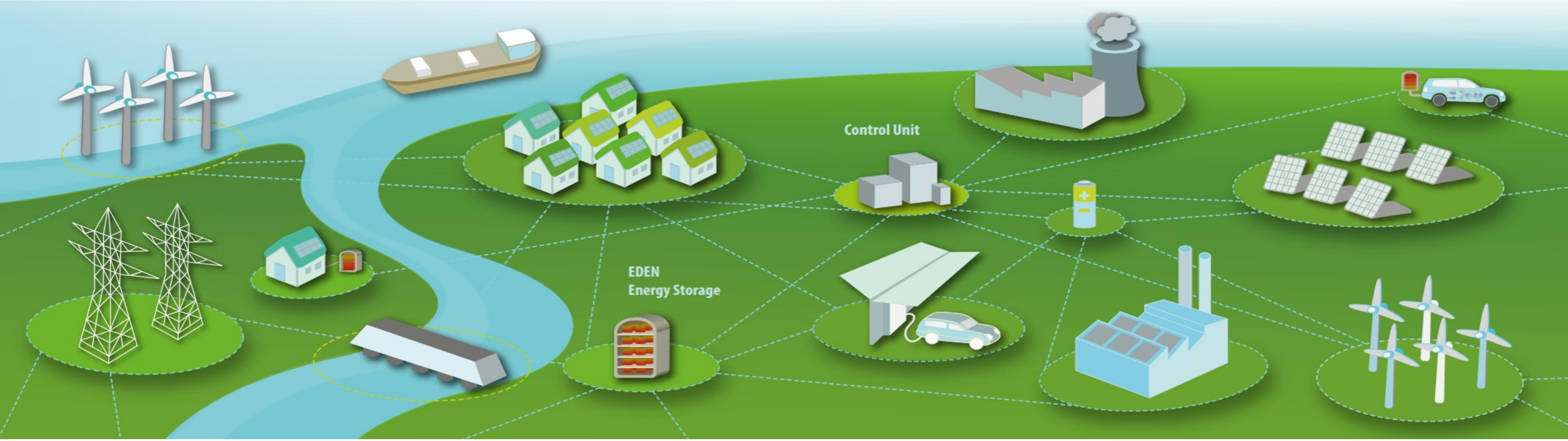
Design and modeling of a hybrid reversible solid oxide fuel cell – organic Rankine cycle

ORC 2017
4th International Seminar on Organic Rankine Cycle Power Systems



ARES

FONDAZIONE BRUNO KESSLER

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Summary

- What Is FBK and ARES
- Energy research in ARES
- Overview of the analysis
- The Experience On Hydrogen Storage: SOE and SOFC layouts
- The possible WHR integration
- Description of the steady state models
- Optimization process
- Conclusions
- Working in Progress

What Is FBK and ARES

SOLUTION PROVIDERS with approach oriented to **EXCELLENCE**

More than **350 researchers**; **220 students**, PhD and visiting professors; **8 hubs**; **7 facilities**; **30 spin-offs e start-ups**; >100 scientific events per year.

CMM
CENTER FOR MATERIALS AND MICROSYSTEMS

ARES
APPLIED RESEARCH ON ENERGY SYSTEM

1 of the 8 FBK's hub > **150 employees; 109 researchers**; **41 students**, PhD and visiting professors; **6 research units** (ARES one of these).


Scientific and Technological Hub


ECT

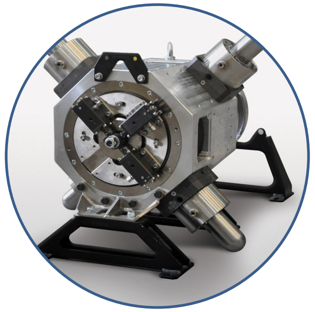

Humanities Hub

For more info:
www.fbk.eu
cmm.fbk.eu

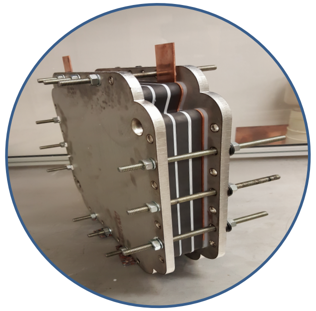
Energy Research In ARES

RESEARCH PILLARS


Concentrated Solar Power

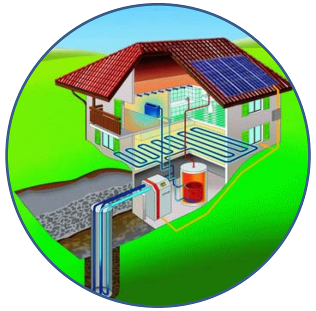

Thermodynamic Cycles


Hydrogen Production & Storage


Batteries

SUPPORT to the INDUSTRY and LOCAL AREA


Technology innovation


Modelling of Energy scenarios and transitions


Efficiency and Sustainability in Industries

PLATFORMS of INTEGRATION

Smart Buildings & Communities

Smart Energy Systems

Overview of the analysis

THE GOAL OF THE ANALYSIS

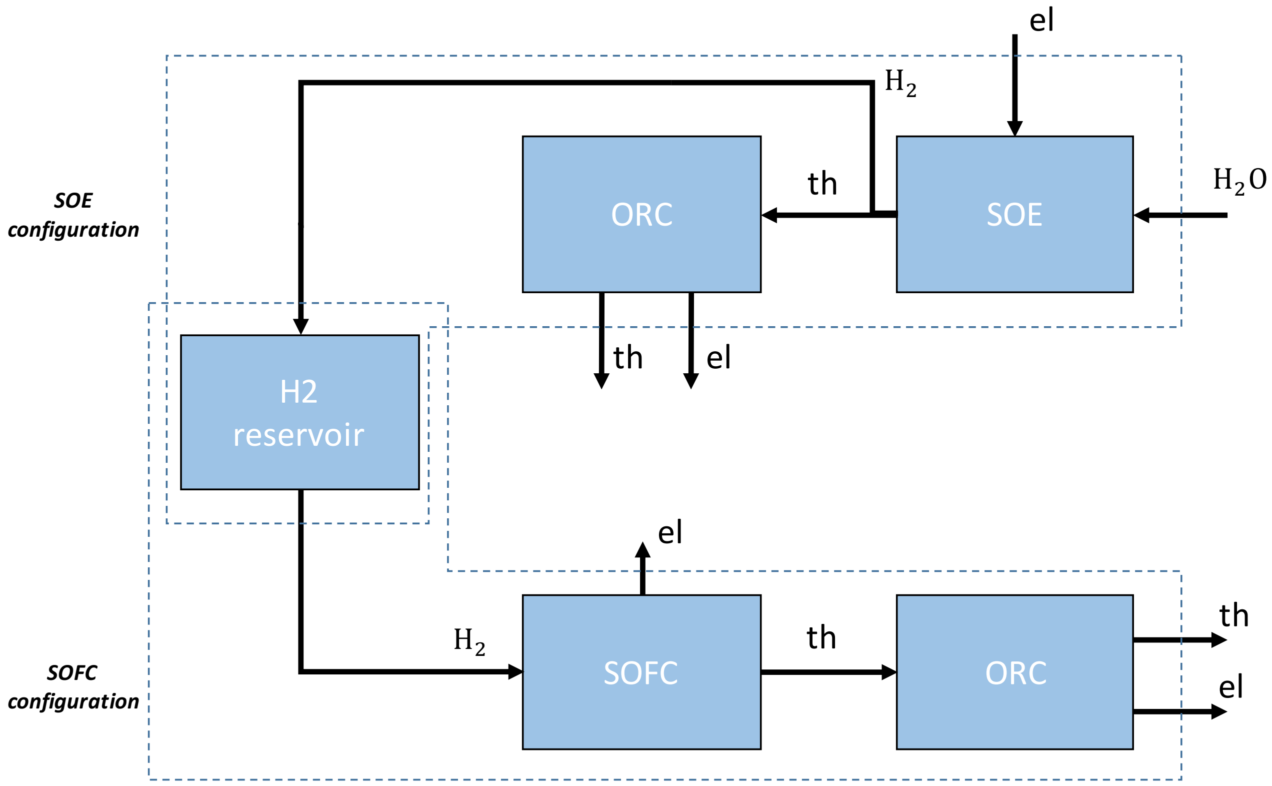
- **Reversible Solid Oxide Fuel Cell and Solid Oxide Electrolyzer** (rSOFC/SOE) system coupled with ORC → **Exploiting waste heat coming from the hydrogen conversion** process.

THE APPROACH

- **Simplified approach to implement the Steady State (SS)** behavior of the whole integrated layout.

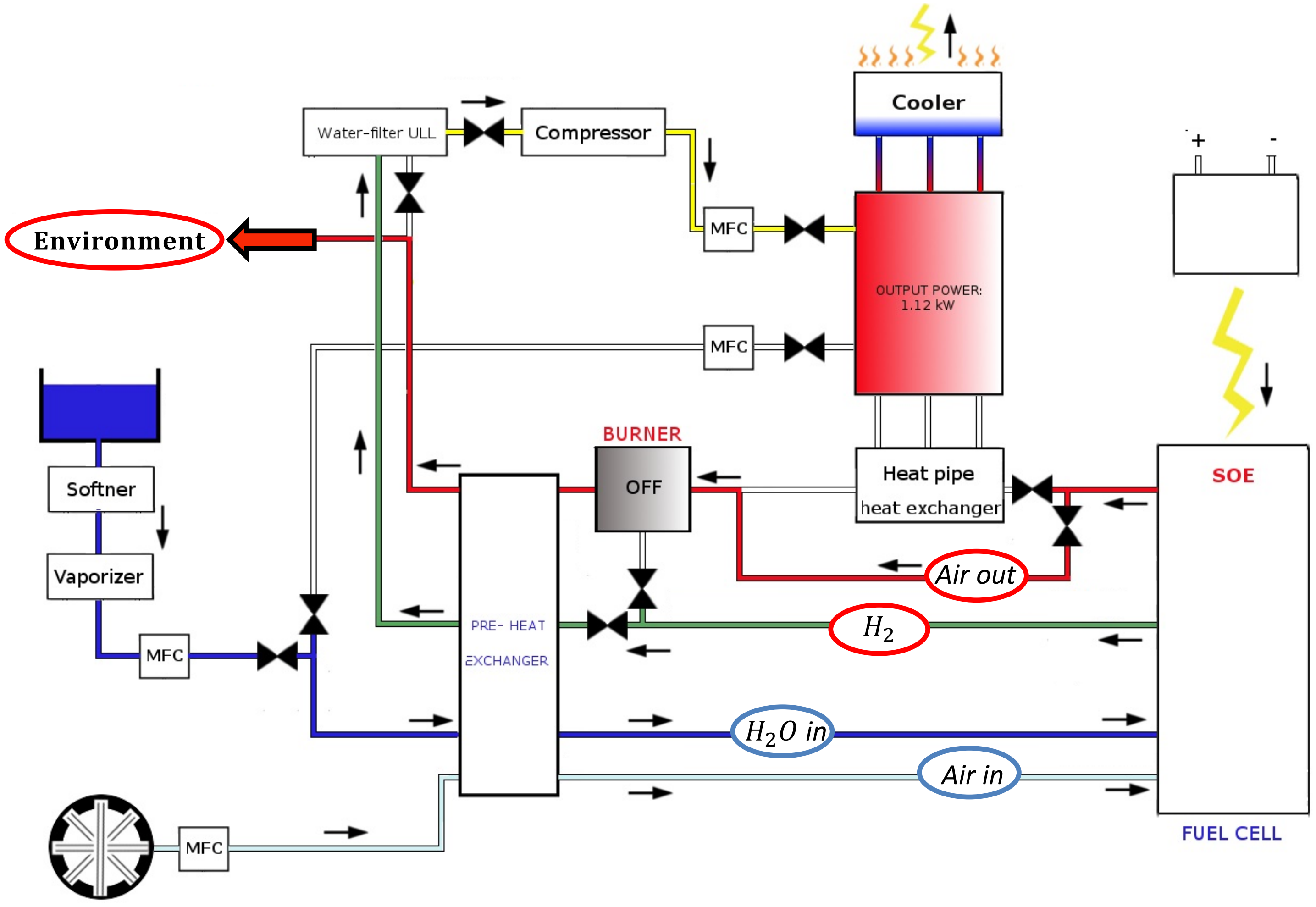
THE SOLUTION

- **A model built through experimental data** is used to improve the system layout with a feasible waste heat recovery solution.



The Experience On Hydrogen Storage From Eden Project*: SOE Configuration

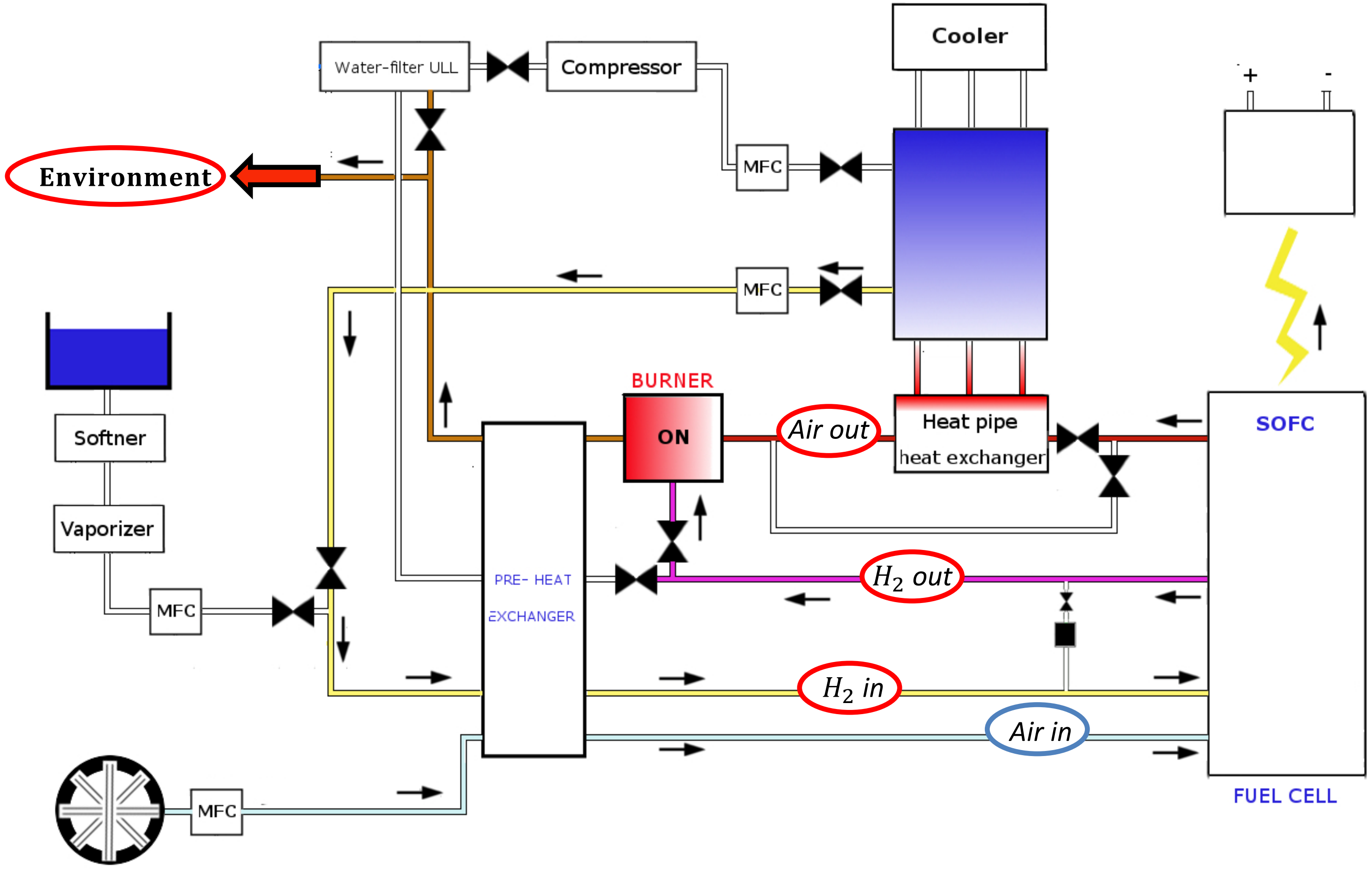
- Integration of reversible SOE with a **magnesium-based** hydrogen **storage**.
- **Solid state storage** requires to be cooled down to **absorb hydrogen**.
- **High temperature air flux** (@ 800 ºC) from the electrolyzer is **used to heat up the incoming air** for the electrolysis. **Then, released to the environment.**
- **High temperature H_2** (@ 800 ºC) coming from the electrolyzer **used to heat up the** incoming **water flux** for the electrolysis**.**
- Cooled H_2 **is then absorbed** by the magnesium hydrides.



*The research leading to these results has received funding from the European union's seventh framework programme (FP7/2007-2013) for the fuel cells and hydrogen joint technology initiative under grant agreement n° 303472

The Experience On Hydrogen Storage From Eden Project*: SOFC Configuration

- Integration of reversible SOFC with **magnesium-based** hydrogen **storage**.
- **Solid state storage** requires heat to **desorb hydrogen**.
- **Waste heat and unconverted hydrogen** coming from the fuel cell outlet used **to warm up** (@ 300 ºC) **the hydrogen tank** for the desorption process.
- A catalytic burner converts the **residual hydrogen to preheat** the fluxes of **hydrogen and air** going to the cell.
- The **exhaust gases** are **released to the ambient** with a considerable level of enthalpy.



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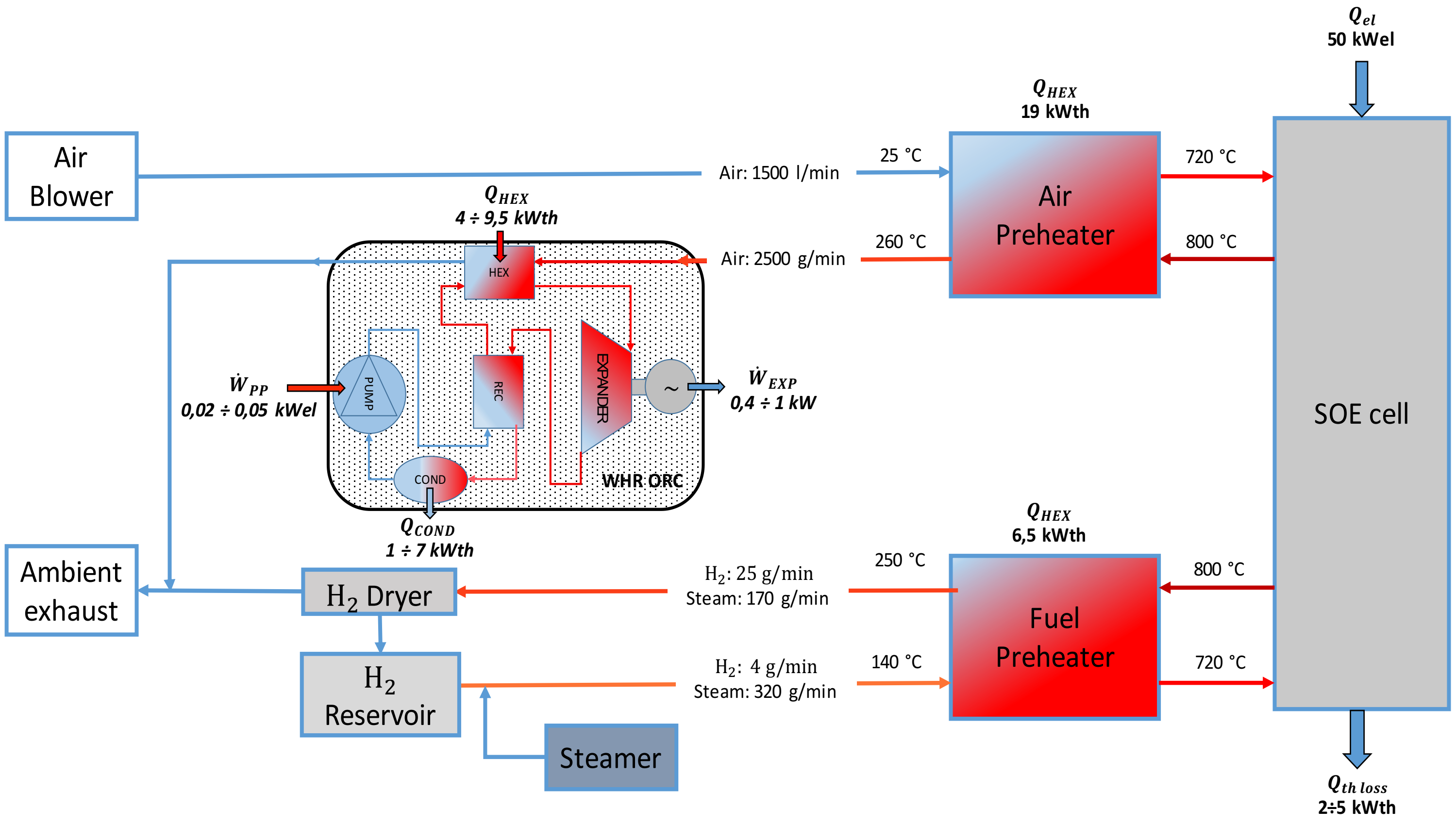
ORC integration within the SOE layout

- **WHR exchanger at the air preheater** outlet has different advantages:
  - ↑ ***No modifications of the system layout***.
  - ↑ *Exhaust stream composed by air.* ***NO*** *necessity of* ***high-cost exchanger materials.***
- **Alternative position at the hydrogen dryer**, to recover the steam released to the ambient:
  - ↑ ***Latent heat available*** *in this part of the circuit.*
  - ↓ ***Flow rate too low*** *for a proper recover.*

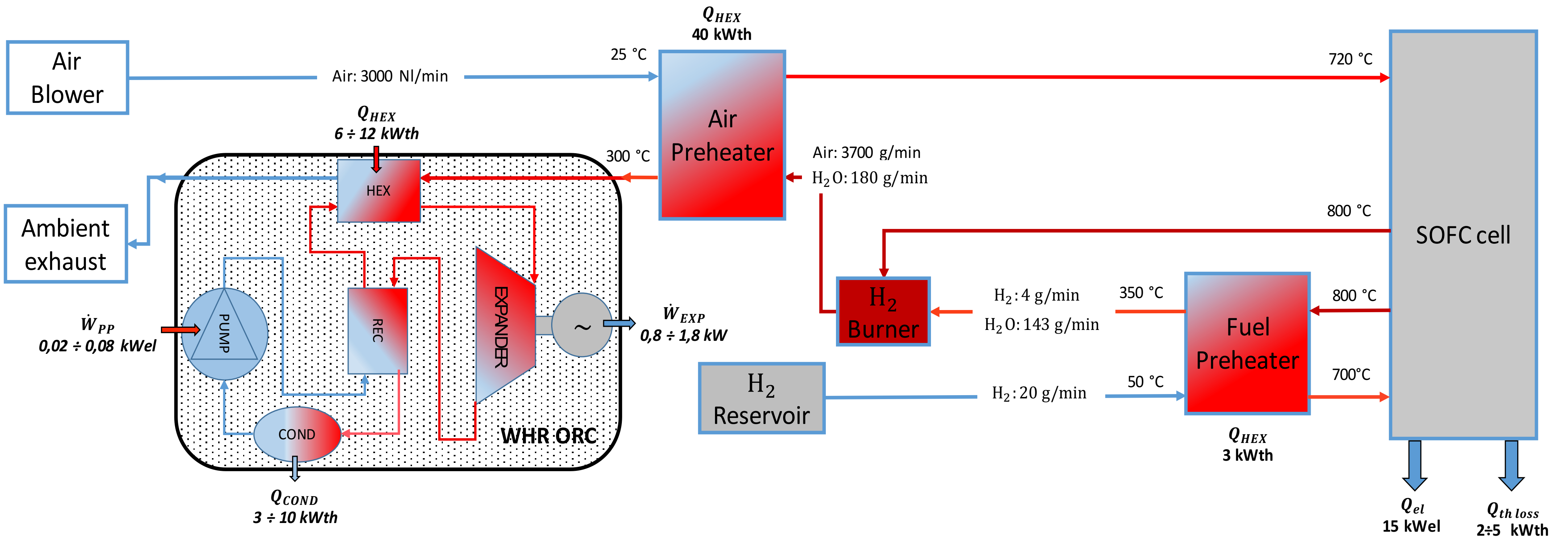


BoP for a typical 50 kWel SOE/15 kWel SOFC reversible system with possible WHR implementations.

All the layout's auxiliaries are also depicted
(Source: EDEN EU project, h2eden.eu website, 2015)

ORC integration within the SOFC layout

- For the SOFC configuration, **the mass flow rate is higher than the SOE solution** due to the compound of air and water formed by the hydrogen **lean catalytic combustion**.

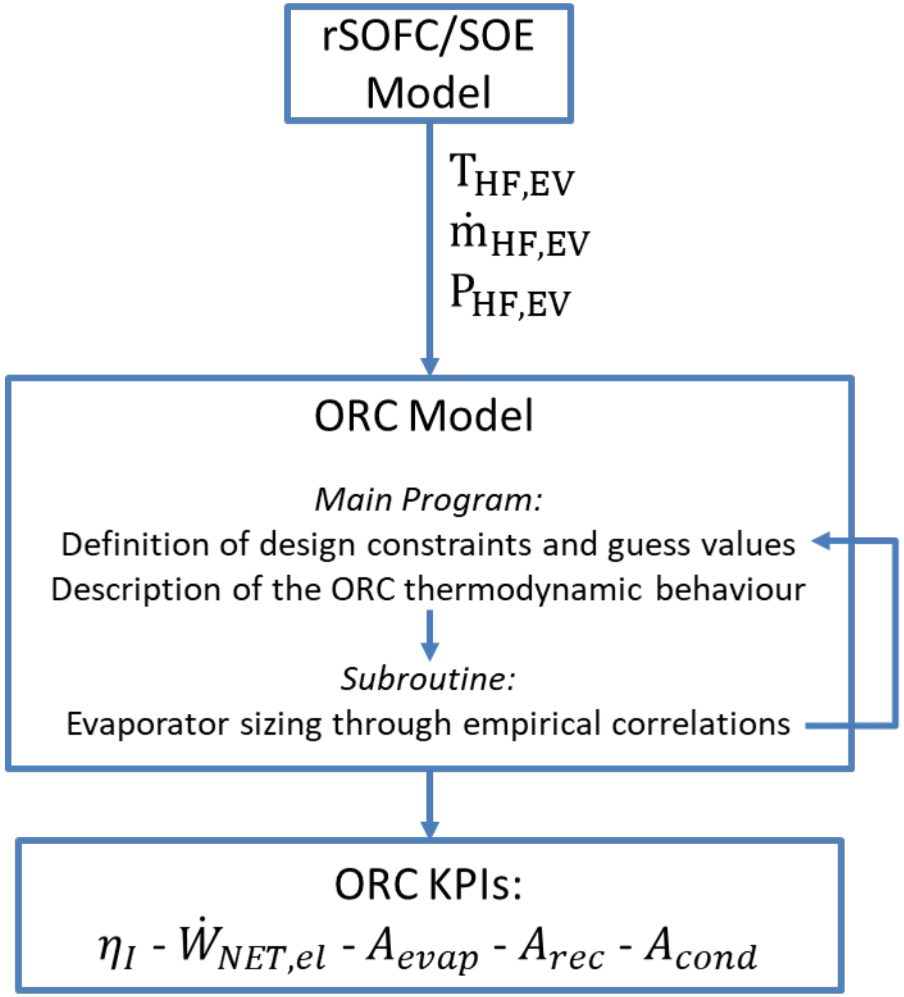


BoP for a typical 50 kWel SOE/15 kWel SOFC reversible system with possible WHR implementations.

All the layout's auxiliaries are also depicted
(Source: EDEN EU project, h2eden.eu website, 2015)

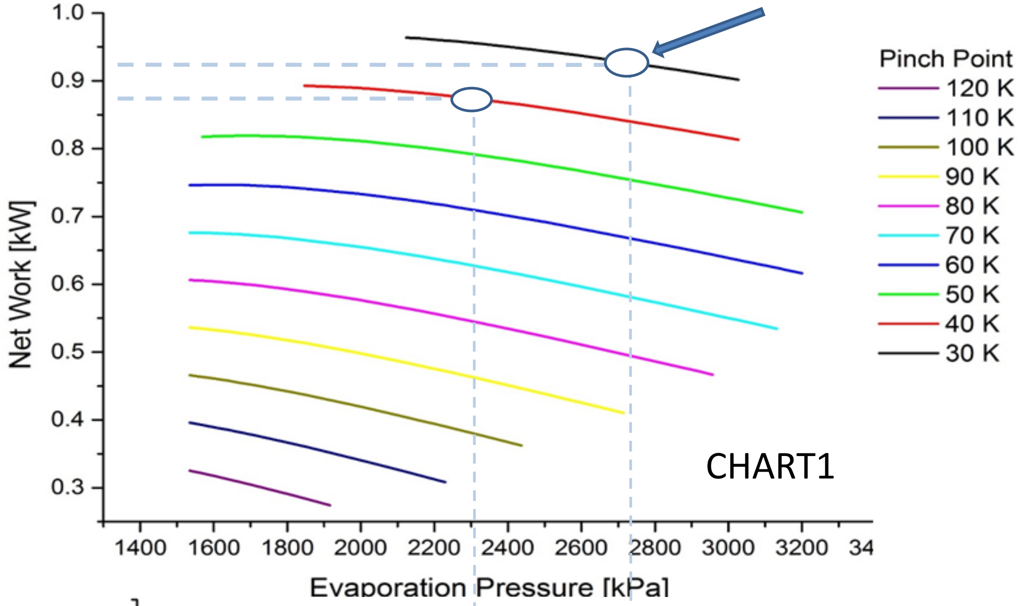
Steady State Model

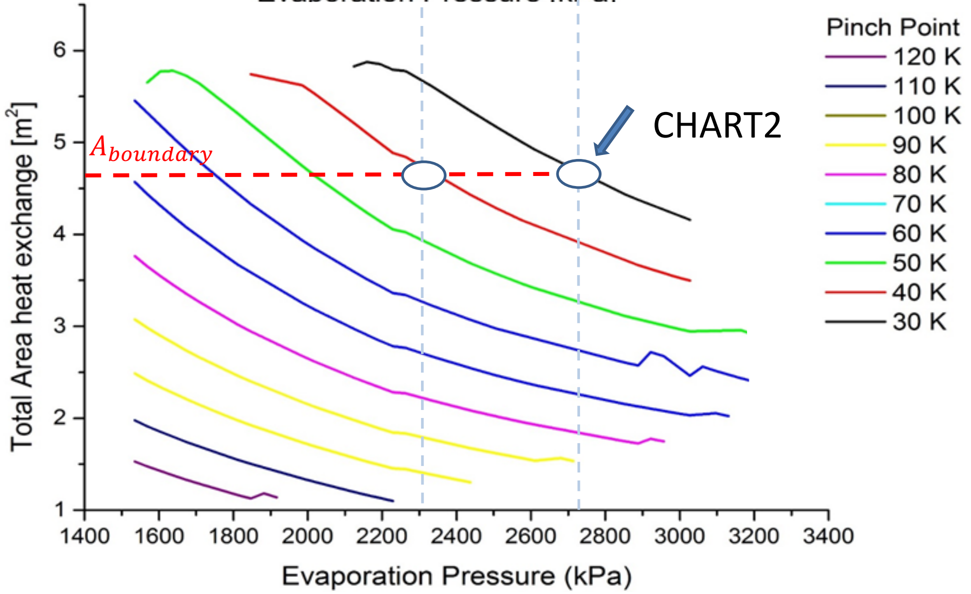
- **Steady State Model** based on a thermodynamic BoP written using the commercial software **Engineering Equation Solver (EES)**.
- **Waste flux thermodynamic data** are provided as **outputs by the SOFC/SOE model**.
- **Input for the ORC design model**. The heat exchangers total areas are defined with a previously available discretized model.
- Efficiency (η_I), Net power ($\dot{W}_{NET,el}$) and total heat exchanger area (A_{evap} - A_{rec} - A_{cond}) are the model **Key Performance Indicators.**



Optimization For The SOE WHR Implementation

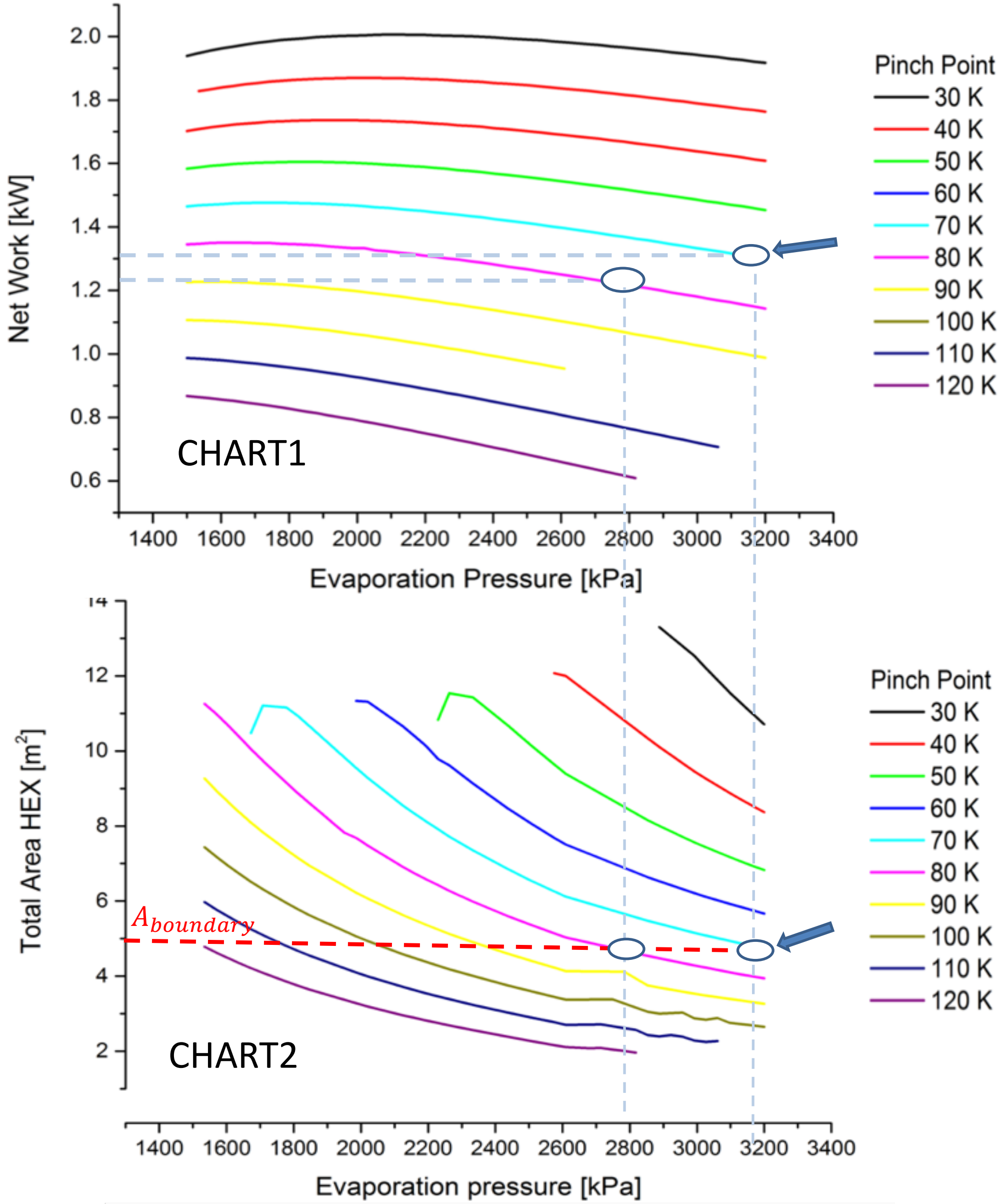
- CHART1: **Power output** VS **Evaporation pressure**.
- CHART2: **Total heat exchanger area** VS **Evaporation pressure**.
- **Maximization of the net power** and **total heat exchangers surface,**
  - **Simulation avoids very low pinch point**, which would lead to very high heat exchanger surfaces, despite the optimal performance.
- **A compromise between the three variables** (pressure, heat exchangers area and power output) needs to be achieved.
- **Possible recovery of the waste heat** coming from the air-to-air hot outlet, convertible in a **net power up to 0.95 kWel**.





Optimization for the SOFC WHR implementation

- CHART1: **Power output** VS **Evaporation pressure**.
- CHART2: **Total heat exchanger area** VS **Evaporation pressure**.
- Consider the previous **trade-off between maximum power** and **total heat exchanger area**
- Theoretical **maximum net power of 1,3 kW** with a pinch point of 70K.
- **Higher power available compare to the SOE** model due to the **higher hot flow rate** of mixed air and steam available in the SOFC configuration.



Conclusions

- **SOE/ORC: possible recovery** of the waste heat coming from the **air-to-air recuperator hot outlet**.
- Convertible in a **net power up to 0.95 kWel**.
- Equal to a theoretical **overall electric efficiency improvement of 2%**.

- **SOFC/ORC:** Net power available equal to **1.3 kW** considering the stream of **combustion gases leaving the preheater.**
- Theoretical **overall electric efficiency improvement of almost 8%.**

- Improvement of the overall efficiency for the SOE and SOFC systems are theoretically feasible without completely redesigning the system layout.

Working in Progress

WHAT WE HAVE DONE:

- **Feasibility study** of a **small ORC system** to recover heat released by a **rSOFC/SOE system** with a **solid state hydrogen storage**.
- **Analysis performed** in a steady state model with the target of **improving power output** and overall **system efficiency.**
- **Preliminary analysis** has been carried out on both **SOFC and SOE layouts**.
- **The model merges** the model related to the **hydrogen layout and the ORC part.**
- **Optimization process** of the **net power** available from the ORC machine, keeps count of the technological constraints of total **heat exchanger surface**.

WHAT WE ARE GOING TO DO:

- Validate the analysis with a detailed **dynamic model.**
- Dynamic simulations for **transient regimes while switching from SOE to SOFC and vice-versa**.
- **Economic analysis** on the impact of the WHR system on the overall layout.

THANK YOU FOR THE ATTENTION

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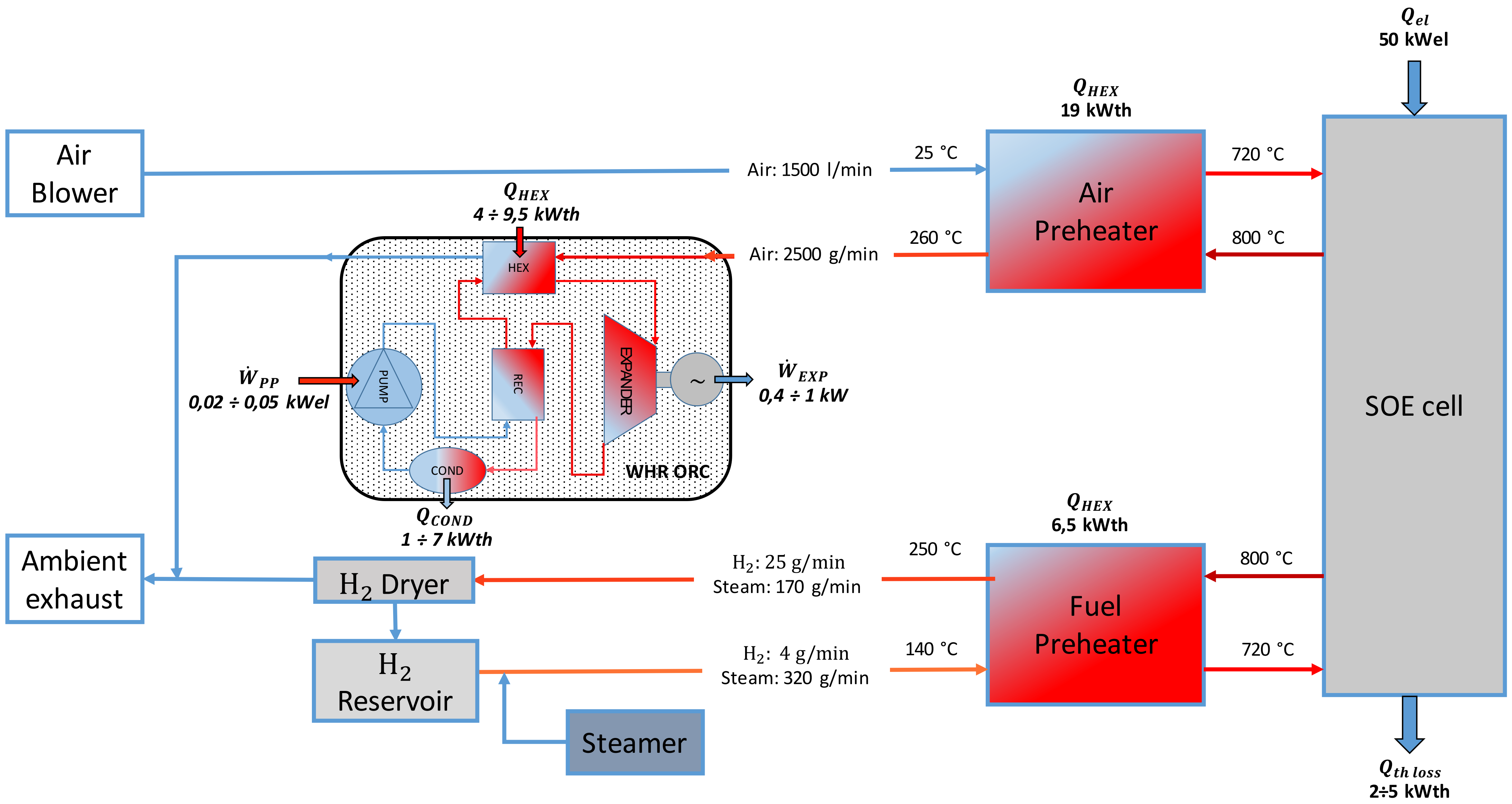
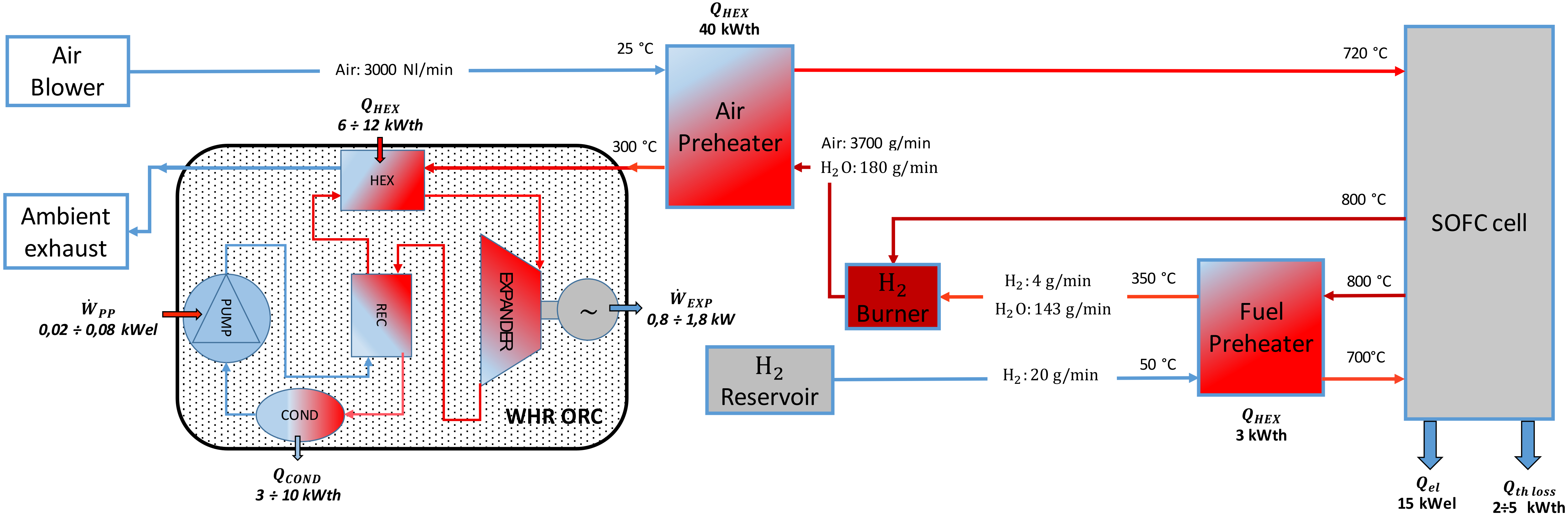
BoP SOE/ORC



Q_{el}
50 kWel
Q_{HEX}
19 kWth
Air Blower
Air: 1500 l/min
25 °C
Air Preheater
720 °C
Q_{HEX}
4 ÷ 9,5 kWth
HEX
Air: 2500 g/min
260 °C
800 °C
$\dot{W}_{PP}$
0,02 ÷ 0,05 kWel
PUMP
REC
EXPANDER
~
$\dot{W}_{EXP}$
0,4 ÷ 1 kW
SOE cell
COND
WHR ORC
Q_{COND}
1 ÷ 7 kWth
Q_{HEX}
6,5 kWth
Ambient exhaust
H_2 Dryer
H_2: 25 g/min
Steam: 170 g/min
250 °C
800 °C
Fuel Preheater
H_2 Reservoir
H_2: 4 g/min
Steam: 320 g/min
140 °C
720 °C
Steamer
$Q_{th\ loss}$
2÷5 kWth

BoP SOFC/ORC


Air Blower
Air: 3000 Nl/min
25 °C
Q_{HEX} 40 kWth
Air Preheater
720 °C
SOFC cell
Q_{HEX} 6 ÷ 12 kWth
300 °C
Air: 3700 g/min
H_2O: 180 g/min
Ambient exhaust
HEX
REC
EXPANDER
PUMP
COND
WHR ORC
~
$\dot{W}_{PP}$ 0,02 ÷ 0,08 kWel
$\dot{W}_{EXP}$ 0,8 ÷ 1,8 kW
Q_{COND} 3 ÷ 10 kWth
800 °C
H_2 Burner
H_2: 4 g/min
H_2O: 143 g/min
350 °C
Fuel Preheater
800 °C
700°C
H_2 Reservoir
H_2: 20 g/min
50 °C
Q_{HEX} 3 kWth
Q_{el} 15 kWel
$Q_{th\ loss}$ 2÷5 kWth

Correlations

Plate heat exchangers are assumed to be used in the ORC.
The heat exchangers total areas are defined with a discretized model.

- Thonon's equation [16] is used for the single-phase zones:

$$\text{Single phase: } Nu = C\ Re^n\ Pr^n$$

- Boiling heat transfer correlation is derived from [17]:

$$\text{Two phase boiling heat transfer coefficient: } h_{tp,ev} = C\ h_{liquid}\ Bo^{0.5}$$

- Kuo correlation [18] is used to describe the condensation process:

$$\text{Condensation heat transfer coefficient: } h_{tp} = C\ (0.25Co^{-0.45}\ FR_l^{0.25} + 75Bo^{0.75})$$

[16] B. Thonon, "Recent research and developments in plate heat exchangers," Fuel and Energy Abstracts 36, p. 361, 1995.
[17] Y. Hsieh and T. F. Lin, "Saturated flow boiling heat transfer and pressure drop of refrigerant R-410A in a vertical plate heat exchanger," International Journal of Heat and Mass Transfer 45, pp. 1033-1044, 2002.
[18] W. S. Kuo, Y. M. Lie, Y. Y. Hsieh and T. F. Lin, "Condensation heat transfer and pressure drop of refrigerant R-410A flow in a vertical plate heat exchanger.," International Journal of Heat and Mass Transfer 48, pp. 5205-5220, 2005.

Hypothesis

ORC technical parameters	SOFC/SOE technical parameters
$T_{amb} = 20°C$	$\Delta P_{SOFC,air}$ = 2 kPa
$T_{cond} = 15°C$	$\Delta P_{SOE,air}$ = 1,5 kPa
$P_{cond} = 2$ bar	$\Delta P_{SOFC,fuel}$ = 1 kPa
$\eta_{is,exp} = 0,85$	$\Delta P_{SOE,fuel}$ = 2 kPa
$\eta_{el,mec,exp} = 0,85$	$\Delta P_{air,preh}$ = 2 kPa (experimental data)
$\eta_{exp,vol} = 0,85$	
$\eta_{is,pp} = 0,85$	
$\eta_{el,mec,pp} = 0,90$	
Working Fluid = R245fa	
β = 45º	