

# Techno-economic comparison of different cycle architectures for high temperature waste heat to power conversion systems using CO<sub>2</sub> in supercritical phase

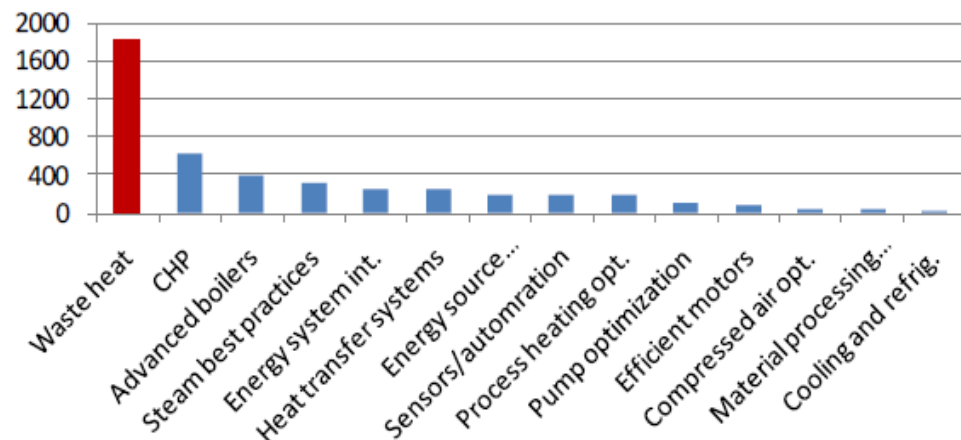
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# Waste Heat Recovery: some data

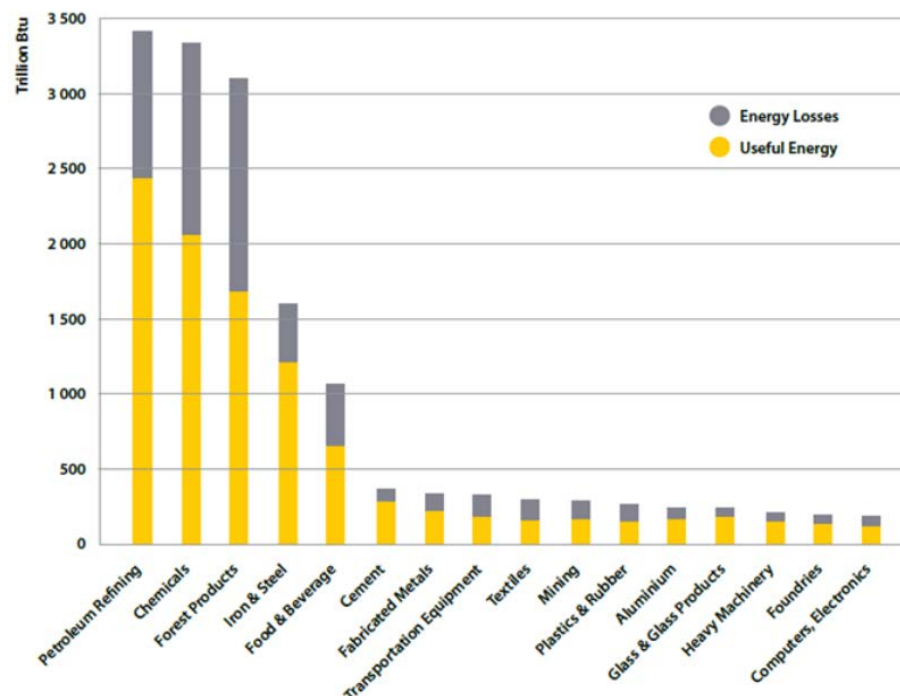
- The energy rejected from industry under the form of heat is estimated to be the 20-50% of its overall energy consumption
- The recovery of industrial waste could bring a saving of 1800 TeraBTU/year with an economic value of \$ 6 billion/year (US DOE, 2004)
- In the UK 163 TeraBTUs/year are rejected in the environment, almost one sixth of the overall industrial energy consumption.

**Possible savings by application  
(TeraBTUs/year)**



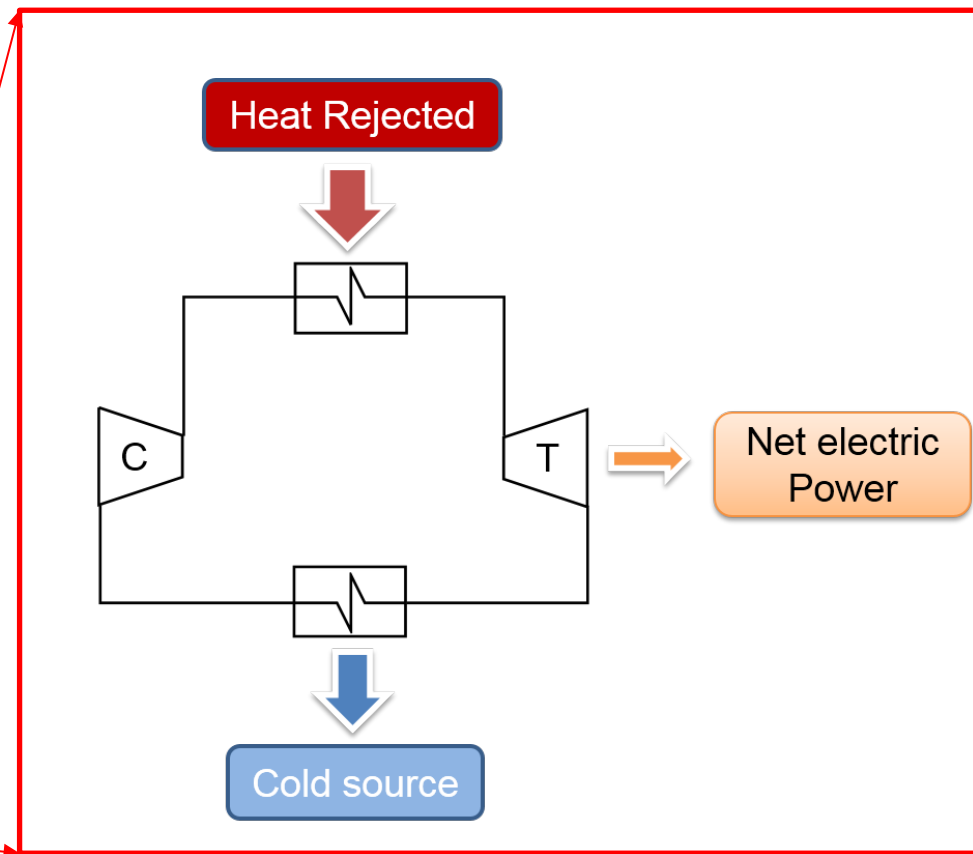
# Waste Heat Recovery: some data

- Particular industrial sectors reject a more significant percentage of the overall energy consumption to the environment
- Main relevance in energy intensive industrial plants
- In many cases this energy is rejected in form of high thermal grade heat (steel, cement, chemical industry)
- The heat recovered has to be used or stored, not always is possible



# Waste Heat Recovery: technologies

- Heat re-use and storage
  - Steam production
  - Heat pumps
- Heat adsorption
- Thermochemical conversion
- Thermal water desalination
- Heat to power conversion
  - Thermoacoustic
  - Thermoelectricity
  - **Thermodynamic cycles**



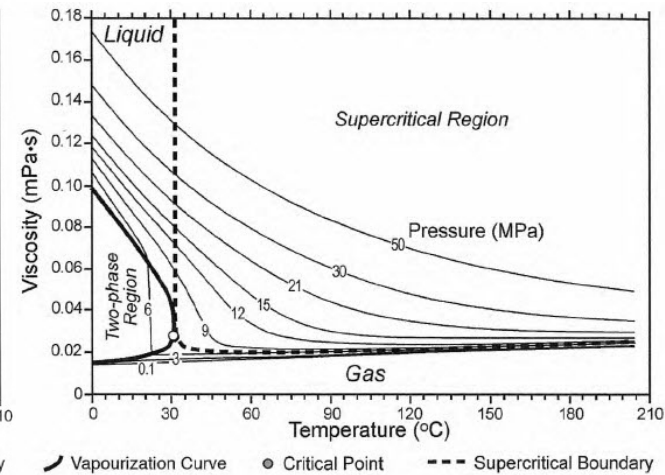
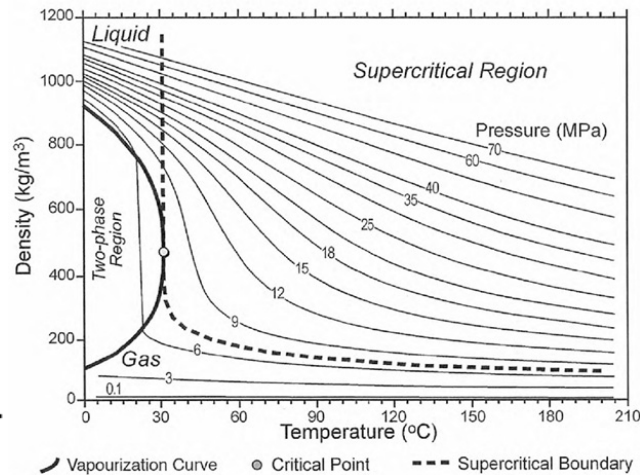
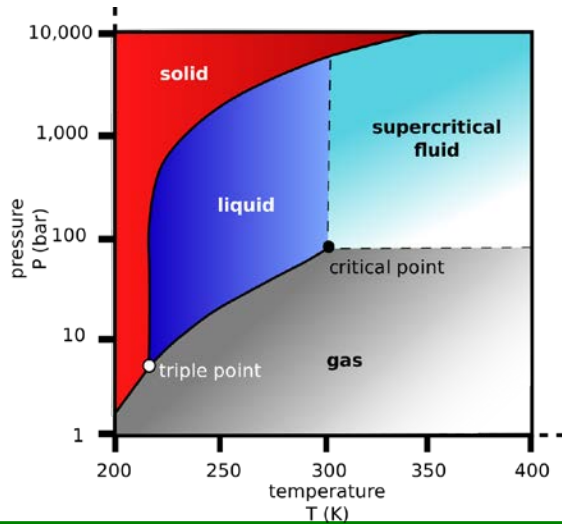
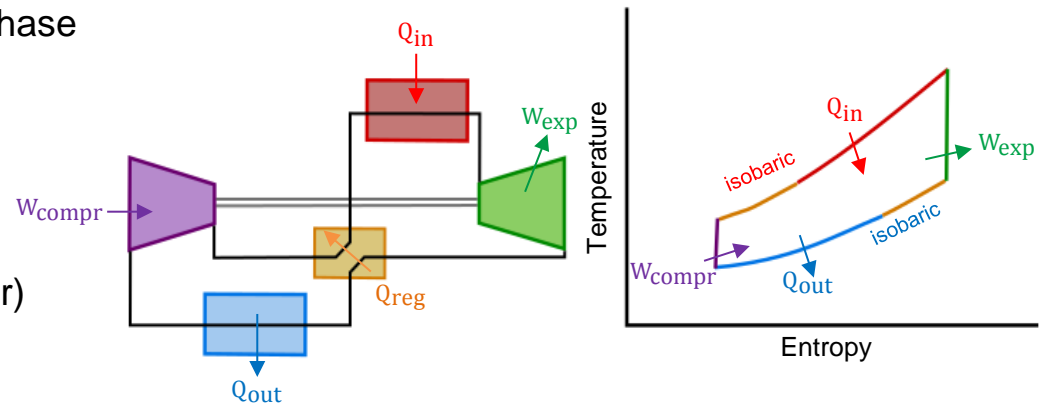
# WHR: Heat to power conversion

WHR applications	Range of temperatures	Heat to power conversion technology
Ultra Low	$T < 120\text{ }^{\circ}\text{C}$	Kalina, TFC
Low	$120\text{ }^{\circ}\text{C} < T < 230\text{ }^{\circ}\text{C}$	ORC, Kalina, Goswami
Medium	$230\text{ }^{\circ}\text{C} < T < 650\text{ }^{\circ}\text{C}$	ORC (up to $500\text{ }^{\circ}\text{C}$ )
High	$650\text{ }^{\circ}\text{C} < T < 870\text{ }^{\circ}\text{C}$	Rankine (from $700\text{ }^{\circ}\text{C}$ )
Ultra High	$T > 870\text{ }^{\circ}\text{C}$	Rankine

There is a gap...

# Supercritical carbon dioxide Brayton cycle

- Carbon dioxide (CO<sub>2</sub>) in supercritical phase
  - Liquid-like density
  - Gas-like viscosity
- Joule-Brayton cycle
- Critical point of CO<sub>2</sub> (30.98 °C, 73.8 bar)
- High pressures and high temperatures



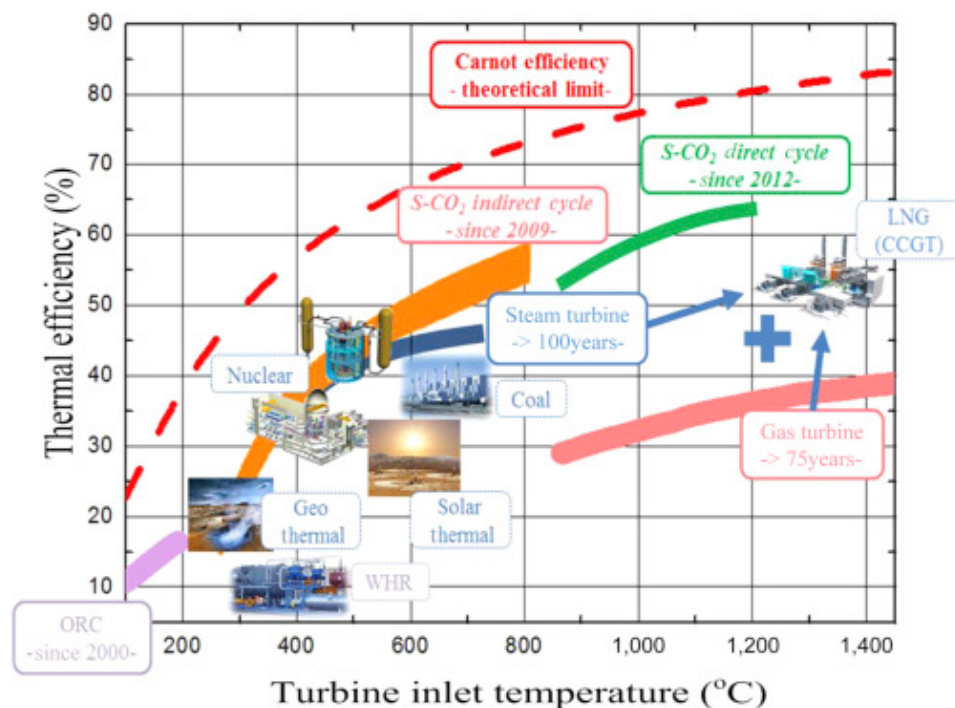
# Why sCO<sub>2</sub>: other reasons

- Far from the critical point the sCO<sub>2</sub> density decreases
- High efficiencies if the goal of higher turbine inlet temperatures can be achieved
- Not toxic, Eco-friendly and abundant
- High thermal stability
- Lower compression work near the critical point
- High number of possible applications

Figure 2: ODP and GWP for Various Refrigerants

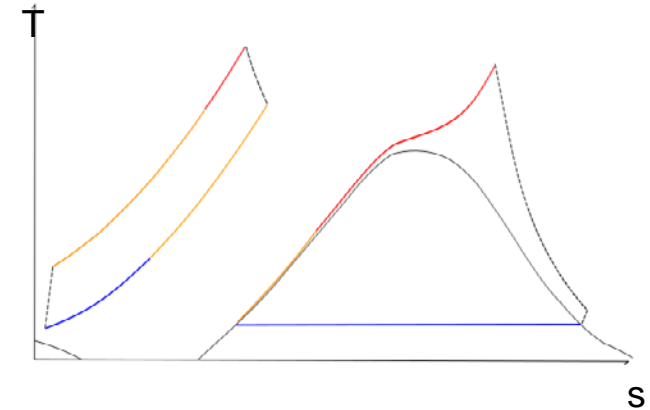
REFRIGERANT	TYPE	ODP	GWP (100yr)
R-12	CFC	0.820	10,600
R-22	HCFC	0.034	1,700
R-404A	HFC	0	3,800
R-410A	HFC	0	2,000
R-290 (Propane)	Natural	0	~20
R-717 (Ammonia)	Natural	0	<1
R-744 (CO <sub>2</sub> )	Natural	0	1
HFO-1234yf	HFO	0	4

Source: Calm & Hourahan, 2001



# sCO<sub>2</sub> vs Rankine cycle

- Heat supplied and rejected at a higher averaged values of temperature;
- Better thermal matching between the working fluid and the hot source;
- Higher density allows downsized and less complex turbomachines



CONS

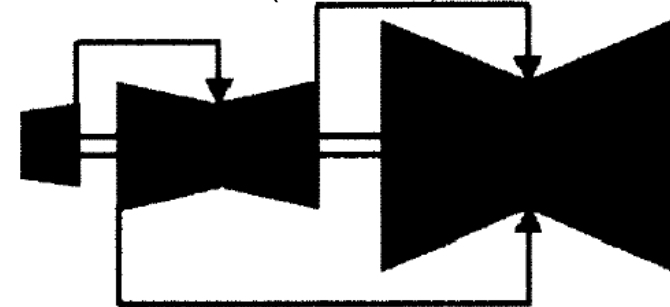
- High thermal load in the regenerators lower expansion ratio

sCO<sub>2</sub> (300 MW)

He (300 MW)

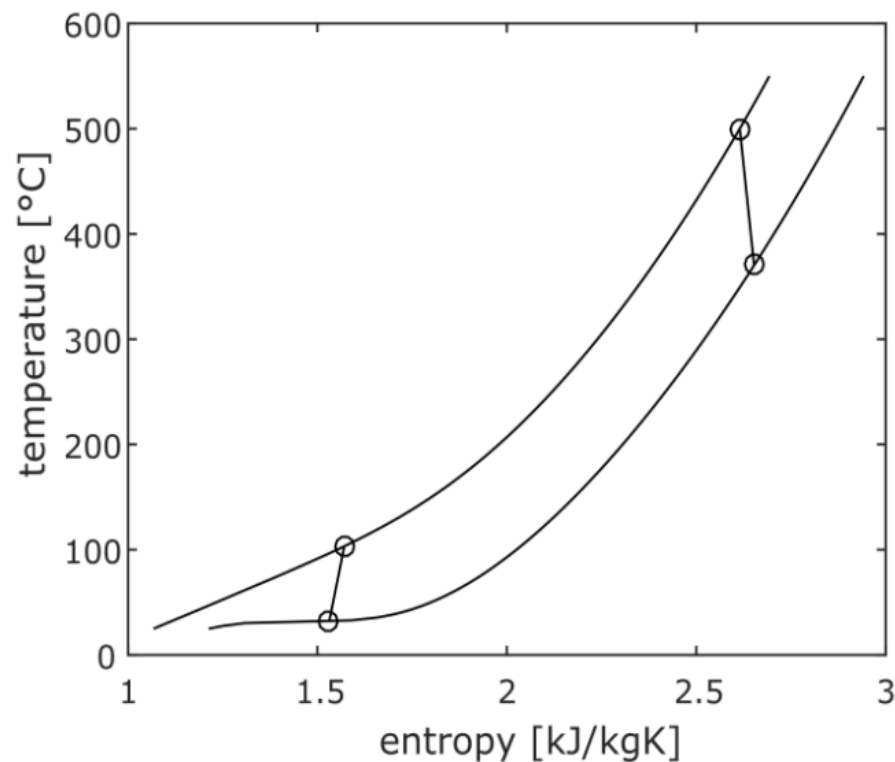
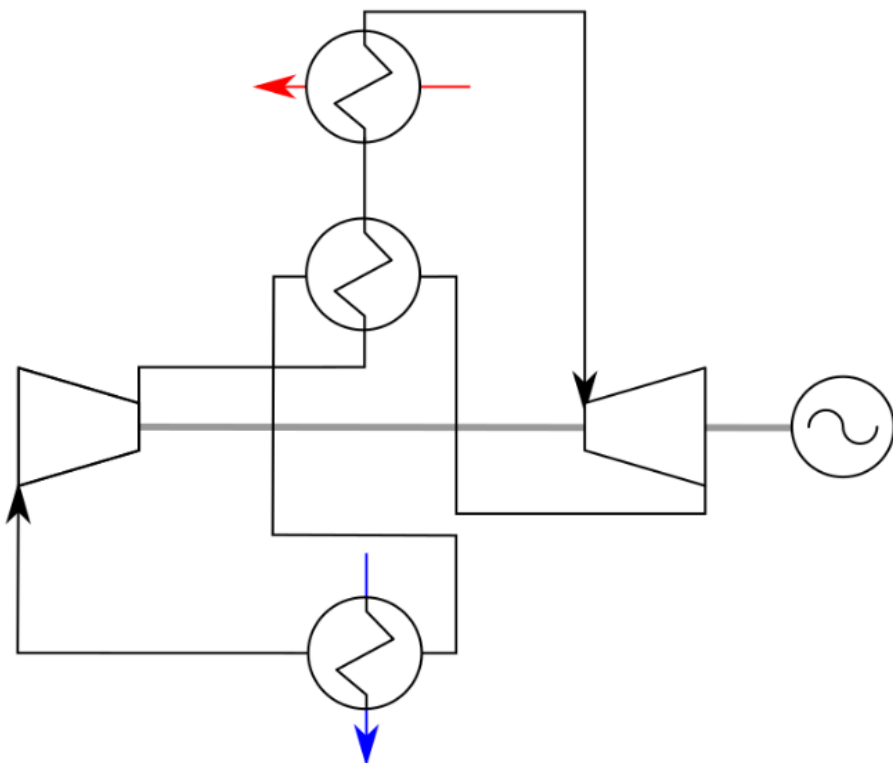
1 m

Steam (250 MW)

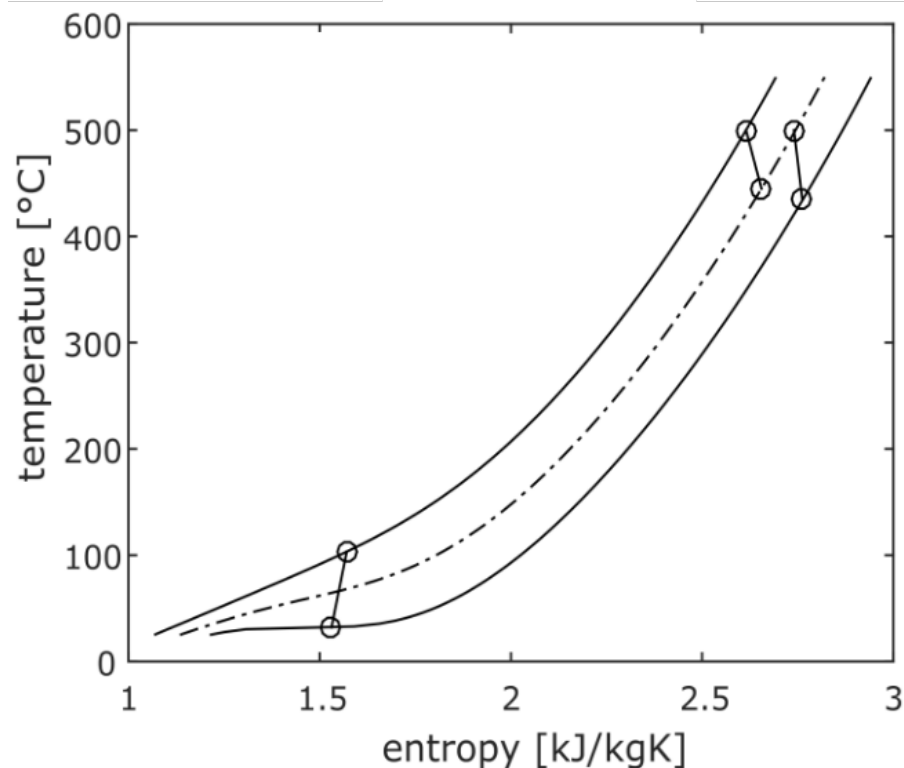
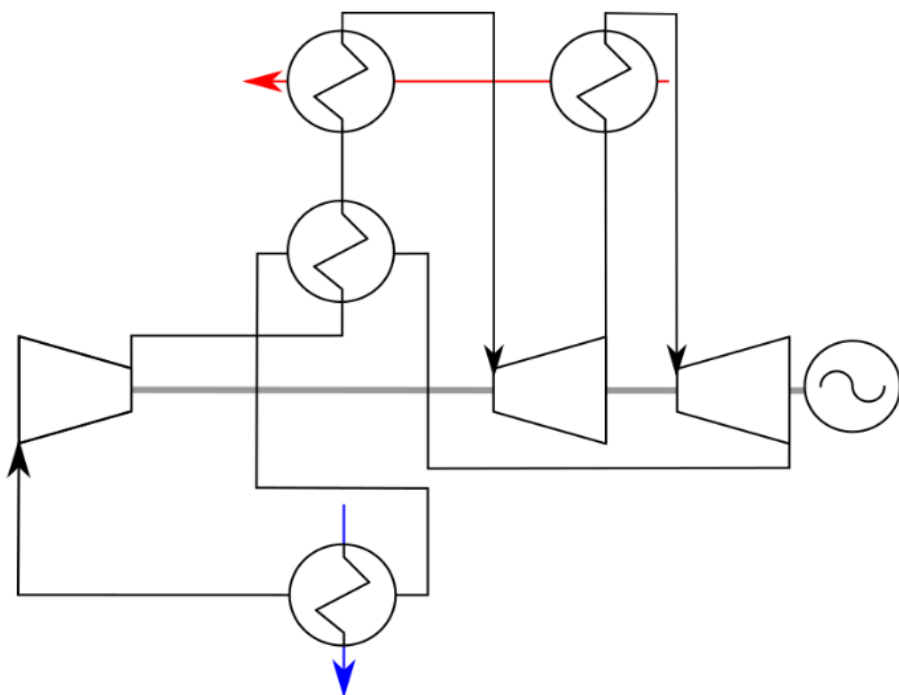


Source: Sandia National Laboratories, Technical report (2011)

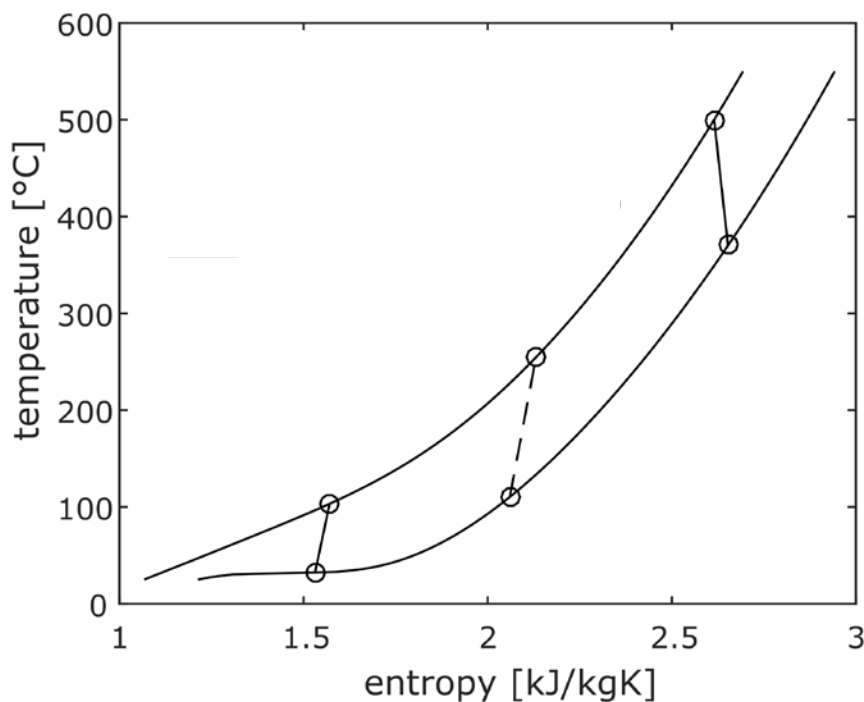
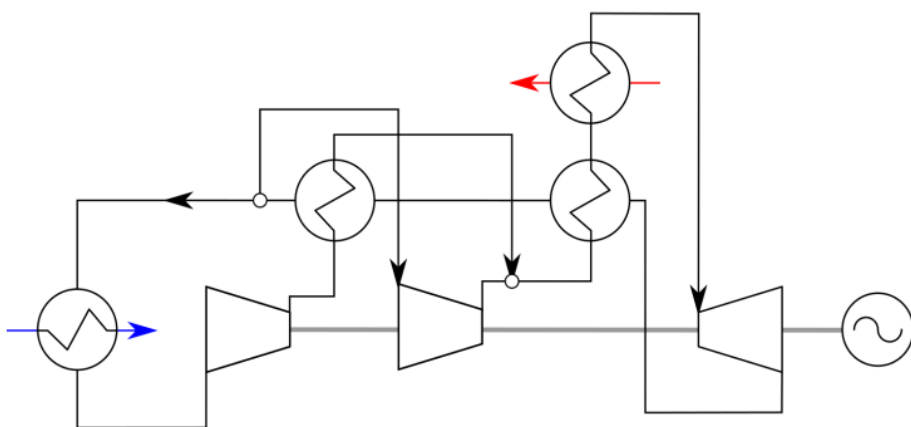
# Simple Regenerated (SR) layout



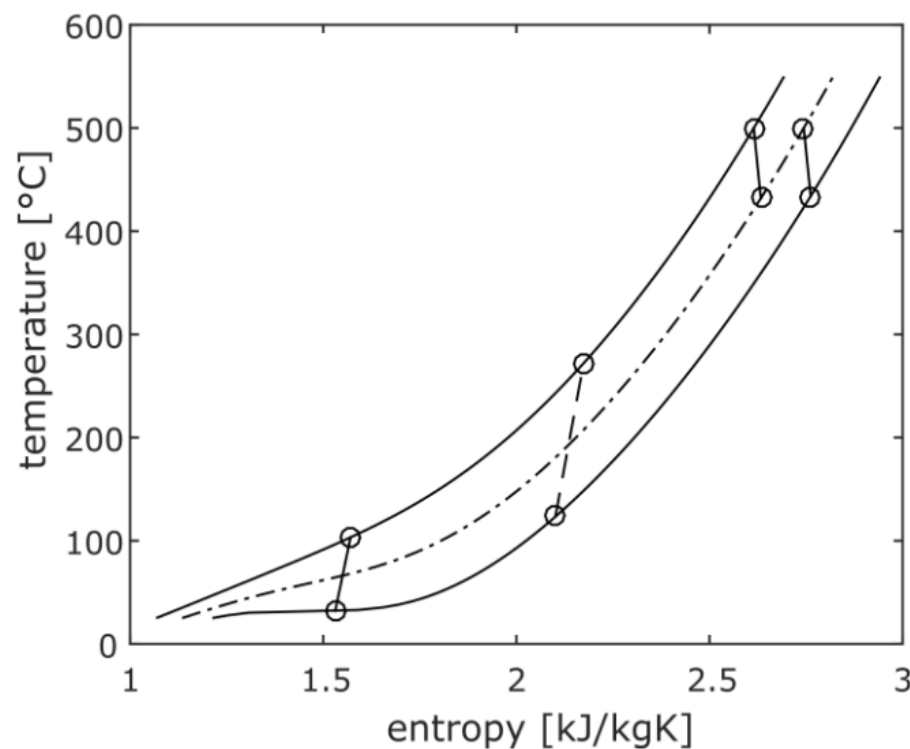
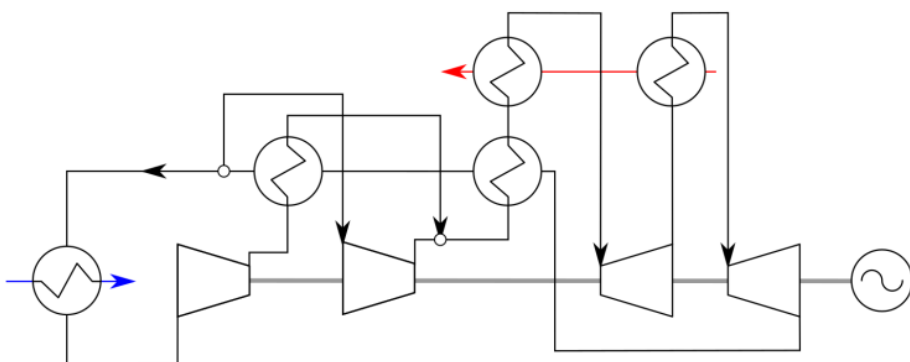
# Reheating (RH) layout



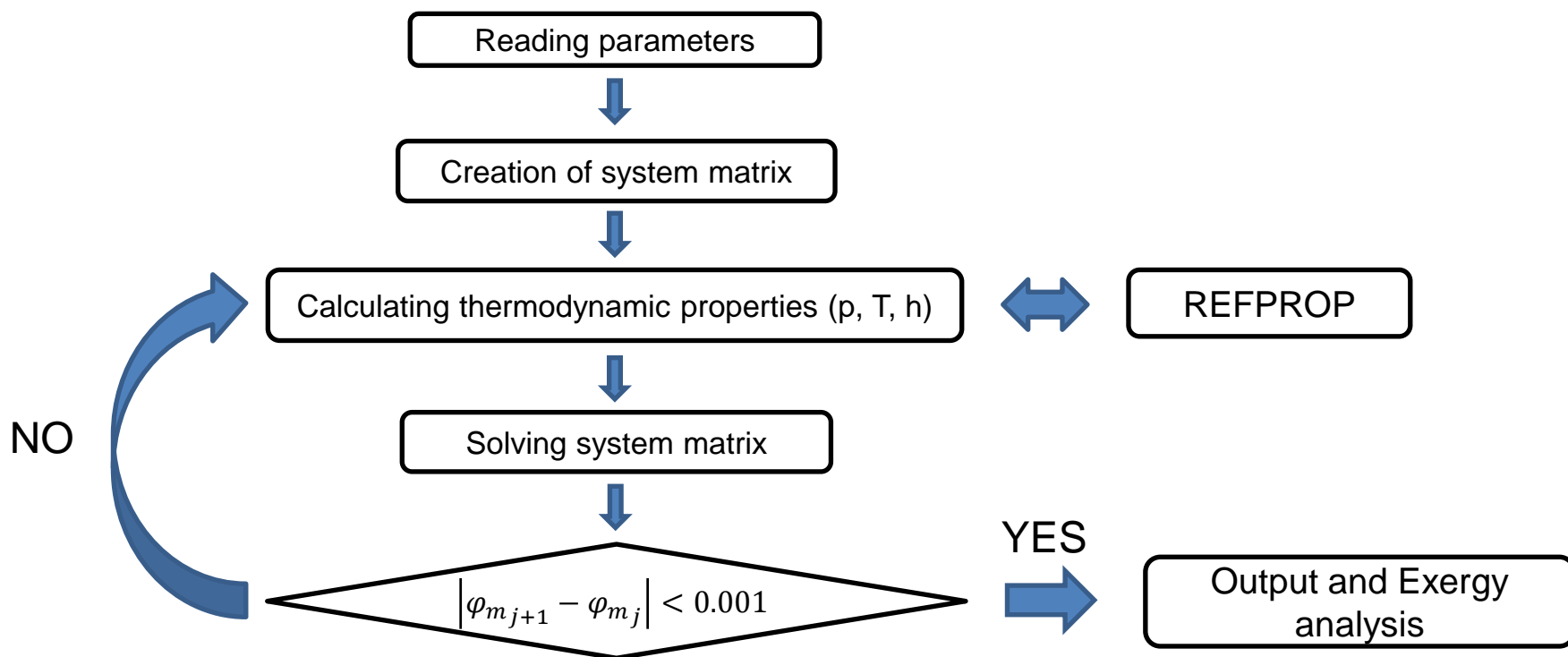
# Recompression (RC) layout



# Recompression Reheating (RCRH) layout



# Methodology: CycleTempo



# Cycle Tempo: governing equations

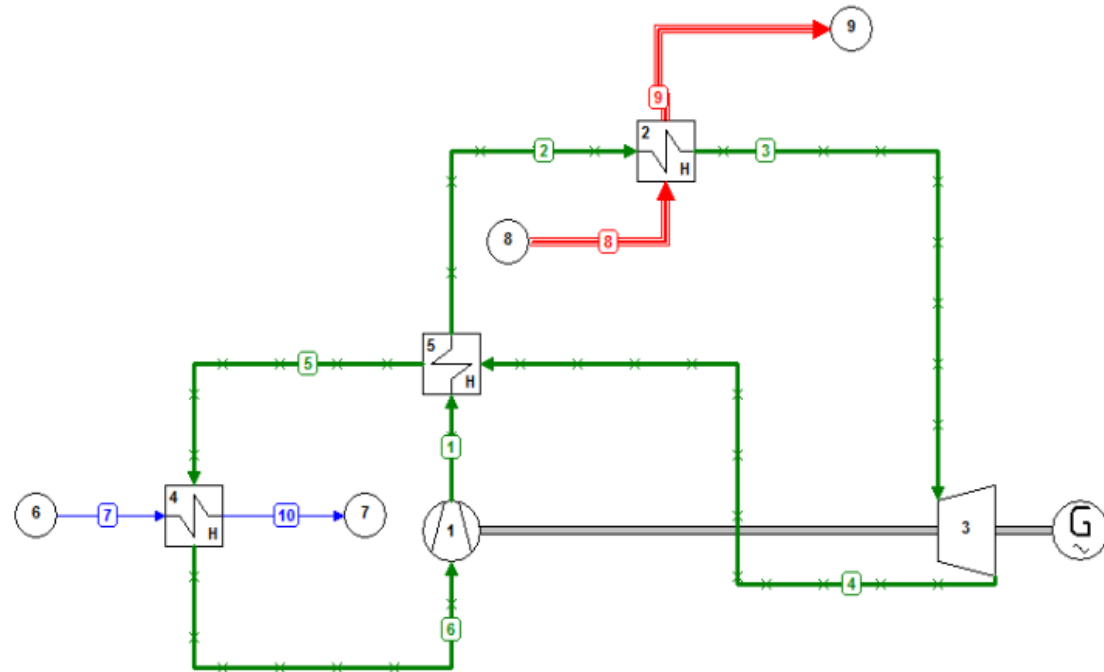
➤ Steady state analysis

➤ Governing equations:

$$\sum_i m_i = 0 \quad (\text{mass balance})$$

$$\sum_i m_i h_i = 0 \quad (\text{energy balance})$$

$$\sum_i m_i [(h_i - h_0) - T_0 (s_i - s_0)] = 0 \quad (\text{exergy equation})$$



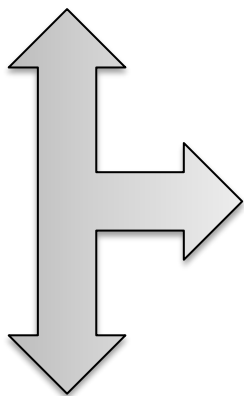
# Cycle Tempo: Creation of system matrix

			Number of pipes →								Mass flows		
Components	nr	Balance	1	2	3	4	5	6	7	10			
Heater	2	mass		1	-1						$m_1$		0
Turbine	3	mass			1	-1					$m_2$		0
Regenerator	5	mass	1	-1		1	-1				$m_3$		0
Compressor	1	mass	-1					1			$m_4$		0
Chiller	4	mass						-1	1	-1	$m_5$		0
Heater	2	energy		$h_2$	$-h_3$						$m_6$		$P_{\text{gas}}$
Chiller	4	energy					$h_5$	$-h_6$	$h_7$	$-h_{10}$	$m_7$		0
Regenerator	5	energy	$h_1$	$-h_2$		$h_4$	$-h_5$				$m_{10}$		0

**Kind of equation** (points to the 'Balance' column)

**Thermal power supplied by the exhaust gases** (points to the  $P_{\text{gas}}$  cell)

# Methodology: Overall analysis



**OUTPUT**

- Heat exchangers' transfer area
- sCO<sub>2</sub> mass flows
- Net power output
- Cycle efficiency
- Exergy efficiency

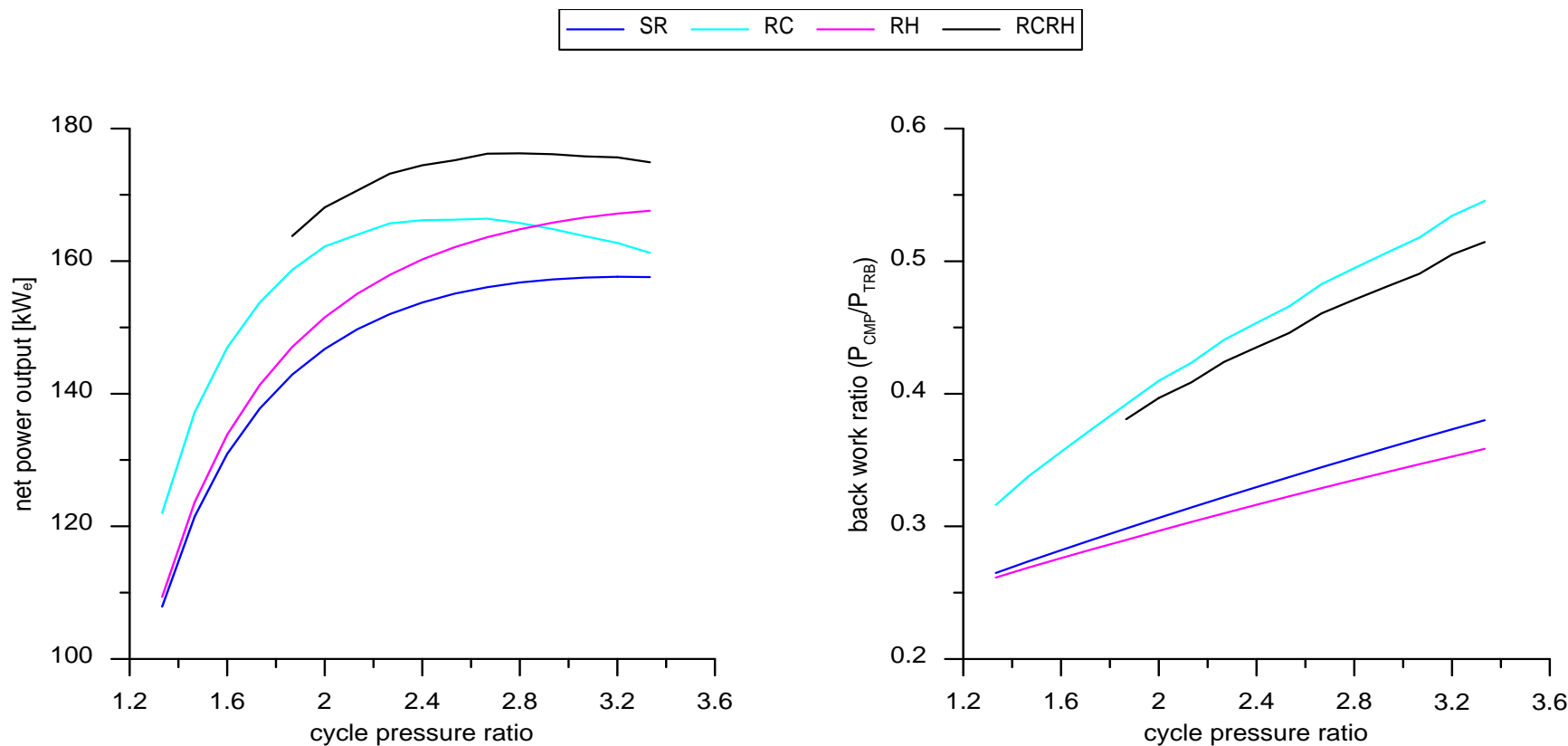
# Results: Assumptions

- Pressure and temperatures assumed accordingly with the limits of the currently material technology
- Isentropic efficiencies of the turbomachines have been assumed accordingly with the experimental tests carried out by SNL
- High grade Waste Heat Recovery applications

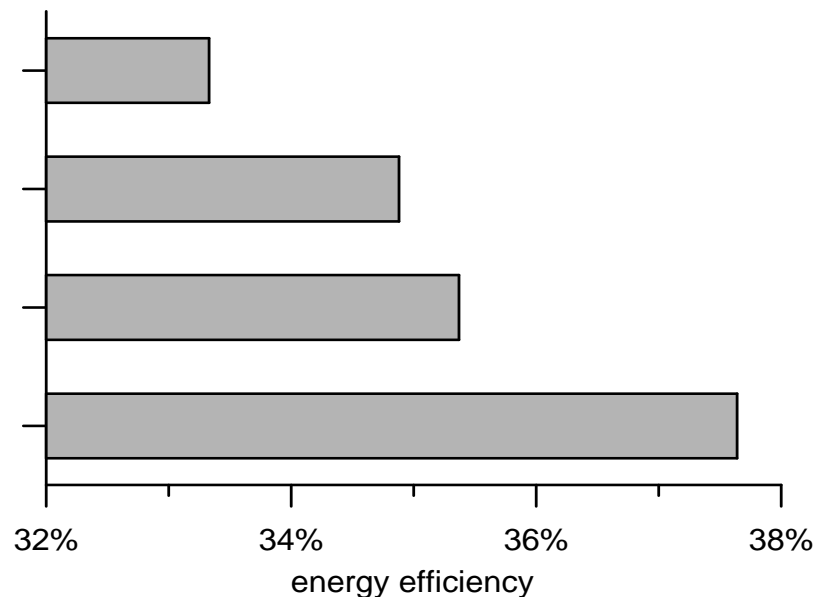
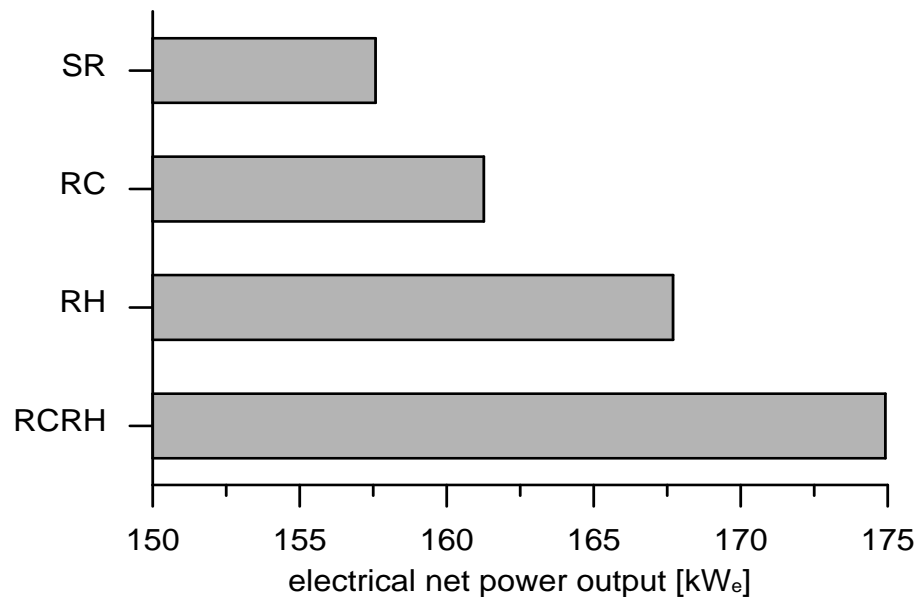
Thermodynamic conditions	Turbine	Compressor
Inlet Pressure	250	75
Inlet Temperature	500	32
Outlet pressure	75	250
Isentropic efficiencies	0.85	0.7
Mechanical efficiencies	0.98	
Generator efficiency	0.95	

Heat exchangers	Heater	Regenerators	Cooler	Sources	Flue gases	Cooling water
U [ $\text{W/m}^2\text{K}$ ]	100	1700	2900	Inlet temp [ $^{\circ}\text{C}$ ]	900	15
Cost coefficient $k$	7.0	1.8	8.0	Outlet temp [ $^{\circ}\text{C}$ ]	500	45
Pinch point	5			Mass flow [ $\text{kg/s}$ ]	1	Not fixed

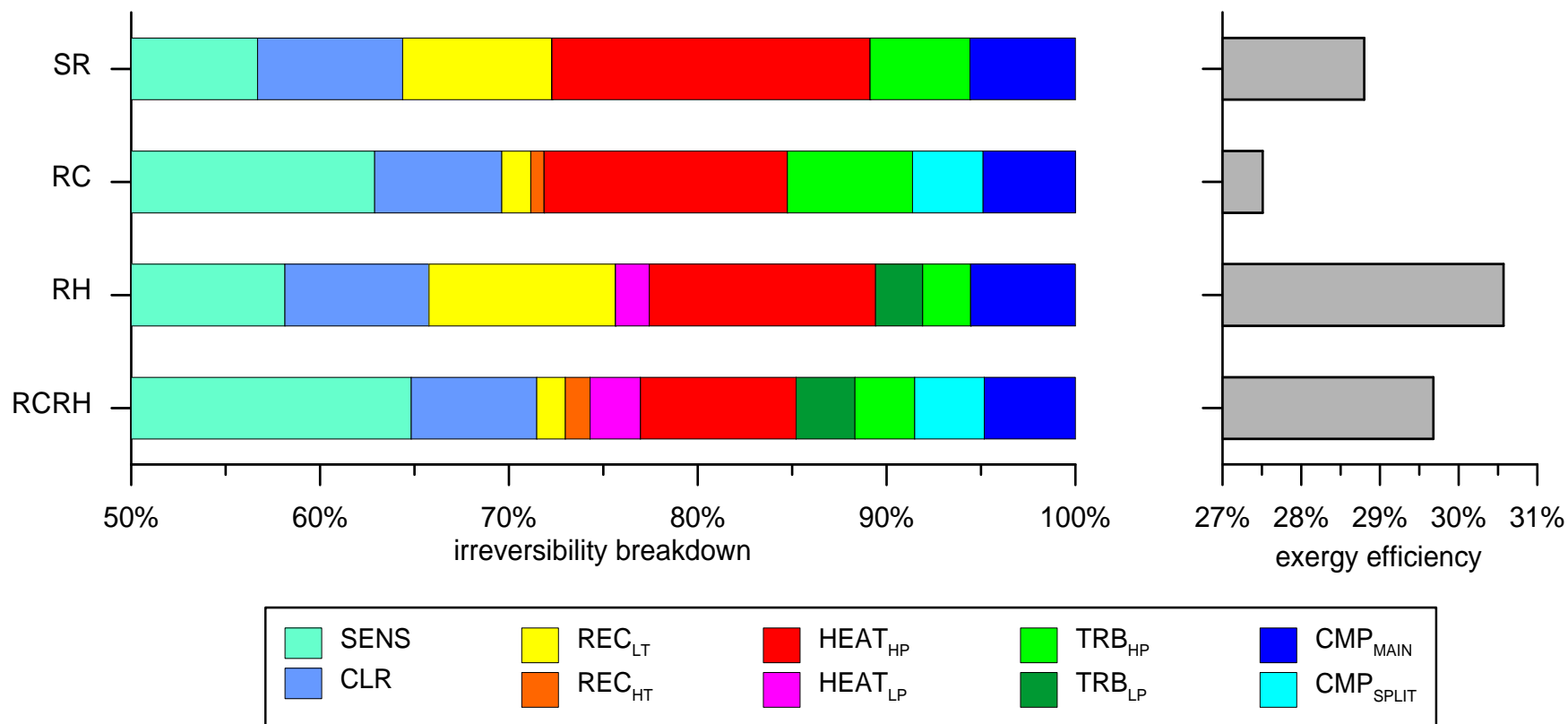
# Results: parametric analysis



# Results: 1<sup>st</sup> Principle analysis



# Results: Exergy analysis



# Investment cost analysis

To calculate the CAPEX for each layout component and then for the overall cost of the different cycle schemes, the following correlations have been adopted:

$$c_T = 479.34m \left( \frac{1}{0.93 - \eta_T} \right) \ln(\beta) (1 + \exp(0.036T_{in} - 54.4))$$

$$c_C = 71.10m \left( \frac{1}{0.92 - \eta_C} \right) \beta \ln(\beta)$$

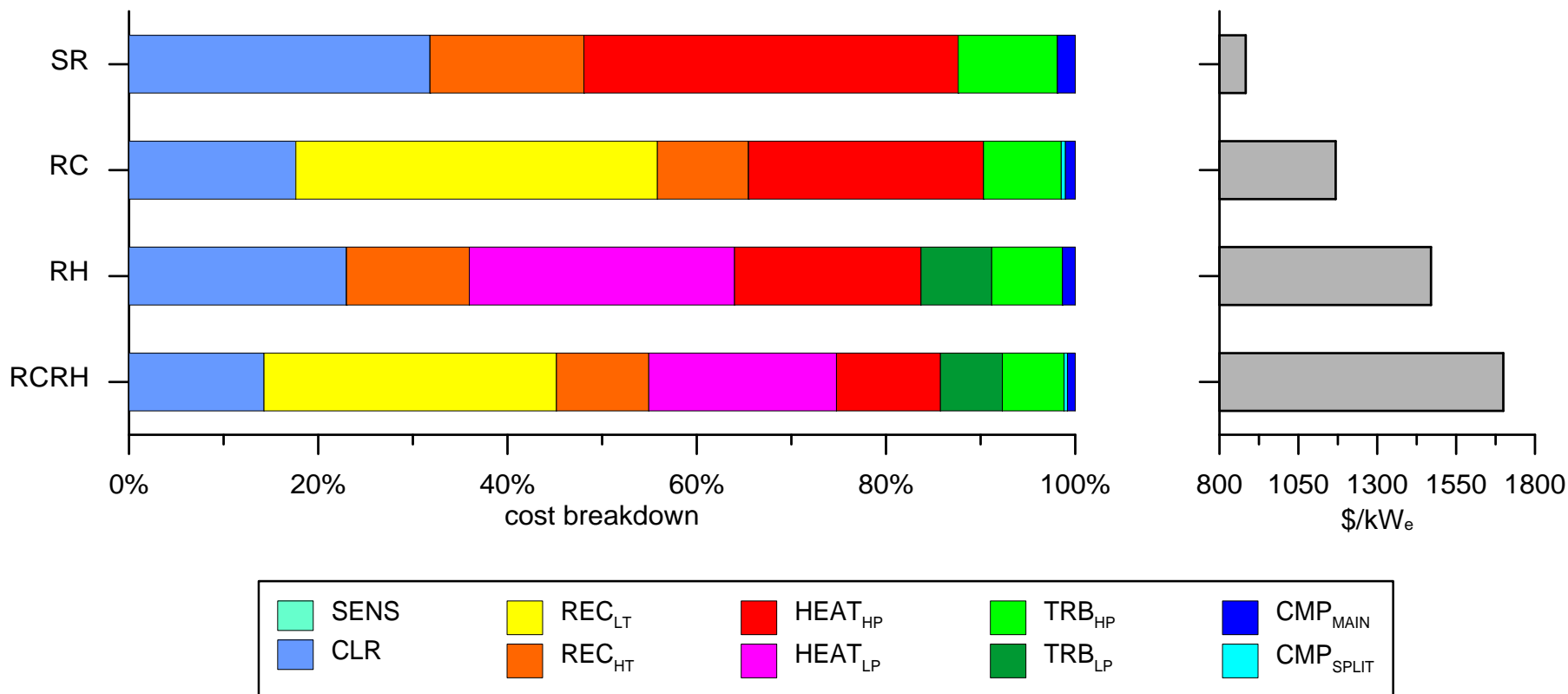
$$c_{HX} = k 2681A^{0.59}$$

$$c_{HX} = k 130 \left( \frac{A}{0.093} \right)^{0.78}$$

Where:

- the temperature is expressed in °C
- the mass flow in kg/s
- the heat transfer area in m<sup>2</sup>

# Results: Investment cost analysis



# Questions?