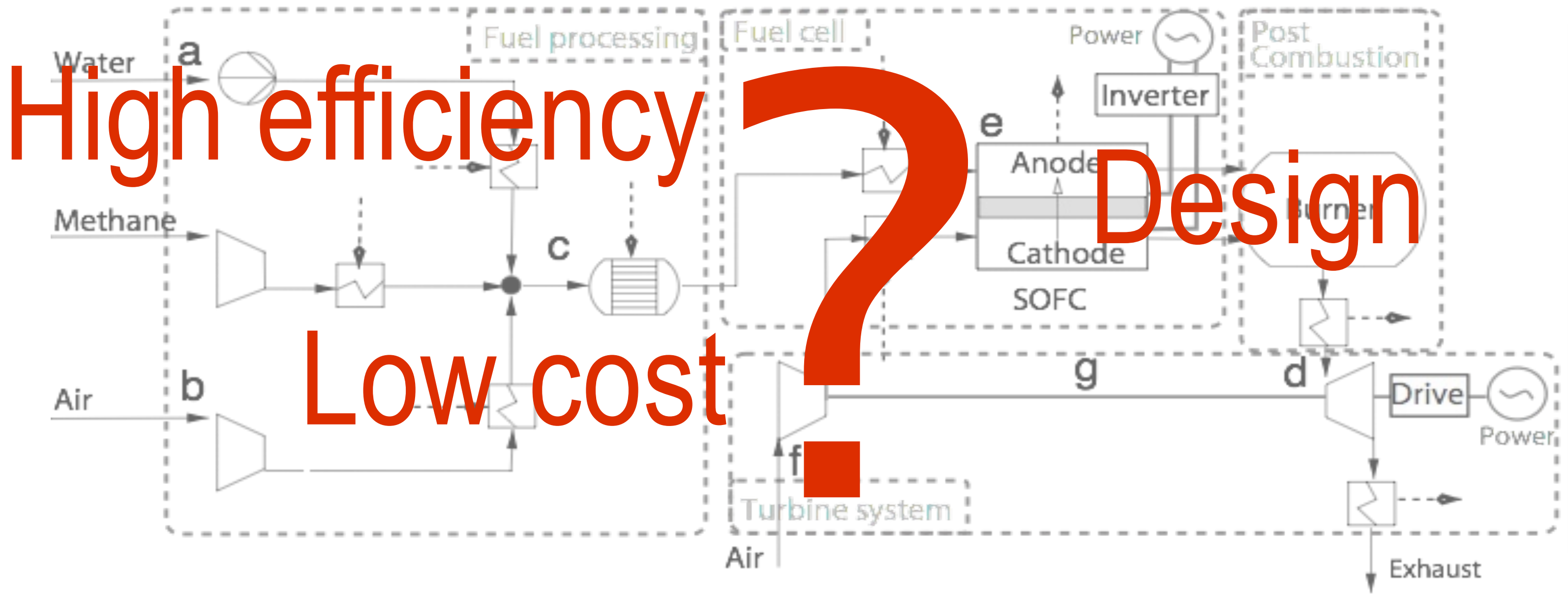
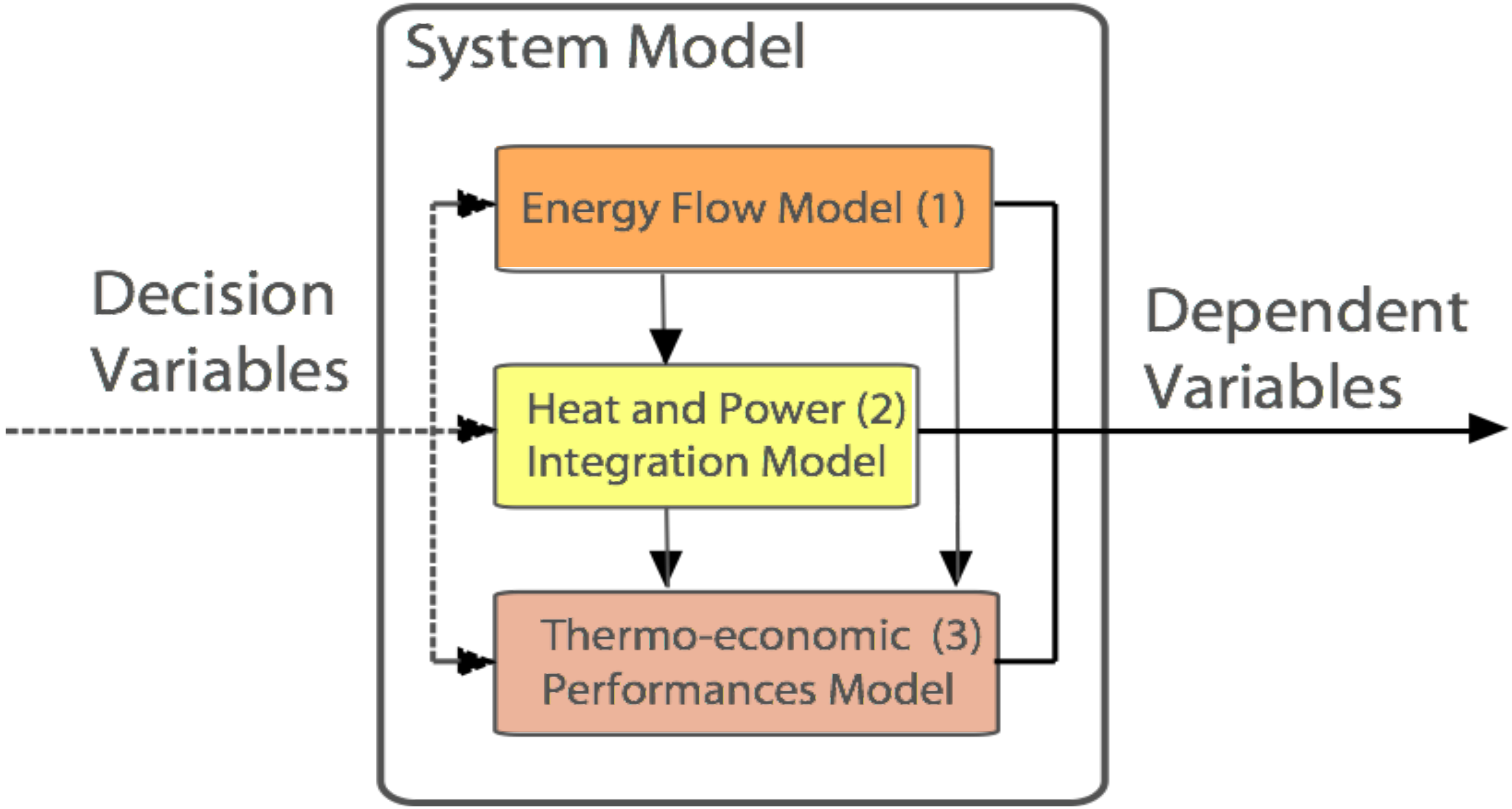
Thermo-economic Optimization of a Solid Oxide Fuel Cell, Gas Turbine Hybrid System

Goal and methodology

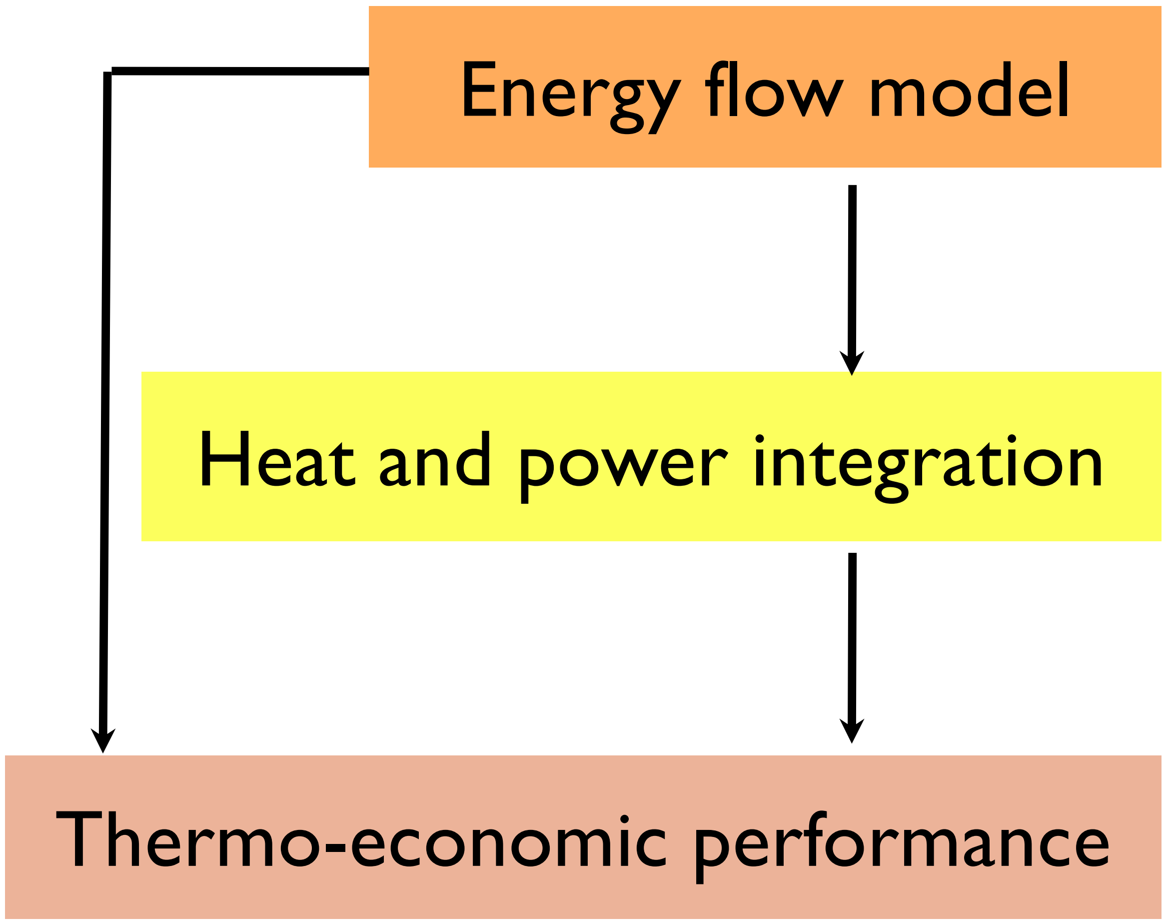
Optimal design of Fuel Cells (FC) systems where the configuration is unknown a priori



Modeling the system



Modeling tools



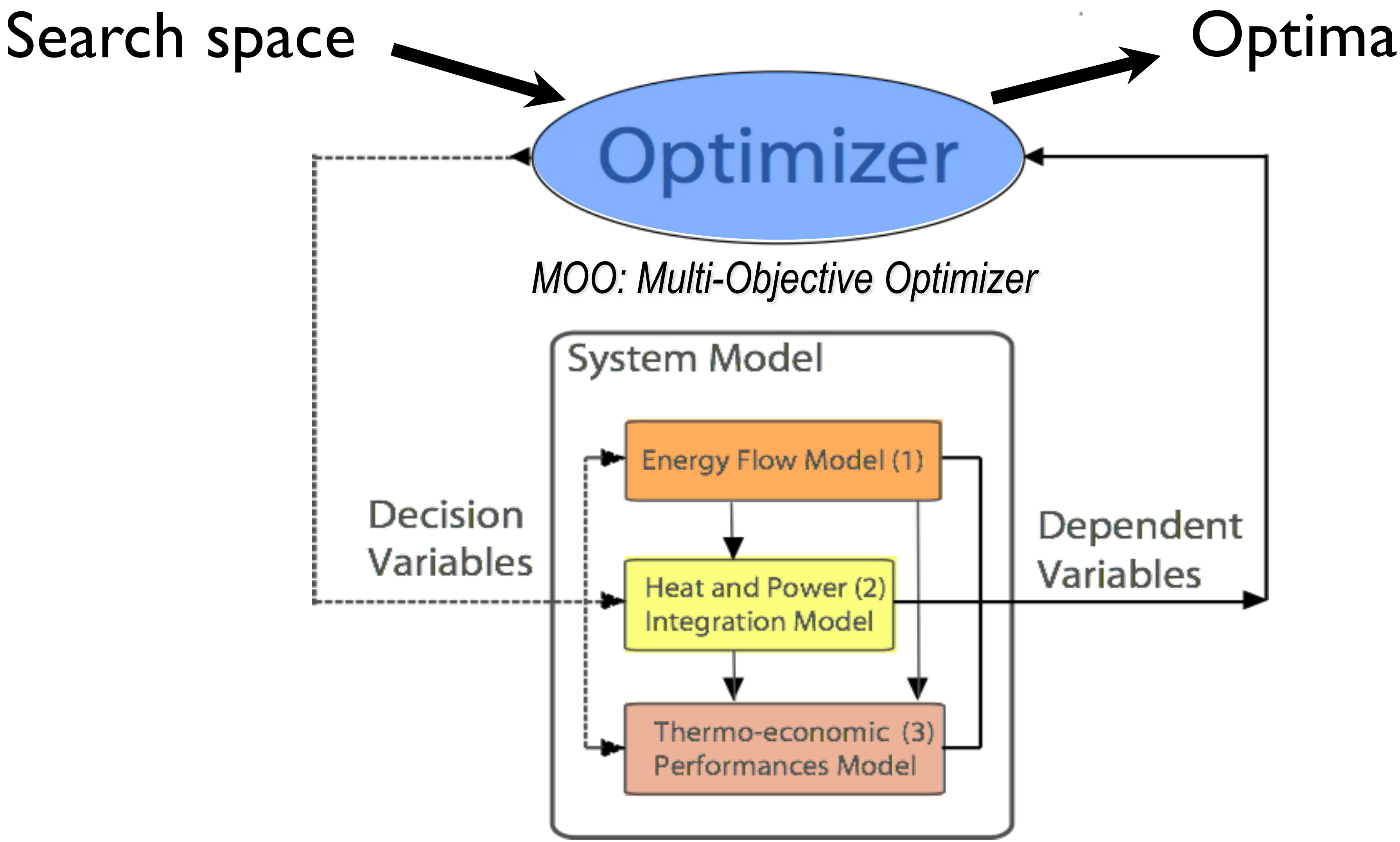
System performances

Software : Matlab

- Sequential computation
- The **sizing** of the components is computed to reach the required thermodynamic state
- The **costing** is then computed knowing the components sizes

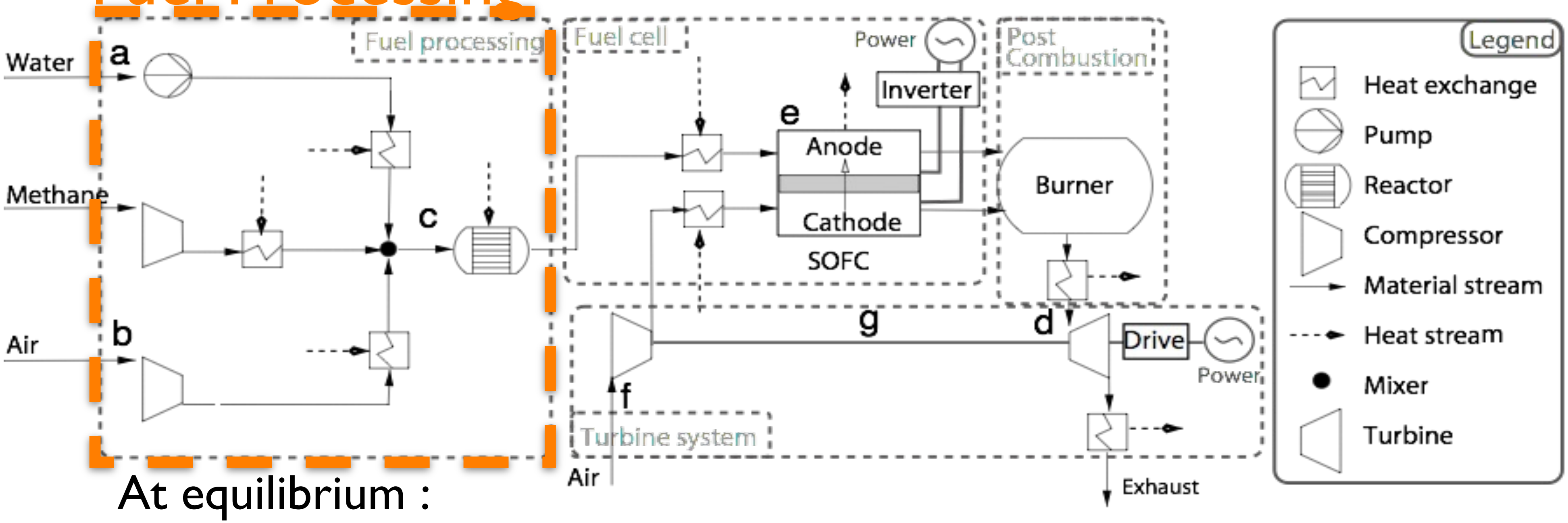
OSMOSE - under development at EPFL-IPESE

Optimize the model



SOFC-µGT model (30 kWe net output)

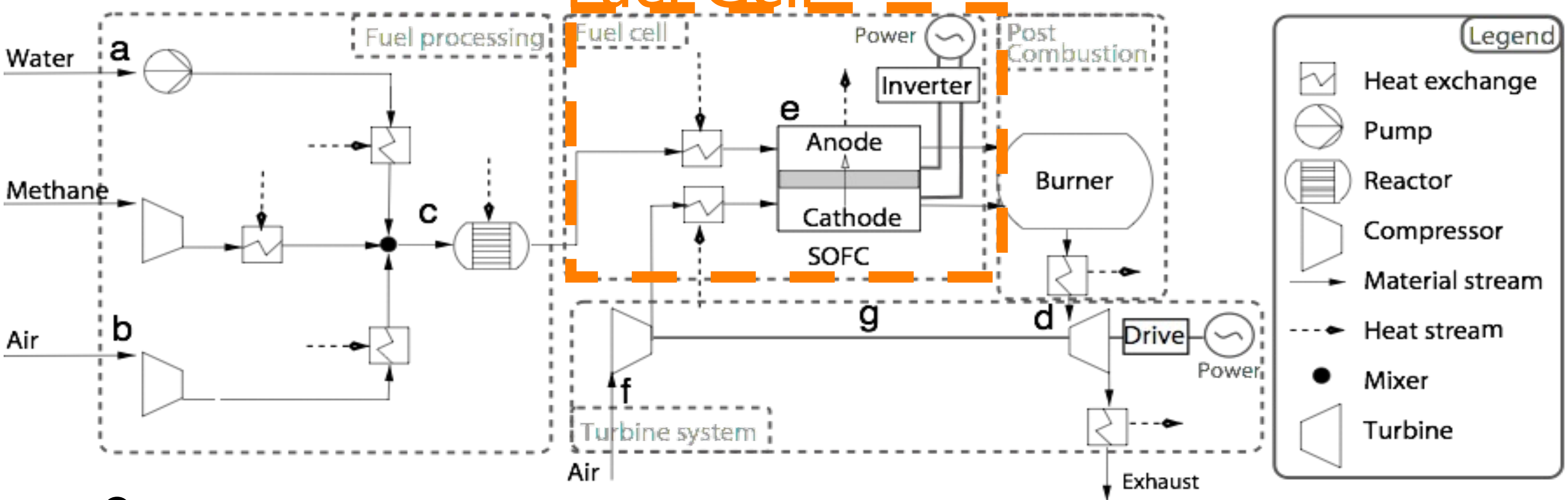
Fuel Processing



At equilibrium :

- Steam methane reforming (SMR)
- Partial oxidation (POX)
- Combination of two

Fuel Cell



- Planar anode supported cells with LSM cathode
- Operating temperature : 800°C
- 200 cm² active area
- 100 K maximum gradient in stack
- Cost calculations : cell area, number of 100 cells stacks, housing.

Fuel cell costs

$$C_{cell} = A_{cell} \cdot C_{spec}$$

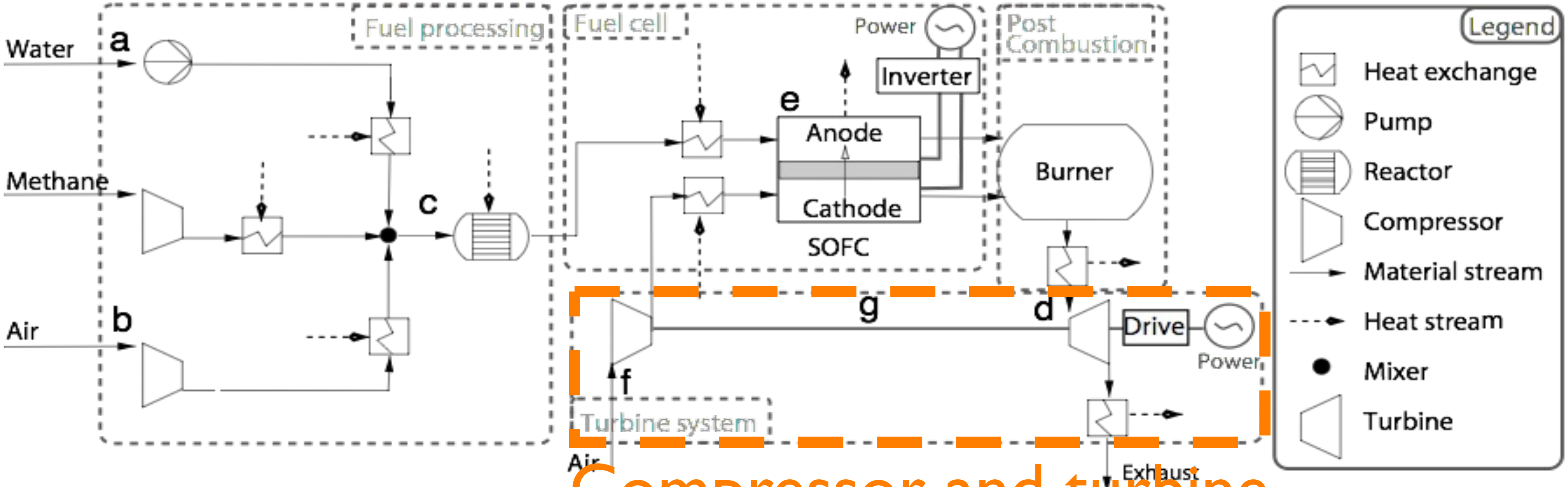
$$N_{stack} = \frac{N_{cells}}{N_{cells}^{max}}$$

$$C_{VolumeBareModule} = C_{VolumePurchase} \cdot f_{BM} \cdot f_{pressure}$$

$$C_{volumepurchase} = 10^{K_1 + K_2 log_1 0(ThermalLoad)}$$

$$C_{FCstack} = f_{BM} \cdot \left(C_{cell} \cdot N_{cells} + 2 \cdot N_{stack} \cdot A_{cell} \cdot f_{hs} \cdot C_{h,spec}\right)$$

$$C_{fc} = f_{actualization} \cdot \left(C_{VolumeBareModule} + C_{FCstack}\right)$$



Compressor and turbine

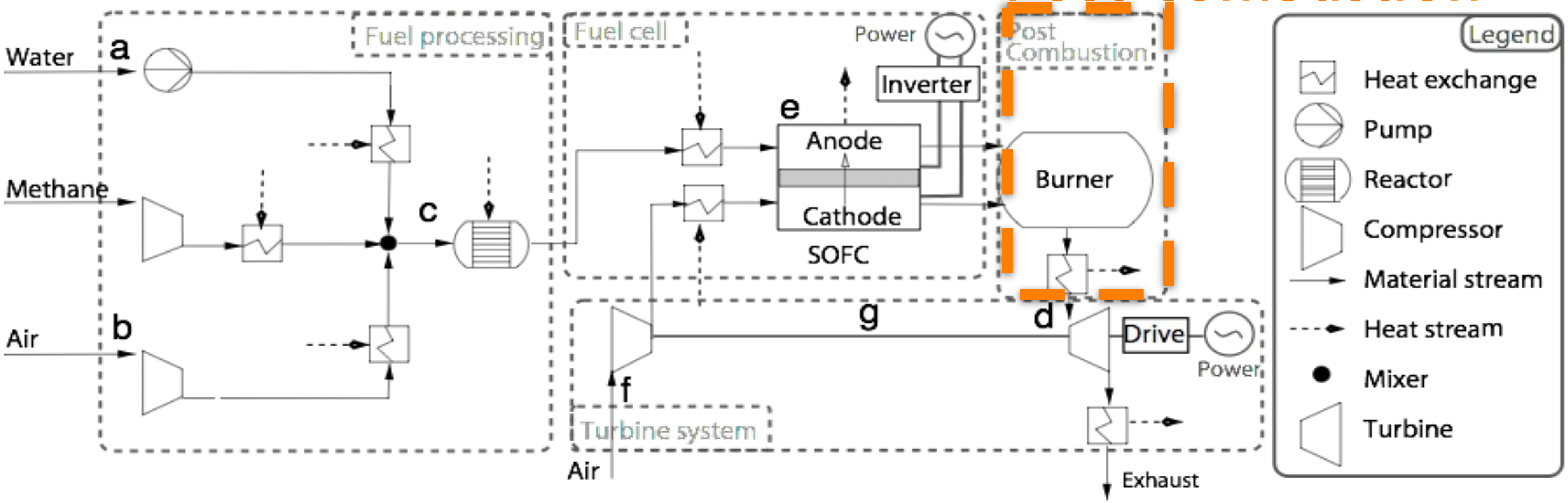
- High speed compressor and turbine (>100 000 rpm)
- Single shaft
- Air bearings technology
- Rotational speed, diameter, tip speed and efficiencies are computed

Gas Turbine costs

$$C_{Drive} = P_{shaft} \cdot C_{DriveSpec}$$

$$C_{microGT} = f_{actualization} \cdot (C_{Drive} + C_{ct})$$

Post-combustion



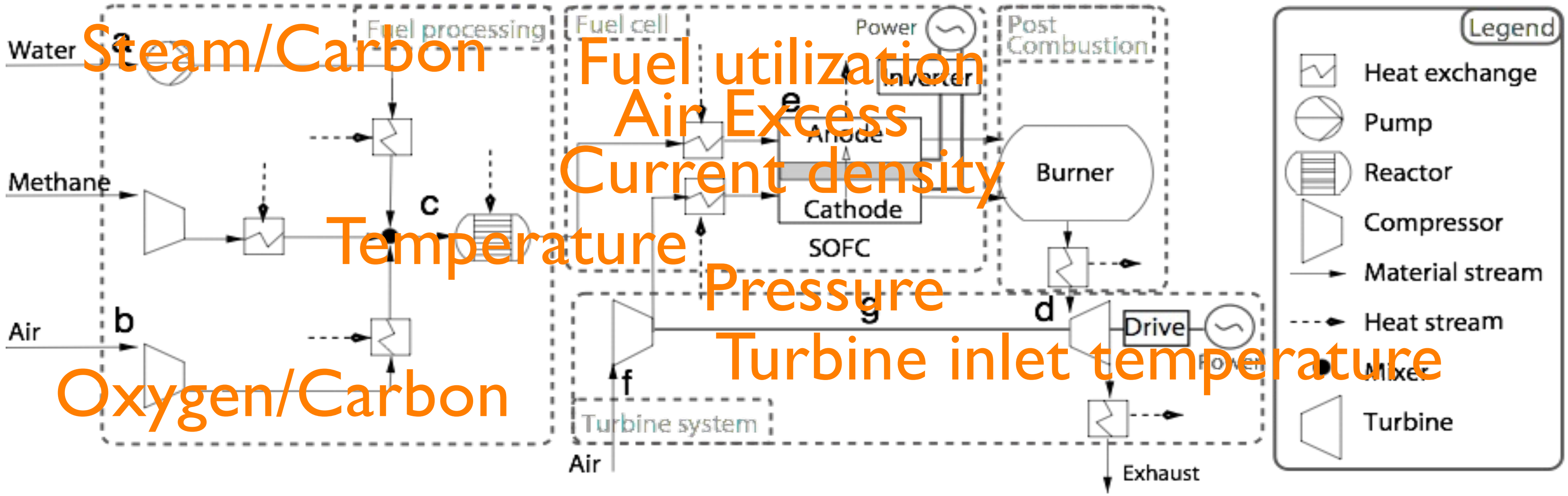
- Complete combustion of anode depleted gas
- Heat exchanger to lower temperature to turbine inlet temperature

Optimization

Two objectives:

- Maximum Efficiency
- Minimum installed Cost

Search space



30 kWe hybrid cycle

pressurized SOFC with high speed µGT

Search space

Fuel utilization	[0.5 ; 0.80]	-
Pressure	[1.1 ; 6]	bar
Oxygen to carbon ratio	[0.001 ; 0.5]	-
Steam to carbon ratio	[0.4 ; 4]	-
Turbine inlet temperature	[800 ; 1350]	K
Air excess ratio	[1.5 ; 5]	-
Current density	[1000 ; 5000]	A/m^2
Reformer temperature	[800 ; 1100]	K

Fuel cell equations (1)

Non-ohmic losses	
Cathode	
Butler Volmer current overpotential	$i = i_{0,c} \cdot (e^{\frac{F}{2RT_s} \cdot \eta_c} - e^{-\frac{F}{2RT_s} \cdot \eta_c})$
Cathode base current	$i_{0,c} = \frac{2 \cdot R \cdot T_s \cdot \sigma_c}{F}$
Cathode conductance	$\sigma_c = \sigma_{0,c} \cdot e^{-\frac{E_{A,c}}{R \cdot T_s}}$
Anode	
Butler Volmer current overpotential	$i = i_{0,a} \cdot (e^{\frac{2F}{RT_s} \cdot \eta_a} - e^{-\frac{F}{RT_s} \cdot \eta_a})$
Anode base current	$I_{0,a} = \frac{R \cdot T_s \cdot \sigma_a}{3F}$
Anode conductance	$\sigma_a = \sigma_{0,a} \cdot e^{-\frac{E_{A,a}}{R \cdot T_s}}$

Fuel cell equations (2)

Electro-chemical	
Current	$I = \frac{\dot{n}_{O_2,m} \cdot 4F}{N_{cells}}$
Power	$\dot{E}_{FC}^{-} = -\Delta G_{stack} - R_{tot} \cdot I^2 - (\eta_a + \eta_c + \eta_{diff,a} + \eta_{diff,c}) \cdot N_{cells} \cdot I$
Available gibbs free enthalpy flow	$\Delta \dot{G}_{stack} = (\dot{G}_{c,out} + \dot{G}_{a,out}) - (\dot{G}_{c,in} + \dot{G}_{a,in})$
Current density	$i = \frac{I}{A_{cell}}$
Stack potential	$U = \frac{\dot{E}_{FC}^{-}}{I}$
Cell potential	$U_{cell} = \frac{U}{N_{cells}}$

Fuel cell equations (3)

other model equations

Fuel utilization $$\mu = \frac{\dot{n}_{O_2,m}}{\dot{n}_{o_2,c,in} - \dot{n}_{O_2,pc,out}}$$

Air excess $$\lambda = \frac{\dot{n}_{O_2,c,in} + \dot{n}_{O_2,fp,in}}{\dot{n}_{O_2,c,in} + \dot{n}_{O_2,fp,in} - \dot{n}_{O_2,pc,out}}$$

Ohmic losses

Total resistive loss $$R_{tot} = R_i + R_e$$

Interconnect resistive loss $$R_i = \frac{R_{i,a} + R_{i,c}}{A_{cell}} \cdot N_{cells}$$

Electrolyte resistive loss $$R_e = \frac{1}{\sigma_e} \cdot \frac{L_e}{A_{cell}} \cdot N_{cells} \cdot f_{cc}$$

Electrolite conductance $$\sigma_e = \sigma_{0,e} \cdot e^{-\frac{E_{A,e}}{RT_s}}$$

Diffusion losses

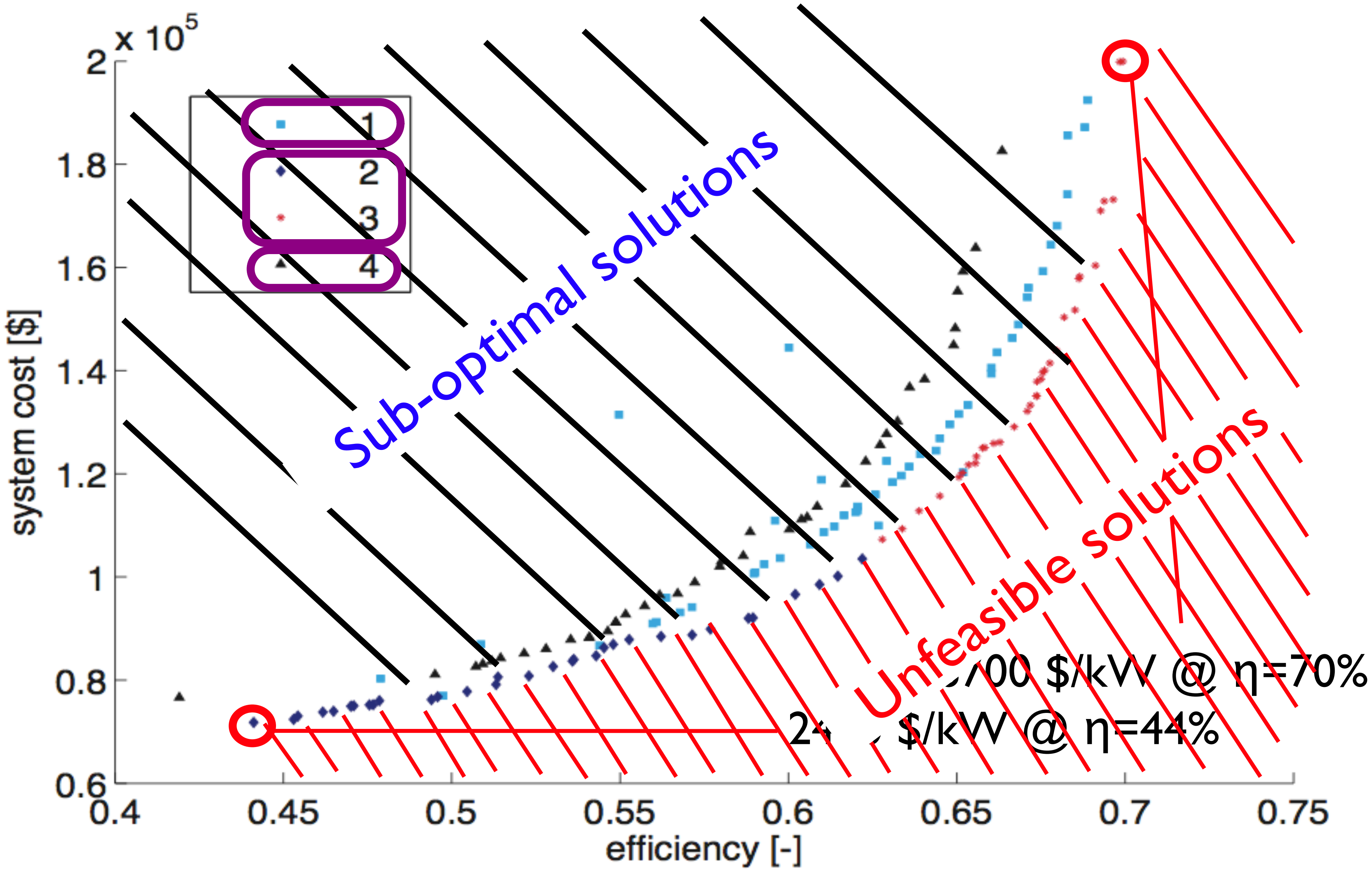
Anode polarization $$\eta_{diff,a} = -\frac{RT_s}{2F} \cdot log(1-\mu)$$

Cathode polarization $$\eta_{diff,c} = -\frac{RT_s}{2F} \cdot log(1-\frac{\mu}{\lambda})$$

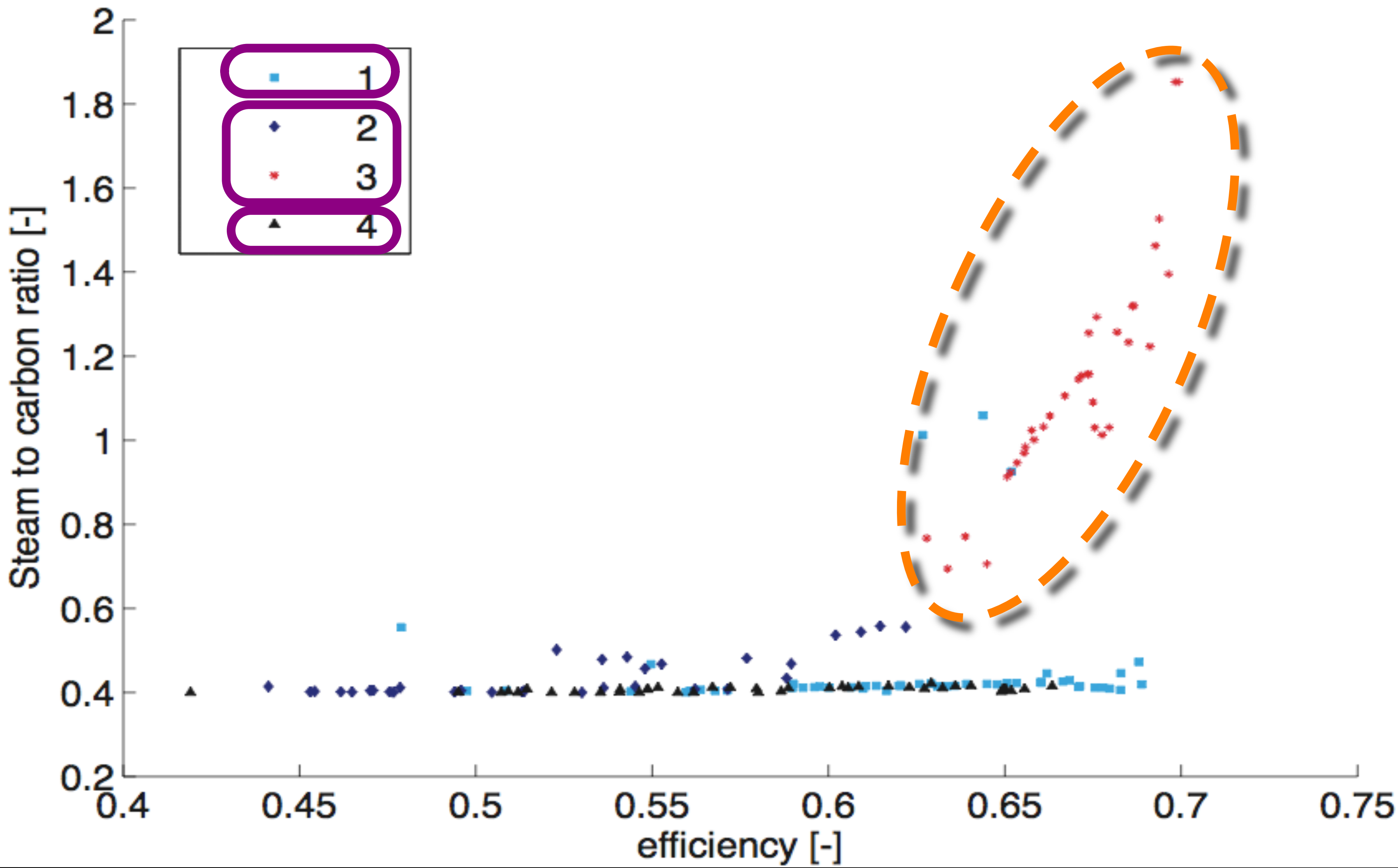
Chemical reaction equations

Name	Reaction	Reaction enthalpy
Steam methane reforming	$CH_4 + H_2O \leftrightarrow CO + 3H_2$	$\Delta H_0 = 206.11 kJ/mol$
Water gas shift	$CO + H_2O \leftrightarrow CO_2 + H_2$	$\Delta H_0 = -41.160 kJ/mol$
Hydrogen combustion	$2H_2 + O_2 \rightarrow 2CO_2$	$\Delta H_0 = -571.6 kJ/mol$
carbon monoxide combustion	$2CO + O_2 \rightarrow 2CO_2$	$\Delta H_0 = -565.8 kJ/mol$
Methane partial oxydation	$CH_4 + \frac{1}{2}O_2 \rightarrow CO + 2H_2$	$\Delta H_0 = -35.715 kJ/mol$

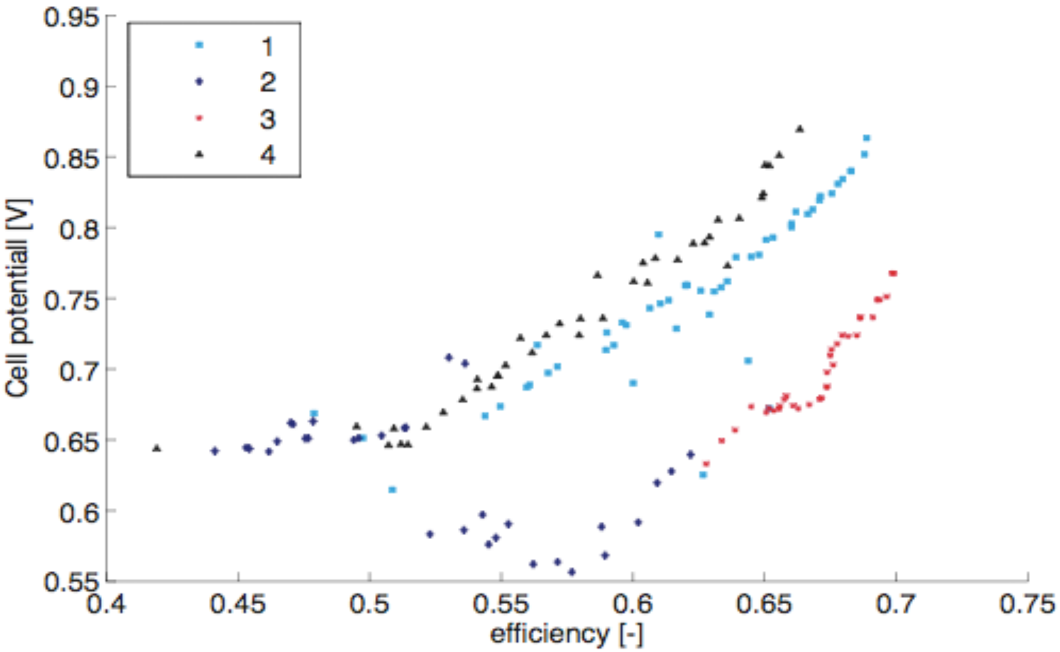
Tradeoff: Efficiency - System Cost

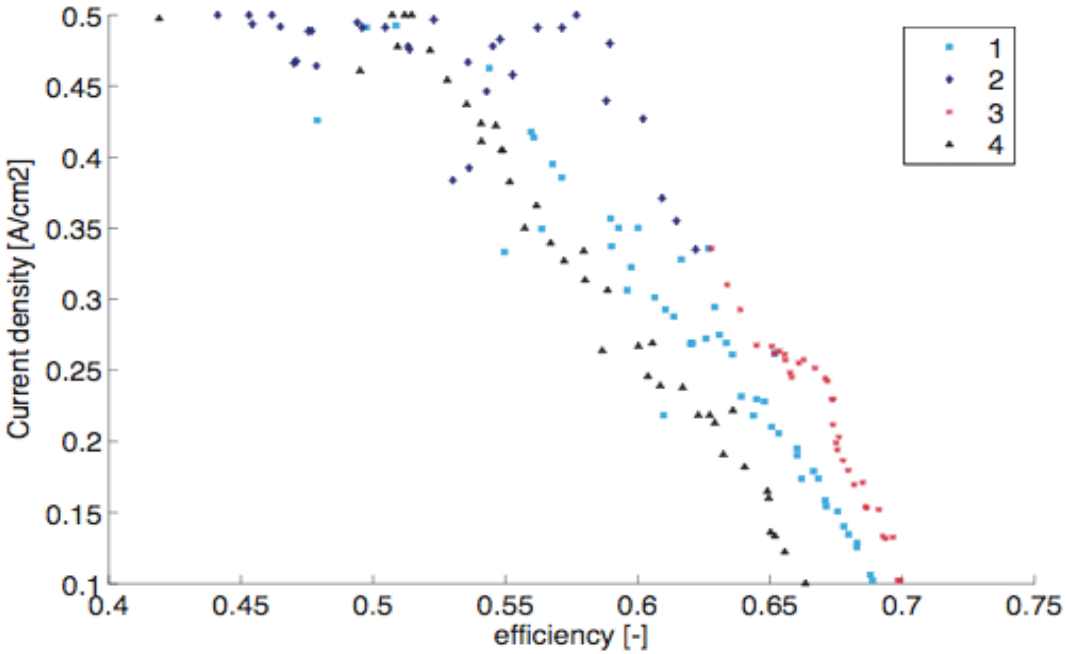


Steam to Carbon ratio

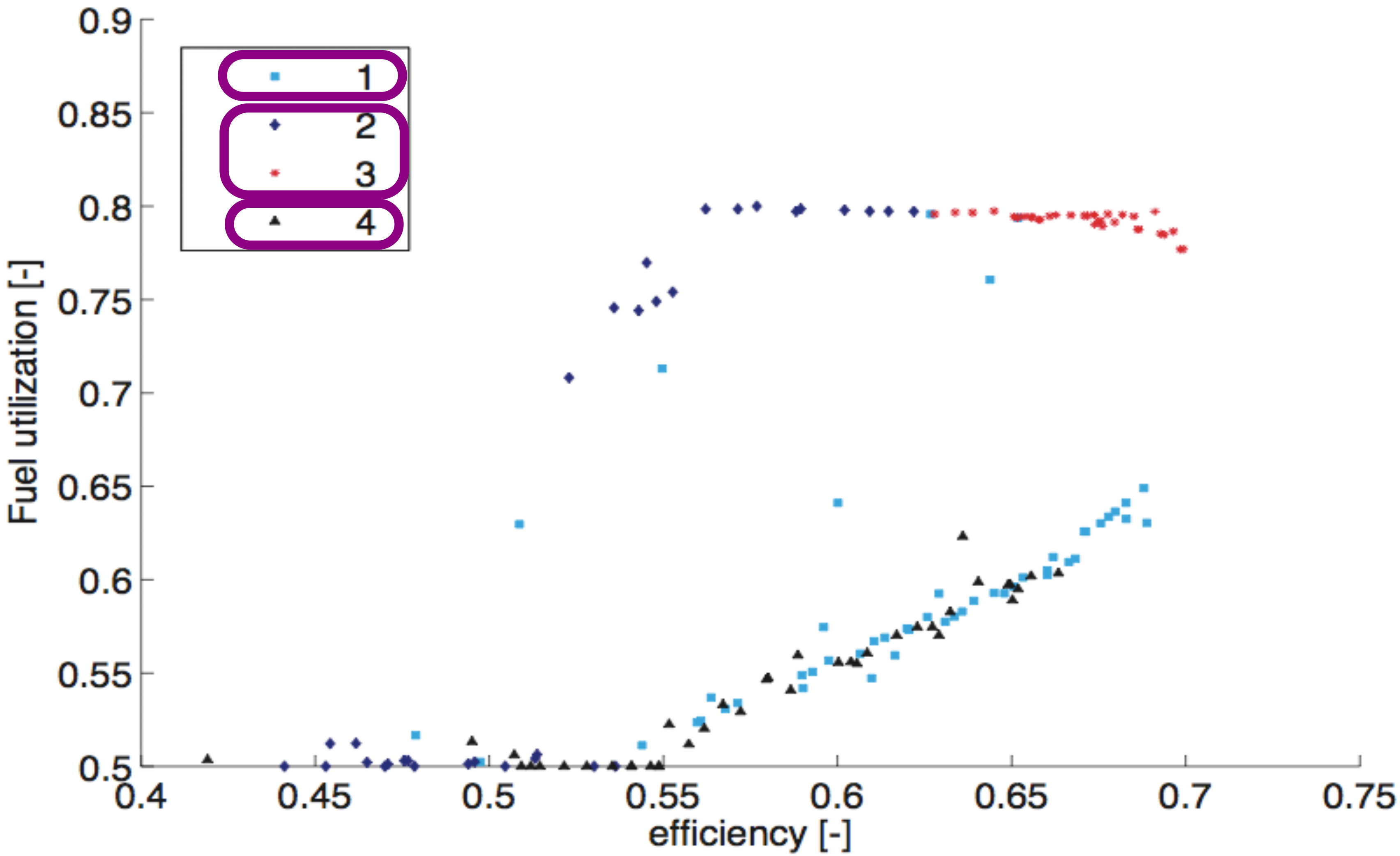


Cell potential & current density

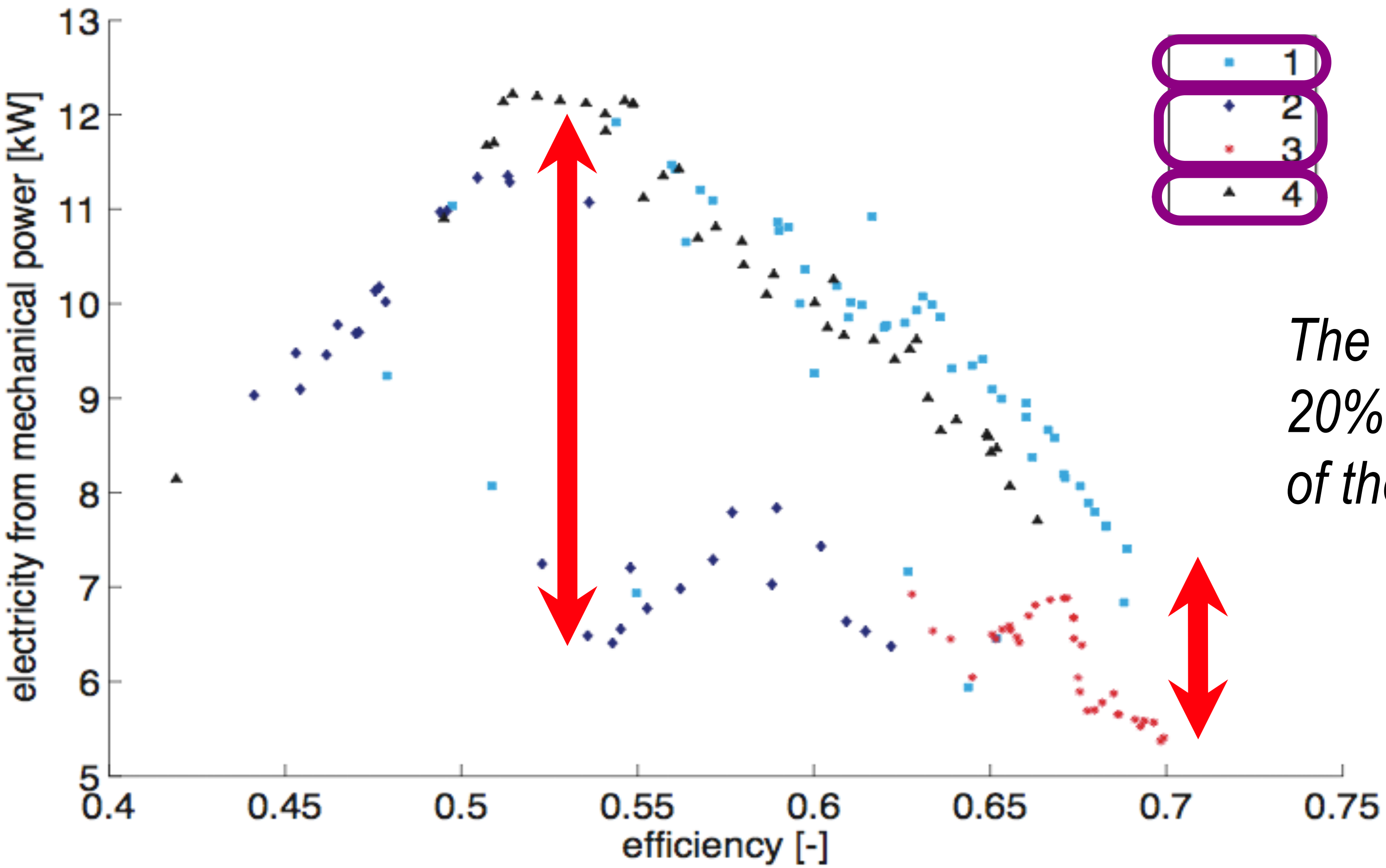




Fuel utilization

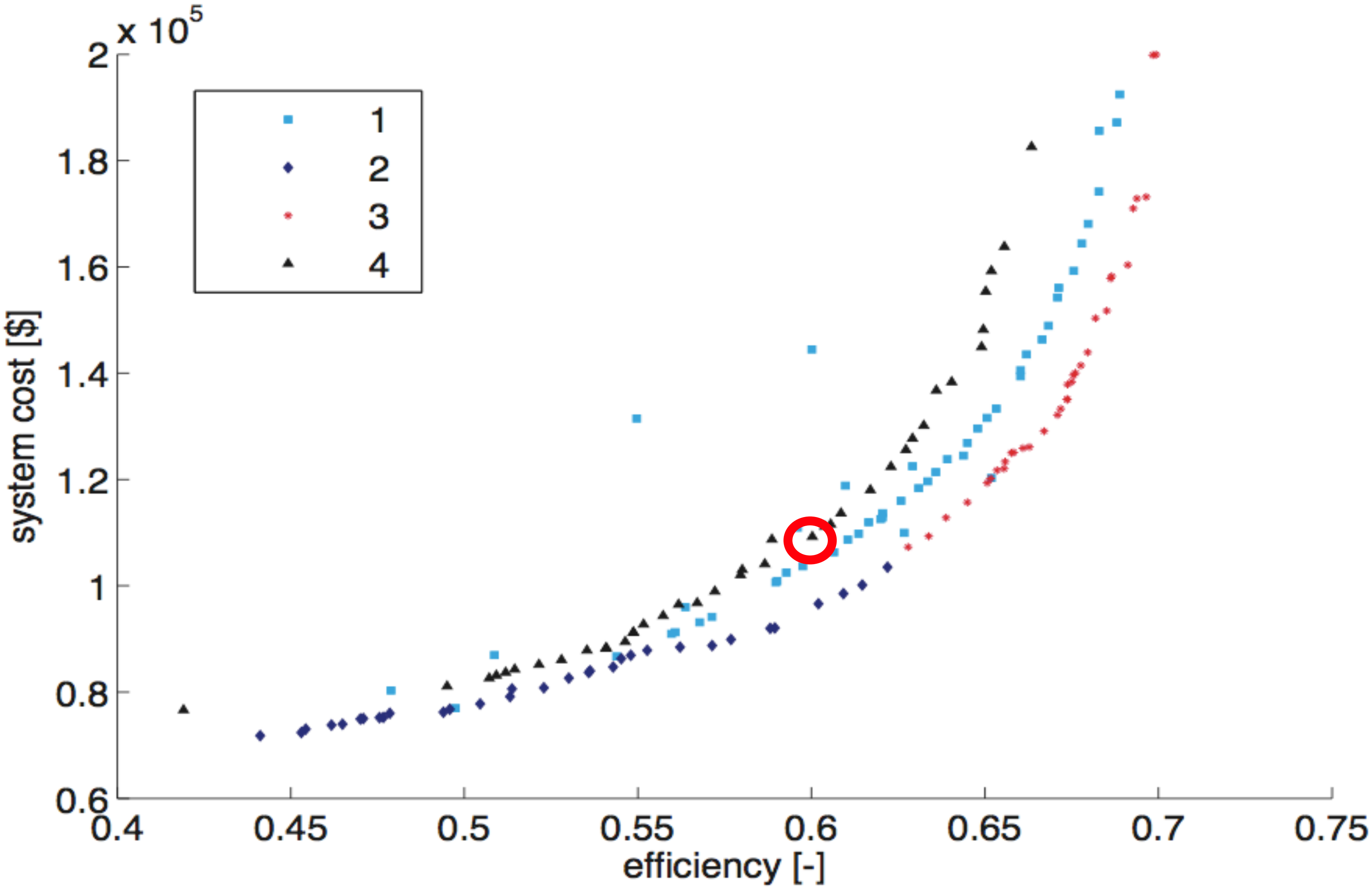


Turbine power

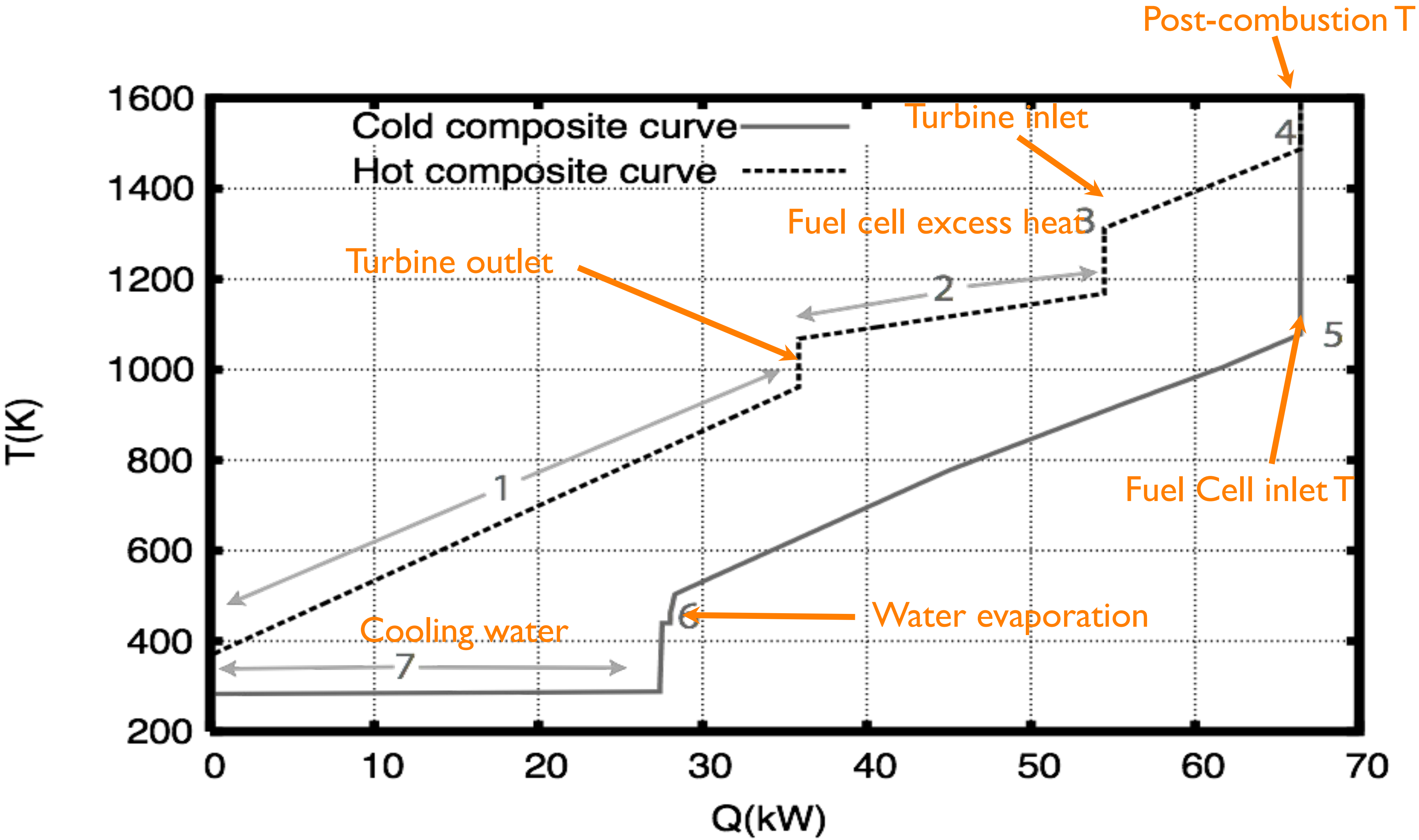


The turbine delivers 20% to 40% of the total power

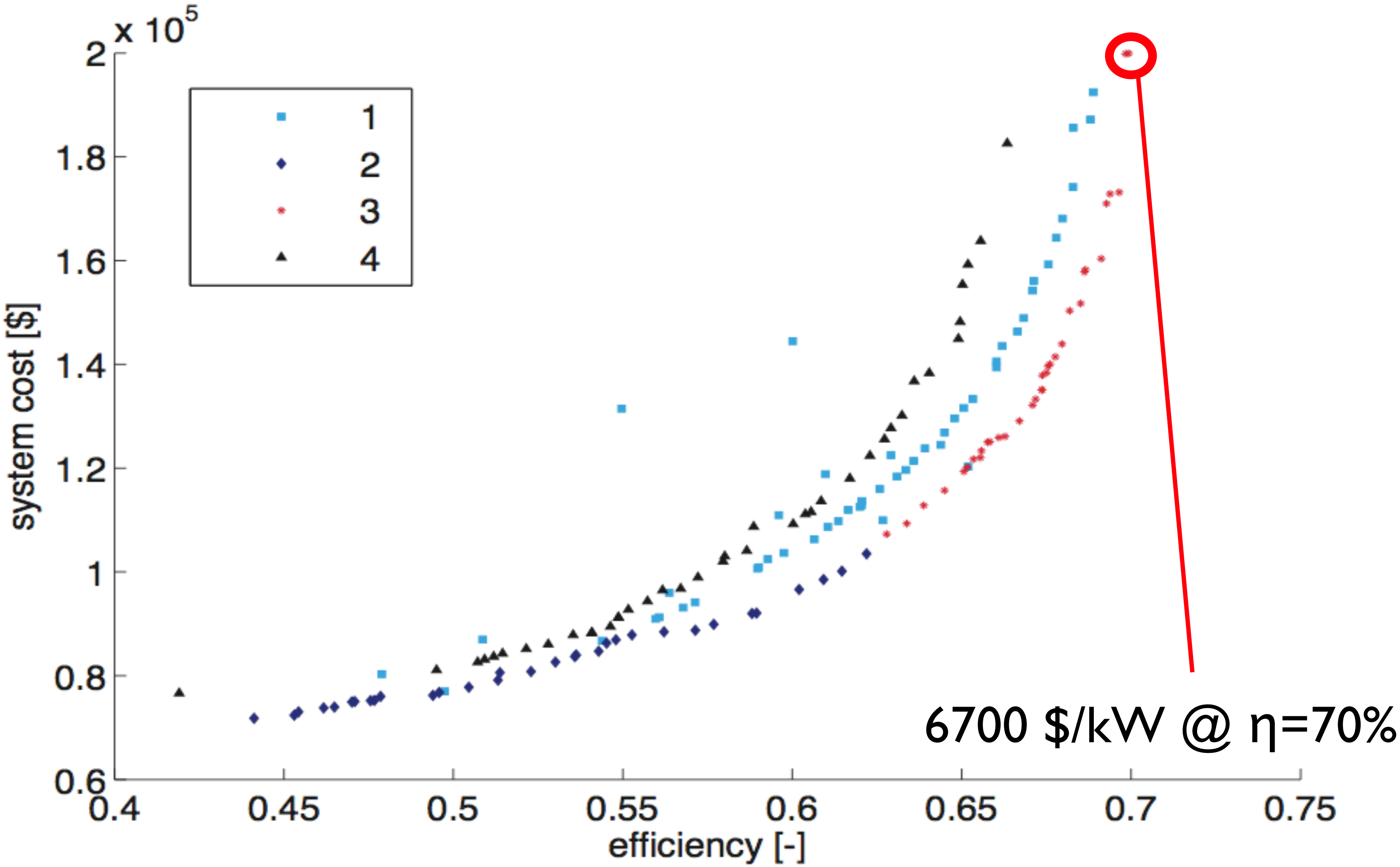
Heat integration example



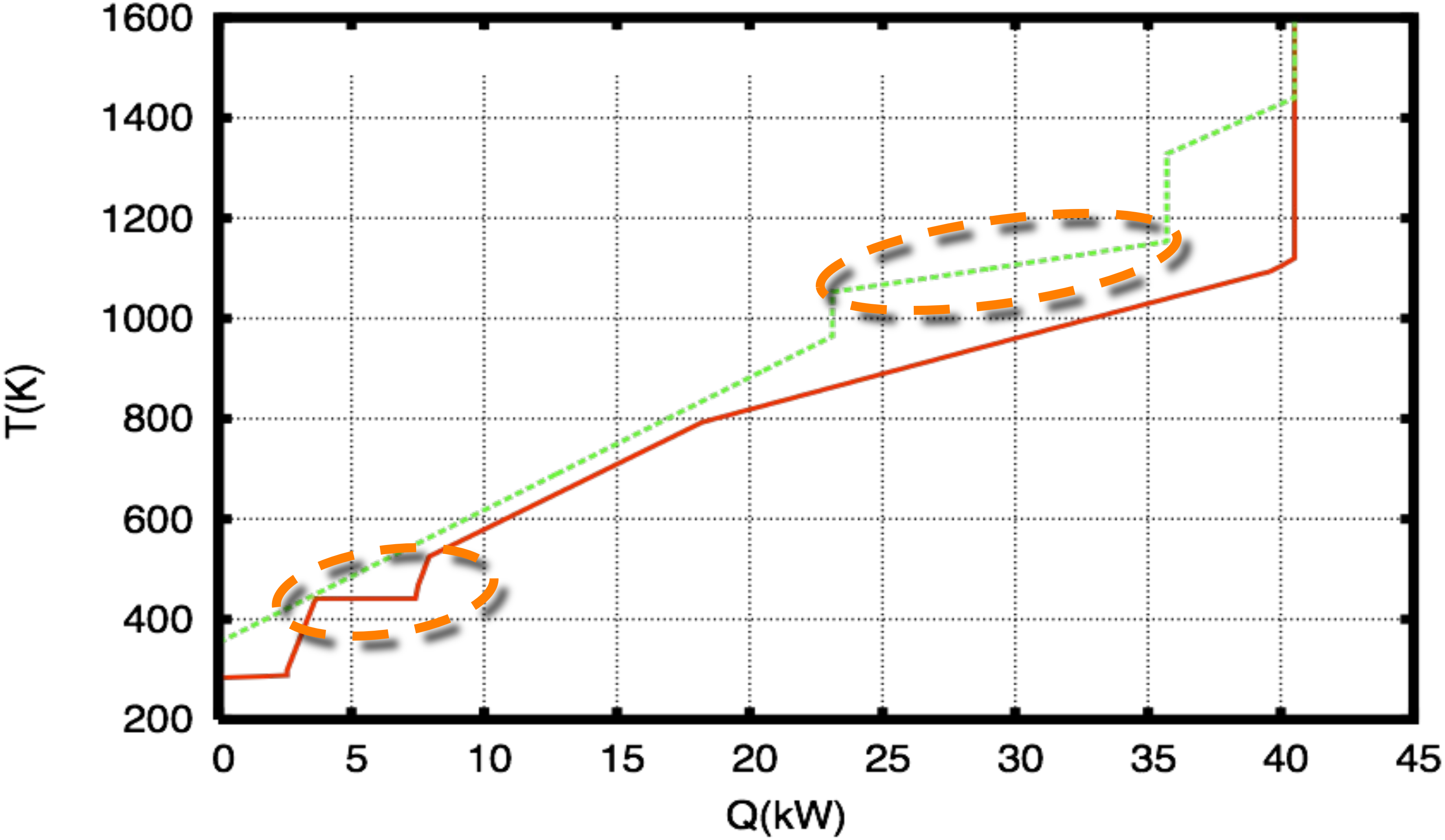
Heat integration example



Most efficient case:

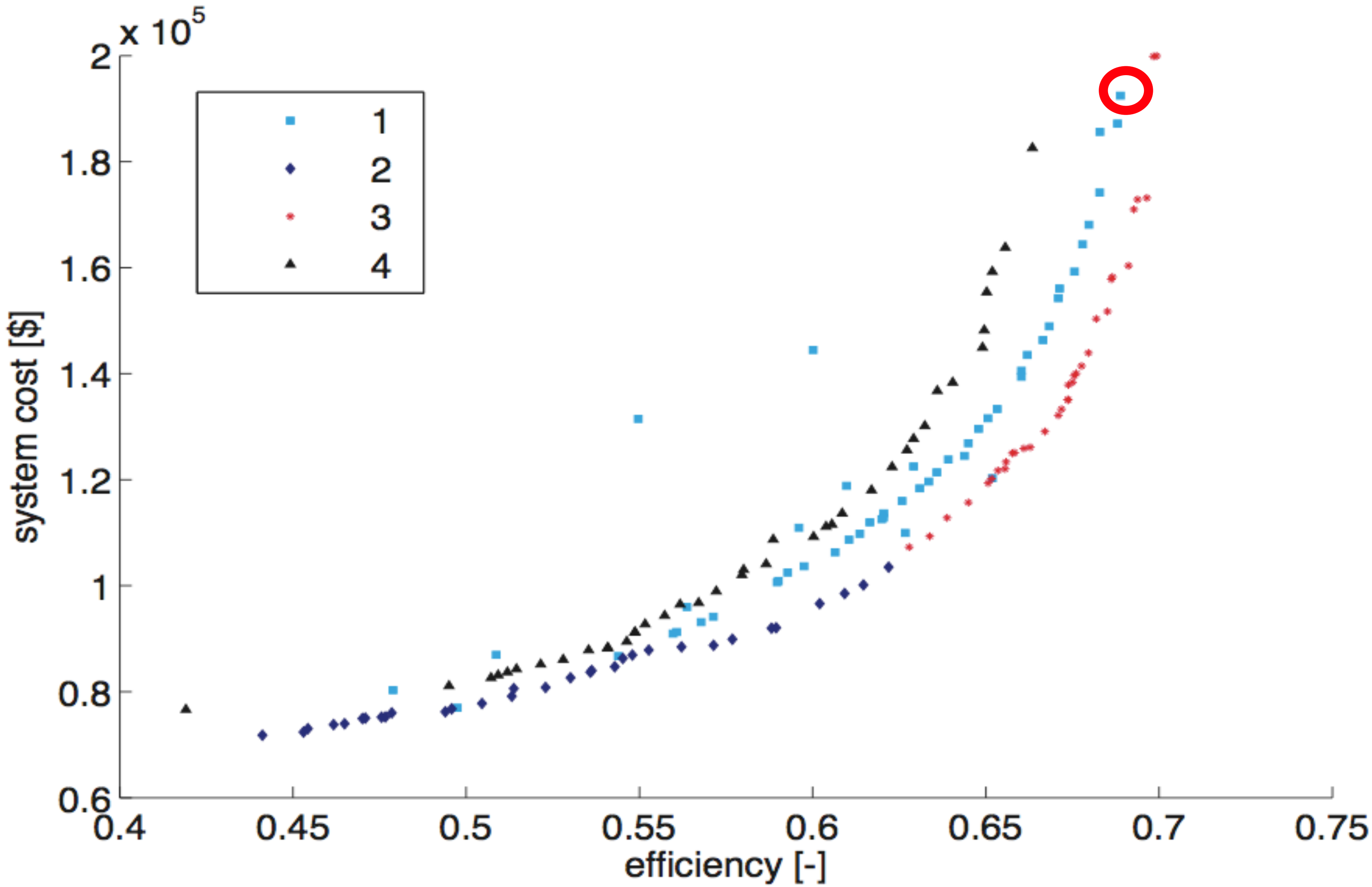


Most efficient case:

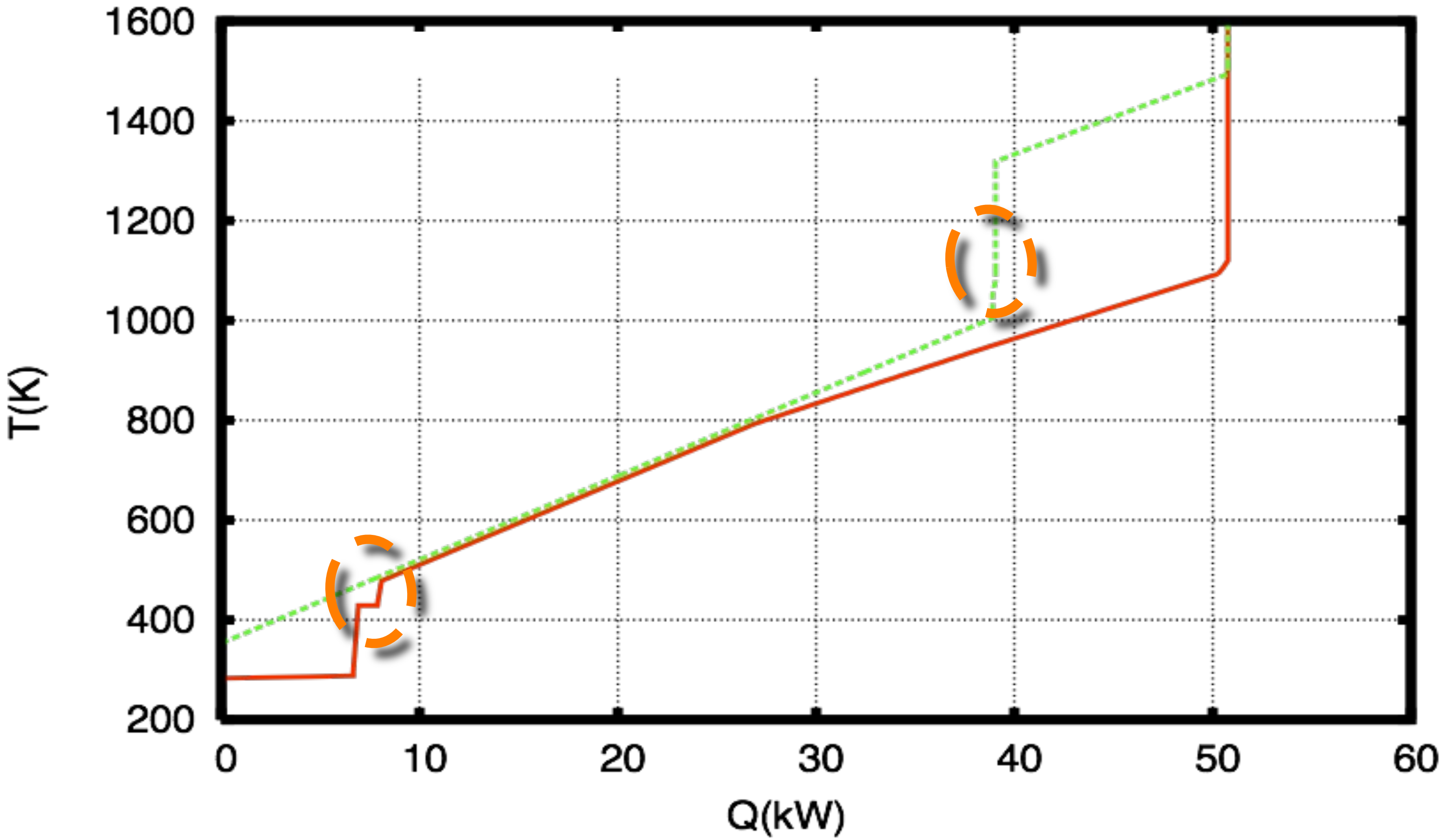


S/C = 2
η = 0.70
λ = 1.9

Another high efficiency case…



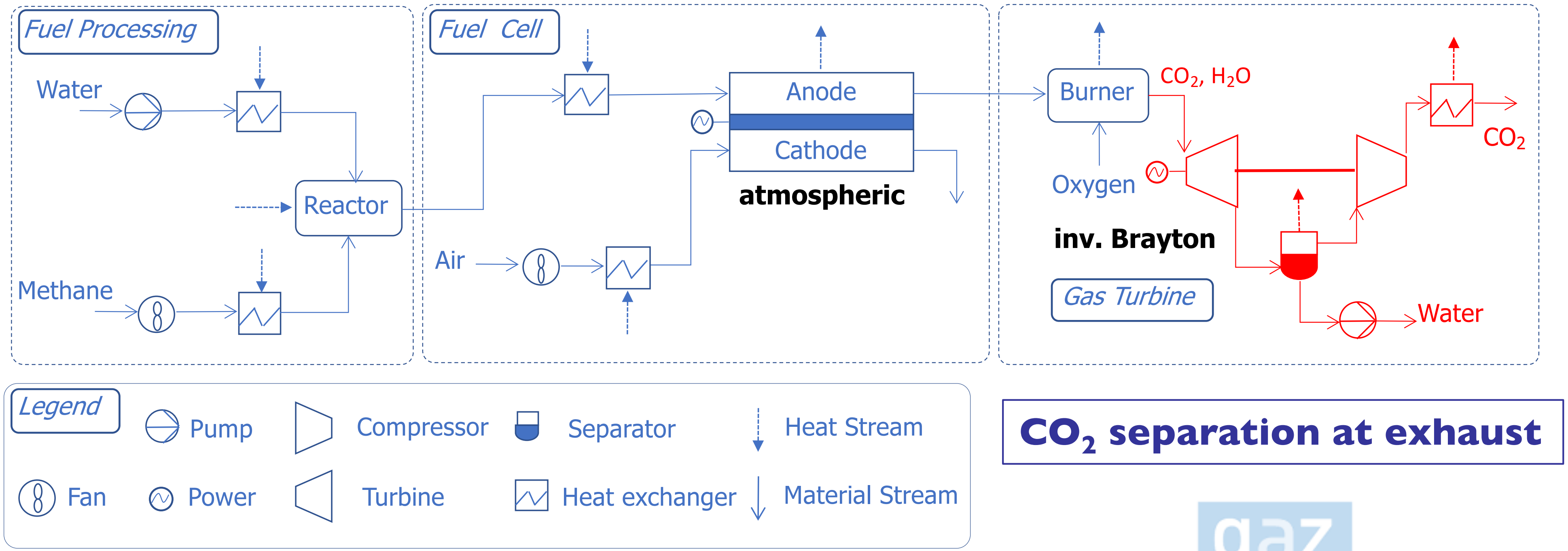
…shows a very distinct configuration



S/C = 0.4
η = 0.69
λ = 3.2

SOFC + microgasturbine

LABORATORY FOR APPLIED MECHANICAL DESIGN
Prof Jürg Schiffmann



CO_2 separation at exhaust

State of the Art Analysis

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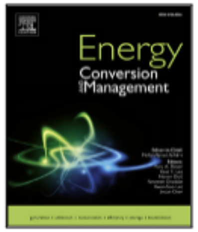

Review

Readiness evaluation of SOFC-MGT hybrid systems with carbon capture for distributed combined heat and power

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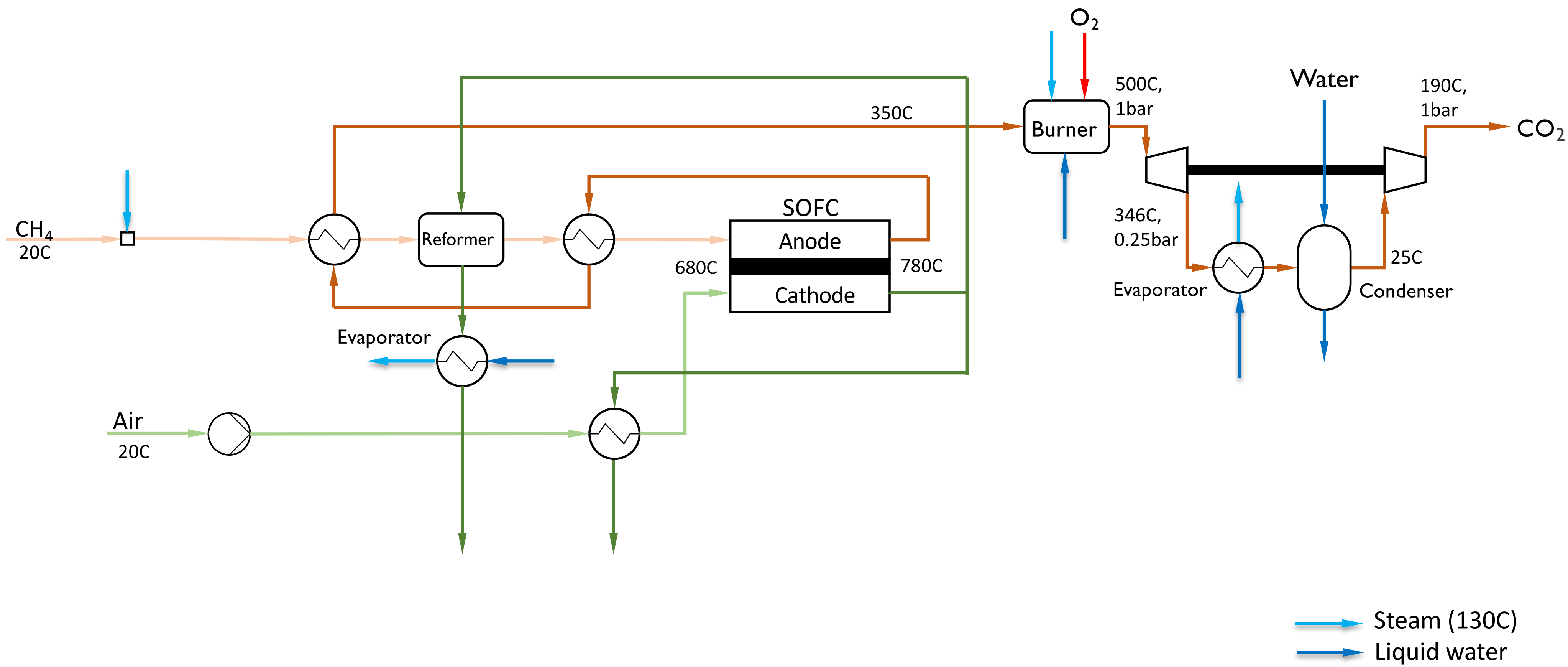
Selected Heat Exchanger Network



Micro Gas Turbine

- Inverted Brayton-Ranking Cycle
  - Subatmospheric Expansion
- Micro Gas Turbine:
  - 1.5 kWe
  - > 300'000 RPM
  - Gas Bearing Supported
  - Integrated Electrical Machine
- Research challenges
  - Extreme Temperature
  - High Thermal Gradient
  - Bearings µm Clearances
  - Integrated Multiphysics Optimization