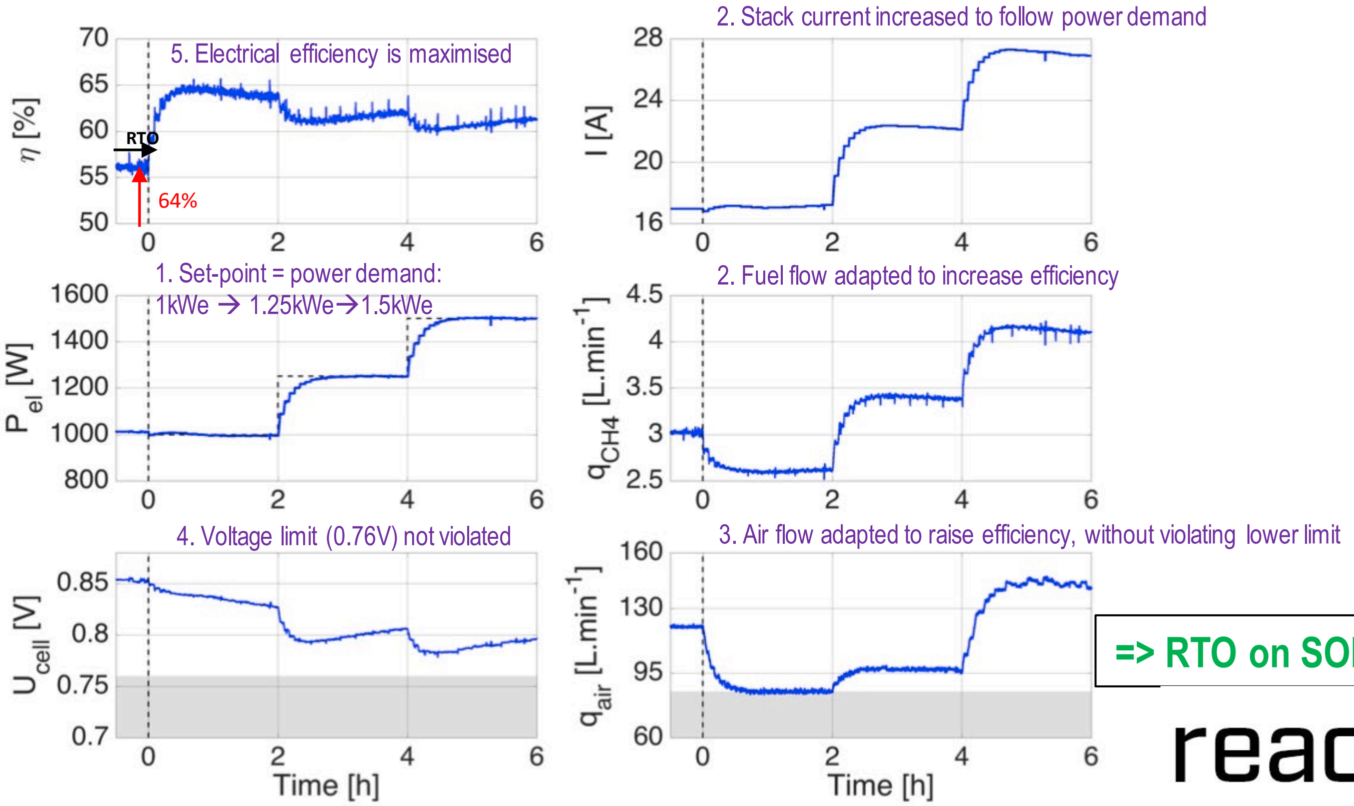


Jan Van herle / gem.epfl.ch

Real-time optimisation (RTO) under safety constraints – experimentally proven on a commercial SOFC system

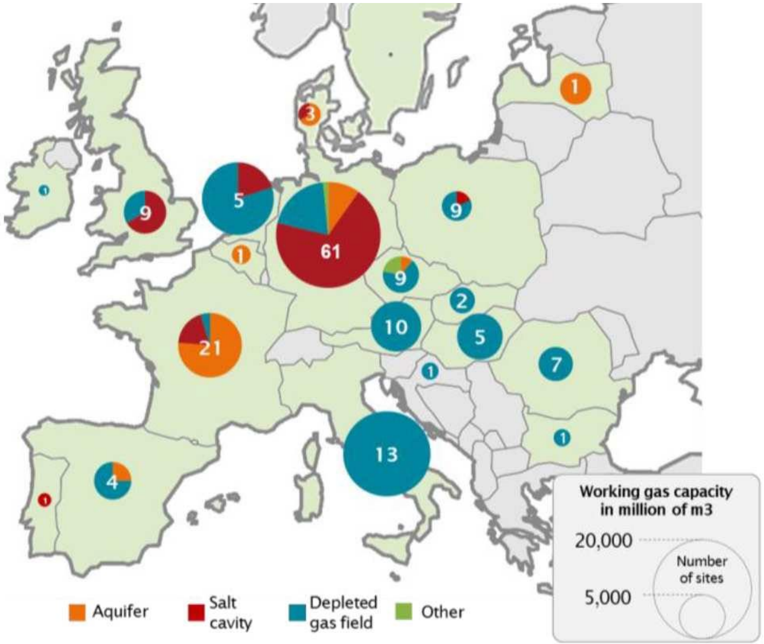
RTO Control of a 1.5 kWe BlueGen mCHP

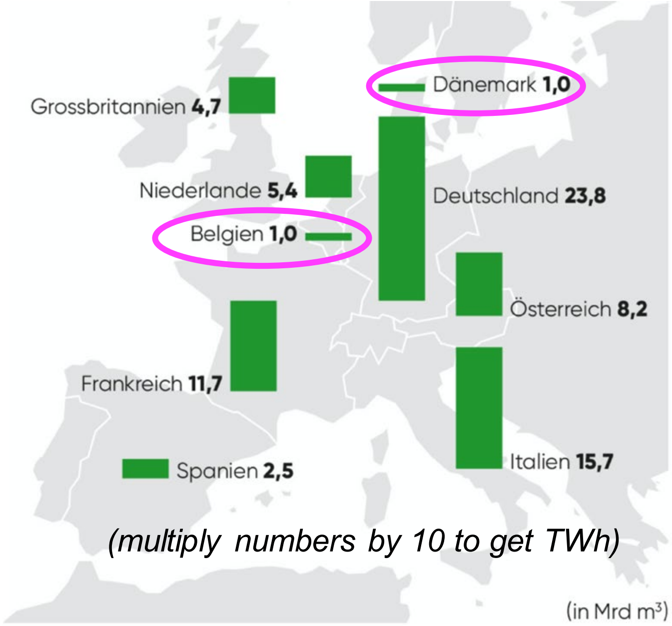




=> RTO on SOE ongoing

Seasonal gas storage (CH_4)





10 TWh = 10 million m^3 (100 bar) = 1 km^2 x 10 m

Switzerland currently has no gas storage.

With 1 bio m^3 NG storage (10 TWh), it could bridge its future winter electricity gap (a deficit of ~1 TWhe / month). 10 TWh of NG from P2G requires **15 TWhe of electricity**, which could be covered from existing + future hydropower (>40 TWhe) and future PV (>30 TWhe).

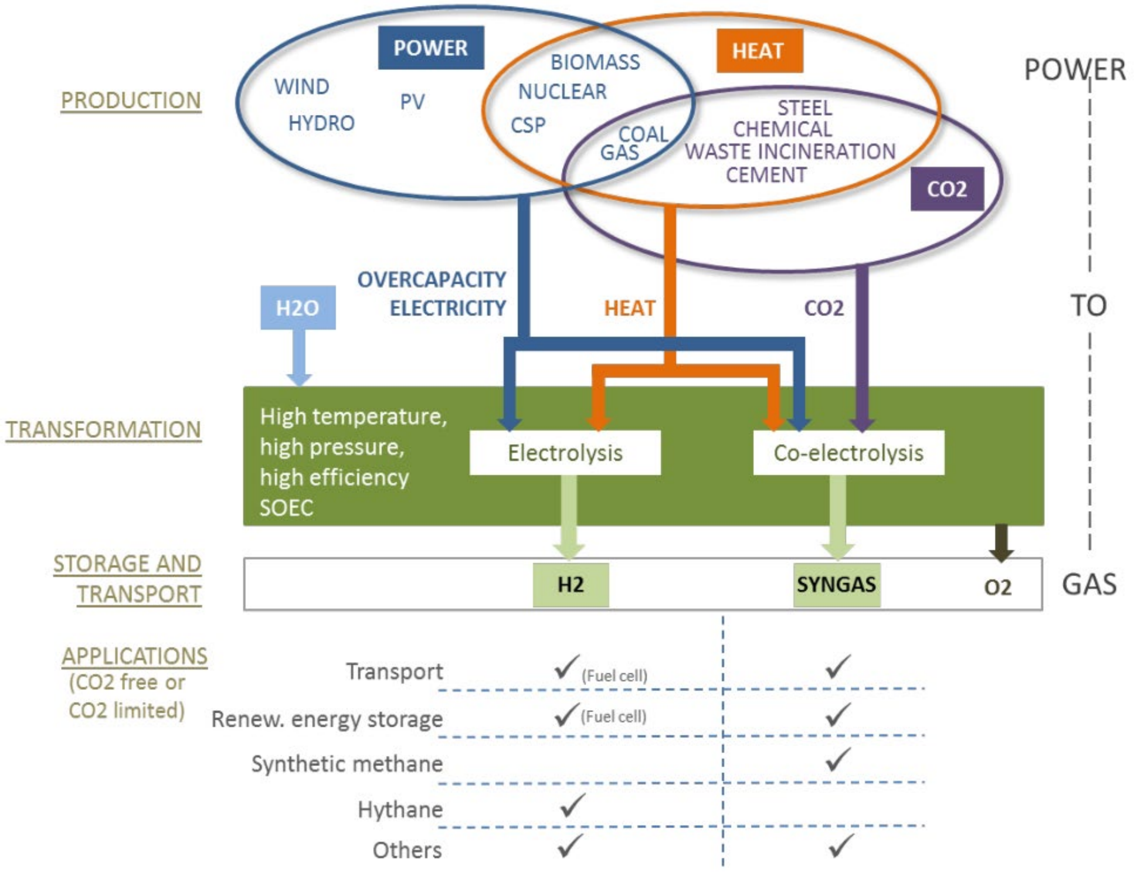
Feasibility checks

- 10 TWh CH_4 : 1 km^2 x 10 m storage (0.01 km^3)
- 30 TWhe solar PV : 150 km^2 panels (same amount as roof area)
- 110 km^2 or 4 km^3 hydro-storage lakes for ~20 TWhe

1) 15 TWhe + 3 TWh heat => (90% el. eff., 1.4 V) 13.5 TWh H_2 (LHV)
2) 13.5 TWh H_2 + 2 Mt CO_2 => (75% meth. eff.) 10 TWh CH_4 + 3 TWh heat

- Swiss waste incineration : 4 Mt CO_2 and 8 TWh heat loss per year
- => (3000h/yr) 5 GWe electrolysers needed => (1 W/cm^2) 0.5 km^2 membrane area => 5000 m^2 stack footprint (100 layers / stack) ≈2500 m^3 ≈1500 m^3 steel ≈12 kt steel (stack only)

SOE integration opportunities



EPFL

PtX relevant publications 2018-2019

- Techno-Economic Optimization of **CO_2-to-Methanol** with Solid-Oxide Electrolyzer , Hanfei Zhang, Ligang Wang, Jan Van herle, François Maréchal, Umberto Desideri, *Energies*, ***12***(19), 3742; https://doi.org/10.3390/en12193742 (2019)
- Balancing wind-power fluctuation via onsite storage under uncertainty: **power-to-hydrogen-to-power** versus lithium battery, Y Zhang, L Wang, N Wang, L Duan, Y Zong, S You, F Maréchal, J. Van herle, Y Yang, *Renewable and Sustainable Energy Reviews* **116**, 109465 (2019)
- Fuel cell-battery hybrid systems for mobility and off-grid applications: A review, Shuai Ma, Mang Lin, Tzu-En Lin, Tian Lan, Xun Liao, F Marechal, J Van herle, Yongping Yang, Changqing Dong, Ligang Wang, *Renewable and Sustainable Energy Reviews* **135**, Jan 2019, 1110119 (2019)
- Design of a Pilot SOFC System for the **Combined Production of Hydrogen and Electricity** under Refueling Station Requirements, M. Perez-Fortes, A. Mian, S. Santhanam, L. Wang, S. Diethelm, E. Varkaraki, I. Mirabelli, R. Makkus, R. Schoon, F. Marechal, J. Van herle, *Fuel Cells*, 19 (4), 389-407, DOI: 10.1002/fuce.201800200 (2019)
- **Reversible solid oxide systems** for energy and chemical applications–Review & perspectives, Venkataraman, Vikrant; Pérez-Fortes, Mar; Wang, Ligang; Hajimolana, Yashar S; Boigues-Muñoz, Carlos; Agostini, Alessandro; McPhail, Stephen J; Maréchal, François; Van Herle, Jan; Aravind, PV, *Journal of Energy Storage* **24**, 100782 (2019)
- **Power-to-methane via co-electrolysis** of H_2O and CO_2: The effects of pressurized operation and internal methanation Wang, Ligang; Rao, Megha; Diethelm, Stefan; Lin, Tzu-En; Zhang, Hanfei; Hagen, Anke; Maréchal, François, *Applied Energy* **250**, 1432-1445 (2019)
- Trade-off designs of **power-to-methane** systems via solid-oxide electrolyzer and the application to biogas upgrading, Jeanmonod, Guillaume; Wang, Ligang; Diethelm, Stefan; Maréchal, François; Van herle, Jan, *Applied Energy* **247**, 572-581 (2019)
- **Power-to-fuels** via solid-oxide electrolyzer: Operating window and techno-economics, Wang, Ligang; Chen, Ming; Küngas, Rainer; Lin, Tzu-En; Diethelm, Stefan; Maréchal, François, *Renewable and Sustainable Energy Reviews* **110**, 174-187 (2019)
- Trade-off designs and comparative exergy evaluation of solid-oxide electrolyzer based **power-to-methane** plants , Wang, Ligang; Düll, Johannes; Van herle, Jan; Maréchal, François, *International Journal of Hydrogen Energy* **44**, 19, 9529-9543 (2019)
- Optimal design of solid-oxide electrolyzer based **power-to-methane** systems: A comprehensive comparison between **steam electrolysis and co-electrolysis**, Wang, Ligang, Perez-Fortes, Mar, Madi, Hossein, Diethelm, Stefan, Van Herle, Jan, Marechal, Francois, *Applied Energy* **211**, 1060-1079 (2018)

EPFL

PtX relevant publications 2020-2021

- **Triple-Mode Grid-Balancing** Plants via **Biomass** Gasification and Reversible Solid-Oxide Cell Stack: Economic Feasibility Evaluation via Plant Capital-Cost Target Y Zhang, N Wang, C Li, M Pérez-Fortes, L Duan, J Van herle, F Maréchal, TE Lin, ...*Frontiers in Energy Research* 9, 121 (2021)
- Techno-economic comparison of 100% renewable **urea** production processes , H Zhang, L Wang, J Van herle, F Maréchal, U Desideri *Applied Energy* (**2021**), 284, 116401
- **Reversible** solid-oxide cell stack based **power-to-x-to-power** systems: economic potential evaluated via plant capital-cost target, Yumeng Zhang, Ningling Wang, Xiaofeng Tong, Liqiang Duan, Tzu-En Lin, François Maréchal, Jan Van herle, Ligang Wang, Yongping Yang , *Applied Energy* (**2021**), 290, 116700
- Techno-economic optimization of an integrated **biomass waste gasifier** – solid oxide fuel cell plant, Mar Pérez-Fortes, Victoria Xu Hong He, Arata Nakajo, Jürg Alexander Schiffmann, Francois M. A. Maréchal, Jan Van herle, *Frontiers in Energy Research* 9, 247, section Process and Energy Systems Engineering
- Techno-economic evaluation of **biomass-to-fuels** with solid-oxide electrolyzer, Hanfei Zhang, Ligang Wang, Jan Van herle, François Maréchal, Umberto Desideri, *Applied Energy* **270**, 115113 (2020)
- **Reversible** solid-oxide cell stack based **power-to-x-to-power** systems: Comparison of thermodynamic performance, Ligang Wang, Yumeng Zhang, Mar Pérez-Fortes, Philippe Aubin, Tzu-En Lin, Yongping Yang, François Maréchal, *Applied Energy* **275**, 115330
- **Triple-mode grid-balancing** plants based on **biomass** gasification and reversible solid-oxide cell stack: concept and performance, L Wang, Y. Zhang, C. Li, M Perez-Fortes, Tzu-En Lin, Y Yang, F Maréchal, J Van herle, *Applied Energy* **280**, 115987 (2020)
- Enhancing the operational flexibility of thermal power plants by **coupling high-temperature power-to-gas** Y Sun, L Wang, C Xu, J. Van herle, F Maréchal, Y Yang, *Applied Energy* **263**, 114608 (2020)
- Green **ammonia**, H Zhang, L Wang, J Van herle, F Maréchal, U Desideri, *Applied Energy* **259**, 114135 (2020)
- Techno-economic optimization of **biomass-to-methanol** with solid-oxide electrolyzer H Zhang, L Wang, M Pérez-Fortes, J Van herle, F Maréchal, U Desideri, *Applied Energy* **258**, 114071 (2020)

EPFL

Achievements

- Two 5 kWe SOE stacks have been tested :
  - Stack 1801 in 2022 during 2 weeks
  - Stack 1803 in 2023 during 1 week

- Thermal balance is complex. Exothermal stack conditions (1.37 V) improve the thermal management for a limited penalty in electrical efficiency (86% LHV)

- Both stacks were succesfully coupled to a H_2 compressor and the OST methanator. Improvement of the coupling methodology could decrease the impact of the coupling on the stack.

- Electrical efficiency is significantly above the efficiency of a water electrolysis (PEM)-methanator system.

Acknowledgments

SolydEra

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Bundesamt für Energie BFE
Office fédéral de l'énergie OFEN

Clean Hydrogen Partnership

OST
Ostschweizer Fachhochschule

Horizon 2020
European Union Funding
for Research & Innovation

gaz nat

reactt

Hes·so// VALAIS WALLIS

Thank you for your attention

SOE operating principle