sCO_2 Power Cycle Design without Heat Source Limitation: Solar Thermal Particle Technology in the CARBOSOLA Project

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The CARBOSOLA Project

Main Objectives:

- Assess techno-economic potential of sCO_2 power cycles
  - Use case 1: GT bottoming cycle, $T_{sCO2} < 550$ °C
  - **Use case 2: CSP, $T_{sCO2} > 600$ °C**
- Build Europe's most powerful testing facility for sCO_2 components
  - $T_{max} \approx 650$ °C
  - $p_{max} \approx 300$ bar
  - $\dot{Q}_{heater} \approx 1.5\ MW_t$
- Design demonstrator
  - $T_{max} \approx 500$ °C
  - $\dot{Q}_{heater} \approx 20\ MW_t$

Partners

SIEMENS energy

TECHNISCHE UNIVERSITÄT DRESDEN

DLR

HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Funding

Gefördert durch:

Bundesministerium für Wirtschaft und Energie

aufgrund eines Beschlusses des Deutschen Bundestages

Overview

Assess techno-economic potential of CSP sCO_2 plants

This study:

1. Define boundary conditions and technologies
2. Develop simplified techno-economic models of chosen sCO_2 cycles and CSP technologies
3. Run a large number of simulations with variations of the main parameters
4. Identify the variants with the highest economic potential
5. Compare results with steam reference system and check sensitivity for cost models

Next steps:

- Build detailed annual yield models

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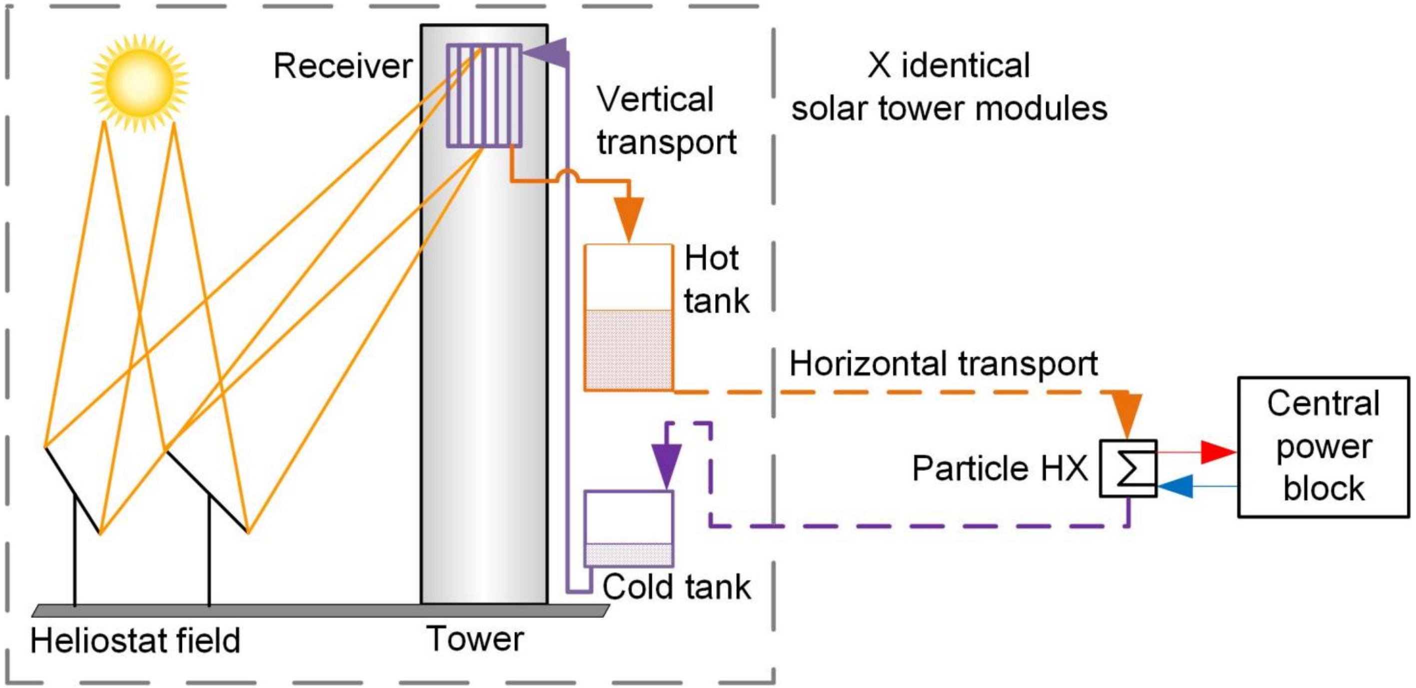
Solar Particle Technology

- Heat transfer medium: Bauxite particles
- Particle temperatures can be chosen freely within the technical limits of the power block (> 1000 °C)
    - Enables high-temperature power cycle
    - Smaller storage, HXs…
- Low cost material
- Enables direct absorption solar receiver (high efficiency)
- Easy handling

- Additional variants employing state of the art molten salt as the heat transfer medium were modeled. Results for these can be found in the paper.



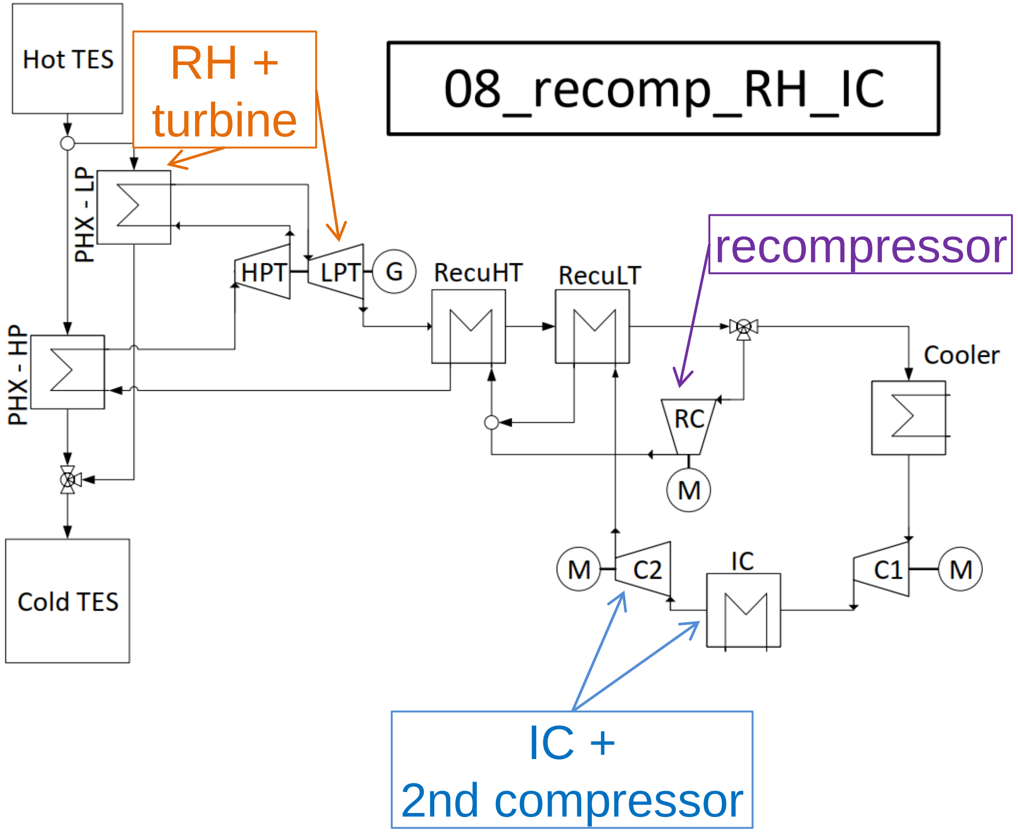
Solar Plant Boundary Conditions

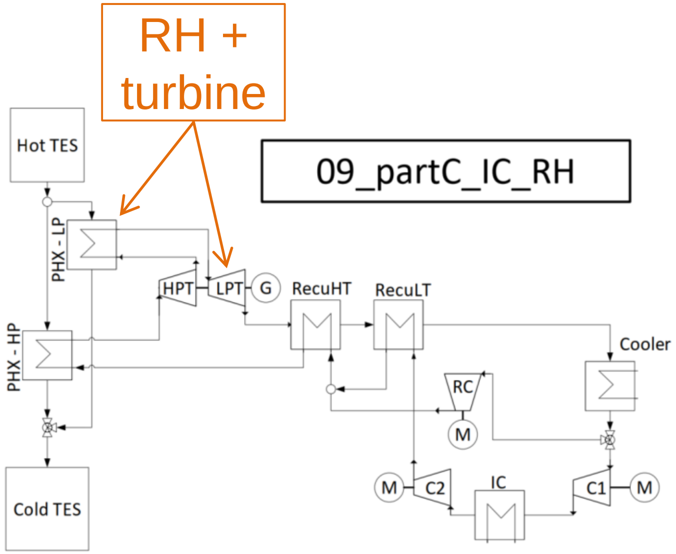
Location	Postmasburg, South Africa
Design semi-net capacity	115 MW_e
Storage capacity	12 h
Cooling	dry
Design point ambient temperature	19 °C
Hot particle temperature	900 °C
Cold particle temperature	Defined by sCO_2 cycle and primary heat exchanger

Source: Google Earth

Power Cycle Variants

	sCO2 cycles
4 simple recuperated cycles	01_simple
	02_simple_RH
	03_simple_IC
	04_simple_RH_IC
4 recompression cycles	05_recomp
	06_recomp_RH
	07_recomp_IC
	08_recomp_RH_IC
2 partial cooling cycles	09_partC_RH
	10_partC





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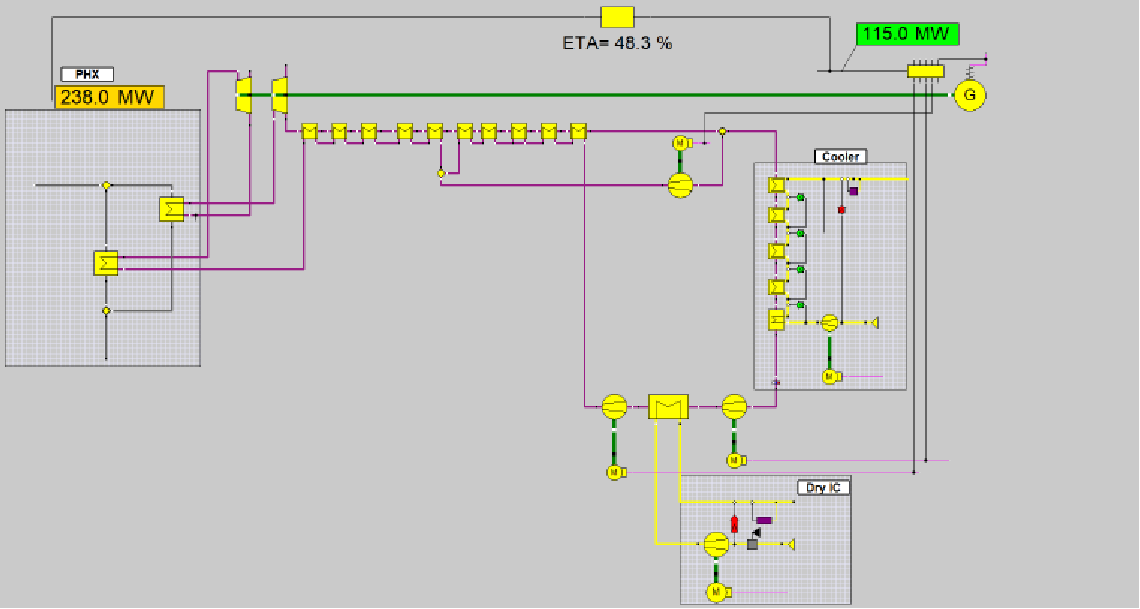
Power Block Parameters

- For all 10 cycle variants, the following parameters were varied, where applicable:

Parameter	Unit	Range	Comment
TIT	[°C]	550…700	
TIP	[bar]	260 ; 300	
CIP	[bar]	45…100	Extreme values only in partial cooling cycles
TTD Recuperator	[K]	5…	Terminal temperature difference in recuperators
$U^*A_{cooler/IC}$	[MW/K]	…18	
r_{recomp}	[%]	25…45	Recompression fraction
TTD PHX,HP	[K]	5…300	Terminal temperature difference in HP-PHX
TTD PHX,LP	[K]	5…300	Terminal temperature difference in reheater

Ebsilon Professional v14 model

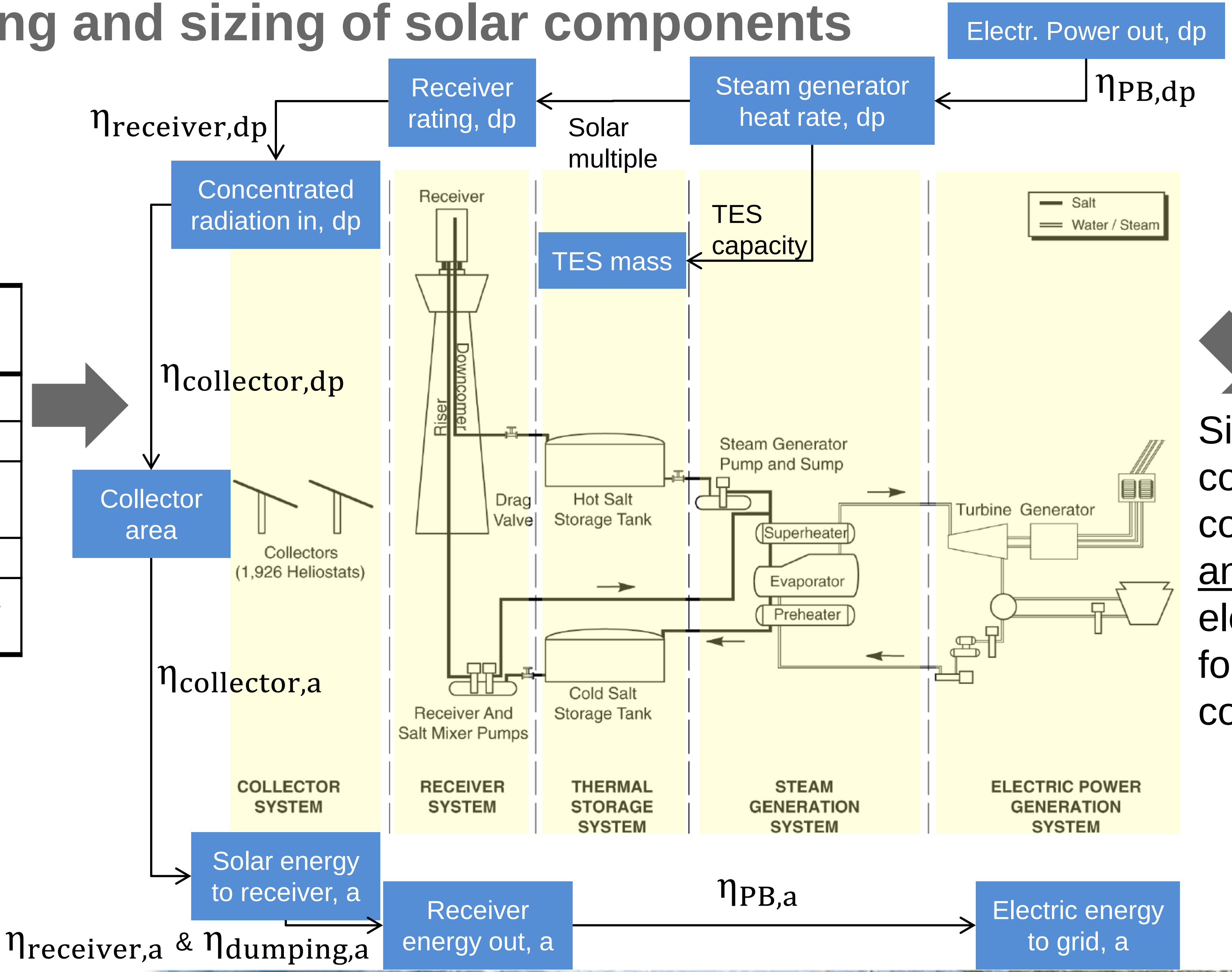


Design point cycle efficiency and parameters for component cost model (T, p, $\dot{Q}$, P, U^*A, $\dot{V}$, …)

Annual yield modeling and sizing of solar components

- Sizing and efficiency assumptions for all plants

Parameter	Design point	Annual average
Solar multiple	2.5	
TES capacity	12 h	
Collector field efficiency	73.5 %	52.7 %
Receiver efficiency	90.0 %	86.7 %
PB efficiency, a	From Ebsilon	PB efficiency, dp x 99 %

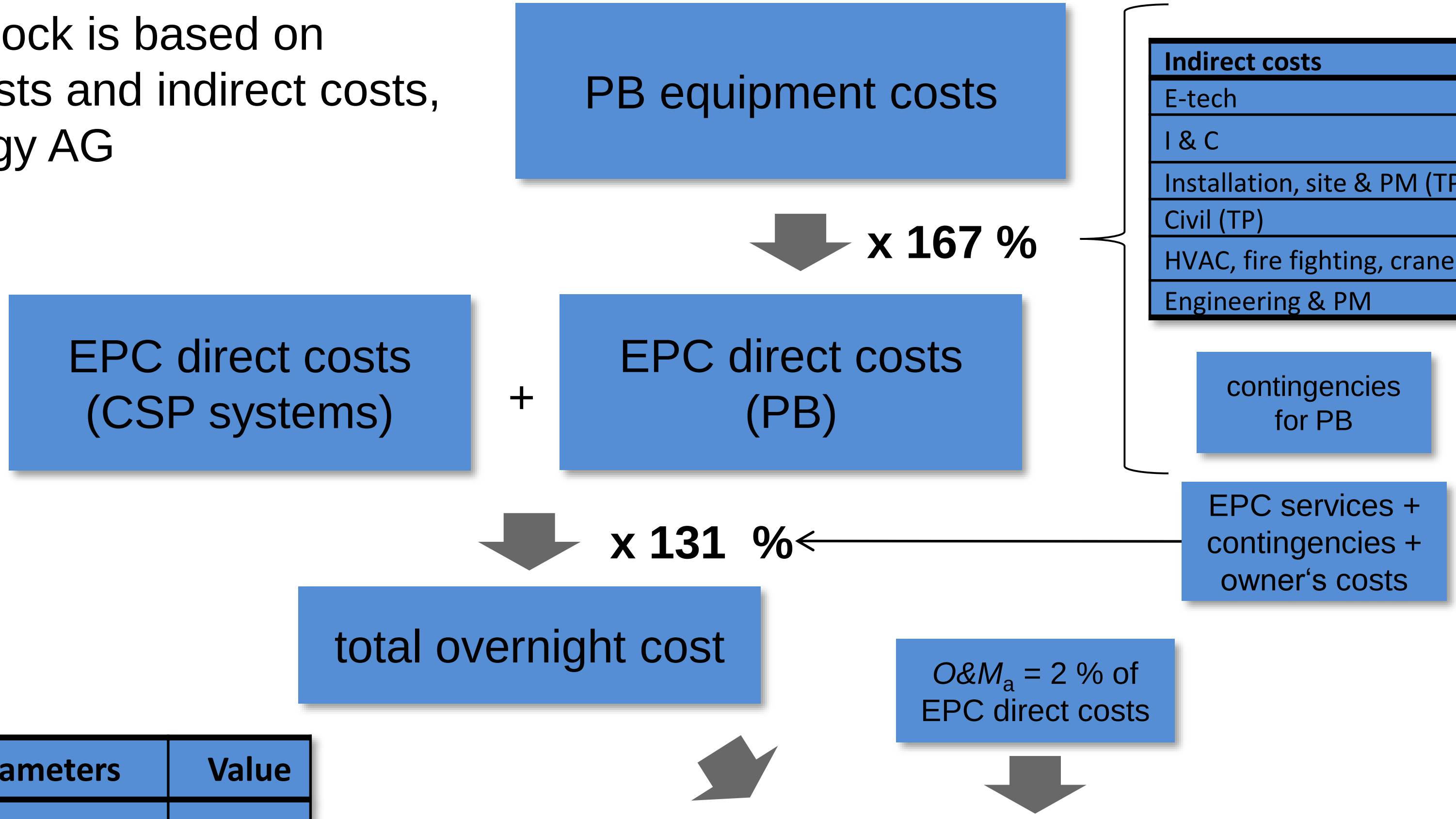


Sizing of solar components for cost models and <u>annual</u> electricity yield for levelized costs

dp: design point
a: annual
PB: power block
TES: thermal energy storage

Economic model

- The economic model for the power block is based on proprietary models for component costs and indirect costs, contingencies, etc. by Siemens Energy AG
- Costs for the rest of the plant are estimated on a system-level by DLR
- Additional sources of the cost models are:
  - [NETL, 2019]
  - [Buck and Giuliano, 2019]



Indirect costs
E-tech
I & C
Installation, site & PM (TP)
Civil (TP)
HVAC, fire fighting, cranes
Engineering & PM

Financial parameters	Value
Real debt interest rate	8 %
Lifetime	25 a
Fixed charge rate (*FCR*)	9.37 %

$$LCOE = \frac{FCR * C_{\text{overnight}} + O\&M_{\text{a}}}{\Sigma P_{\text{out,a}}} \quad \left[\frac{\text{USD}}{\text{kWe h}}\right]$$

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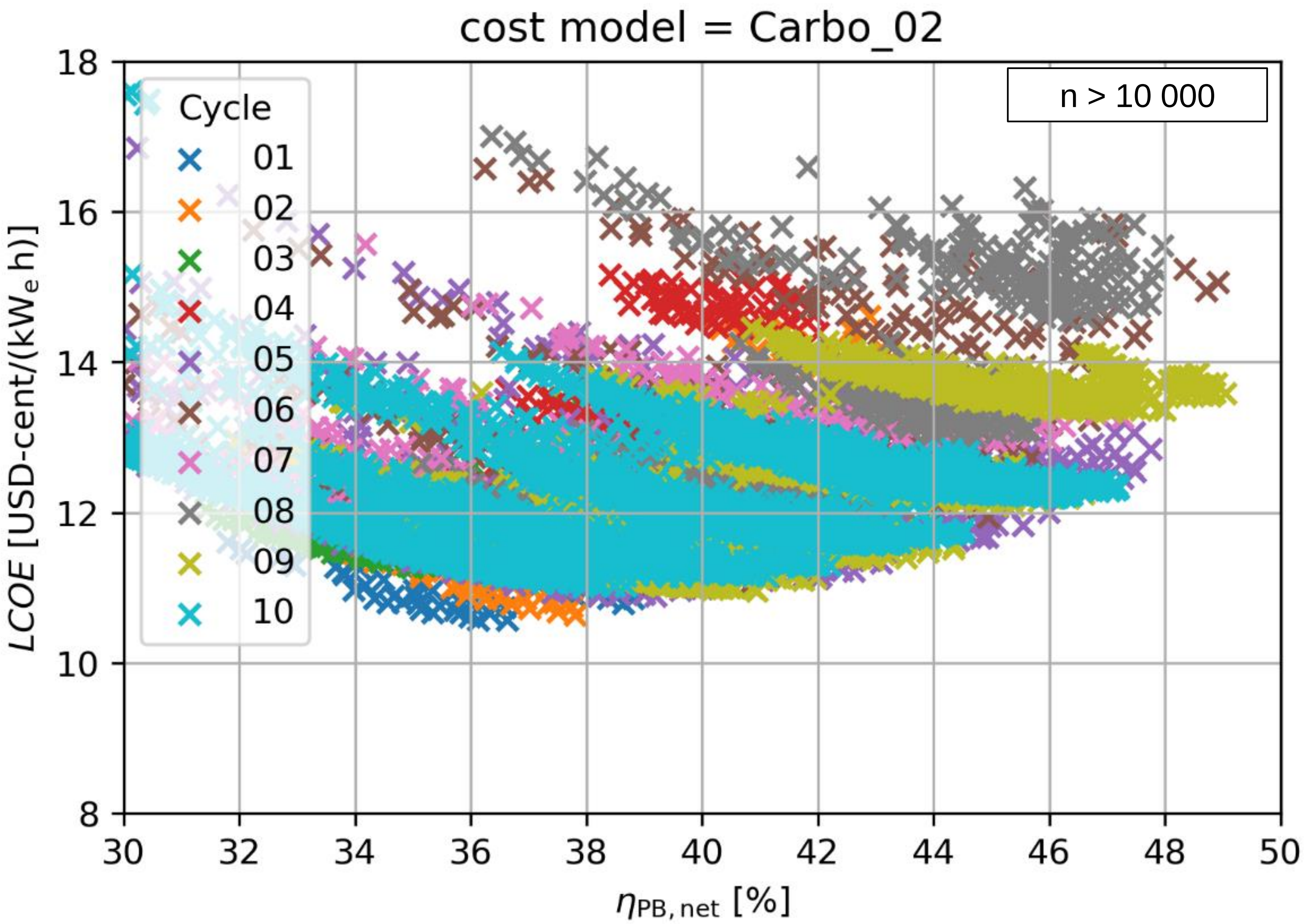
Results: LCOE vs. Power block efficiency

sCO2 cycles
01_simple
02_simple_RH
03_simple_IC
04_simple_RH_IC
05_recomp
06_recomp_RH
07_recomp_IC
08_recomp_RH_IC
09_partC_RH
10_partC

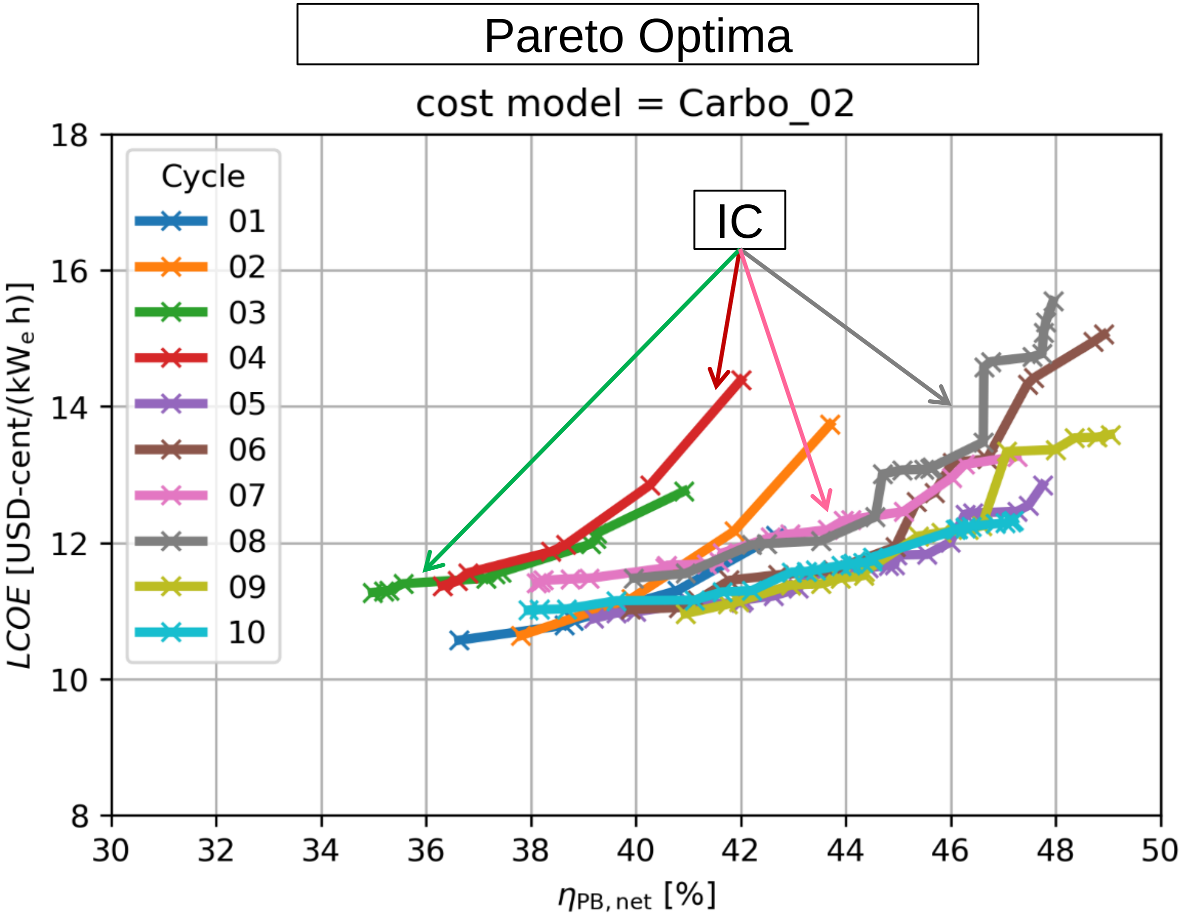


Results: LCOE vs. Power block efficiency (2): Cycle selection

sCO2 cycles
01_simple
02_simple_RH
03_simple_IC
04_simple_RH_IC
05_recomp
06_recomp_RH
07_recomp_IC
08_recomp_RH_IC
09_partC_RH
10_partC

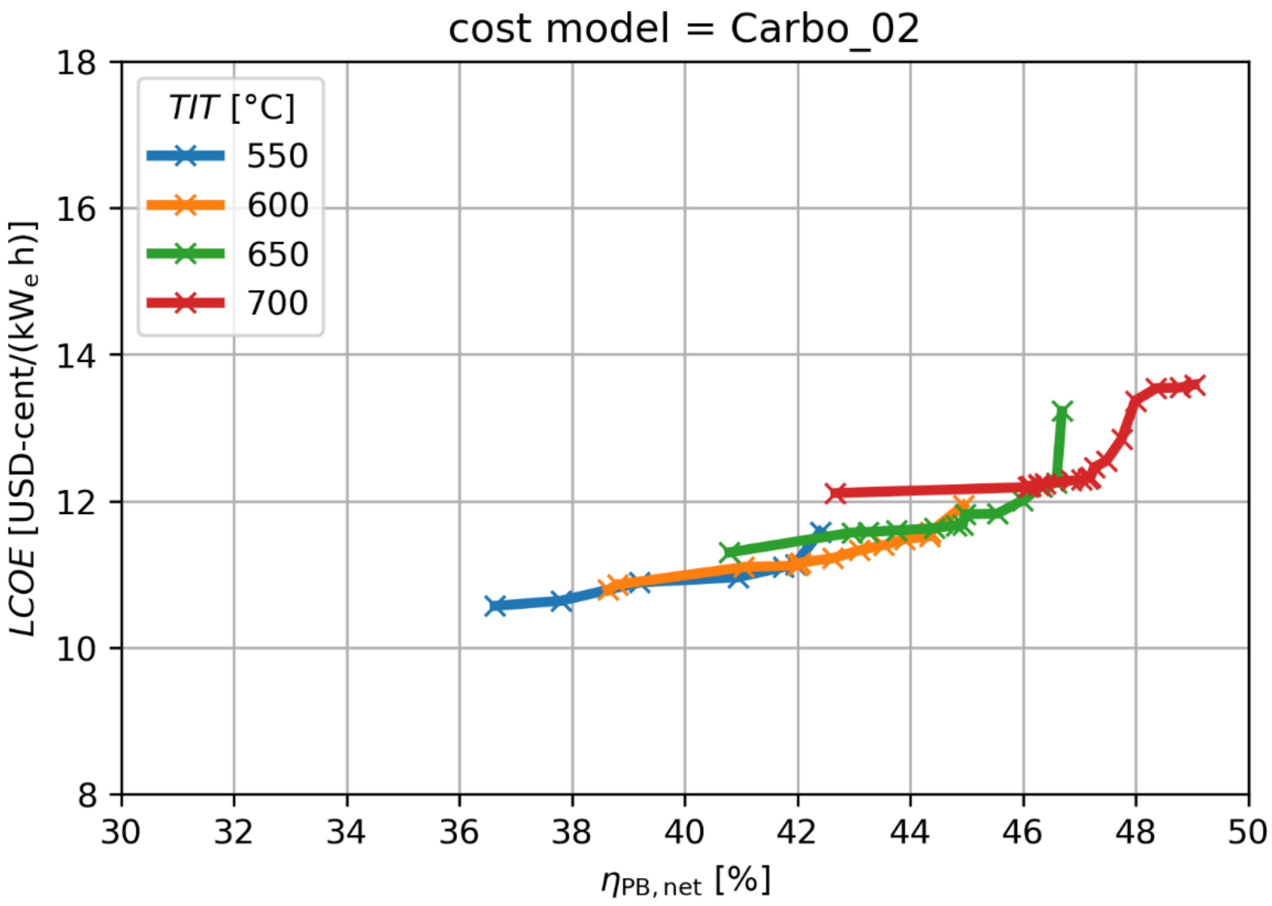
- IC cycles (03, 04, 07, 08) perform worse than variants without IC.
- RH cycles (02, 06, 09) generally render higher LCOEs than their non-RH counterparts. An exception are partial cooling cycles with and without RH, which perform similarly.
- For detailed modeling, the following cycles are therefore selected:
  - **01: simple recuperated**
  - **05: simple recompression**
  - **09/10: partial cooling**

Only the lowest LCOE configurations



Results: LCOE vs. Power block efficiency (3): TITs

- Higher TITs are not economical according to the current cost model („Carbo_02“).
- Even if the cost of the PHX is modeled to be temperature independent, there is no clear economic benefit of higher TITs (not shown).



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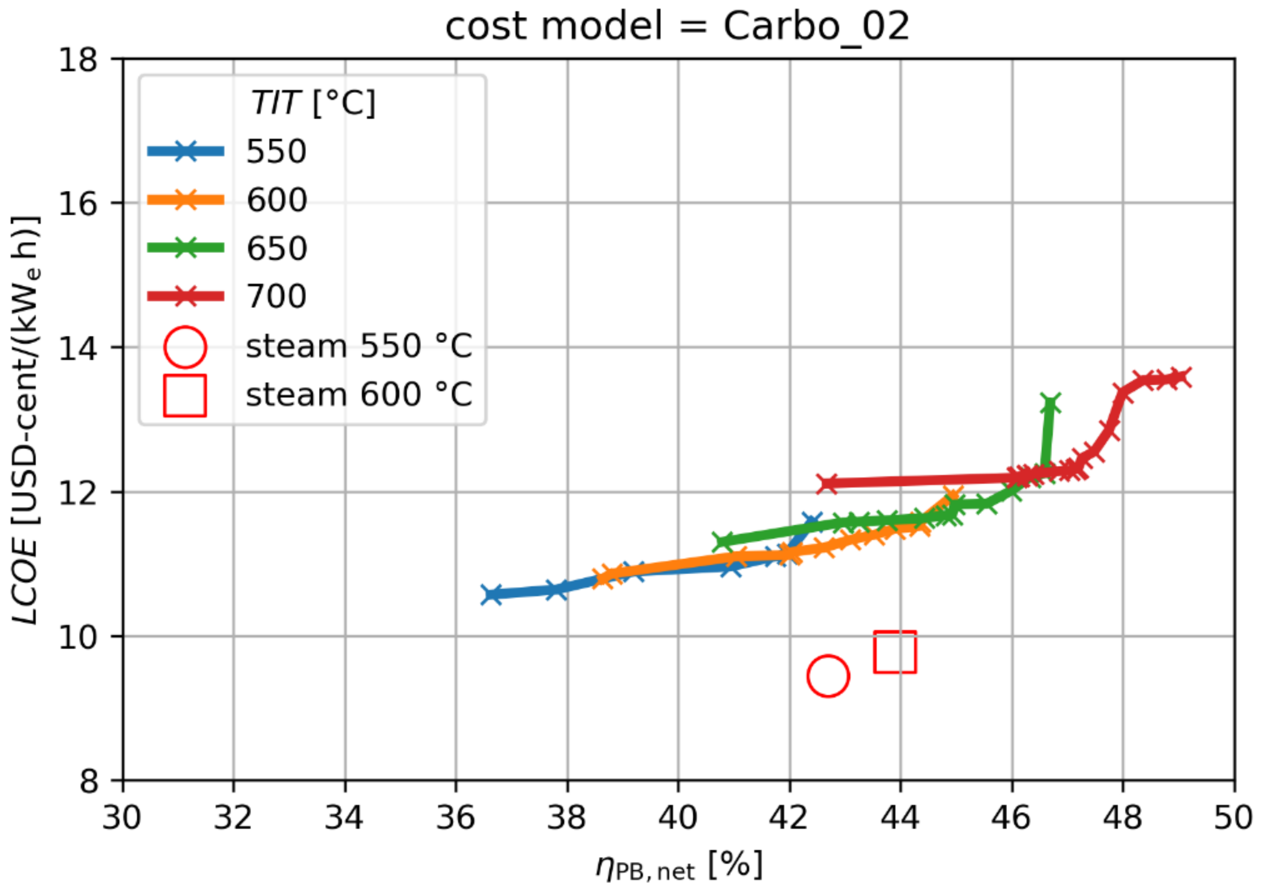
Comparison with Reference System Costs

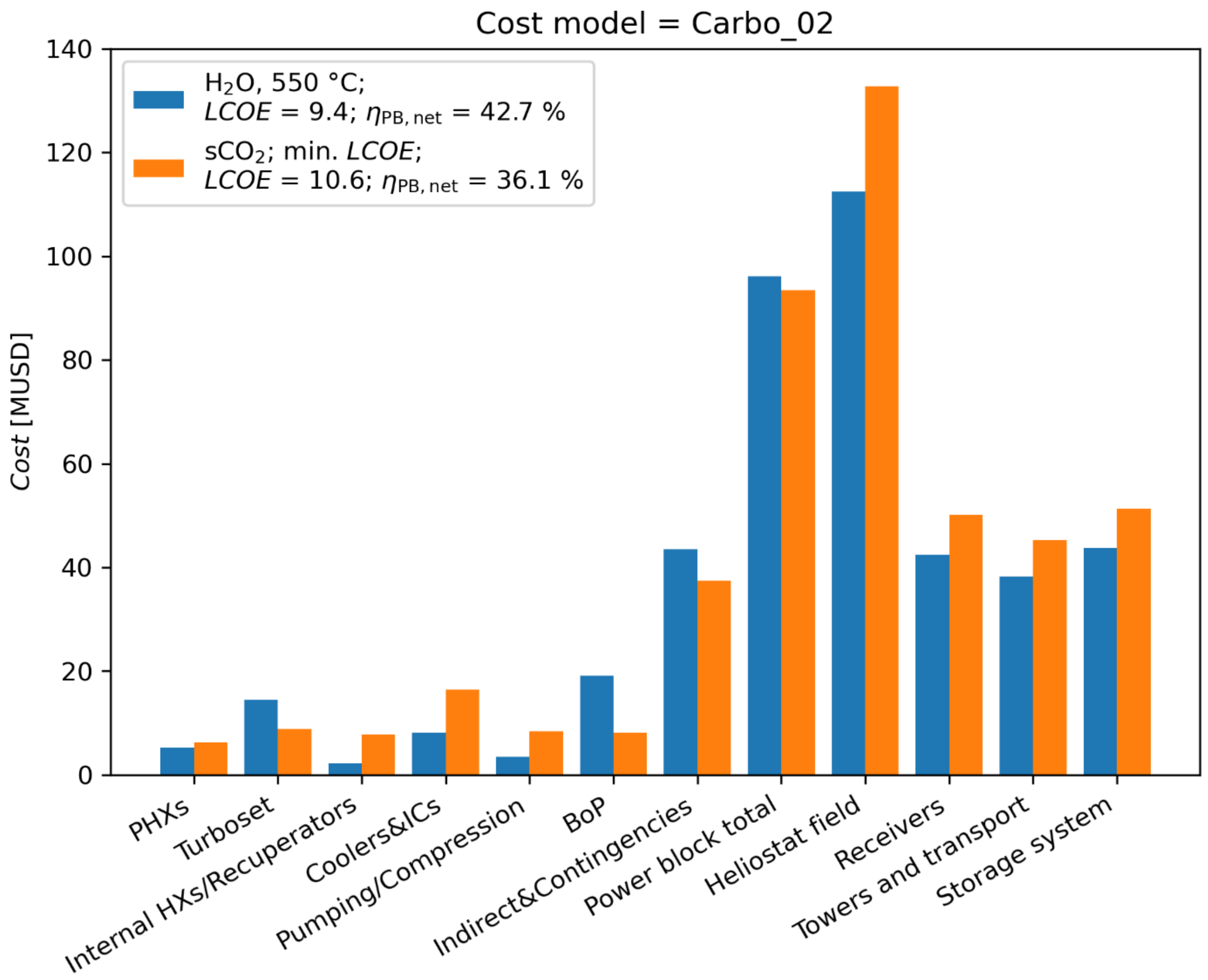
- 2 Reference steam cycles:
  - *TIT* = 550 °C, subcritical, $\eta_{\mathrm{PB,net}} = 42.6\ \%$ (state of the art)
  - *TIT* = 600 °C, subcritical, $\eta_{\mathrm{PB,net}} = 43.9\ \%$ (next generation)
- The steam generator cost for the reference steam system is calculated with the same cost model as for the sCO_2 systems.
- The reference system LCOE are considerably lower (~10 %) than those of the best performing sCO2 cycles.



Sensitivity Analysis: Lower PB Equipment Costs

Component	**Reference**	**sCO_2**	**sCO_2 low**
PHX cost		Carbo_02	
Coolers&IC	Siemens	Carbo_02	*Lower boundary*
Compressors			Carbo_02 x 50 %
Turbines			
Recuperators			
Indirect costs (sCO_2 only)			
LCOE **[USD-cent/(kW_e h)]**	**9.4**	**10.6**	**9.4**

- To break even with steam reference plant: Costs for compressors, turbines and recuperators as well as the indirect costs would **need to be lowered by 50 %.**



Results: Why do these findings appear to disagree with those of other studies?

- Techno-*economic* comparisons with steam power blocks are rare (in CSP literature).
- If sCO_2 power block costs are not calculated but defined, those values as defined by literature are commonly much lower than those found in this study.
- Commonly, indirect costs for the power block are either omitted or estimated at much lower values.
- Sometimes, lower interest rates are assumed, which favors higher-performance configurations.
- Costs for certain sCO_2 equipment according to the CARBOSOLA designs was found to be higher than in some literature (e.g. for coolers, turbines, PHX).
    - Particle PHX cost models have a high uncertainty.

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Conclusions and Outlook

- A techno-economic model was developed to conduct simplified LCOE calculations for particle-sCO_2 solar power plants.
- It was found that sCO_2 cycles **with lower efficiencies** than state of the art steam cycles render the lowest LCOE.
- The best performing variants still produce electricity at more than **10 % higher costs than steam** reference cases.
- LCOE values of all systems, including the reference ones, seem high. This is partially caused by rather conservative financing assumptions and non-optimized solar subsystems.

- An annual hourly energy yield model will be developed to evaluate the chosen variants more accurately. This includes:
  - Hourly simulation of the power cycle under real world ambient conditions.
  - Modeling and optimization of the solar field.

Thanks!

Any questions or comments?

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Sources

GT2019-90493

SCO2 POWER CYCLE COMPONENT COST CORRELATIONS FROM DOE DATA SPANNING MULTIPLE SCALES AND APPLICATIONS

Nathan T. Weiland
National Energy Technology Laboratory
Pittsburgh, PA, USA

Blake W. Lance
Sandia National Laboratories
Albuquerque, NM, USA

Sandeep R. Pidaparti
National Energy Technology Laboratory
KeyLogic
Pittsburgh, PA, USA

ÉCOLE DOCTORALE RESSOURCES PROCÉDÉS PRODUITS ENVIRONNEMENT
LABORATOIRE RÉACTION ET GÉNIE DES PROCÉDÉS

THÈSE DE DOCTORAT

Présentée par

Qiao ZHAO

Pour l'obtention du grade de

Docteur en Science de l'Université de Lorraine
Spécialité : Génie des Procédés et des Produits

Conception and optimization of supercritical CO_2 Brayton cycles for coal-fired power plant application

ELSEVIER
Solar Energy
Volume 181, 15 March 2019, Pages 27-36

Supercritical carbon dioxide power cycle design and configuration optimization to minimize levelized cost of energy of molten salt power towers operating at 650 °C

Ty Neises, Craig Turchi

2[nd] European supercritical CO2 Conference
August 30-31, 2018, Essen, Germany

2018-sCO2.eu-128

IMPACT OF SOLAR TOWER DESIGN PARAMETERS ON SCO2-BASED SOLAR TOWER PLANTS

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Stefano Giuliano
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G3P3
Techno-Economic Analysis of Up-Scaled CentRec® Receiver

Modelling Parameters and Results

DLR

Proceedings of the ASME 2019
13[th] International Conference on Energy and Sustainability
ES2019
July 15-17, 2019, Bellevue, WA, USA

ES2019-3893

PARAMETRIC ANALYSIS OF PARTICLE CSP SYSTEM PERFORMANCE AND COST TO INTRINSIC PARTICLE PROPERTIES AND OPERATING CONDITIONS

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Technoeconomic Analysis of Alternative Solarized s-CO_2 Brayton Cycle Configurations

This paper evaluates cost and performance tradeoffs of alternative supercritical carbon dioxide (s-CO_2) closed-loop Brayton cycle configurations with a concentrated solar heat source. Alternative s-CO_2 power cycle configurations include simple, recompression, cascaded, and partial cooling cycles. Results show that the simple closed-loop Brayton cycle yielded the lowest power-block component costs while allowing variable temperature differentials across the s-CO_2 heating source, depending on the level of recuperation. Lower temperature differentials led to higher sensible storage costs, but cycle configurations with lower temperature differentials (higher recuperation) yielded higher cycle efficiencies and lower solar collector and receiver costs. The cycles with higher efficiencies (simple recuperated, recompression, and partial cooling) yielded the lowest overall solar and power-block component costs for a prescribed power output.
[DOI: 10.1115/1.4033573]

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Additional slides

Cost models – PHX

- Buck & Giuliano (2018):
  assuming $HTC_{\text{Particles}}$ = 250 W/(m² K)

$$C_{\text{PHX}} = 3266.8\ \text{USD} \left(\frac{UA_{\text{PHX}}}{\text{W}_\text{t}/\text{K}}\right)^{0.66}$$