SFERA-III

Solar Facilities for the European Research Area

1st Summer School "Thermal energy storage systems, solar fields and new cycles for future CSP plants"
WP1 Capacity building and training activities
Odeillo, France, September 9th-11th 2019

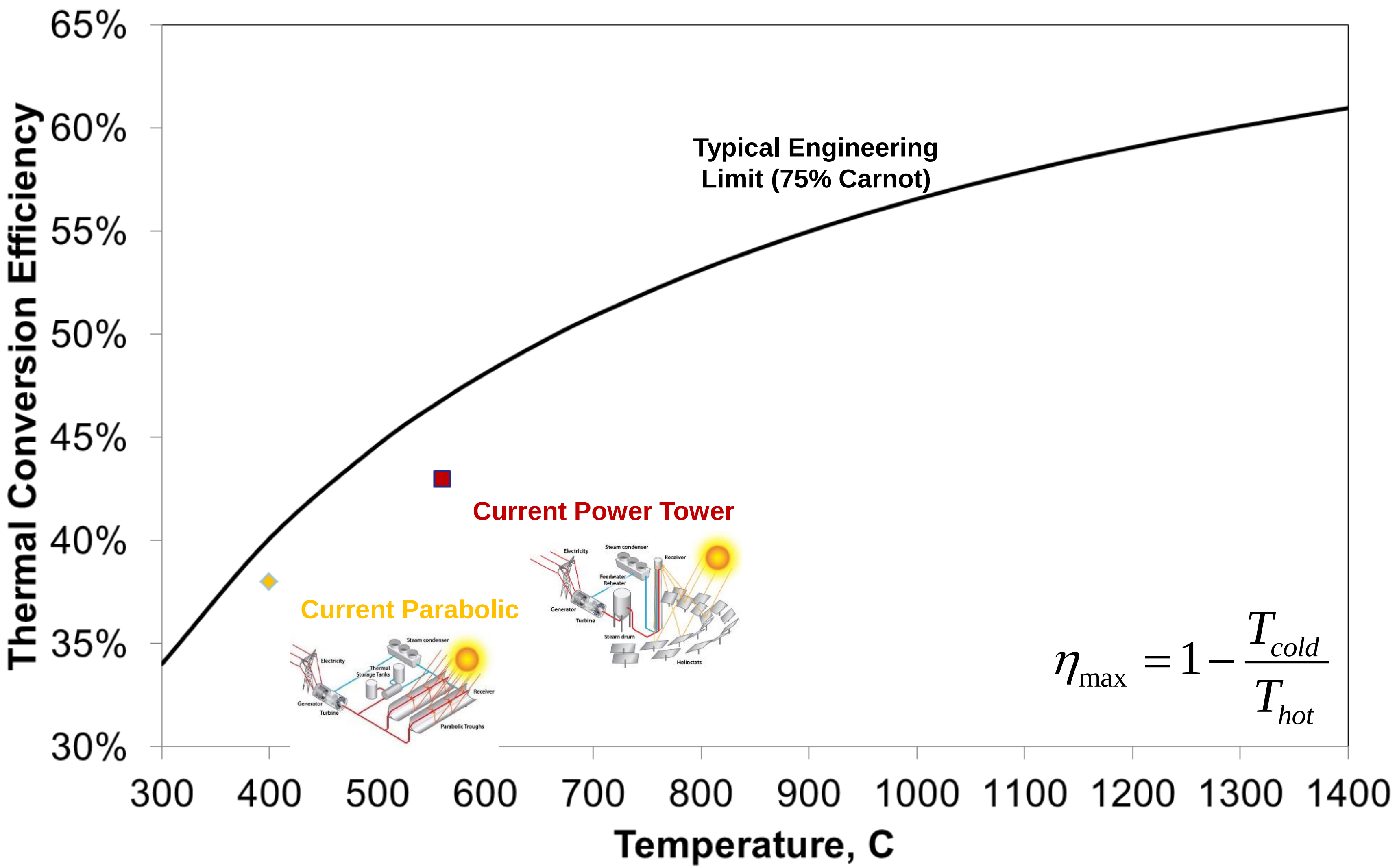
sCO2 cycles for CSP plants: challenges and issues

Manuel Romero, IMDEA Energy, Spain

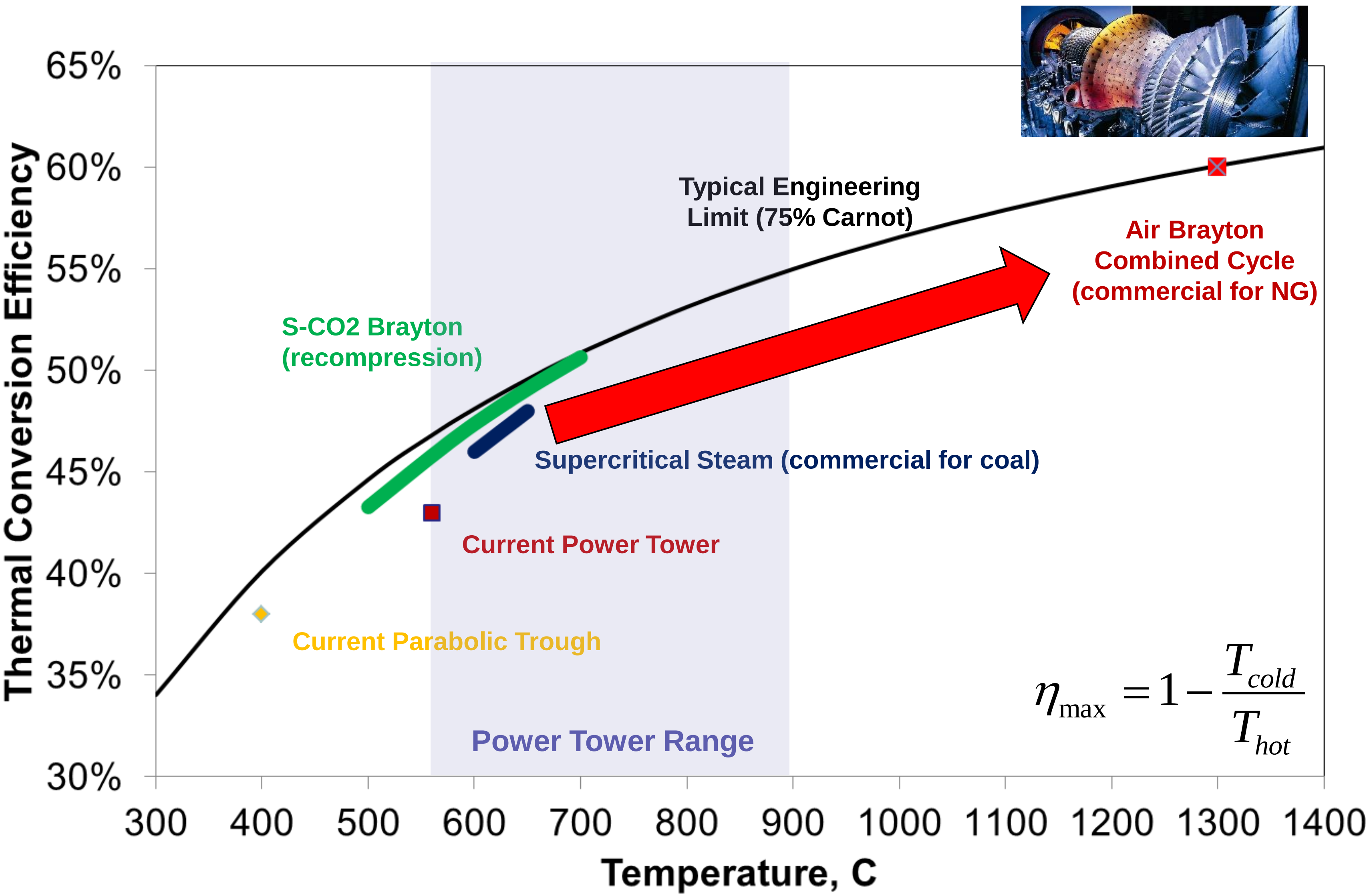
NETWORKING

THIS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO 823802

Thermodynamics cycles application

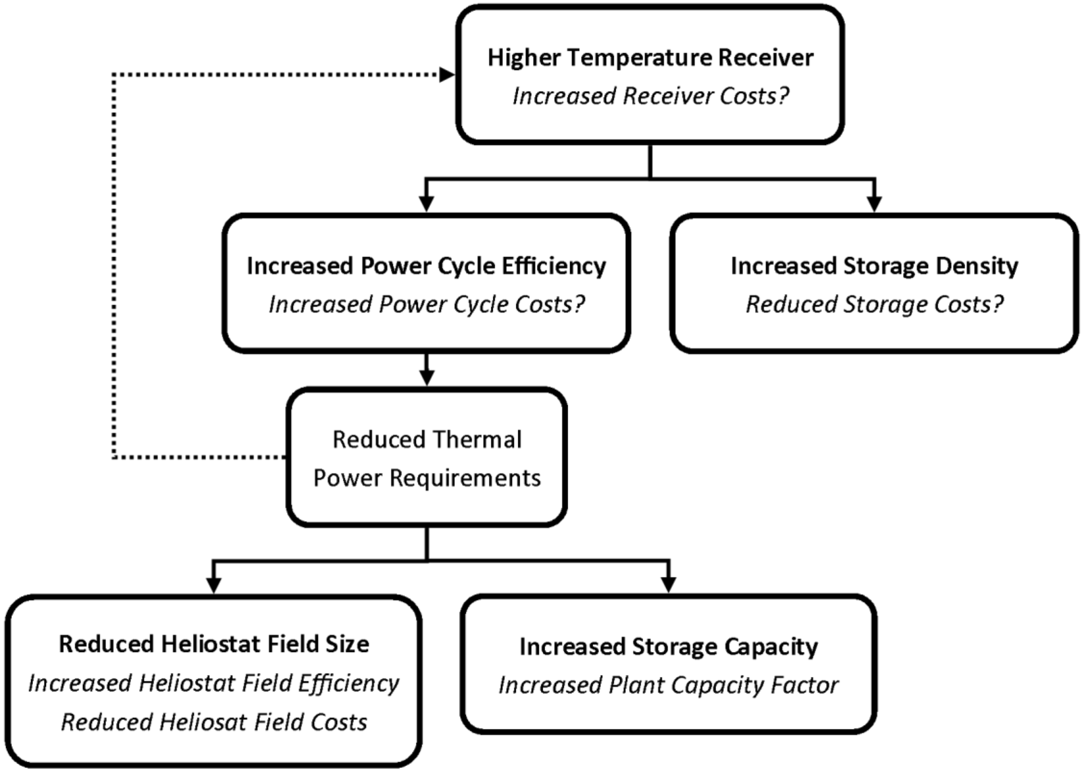


Thermodynamics cycles application



The Effects of Higher Temperatures

Increasing the operating temperature of the receiver has a cascade of effects throughout the entire power plant

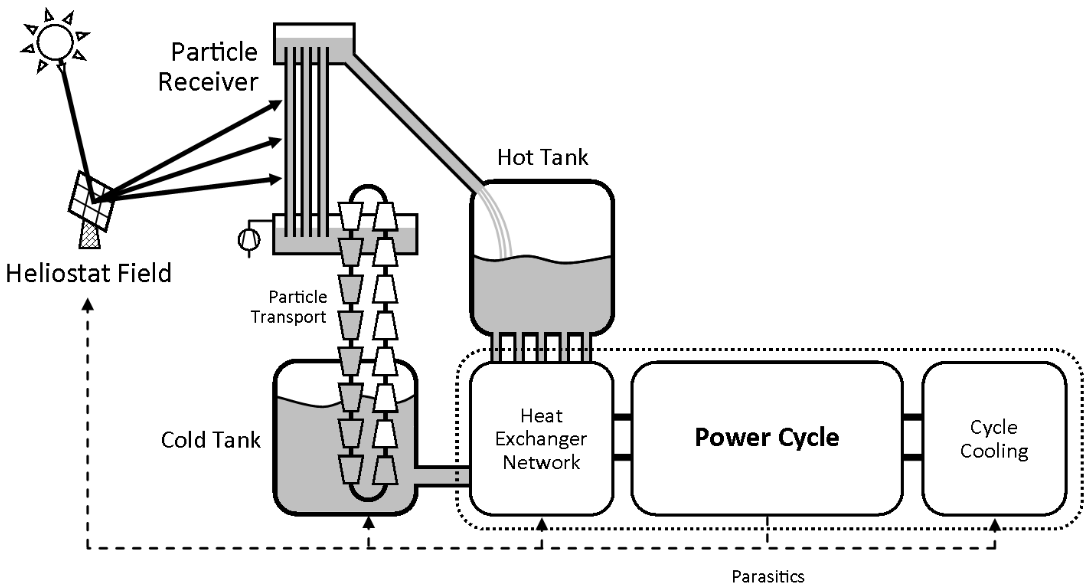


- Integrated **techno-economic analysis** is needed

NEXT-CSP Project

Main objective of Next-CSP project is:

- To improve the reliability and performance of Concentrated Solar Power (CSP) plants through the development and integration of a new technology based on the use of high temperature (**650-800 ºC**) particles as heat transfer fluid and storage medium.



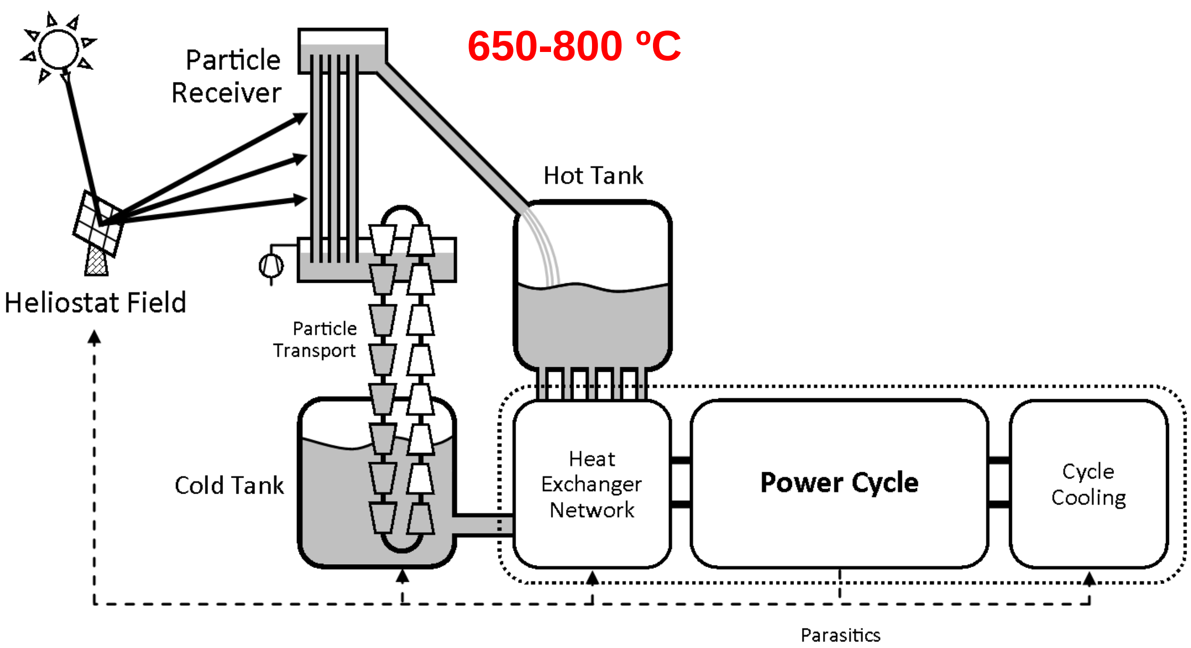
IMDEA Energy (in collaboration with EDF) role on NEXT-CSP project:

- *Assessment of the highly efficient thermodynamic cycles that can be combined with the high temperature solar loop (**WP6**)*

- *Scale-up to a 150 MW solar power plant – Preliminary design, risk analysis, cost and value assessment (**WP7**)*

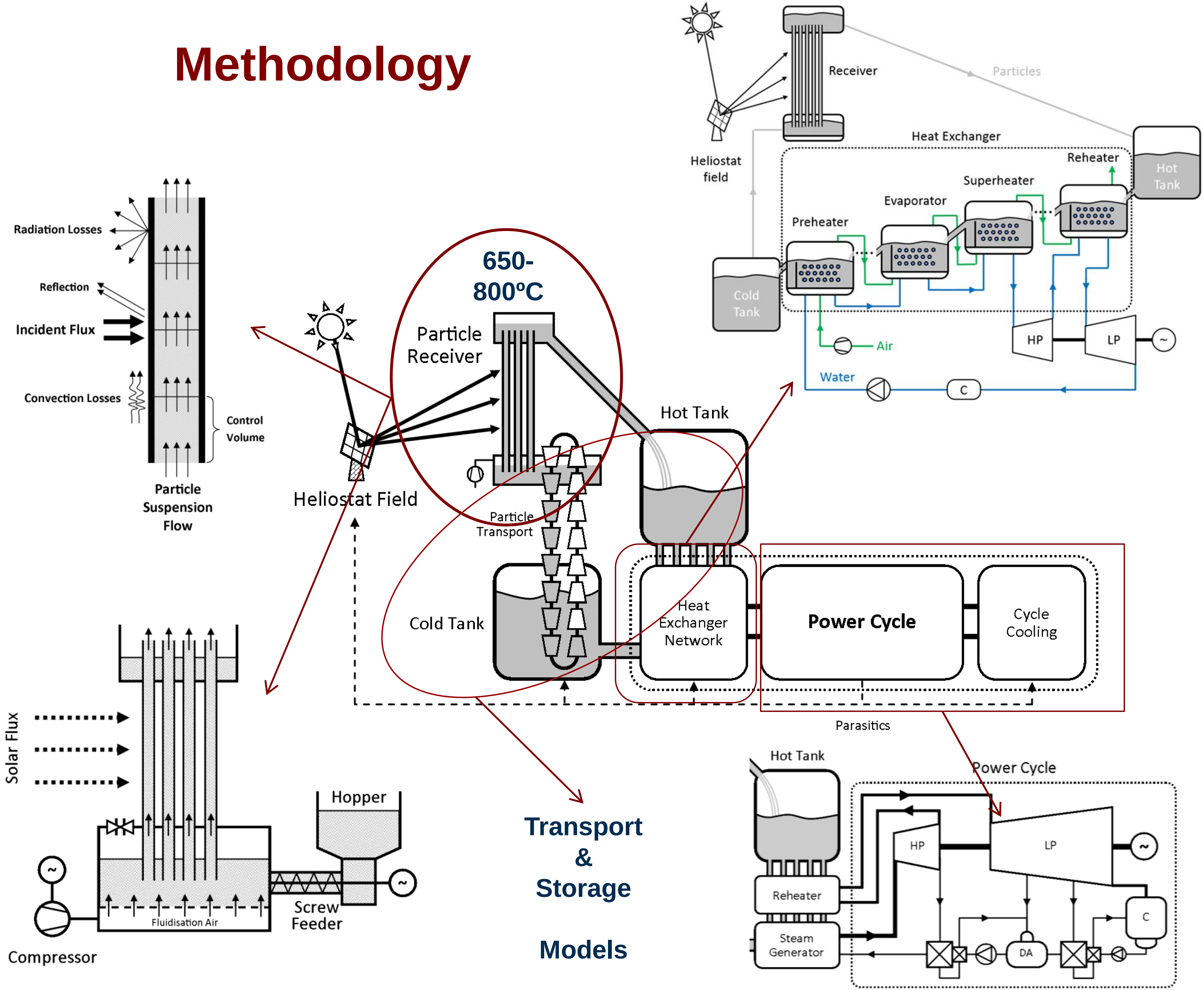
NEXT-CSP Project Objective

- To improve the reliability and performance of Concentrated Solar Power (CSP)
- Commercial state-of-the-art technology for CSP < 565 ºC ------- $\eta \approx 42\%$
- Higher temperature solar receiver (up to 800 ºC) allows for highly efficient cycles (Carnot's Theorem)



- Cycles screened: supercritical steam, supercritical CO_2, Combined Cycle
- Target: Cycle efficiency > 45 % (up to 50 %)

Methodology



Comparison of thermodynamic cycles

❖ Investigating novel work transfer fluids for the power block (supercrit. CO_2)

✓ *Excellent thermal properties (& compact turbomachinery). Excellent theoretical thermodynamic power cycle efficiency*

Plant Nominal Performance	Units	Std. Rankine	Brayton 650 ºC	Brayton 750 ºC	Brayton 1,000 ºC	Combined Cycle	Brayton He	Brayton sCO_2	Reference M. Salts
Heliostats efficiency	[%]	72.1	72.1	72.1	67.8	72.1	72.1	72.1	72.1
Receiver efficiency	[%]	82.3	80.7	77.3	72.2	83.1	81.0	79.7	87.5
Thermal power to storage / power block	[MW]	23.4	23.0	21.7	20.6	23.7	23.1	22.7	25.7
HTX efficiency	[%]	95.0	95.0	95.0	95.0	95.0	95.0	95.0	99.0
Net Electrical power	[MW]	9.1	6.8	7.6	9.4	21.5	7.4	10.4	10.0
Net Power cycle efficiency	[%]	40.8	31.26	37.1	47.9	42.6	33.9	48.2	40.0
Sun-to-electricity efficiency	[%]	22.9	17.3	19.4	22.3	24.2	18.8	26.4	24.9

DPS plant conditions:

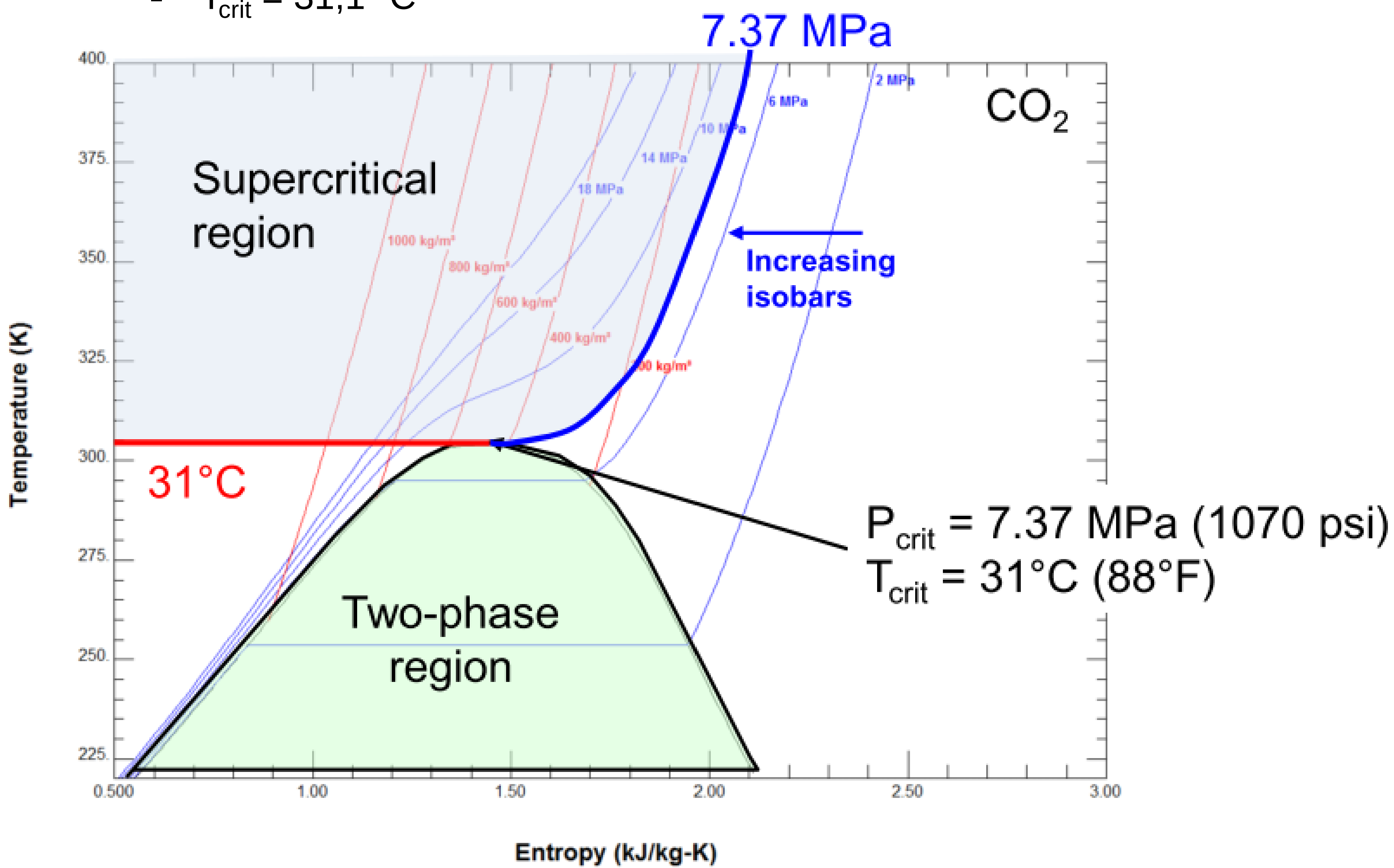
✓ 57 MW_{th} (receiver)

✓ Very high net power cycle efficiency (at moderate temperature range). Much more room of improvement at higher temperatures

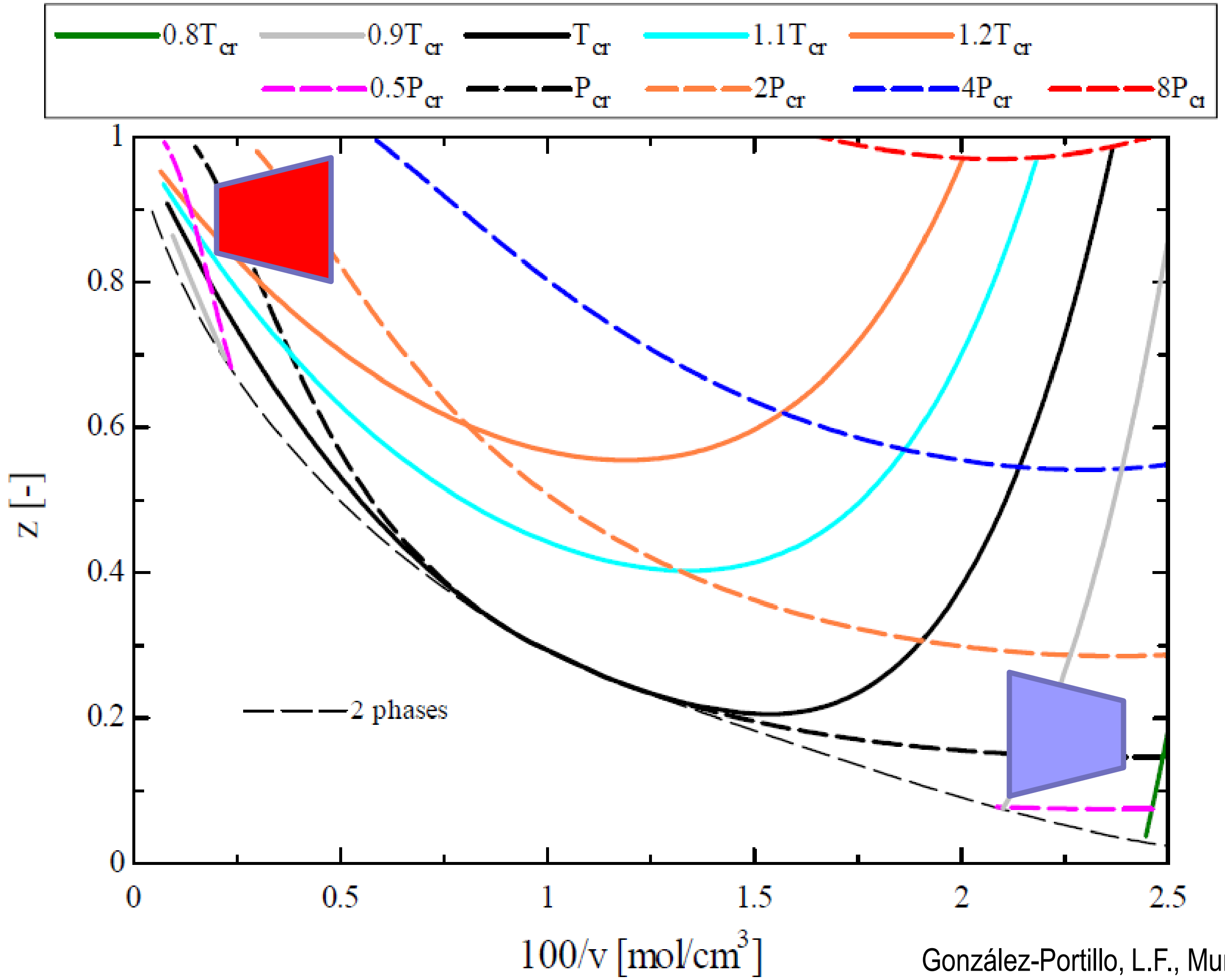
✓ Very sensitive cycle depending on working operative conditions. Detailed optimization process required for power cycle working operative conditions selection

What is supercritical CO_2

- sCO_2 is a fluid state above critical temperature and critical pressure
  - p_{crit} = 73,9 bar
  - T_{crit} = 31,1 ºC



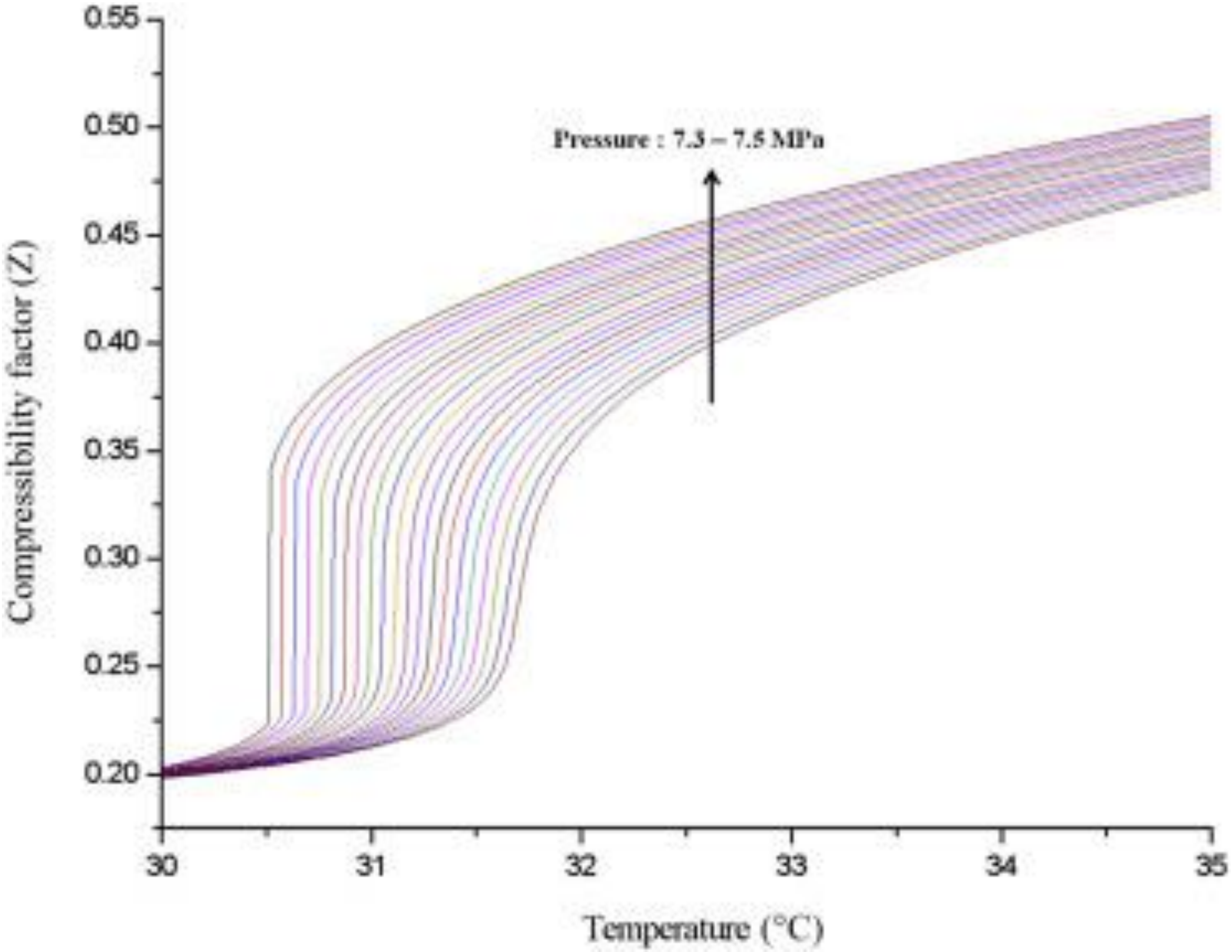
Compressibility factor, z, of CO_2 versus density, 100/v, for different values of pressure and temperature (expressed as a function of the critical pressure, Pcr, and critical temperature, Tcr, respectively).



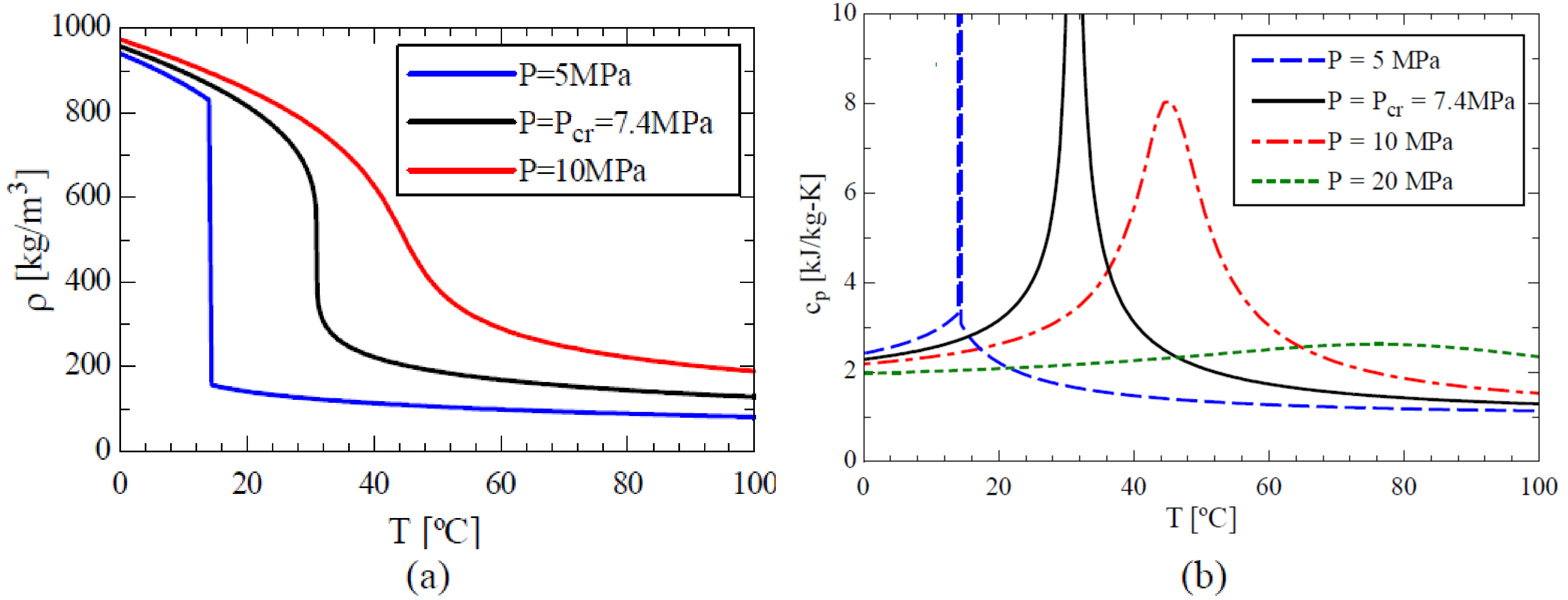
The compressibility factor, Z, is defined as the molecular volumetric ratio of a fluid compared with ideal gas.

$$z = \frac{Pv}{RT}$$

González-Portillo, L.F., Muñoz-Antón, J. and Martínez-Val, J.M. (2019) , Energy Conversion and Management, 192, pp. 359–373.



For CO_2 near the critical point, the compressibility factor decreases to 0.2–0.5 and the compression work can be substantially decreased.

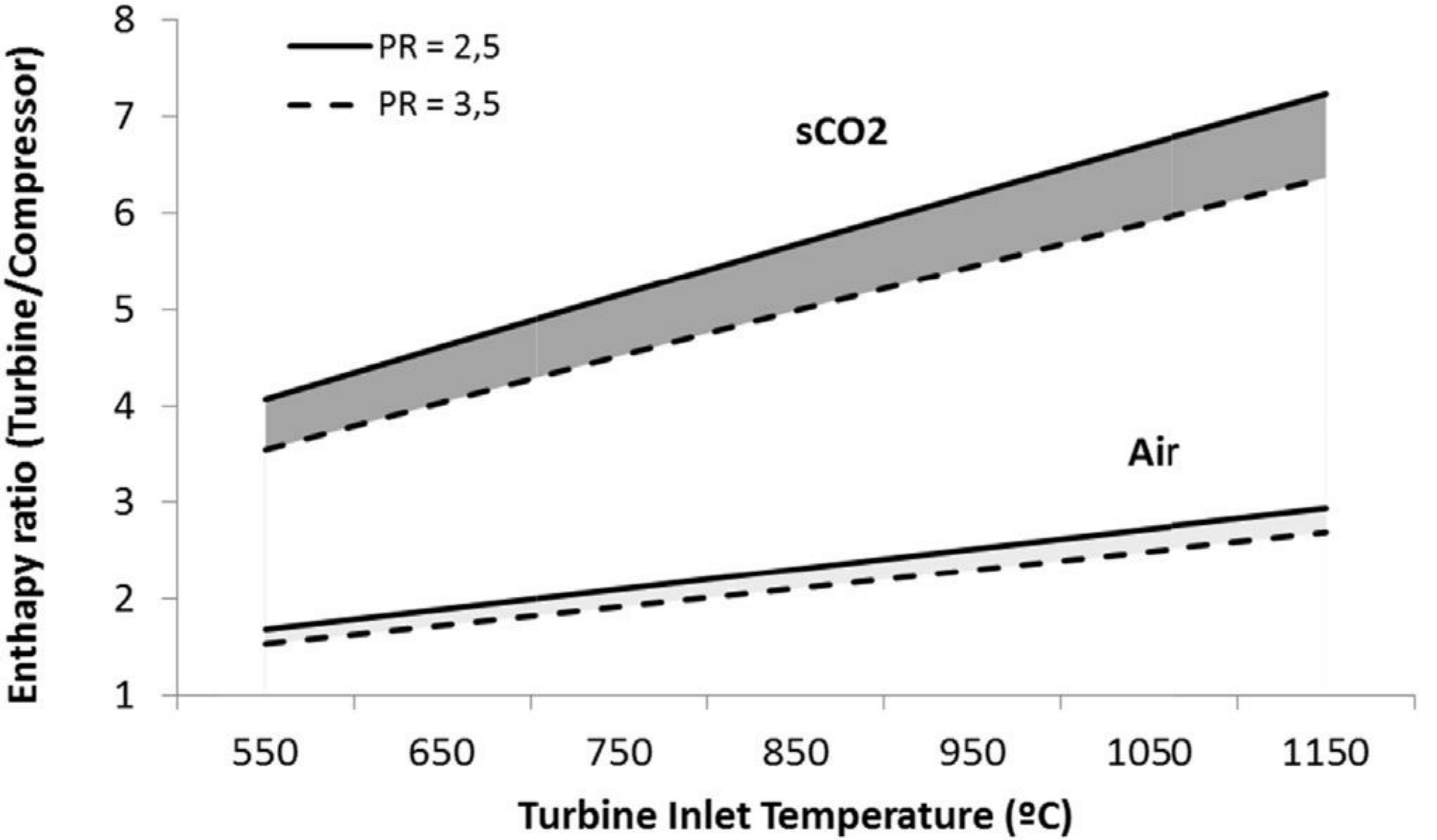


(a) Density, ρ, and (b) isobaric specific heat capacity, c_p, of CO_2 at subcritical, critical and supercritical pressures as a function of temperature, T

$$dh = c_p dT$$ isobaric

González-Portillo, L.F., Muñoz-Antón, J. and Martínez-Val, J.M. (2019) ,
Energy Conversion and Management, 192, pp. 359–373.

Enthalpy ratio between turbine an compressor for sCO2 (solid lines and dark grey shaded area) and air (slashed line and light grey shaded area). For two pressure ratio cases (PR).

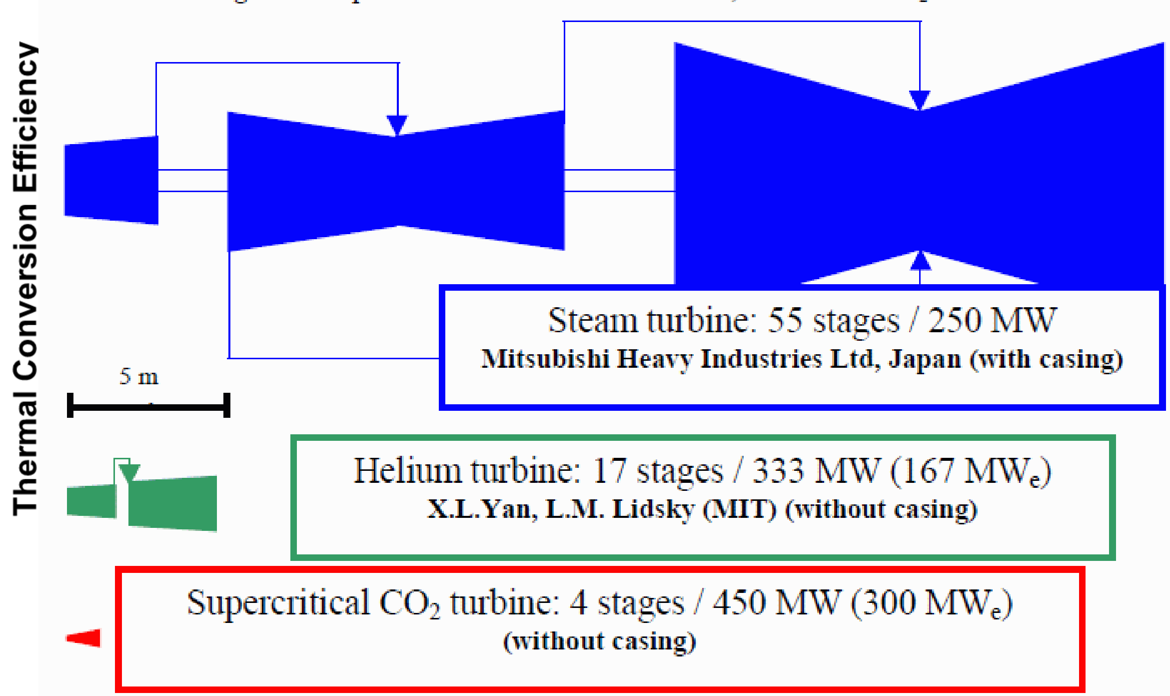


M.A. Reyes-Belmonte, A. Sebastian, M. Romero, J. Gonzalez-Aguilar. Energy 112 (2016) 17-27

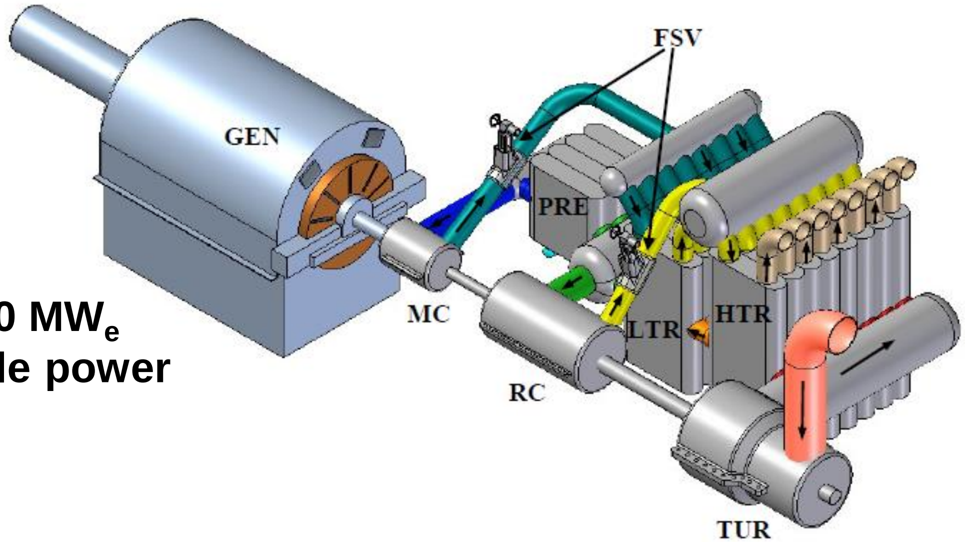
Attractive features of sCO_2 Brayton Cycle

- Higher efficiency than steam Rankine
- High density working fluid (compact turbomachinery)
- Low-cost, low toxicity
- Thermally stable fluid at temperatures of interest to CSP (550 ºC to 750 ºC)
- Single phase reduces operational complexity; integrates well with sensible heat storage in CSP systems
- **Industry interest**
  - Nuclear
  - Fossil
  - CSP
  - Heat recovery
  - Marine powering

Fig. 51 Comparison of turbine sizes for steam, helium and CO_2

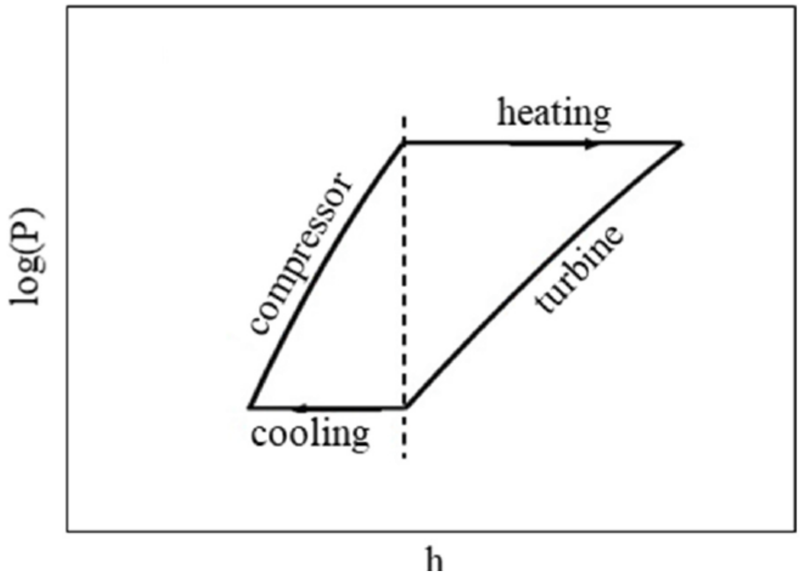


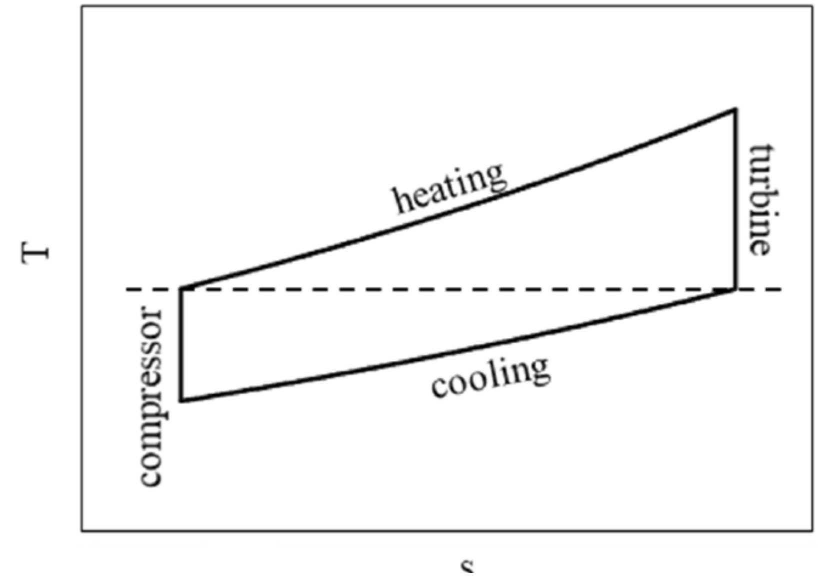
However, the cycle pressure ratio of the S-CO_2 Brayton cycle is much smaller compared with the steam Rankine cycle and the turbine outlet temperature is relatively high. Therefore, a large amount of heat must be recuperated to increase the thermal efficiency. In other words, the recuperation process in the S-CO_2 Brayton cycle greatly influences the thermal efficiency.

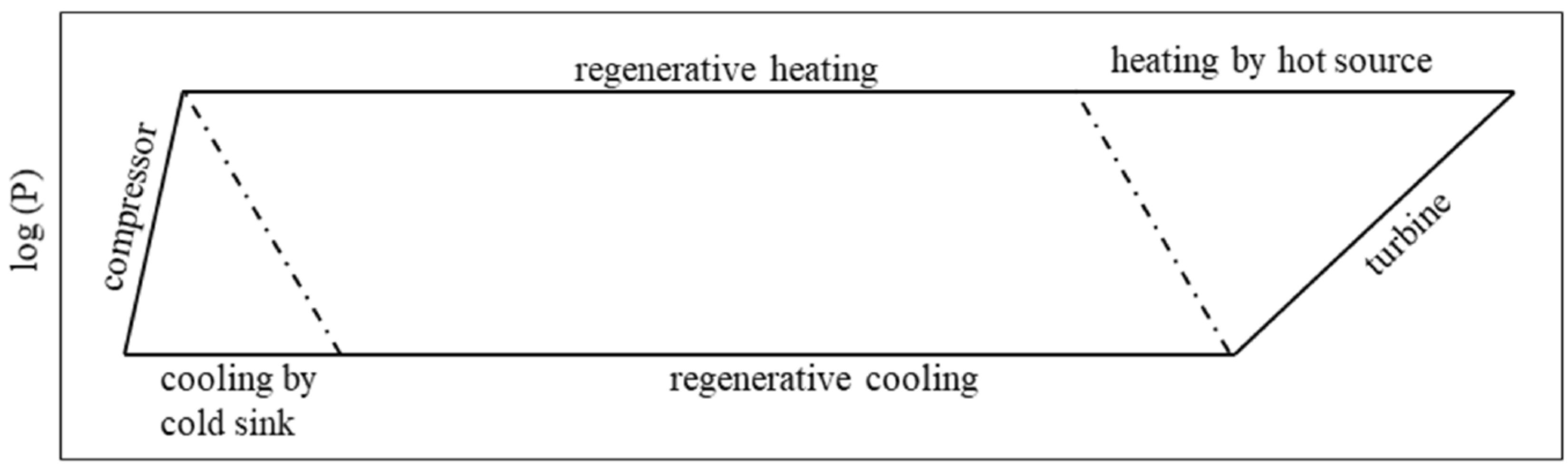


MIT depiction of 150 MW_e recompression-cycle power system (2006)

$$dh = Tds + vdP$$

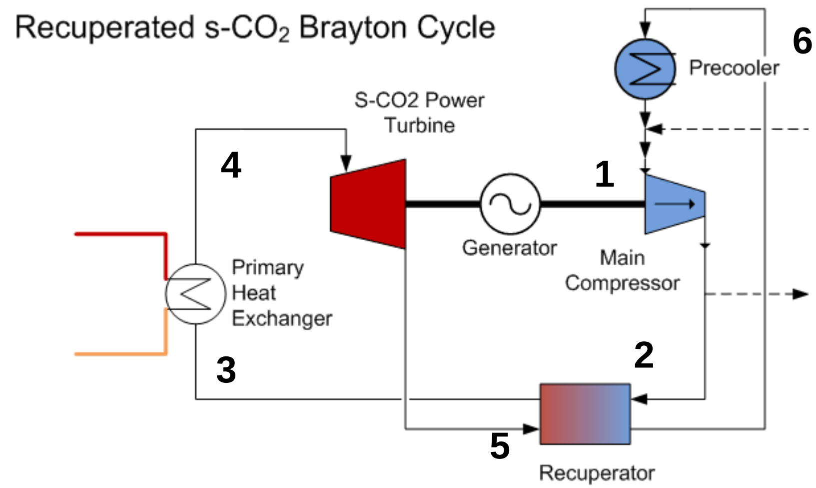

heating
compressor
turbine
cooling
log(P)
h

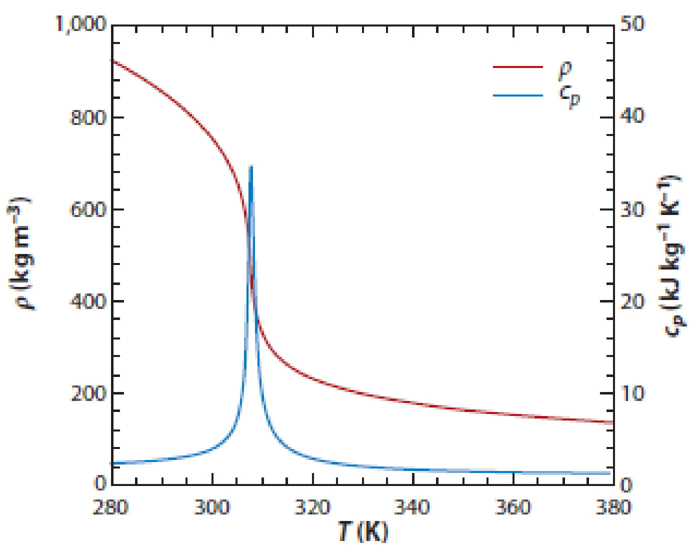

heating
turbine
T
compressor
cooling

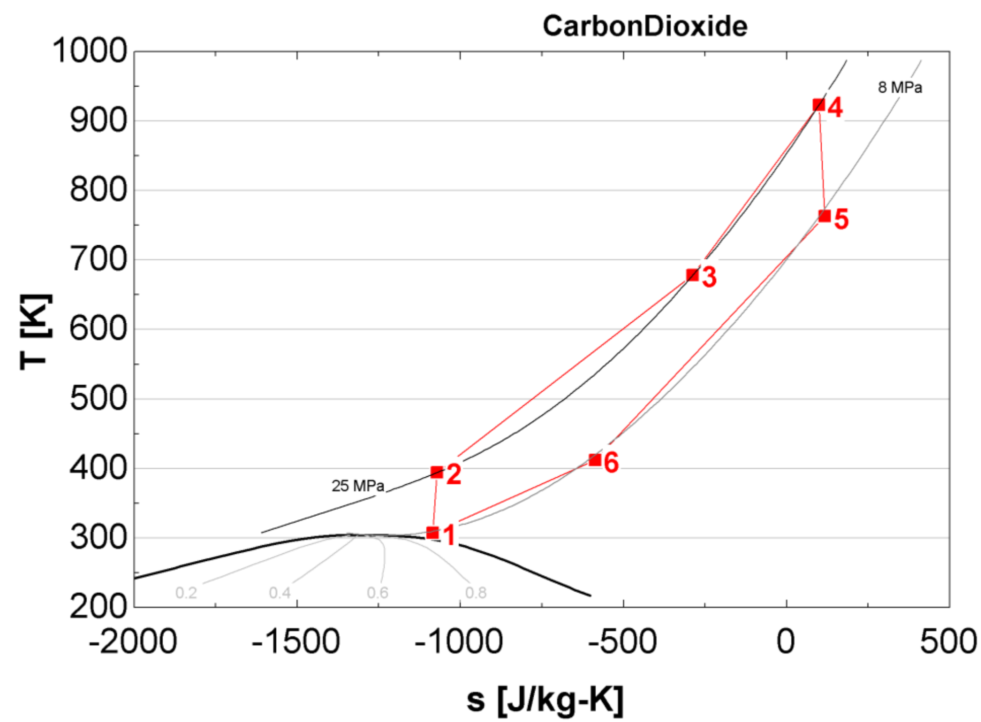

regenerative heating
heating by hot source
compressor
log (P)
turbine
cooling by
cold sink
regenerative cooling

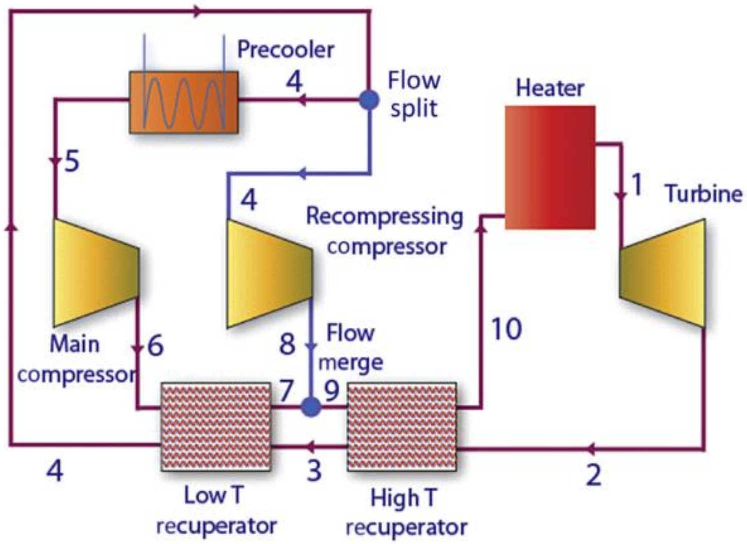
What is supercritical CO_2

- sCO_2 is a fluid state above <u>critical temperature</u> and <u>critical pressure</u>
  - p_{crit} = 73,9 bar
  - T_{crit} = 31,1 ºC
- Peculiar properties midway between a gas and a liquid (drastic changes near critical temperature)



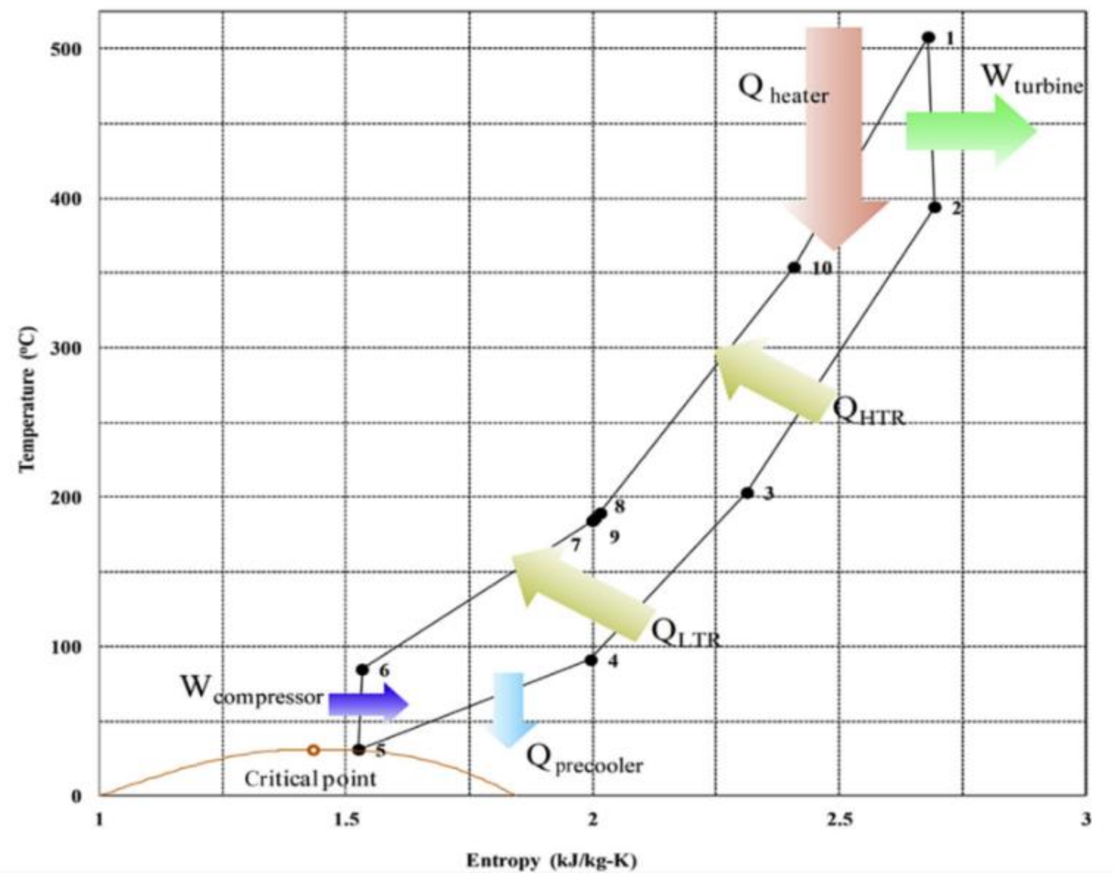






Supercritical CO2 Power Recompression Cycle

- Large amounts of heat must be recuperated
- Need of compact heat exchangers
- specific heat of the cold side flow is two to three times higher than that of the hot side flow in recuperators.
- CO_2 flow is split to compensate for the specific heat difference.
- Recompression improves
- Air cooling strong penalty



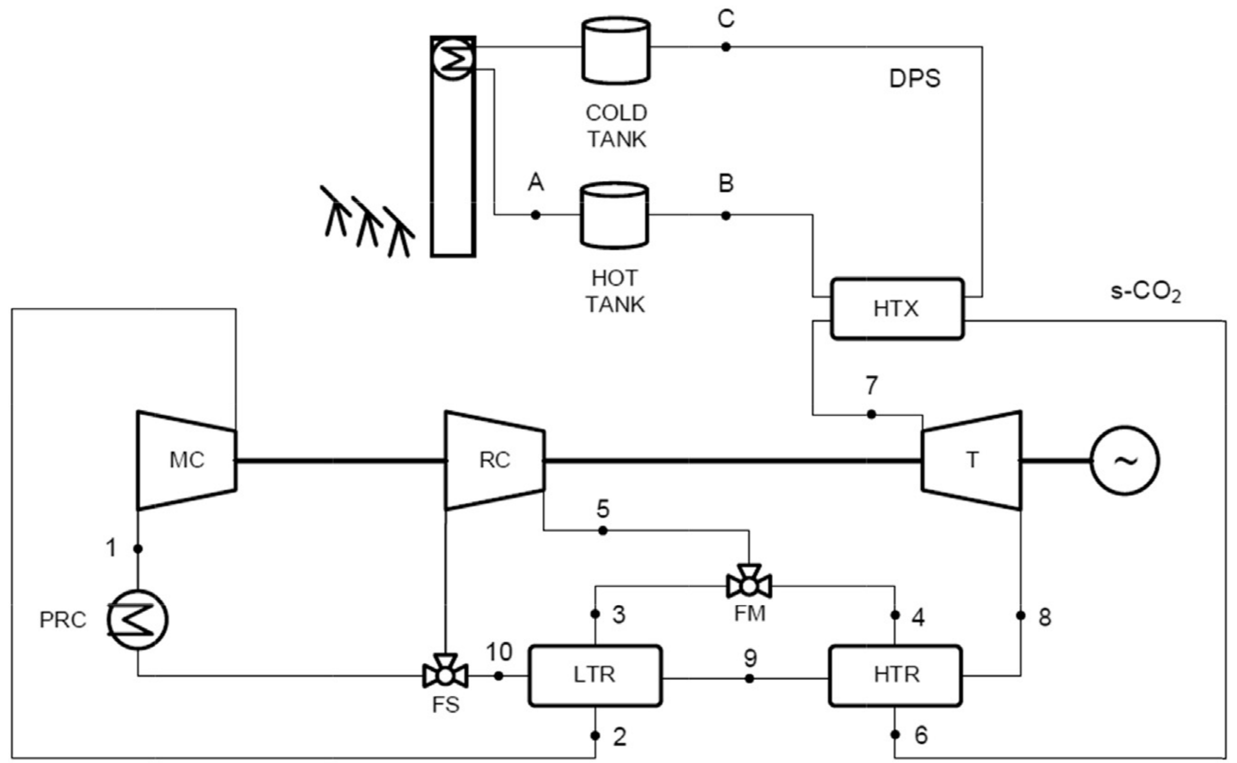
Ahn, Y. et al. (2015) N*uclear Engineering and Technology*, 47(6), 647–661.

Supercritical CO2 Power Cycle Design: Boundary conditions

		SANDIA	NREL	Tokyo Institute of Technology	CEA Cadarache	MIT	Indian Institute of Science	IMDEA Energy
Main Compressor Inlet Temperature	(ºC)	32-40	50	35	35	32-50	35-50	40
Main Compressor Inlet Pressure	(bar)	77-80	-	68-82.6	81-85	-	75-85	78
Upper Pressure	(bar)	200-300	250	120-260	253	150-300	200-300	248
Turbine Inlet Temperature	(ºC)	400-750	650	650	497-515	550-700	550-750	650-730
HT Recuperator Effectiveness	(-)	-	0.97	0.91	<0.925	0.93-0.98	-	0.88
LT Recuperator Effectiveness	(-)	-	0.97	0.91	<0.925	0.88-0.94	-	0.85
Minimum ΔT	(ºC)	-	5	-	10	-	10	10
HP Turbine Efficiency	(-)	0.90-0.93	0.93	0.92	0.93	0.90-0.93	0.75	0.92
Compressor Efficiency	(-)	0.85-0.87	0.88	0.88	0.87-0.88	0.89-0.95	0.8	0.88
Relative Pressure Losses	(-)	0.01	-	0.008-0.02	0	0.005-0.02	0.035	0.01
Recompression Mass Fraction	(-)	0.4	-	0.4	0.31-0.44	0.2-0.4	0.1-0.33	0.25
Cycle Thermal Efficiency	(%)	45.5-48.3	49.7	46.5-49.9	42.6-43.9	45.3-53.0	36.7-49.8	49.3

M.A. Reyes-Belmonte, A. Sebastian, M. Romero, J. Gonzalez-Aguilar. Energy 112 (2016) 17-27

II. Supercritical SO_2 power cycle



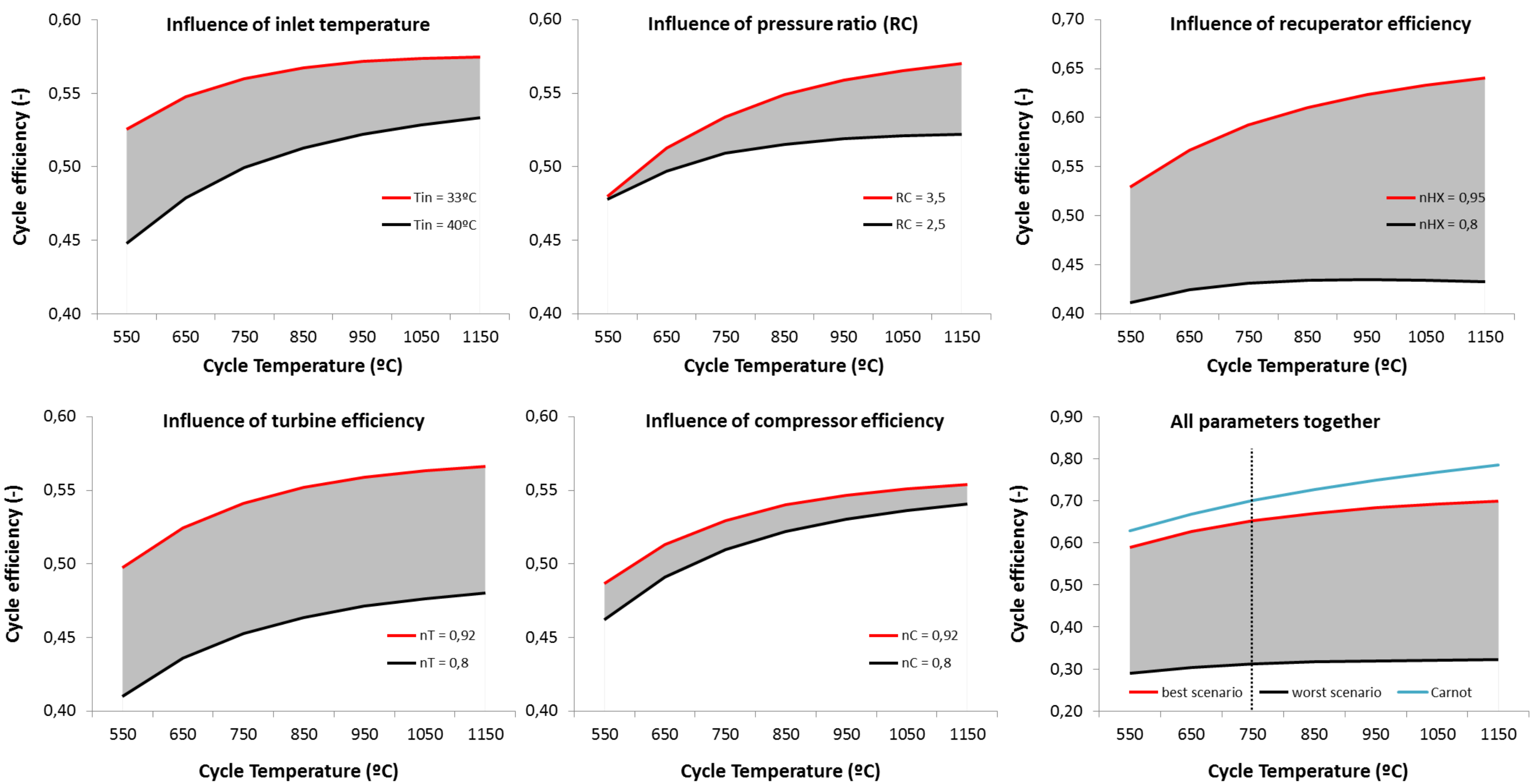
Parameter	Unit	Value	Parameter	Unit	Value
Main compressor inlet temperature	ºC	33 - 40	**HT Recuperator effectiveness**	%	90 - 95
Main compressor inlet pressure	bar	78	**LT Recuperator effectiveness**	%	90 - 95
Turbine inlet temperature	ºC	650 - 730	**Turbine isentropic efficiency**	%	92
Upper pressure	bar	248	**Compressor isentropic efficiency**	%	88

M.A. Reyes-Belmonte, A. Sebastian, M. Romero, J. Gonzalez-Aguilar. Energy 112 (2016) 17-27

II. Supercritical SO_2 power cycle

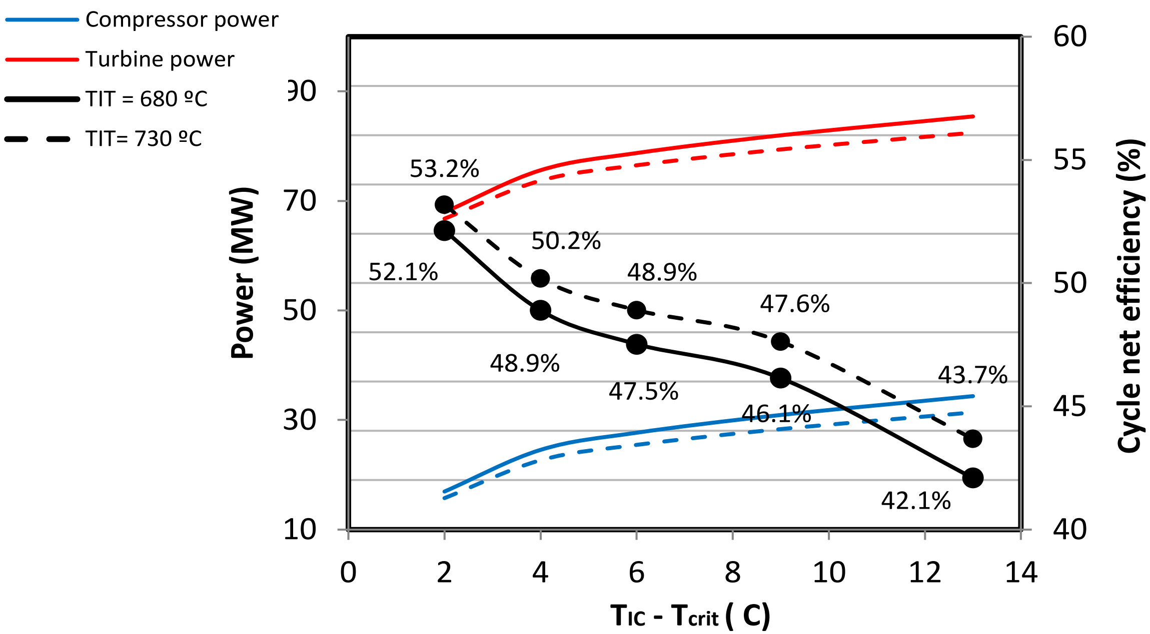
- Sensitivity study

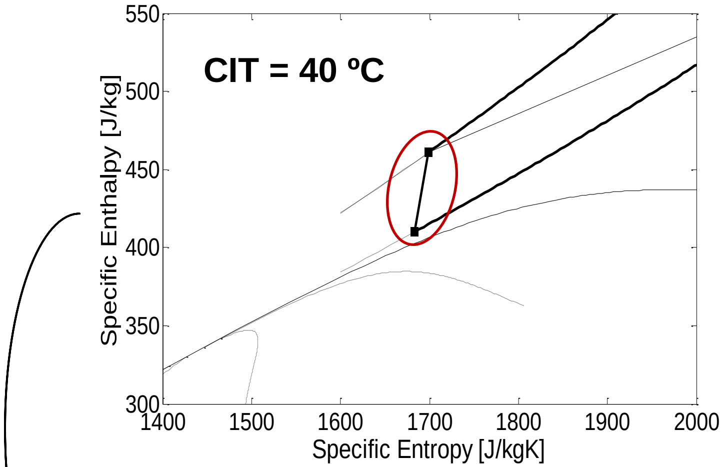
Cycle- efficiency (reference case)			51%
Inlet temperature	35 ºC	Compressor efficiency	0.9
Maximum temperature	650 ºC	Turbine efficiency	0.9
Pressure ratio	3	Recuperator efficiency	0.9

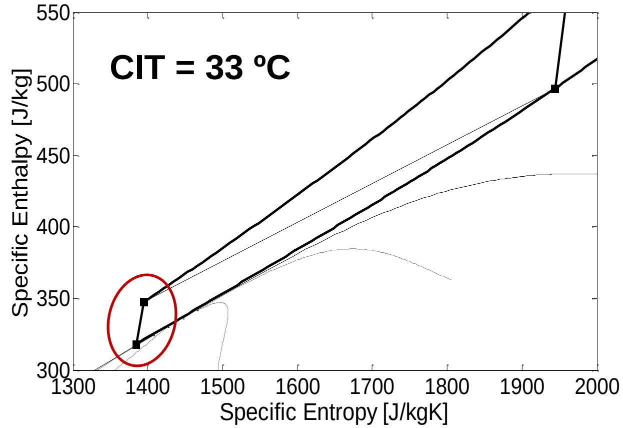


II. Supercritical SO_2 power cycle

(Effect of hot and cold temperatures)







Parameter	Unit	Case 1	Case 2	Case 3	Case 4
Compressor inlet temperature	ºC	33	40	33	40
Turbine inlet temperature	ºC	680	680	730	730
LP Compressor inlet pressure	bar	78	78	78	78
HP Compressor outlet pressure	bar	248	248	248	248
LP Compressor power consumption	MW	9.02	18.65	8.38	17.09
HP Compressor power consumption	MW	7.91	12.26	7.35	11.24
Turbine power production	MW	67.94	81.98	66.76	79.40
Power cycle net power production	MW	50	50	50	50
sCO_2 mass flow	kg/s	401.14	484.02	373.02	443.67
Cycle thermal efficiency	%	53.20	47.13	54.25	48.64
Net cycle efficiency	%	52.13	46.14	53.17	47.62

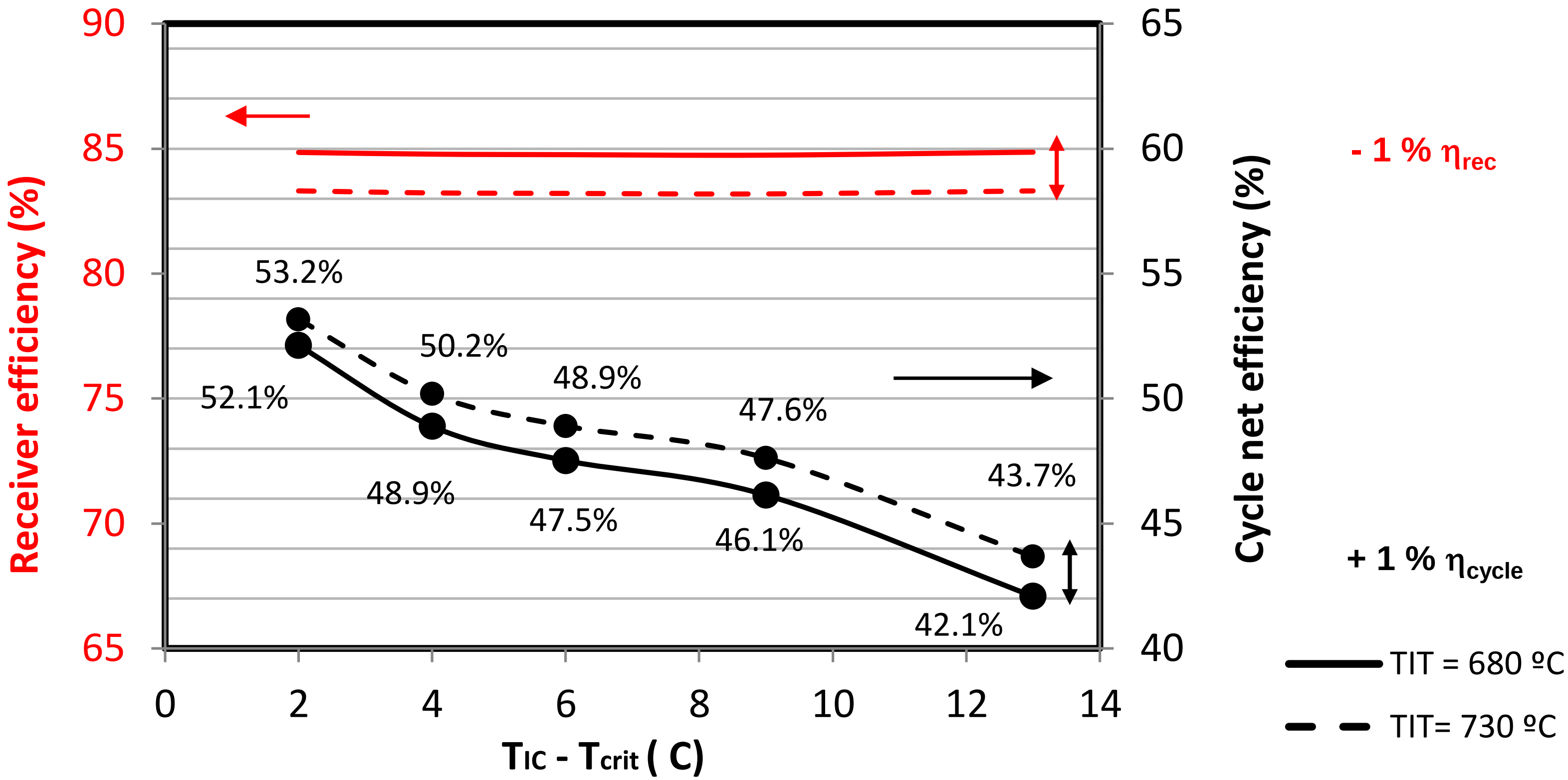
T_{crit} = 31,1 ºC

Conclusions:

- **CIT** severe effect on η_{net}
- **TIT** small effect on η_{net}

II. Supercritical SO_2 power cycle

(Effect of hot temperatures and receiver)

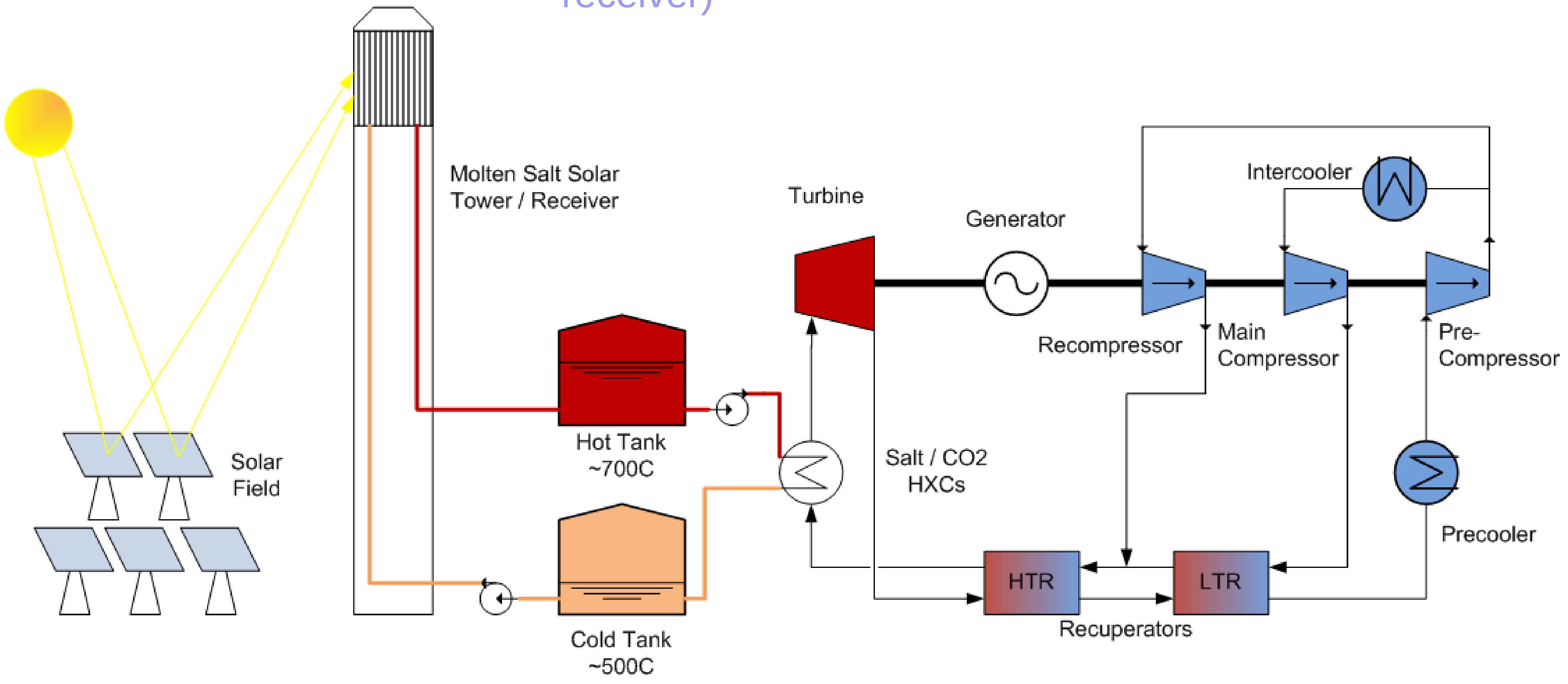


Conclusions:

- Increasing 50 ºC TIT → **+ 1 % η_{cycle}** but **- 1 % η_{rec}**

CSP with sCO_2 Conceptual Design – example

Dry-cooled, “partial-cooling” cycle coupled to high-temperature molten salt power tower (or particle receiver)



DOE's "STEP" project will demonstrate a 10 MW_e recompression cycle

- In negotiation with winning proposal team of GTI/SwRI/GE
- Operational in 2020

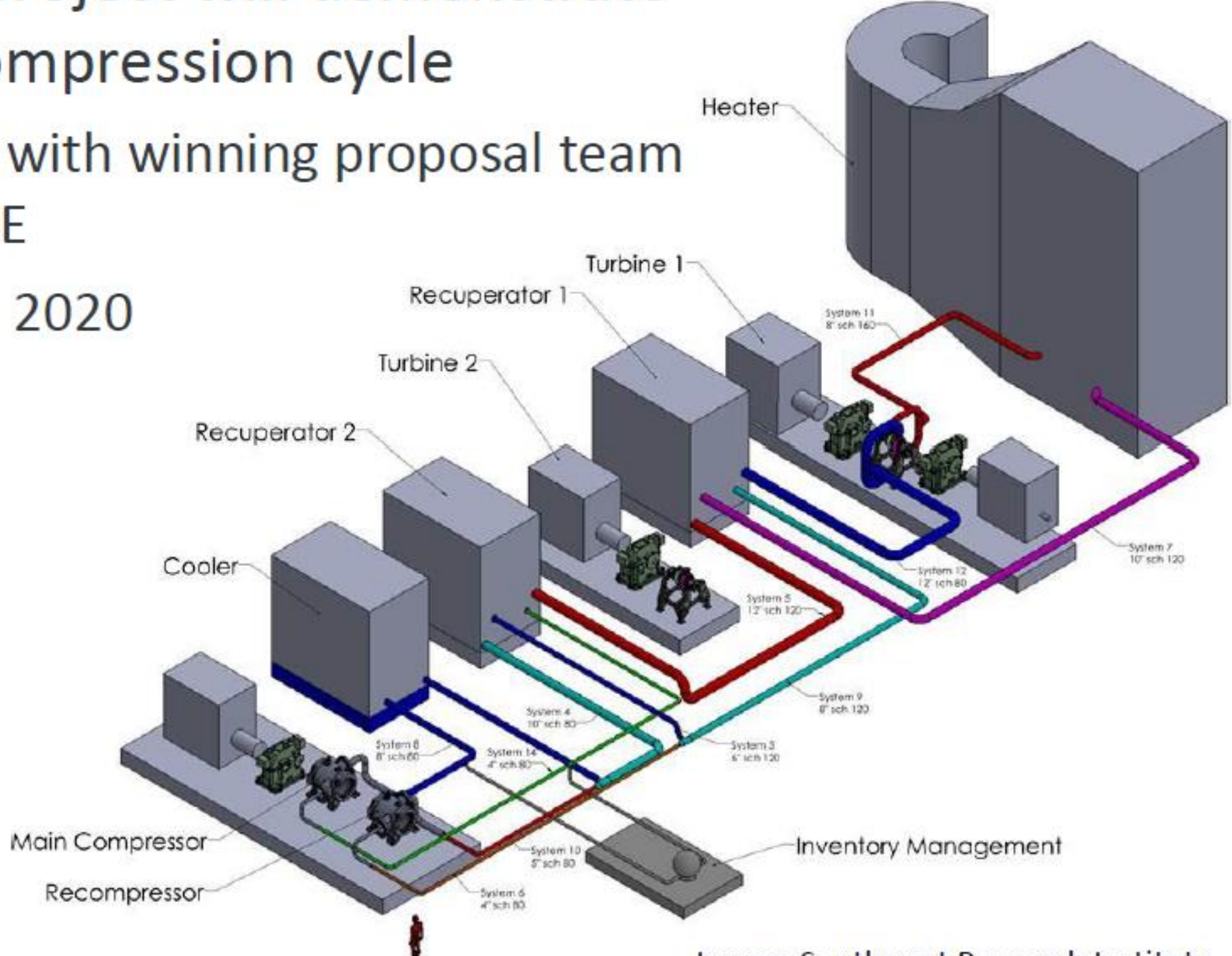


Image: Southwest Research Institute

Supercritical
Transformational
Electric
Power

Supercritical Transformational Electric Power (STEP)

Cross-program DOE initiative to demonstrate the sCO_2 power cycle at commercial scale.
Up to $80M federal contribution, 20% industry cost share, and 6-year duration (see DE-FOA-0001457, released March 2016)

10 MW_e Pilot Plant Test Facility:

- sCO_2 Recompression Brayton Cycle at turbine inlet operating temperatures of 700°C,
- Reconfigurable facility to support testing a variety of components or subsystems, and
- Capability to monitor and characterize primary components or subsystems (turbomachinery, heat exchangers, recuperators, bearings, seals, etc.)

Map pathway towards an overall power cycle efficiency of 50% or greater

Demonstrate steady-state, dynamic, transient load following, and limited endurance operations

sCO_2 Brayton Cycle Research Activities

- Corrosion and materials compatibility data at high T, P
- Cost-effective and durable recuperators
- Design and validation of primary heat exchangers; understanding of sCO_2/HTF interactions
- Validation of power turbine bearings, seals, stop-valves
- Modeling start/stop, off-design and other transient operations
- Cycle operating methodology for dry-cooled systems
- Demonstration of cycle operations and equipment durability at commercially relevant scale (10 MW_e)

- Major research institutions and power companies from around the world are engaged in its development
  - E.g., GE, Dresser-Rand, Toshiba, Samsung

SCO_2-Flex: design a 25MWe coal-fired SCO_2 cycle

SCO2-Flex Objective

Developing and validating (at simulation level the global cycle and at relevant environment) a scalable/modular design of a **25MWe Brayton cycle using supercritical CO_2**, able to increase the operational **flexibility** and the **efficiency** of existing and future coal and lignite power plants

Budget

- 5.6 million Euros (~42 million RMB)

EDF's role in this project

- Project management
- Thermodynamic and process engineering
- SCO_2 Brayton cycle specification

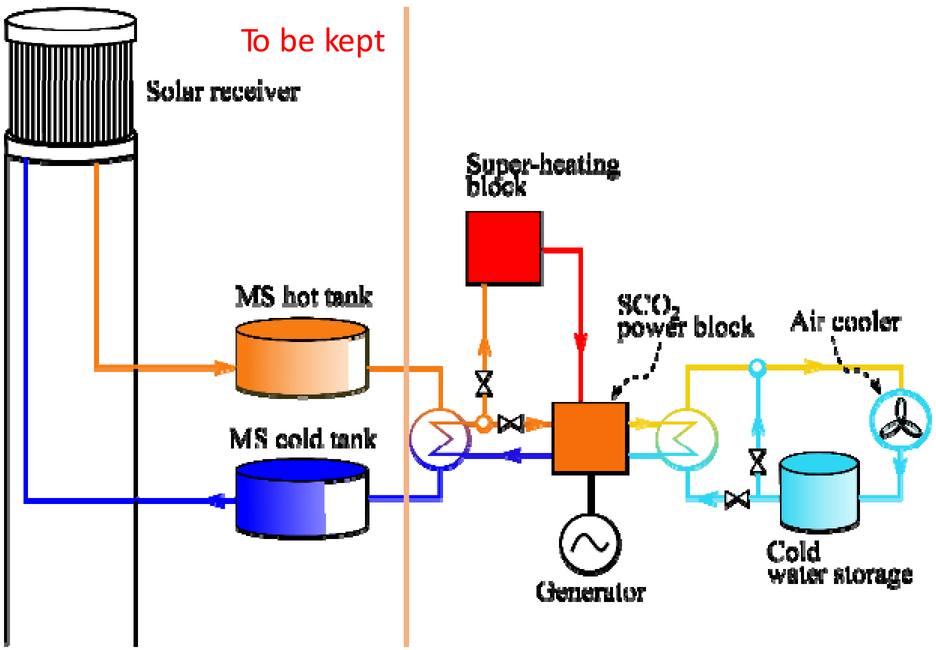
Partners

- BAKER HUGHES, GE
- UJV REZ
- CENTRO SVILUPPO MATERIALI
- CENTRUM VYZKUMU REZ
- FIVES
- ZABALA
- POLITECNICO DI MILANO,
- UNIVERSITAET DUISBURG-ESSEN,
- UNIVERSITAET STUTTGART.

SHOUHANG-EDF 10MWe SCO_2 Demonstration Project

- World first industrial scale application of SCO_2 on CSP molten salt plant

Shouhang-EDF 10MWe SCO_2 demo project: system concept



System design concept

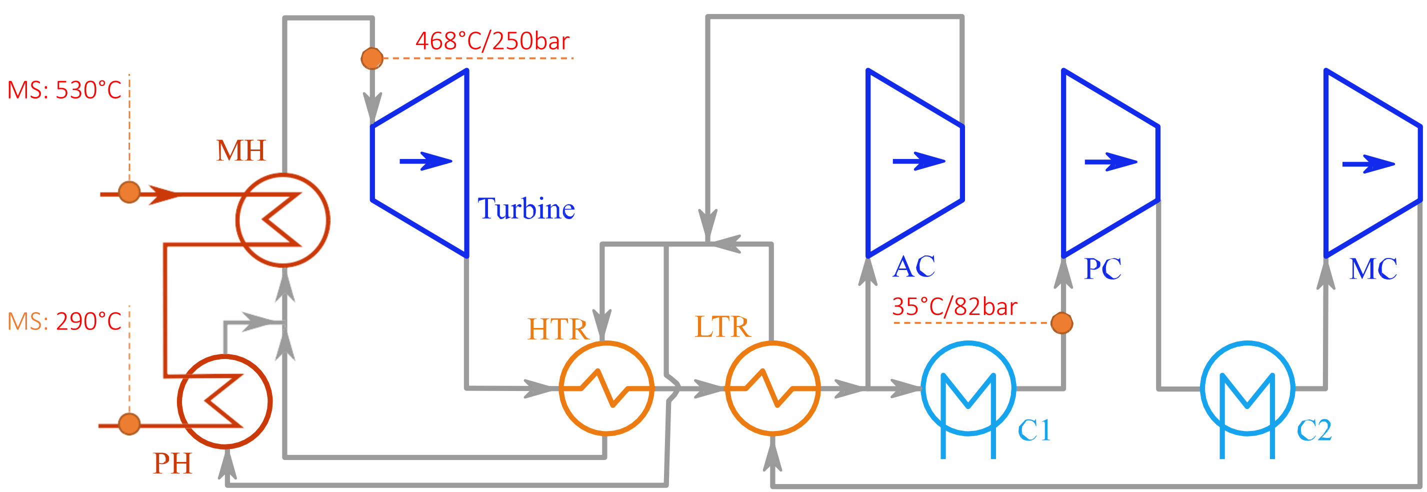
- Keep the current solar field
- Keep the current thermal storage system
- Install a 10MWe SCO_2 power block in parallel with the current 10MWe water steam Rankine cycle
- Use dry cooling
- Optimized cycle for CSP application
- Super-heating to further increase CO2 temperature to a >600 °C

Cycle design for Shouhang-EDF SCO_2 project: recompression cycle with intercooling and preheating

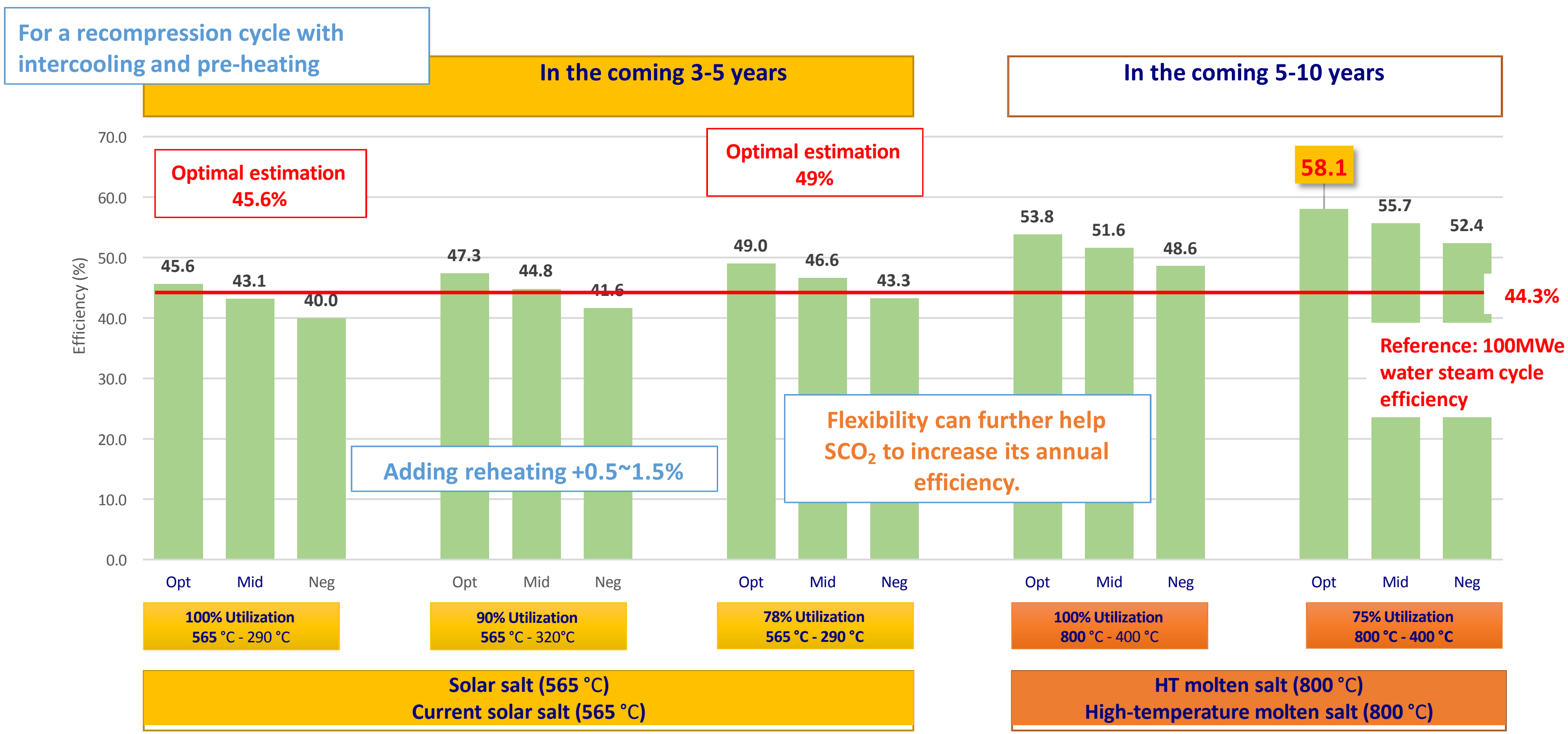
Key cycle features:

- Recompression to increase the recuperation effectiveness
- Intercooling to reduce compressor consumption and to increase thermal storage utilization
- Pre-heating to better utilize the low-temperature molten salt

Cycle net efficiency: 35.6%
Thermal storage utilization: 100%
Design power output: 10.3MWe



Commercial interest for SCO_2 cycle: Even with a not so- complex cycle, it could achieve higher efficiency



Shouhang-EDF 10MWe SCO_2 demo project: Brief planning

2018
- May. 22 — Contract signed between Shouhang, EDF R&D and EDF China
- Dec. 30 — Conceptuel design

2019
- Feb. 15 — Request for proposal
- Jun. 30 — Fix the Short list (Current status)
- Aug. 30 — Fix the main equipment supplier

Basic design — FSR

Detailed engineering design

2020
- Mar. 30 — Civil works
- Aug. 30 — Test of main heat exchangers
- Dec. 30 — Test of turbo-machinary

2021
- Feb. 30 — Cycle commissioning
- Apr. 30 — Cycle starting

2022

EDF

Conclusions

- The thermal efficiency can be increased up to 5% point compared with the steam Rankine cycle.
- The turbomachinery can be much smaller and the overall system size can be reduced up to four times compared with the conventional steam Rankine cycle.
- Efficiency very sensitive to CIT.
- The competitiveness of the dry air cooled S-CO2 cycle has been investigated by multiple researchers without consensus
- Recuperation becomes critical and recuperators require very compact designs
- Early demonstrations foreseen in couple of years with CSP

References

- *Optimization of a recompression supercritical carbon dioxide cycle for an innovative central receiver solar power plant,* M.A. Reyes-Belmonte, A. Sebastián, M. Romero, J. González-Aguilar, Energy 2016)– Vol. 112 – pp: 17-27
- *Annual performance of subcritical Rankine cycle coupled to an innovative particle receiver solar power plant,* M.A. Reyes-Belmonte, A. Sebastián, J. Spelling, M. Romero, J. González-Aguilar Renewable Energy 130 (2019) 786-795
- Flexible electricity dispatch for CSP plant using un-fired closed air Brayton cycle with particles based thermal energy storage system. F. Rovense, M.A. Reyes-Belmonte, J. Gonzalez-Aguilar, M. Amelio S. Bova,M. Romero. Energy 173 (2019) 971-984
- *Particles-based Thermal Energy Storage Systems for Concentrated Solar Power Applications,* M.A. Reyes-Belmonte, E. Diaz, J. González-Aguilar, M. Romero, SolarPACES 2017
- *Heat Exchanger Modelling in Central Receiver Solar Power Plant Using Dense Particle Suspension, M.A. Reyes-Belmonte, F. Gómez-García, J. González-Aguilar, M. Romero, H. Benoit, G. Flamant, AIP Conference Proceedings 1850 (1), 030042*
- *Performance Comparison of Different Thermodynamic Cycles for an Innovative Central Receiver Solar Power Plant,* M.A. Reyes-Belmonte, A. Sebastián, J. González-Aguilar, M. Romero, *AIP Conference Proceedings 1850 (1), 160024*
- *Preliminary design and performance analysis of a multi-megawatt scale dense particle suspension receiver,* A. Gallo, J. Spelling, M. Romero, J. González-Aguilar, SolarPACES 2014
- *Plant layout proposal: A high-efficiency solar thermal power plant using a dense particle suspension as the heat transfer fluid*, J. Spelling, A. Gallo, M. Romero, J. González-Aguilar. SolarPACES 2014


Thank you for your attention