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Rome, Italy

30th SolarPACES Conference

Optimizing CO2-mixture based power cycles for CSP applications: A multi-objective approach

Balkan Mutlu, Kumar Patchigolla, Dhinesh Thanganadar

nziic.co.uk

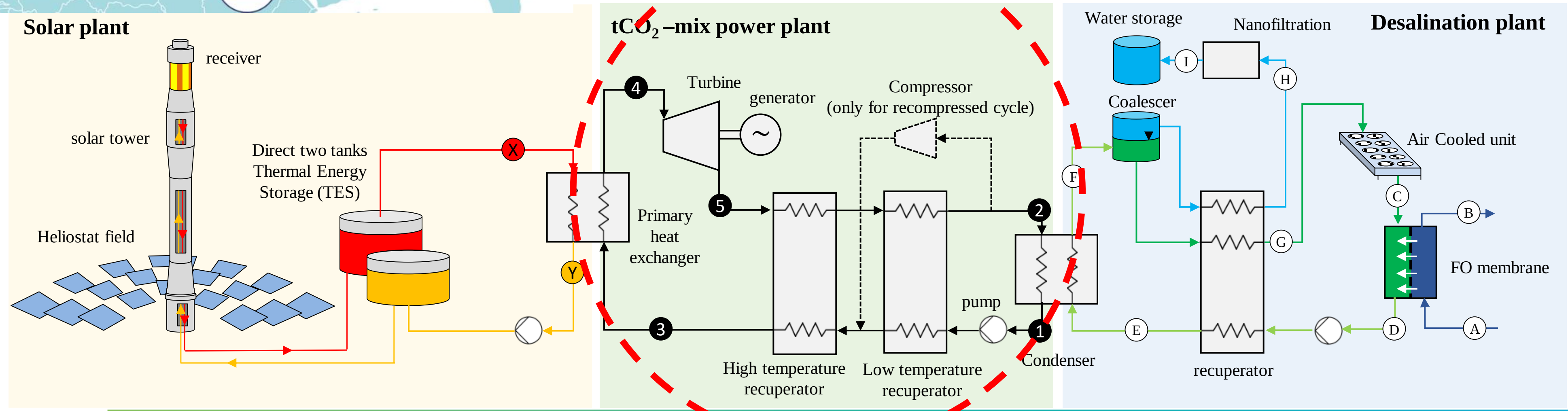
DESOLINATION Concept

- 13 Universities
- 3 Research centre
- 2 Large Industrial Partners
- 4 SME

Duration: 64 months

Start Date: 01 Jun 2021

Estimated Project Cost: €13.8 mil



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Teesside University

Horizon 2020 European Union Funding for Research & Innovation

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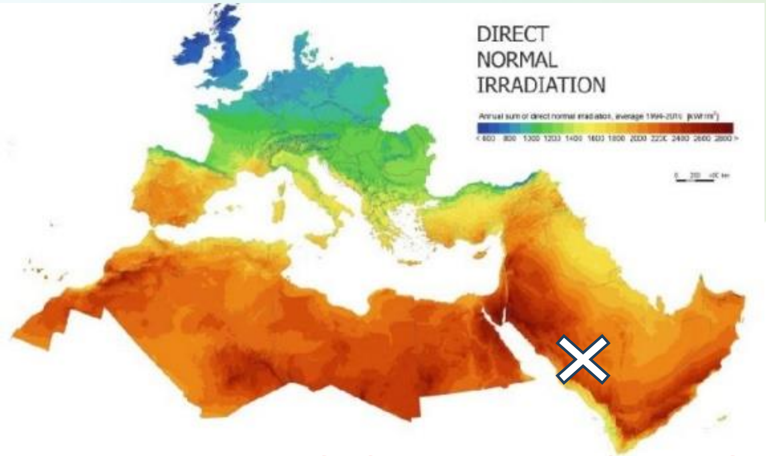
NORTHERN POWERHOUSE

DESOLINATION

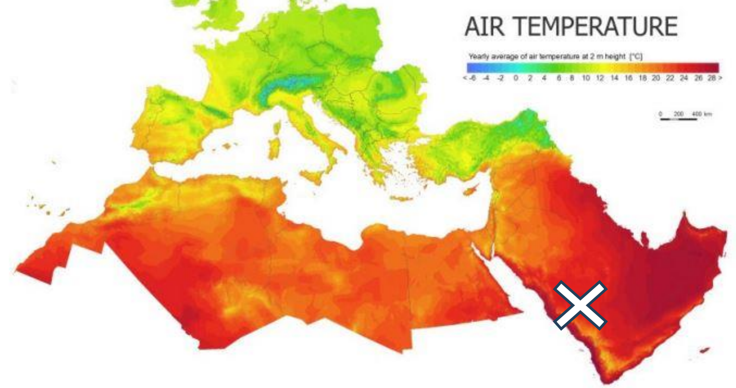
Research Gap

T_{max}=550/700ºC T_{min}=50ºC

Generation	1st gen.	2nd gen.		3rd gen.		
Receiver outlet temp.	~250 - 450℃	~500 - 565℃	~720℃	Expected to be >700℃		
Typical plant or technology	PTC, SPT, LFR (SEGS I, Sierra, eLLO)	PTC, SPT, LFR ~500 - 565℃ (Archimede, Ivanpah, Dacheng)	PDC (Maricopa)	Salt		Air, He, CO_2, etc.
Heat transfer medium	Oil or steam	Steam or salt	Gas	Salt	Particle	Gas
Thermal energy storage	Early designs: No or small → Recent designs:Yes	Early designs: No or small → Recent designs:Yes	No	Yes		
Power cycle	Steam Rankine cycle		Stirling	Brayton cycle		
Peak temp. of cycle	~240-440℃	~480-550℃	~720℃	Expected to be >700℃		
Design cycle eff.	~28-38%	~38-44%	~38%	Expected to be >50%		
Annual solar-electric eff.	~9-16%	~10-20%	~25%	~25-30%		



CO_2 T_{crit} =31 ºC



Khan et al. 2022. Progress in technology advancements for next generation concentrated solar power using solid particle receivers

Dopants and properties

	$CO_2+C_6F_6$	CO_2+SO_2	CO_2+SiCl4	CO_2+TiCl_4	$CO_2+C_2H_3N$
BIP	0.033	0.0242	0.13933	0.0745	0.054
EoS	Standard PR	Standard PR	Standard PR	Standard PR	Standard PR
Thermal levels	550°C Only	550 and 700°C	550 and 700°C	550 and 700°C	550°C Only

%comp

i / j	$T_{j=0}$	T_{j+1}	T_{j+2}	.	T_{j+n}
$P_{i=0}$	$h_{i,j}$	$h_{i,j+1}$	$h_{i,j+2}$	.	$h_{i,j+n}$
P_{i+1}	$h_{i+1,j}$	$h_{i+1,j+1}$	$h_{i+1,j+2}$	.	$h_{i+1,j+n}$
P_{i+2}	$h_{i+2,j}$	$h_{i+2,j+1}$	$h_{i+2,j+2}$	.	$h_{i,j+n}$
.	.	.	.	.	.
P_{i+m}	$h_{i+m,j}$	$h_{i+m,j+1}$	$h_{i+m,j+2}$	.	$h_{i+m,j+n}$

i / j	$T_{j=0}$	T_{j+1}	T_{j+2}	.	T_{j+n}
$P_{i=0}$	$s_{i,j}$	$s_{i,j+1}$	$s_{i,j+2}$	.	$s_{i,j+n}$
P_{i+1}	$s_{i+1,j}$	$s_{i+1,j+1}$	$s_{i+1,j+2}$	.	$s_{i+1,j+n}$
P_{i+2}	$s_{i+2,j}$	$s_{+2,j+1}$	$s_{i+2,j+2}$	.	$s_{i,j+n}$
.	.	.	.	.	.
P_{i+m}	$s_{i+m,j}$	$s_{i+m,j+1}$	$s_{i+m,j+2}$	.	$s_{i+m,j+n}$

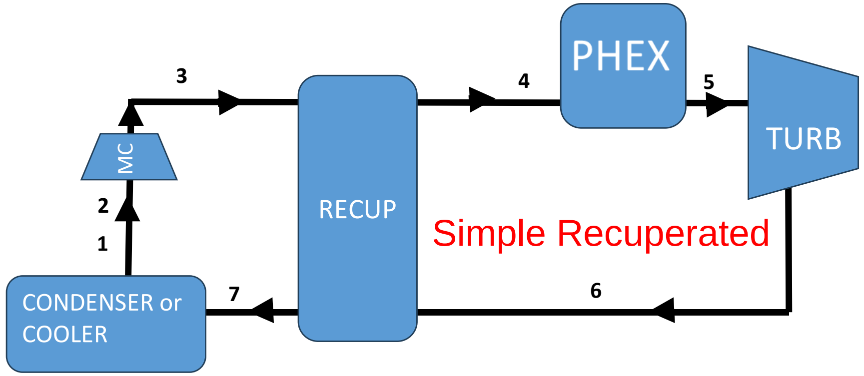
Resolution

- 1°C (390-750)
- 1 bar (20-300)
- 1% (50-100)

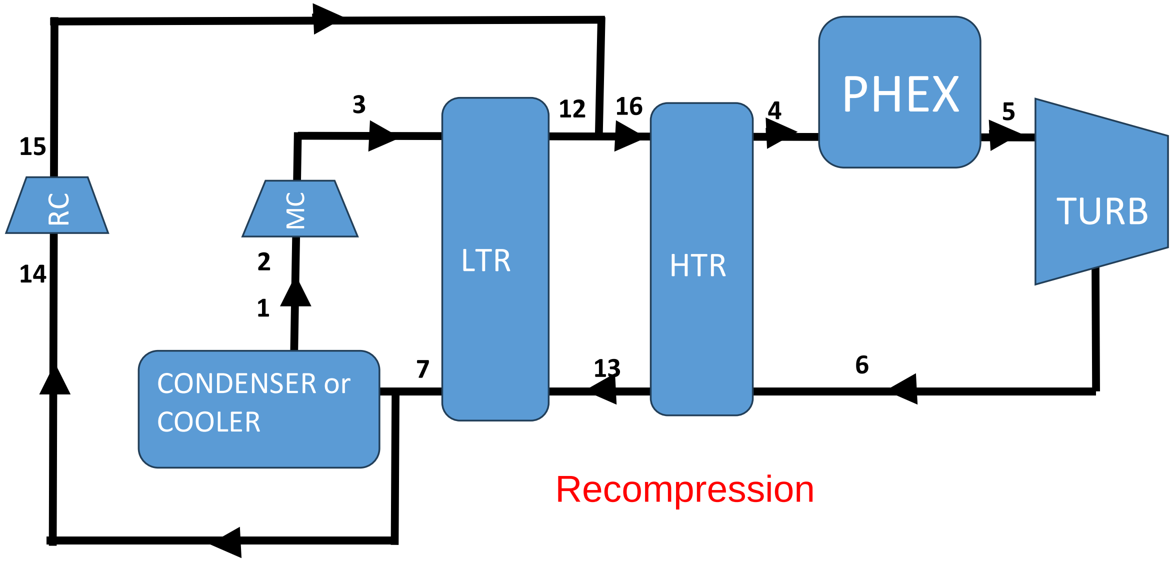
Chemical Engineering Design Library (ChEDL)
https://github.com/CalebBell/thermo

Cycle Layouts

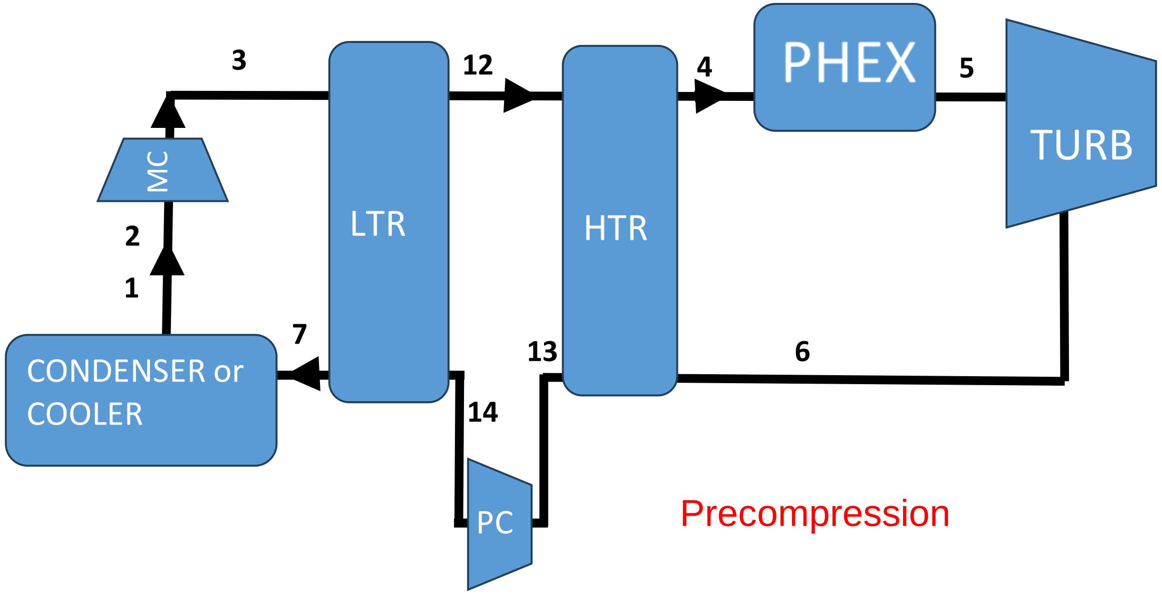
Isentropic efficiencies
Minimum pinch for HEXs
Pressure drops accros HEXs



Simple Recuperated



Recompression



Precompression

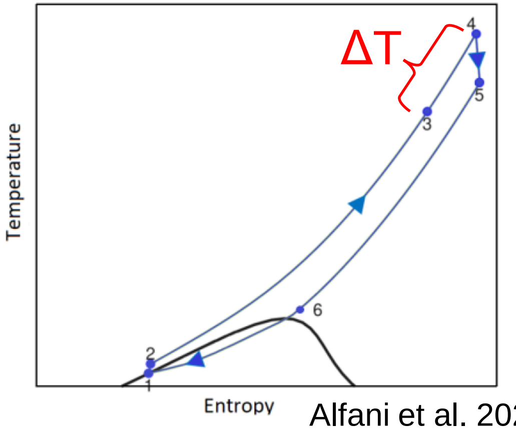
Simultanous Optimisation Strategy

Fluid Properties → Dopant and composition selection ⟳ CO_2-mixture Power Block Design Parameters *(Simple, Precompression, Recompression)*

Proposed simultaneous Multi-objective Global Optimization with MATLAB

Thermal efficiency vs ΔT across PHEX → Multi-criteria decision-making

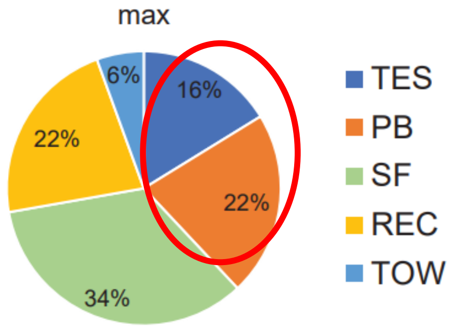
η_{th}



Max η_{th} → Min Solar Field cost

Max ΔT → Min TES Costs

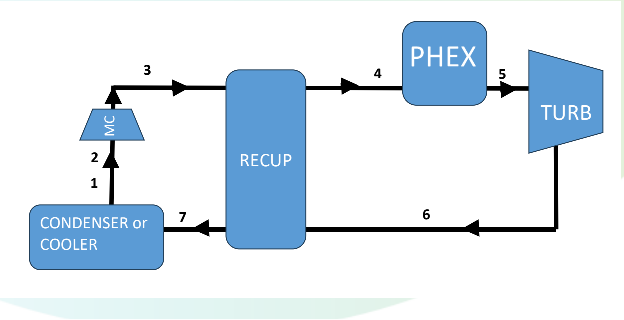
Max spec work → Min Power Block cost

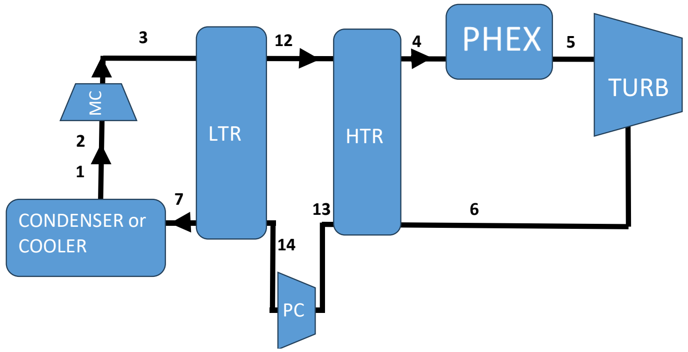


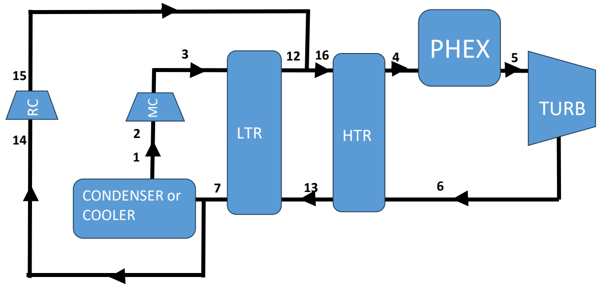
Alfani et al. 2022. Techno-economic analysis of CSP incorporating sCO2 brayton power cycles: Trade-off between cost and performance

Boundary Conditions and Bounds

	T_{max}	Dopants	CO_2 Composition	T_{min}	P_{min}	P_{max}	PR	Split Ratio
Simple Recuperated	550°C 700°C	SO_2 $TiCl_4$ $SiCl_4$ C_2H_3N C_6F_6 SO_2 $TiCl_4$ $SiCl_4$	50% to 100%	50°C	60 to 140 bar	250 bar	-	-
Precompression	550°C 700°C	SO_2 $TiCl_4$ $SiCl_4$ C_2H_3N C_6F_6 SO_2 $TiCl_4$ $SiCl_4$	50% to 100%	50°C	40 to 120 bar	250 bar	1 to 2	-
Recompression	550°C 700°C	SO_2 $TiCl_4$ $SiCl_4$ C_2H_3N C_6F_6 SO_2 $TiCl_4$ $SiCl_4$	50% to 100%	50°C	60 to 140 bar	250 bar	-	0 to 1







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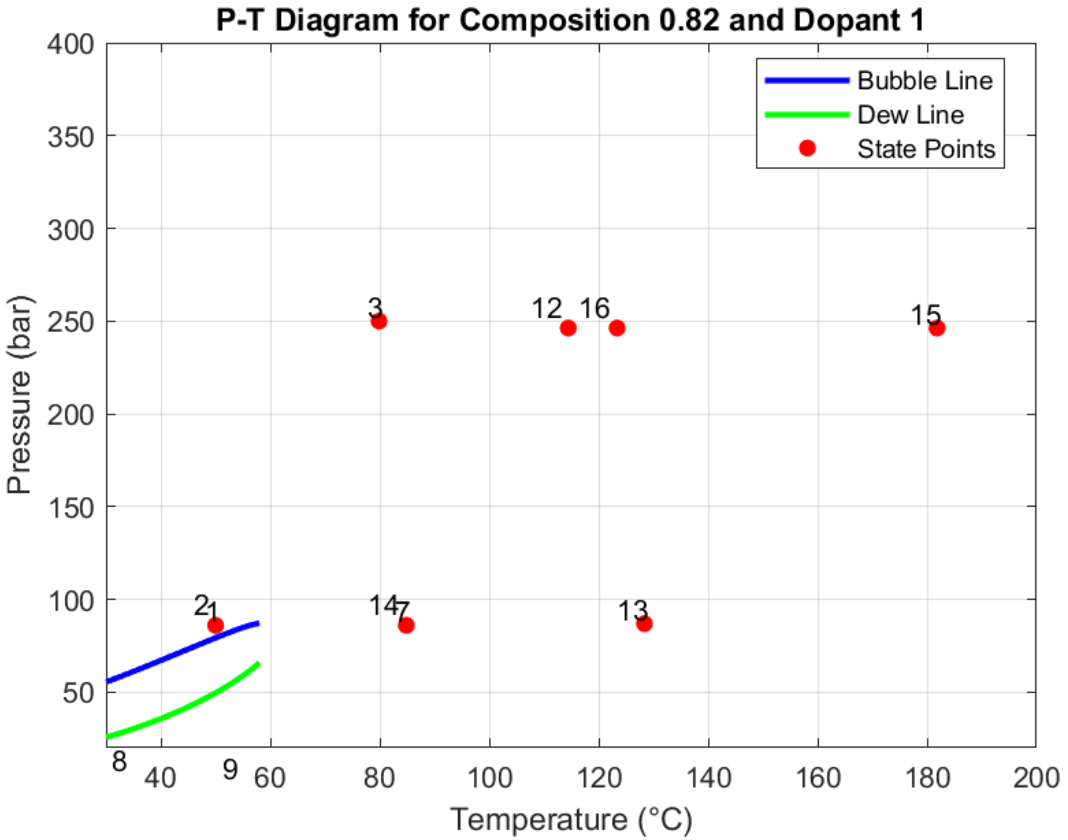
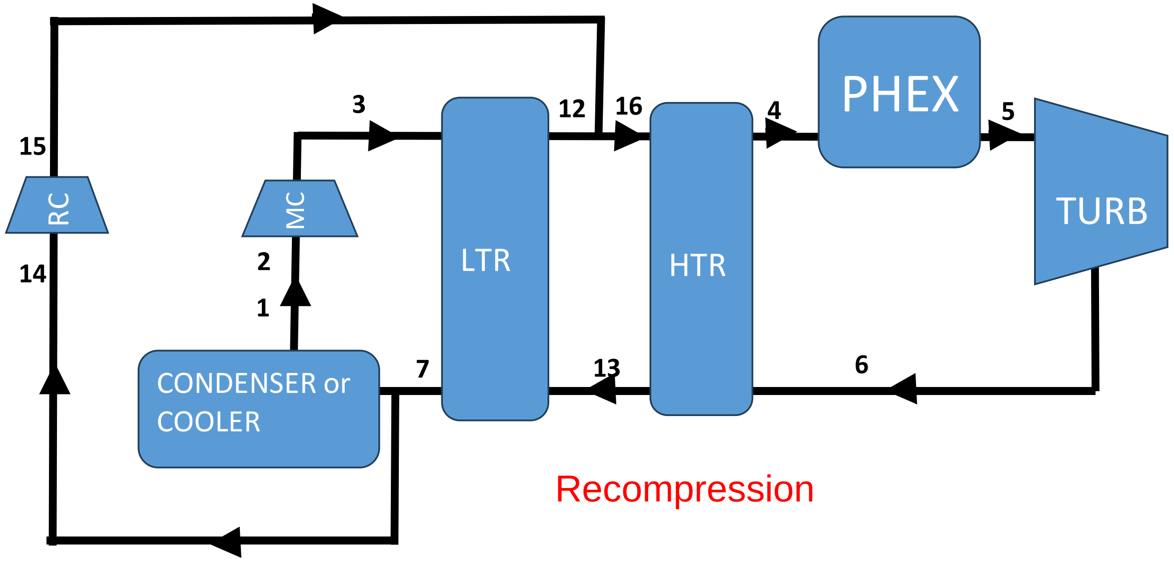
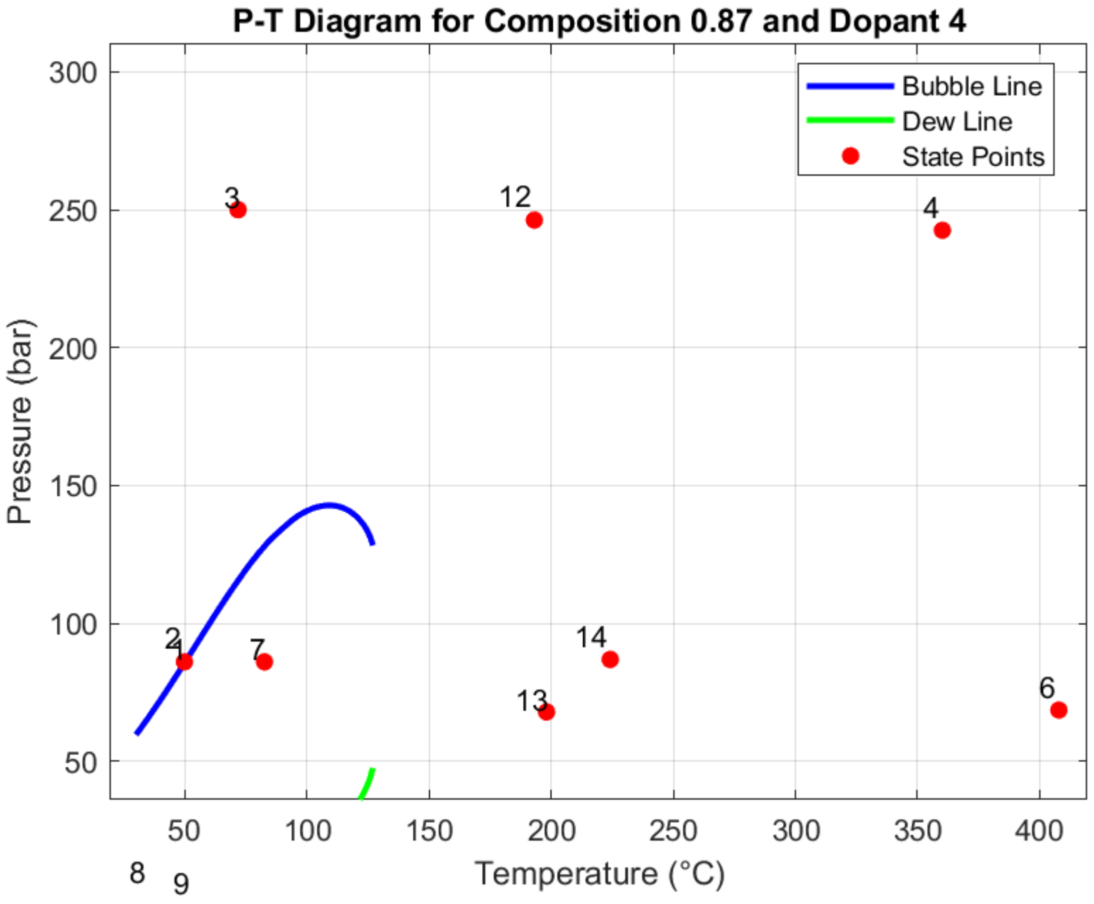
Constraints for termination

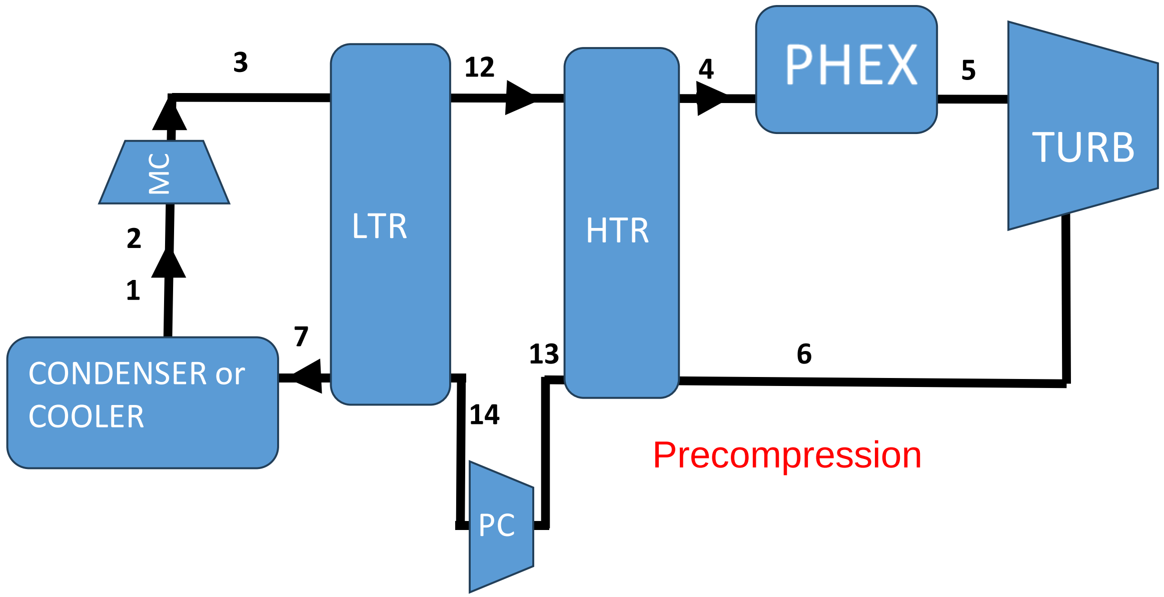




Recompression

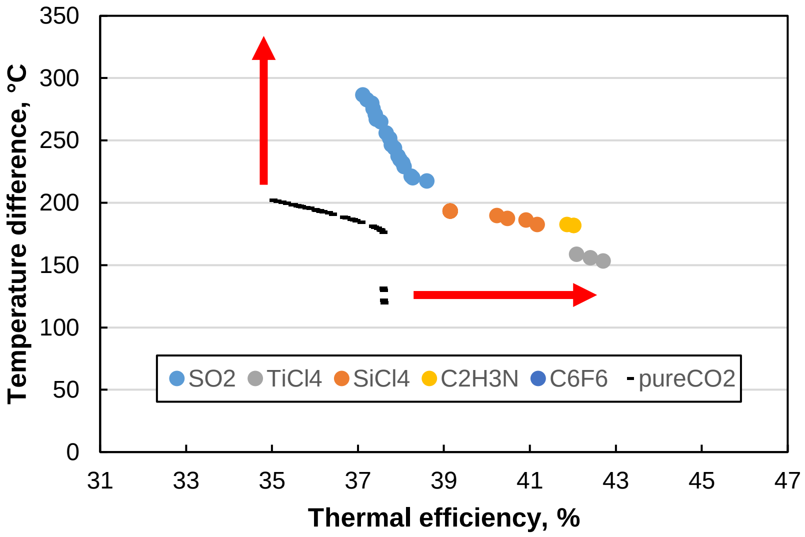
Constraints for termination



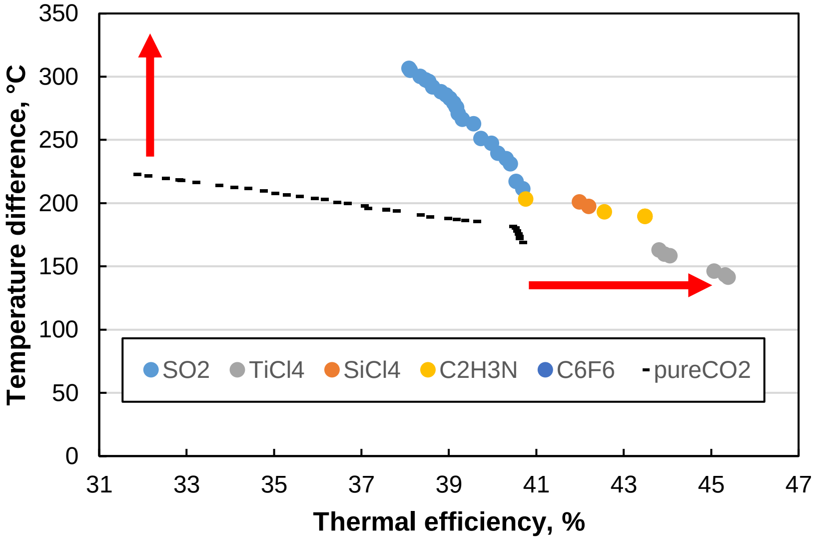


Genetic Optimization Results

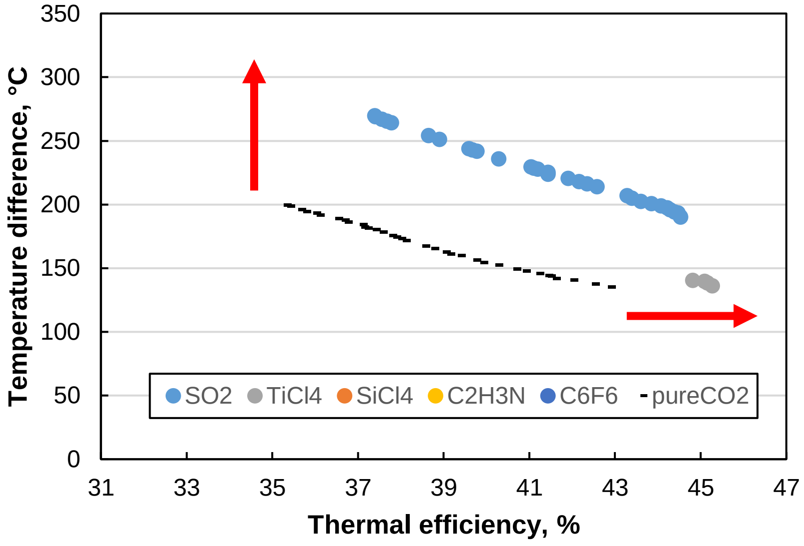
550 °C



Simple Recuperated



Precompression



Recompression

mcdm

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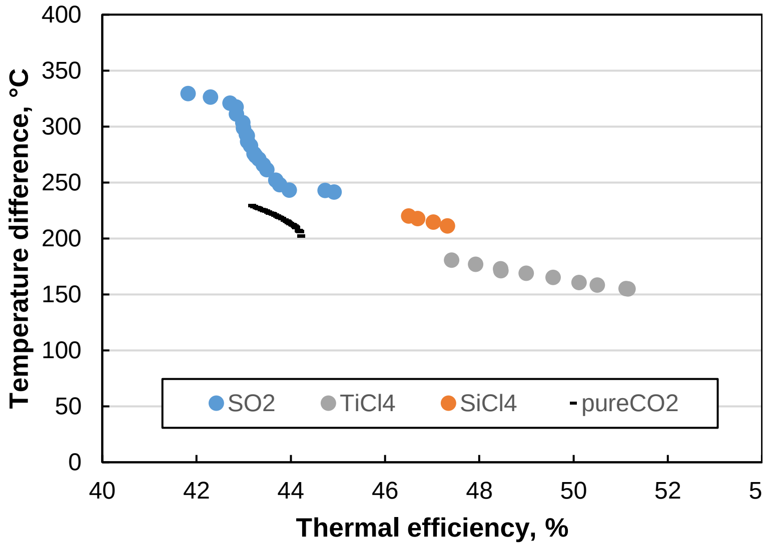
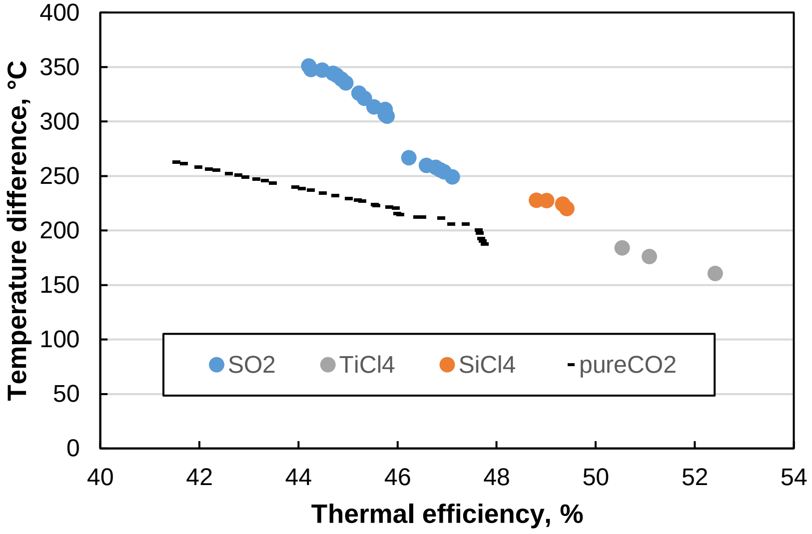
Genetic Optimization Results

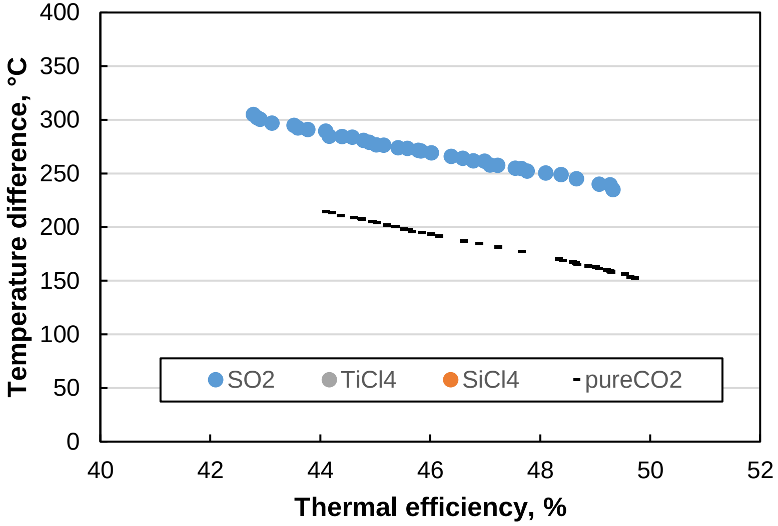
700 °C



Simple Recuperated



Precompression



Recompression

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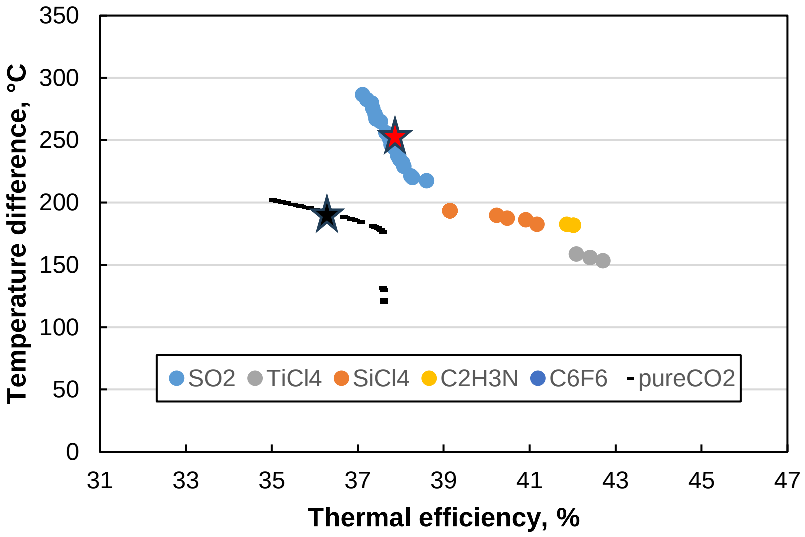
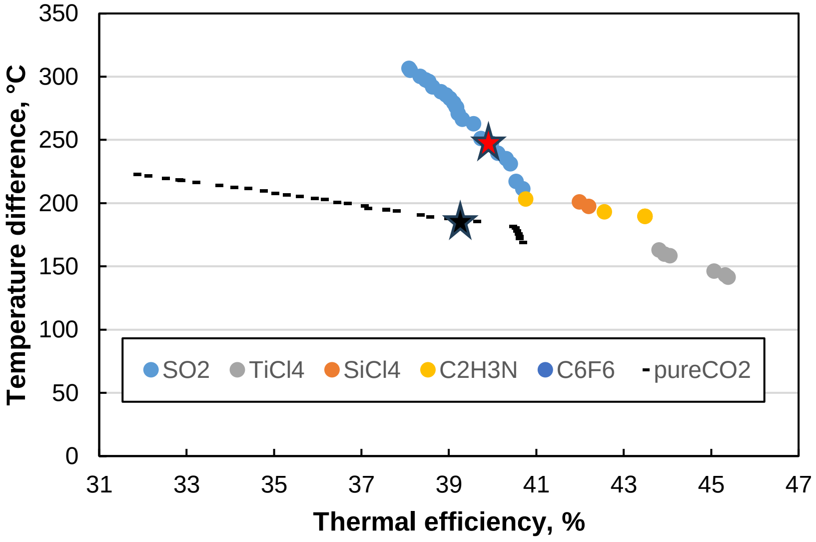
Multi-criteria Decision Making (MCDM)

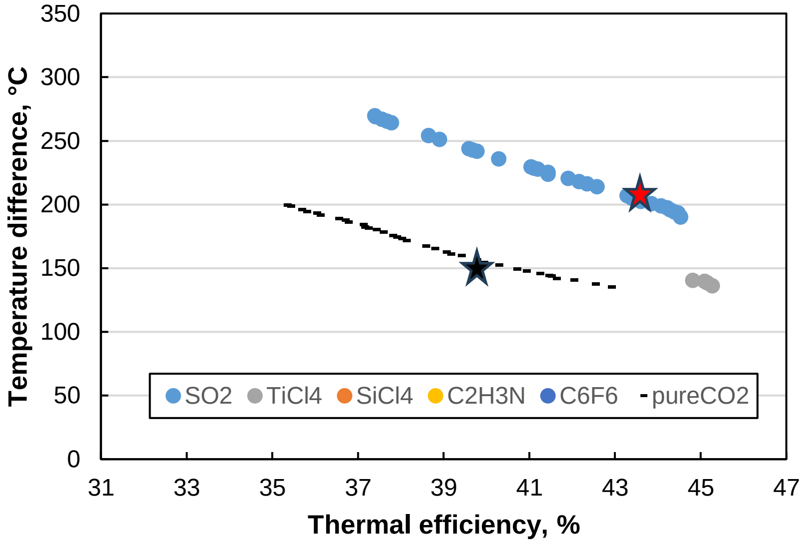
550 °C



Simple Recuperated



Precompression



Recompression

Standard weightage: 50% η – 50% ΔT

Method: TOPSIS L_∞

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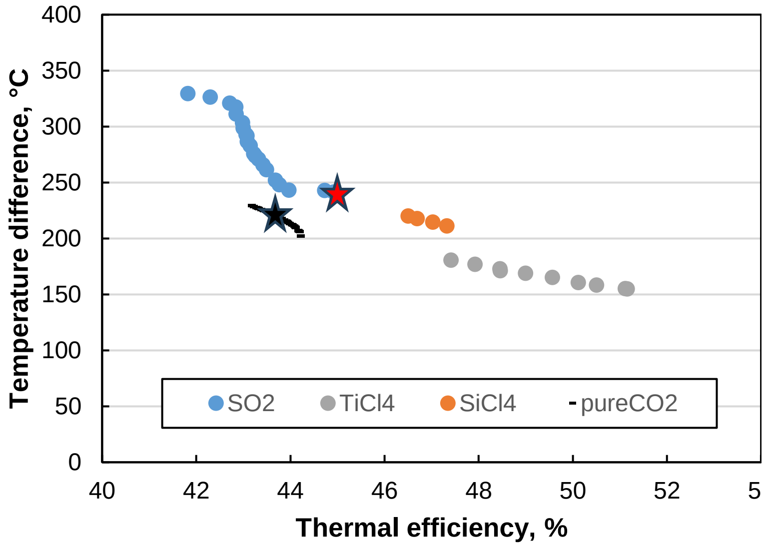
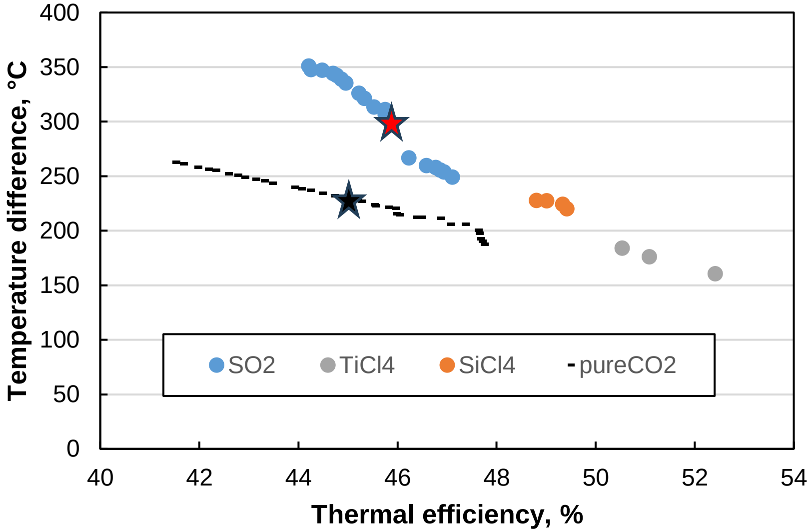
Multi-creteria Decision Making (MCDM)

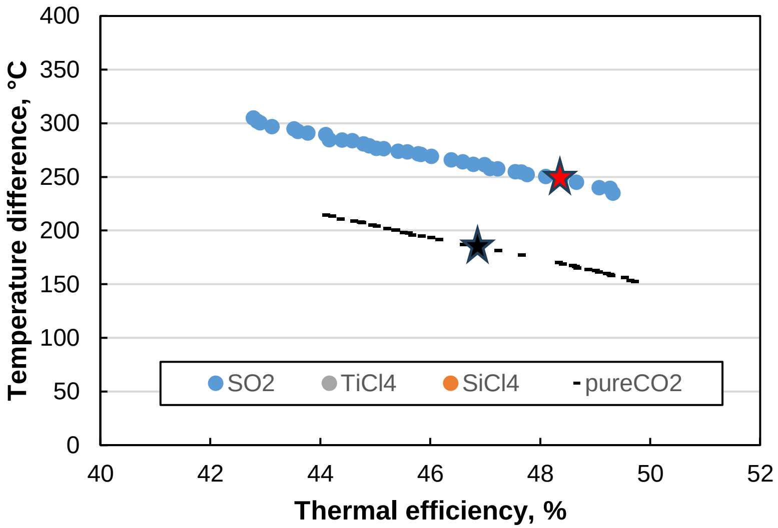
700 °C



Simple Recuperated



Precompression



Recompression

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Selected solutions and improvements

Blend cycles

Blend cycles	T_{max}	Dopant	Molar CO_2	P_{min} (bar)	PR	Split Ratio	η_{th}	ΔT	*ω* (kJ/kg)	*capex* ($/kWe)
Simple Recuperated	550°C	SO_2	82.0%	79.3	-	-	38.0%	231.9	106.9	522.2
	700°C	SO_2	85.0%	71.3	-	-	44.9%	241.4	131.1	581.4
Precompression	550°C	SO_2	77.6%	59.9	1.45	-	40.4%	231.0	111.4	624.6
	700°C	SO_2	71.9%	63.0	1.39	-	46.6%	259.6	139.9	670.9
Recompression	550°C	SO_2	67.4%	66.7	-	39.7%	44.2%	197.4	102.0	613.0
	700°C	SO_2	66.7%	66.2	-	29.6%	48.3%	248.2	138.0	646.0

%η_{th}	%ΔT	%*ω*	%*PBcapex*
4%	23%	24%	-16%
3%	8%	7%	-14%
2%	24%	22%	-6%
3%	14%	8%	-7%
12%	23%	28%	-10%
4%	36%	4%	-13%

sCO2 cycles

sCO2 cycles	T_{max}	Dopant	Molar CO_2	P_{min} (bar)	PR	Split Ratio	η_{th}	ΔT	*ω* (kJ/kg)	*capex* ($/kWe)
Simple Recuperated	550°C	SO_2	100.0%	74.0	-	-	36.6%	188.5	86.2	624.7
	700°C	SO_2	100.0%	64.1	-	-	43.4%	223.4	122.4	672.9
Precompression	550°C	SO_2	100.0%	72.1	1.26	-	39.6%	185.6	91.6	663.3
	700°C	SO_2	100.0%	55.1	1.22	-	45.2%	227.0	129.2	721.4
Recompression	550°C	SO_2	100.0%	93.0	-	20.0%	39.3%	161.0	80.0	679.0
	700°C	SO_2	100.0%	93.0	-	13.2%	46.5%	183.0	132.2	740.0

Conclusions

- A list of dopants (5) can be explored for technoeconomic performance for predefined layouts,t/c (3)
- Automated optimisation per layout with realistic conditions
- Multi-creteria Decision Making (MCDM) for two competing objectives, TES/HTF agnostic
- CO_2-SO_2 mixture dominating all temperature levels and cycle layouts
- ~20% decrease in PB CAPEX & TES costs for same or more efficiency

Shortcomings:

- Material compatibility and operational challanges
- Uncertainities in cost estimations for power block components

Thank You
For Your Attention

Any Questions?



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