FUNDAMENTAL THERMO-ECONOMIC APPROACH TO SELECTING SCO2 POWER CYCLES FOR CSP APPLICATIONS

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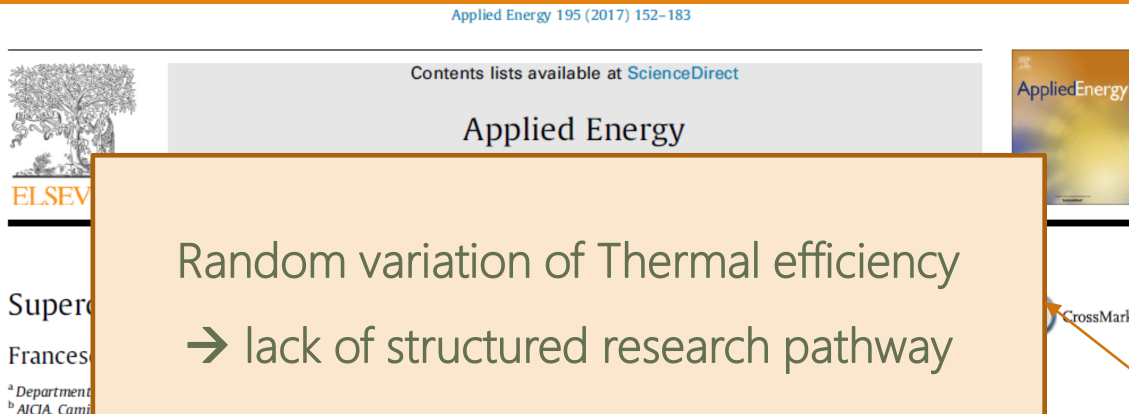
4. INTRODUCTION & SCOPE OF THE WORK

- Introduction & scope of the work
- Simulation tools
  - Heat exchangers
  - Turbomachinery
  - Complementary assumptions
  - Thermal Energy Storage
- Results
  - Thermodynamic analysis
  - Thermo-economic analysis
- Conclusions

1. INTRODUCTION: REVIEW OF THE STATE OF THE ART



Random variation of Thermal efficiency

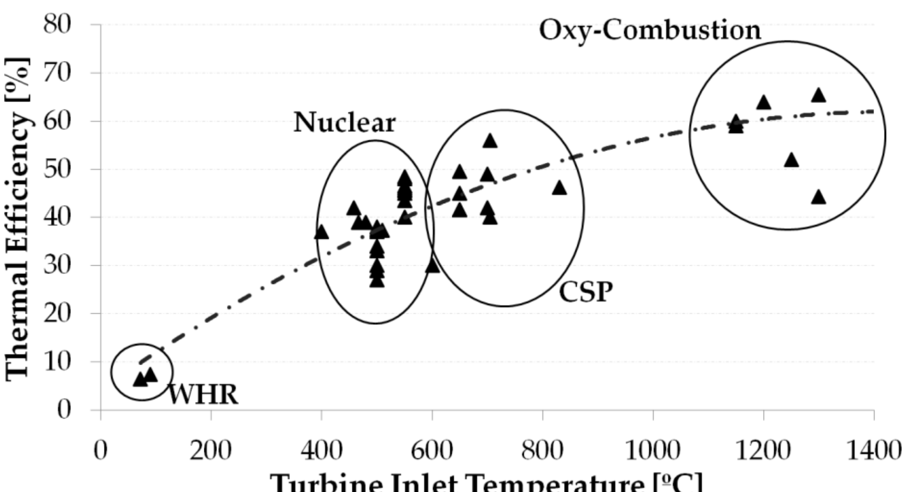
→ lack of structured research pathway

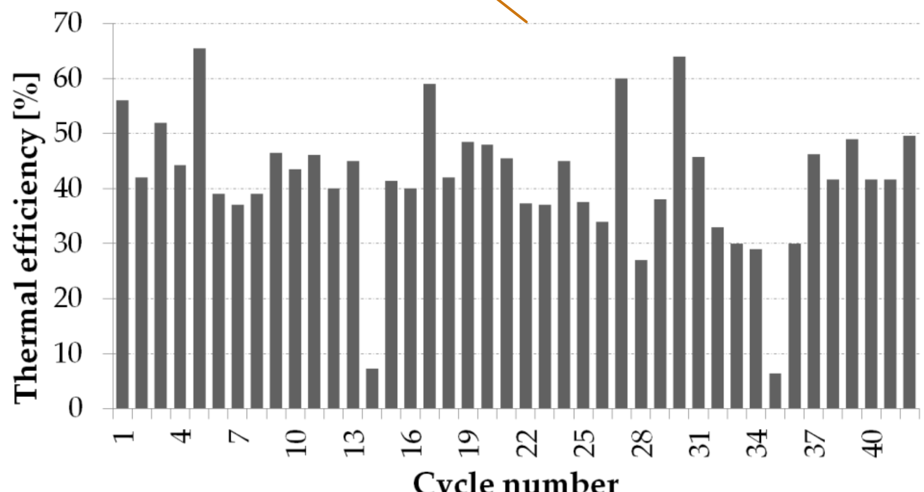
More than 150 references included!

Both simple and combined cycles considered

42 different configurations found (stand-alone cycles)

Chronological Order (from left to right)



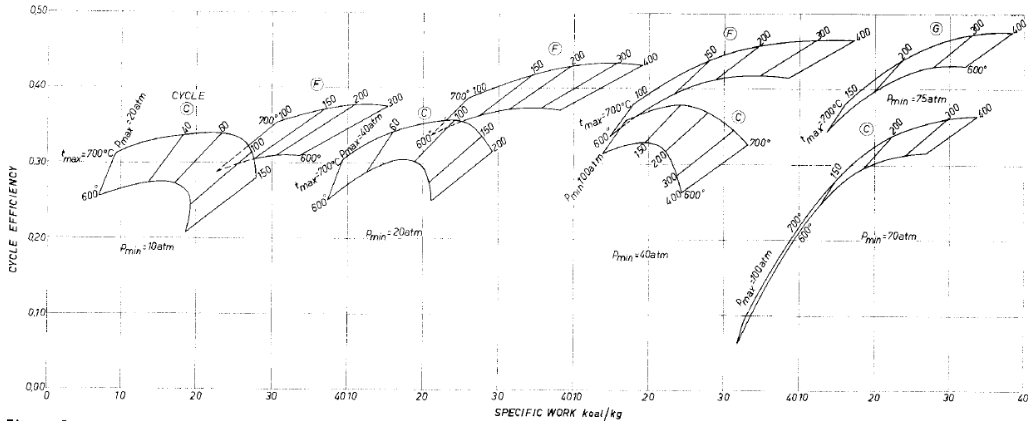


1. INTRODUCTION: PREVIOUS WORK

- Set up and develop a systematic analysis of different sCO2 cycles proposed in literature
  - Overcome the absence of thorough and rigorous analysis of underlying thermodynamic principles of sCO2 cycles

Our study

- 12 most interesting cycles are selected
- Common boundaries conditions are set
- Four TIT levels (550,750,950 and 1150 ºC)
- Pure thermodynamic analysis, without technical restriction in terms of pressures and temperatures
- Pressure ratio is varied from 2 to highest value allowed by recuperation process (one single restriction)



(Angelino, G., 1969. "Real Gas Effects in Carbon Dioxide Cycles.". In ASME 1969 Gas Turbine Conference and Products Show.)

- Obtain Thermal Efficiency vs Specific Work diagrams, as a function of TIT and PR (Angelino)
- Separate thermodynamic potential of each cycle from inherent technological constraints
- Provide a clear insight into the cycle's potential, regardless of the application

1. INTRODUCTION: PREVIOUS WORK

Proceedings of ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition
GT2017
June 26-30, 2017, Charlotte, NC, USA

GT2017-64418

ANALYSIS OF THE THERMODYNAMIC POTENTIAL OF SUPERCRITICAL CARBON DIOXIDE CYCLES: A SYSTEMATIC APPROACH

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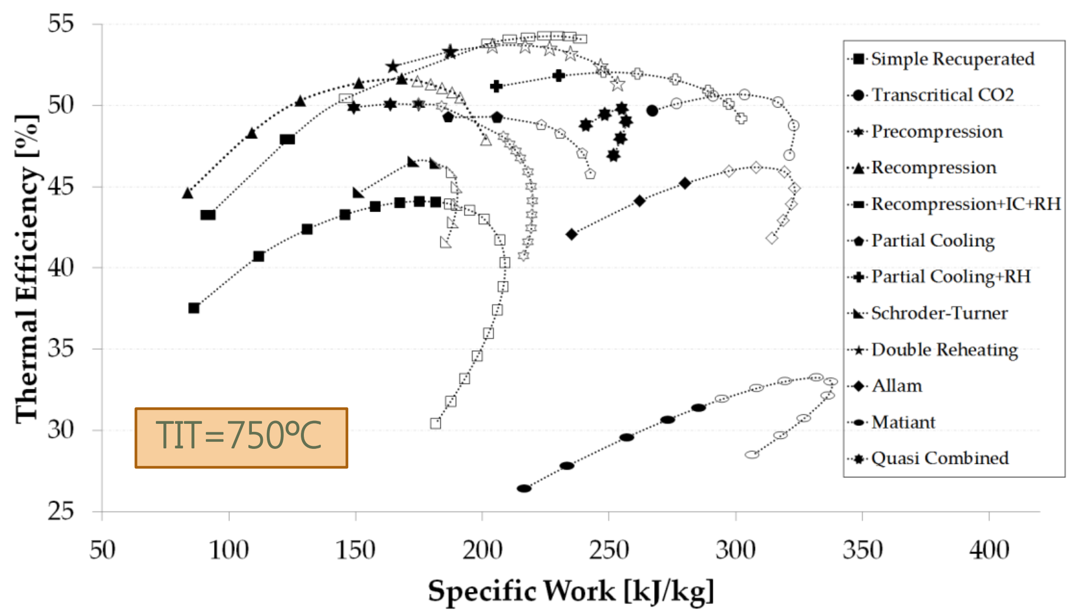
Definition of the cycles of interest for different applications (for each TIT)

Representative technological pressure limits

Black markers → Pmax ≤ 40 MPa

White markers → Pmax > 40 MPa

Some of the plots have been trimmed near the left end in order to facilitate the reading



1. INTRODUCTION: SCOPE OF THE WORK

- Study the potential of sCO2 technology for CSP applications (Solar Towers) incorporating a Thermal Energy Storage (TES) system operating on high temperature molten salts

CSP Power Plant specifications:

- 50 MWel
- 10 hours storage capacity (TES made up of hot/cold tanks for extended operation at full load)

<u>Alternative Thermo-Economic approach:</u>

Three TIT levels considered: 800, 900 and 1000 ºC → solar only and hybrid solutions

- Figures of merit → Thermal Efficiency ($\boldsymbol{\eta_{th}}$) , Specific Work ($\boldsymbol{W_s}$)

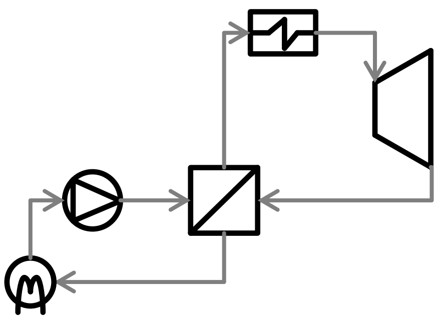
  Temperature rise across solar receiver ($\boldsymbol{\Delta T_{solar}}$), Solar Share ($\boldsymbol{SS}$)

- Economic analysis → Solar field Cost (inversely proportional to $\boldsymbol{\eta_{th}}$)

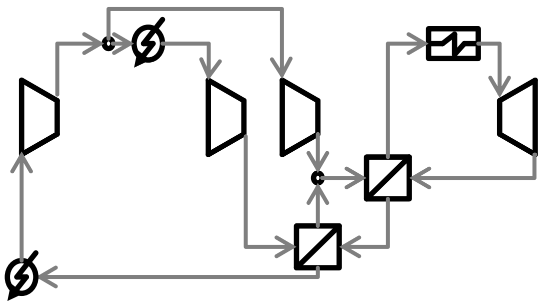
  → TES Cost (inversely proportional to $\boldsymbol{\Delta T_{solar}}$)

- $\boldsymbol{\eta_{th}}$ and $\boldsymbol{\Delta T_{solar}}$ achieve their maximum values at different Pressure Ratios → Compromise is mandatory

1. INTRODUCTION: CYCLES CONSIDERED



- Transcritical CO_2
  - Originally proposed by Angelino (1969)
  - Pseudo-Rankine cycle adapted to the supercritical region. Fairly high turbine inlet temperature but very low pressure ratio, exhibiting superheated vapour (gas) at turbine exhaust
  - Reduces compression work by performing this task near the supercritical point



- Partial Cooling
  - Originally proposed by Angelino (1969) in a transcritical embodiment, hereby considered in the adaption made by Dostal (2004)
  - Very similar to Recompression one, with a mere addition of a cooler and pre-compressor line before the split-valve.
  - Twofold benefit: a) Reduction of pinch-point problem in low-temperature recuperator thanks to lower mass flow rate on the cold side, b) Reduction of cooler size due to lower thermal duty
  - Higher specific work and lower sensitivity of global efficiency upon deviation from optimum pressure ratio

4. SIMULATION TOOLS

- Introduction & scope of the work
- **Simulation tools**
  - Heat exchangers
  - Turbomachinery
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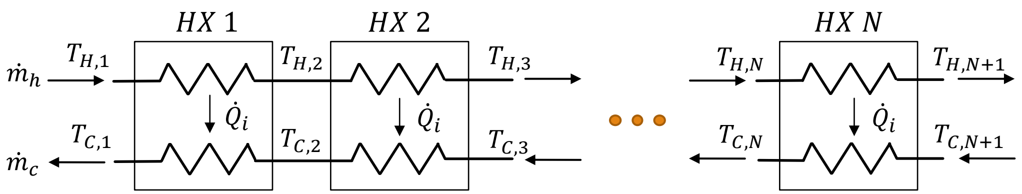
3. SIMULATION TOOLS: HEAT EXCHANGERS

- One-dimensional model, equipment divided in a suitable number of sub-heat exchangers (Nellis&Klein)
  - Each sub-HX characterised by the same duty
  - Small temperature changes considered → constant sCO2 properties
  - Possibility to use ε-NTU methodology in each sub-HX



$$\dot{Q}_i = \dot{Q}_{tot}/_N \; for \; i = 1 \dots N$$

- Original methodology to control pinch-point in the heat exchanger
  - A value of ε=95% is assumed for each sub-HX
  - Differences between hot and cold fluids are computed for all divisions (ΔT_i)
  - The resulting minimum difference (ΔT_{pinch}) checked to be ≥ 5ºC
  - If ΔT_i < 5ºC for any given i, the corresponding ε is modified until the target ΔT_{pinch} is achieved

3. SIMULATION TOOLS: TURBOMACHINERY

- Turbomachinery simulation is fairly simple, given that it is intended for on-design performance only

- A lumped volume model is employed, defining polytropic efficiencies
  - Polytropic efficiency instead of Isentropic one → better capture the influence of very different pressure/temperature levels
  - Representative values are computed considering the ones declared in literature (Polytropic efficiencies reverse-calculated from isentropic ones)
  - 89% Compressors, 90% Turbines, 83% Pumps
  - Isentropic efficiencies are then calculated depending on the operating conditions of each turbomachine

3. SIMULATION TOOLS: COMPLEMENTARY ASSUMPTIONS

- Compressor Inlet Conditions

Cycle	$T_{in,compr}$ [°C]	$P_{in,compr}$ [MPa]	$\eta_{pol,T}$ [%]	$\eta_{pol,C}$ [%]	$\eta_{pol,pump}$ [%]	ΔP_{HX} [%]
Transcritical Simple Recuperated	15	5	90	89	83	1
Supercritical Partial Cooling	32	5	90	89	83	1

15°C and 5 MPa to enable condensation

5 MPa to enable pre-compression

- Heat Exchangers pressure drops set to 1%

- Piping pressure drops neglected

- Thermo-physical properties of sCO2 obtained with open-source database CoolProp

- Solar field Cost obtained with the software SAM (System Advisor Model)

3. SIMULATION TOOLS: THERMAL ENERGY STORAGE

Intermediate-High TIT levels (>600ºC) → Solar Salt cannot be employed in TES system

FLiNaK: Ternary eutectic alkaline metal fluoride salt mixture, LiF-NaF-KF (46.5-11.5-42 mol %)

Salt	Composition	Freezing Point [ºC]	Boiling Point [ºC]	Density [kg/m^3]	Specific heat J/kgK]	Price [$/kg]
Solar Salt	$NaNO_3$-KNO_3	220	600	$-0.636 \cdot T + 2090$	$0.172 \cdot T + 1443$	1.1
FLiNaK	LiF-NaF-KF	454	1570	$2408.9 - 0.624 \cdot T$	$1267.2 + 1.0634 \cdot T$	8.6

- Constant ΔT=20ºC between FLiNaK and sCO2

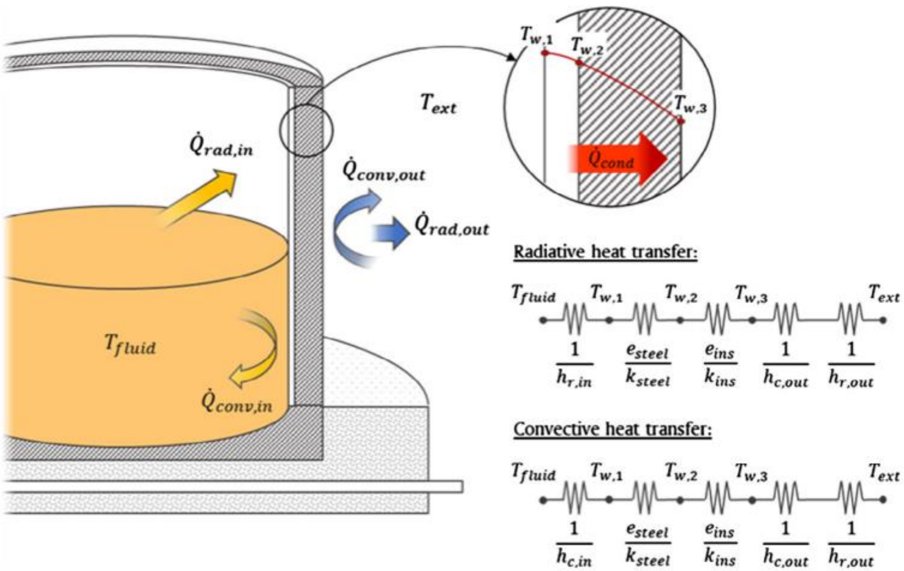
At those conditions, far from the critical region, sCO2 can be assumed to be an ideal gas.

- Freezing point 454ºC → minimum temperature 474ºC

ΔT_{solar} maximum value: 346 ºC

- Maximum temperature 820ºC ($T_{sub,receiver}$=800ºC)

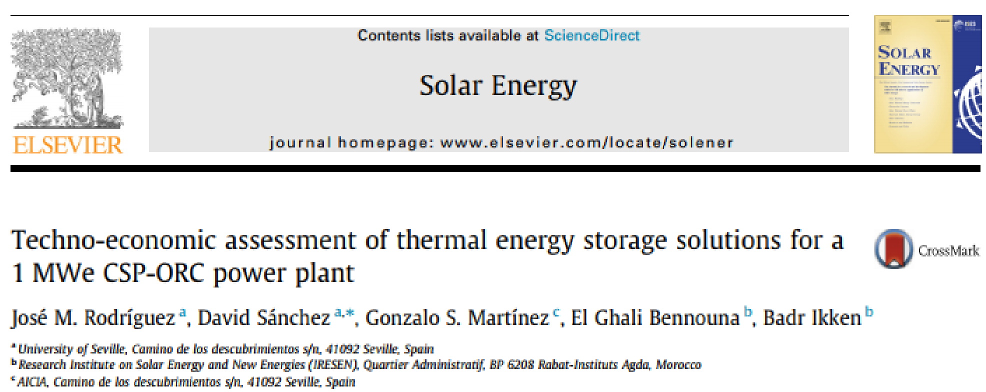
3. SIMULATION TOOLS: THERMAL ENERGY STORAGE



In-house model

(validated)

Installation and **insulation** costs, along with **foundations** and all **auxiliaries equipment** ones, are included in the in-house model.
Cost indexes to account the inflation and **cost scaling factors** have been employed to correct the results obtained.



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ELSEVIER

Techno-economic assessment of thermal energy storage solutions for a 1 MWe CSP-ORC power plant

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4. RESULTS

- Introduction & scope of the work
- Simulation tools
  - Heat exchangers
  - Turbomachinery
  - Complementary assumptions
  - Thermal Energy Storage
- **Results**
  - Thermodynamic analysis
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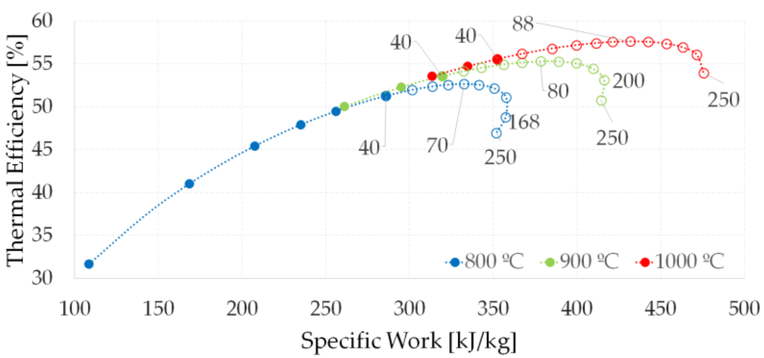
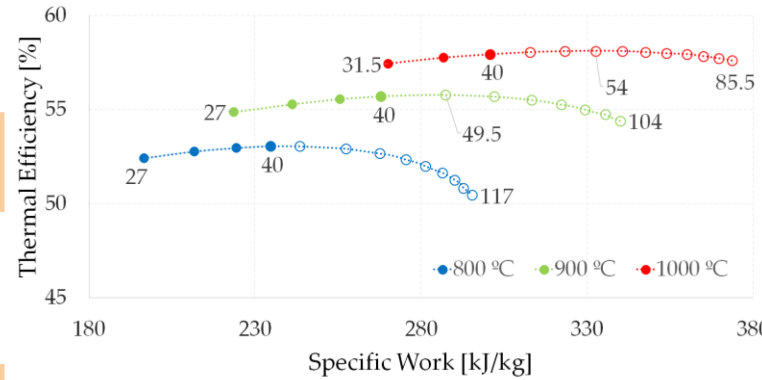
4. RESULTS: THERMODYNAMIC ANALYSIS

Transcritical CO2

Partial Cooling

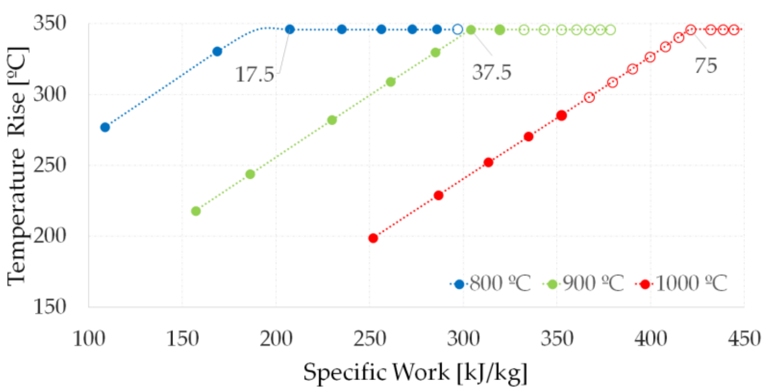


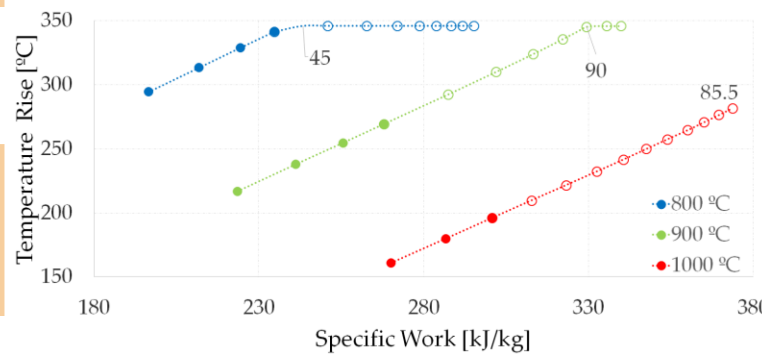


Shape changes significantly

Maximum values at different PR

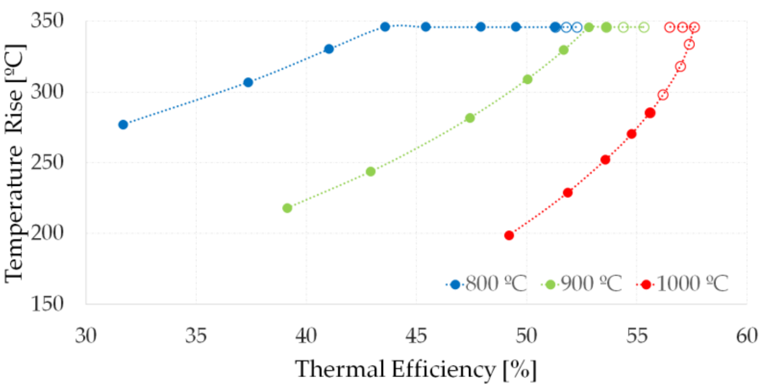
Peak performance above technological limit

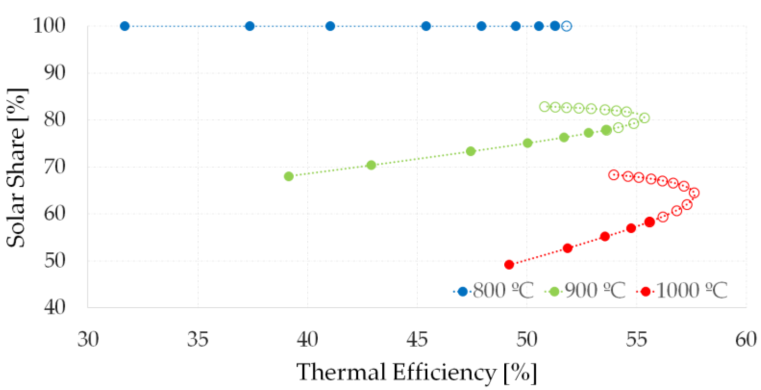




4. RESULTS:THERMODYNAMIC ANALYSIS

Transcritical CO2



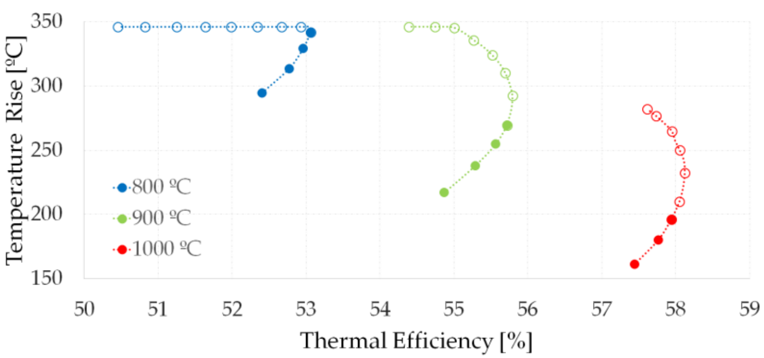


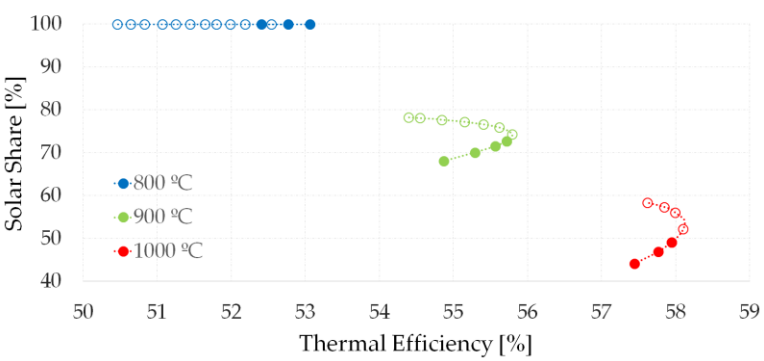
ΔT_{solar} and η_{th} are not directly proportional within technological limit

Larger increase in ΔT_{solar} rather than in η_{th} for the same rise of PR

Transcritical CO2 presents higher *SS* values

Partial Cooling

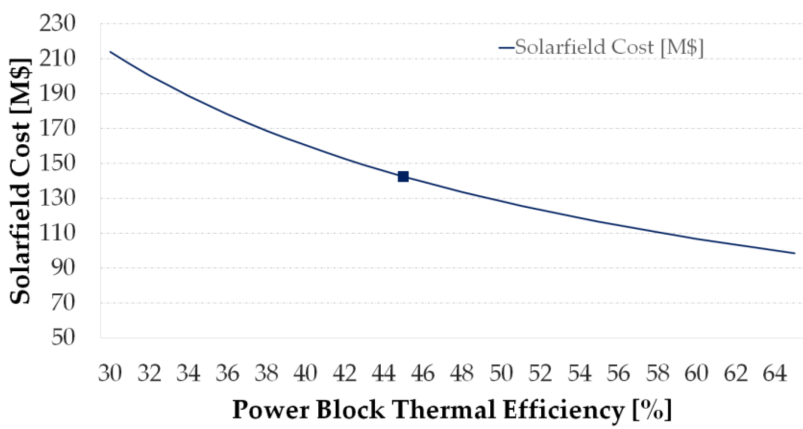


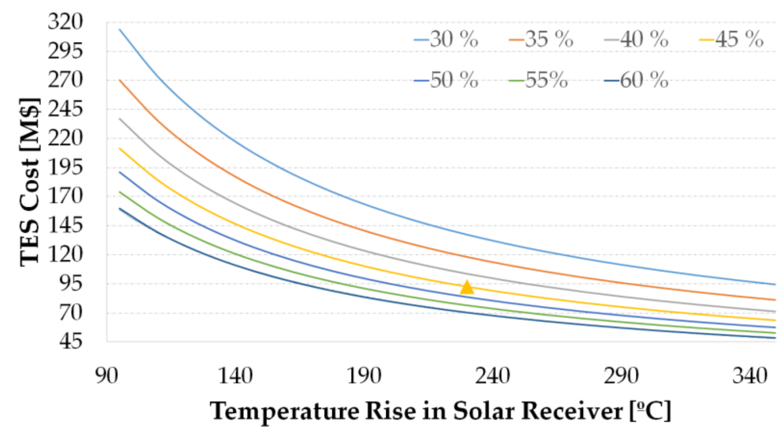


4. RESULTS: THERMO-ECONOMIC ANALYSIS

Reference case: $\eta_{th} = 45\%$, $\Delta T_{solar} = 230ºC$

Sensitivity Analysis: $\eta_{th} = 30 \div 60\%$, $\Delta T_{solar} = 90 \div 350ºC$





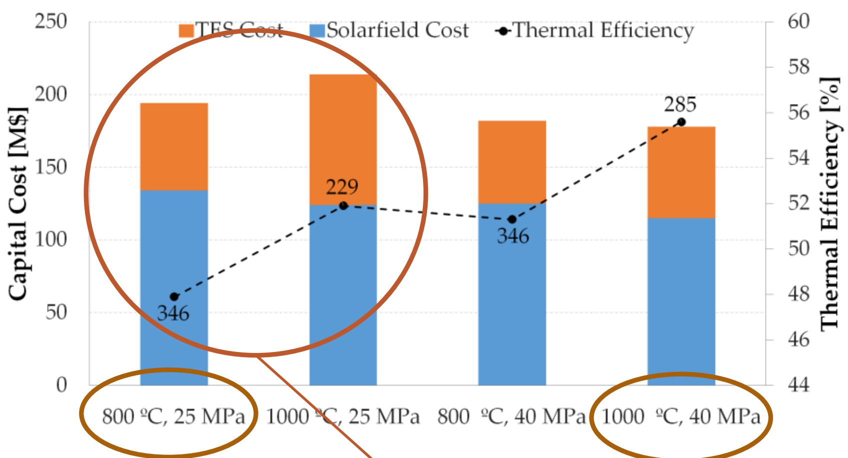
$\eta_{th} \uparrow \quad \rightarrow \quad Solar\ field\ Cost \downarrow$

$\Delta T_{solar} \uparrow \quad \rightarrow \quad TES\ Cost \downarrow$

$\eta_{th} \uparrow \quad \rightarrow \quad TES\ Cost \downarrow$

4. RESULTS: THERMO-ECONOMIC ANALYSIS

Transcritical CO2



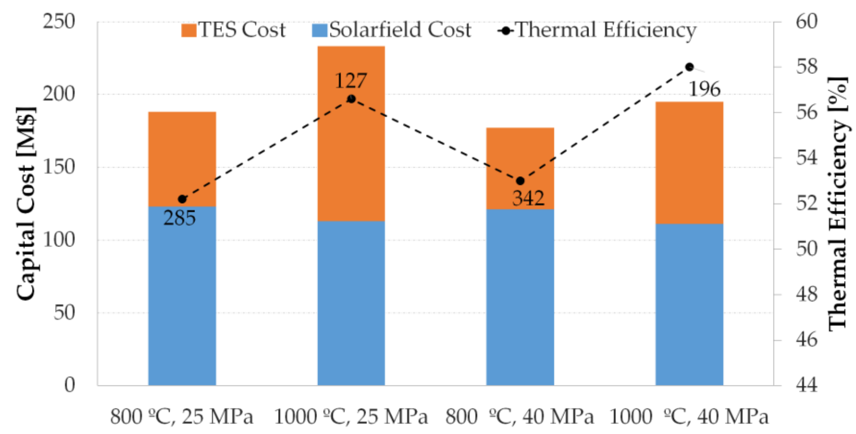
$TIT \uparrow \rightarrow \eta_{th} \uparrow \rightarrow Solar\ field\ Cost \downarrow$

$TIT \uparrow \rightarrow \Delta T_{solar} \downarrow \rightarrow TES\ Cost \uparrow$

$TIT \uparrow \rightarrow Total\ Cost \uparrow$

TES cost offsets the Solar field cost reduction!

Partial Cooling



$PR \uparrow \rightarrow \eta_{th} \uparrow \rightarrow Solar\ field\ Cost \downarrow$

$PR \uparrow \rightarrow \Delta T_{solar} \uparrow \rightarrow TES\ Cost \downarrow$

$PR \uparrow \rightarrow Total\ Cost \downarrow$

Not trivial!

4. RESULTS: THERMO-ECONOMIC ANALYSIS

$PR \uparrow \rightarrow \eta_{th} \uparrow \rightarrow Solar\ field\ Cost \downarrow$

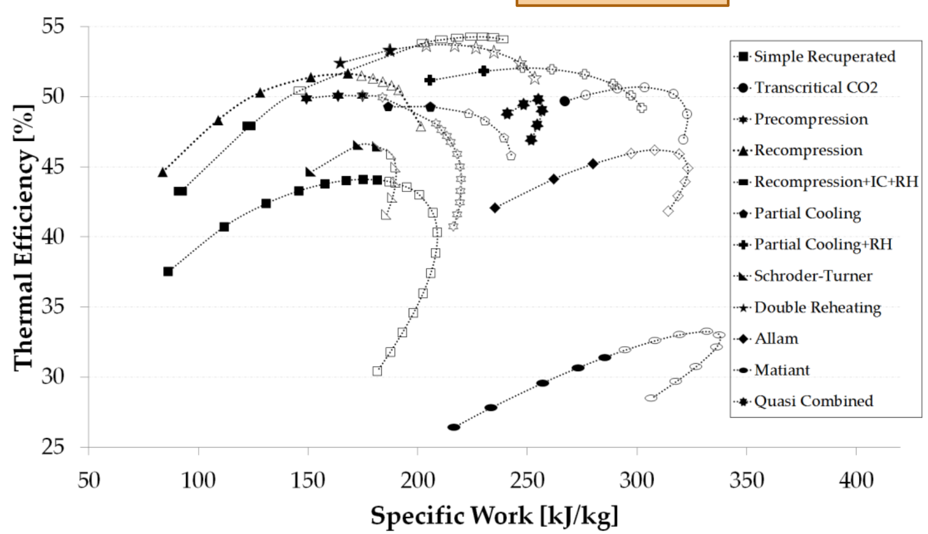
$PR \uparrow \rightarrow \Delta T_{solar} \uparrow \rightarrow TES\ Cost \downarrow$

$PR \uparrow \rightarrow Total\ Cost \downarrow$

Not trivial...

...but it can be known in advance!

TIT=750ºC



4. CONCLUSIONS

- Introduction & scope of the work
- Simulation tools
  - Heat exchangers
  - Turbomachinery
  - Complementary assumptions
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5. CONCLUSIONS

Thermodynamic approach

Transcritical CO2 → higher W_s, ΔT_{solar} and SS

Partial Cooling → higher η_{th}

Transcritical CO2				
	Thermal Efficiency [%]	Specific Work [kJ/kg]	Temperature Rise [ºC]	Solar Share [%]
800ºC, 25 MPa	47,9	235,2	346,0	100,0
1000ºC, 25 MPa	51,9	286,7	228,9	52,8

Partial Cooling				
	Thermal Efficiency [%]	Specific Work [kJ/kg]	Temperature Rise [ºC]	Solar Share [%]
800ºC, 25 MPa	52,2	188,5	284,8	100,0
1000ºC, 25 MPa	56,7	241,1	128,4	39,0

5. CONCLUSIONS

Thermo-economic approach

Partial Cooling seems to better combine thermodynamic and economic features, obtaining a higher η_{th} with similar Solar field and TES costs (for 800ºC)

In particular, it seems to be a larger benefit coming from higher PR rather than higher TIT, at least for the two cycles considered.

Same technology and materials, but heavier equipment

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