EFFECT OF THE AMBIENT TEMPERATURE ON THE PERFORMANCE OF SMALL SIZE sCO_2 BASED PULVERIZED COAL POWER PLANTS

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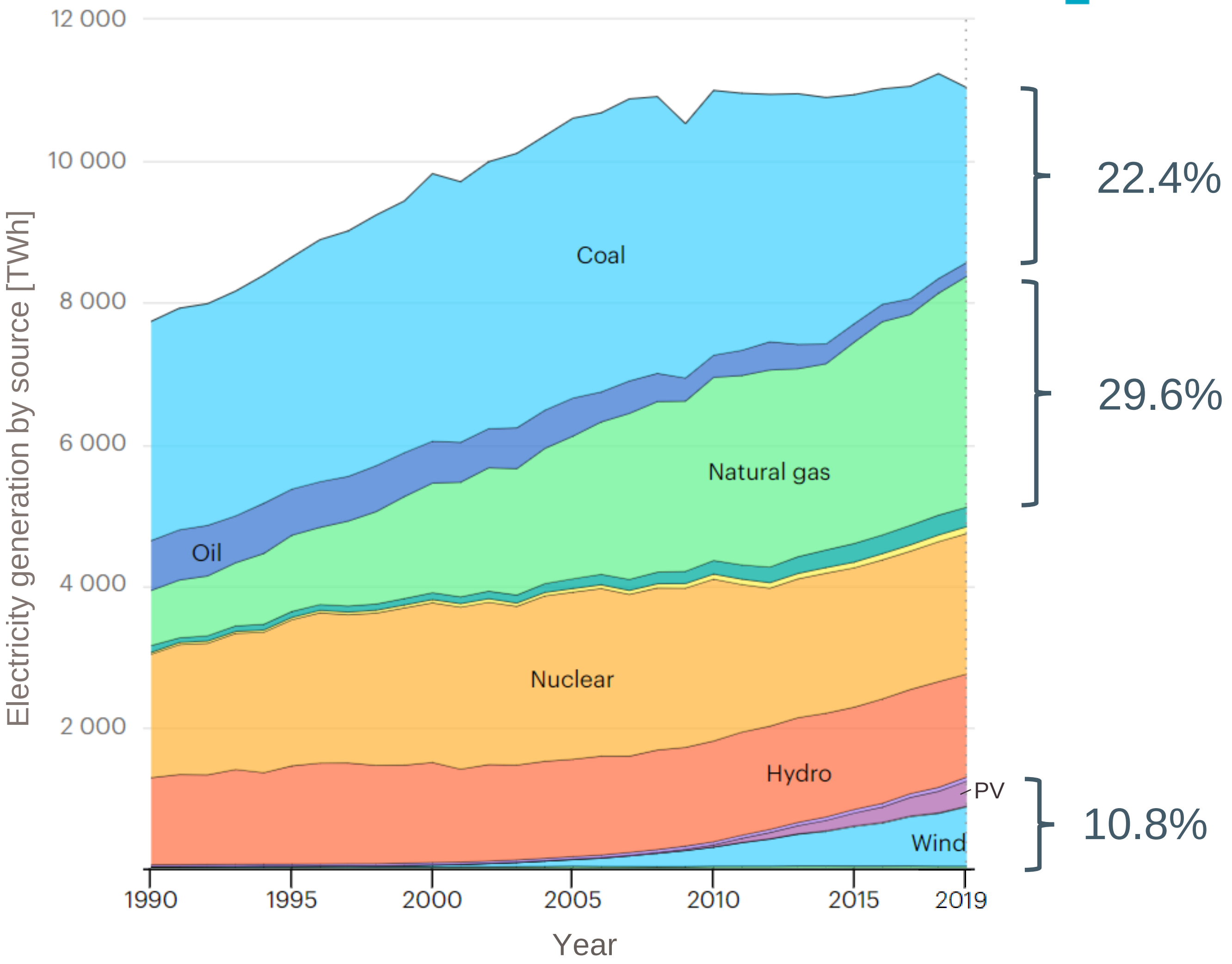
The sCO2-flex project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 764690.

Why sCO2-flex?

Motivation

- Growing share of non-dispatchable RES in the electricity mix.
- Still predominant role of fossil fuels
- traditional power plants are required to **shift from base load operation to cover peak demand.**



Electricity generation by source, OECD countries, 1990-2019
Source: International Energy Agency

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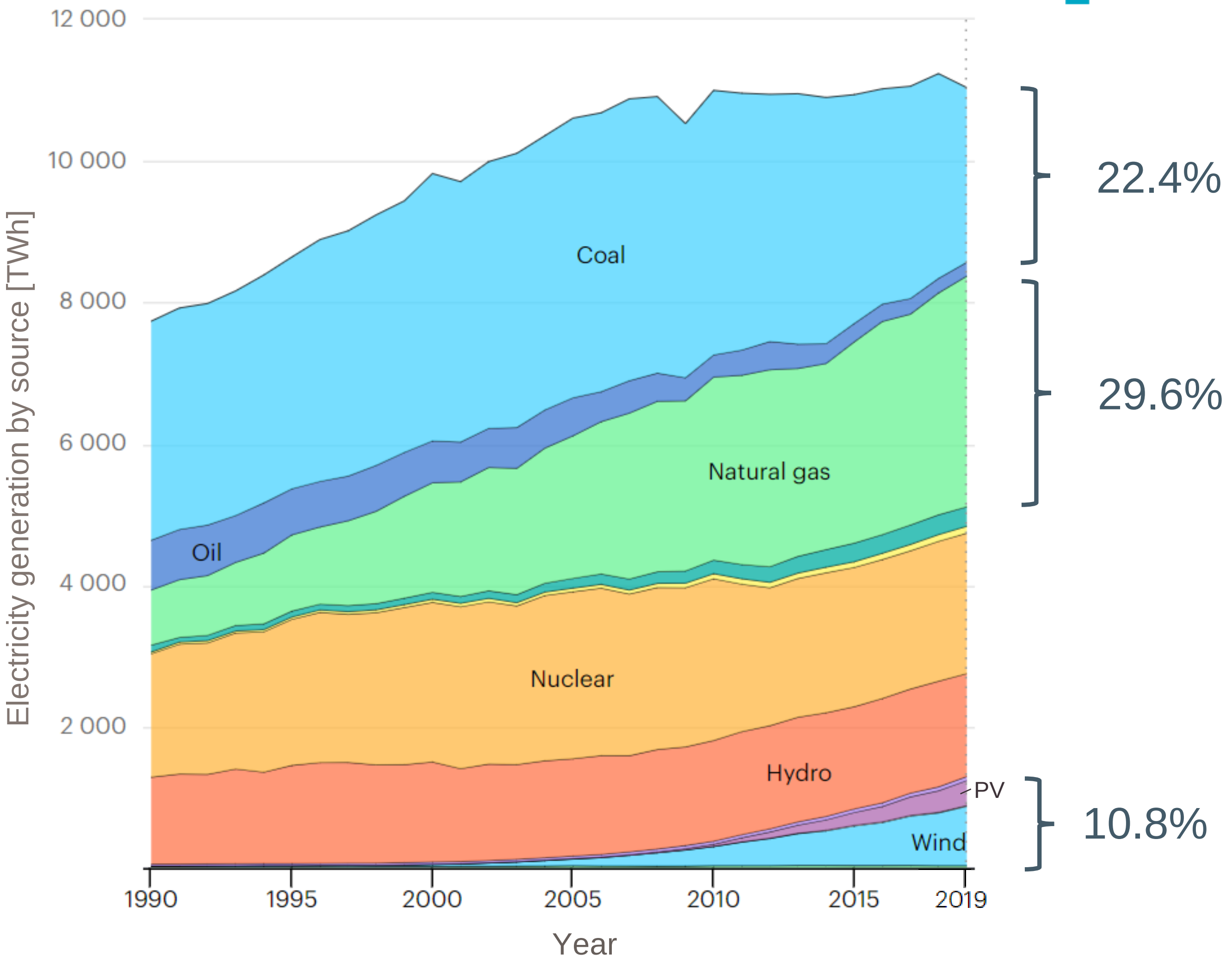
Objective

The design of a **25 MW_{el} highly flexible coal fired plant based on a supercritical CO_2 Brayton cycle**, to prepare the implementation of demonstration projects (TRL6).



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The sCO2-flex H2020 project

sCO2-flex consortium is made of **10 partners from 5 European countries**:

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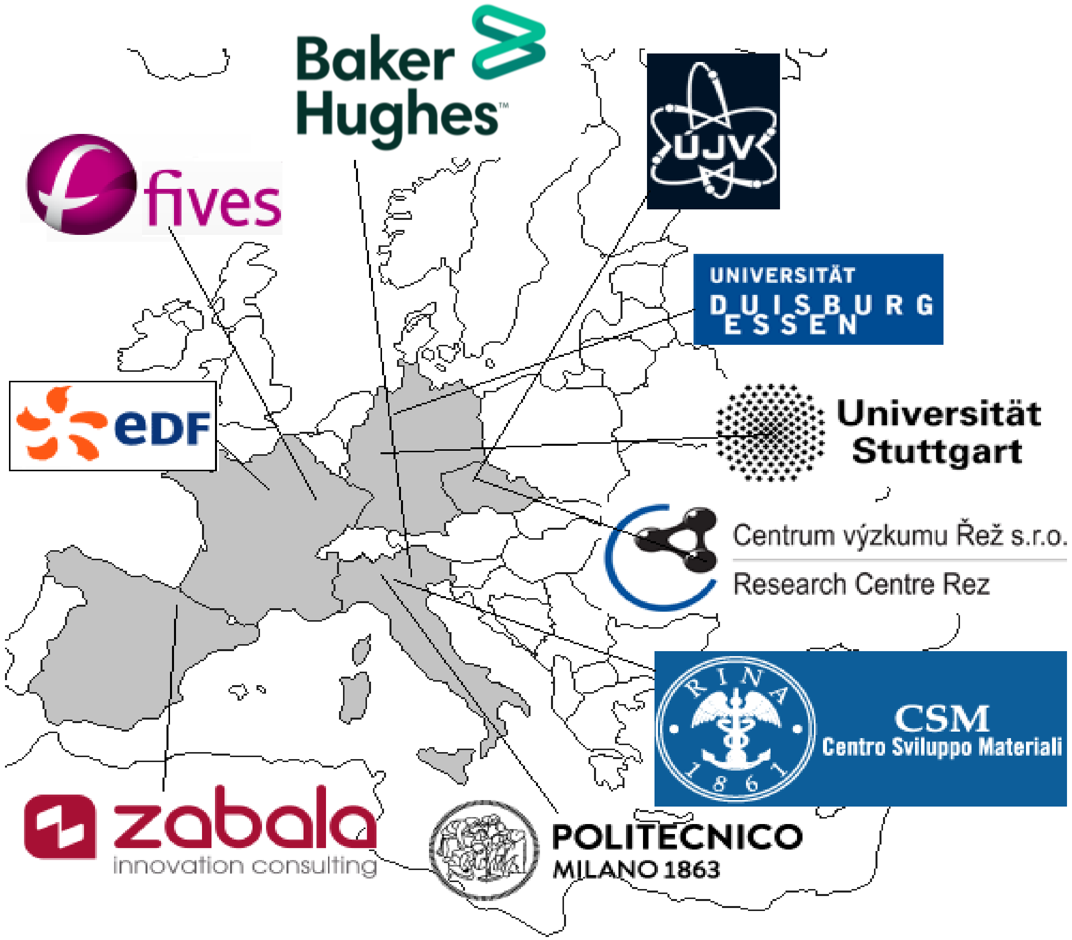
2. **Zabala:** Dissemination and communication
3. **BHGE:** Turbomachinery design
4. **UJV REZ:** Pulverized coal boiler development
5. **RINA-CSM:** Materials testing
6. **CVR:** sCO_2 test loop validation
7. **Fives Cryo:** Recuperators development
8. **USTUTT:** Heat exchanger testing
9. **UDE:** Turbomachinery numerical validation



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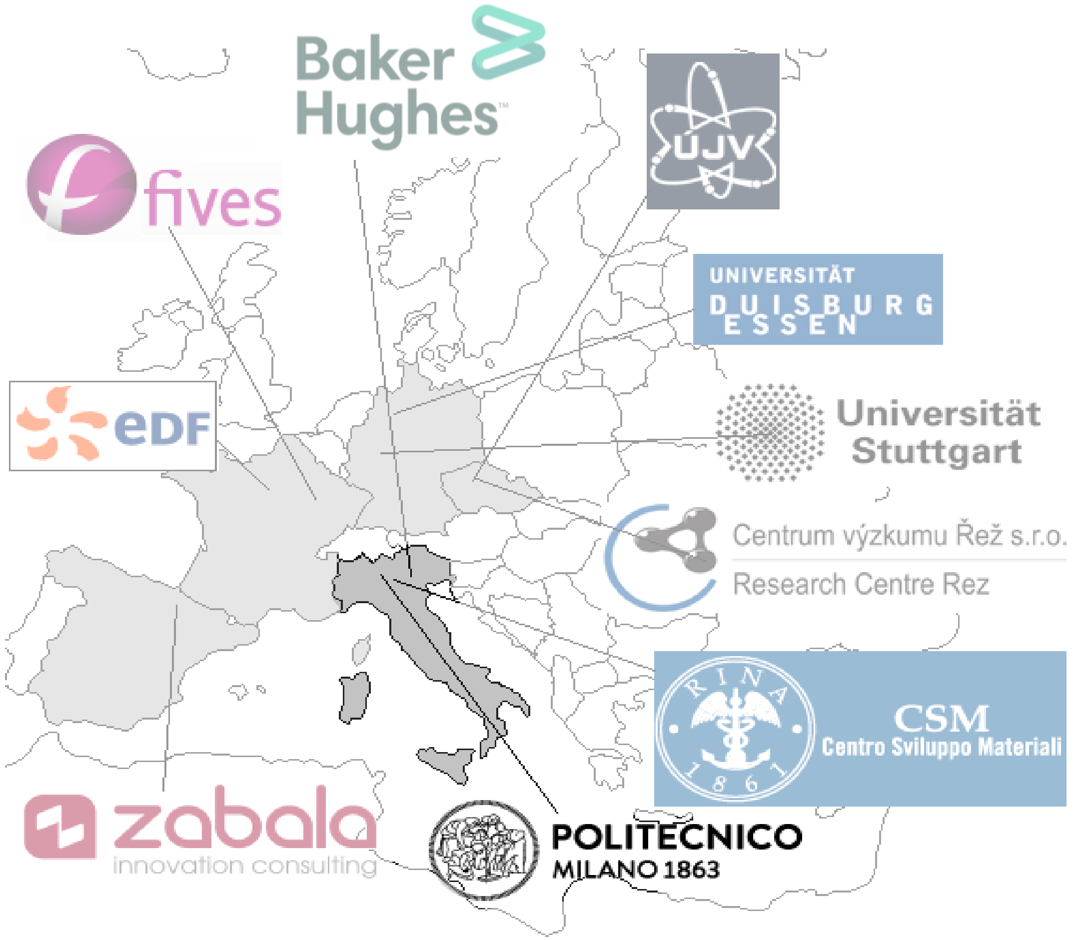
8. USTUTT: Heat exchanger testing
9. UDE: Turbomachinery numerical validation
10. **<u>POLIMI:</u>**
    - **Optimization of system design**
    - Definition of optimal **part-load operation strategy**
    - Application to **other energy sources** (CSP, WHR, biomass, …)



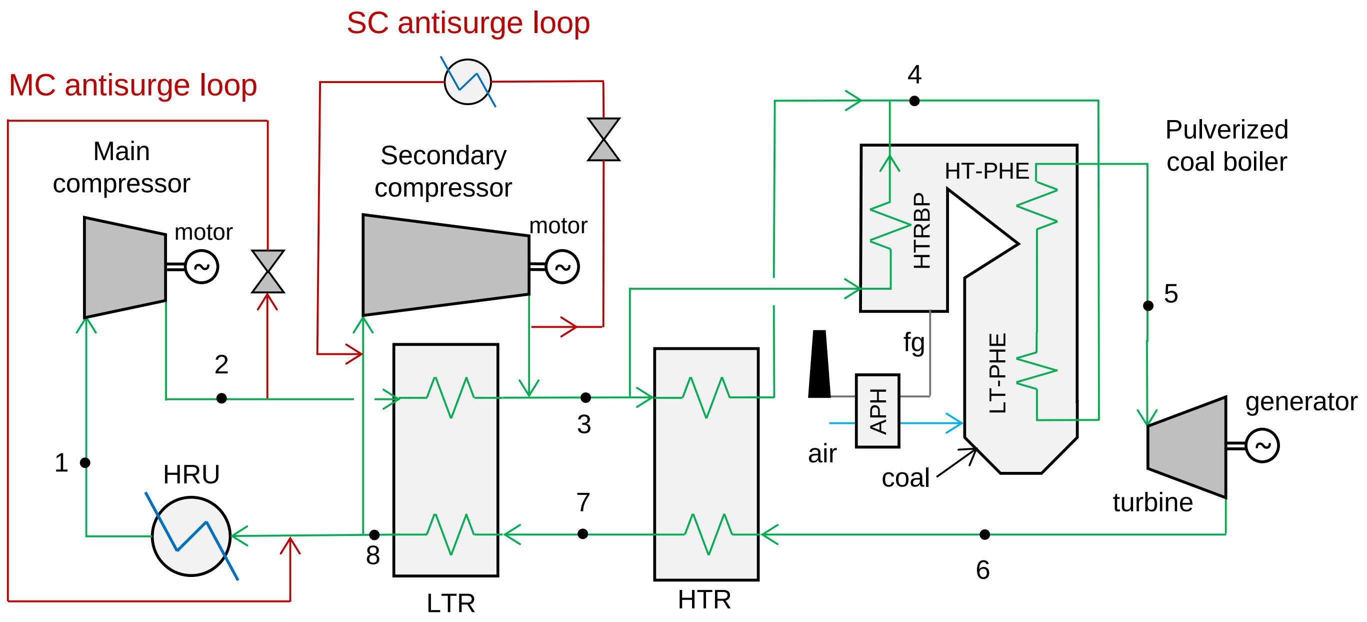
sCO2-flex plant design

Configuration:

- Recompressed cycle **with HTR bypass** allows for a lower average temperature of heat introduction
- **Reduction of stack losses**

sCO$_2$ plant parameters	
Plant design W$_{net}$, MW$_{el}$	25
Turbine inlet T, °C	620
Compressor inlet T, °C	33
Turbine isentropic efficiency	85.4 %
Main comp. polytropic eff.	82.4 %
Second. comp. polytropic eff.	81.8 %
LTR and HTR pinch point, °C	10
Cycle efficiency, %	**42.36**
Boiler efficiency, %	**94.37**
Overall efficiency, %	**39.98**

*The reported results are not the definitive one of the project



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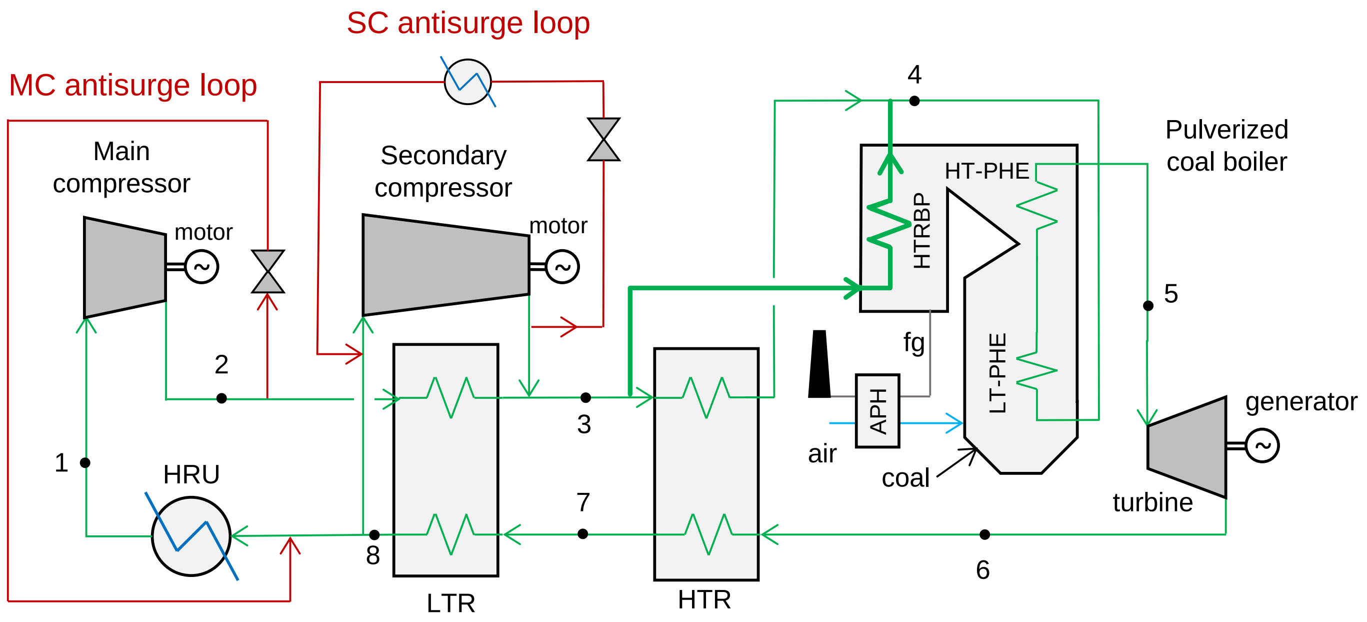

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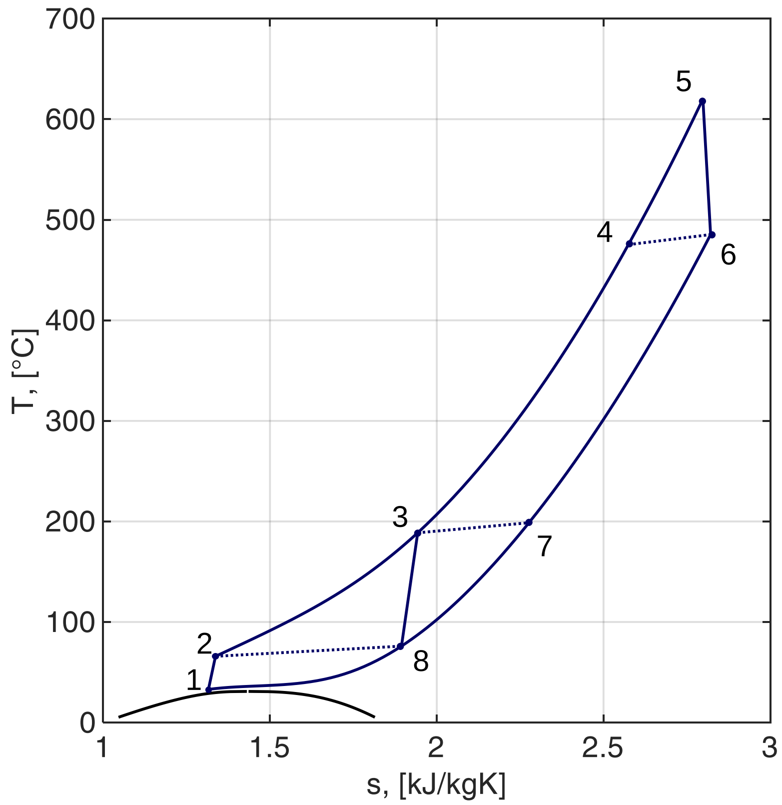

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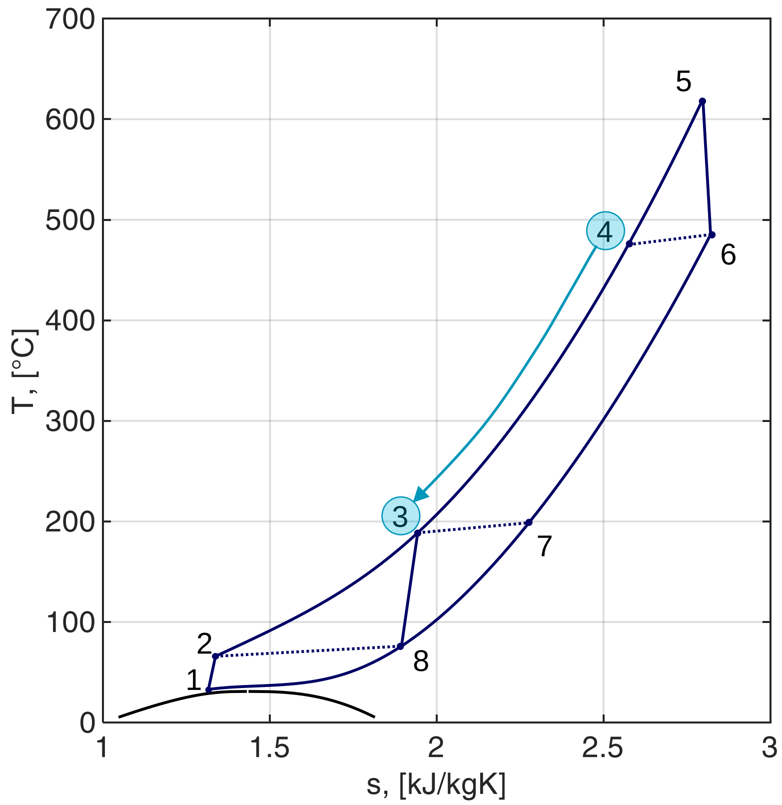


Adopting he HTR bypass → CO_2 inlet T in the boiler is reduced from T_4 to T_3

Coal boiler design

Two-pass pulverized coal boiler with:

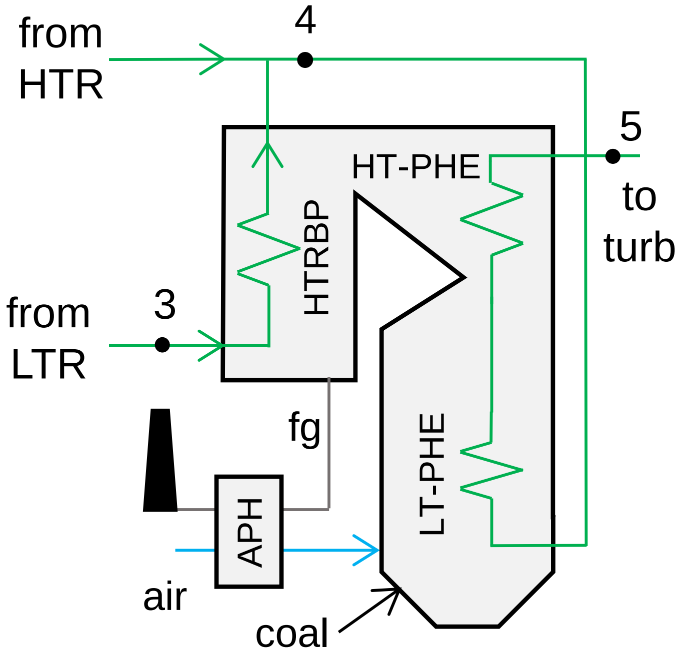
- LT-PHE in boiler furnace
- HT-PHE in radiative-convective co-current section
- CO_2 bypass preheating in counter-flow section

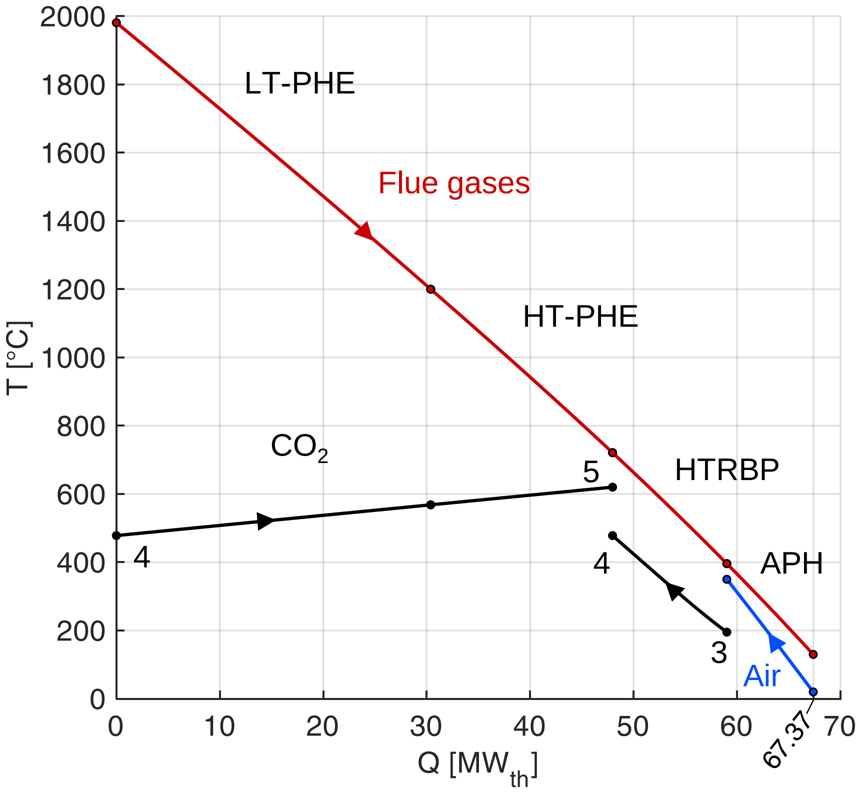
Coal: BILINA HP1

Air preheater: Ljungstrom type

Materials: - INCONEL617 for HT
- P92 for LT

Boiler parameters	
Coal flow rate, kg/s	3.70
Comb. air flow rate, kg/s	24.56
Flue gases flow rate, kg/s	27.92
Adiabatic flame T, °C	1981
Stack temperature, °C	130
Boiler pinch point, °C	101.1
Ljungström pinch point, °C	45.9
Air excess	20%





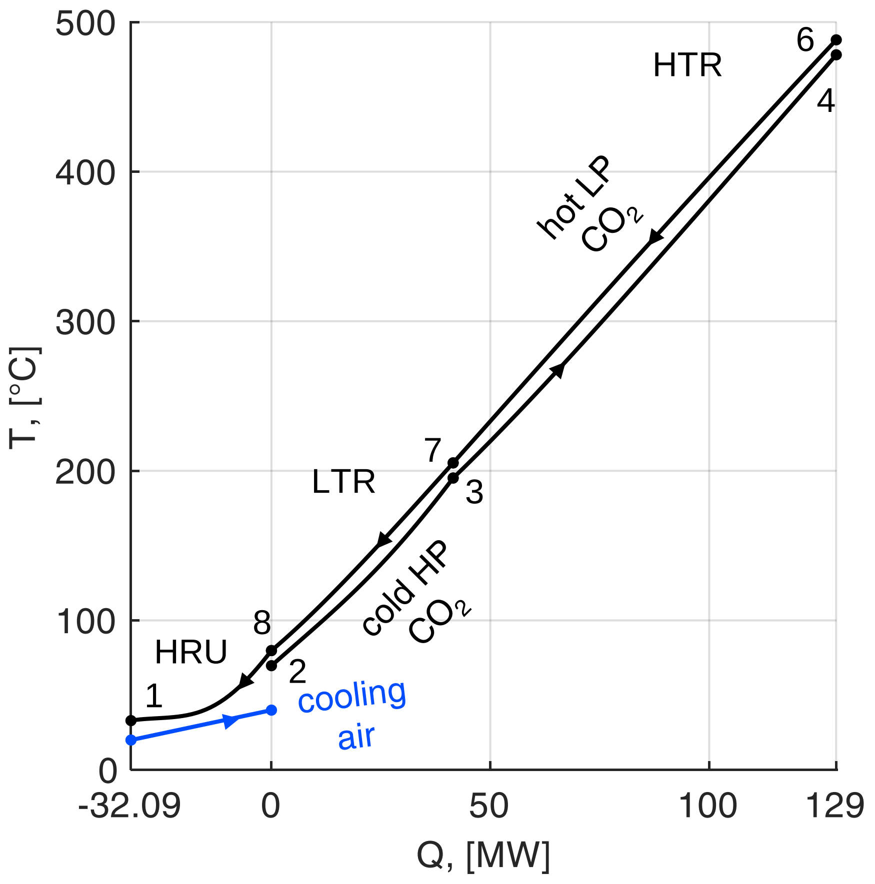
Heat exchangers design

Configuration:

- All **recuperators** are designed adopting a discretized **PCHE** model based on Dostal PhD thesis.
- **Heat rejection unit** is modelled as a dry air-cooled unit tuning the design parameters on manufacturer data.

Heat exchanger size				
	Duty	ΔT_{mln}	HX area	Metal mass
	MW_{th}	°C	m^2	kg
HRU	32.1	15.1	2182	17217
LTR	41.5	12. 6	4644	29120
HTR	87.5	14.7	11512	72185
HTRBP	11.1	227.4	504	30686
PHE	48.0	369.2	913	45330

Aggregate TQ diagram



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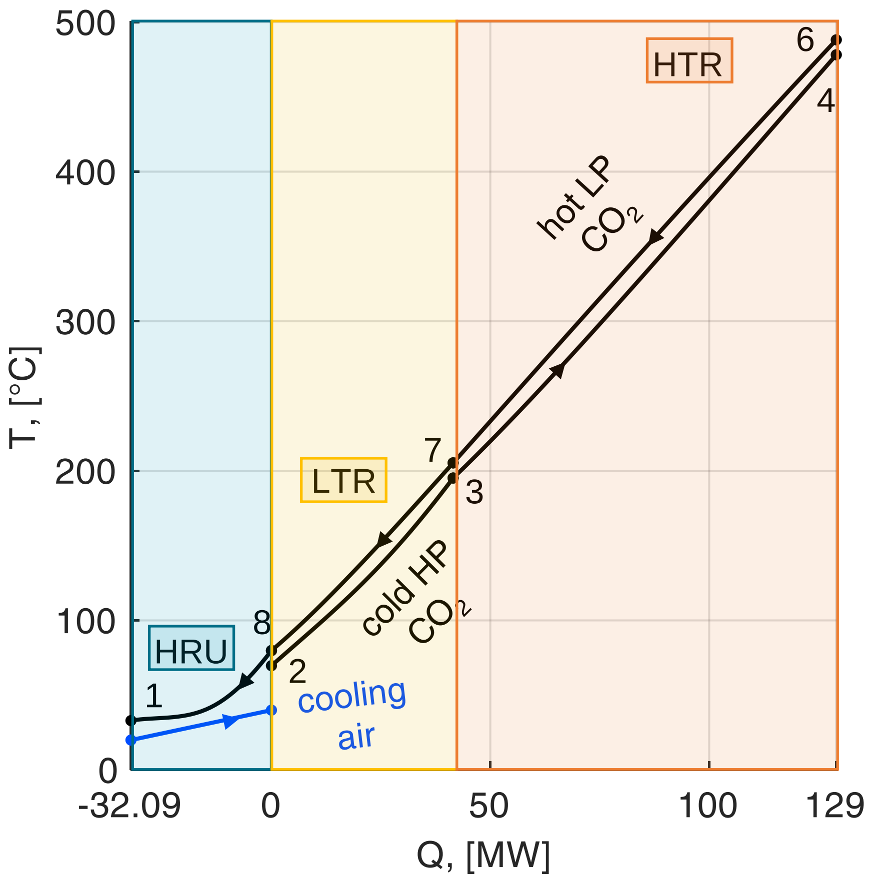

Motivation and objectives of this work

sCO_2 power cycles are particularly suited for air-cooling due to CO_2 **high critical temperature** and **high temperature variation in the HRU** (around 35°C)

The adoption of dry air-cooled HRU allows the following advantages:

- reasonable footprint and small cold-end temperature differences
- a significant reduction of water consumption
- an easy installation independently of the availability of a river or sea in proximity of the site location.

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- Ambient air temperature variation on daily and seasonal base can affect the cycle minimum temperature with a consequent impact on sCO_2 power plant performance and operability.

The design and operation of the HRU is not trivial and may strongly affect the operation of a sCO_2 power plant due to its **crucial role in the control of the main compressor inlet temperature**.

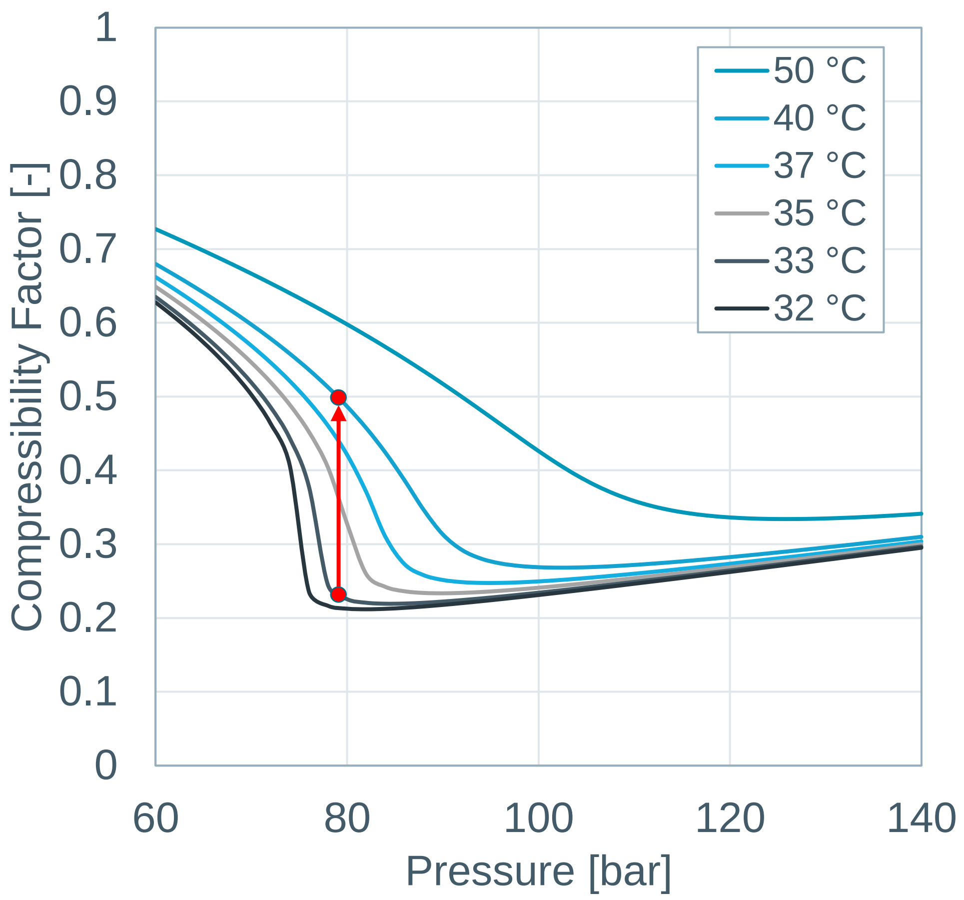
Effects of ambient temperature variation

With no corrective actions, the increase of T_{amb} causes an **increase of compressor inlet temperature**.

↓

Departure from the critical point region, resulting in a marked drop of density of the working fluid.

Higher main compressor specific consumption (for a given pressure ratio) and a **rapid increase of the CO_2 volumetric flow rate** (for a fixed coal mass flow rate at boiler burners).



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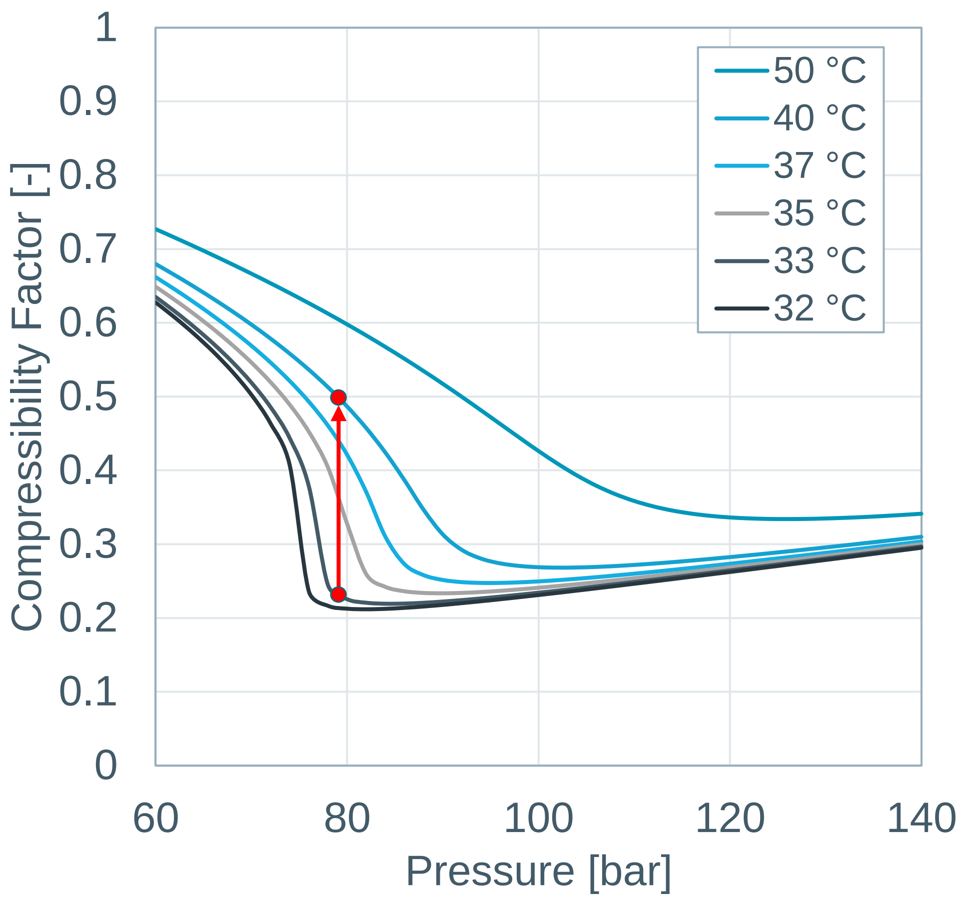
These lead to two effects:

- **penalization the cycle thermodynamic efficiency**
- **significant limitation the operability of the system in part-load and off-design conditions**



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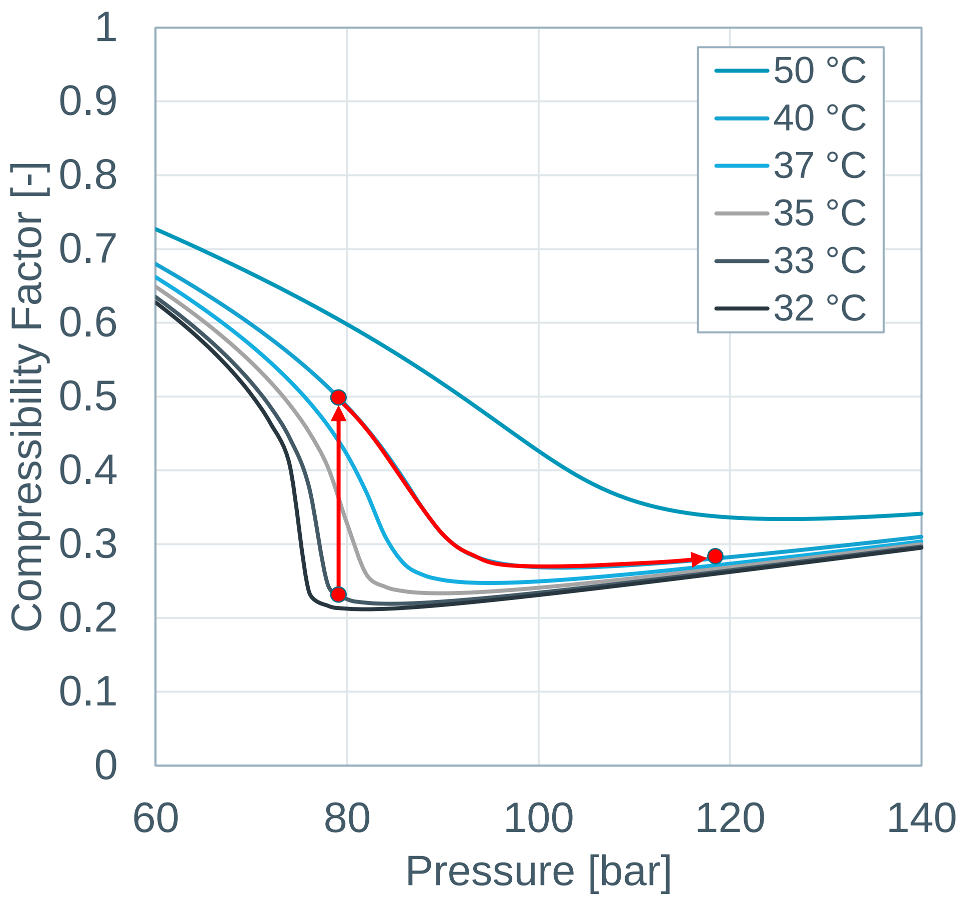

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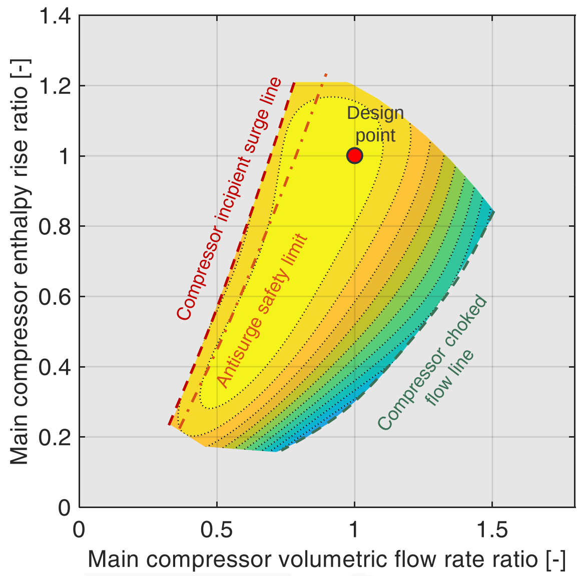

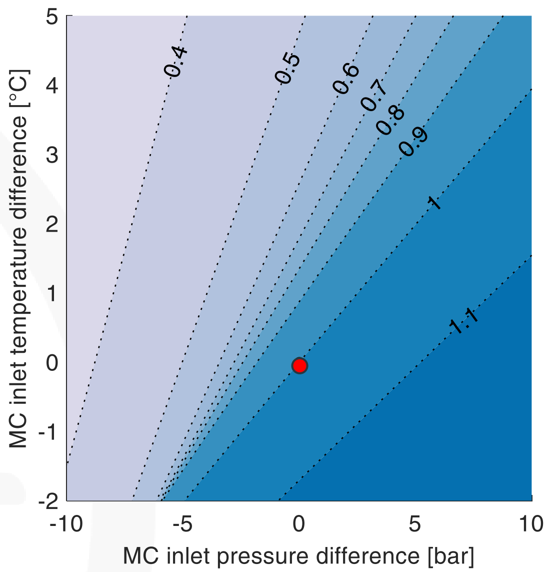

Main compressor:

- A **very small inlet temperature increase** (+2°C) at constant inlet pressure pushes the operative point at the limit of the compressor map.
- Increasing the inlet pressure would partially solve this issues but will result in a **marked reduction of cycle pressure ratio**

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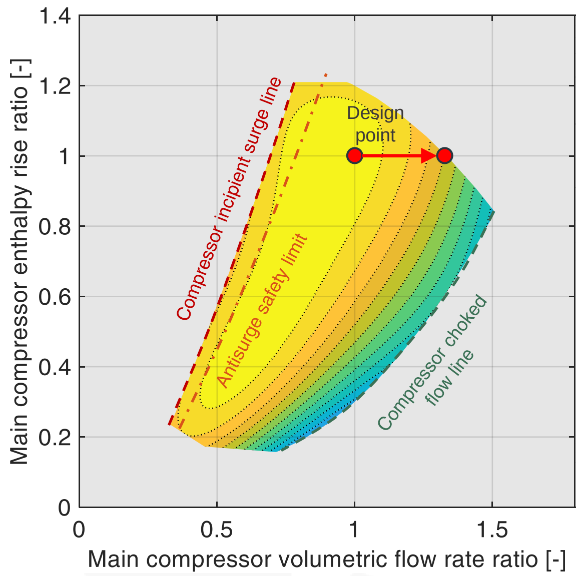

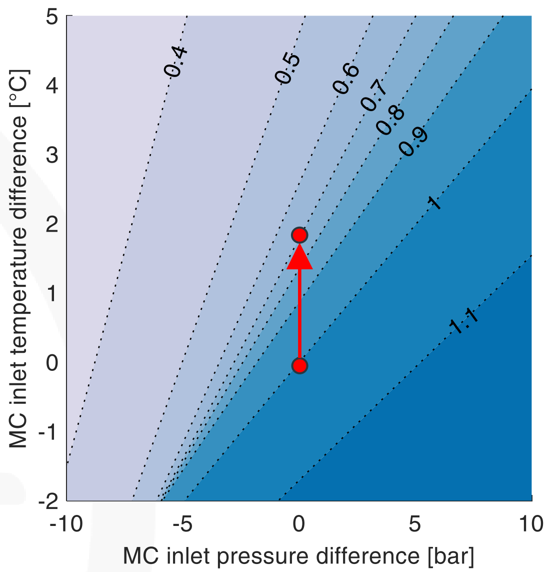

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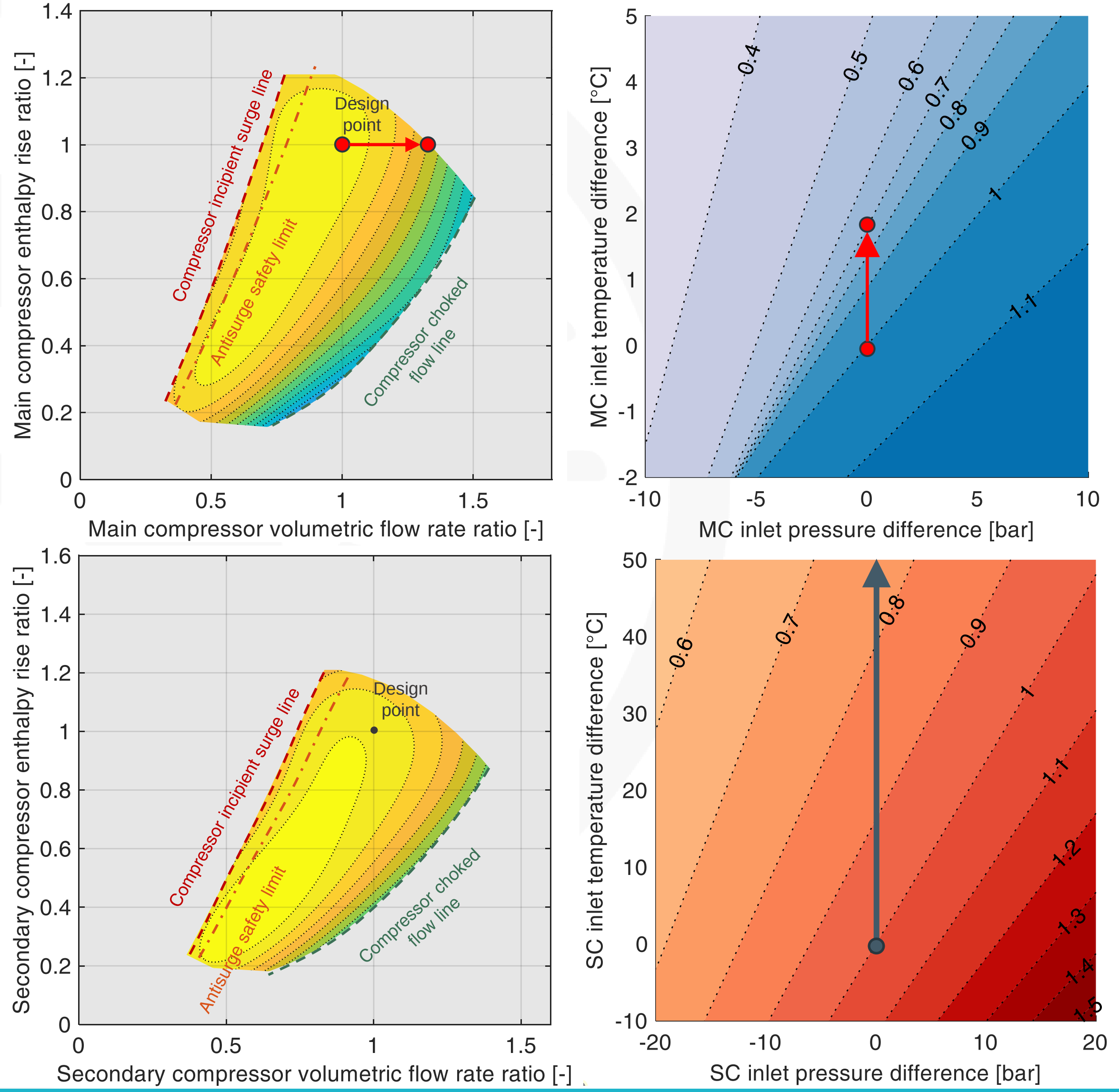

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Secondary compressor:

- This problem does not affect the secondary compressor which works far from critical point and with lower real gas effects at inlet condition

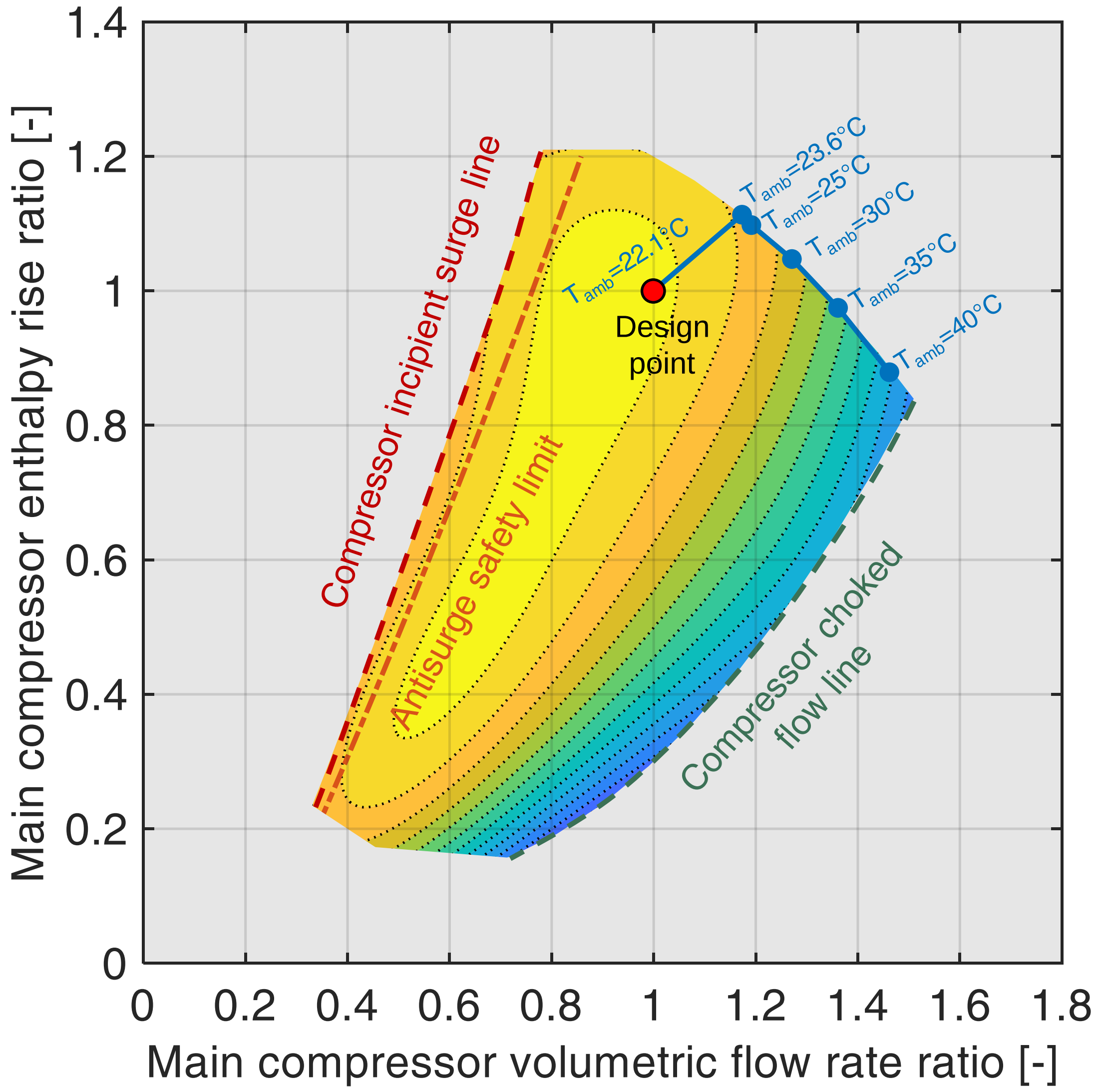
Control strategy S1

Nominal ambient temperature: 20°C

1) A first action consists in keeping the main compressor inlet temperature equal to the nominal value (33°C) by **increasing the cooling air mass flow rate** by adjusting the HRU fan rotational speed.

   This solution is possible until the maximum HRU fan rotational speed is reached (**125% of design value**).

   Maximum ambient temperature: 22.1°C



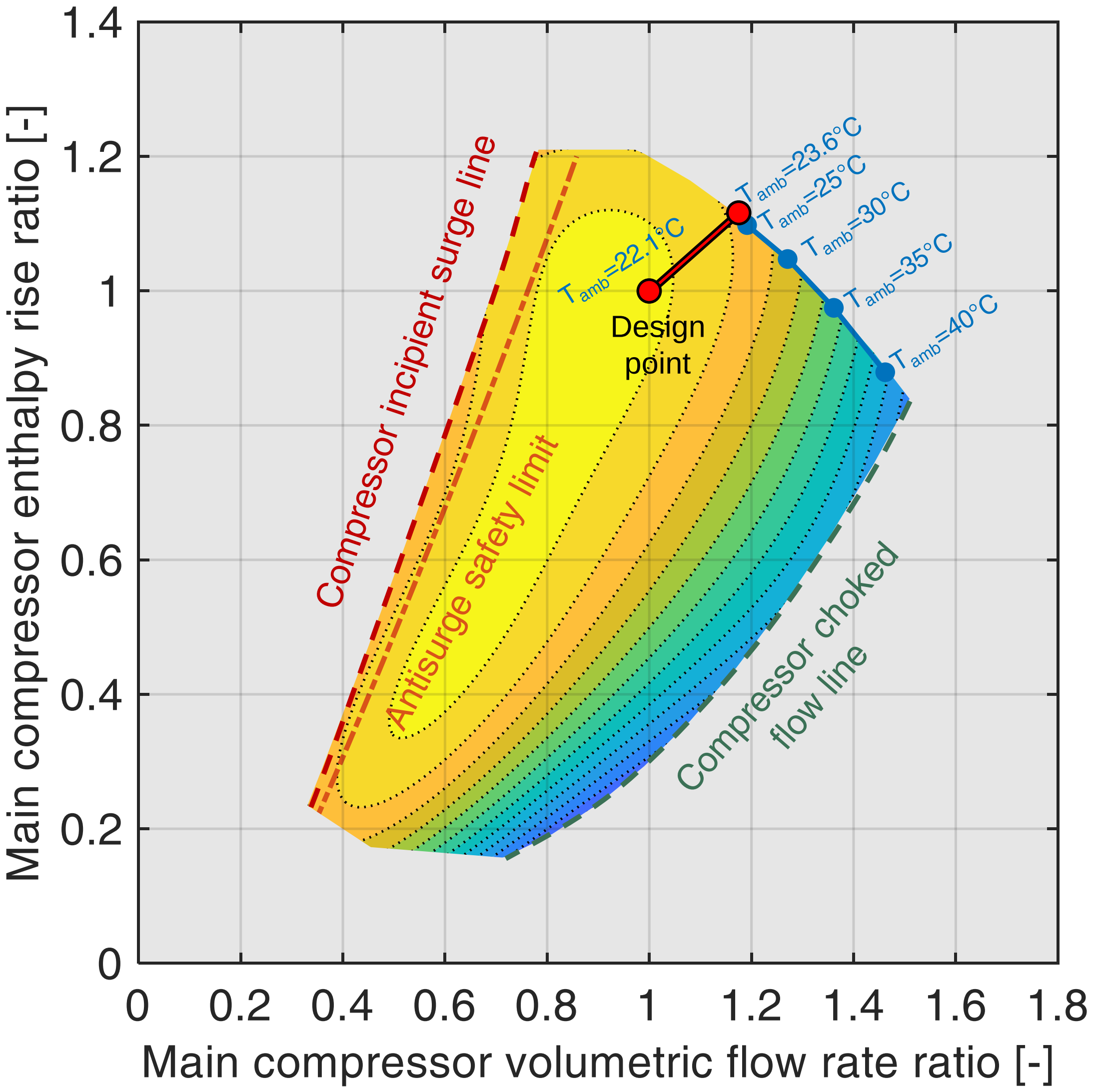
Control strategy S2

2) For an ambient temperature higher than 22.1°C, the HRU fan rotational speed cannot increase anymore.
Main compressor inlet temperature rises.

Main compressor **volumetric flow rate and enthalpy head increase** leading to an efficiency penalization of the component.

It is still possible to fuel the system with a nominal coal mass flow rate.

Maximum temperature: 23.6°C



Control strategy S3

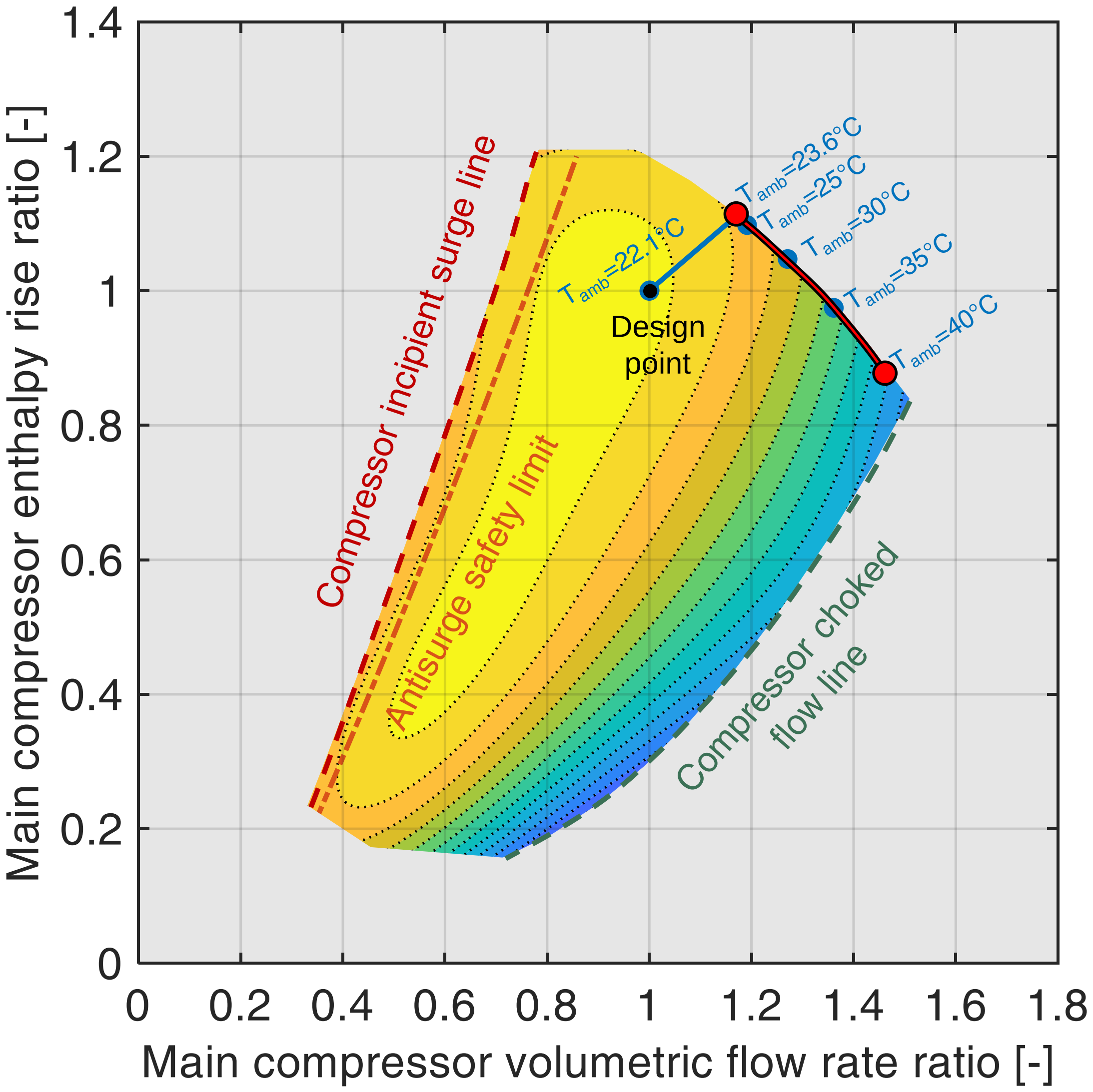
3) For an ambient temperature of 23.6°C corresponding to a compressor inlet temperature of 33.9°C, the upper bound of the main compressor operative map is reached.

⬇

The only possibility to operate the system for higher ambient temperatures is to **reduce the amount of pulverized coal** fed to the boiler burners.

⬇

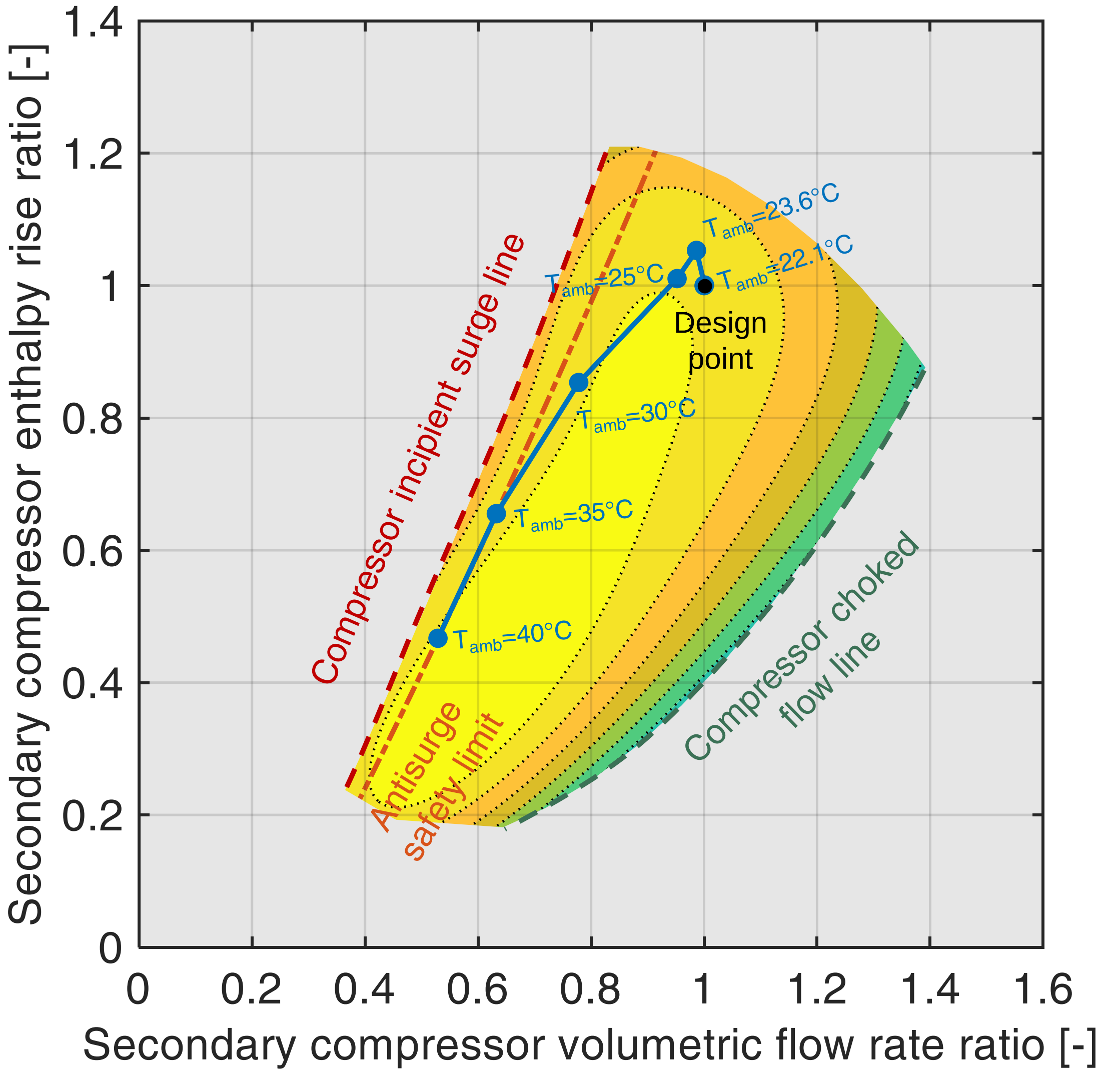
Significant limitation of the plant maximum power output that can be offered on the energy market during high ambient temperature hours.



Secondary compressor

On the contrary, the operative point of the secondary compressor is progressively pushed towards the surge safety limit involving the **activation of the antisurge loop**.

Minor penalization with respect to the **reduction of the amount of pulverized coal** fed to the boiler burners.



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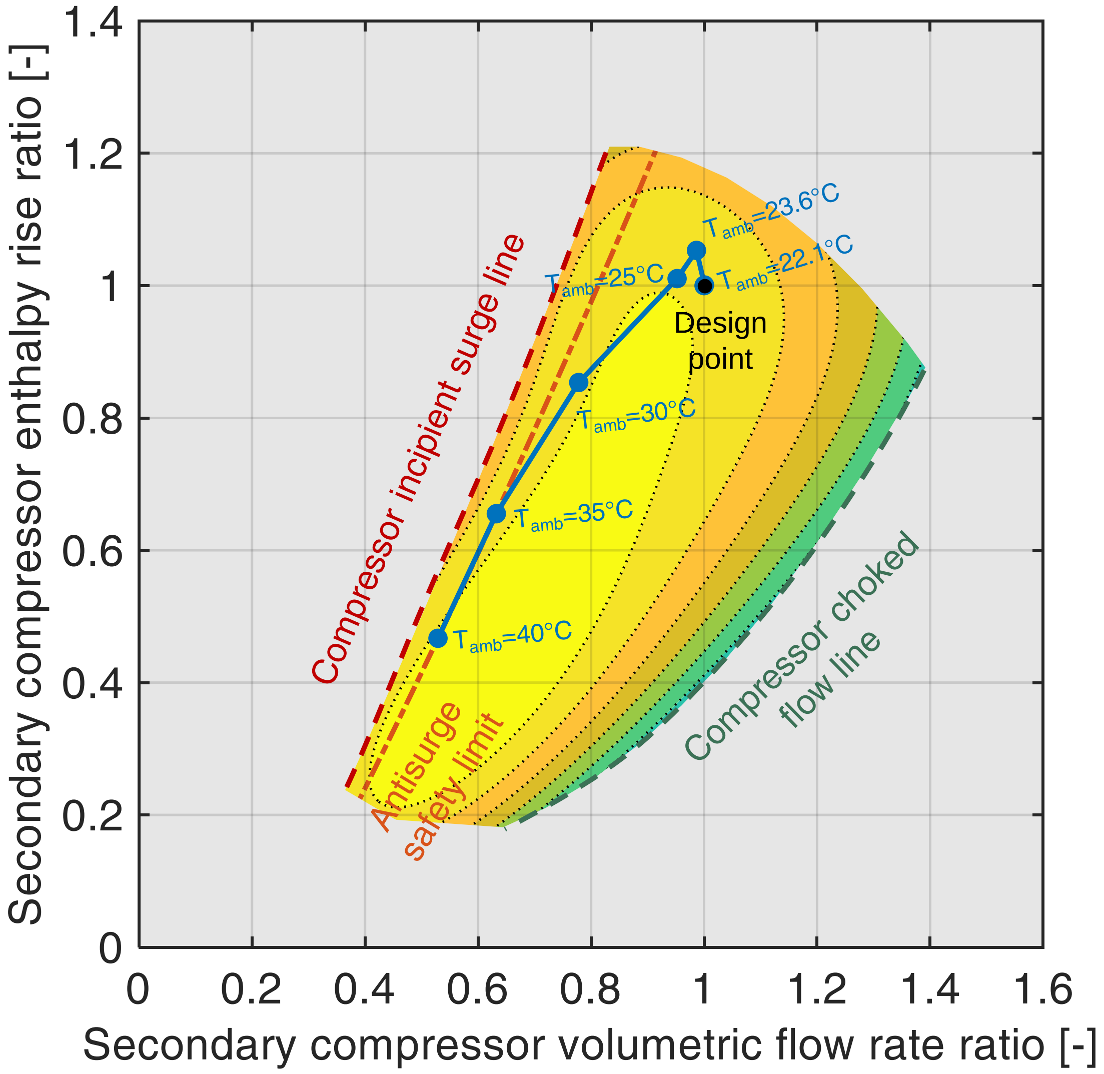
A possible solution: **variation of the split ratio.**

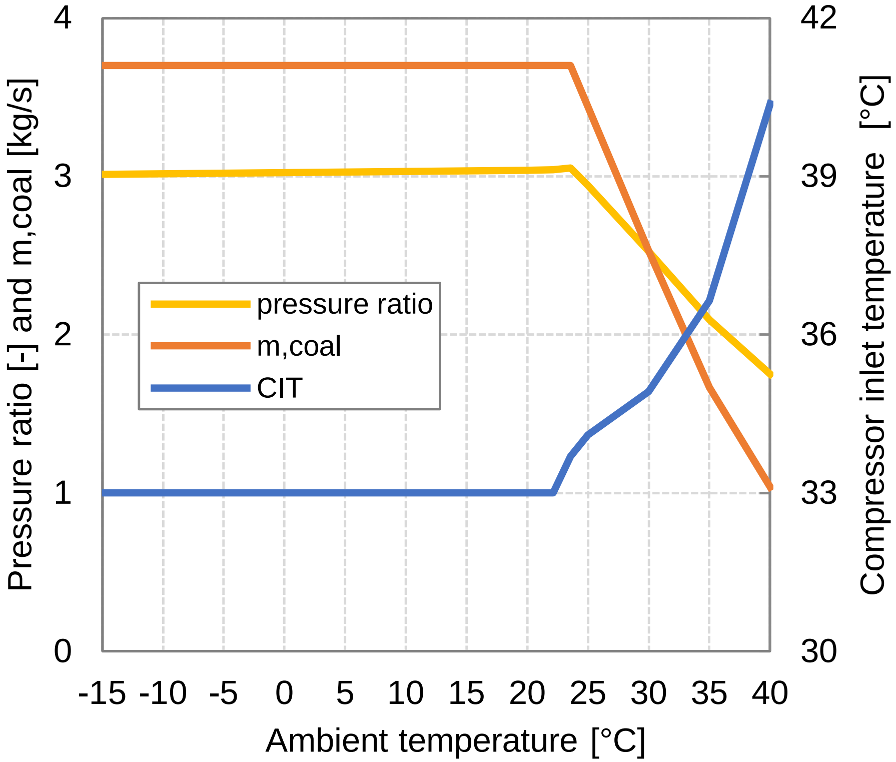
As T_{amb} increases, the CO_2 additional flow rate is sent from MC to SC preserving system operability without limiting fuel mass flow rate.

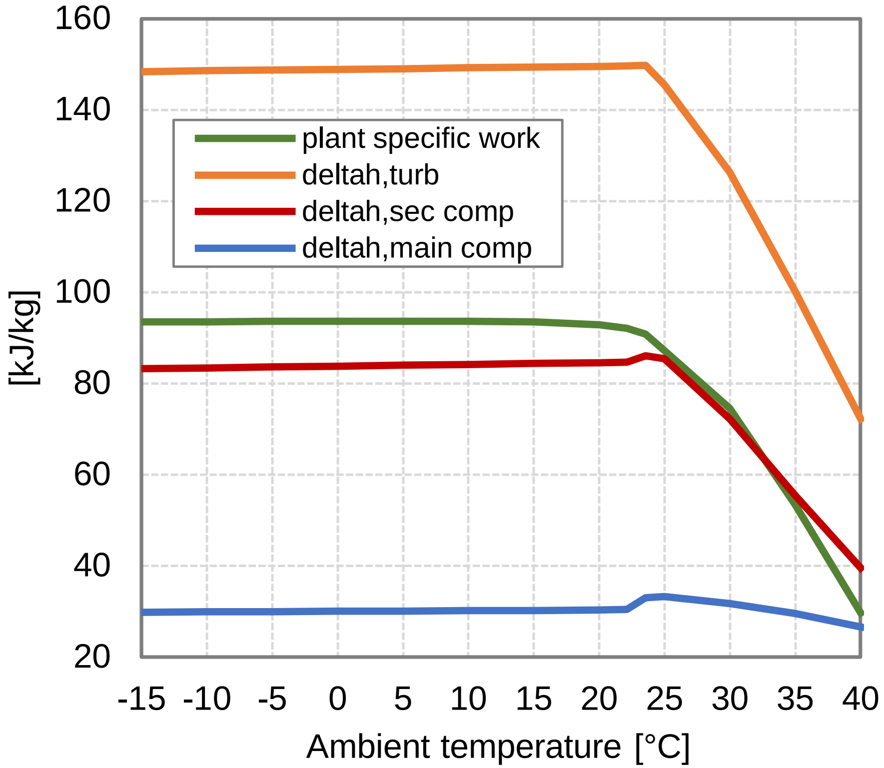
This solution has not been investigated in this work and it will be evaluated in future publications.



Ambient temperature variation results

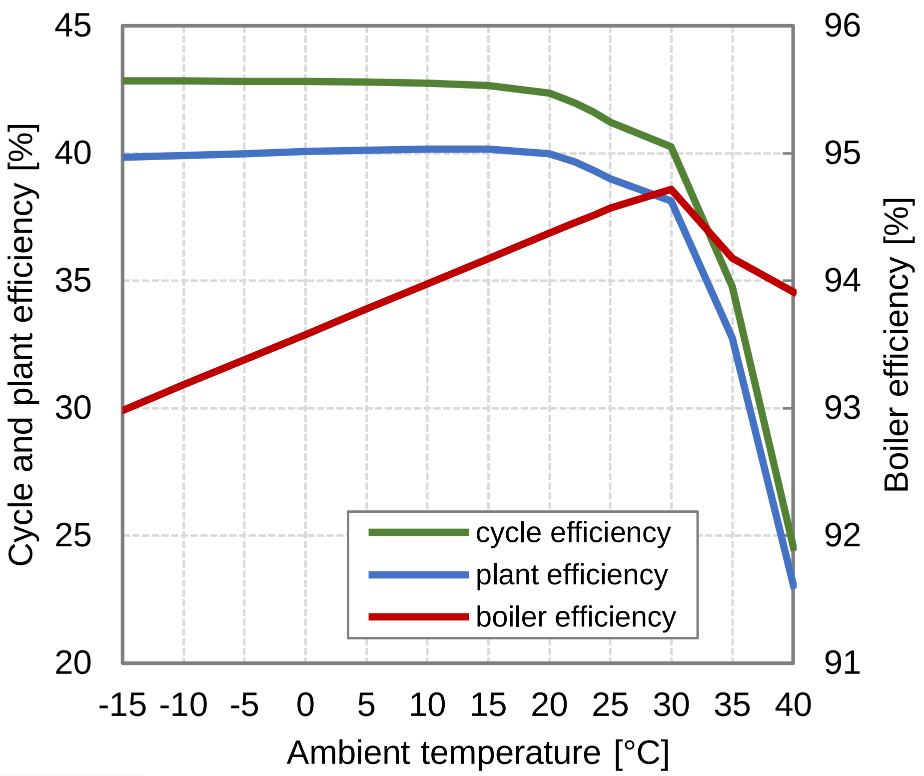
- When T_{amb} decreases below nominal value the **CIT is kept equal to the nominal value** by reducing the HRU fan rotational speed
- As the fan RPM reaches the limit, the **main CIT start to rise**
- As the MC operative point reaches the upper limit, the **coal mass flow rate decreases remarkably**

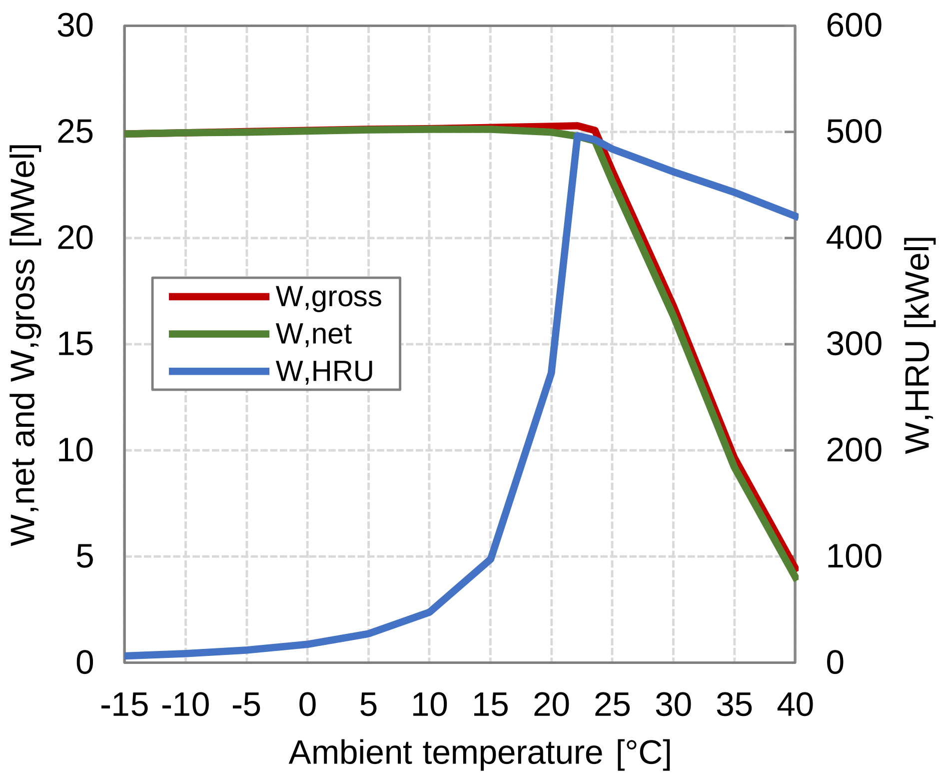




Ambient temperature variation results

- The cycle (and plant) efficiency decreases as the **pressure ratio decrease** and depart from the optimal one
- The **maximum net power output deliverable to the electrical grid drastically decrease** as it is no more possible to fuel the nominal coal mass flow rate





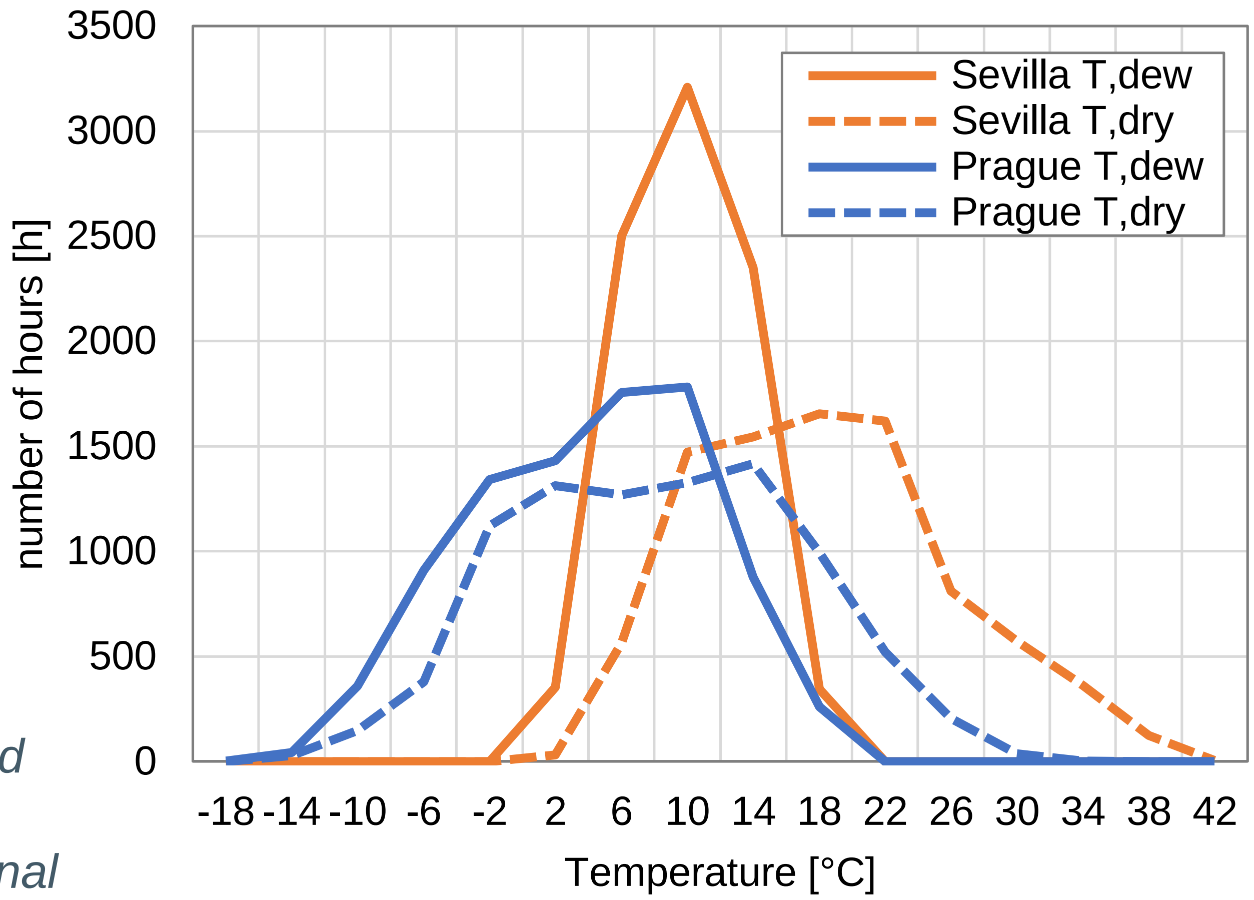
Application to Prague and Seville locations

In order to assess the potential loss of electricity production due to the ambient temperature variation, the results obtained have been applied to:

- **Prague** (representative of a "**cold**" location)
- **Sevilla** (representative of a "**hot**" location)

A weekly load distribution representative of a coal power plants in a future scenario with high share of RES is adapted from:

"M. Astolfi, E. De Lena, and M. C. Romano, Improved flexibility and economics of Calcium Looping power plants by thermochemical energy storage. International Journal of Greenhouse Gas Control, 2019."



Source: "EnergyPlus", *U.S. Department of Energy*.

Results for Prague and Seville

Energy production of the dry-air cooled coal fired sCO_2 power plant is **compared with** the annual yield attainable with a **constant ambient temperature of 20°C** (nominal value) for the whole year and **representative of a water-cooled system**.

Plant located in Prague is just slightly affected, as its ambient temperature exceed 20°C just for 765 hours a year.

	20°C	Prague, T_{dry}		Sevilla, T_{dry}	
	GWh	GWh	ΔE_{el}%	GWh	ΔE_{el}%
Jan.	8.40	8.36	-0.5%	8.40	-0.0%
Feb.	7.43	7.39	-0.5%	7.43	-0.0%
Mar.	8.20	8.17	-0.3%	8.19	-0.1%
Apr.	7.88	7.86	-0.2%	7.81	0.9%
May	8.40	8.32	-0.9%	7.95	5.3%
Jun.	7.88	7.82	-0.7%	6.96	11.7%
Jul.	8.20	8.13	-0.9%	6.56	20.0%
Aug.	8.40	8.22	-2.1%	6.74	19.7%
Sep.	7.68	7.68	-0.0%	6.75	12.1%
Oct.	8.40	8.39	-0.1%	7.97	5.1%
Nov.	8.07	8.05	-0.3%	8.05	0.3%
Dec.	8.00	7.97	-0.4%	8.00	0.0%
Year	**96.92**	**96.36**	**-0.6%**	**90.80**	**-6.3%**

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On the contrary, **plant located in Sevilla is strongly penalized.**

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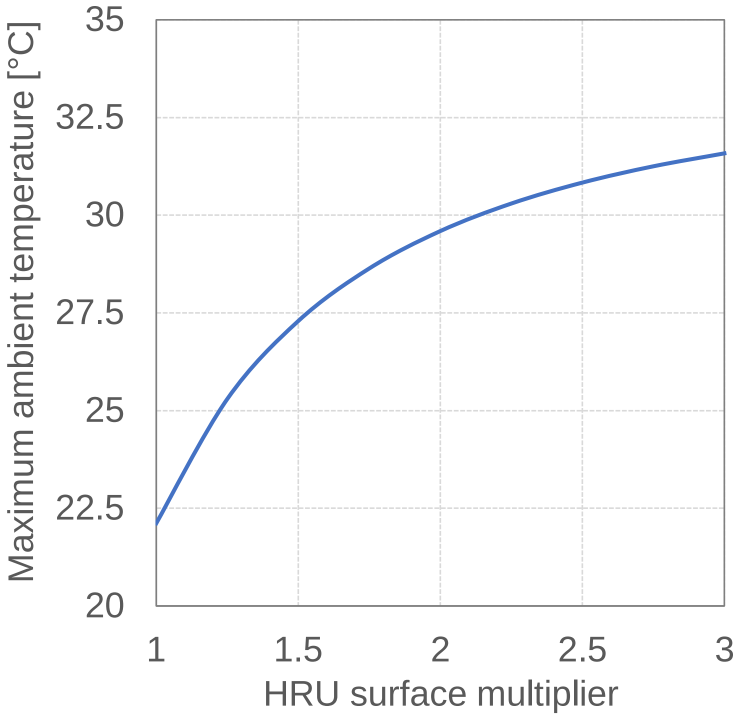
Possible solutions

Oversizing the HRU

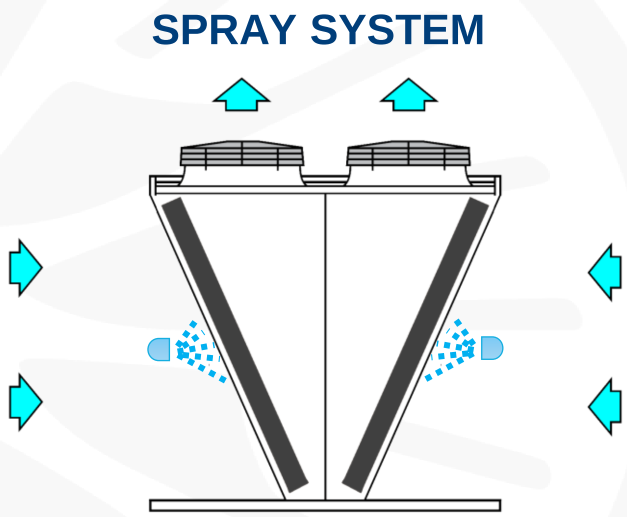
The quantification of the potential of adopting a larger HRU is evaluated by finding the maximum ambient temperature that allows to operate the plant in nominal conditions (CIT=33°C) with maximum HRU fan rotational speed (+125%).



- Maximum ambient temperature for nominal CIT and fan speed 125% up to ambient temperature of **32°C (against 22.1°C)**
- “Only” +8% on capital cost
- Possible increase of nominal performance in nominal condition

Possible solutions

Wet-and-dry systems

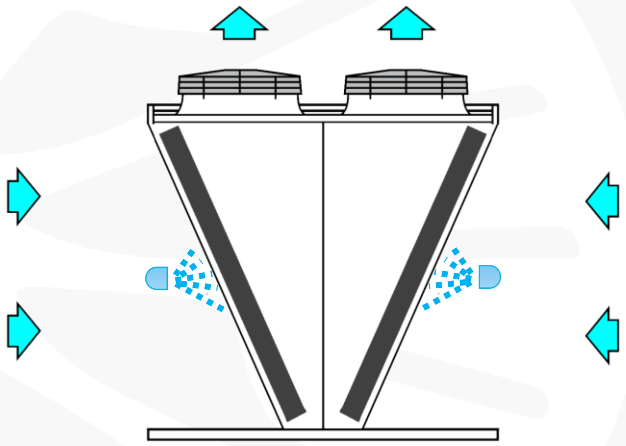


- High performance
- Water treatment required
- Limit on hours in in wet operation

Possible solutions

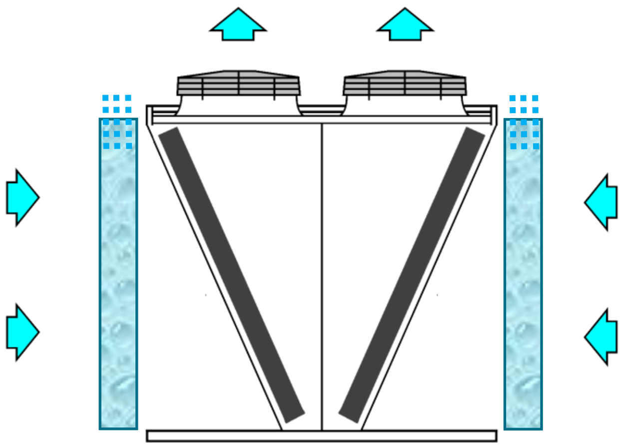
Wet-and-dry systems

SPRAY SYSTEM



- High performance
- Water treatment required
- Limit on hours in in wet operation

ADIABATIC SYSTEM



- Good performance
- No water treatment required
- No limit on hours in in wet operation

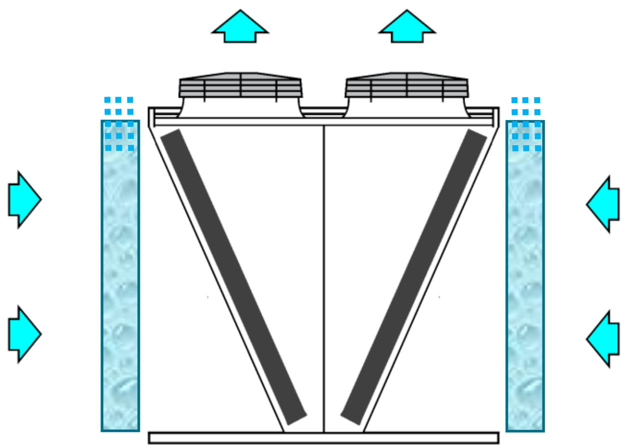
Possible solutions

Wet-and-dry systems

SPRAY SYSTEM

- High performance
- Water treatment required
- Limit on hours in in wet operation

ADIABATIC SYSTEM



- Good performance
- **No water treatment required**
- **No limit on hours in in wet operation**

More flexible operation and suitable to very different locations

Allows to decrease the air cooling temperature close to the wet bulb temperature

Wet-and-dry HRU Sevilla

Against the 20°C
water cooled scenario

- **Electricity production** adopting wet-and-dry HRU solutions seems to be **competitive with water-cooled HRU even in hot locations**
- Water consumption is around **0.13%** of the one associated to the adoption of a **water cooled HRU** for the same kind of plant

	Dry cooling $\Delta E_{el}\%$	Wet-&-dry $\Delta E_{el}\%$	Spray hours	Water, ton
Jan.	0.0%	0.0%	0	0
Feb.	0.0%	0.0%	14	15
Mar.	-0.1%	0.0%	88	194
Apr.	-0.9%	0.0%	150	524
May	-5.3%	+0.1%	311	1637
Jun.	-11.7%	0.0%	469	2944
Jul.	-20.0%	+0.1%	642	4987
Aug.	-19.7%	0.0%	650	4996
Sep.	-12.1%	+0.1%	550	3167
Oct.	-5.1%	+0.1%	302	1512
Nov.	-0.3%	+0.1%	76	233
Dec.	0.0%	0.0%	7	4
Year	**-6.3%**	**+0.1%**	**3259**	**20214**

Conclusion

- Coal fired power plants based on **dry air-cooled sCO_2 cycles**, differently from steam Rankine cycles, **are strongly affected** in their operation **for ambient temperatures higher than the nominal one.**
- **Most critical component is the main compressor** which volumetric flow rate increase is limited by the operative map leading to a decrease of maximum attainable power output for ambient temperatures just few degrees Celsius above the nominal value.
- The actual effect of this **limitation on the plant operability during a representative year strongly depends on the location**. Analysis is repeated for Prague and Sevilla demonstrating that in the first the annual penalization is nearly negligeable while it is significant in the second.
- In case of strong penalization of annual energy output for hot climate **locations two solutions are proposed**: first one requires to **oversize the HRU** while the second to adopt **wet-and-dry coolers**.

Thank you for the attention!

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Politecnico di Milano
Energy Department

Backup slides

Brief economic analysis

sCO2flex

Investment costs		
HRU, M$	2.09	3.99%
Main Compressor, M$	2.38	4.56%
Secondary Compressor, M$	2.83	5.42%
Turbine, M$	2.20	4.21%
LTR, M$	4.15	7.95%
HTR, M$	6.50	12.45%
Boiler, M$	21.49	41.14%
Compressors motors, M$	1.38	2.65%
Gearbox, M$	0.44	0.83%
Generator, M$	0.80	1.54%
Contingency, M$	3.10	5.93%
Engineering, M$	4.87	9.32%
Total capital cost, M$	**52.23**	
Plant specific cost, $/kWel	**2089**	