Determining best values of operational parameters for reversible Solid Oxid Cell Systems

Fully Integrated
Reversible Solid Oxide Cell System
FIRST

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The project FIRST

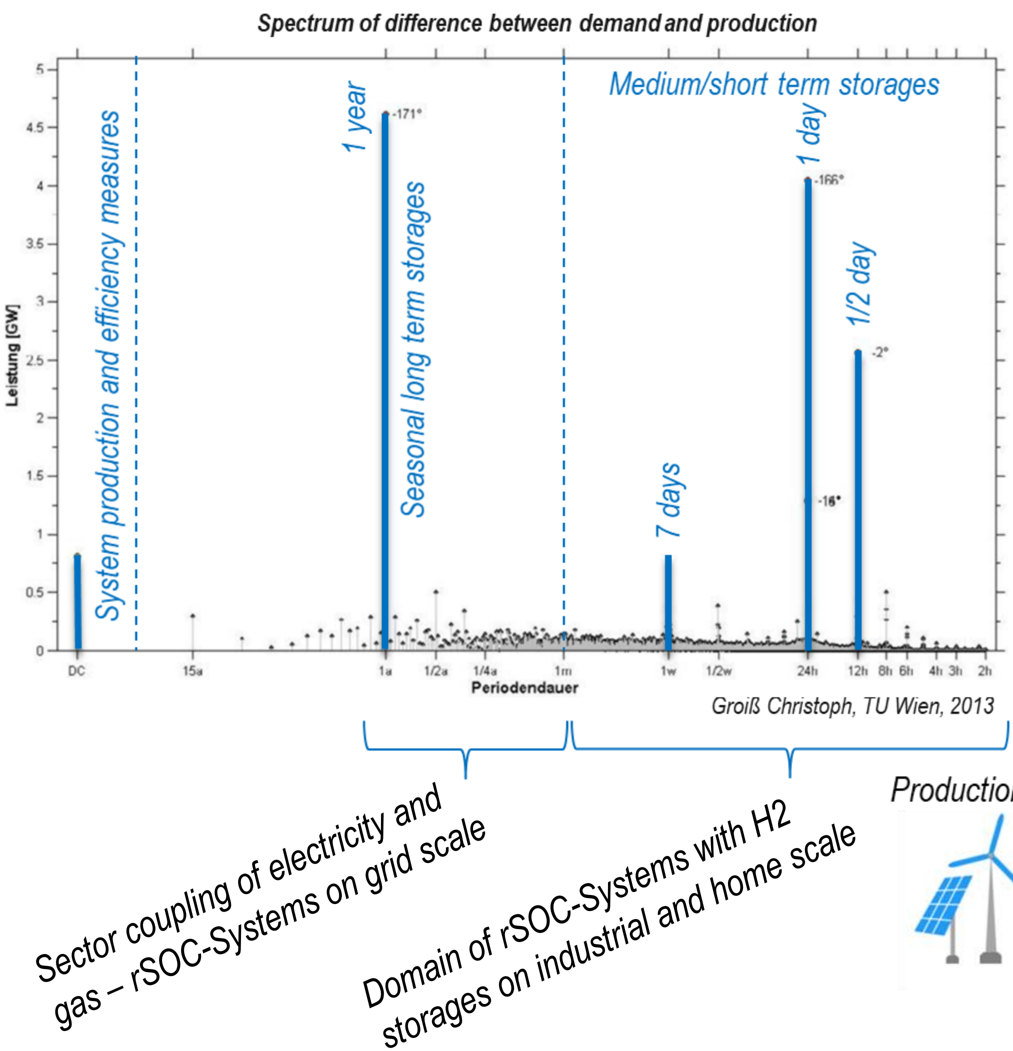
Fully Integrated Reversible Solid Oxide Cell System FIRST

- ***rSOC-System development***
- ***Testing in Living-Lab***
- ***Investigation of application scenarios***
- ***Economical impact assessment***

The project started in November 2019 and is running until October 2023.

Motivation for rSOC-Systems

Renewables energy production (except biomass) is temporal volatile!



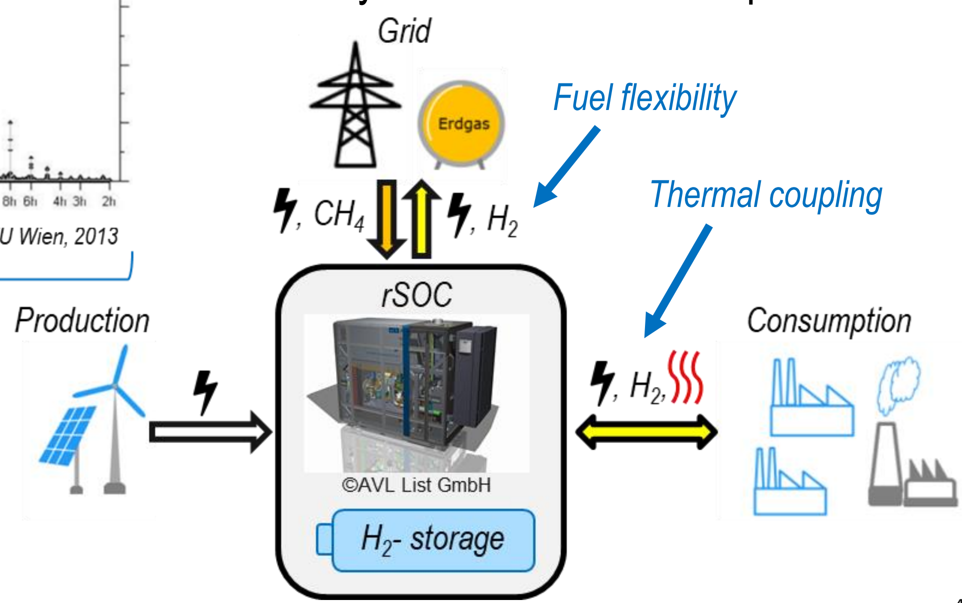
Conclusion:

We need an energy system that...

- … can provide flexibility with required time constants
- … is highly efficient

Possible Solution:

rSOC-Systems meet these requirements!



Motivation for rSOC-Systems

Renewables energy production (except biomass) is temporal volatile!

Research Questions:

How must the rSOC-System be designed to meet the requirements?

- Flowsheet for thermal integration
- Influence of operational Parameters

Conclusion II:

We need rSOC-System models to:

- Determine best values for operation parameters
- Simulate system behaviour in real applications

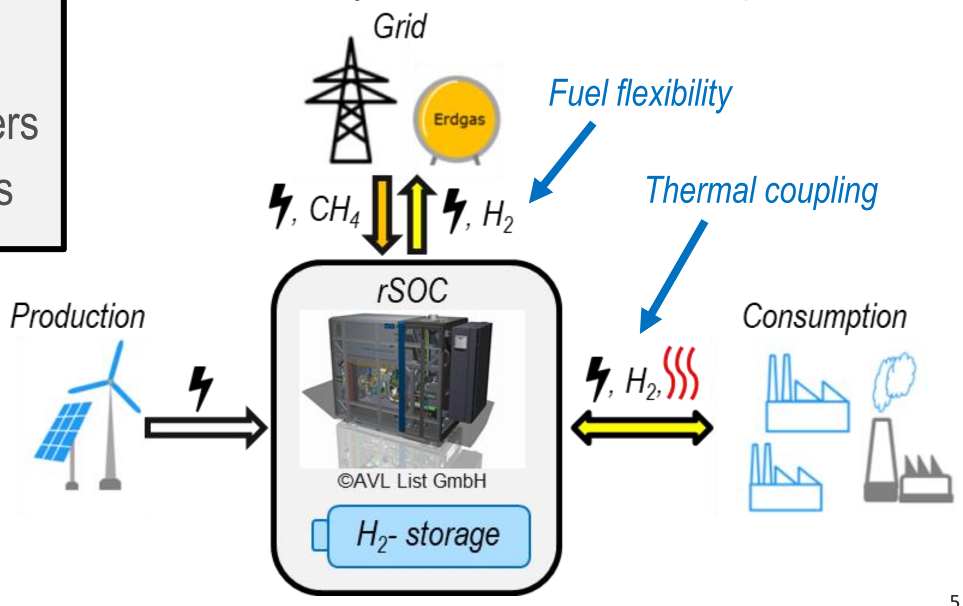
Conclusion:

We need an energy system that...

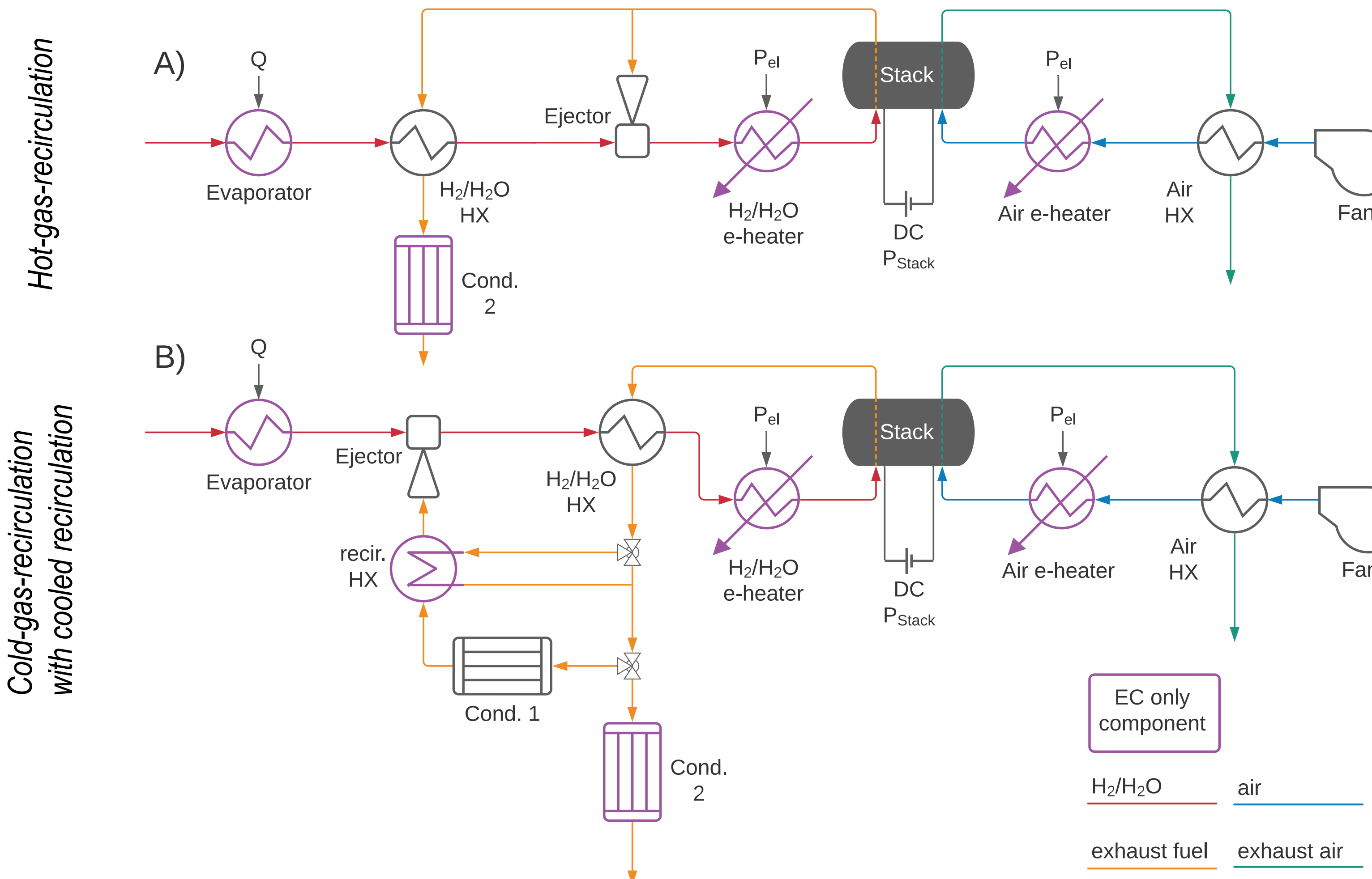
- … can provide flexibility with required time constants
- … is highly efficient

Possible Solution:

rSOC-Systems meet these requirements!



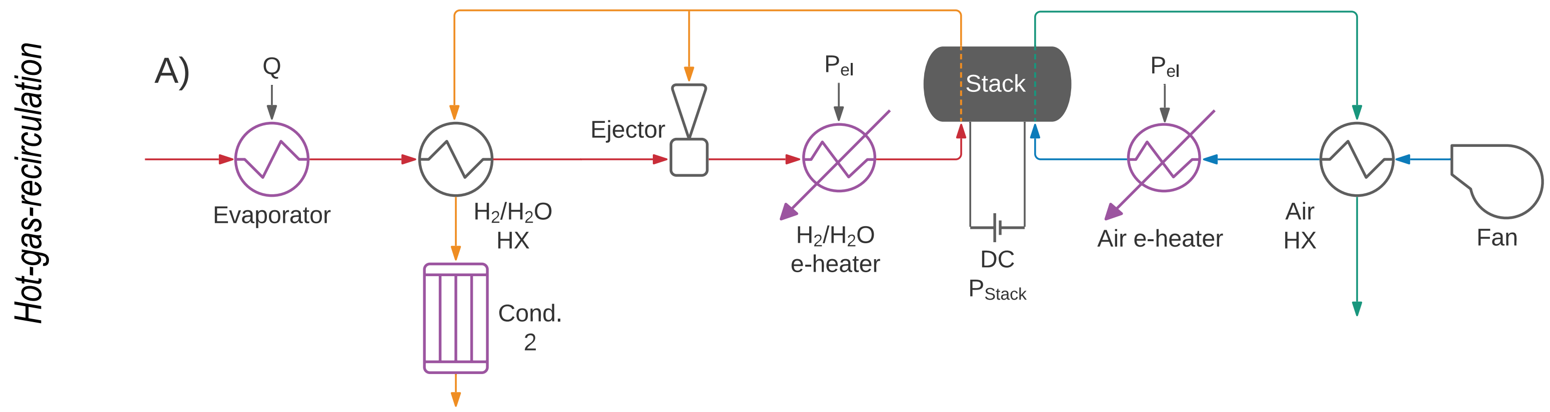
rSOC-System H_2-flowsheets



Further discussed flowsheets:

- Two options for place of recirculation (A, B)

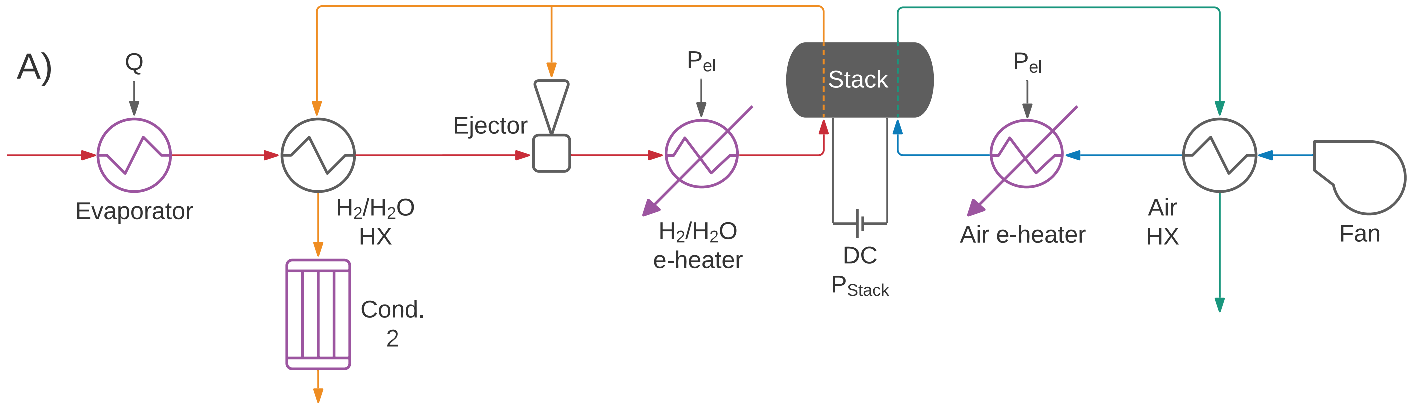
System Modelling approach



Component	Output	Input Parameter
System	H_2/H_2O mass flow	Fuel utilization, Stack current
	Recirculation mass flow	Recirculation rate
	Air mass flow (EC)	Air excess ratio (EC)
Stack	Stack characteristics	Temperature
Evaporator	Thermal power from change in enthalpy (5K superheating)	
Heat exchanger	Fluid temperatures	Pinch point ΔT, Heat exchanger constant
Condenser	Thermal power from change in enthalpy, condensation from saturation pressure and efficiency	Subcooling temperature
E-heater	Electric power (EC)	Temperature of gas
Fan	Electric power	Air excess ratio (EC), pressure drop, efficiency

System Efficiency and Scenarios

Hot-gas-recirculation



Scenarios of application:

Energy sector:

- No thermal interaction with environment
- Heat provided electrically

Industry sector scenario:

- Full thermal coupling – processes can provide waste heat and rSOC waste heat can be integrated

System Efficiency:

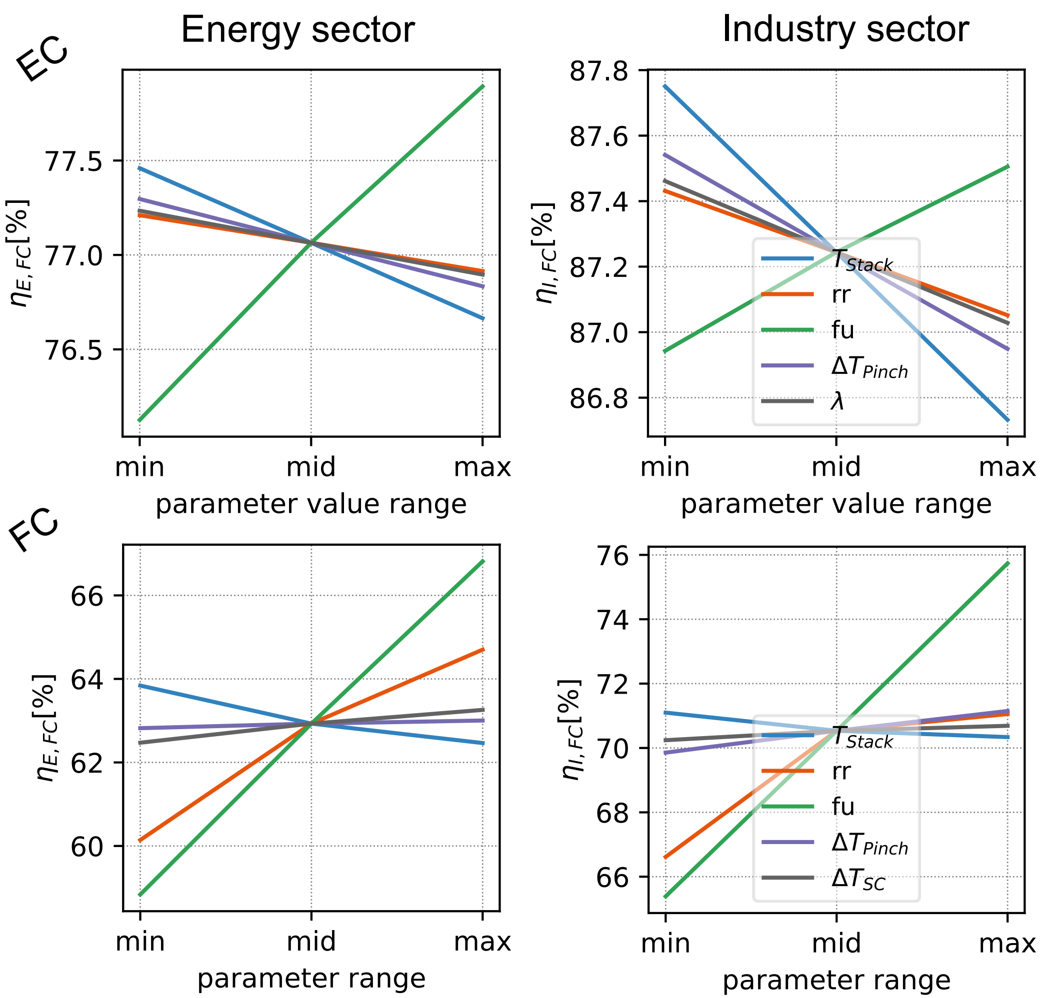
$$\eta_{EC} = \frac{P_{fuel}}{P_{Stack}+P_{fan}+P_{e-heater}+Q_{evaporator}}$$

$$\eta_{FC} = \frac{P_{Stack}(+Ex_{air}+Ex_{fuel}+Ex_{Condenser1})}{P_{Fuel}+P_{fan}}$$

If heat provided by waste heat of industry process, use it`s "quality" (Exergy):

$$Ex = Q * \left(1 - \frac{T_{ambient}}{T_Q}\right)$$

Sensitivity on system parameters

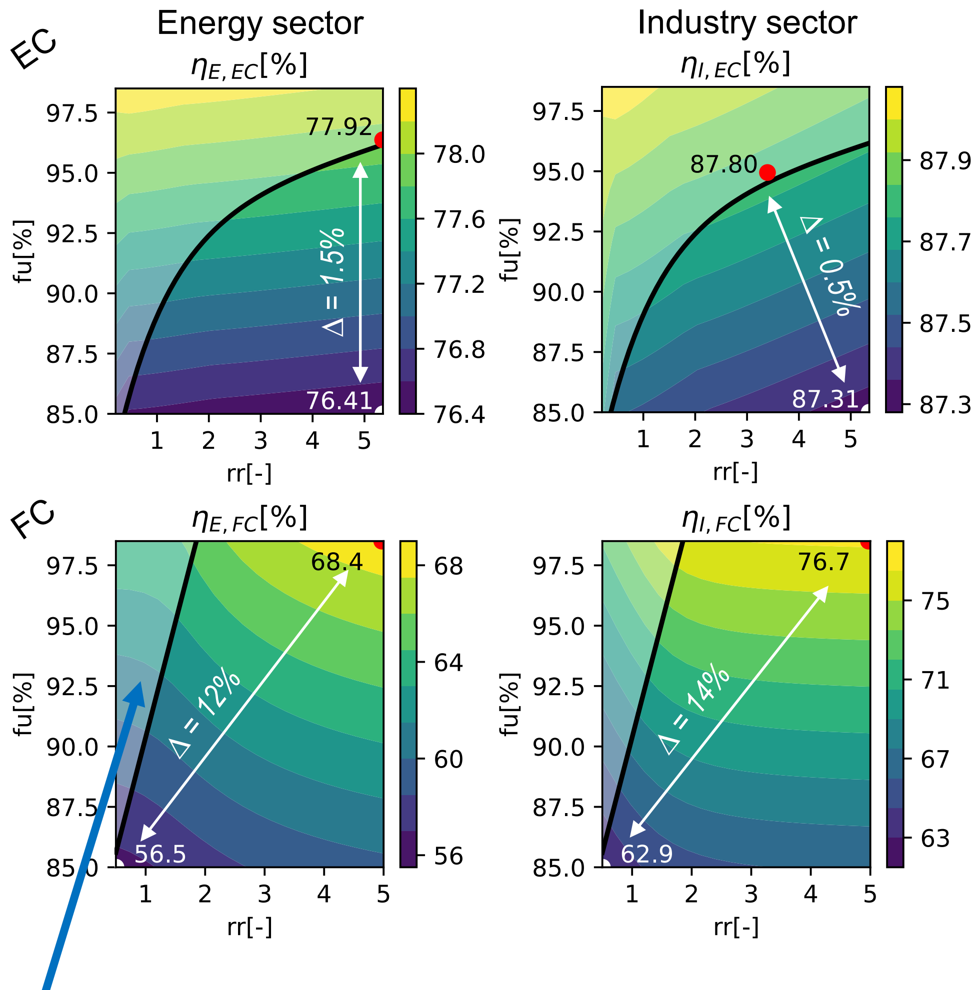


Observations:

- Increase in fuel utilization always beneficial
- Increase in recirculation rate beneficial for FC with rcond.
- Air excess ratio small
- T_{stack} small
- Small ΔT_{pinch} in EC and big in FC

Parameter	Min.	Max.
Stack temperature (T_{Stack}) [°C]	700	800
Recirculation rate (rr) [-]	0.5	5
Fuel utilization (fu) [-]	0.85	0.985
Fuel HX (ΔT_{Pinch}) [°C]	5	15
Air HX (EC / FC) (ΔT_{Pinch}) [°C]	5 / 70	15 / 90
Air excess ratio (EC only) (λ) [-]	0.5	1.5
Subcooling temp. (FC only) (ΔT_{SC}) [°C]	50	70

Best choice for system parameters



Greyed region is non accessible because of stack limitations!

Observations:

- High recirculation allows high fuel utilization
- EC operation is much less effected by parameter changes than FC operation
- Thermal coupling in the industry scenario has big impact on the efficiency

$$\eta_{EC} = \frac{P_{fuel}}{P_{Stack}+P_{fan}+P_{e-heater}+Q_{evaporator}}$$

$$\eta_{FC} = \frac{P_{Stack}(+Ex_{air}+Ex_{fuel}+Ex_{Condenser1})}{P_{Fuel}+P_{fan}}$$

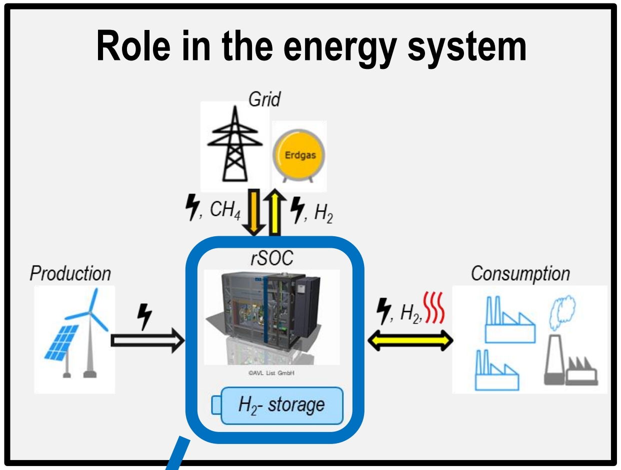
Conclusions for the system design:

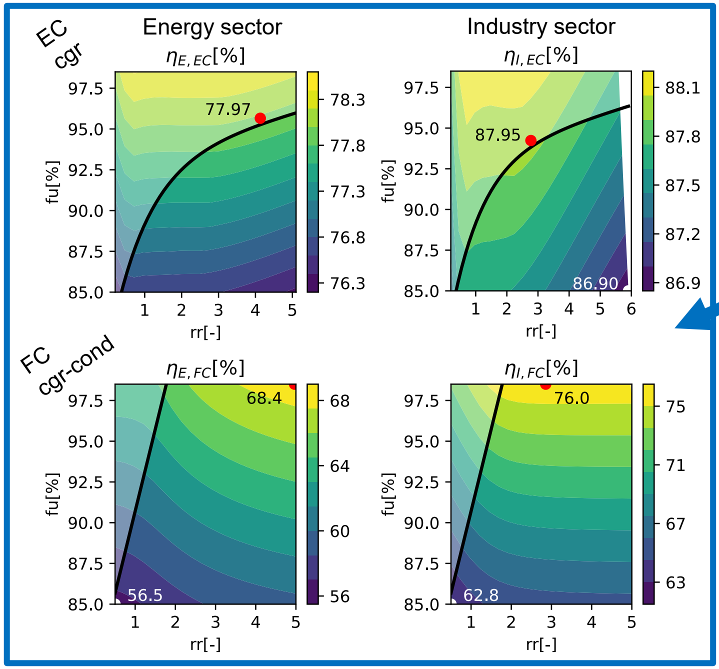
- The rSOC-System should be able to operate in FC mode with best values for operation parameters.

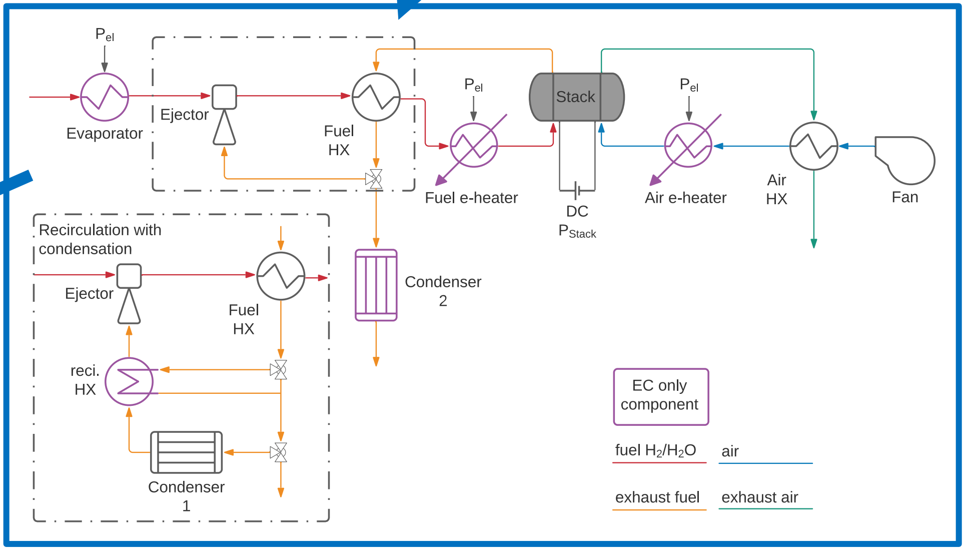
Summary

Review of Content:

- Motivation and Role in the energy system
- Flowsheets
- Modelling approach and parameters
- Best values for parameters
  - T_{stack} small
  - Small ΔT_{pinch} in EC and big in FC
  - High recirculation rates and fuel utilization

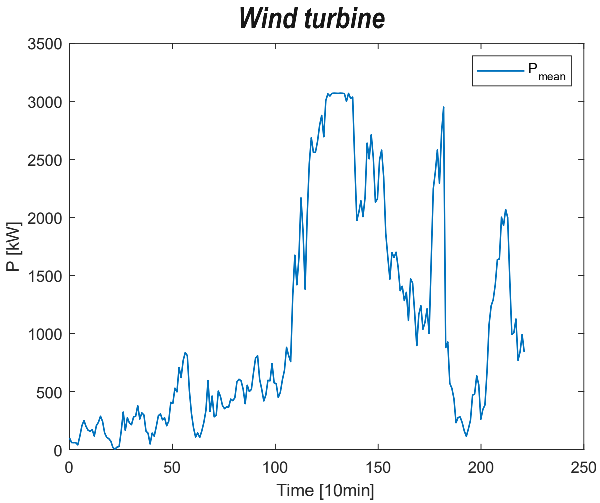


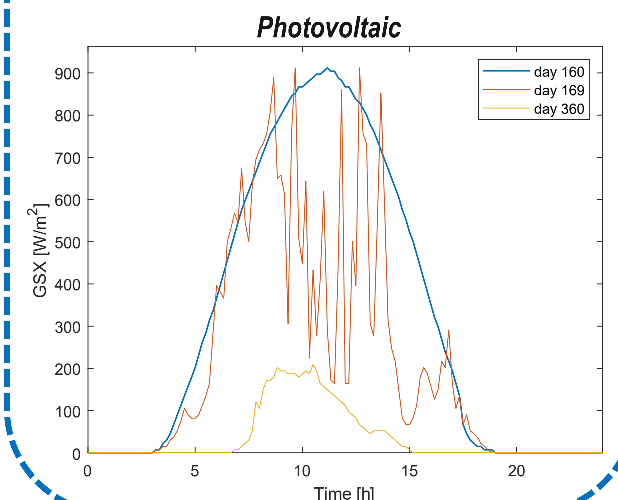




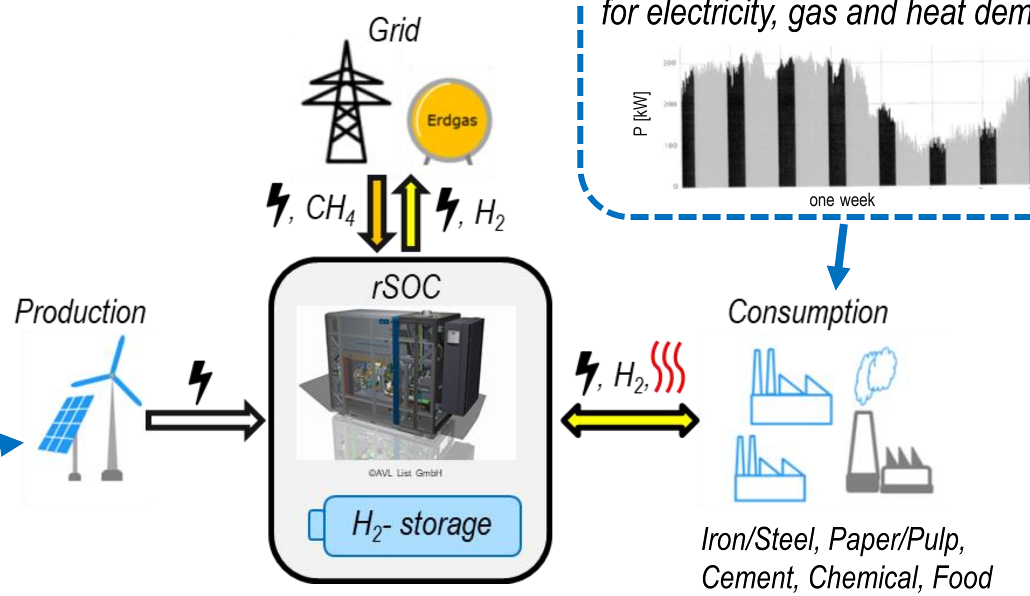
Outlook: Application scenarios

Time series of production for given locations





Representative/synthetic time series for electricity, gas and heat demand.



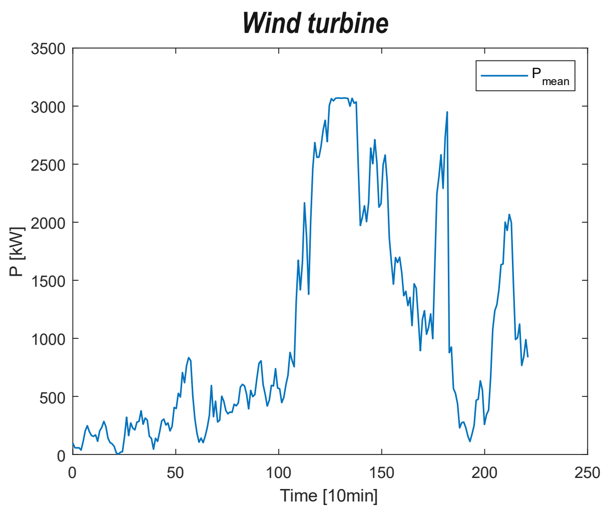
Simulation of application in synthetic set up:

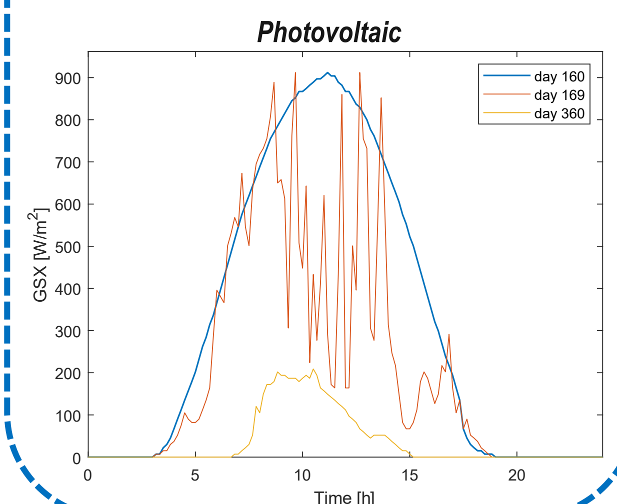
- Time resolved calculation
- Behaviour like real system
- Part load characteristics
- Different flowsheet configurations

Operational optimisation

Outlook: Application scenarios

Time series of production for given locations





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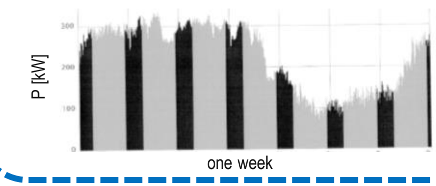
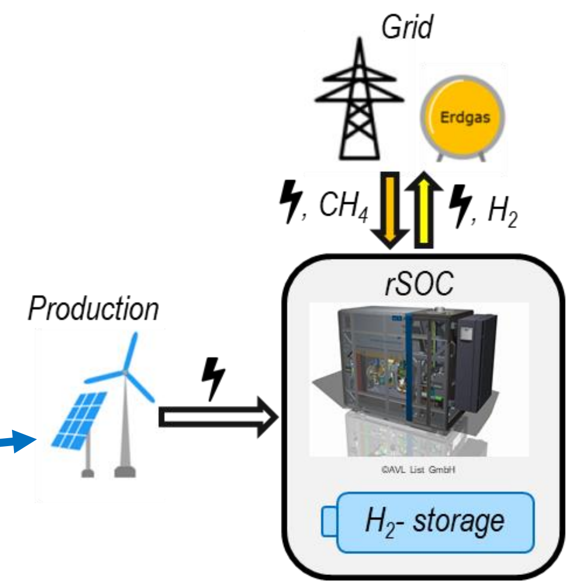




Questions to be answered:

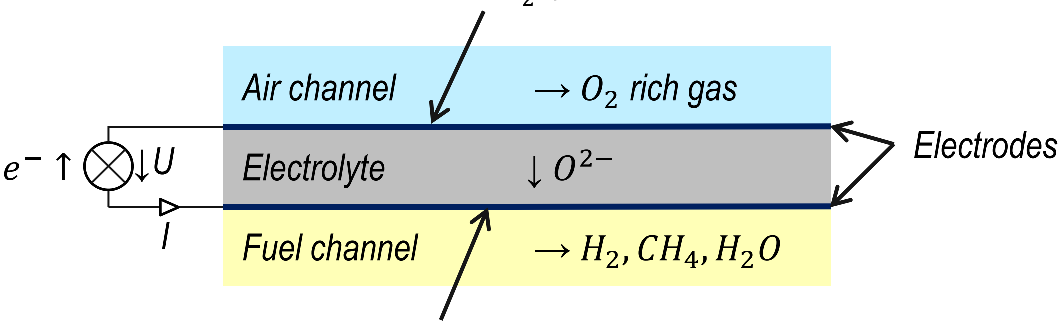
What efficiency can be achieved

- What efficiency can be achieved in a real set up?
- What dynamic behaviour is desired?
- Sensitivity on system parameters (ramp rates, fu, rr , T)
- What flowsheet should be used in which scenario?

Basics of rSOC

Electricity production in the cell (SOFC):

Surface reaction: $O_2 + 4e^- \rightarrow 2O^{2-}$



Reactions: $2O^{2-} \rightarrow O_2 + 4e^-$

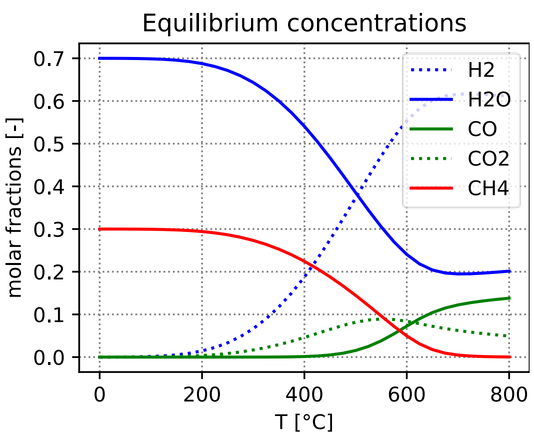
$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$

Nernst Equation:

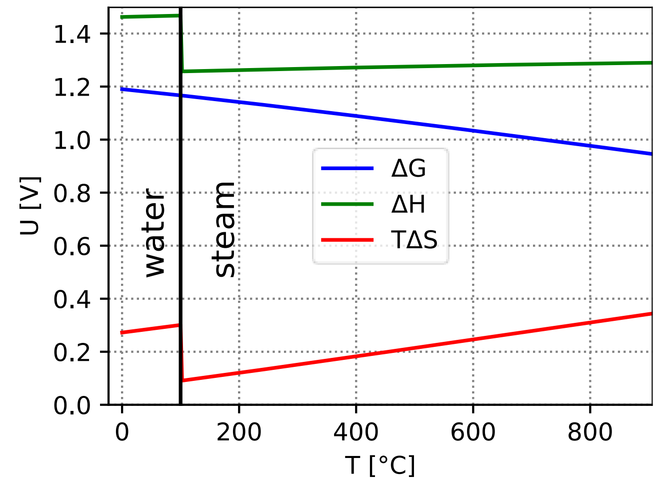
$$U(T,p,x) = \frac{\Delta G}{n_e F}$$

$$\Delta G = \Delta H - T\Delta S$$

$$= \Delta G^0(T) + R_G T ln\left(\frac{x_{H_2O}}{x_{H_2} x_{O_2}^{0.5}}\left(\frac{p_0}{p}\right)^{0.5}\right)$$



Fuel flexibility due to high temperatures



Waste heat utilization for electrolysis

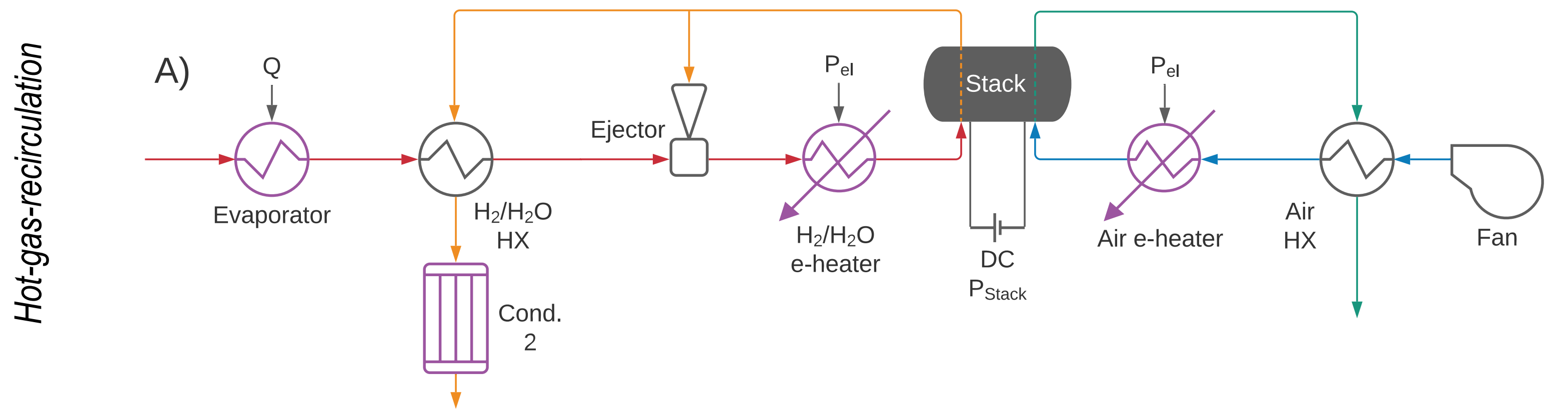
High temperature waste heat in fuel cell operation

Sabatier reaction: $CO_2 + 4H_2 \xleftrightarrow{-165kJ/mol} CH_4 + 2H_2O$

Shift reaction: $CO + H_2O \xleftrightarrow{-41,2kJ/mol} CO_2 + H_2$

CO Methanization: $CO + 3H_2 \xleftrightarrow{-206,2kJ/mol} CH_4 + H_2O$

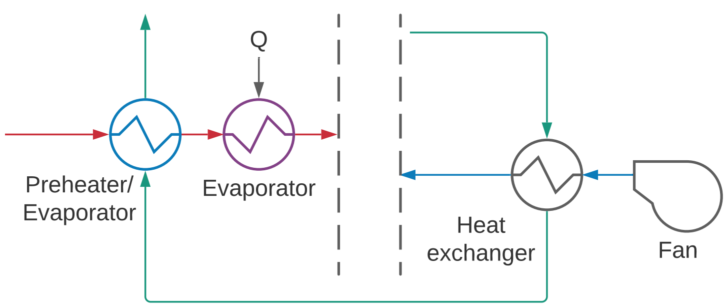
rSOC-System H_2-flowsheets



Improvements:

Electrolysis Cell (EC):

- Enhanced internal heat recovery



Fuel Cell (FC):

- High temperature heat extraction