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Towards, Competitive, Reliable, Safe and Sustainable Concentrated Solar Power (CSP) Plants

Midterm meeting REA, 18-19 April 2024

Supercritical CO_2 cycles for the next generation of CSP plants

PhD student: Vladimir Naumov

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ERGO, TESPS PhD, DIMI, UNIBS

ERGO Energy Technology Group

UNIVERSITY OF BRESCIA

About me

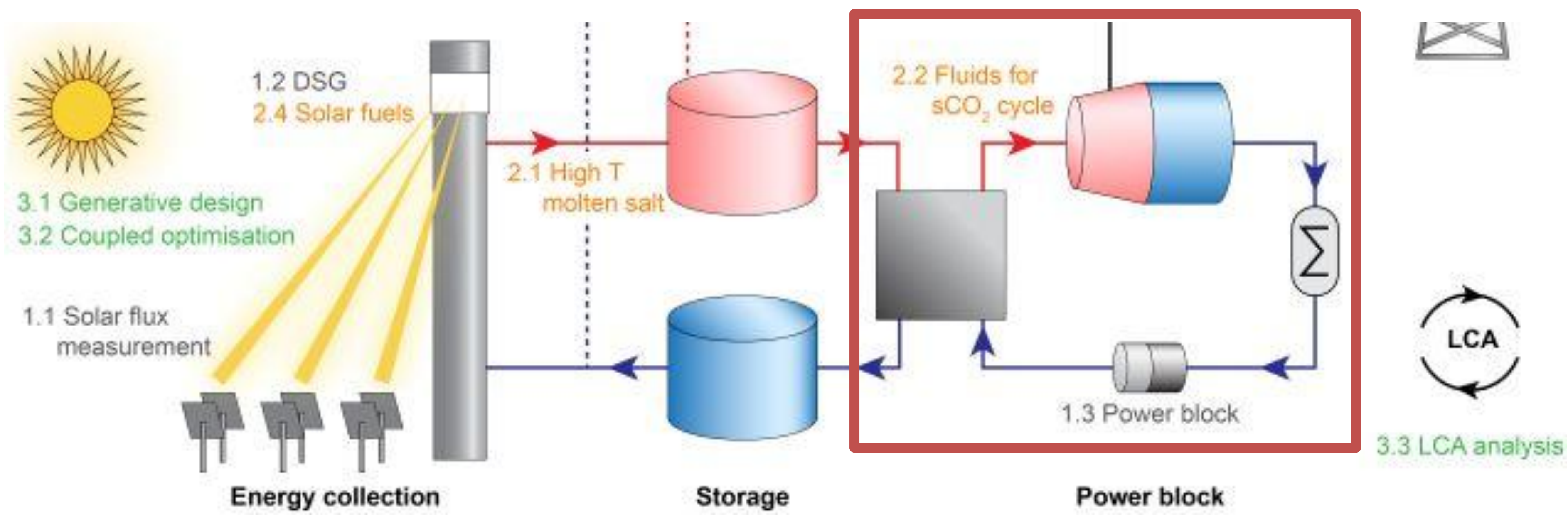
- Bachelor's and Master's degrees in Thermal power and Heat engineering from Moscow Power Engineering Institute (NRU MPEI).
- Worked as engineer/research assistant at NRU MPEI, focusing on perspective power cycles and their equipment.
- Co-author of several papers regarding power cycles.
- 2nd year PhD student at UNIBS

Task 2.2 (DC5): Supercritical CO_2 cycles for the next generation of CSP plants

Objective: Development of a sCO_2 power cycle model that works with modified working fluids (CO_2 with additives in a limited quantity) with a higher efficiency and lower cost compared with a state-of-the-art solar tower technology.

Expected Results: Assessment of advanced working fluids that can be employed in the sCO_2 cycles supported and the identification of the optimal power cycle configuration.

A power cycle model will be developed to determine the thermal to power conversion efficiency supported by both theoretical and experimental activities to assess: (i) the thermodynamic properties of sCO_2 mixtures and (ii) the maximum operating temperature through fluid thermal stability and material corrosion compatibility tests. In this manner, the most promising next generation power cycle configurations for CSP applications will be identified.



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Planned secondments

Task	2024												2025											
	gen-24	feb-24	mar-24	apr-24	mag-24	giu-24	lug-24	ago-24	set-24	ott-24	nov-24	dic-24	gen-25	feb-25	mar-25	apr-25	mag-25	giu-25	lug-25	ago-25	set-25	ott-25	nov-25	dic-25
CSP model																								
Cycle model																								
New fluids search																								
Heat exchangers			B&R design						B&R experiment															
Turbinens/pipes						RWTH																		
Economic evaluation																								

- At Brembana&Rolle S.P.A.:
  - First phase (11.03.2024 – 06.04.2024). Training in thermal and mechanical design of heat exchangers and EMbaffle technology for applications molten salts-sCO_2. Preparation of SolarPACES 2024 abstract.
  - Second phase (16.09.2024 – 12.12.2024). Participation in experimental tests and drafting of reports.
- At RWTH Aachen University (01.06.2024-30.08.2024):
  - Preliminary design and sizing of the main equipment for the sCO_2 mixture power cycle including piping.
  - Comparison of material use and associated cost estimation for steam and sCO_2 mixtures power cycles.
  - Review of simplified off-design modeling approaches presented in the literature for sCO_2, CO_2 mixtures, and steam turbines.
  - Preliminary calculation of CO_2 mixture turbine off-design performance.

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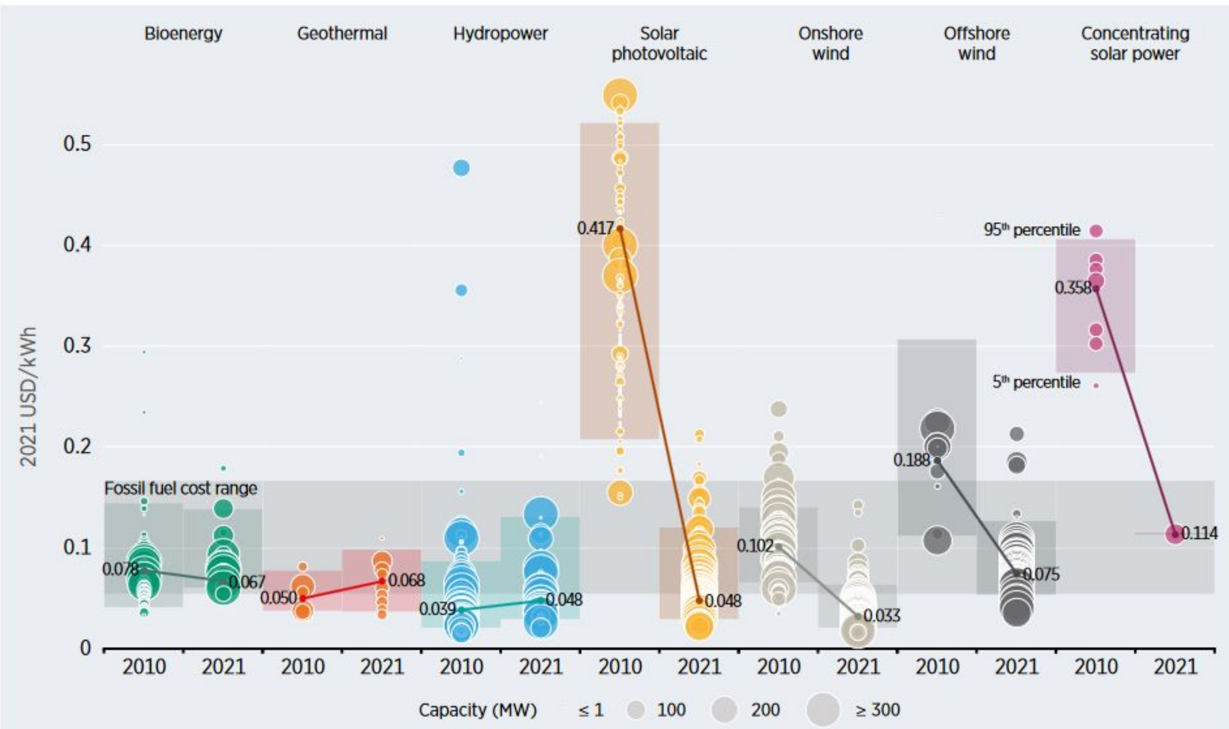
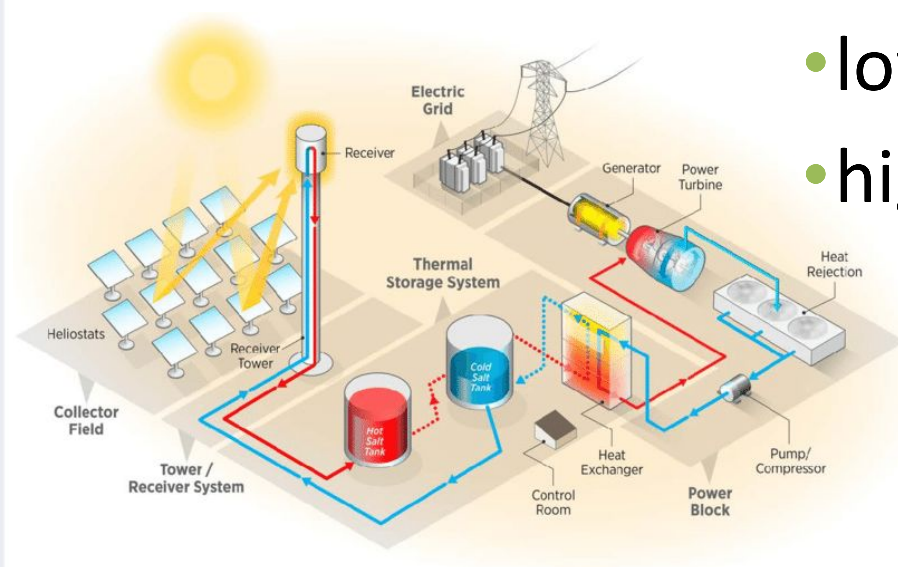
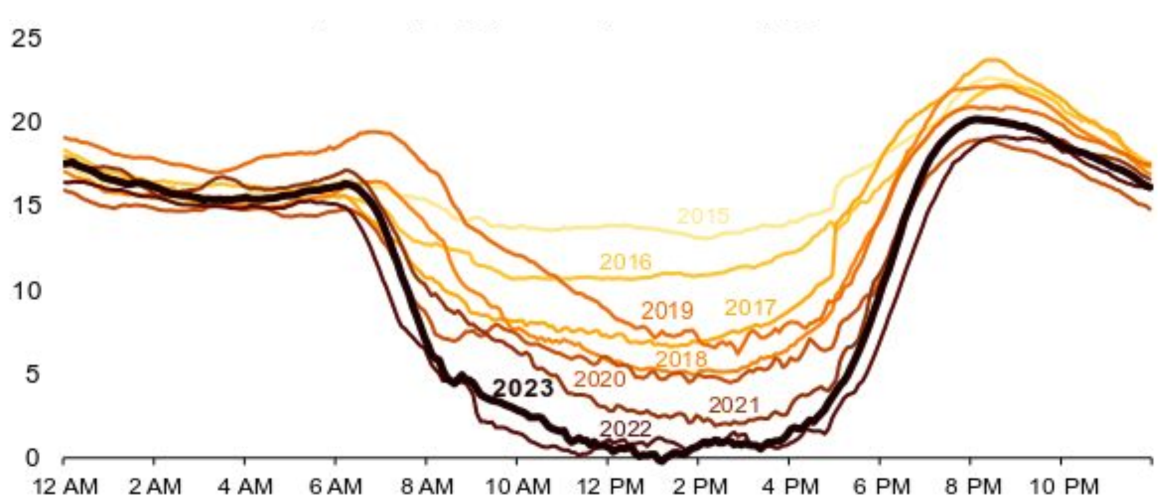
Concentrated Solar Power (CSP)





- CSP plant with sCO_2 mixture and TES
  - lower LCOE
  - higher dispatchability



CSP has higher LCOE but can use efficient TES to balance the power system

Renewable power generation costs in 2021, IRENA, 2022
As solar capacity grows, duck curves are getting deeper in California, EIA, 2023
Mehos, Mark, et al. Concentrating solar power Gen3 demonstration roadmap. NREL, 2017

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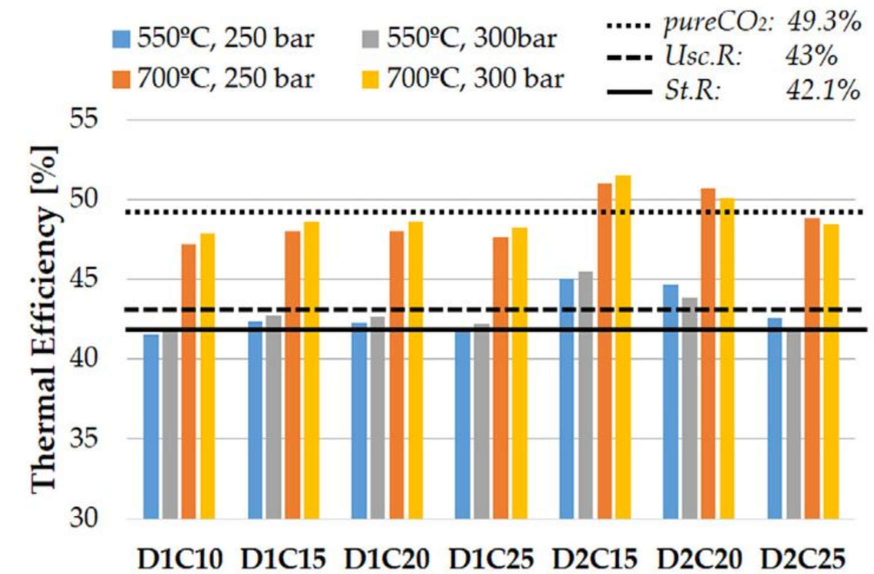
Cycles with CO_2 mixtures

- sCO_2 has higher efficiency than steam at high TIT.
- CO_2 blends allow for higher T_{cr} and use of simpler (regenerated) cycle with high temperature (air-cooled) condensation and higher efficiency.

Blend	Composition [% molar]
D1C10	CO_2–C_6F_6 [90–10]
D1C15	CO_2–C_6F_6 [85–15]
D1C20	CO_2–C_6F_6 [80–20]
D1C25	CO_2–C_6F_6 [75–25]
D2C15	CO_2–$TiCl_4$ [85–15]
D2C20	CO_2–$TiCl_4$ [80–20]
D2C25	CO_2–$TiCl_4$ [75–25]



	MW [kg/kmol]	T_{cr} [°C]	P_{cr} [bar]	Molecular complexity [–]	Thermal Stability
CO_2	44.01	31.06	73.83	–9.324	>700°C[28]
SO_2	64.06	157.60	78.84	–8.230	>700°C[28]
C_6F_6	186.06	243.58	32.73	12.740	up to 625°C[a]
$TiCl_4$	189.69	364.85	46.61	1.922	up to 700°C[33]

However at high T most of dopants decompose.

Two pathways forward

1. Combined cycle with sCO_2 used in low-temperature part of the cycle.

2. Find new dopants with better stability, high critical parameters, and low toxicity/flammability/GWP/ODP etc.

Crespi, Francesco, et al. "Preliminary investigation on the adoption of CO2-SO2 working mixtures in a transcritical Recompression cycle." Applied Thermal Engineering 211 (2022): 118384.
Crespi, F., et al. "Thermal efficiency gains enabled by using CO2 mixtures in supercritical power cycles." Energy 238 (2022): 121899.

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1. Combined cycle with sCO_2 used in low-temperature part of the cycle

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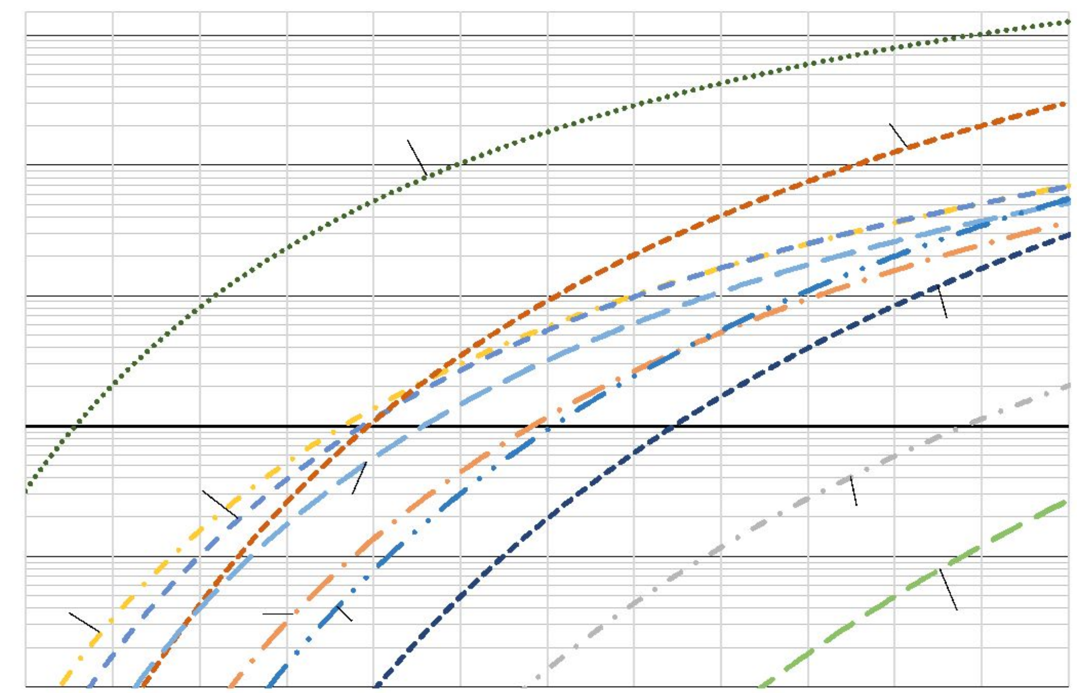
Topping cycle working fluid

For high temperature power cycle two possibilities:

Ideal gas cycle using He, Ar etc. (low efficiencies, low specific power).

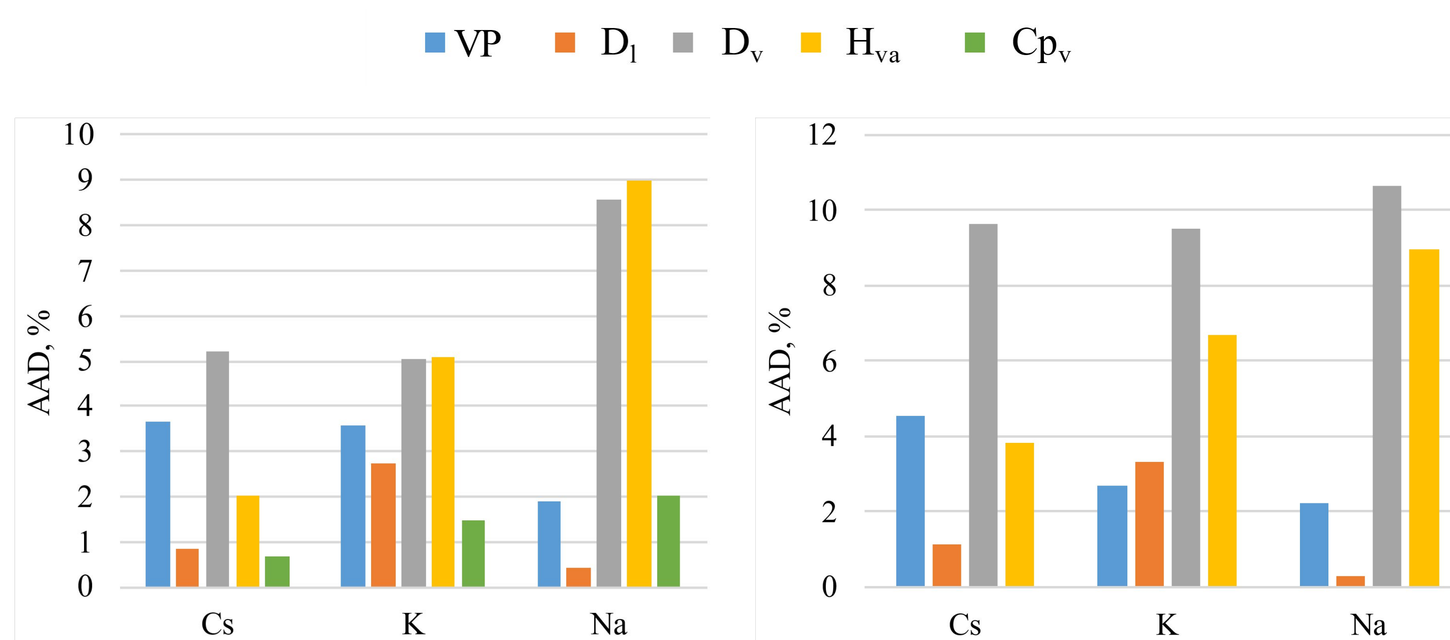
Metal Rankine cycle (higher efficiency, intensified heat transfer).



Most promising: Cesium (Cs), Potassium (K), Sodium (Na).

The Equation of State (SRK EoS with Twu alpha function and Rackett equation) was verified against literature:

- temperatures and pressure <4%,
- condenser, evaporator, and turbine power <8%,
- cycle efficiency <1%.



Comparison with Vargaftik

Comparison with Reynolds

Sun, Qi-qi, et al. "Thermodynamic analysis of potassium Rankine cycle in space nuclear power by energy analysis and exergy analysis." Energy 273 (2023): 127241.

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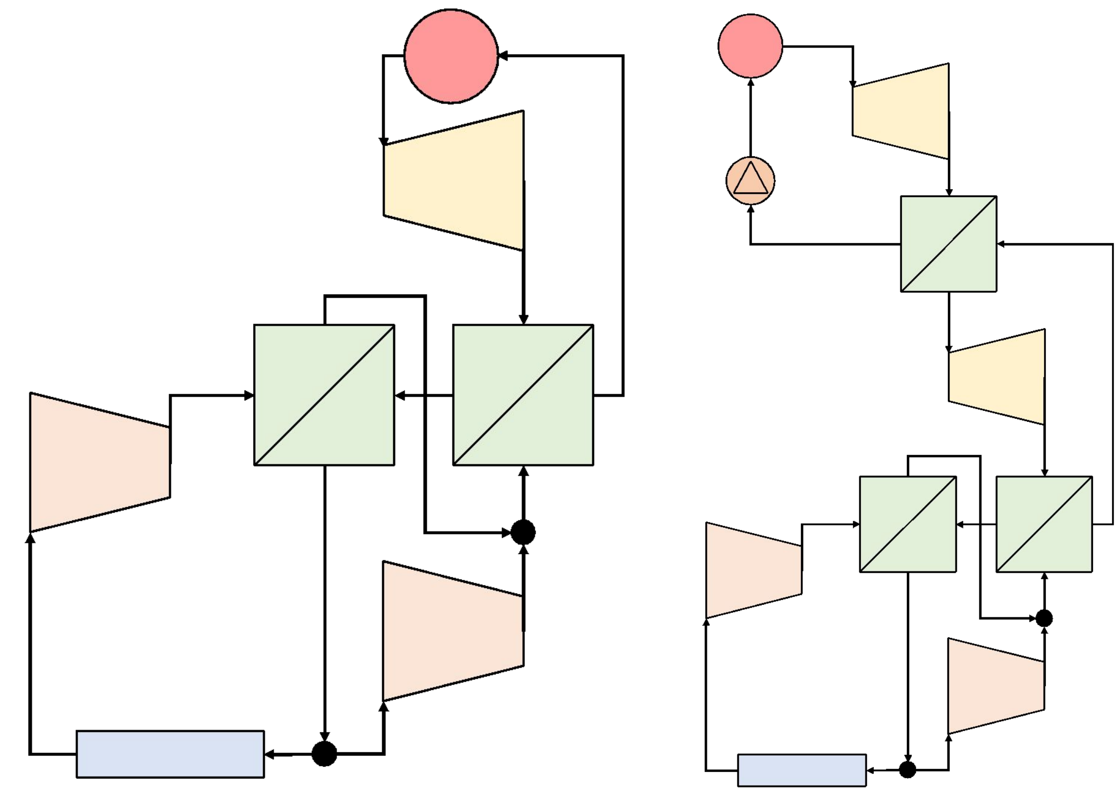
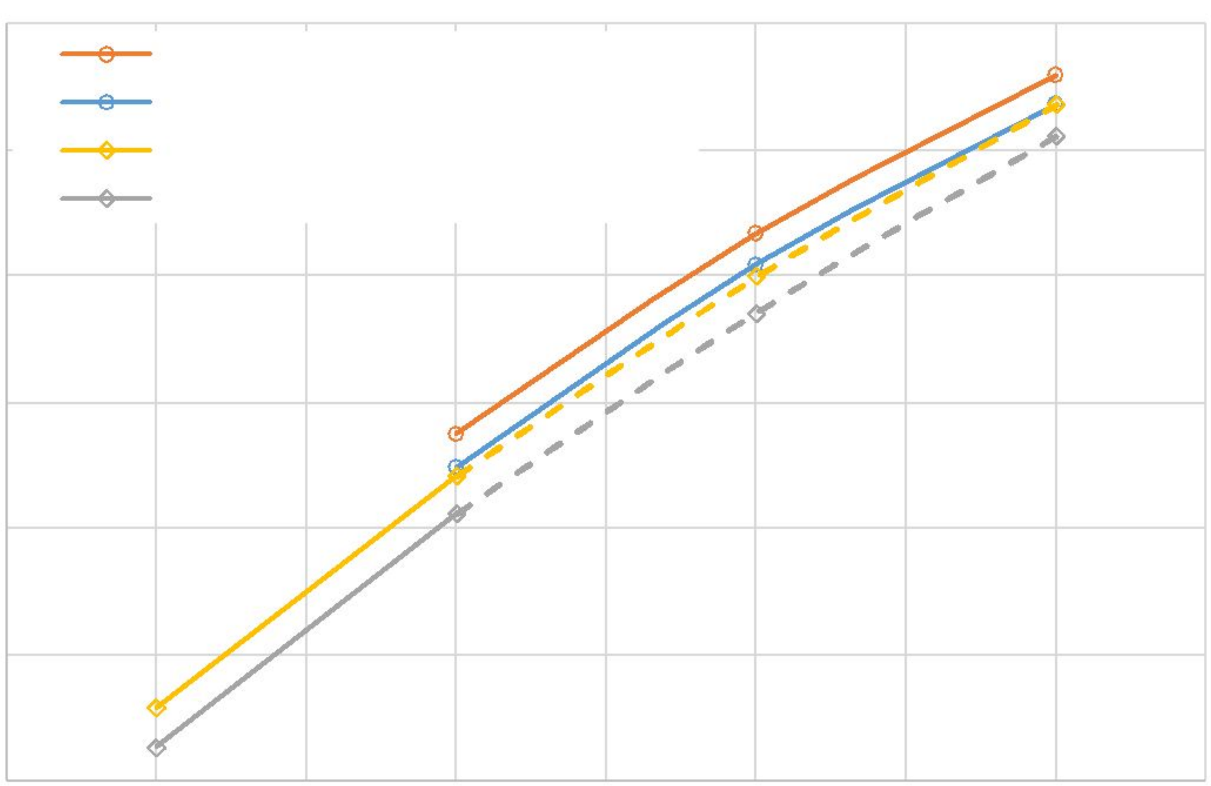
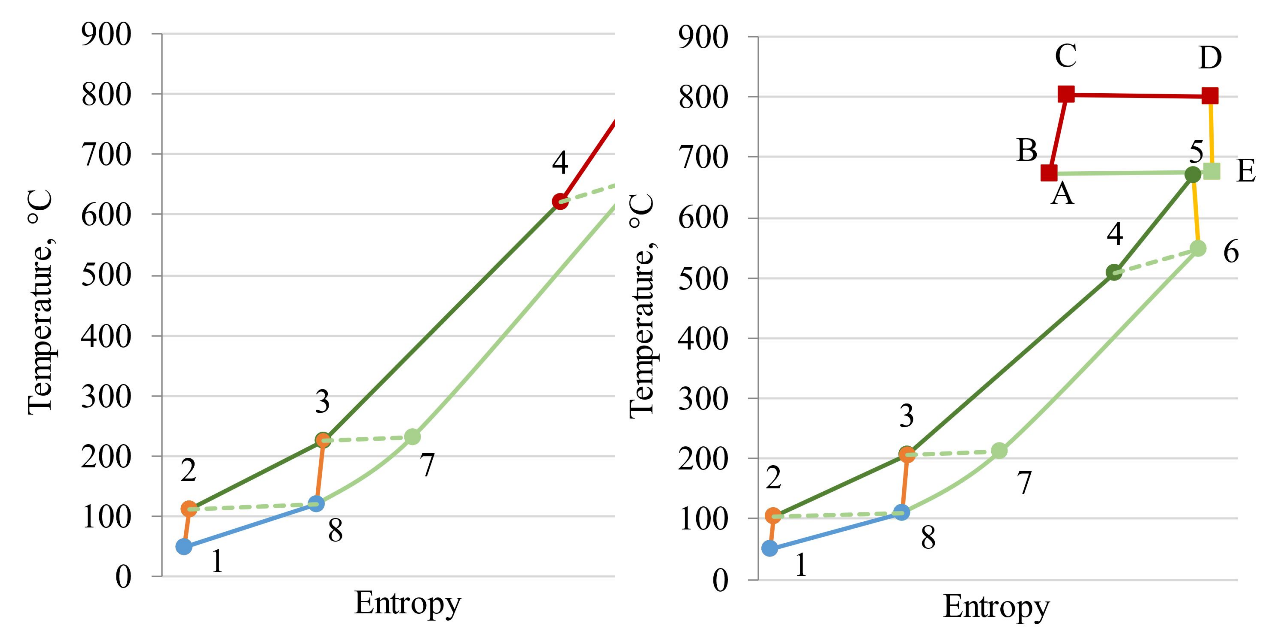
Combined and sCO_2 recompressed cycles comparison

- At 800°C TIT alkali metal turbine exhaust vapor fraction is 95%, at 900°C TIT – 92.3% and at 1000°C – 89.8%.
- Combined cycle thermal efficiency with 300 bar maximum pressure is 53.50% at 800°C, 56.68% at 900°C and 59.19% at 1000°C TIT, while for the recompression cycle, it is 52.83% at 800°C, 56.01% at 900°C and 58.74% at 1000°C TIT.







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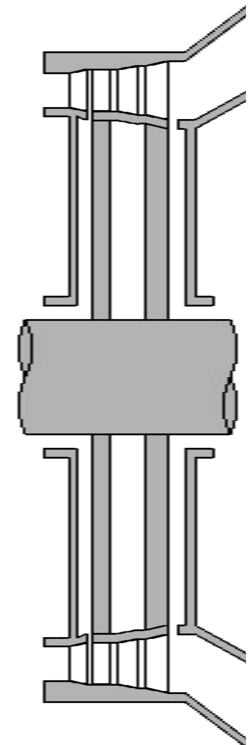
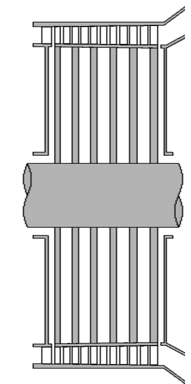
Equipment preliminary designs

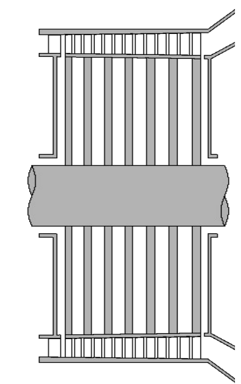
Cycle	Parameter	Combined cycle	Recompression cycle
Cs turbine	Number of stages	2	-
	Mean diameter, m	2.36	-
	Axial length, m	0.41	-
	Alloy	740H	-
sCO_2 turbine	Number of stages	6	7
	Mean diameter, m	1.06	1.07
	Axial length, m	0.36	0.53
	Alloy	709	740H
Cs-sCO_2 heat exchanger	Area, m^2	1617.4	-
	Alloy	709/316H	-
HTR	UA, MW/K	20.55	19.73
	Alloy	316	709
LTR	UA, MW/K	14.96	14.41
	Alloy	VM12	VM12



Cs turbine

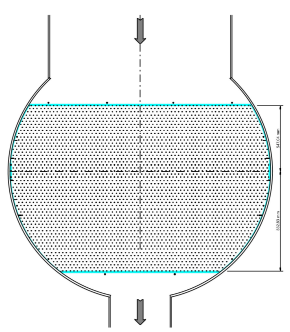


CO_2 bottoming turbine



CO_2 recompression turbine

Cs-sCO_2 heat exchanger



- It is possible to design a combined cycle with 900°C TIT from the same materials as 800°C TIT which means similar cost and designs of equipment (the topping cycle is only several bar).
- For recompression cycle nickel-based alloys have a limit of around 800°C due to sCO_2 corrosion, while high maximum pressures mean a more complex design and thicker walls of all equipment, which leads to higher material use and cost.
- This leads to the efficiency of the recompression sCO_2 cycle at 52.8% at 800°C TIT and combined cycle one at 56.8% at 900°C TIT.
- Furthermore, it might be possible to use austenitic or even stainless steel alloys in the primary heater and turbine of metal cycle at 800 and 900°C TIT, which will significantly reduce the equipment cost.

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2. New dopants for CSP power cycle CO_2 blends

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New dopant search methodology

Criteria for new dopants:

- Thermal stability at high temperature (550-700 °C)
- High critical temperature > 100°C

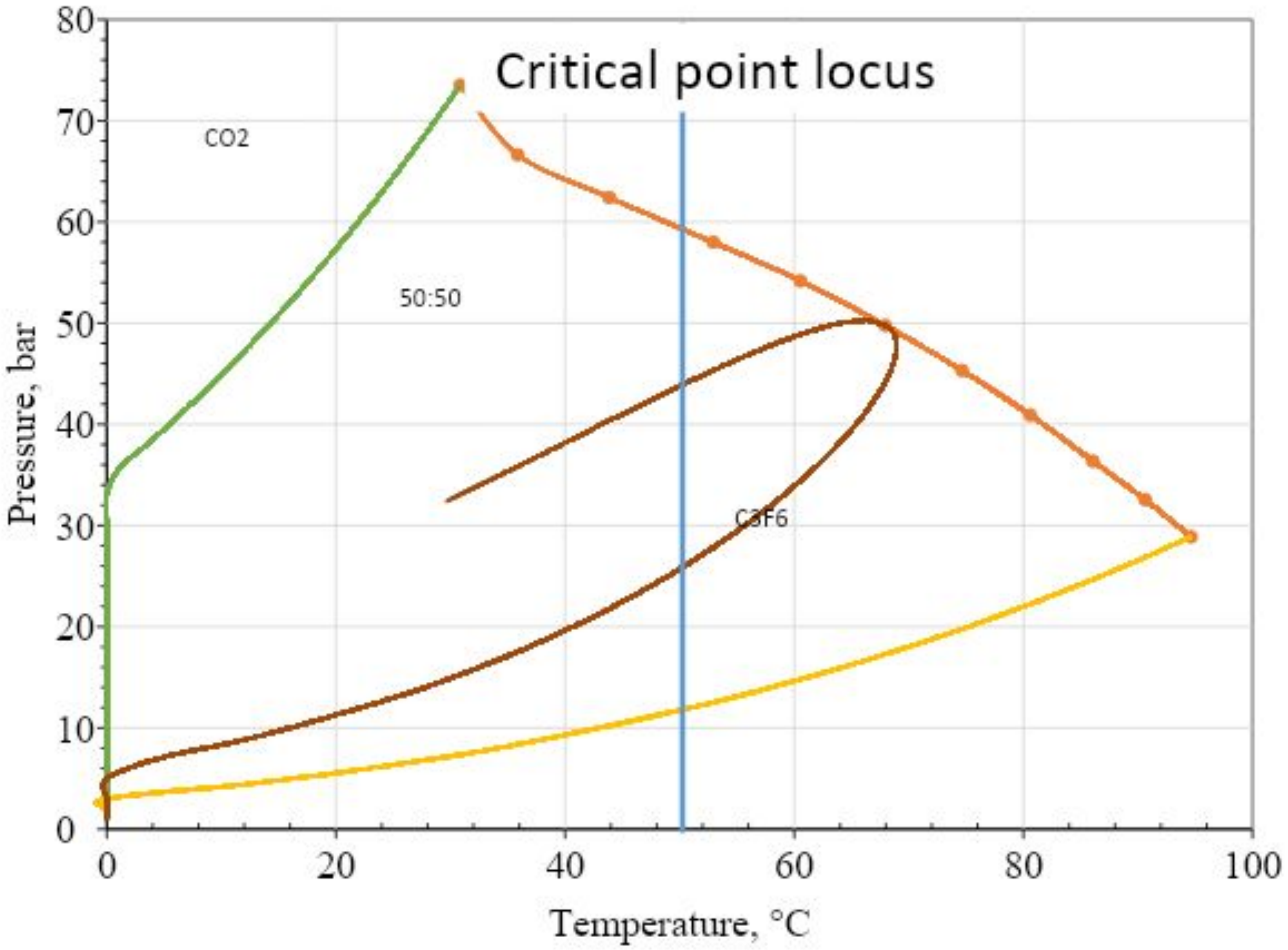
Other characteristics:

- Melting point < T ambient

(avoiding pipes clogging at ambient temperatures)

- Solubility with CO_2
- High molecular complexity

(Minimizing heat capacity differences between the two sides of the recuperator)



*The main **potential candidates** can be found in the groups of (i) perfluorocarbons, (ii) sulfur compounds, (iii) mineral acids as well as (iv) metal halides.*

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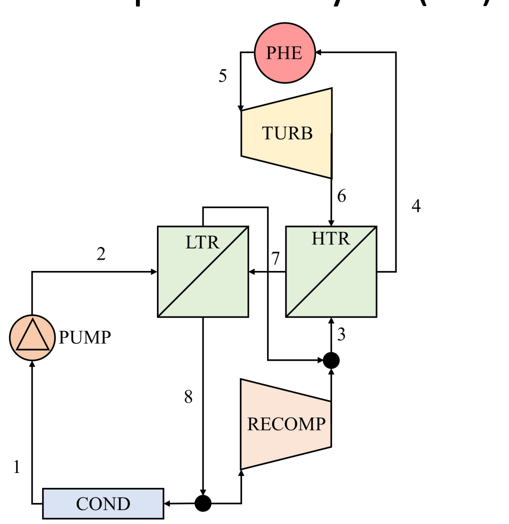
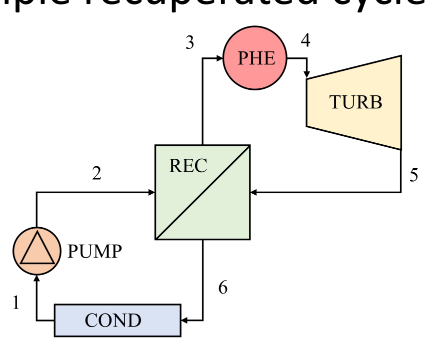
New dopant search

Formula	CAS	Status	T_{melt}, °C	T_{boil}, °C	T_{cr}, °C	P_{cr}, °C	Safety data (NFPA 704)			GWP	ODP	CO_2 mixture data	T_{limit}, °C
							Health	Flammability	Reactivity				
C_3F_6	116-15-4	Is not thermally stable	49	56	94.9	29	2	0	0	17 340	0	yes	<400
$c\text{-}C_4F_8$	115-25-3	Experiments are carried out	-40	-6	115.0	27.7	1	0	0	10 300	0	no	550 assumed in literature
$SiBr_4$	7789-66-4	Very reactive	5	153	383.0	-	3	0	2-w	0	0	no	No
$GeCl_4$	773-14-8	Under consideration	-49.5	86.5	280	38.6	3	0	2-w	0	0	no	>400
$SiCl_4$	10026-04-7	Was not considered for CSP	-69	58	233.9	35.9	3	0	2-w	0	0	yes	650 in stainless steel

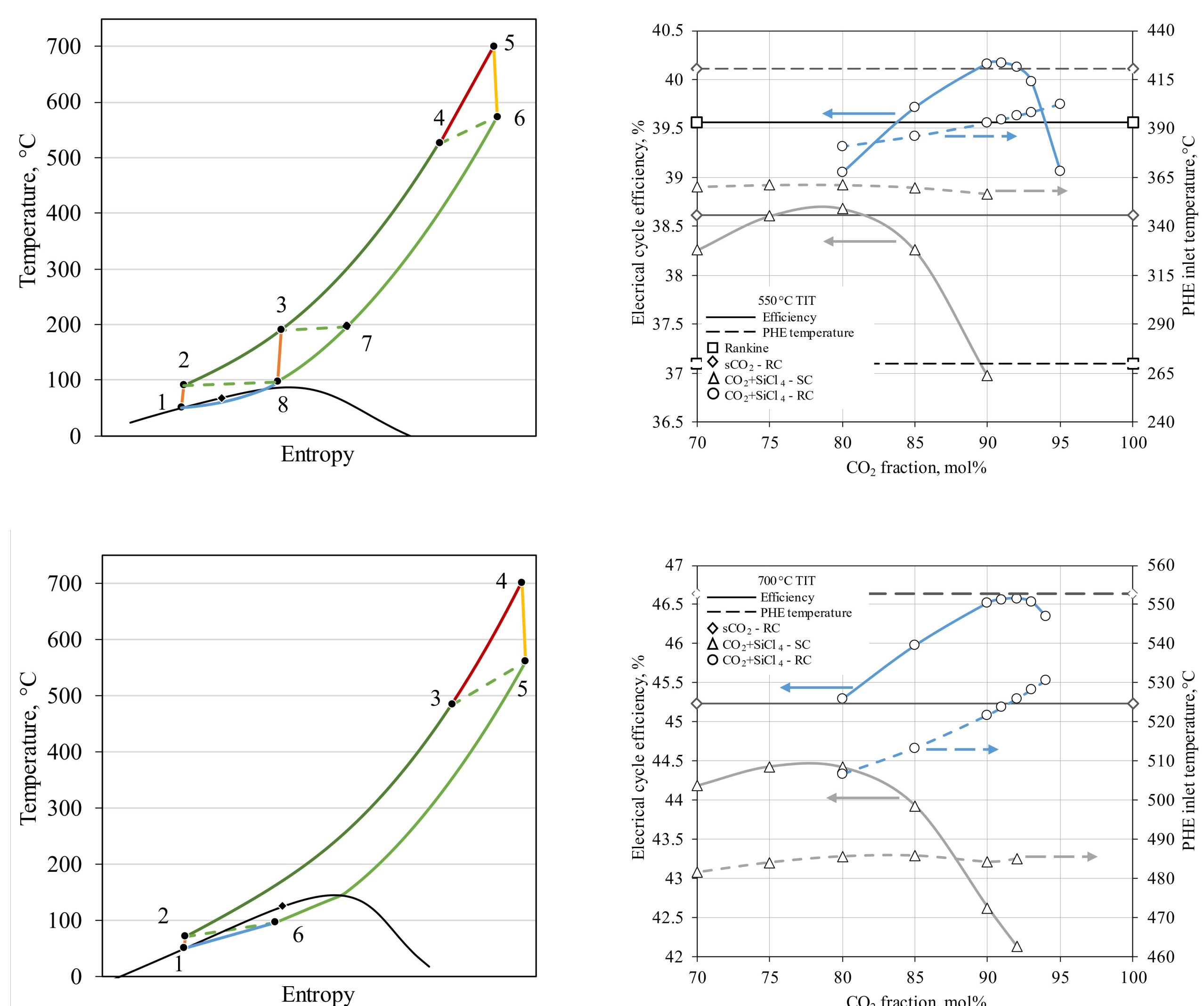
Recompression cycle (RC)



Simple recuperated cycle (CS)



$SiCl_4 + CO_2$ mixture for CSP



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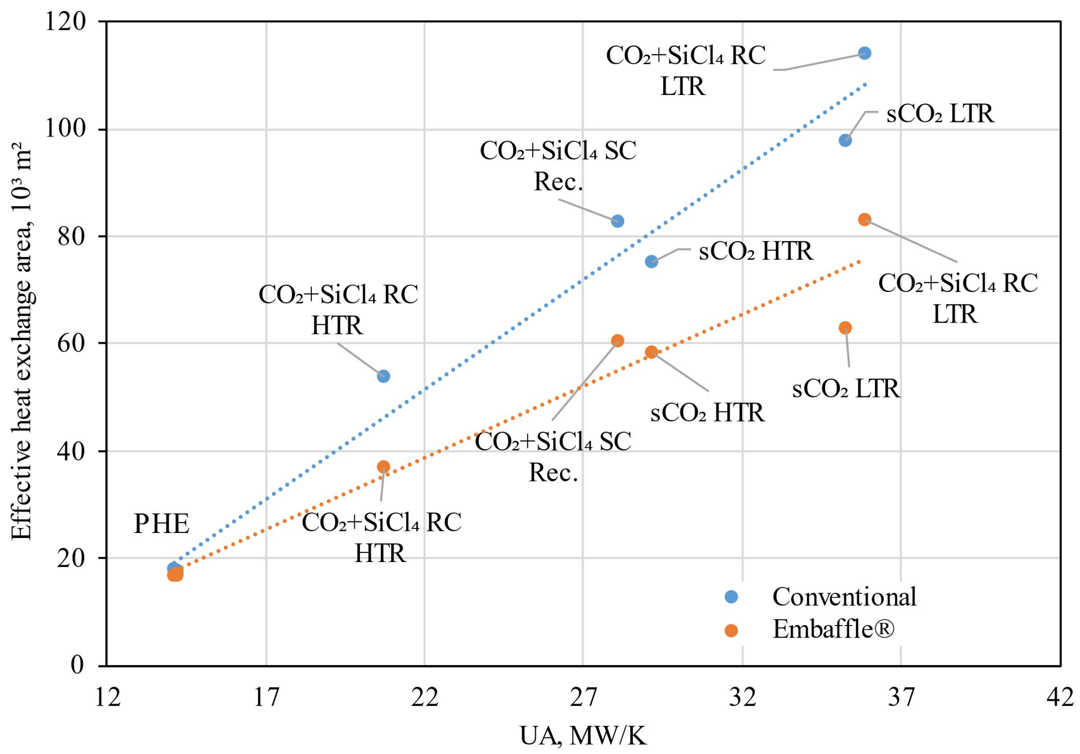
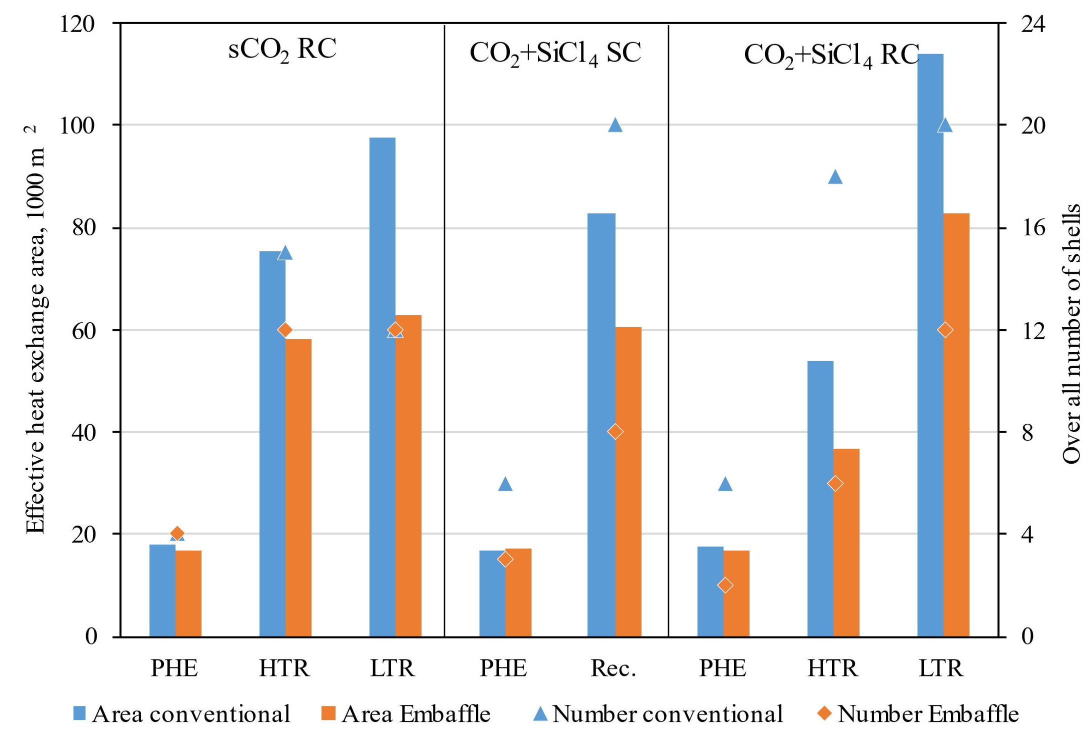
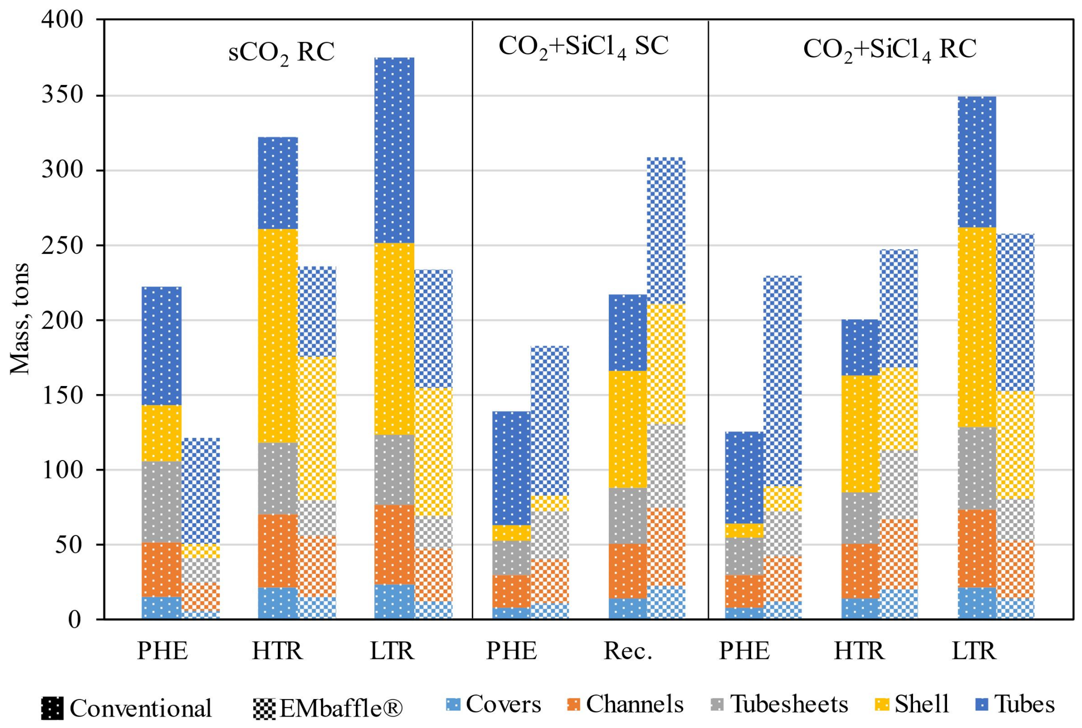
B&R secondment: Shell and Tube Heat Exchangers for CO_2 and $SiCl_4$ + CO_2 mixture for CSP



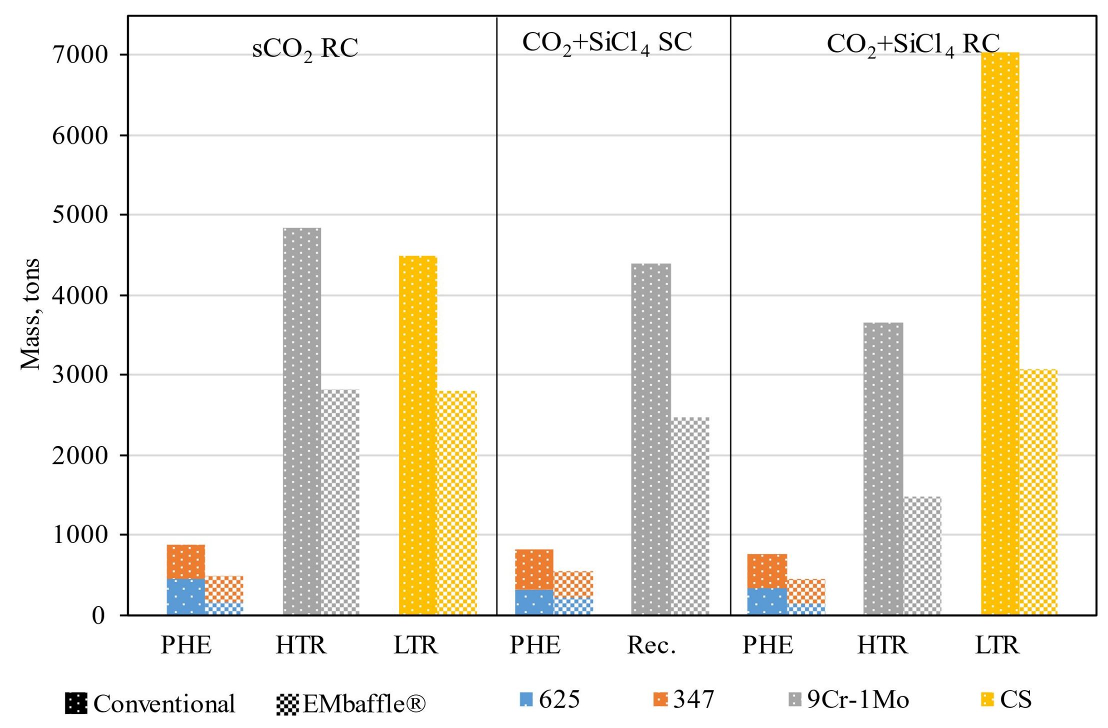
Thermal design



Mechanical design



Material use



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3. CSP modeling

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CSP model structure

Sunpos (Python)
- Sun Elevation, Azimuth

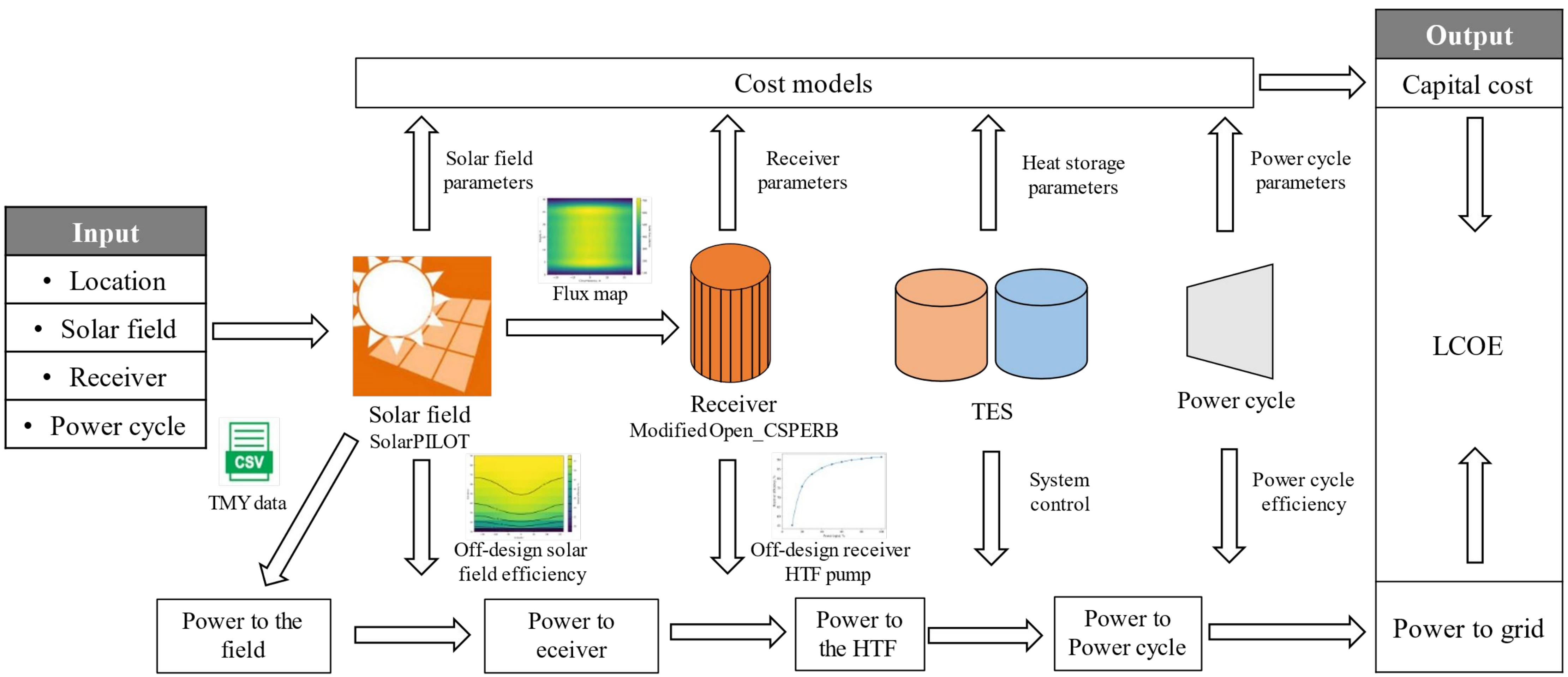
SolarPilot
- Solar field
- Field efficiency map
- Flux map

Receiver model (Asselineau, ANU in Python) + Pump power (Python)
- Receiver efficiency map
- Pump power map

TES model (Python)
- Power to cycle
- Power to storage
- HTF to cycle pump power
- Heat loss

Power unit
- Elctricity produced annualy
- Capacity factor

Economic evaluation
- Capital cost
- LCOE



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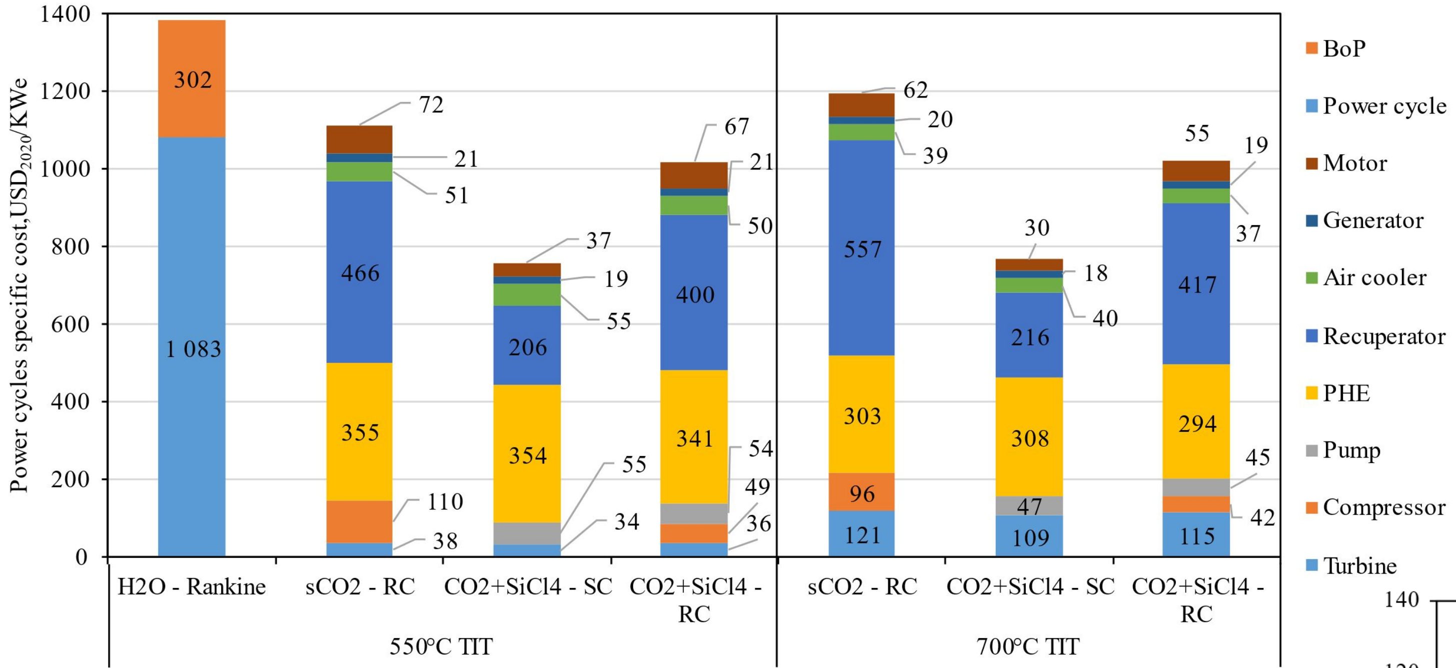
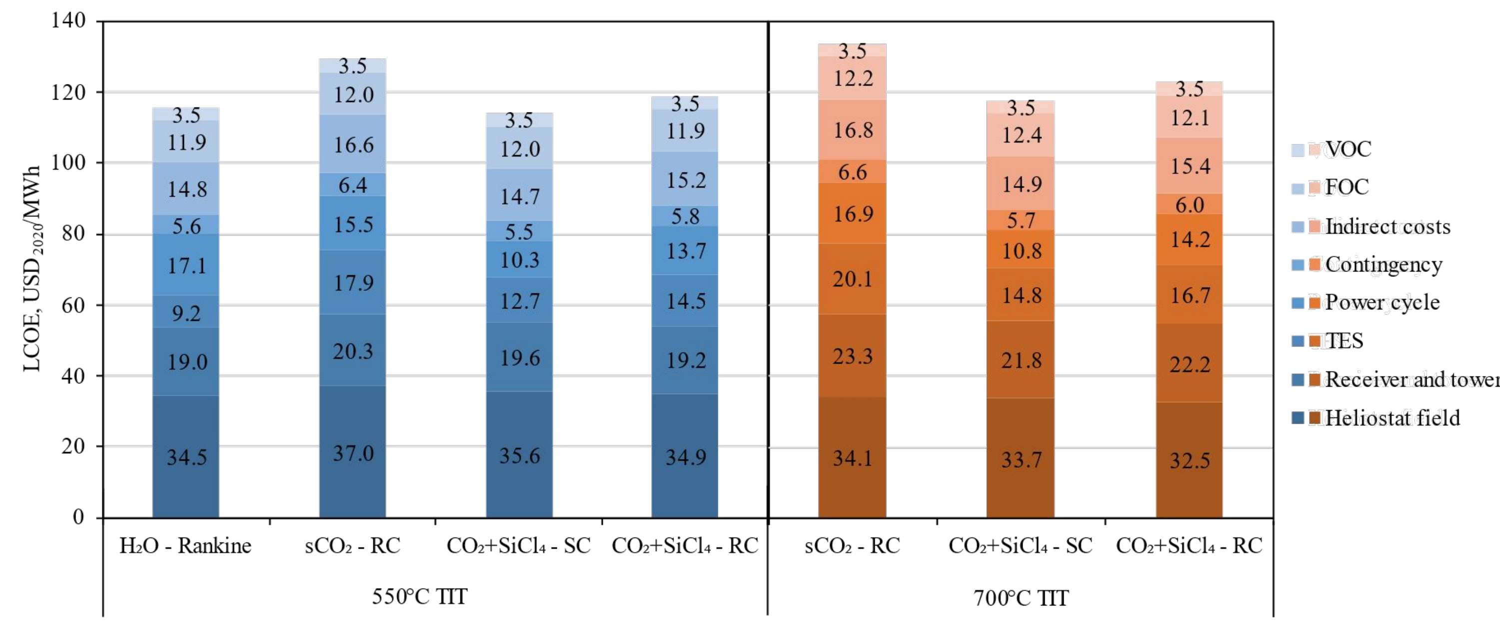
SiCl$_4$ + CO$_2$ mixture for CSP





- Lowest power cycle specific cost = simple cycle
- Mixture cycle = higher efficiency, lower PHE inlet temperature, and higher electricity output
- Higher efficiency of the cycle doesn't guarantee the higher efficiency of CSP due to the higher temperature at the PHE receiver inlet and lower receiver efficiency
- The lowest LCOE is obtained by the simple cycle due to the lower cost of the power cycle and TES.

Power cycle efficiency optimization might be detrimental to CSP performance

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Supercritical CO_2 cycles for the next generation of CSP plants

Vladimir Naumov

The Energy Technology Group (ERGO), PhD program in Energy Transition and Sustainable Production Systems (TESPS), DIMI, UNIBS

Courses and Seminars

Title	Sede e durata/venue and dates	Ore/h
Control of solar energy systems, Prof. Manuel Berenguel	UNIBS, May 31th, 2023	4
Solution of hard physical problems with MatLab, Prof. Davide Picchi	UNIBS, 10.10 -22.11.2023	20
Fuel cells for power production: from basic theory to system applications, Prof. Gioele Di Marcoberardino	UNIBS, 1.10-13.10.2023	8
1st International Summer school: Fluid dynamics for sustainable energy	Desenzano del Garda, 11.09-15.09.2023	38

Publications/Conferences

Title	Author	Journal/ Place	Published
High temperature Cesium-sCO2 combined cycle for concentrating solar power applications	Vladimir Naumov Michele Doninelli Gioele Di Marcoberardino Paolo Iora Costante Invernizzi	Solar Energy	Under review
Comparison of Shell and Tube Heat Exchangers for CO2 and CO2+SiCl4 mixtures cycles	Vladimir Naumov Marta Mantegazza Michele Doninelli Gioele Di Marcoberardino Paolo Iora Marco Rottoli	SolarPACES	In preparation

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3. B&R secondment results

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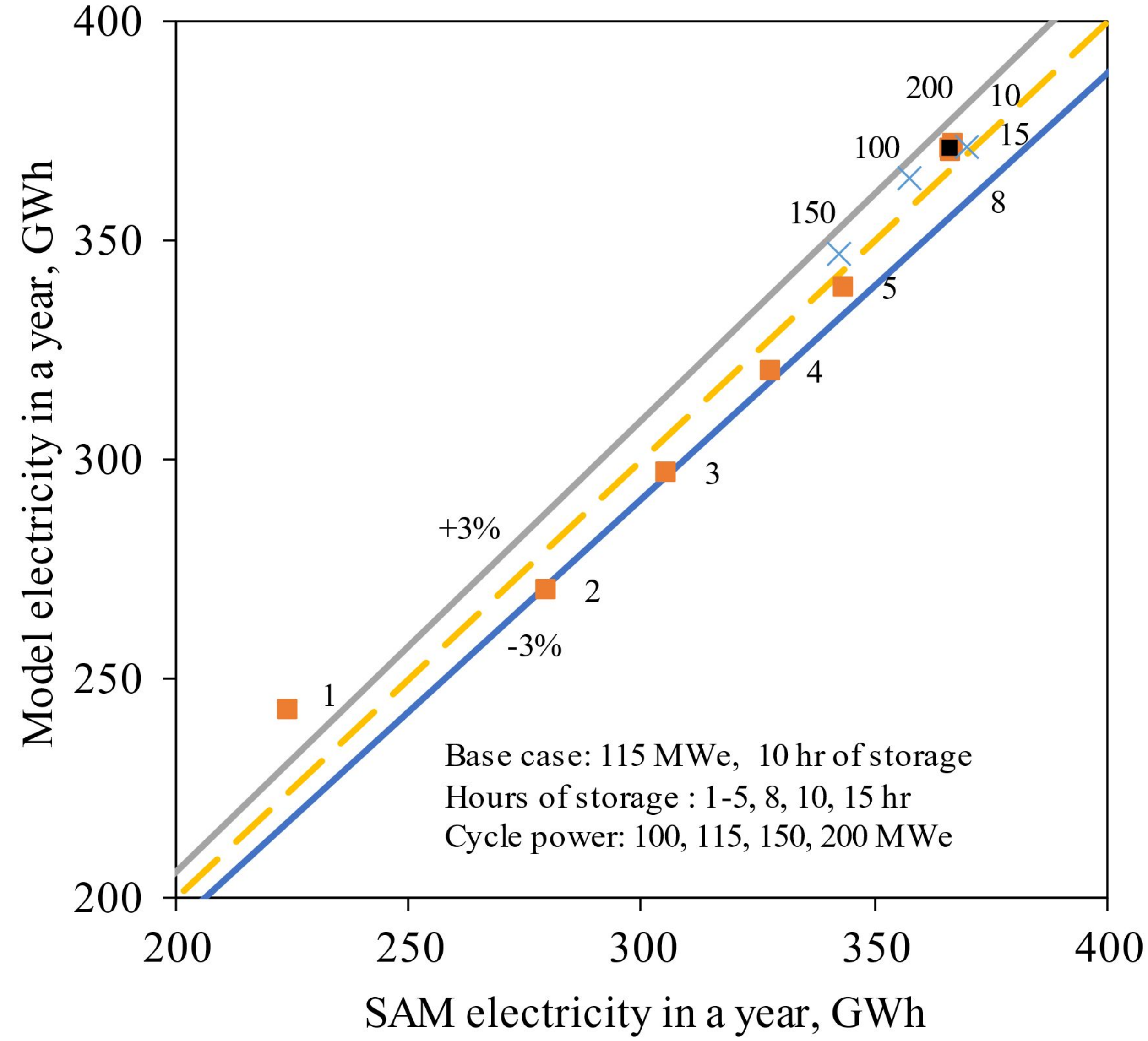
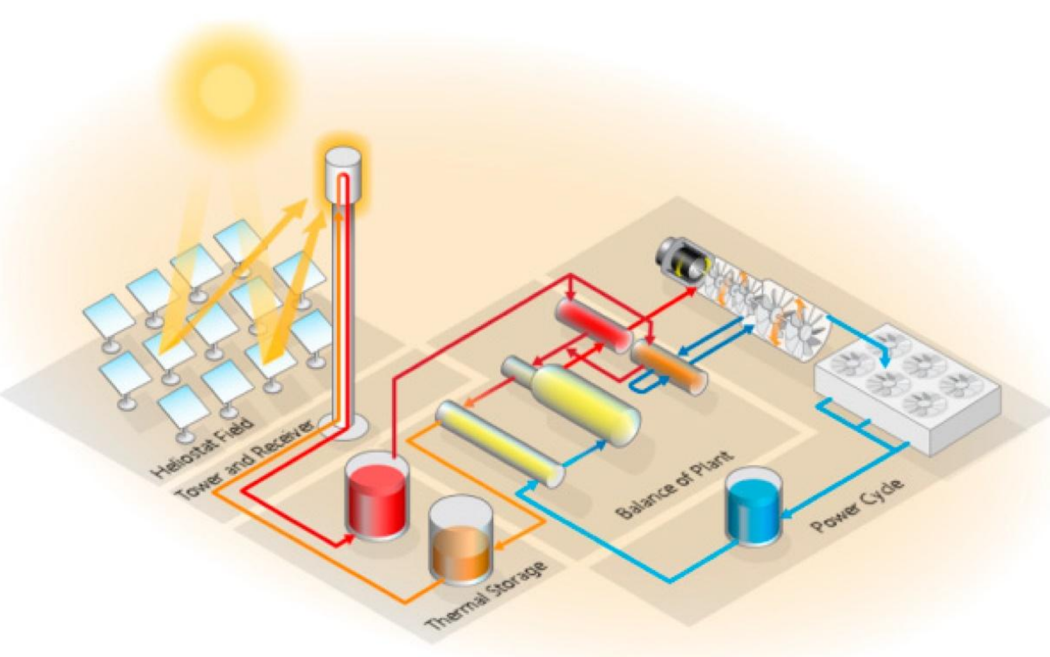
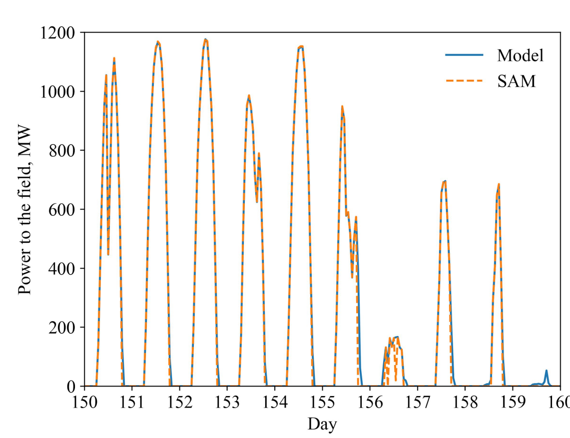
Standard CSP model verification

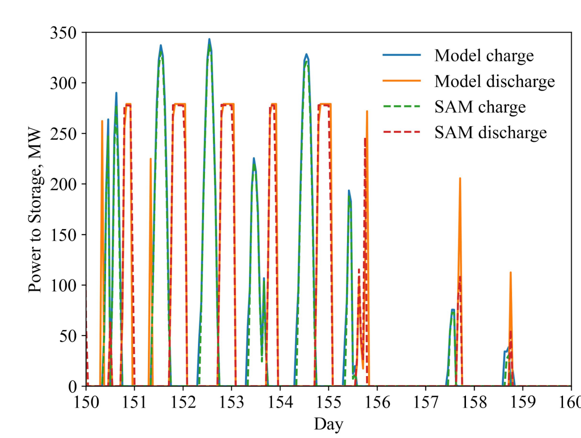
- Comparison with System Advisor Model (SAM) by NREL for standard CSP
- Solar salt as HTF and TES with steam cycle

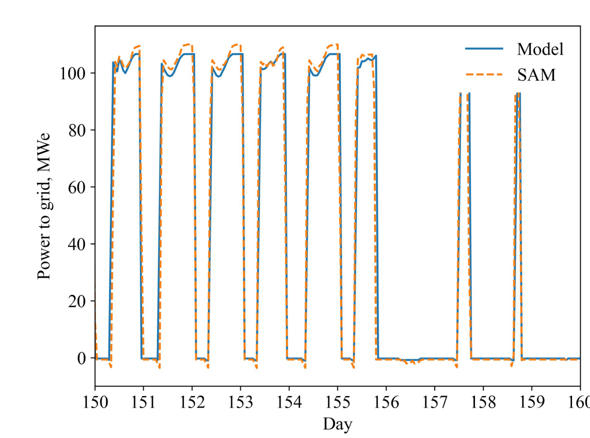
SAM is a free desktop application for techno-economic analysis of energy technologies. It is used by project managers and engineers, policy analysts, technology developers, and researchers to investigate questions about the technical, economic, and financial feasibility of renewable energy projects.











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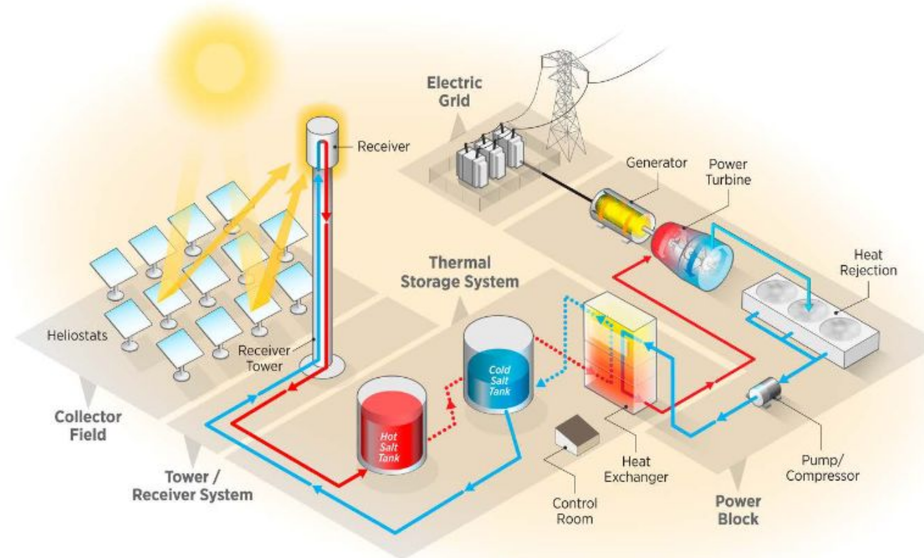
High-temperature CSP model verification

- Comparison with SAM and SolarTherm

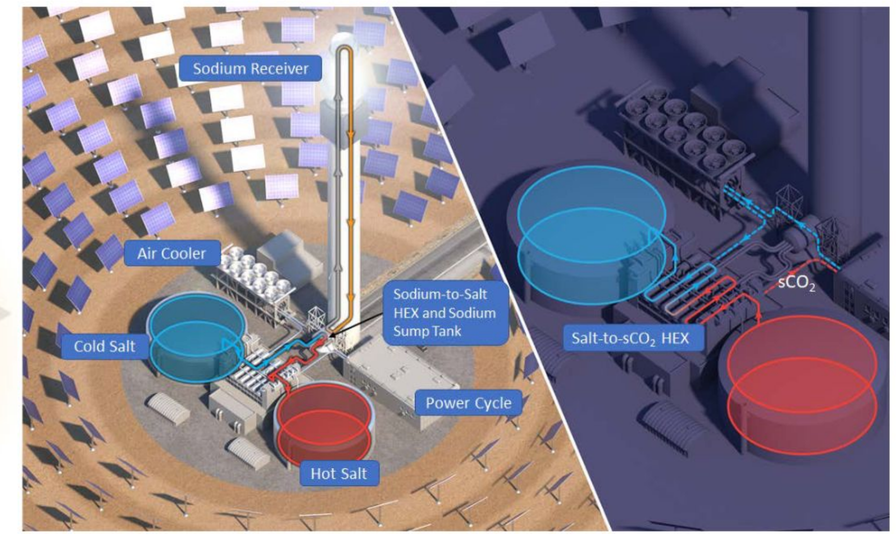
  SolarTherm is a flexible Modelica-based simulator for CSP systems developed in Australian National University (ANU)

  - Chloride salt as HTF and TES with sCO_2 cycle
  - Sodium as HTF and Chloride salt as TES with sCO_2 cycle

Chloride Salt Receiver



Sodium receiver



Parameter	Solar Salt			Chloride Salt Receiver					Sodium receiver					
	SAM	**Model**	**Diff., %**	SAM	Solar Therm	**Model**	**Diff., %**	**Diff., %**	Base case	**Model**	Diff., %	Improved case	**Model**	Diff., %
Annual solar to thermal efficiency, %	44.1	43.7	-1.0	38.4	38.1	40.4	5.2	6.0	44.6	45.2	1.4	42.4	41.8	-1.5
Annual solar to electric efficiency, %	15.7	15.4	-1.9	16.8	17.2	18.2	8.3	5.8	20.4	20.3	-0.4	19.4	18.8	-2.9
Energy per year (GWhe/year)	366.7	372.0	1.4	551.6	559.1	559.4	1.4	0.0	562.0	555.6	-1.1	540.2	515.4	-4.6
Total capital (installed cost), MUSD	645.5	636.2	-1.5	-	630.1	603.5	-	-4.2	579.6	578.4	-0.2	538.3	529.1	-1.7
LCOE, USD/MWh	165.0	161.1	-2.4	79.3	78.6	75.7	-4.5	-3.6	72.7	73.5	1.2	69.6	72.0	3.4

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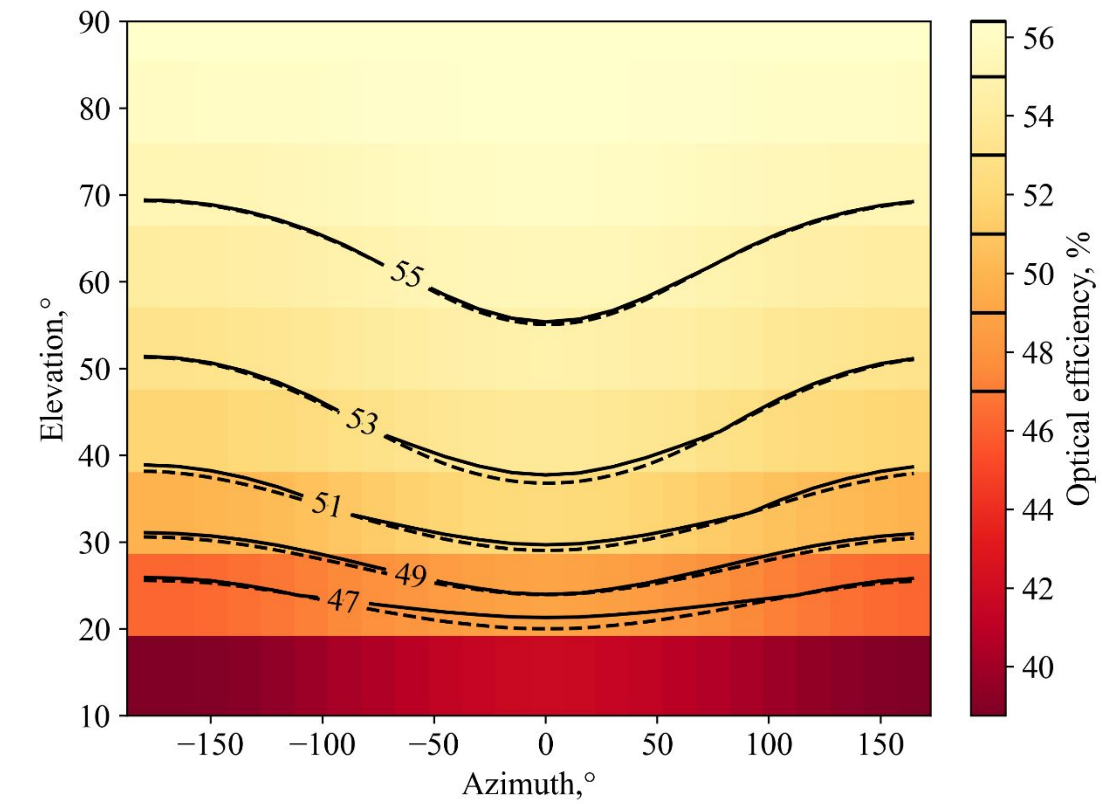
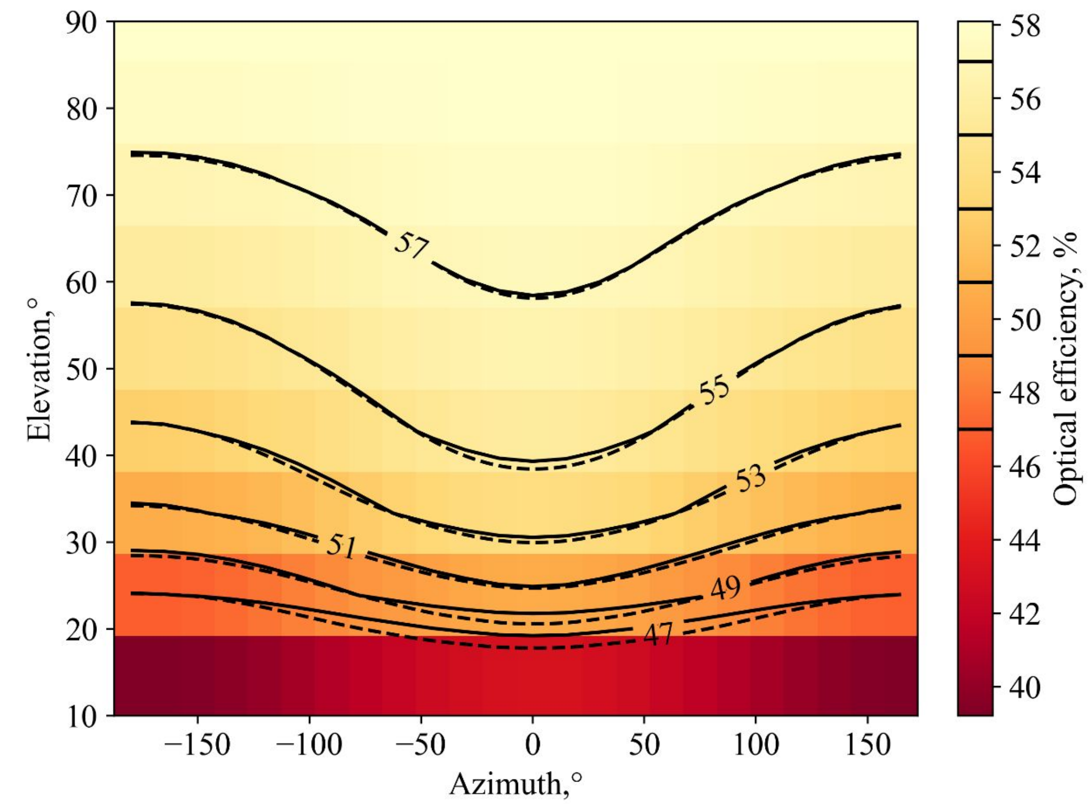
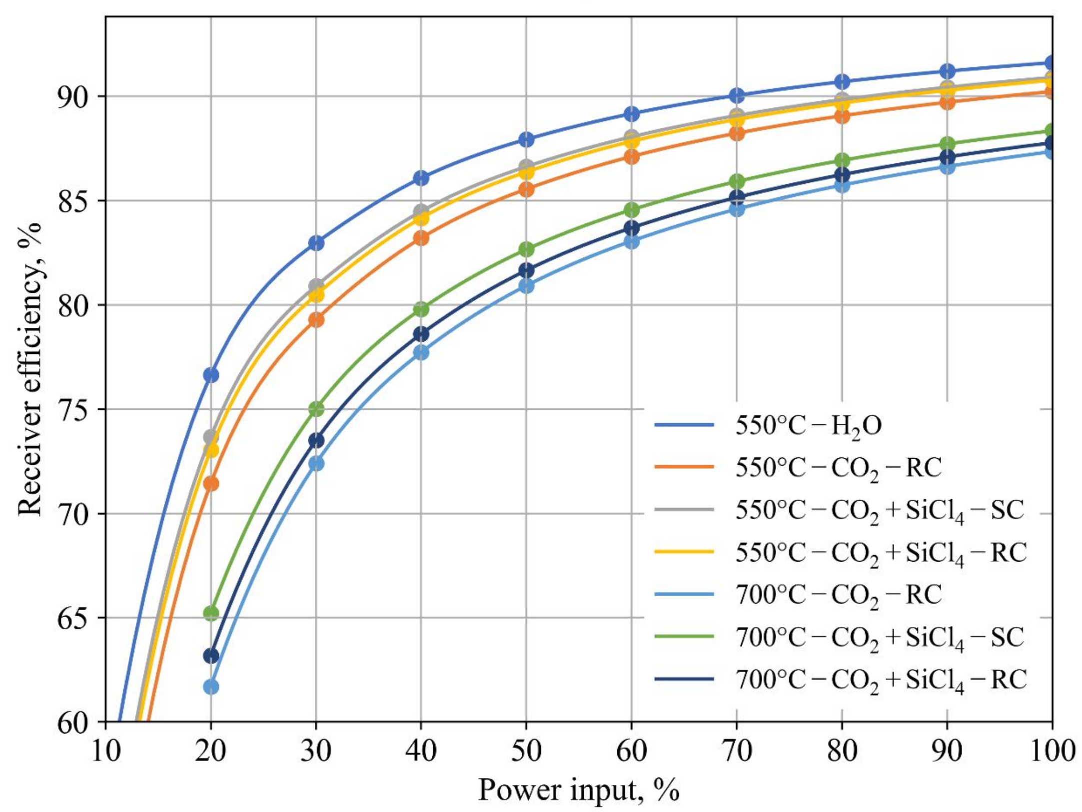
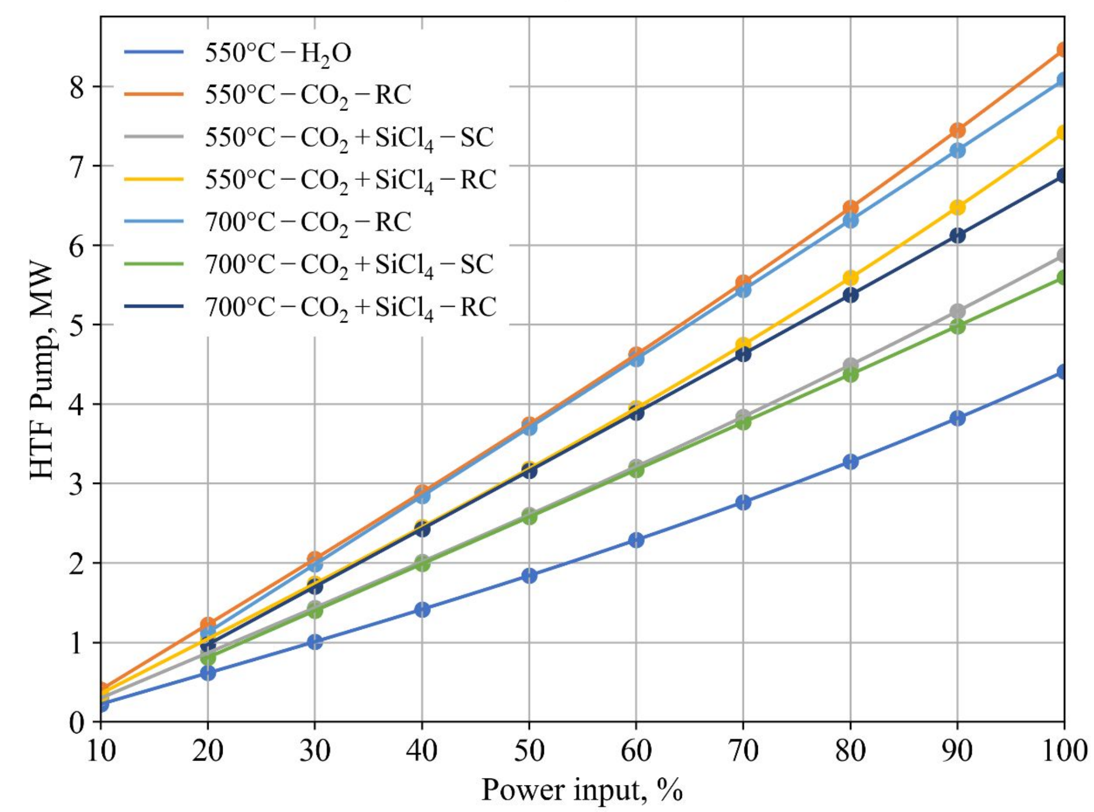
CSP modelling solar field and receiver









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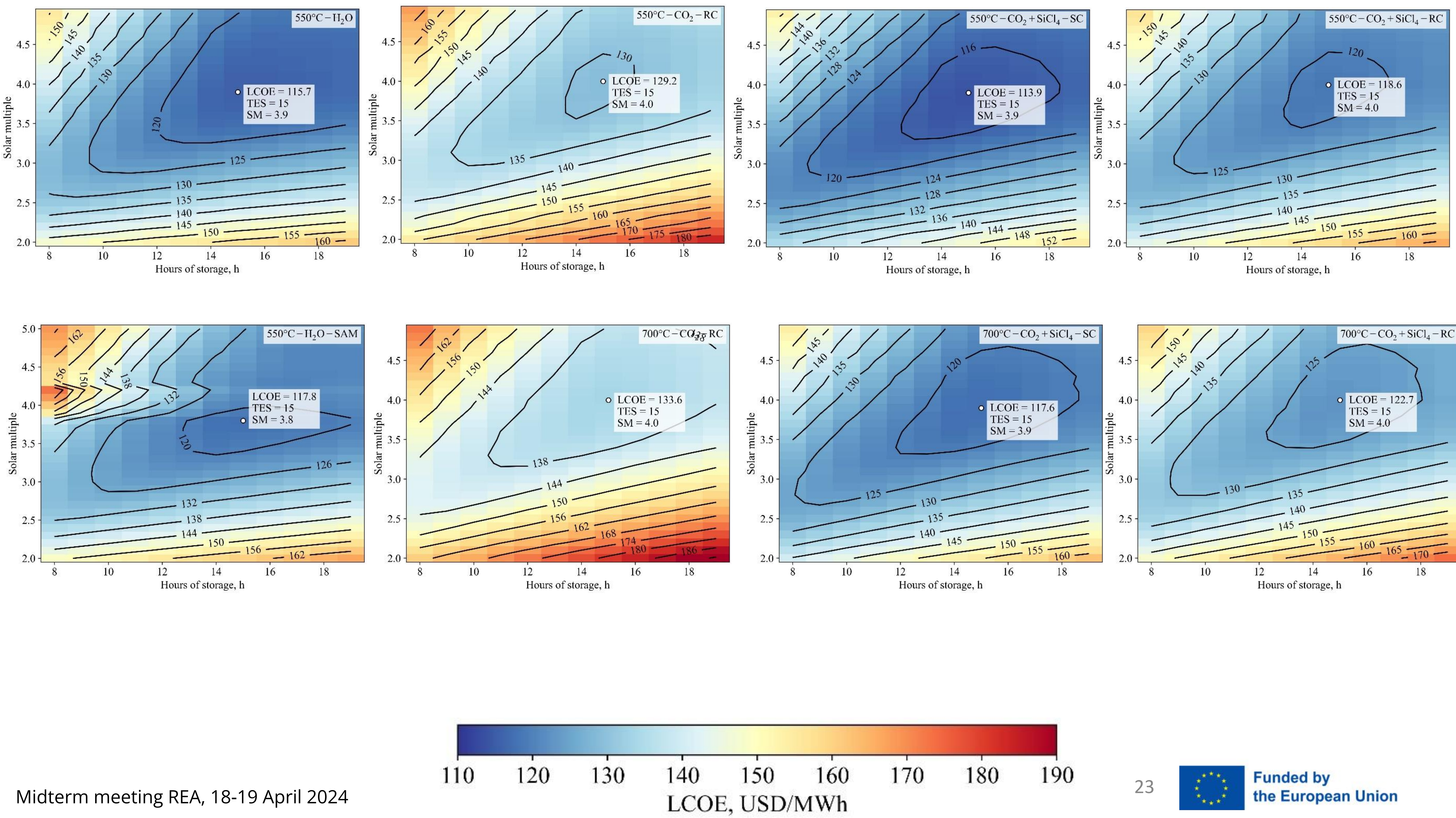
CSP plant optimisation



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Shell and Tube Heat Exchangers for $SiCl_4 + CO_2$ mixture for CSP

Power cycle		sCO_2 RC			CO_2+$SiCl_4$ SC		CO_2+$SiCl_4$ RC		
Heat exchanger		PHE	HTR	LTR	PHE	Rec.	PHE	HTR	LTR
Power, MW		283	582	194	285	533	284	411	195
Hot side	Fluid	Solar salt	sCO_2		Solar salt	CO_2+$SiCl_4$	Solar salt	CO_2+$SiCl_4$	
	Mass flow, kg/s	1429	1748	1748	989	1485	1197	1636	1636
	Tin/Tout, °C	570/441	457/175	175/112	570/381	426/93	570/414	435/193	193/94
	Pin/ΔP, bar	6/0.5	116/1.7	114/1.7	6/0.5	75/1.1	6/0.5	88/1.3	87/1.3
Cold side	Fluid	sCO_2			CO_2+$SiCl_4$				
	Mass flow. kg/s	1748	1748	1249	1485	1485	1636	1636	1187
	Tin/Tout, °C	421/550	170/421	90/170	361/550	74/361	394/550	188/394	87/188
	Pin/ΔP, bar	249/5	249/0.7	250/0.8	249/5	250/0.8	249/5	249/0.7	250/0.8

Power cycle			sCO_2 RC			CO_2+$SiCl_4$ SC		CO_2+$SiCl_4$ RC		
Heat exchanger			PHE	HTR	LTR	PHE	Rec.	PHE	HTR	LTR
Conventional	ΔP Calc./ Allow., bar	Hot	0.48/0.5	1.44/1.74	1.56/1.71	0.44/0.5	0.78/1.12	0.44/0.5	0.78/1.32	0.93/1.3
		Cold	4.17/4.97	0.55/0.75	0.46/0.75	4.28/4.97	0.53/0.75	4.87/4.97	0.64/0.75	0.67/0.75
	Parallel/series		2/2	5/3	4/3	2/3	5/4	2/3	6/3	5/4
	Shell ID, mm		2400	2550	2600	1900	2200	2150	2200	2550
	Effective length, mm		14292	13950	14950	14049	15450	11532	12950	15800
	Total area, 10^3 m^2		18.07	75.20	97.70	16.97	82.68	17.57	53.78	113.88
Embaffle	ΔP Calc./ Allow., bar	Hot	0.44/0.5	1.7/1.74	1.62/1.71	0.44/0.5	1.11/1.12	0.47/0.5	1.24/1.32	1.27/1.3
		Cold	4.75/4.97	0.55/0.75	0.57/0.75	4.87/4.97	0.73/0.75	4.67/4.97	0.7/0.75	0.73/0.75
	Parallel/series		2/2	4/3	3/4	1/3	2/4	1/2	2/3	3/4
	Shell ID, mm		1730	2100	2100	2150	2600	2200	2500	2200
	Effective length, mm		14409	11250	12142	12674	11268	17542	9950	14580
	Total area, 10^3 m^2		16.64	58.16	62.77	17.18	60.33	16.63	36.86	82.91

Alloy	USD/kg
625	81.2
347	19.4
9Cr-1Mo	10.2
CS	4.1

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