The 4th European sCO2 Conference for Energy Systems
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Thermal Efficiency Gains Enabled by Using Supercritical CO_2 Mixtures In Concentrated Solar Power Applications

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SCARABEUS
Supercritical CARbon dioxide/Alternative fluids Blends for Efficiency Upgrade of Solar power plant

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 814985

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Main Research interests: sCO_2 power cycles, Concentrated Solar Power, Power cycles modelling and simulation, Renewable Energy, Heat transfer, Heat Exchangers.

- **09/2011** — B. Sc. in Energy Engineering (Politecnico di Milano)
- **04/2015** — M. Sc. in Energy Engineering - Double Degree Project - (Politecnico di Milano - Universidad de Sevilla)
- **02/2020** — Ph.D. in Energy Engineering (Universidad de Sevilla)
- **Up to nowadays** — Post-doc → SCARABEUS (Universidad de Sevilla)

M.Sc. Thesis

Best Aiming Strategy Definition for Off-Design Conditions due to Passage of Clouds in a Solar Tower

Ph.D Thesis

Open-Access (SCARABEUS web)

Thermo-Economic Assessment of Supercritical CO_2 Power Cycles for Concentrated Solar Power Plants

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- 1. **Introduction to SCARABEUS Concept**
- 2. Computational Environment & Aim of the Study
- 3. Analysis of the Results
  - Best Combination Between sCO_2 Blend and Cycle Layout
  - Influence Of Operating Conditions
  - Impact On Cycle Main Equipment
- 4. Conclusions
- 5. Q&A

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Combination of sCO_2 and Concentrated Solar Power (Solar Tower)

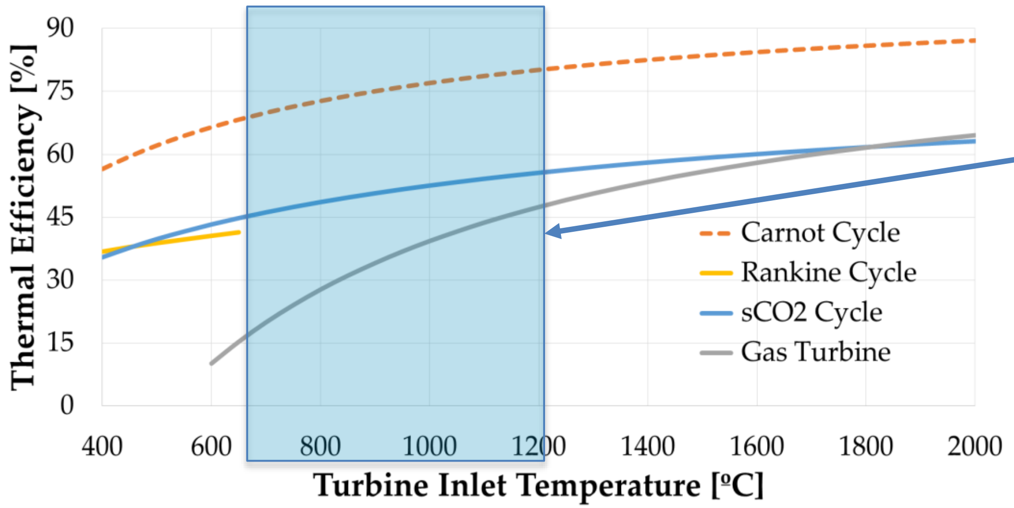
$\eta_{rec} \propto C, T_{rec}$

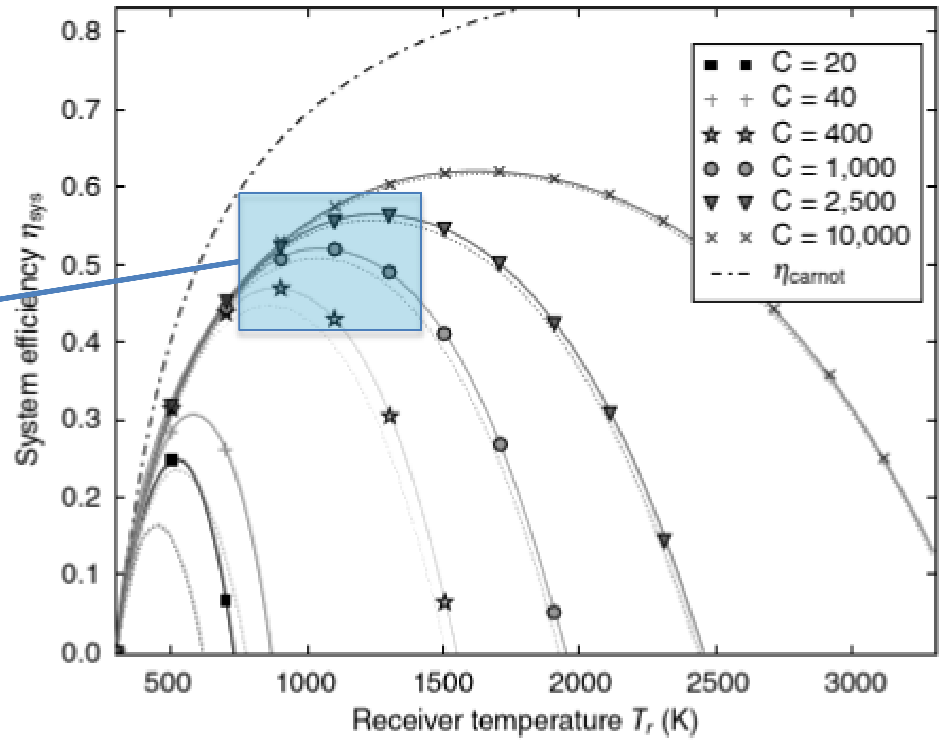
$\eta_{sys} = \eta_{rec} * \eta_{pb}$

Concentration factor = 1000 → η_{sys} optimised by $T = 650 \div 1150ºC$

sCO_2 cycles are promising in this particular range of temperatures

Main Limitation: Need for Compressor Inlet Temperature close to Critical Point





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Combination of sCO_2 and Concentrated Solar Power (Solar Tower)

Main Limitation: Compressor Inlet Temperature close to Critical Point difficult to attain in usual CSP locations

high T_{amb}

⇩

high $T_{in,C}$

⇩

↓ η_{th}

Cycle layout (Turbine Inlet: 300bar, 750ºC)	η_{th} @ 32ºC [%]	η_{th}@ 50ºC [%]	$\Delta\eta_{th}$ [pp]
Simple Recuperated	46.2	43.5	2.7
Precompression	50.0	46.9	3.1
Recompression	51.4	47.9	3.5
Recompr.+IC+RH	53.0	49.1	3.9
Partial Cooling	51.6	48.3	3.3
Partial Cooling+RH	53.9	48.9	5.0
Double Reheated	54	44.3	9.7
Schroder - Turner	49.0	45.3	3.7
Modified Allam	45.6	43.5	2.1
Transcritical CO_2	48.3 (15ºC)	-	-

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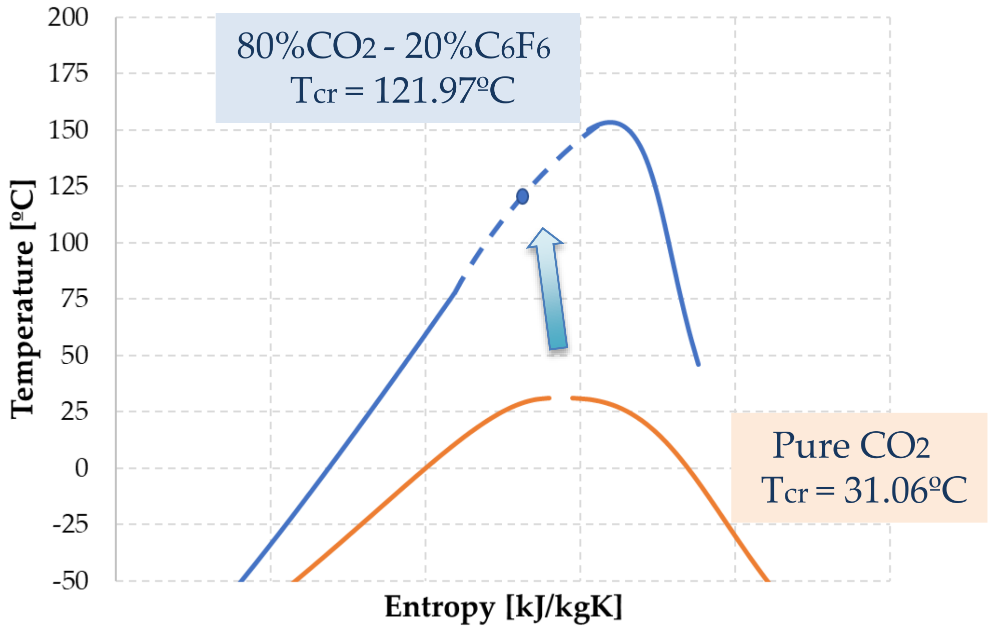
SCARABEUS project → possible solution to overcome this limitation

Supercritical CARbon dioxide/Alternative fluids Blends for Efficiency Upgrade of Solar power plant

- Main Concept:
  Addition of dopants to increase critical temperature, enabling fluid condensation at high ambient temperatures hence increasing cycle performance

- Main Objectives:
  - Thermal efficiency > 50% ($T_{min} \geq 50$ºC)
  - CAPEX and OPEX Reduced by 30% and 35% respectively (compared with SoA steam-based CSP)



- Consortium: five Universities, four companies

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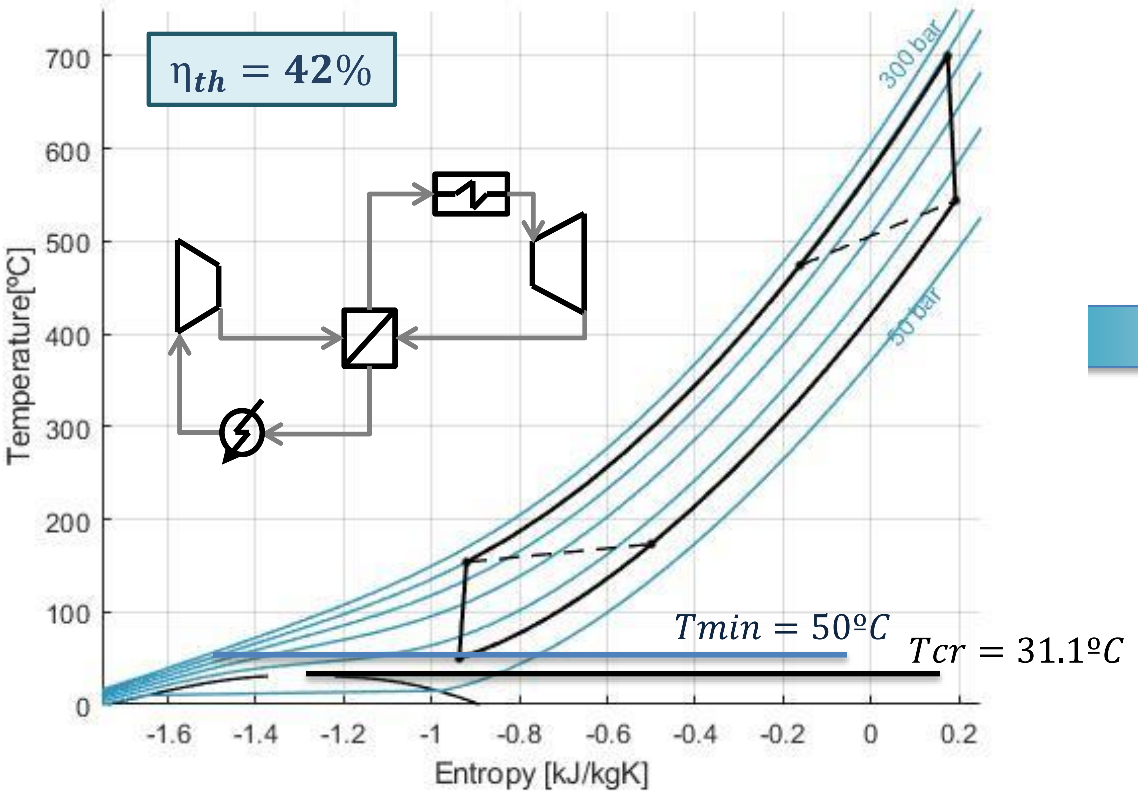
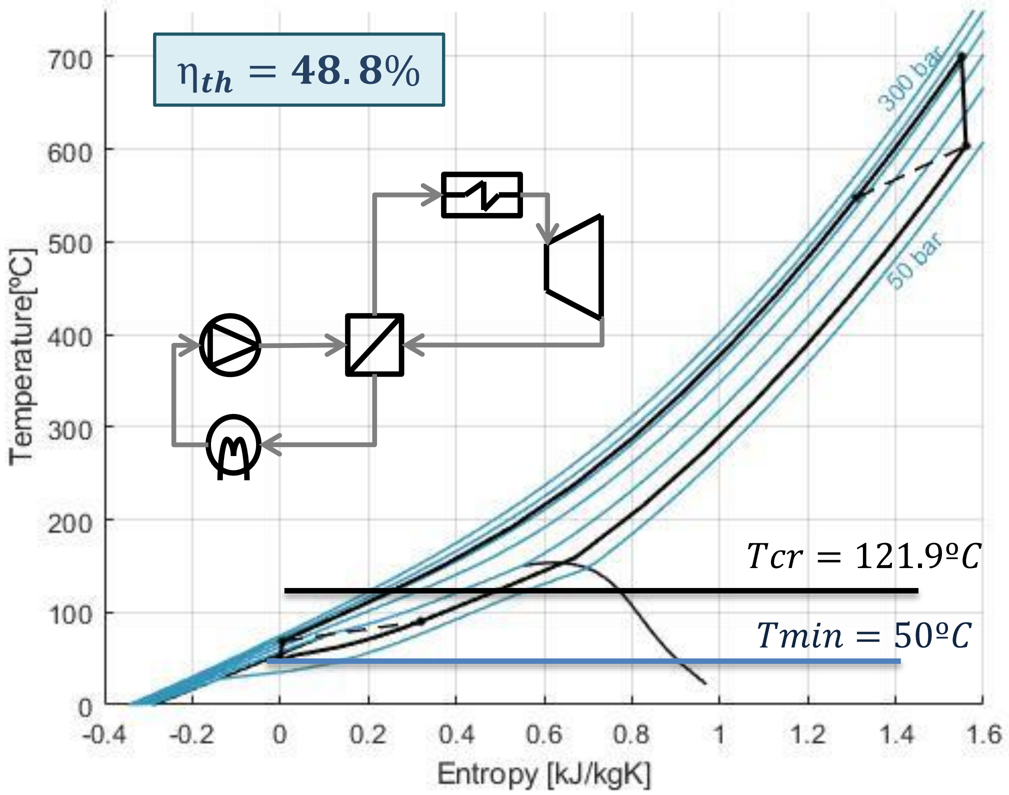
CO_2 blended with dopants → Rise in Critical Temperature → Condensation at high ambient temperature is enabled

Recuperated Brayton (pure CO_2)



Recuperated Rankine (80% CO_2 – 20% C_6F_6)



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Scope of Present Study → explore the actual potential of different sCO_2-based blends

- **Two Candidate Dopants:** Hexafluorobenzene (C_6F_6) and Titanium Tetrachloride ($TiCl_4$)

	Health Hazard	Flammability	Chemical Reactivity	Special Hazard
sCO_2	2	0	0	SA
C_6F_6	1	3	0	-
$TiCl_4$	3	0	2	₩

Due to safety issues, other candidate dopants are currently being investigated by SCARABEUS Consortium. This does not undermine the conclusions of this work.

- **Two Candidate Cycles:** *Recuperated Rankine* and *Precompression* cycles

- **Reference Case:** 100MW (Gross Power)

T_{min} [ºC]	TIT [ºC]	P_{max} [bar]	η_{is} [%] Pump/Turb/Compr
50	550/700	250/300	88 / 93 / 89
ΔT_{min} in HX [ºC]	**ΔP_{HEATER} [%]**	**ΔP_{COND} [%]**	**ΔP_{REC} [%] Low P / High P**
5	1.5	0	1 / 1.5

<u>SCARABEUS Reference Case</u>

T_{min}=50ºC – TIT=700ºC

P_{max}=250bar

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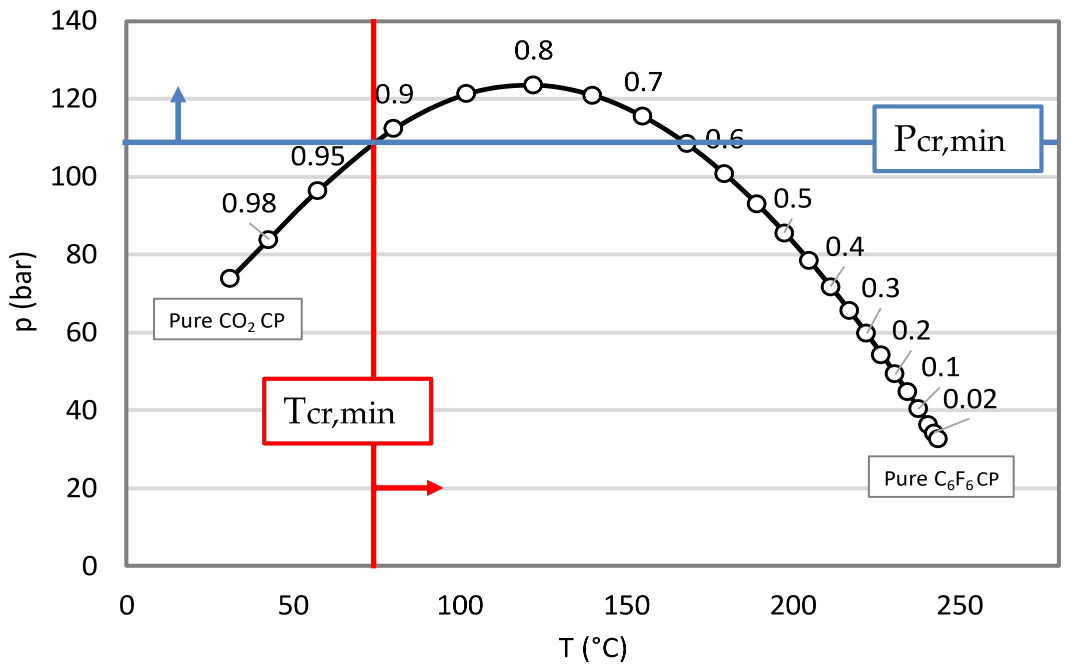
Seven candidate blends, defined by molar fraction of dopant

Mixture Code: DXCYY (applicable to binary mixtures only)

- DX: Dopant (D1=C_6F_6, D2=$TiCl_4$)
- CYY: YY% molar fraction of DX in mixture

Dopant molar fraction selection criterion

$T_{cr} - T_{min} \geq 30ºC \rightarrow T_{cr} \geq 80ºC$ (SCARABEUS case)



Blend	Composition [% molar]	MW [g/mol]	Tcr [ºC]	Pcr [bar]	Pcond [bar]
D1C10	CO_2-C_6F_6 [90-10]	58.21	80.28	112.4	83.51
D1C15	CO_2-C_6F_6 [85-15]	65.32	102.1	121.3	77.52
D1C20	CO_2-C_6F_6 [80-20]	72.42	121.9	123.6	71.83
D1C25	CO_2-C_6F_6 [75-25]	79.52	139.8	121.1	66.36
D2C15	CO_2-$TiCl_4$ [85-15]	65.86	93.76	190.9	99.53
D2C20	CO_2-$TiCl_4$ [80-20]	73.15	149.6	243.7	97.63
D2C25	CO_2-$TiCl_4$ [75-25]	80.43	192.0	247.1	94.52

$\uparrow YY\%$ → $\uparrow MW$, $\uparrow T_{cr}$, $\downarrow P_{cond@50ºC}$

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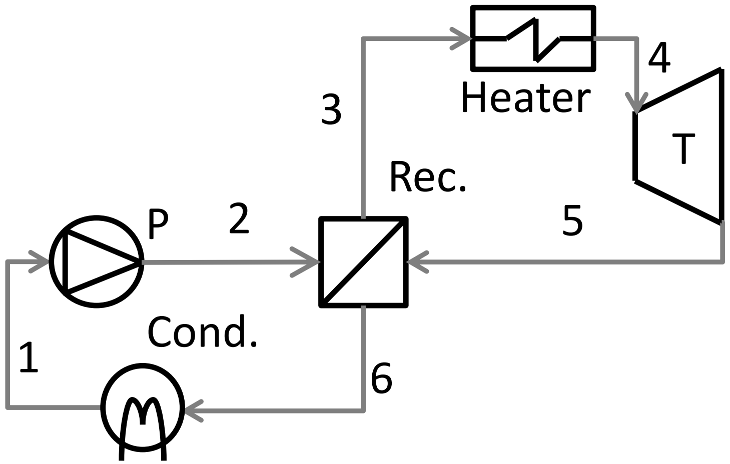
Initial Screening: Part-flow configurations (*Recompression* and *Partial Cooling*) have also been explored but dismissed due to poor thermal performances or poor adaptability to liquid-phase compression when sCO_2 blends are employed.

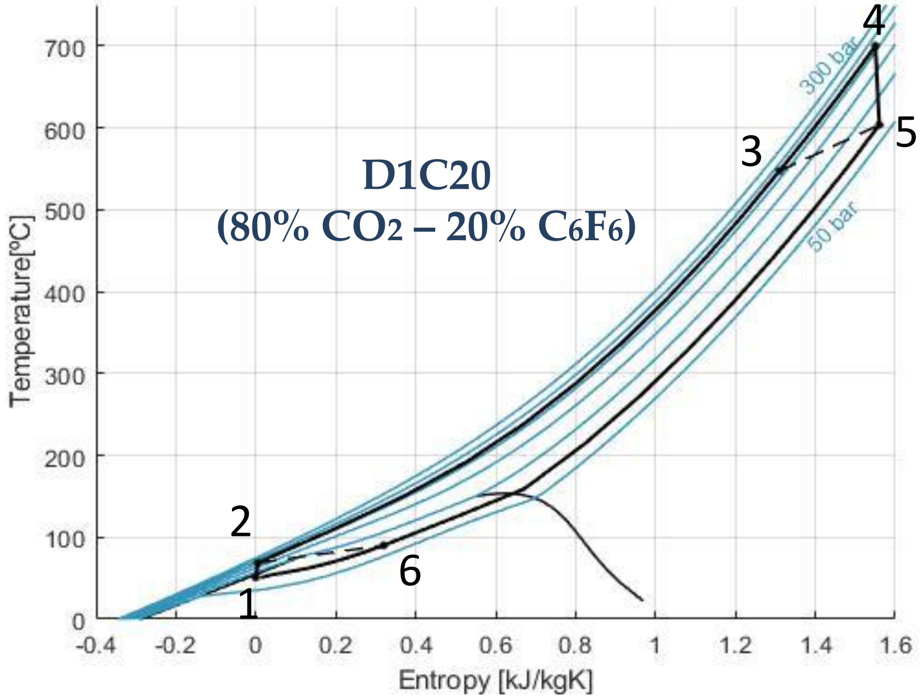
More info in: F. Crespi, G.S. Martínez, P.R. de Arriba, D. Sánchez, F. Jímenez-Espadafor, *Influence of Working Fluid Composition on the Optimum Characteristics of Blended Supercritical Carbon Dioxide Cycles*, **ASME Turbo Expo 2021: Turbomachinery Technical Conference and Expositions** (June 2021)

1) Recuperated Rankine

Very Simple Layout

Strong Dependence of Turbine Exhaust on Condensation pressure, i.e. minimum temperature





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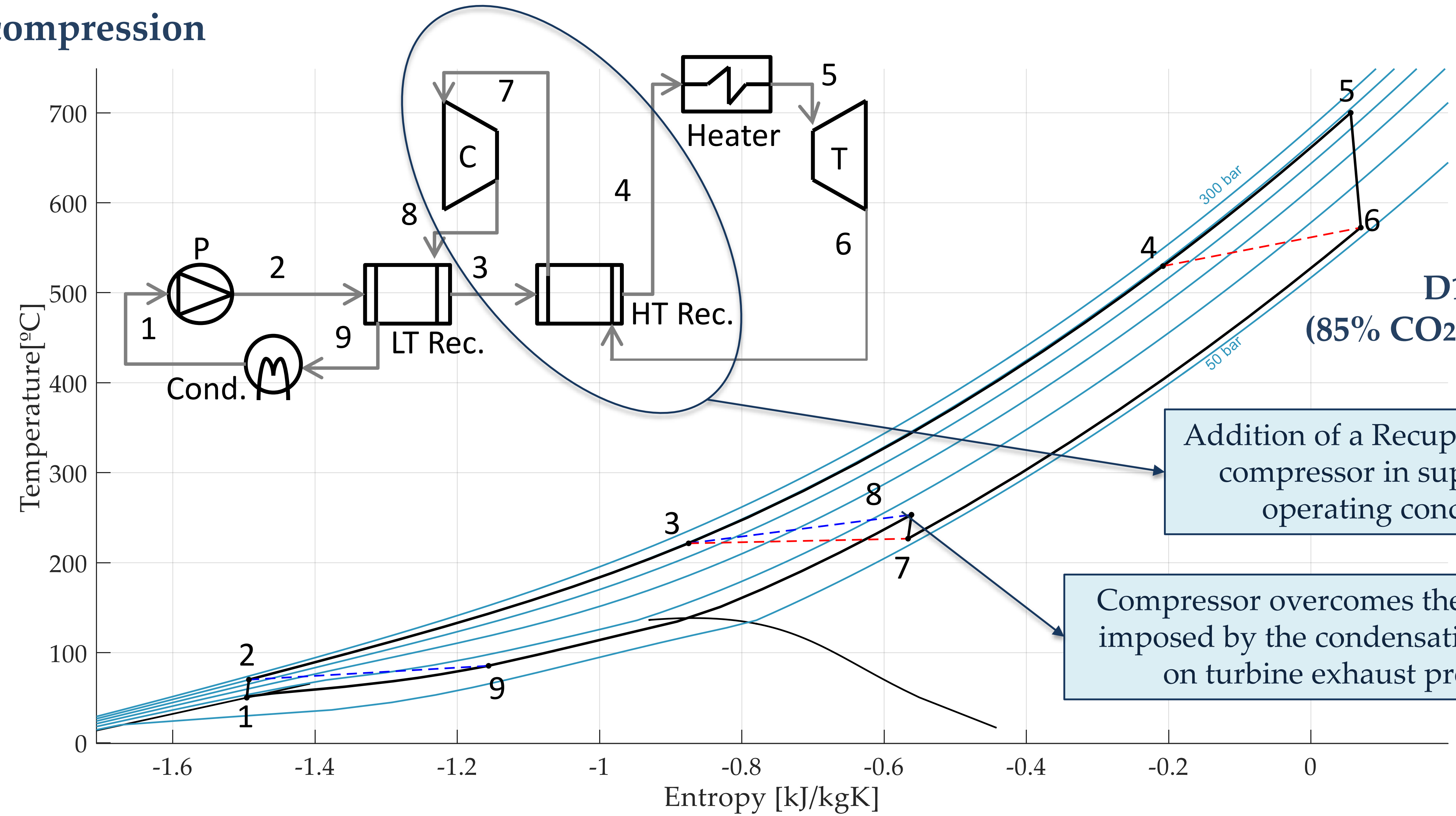
2) Precompression



D1C15

(85% CO_2 – 15% C_6F_6)

Addition of a Recuperator and a compressor in supercritical operating conditions

Compressor overcomes the constraint imposed by the condensation process on turbine exhaust pressure

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a) Calculation of Thermodynamic Properties of the Working Fluid

aspentech

+ Screening, Evaluation and Selection of Candidate dopants

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LEAP Laboratorio Energia e Ambiente Piacenza

b) Cycle modeling and simulation

THERMOFLOW

Thermoflex 29
(released on April 2020)

New *User defined fluid* tool, specifically developed for SCARABEUS project

c) Post processing

MATLAB

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Analysis of the Results: Thermal Efficiency (1)

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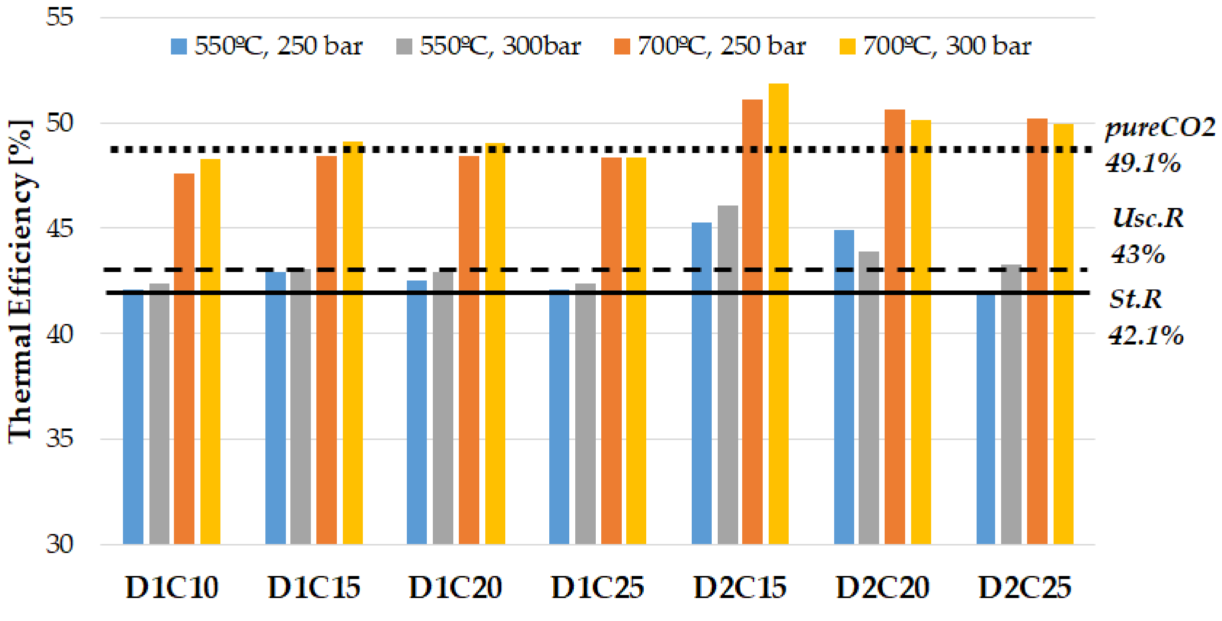
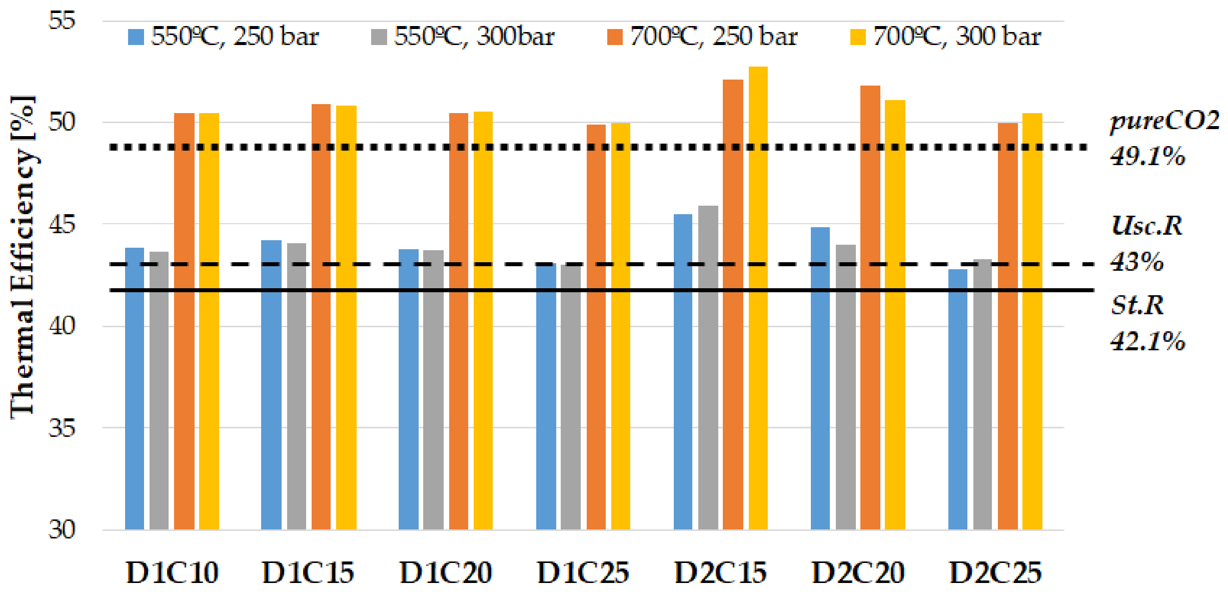


Recuperated Rankine



Precompression

- Thermal efficiency strongly depends on TIT (slightly on Pmax)
- Always enabling η_{th} higher than Standard Rankine (St. R)
- D2C15 always outperforming the other blends
- *Precompression* always enables η_{th} higher than Ultrasupercritical Rankine (Usc. R)

- $TIT \geq 700ºC$, *Precompression* with D1 $\eta_{th} > 50\%$
- $TIT \geq 700ºC$, D2 always $\eta_{th} > 50\%$

SCARABEUS Objective Achieved!

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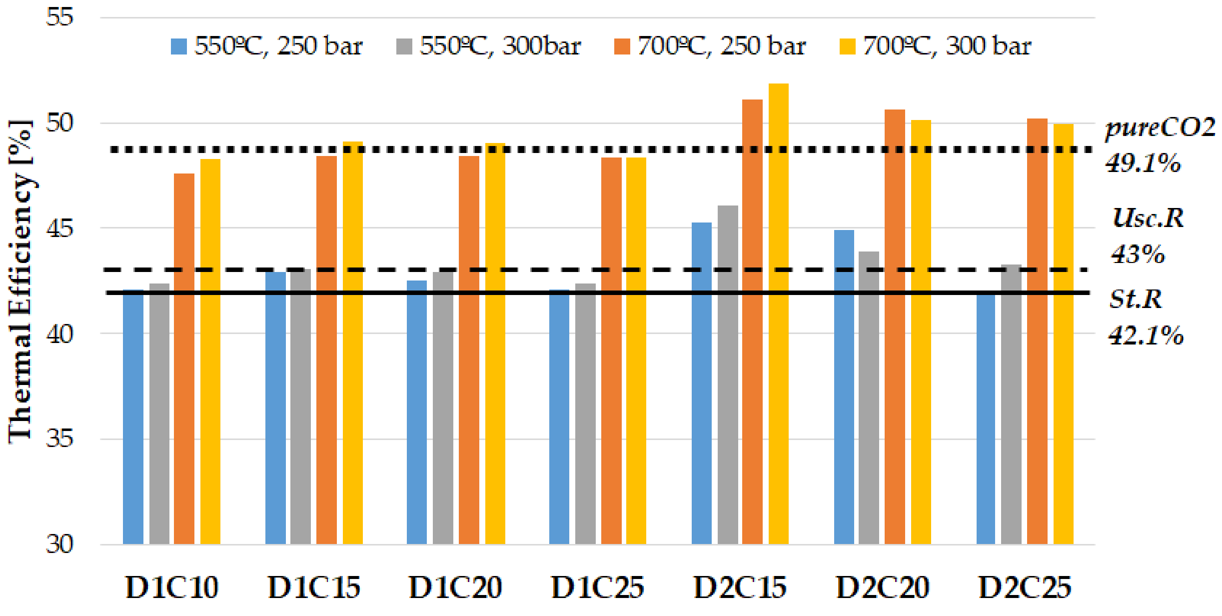
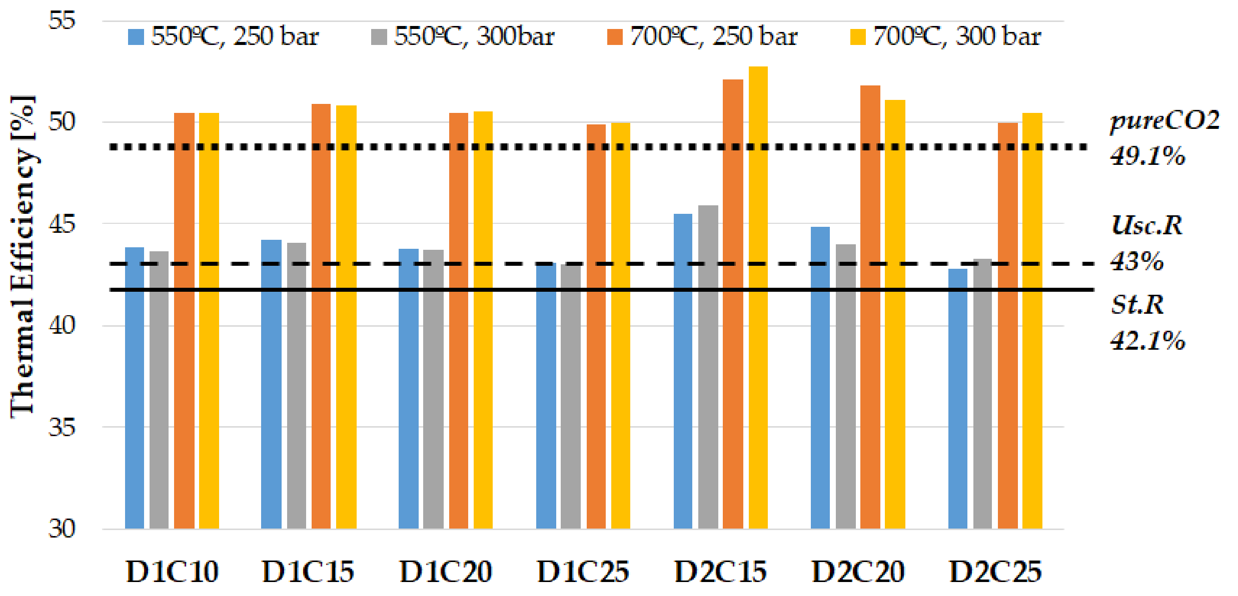


Recuperated Rankine



Precompression

Cycle layout (Turbine Inlet: 300bar, 750ºC)	η_{th} @ 32ºC [%]	η_{th}@ 50ºC [%]	$\Delta\eta_{th}$ [pp]
Simple Recuperated	46.2	43.5	2.7
Precompression	50.0	46.9	3.1

Pure sCO_2

- D1C15 and D2C15 *Rec. Rankine* lead to 5.5 pp and 8pp higher η_{th} than pure sCO_2 *Rec. Brayton* (with lower TIT)
- D1C15 and D2C15 *Precompression* lead to 3.5pp and 5pp higher η_{th} than pure sCO_2 *Precompression* (with lower TIT)
- Blends outperform pure sCO_2 cycles with similar boundary conditions

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Thermal efficiency gains enabled by Precompression with respect to Recuperated Rankine

$$\Delta\eta_{th} = \eta_{th,PRECOMPR.} - \eta_{th,REC.RANKINE}$$

	550ºC/250bar	550ºC/300bar	700ºC/250bar	700ºC/300bar
D1C10	1.76	1.28	2.85	2.14
D1C15	1.25	1.04	2.45	1.68
D1C20	1.27	0.81	2.07	1.53
D1C25	0.99	0.63	1.53	1.59
D2C15	0.25	-0.18	0.97	0.84
D2C20	-0.05	0.12	1.15	0.96
D2C25	0.87	0.01	-0.22	0.46

Compressor overcomes the constraint imposed by the condensation process on turbine exhaust pressure

Higher cycle complexity, but with the interesting addition of one degree of freedom (optimisation)

$\Delta\eta_{th}$ strongly affected by the nature and molar fraction of dopant

- D1 blends → $\Delta\eta_{th}$≈2-3pp , D2 blends → $\Delta\eta_{th}$≈ 0 - 1pp
- Actually, $\Delta\eta_{th} < 0$ for some D2 blends (even if η_{th} slightly higher than D1 are achieved)

***Precompression* exploits the potential of sCO_2-C_6F_6**

***Recuperated Rankine* exploits the potential of sCO_2-$TiCl_4$**

More info in papers submitted to **Turbo Expo 2021** and **ORC Munich 2021** (see last slide for more details)

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Minimum cycle temperature depends on Ambient Temperature

PIT →	30ºC	35ºC	40ºC	45ºC	50ºC	55ºC	60ºC
CO_2	-	43.69	43.15	42.60	42.06	41.51	40.96
D1C10	50.96	50.21	49.36	48.61	47.64	47.03	45.94
D1C15	**51.39**	**50.4**	**50.10**	**49.19**	**48.43**	47.99	47.02
D1C20	50.50	50.25	49.97	48.76	48.41	**48.19**	**47.05**
D1C25	50.46	49.29	48.82	48.59	48.34	47.13	46.97
D2C15	53.47	52.98	52.45	51.89	**51.14**	**50.30**	**49.42**
D2C20	**54.48**	**53.23**	**52.62**	**52.42**	50.65	50.24	48.84
D2C25	52.54	51.35	50.73	49.64	48.34	47.13	46.97

T_{min} is varied from 30 to 60ºC, for 700ºC/250bar case

Cycle considered: *Recuperated Brayton* (sCO2)
Recuperated Rankine (blends)

CO_2-blends prove to enable higher thermal efficiency than pure CO_2, employing a cycle with similar complexity.

Absolute best-performing blend regardless of minimum cycle temperature cannot be identified

- Possibility to tailor the composition of the working fluid to the ambient conditions of the plant site in order to maximise thermal performance
- Further optimisation of supercritical power cycles using CO_2 blends in other applications

Analysis of the Results: Specific Work

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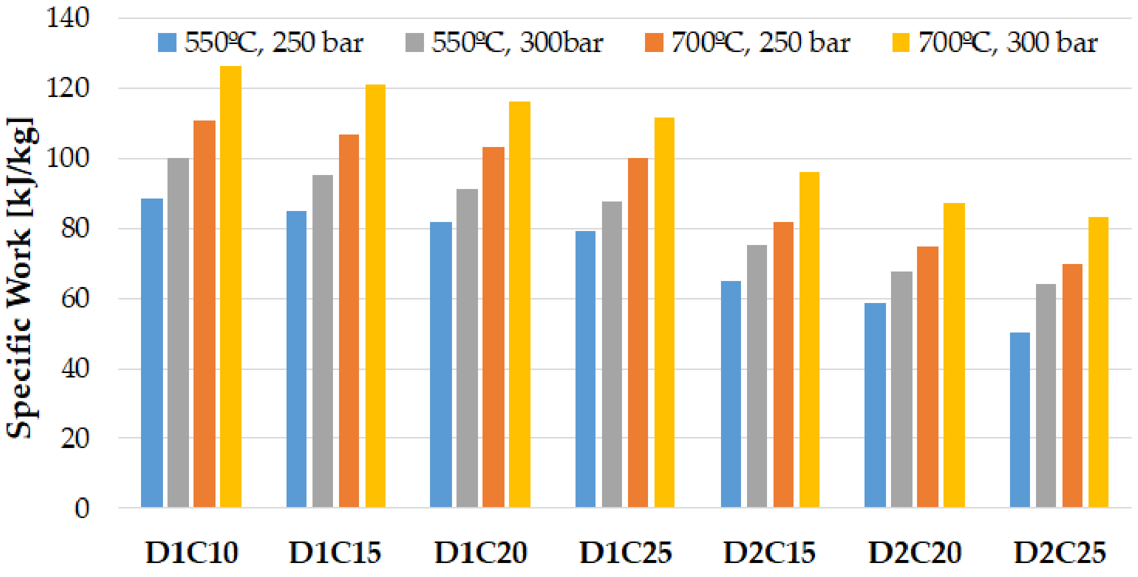
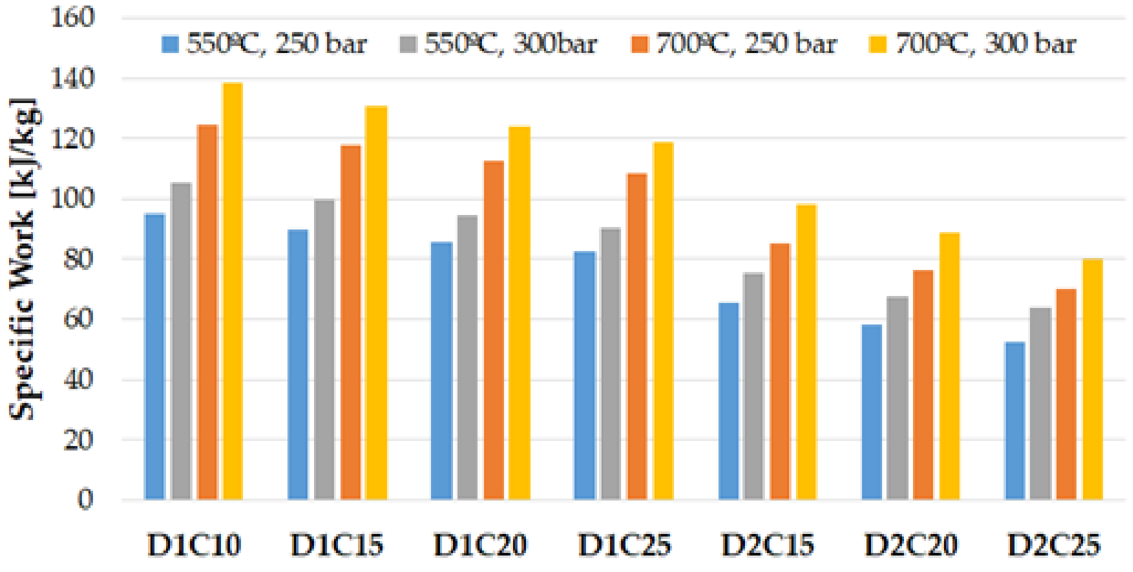


Recuperated Rankine



Precompression

- *Precompression* yelds higher Ws than *Recuperated Rankine* (higher expansion ratio brought by compressor)
- Similar patterns: smallest molar fraction → highest Ws (for a given set of boundary conditions)
- For a given dopant: ↑ molar fraction → ↑ molar weight → ↑ circulating mass flow → ↓ Ws
- D2 present Ws lower than D1 blends → a compromise is needed between these two figures of merit

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- The use of CO_2-based mixtures in supercritical cycles enables $\eta_{th} \geq 50\%$, even for $T_{min} \geq 50$ºC. This is well above what state-of-the-art Rankine cycles running on steam are currently achieving in CSP plants → significant upsurge in performance for this type of application.

- CO_2-based mixtures also enable thermal performance much better than what conventional sCO_2 can attain for the same boundary conditions (due to the deleterious effect of high T_{amb} on the compression process). The gain enabled CO_2-based mixtures is in the order of 5-6 pp (≥10% relative performance improvement with respect to an equivalent embodiment with pure CO_2).

- The performance of supercritical cycle layouts using CO_2-based mixtures depends weakly on turbine inlet pressure, whereas the influence of minimum and maximum cycle temperatures is very strong. Nevertheless, regarding temperature, whilst both temperatures determine thermal efficiency, turbine inlet temperature does not have any influence on the composition of the blend yielding the best performance. This seems to be dependent on minimum cycle temperature only.

- When CO_2-based mixtures are used, cycle optimisation must include WF composition and cycle layout as independent variables. This is because the layout yielding the best η_{th} changes as mixture composition changes.

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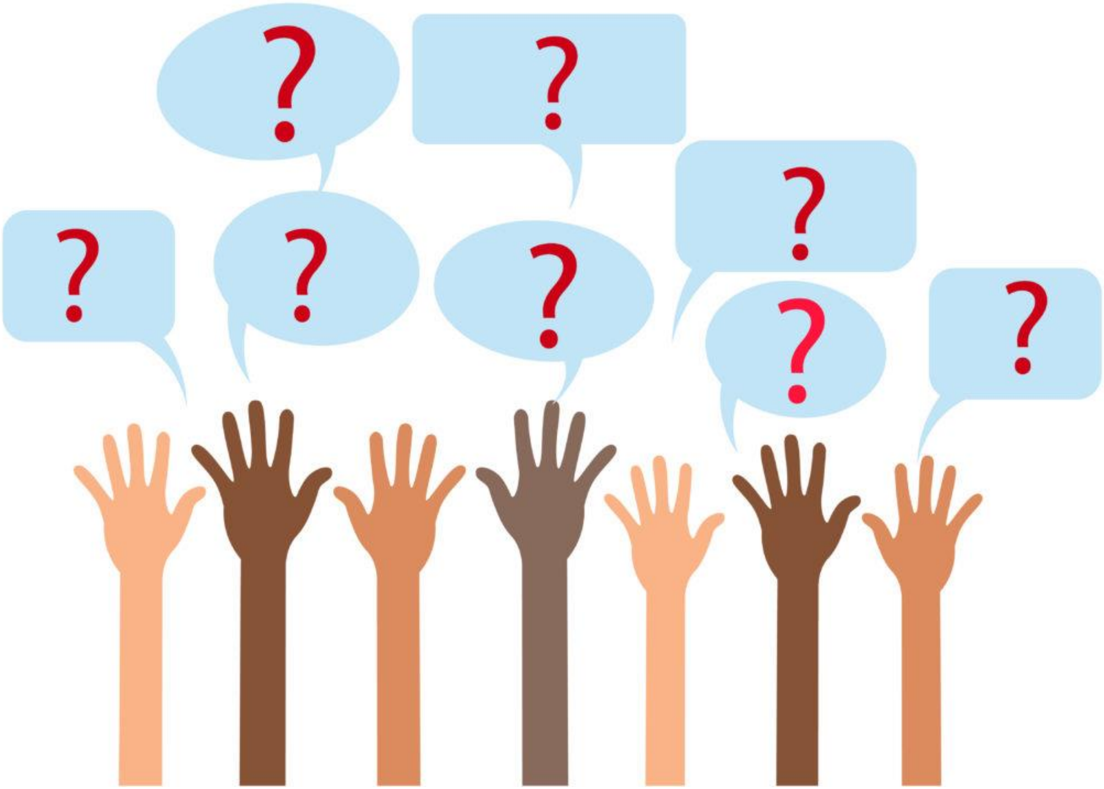
Thank you for your attention!
Any Questions?



Upcoming publication on the same topic

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- F. Crespi, G.S. Martínez, P.R. de Arriba, D. Sánchez, F. Jímenez-Espadafor, *Influence of Working Fluid Composition on the Optimum Characeristics of Blended Supercritical Carbon Dioxide Cycles*, **ASME Turbo Expo 2021: Turbomachinery Technical Conference and Expositions** (June 2021)

- F. Crespi, P.R. de Arriba, D. Sánchez, A. Muñoz, T. Sánchez, *The Potential of Supercritical Cycles Based on CO2 mixtures in Concetrated Solar Power Plants: An Exergy-based Analysis*, **ORC Munich 2021: 6th International Seminar on ORC Power Systems** (October 2021)

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