COMPONENTS' AND MATERIALS' PERFORMANCE FOR ADVANCED SOLAR SUPERCRITICAL CO2 POWERPLANTS

Process parameters of solar sCO_2 Brayton cycle

Deliverable Number 1.1

WP1 "Materials operation conditions and their feasibility studies"

Date: January 13rd, 2021

Deliverable type: Report

Dissemination level: Public

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This project has received funding from the European Union's Horizon 2020 Research and Innovation Action (RIA) under grant agreement No. **958418.**

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ABOUT THE PROJECT

COMPASsCO$_2$ is a 4-year HORIZON2020 project started on 1.11.2020. It is led by the German Aerospace Center (DLR), with eleven additional partners from seven European countries.

COMPASsCO$_2$ aims to integrate CSP particle systems into highly efficient s-CO$_2$ Brayton power cycles for electricity production. In COMPASsCO2, the key component for such an integration, i.e. the particle/s-CO$_2$ heat exchanger, will be validated in a relevant environment. To reach this goal, the consortium will produce tailored particle and alloy combinations that meet the extreme operating conditions in terms of temperature, pressure, abrasion and hot oxidation/carburization of the heat exchanger tubes and the particles moving around/across them. The proposed innovative CSP s-CO$_2$ Brayton cycle plants will be flexible, highly efficient, economic and 100% carbon neutral large-scale electricity producers.

The research focus of COMPASsCO2 is on three main technological improvements: development of new particles, development of new metal alloys and development of the heat exchanger section.

DISCLAIMER

This project has received funding from the European Union's Horizon 2020 Research and Innovation Action (RIA) under grant agreement No. **958418.**

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LIST OF ABBREVIATIONS

COMPASsCO2	Components' and Materials' Performance for Advanced Solar Supercritical CO2 Power Plants
CSP	Concentrating Solar Power
sCO_2	Supercritical carbon dioxide
TRL	Technology Readiness Level
TIT	Turbine inlet temperature
LCOE	Levelized cost of electricity
PHX	Primary heat exchanger
PB	Power block

1 ABSTRACT

The Work Package 1 of the COMPASsCO2 is mainly focused on the materials operation conditions in an industrial environment and is divided into different tasks. The first task of this WP is to identify the process parameters of the sCO_2 Brayton cycle to be driven by solar energy. Within this task, the target process parameters such as design pressure, temperature and flow rates of the supercritical CO2 are defined. Before selecting a Brayton cycle, a literature review is performed by partners of the consortium to learn from worldwide supercritical CO_2 cycles.

The next step is the simulations of several cases defined by a different supercritical CO_2 cycle type. A total of 10 different Brayton cycles were considered.

By varying some parameters, a sensitivity study is performed to assess the net power block efficiency of the cycle and the Levelized Cost of Electricity (LCOE) of the plant as well. Targeting the highest power block efficiency is one of the objectives defined in the Work Program. Nevertheless, as this project also aims to identify potential markets and industrial applications, its economic outcomes have to be competitive too, therefore the consortium is interested on low levelized cost of electricity (LCOE) as well.

The sensitivity study highlighted that the Supercritical Simple Recuperated Brayton cycle provides the lowest LCOE while the Supercritical Partial Cooling Brayton cycle with Intercooling and Reheating delivers the highest power block efficiency with a low LCOE in comparison to other high-efficiency configurations.

Table 1: ***Techno-economic results of the most promising cycles among the 10 sCO2 Brayton cycles options***

Cycle	LCOE [USD-cent/kW_eh]	$\eta_{PB,net}$ [%]
Simple Recuperated Brayton cycle	12.6	42.7
Partial Cooling Brayton cycle with Intercooling and Reheating	14.9	49.0

In accordance with the project objectives, it is the Partial Cooling with Intercooling and Reheating cycle that is selected due to its highest efficiency among the 10 envisaged Brayton cycles options.

Once the cycle is selected, the process parameters regarding the particles-sCO_2 heat exchanger are defined in connection with the best efficiency scenario. The process parameter values are required to estimate the performance and lifetime of the heat exchanger and to identify different candidate alloys for its manufacturing.

2 INTRODUCTION

The goal of this deliverable is to fix the parameters relevant for the heat exchanger design (mass flow, temperatures and pressures). In order to obtain this data, a Brayton cycle needs to be selected. Because this cycle is not commercially applied yet, there are many options described in the literature. The supercritical CO2 Brayton cycle for COMPASsCO2 should have a very high efficiency, as this is one key requirements of the Work Program of this project[1].

Based on the Brayton cycle selected, the heat and mass balance provide the boundary conditions at the heat exchanger, which are the main outcome required by other tasks of the project.

3 LITERATURE REVIEW ON SCO2 THERMODYNAMIC CYCLES

In a first step, a literature review was conducted, in which parameters and lessons learned from worldwide (also non-solar) supercritical CO_2 cycles were summarized. This literature review provided a better understanding of the limitations and possible applications of several types of sCO_2 cycles and their ranges of process parameters. The list of literature reviewed is summarized in the last section of this document (Section 9).

The literature review demonstrated that there is not any consensus on a most suitable sCO_2 cycle for solar applications. For that reason, different cycle types which are described in the next section were identified and assessed.

Furthermore, as the Technology Readiness Level of such thermodynamic cycle is still relatively low, some data were missing from the very high efficiency cycles which hampered our ability to model some of them and assess their economic viability. The main data that were often missing listed below:

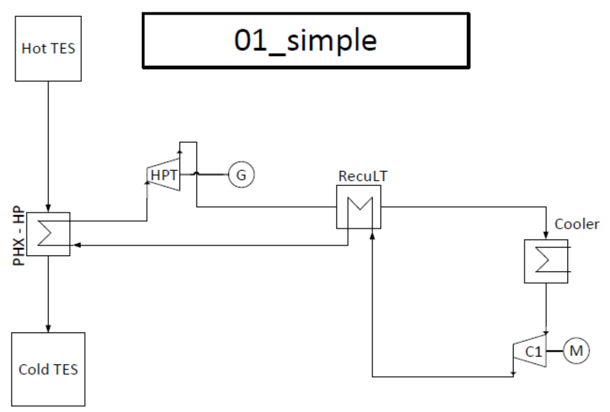
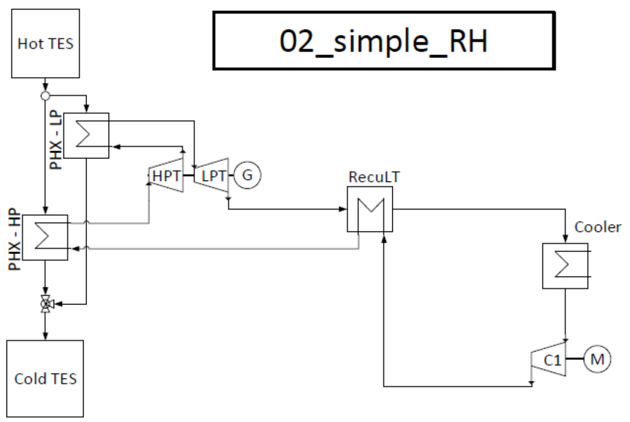
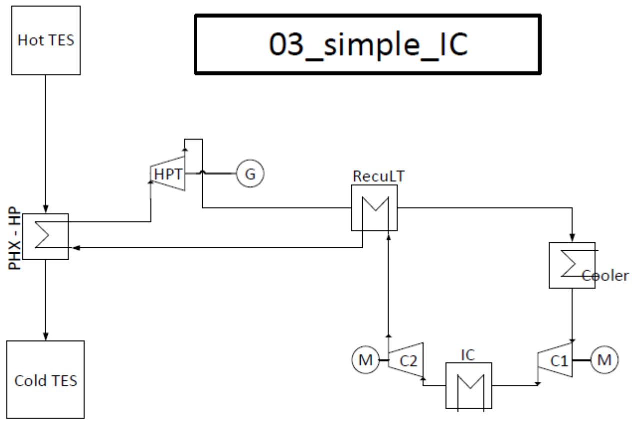
- The cost data of the equipment
- The pressure drops of the components
- The definition of the efficiencies (thermal vs cycle efficiency)
- The parasitic power consumption

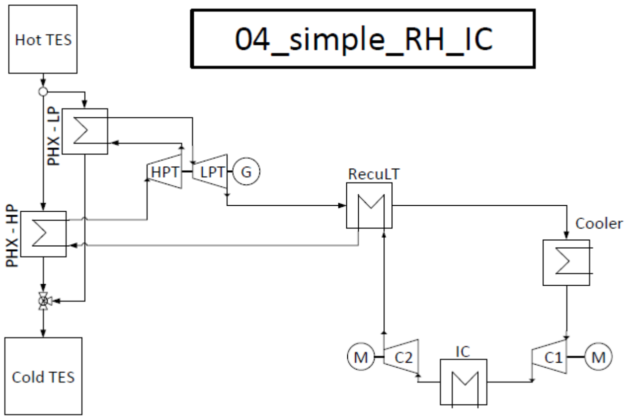
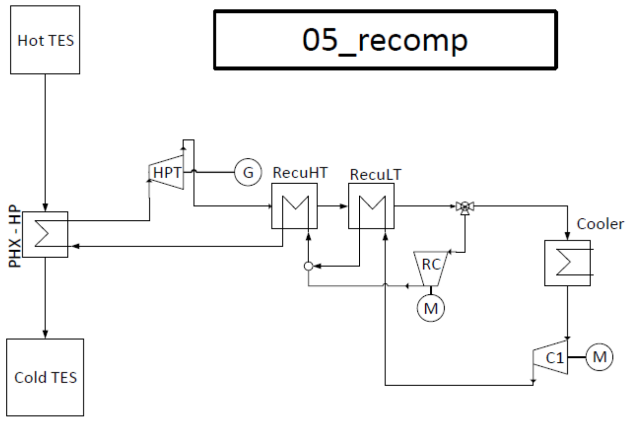
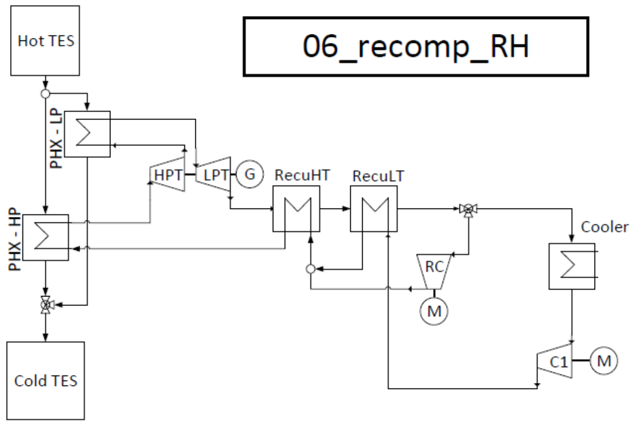
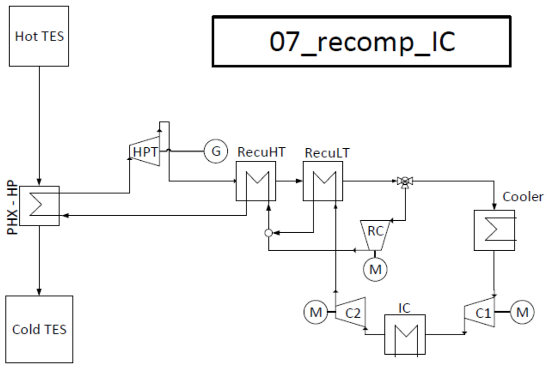
[1] **Work Program: H2020 LC-SPIRE-08-2020**: Novel high performance materials and components (RIA). h2020-wp1820-leit-nmp_en.pdf (europa.eu)

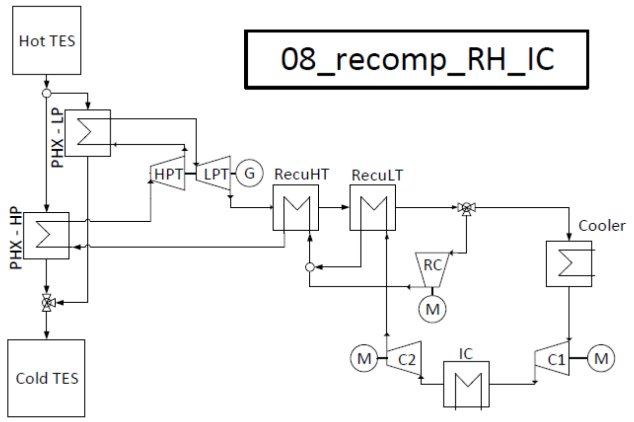
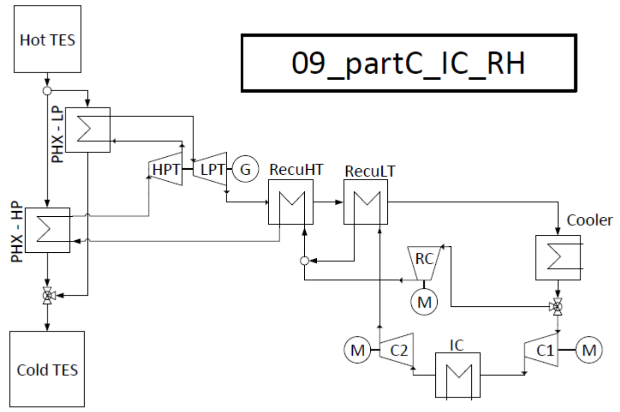
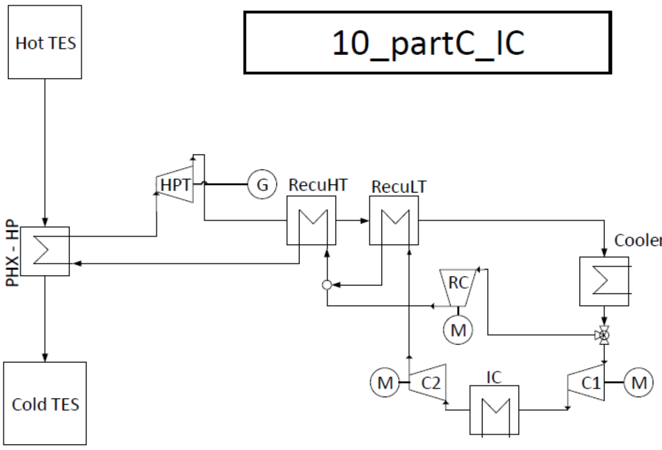
4 BRAYTON CYCLES ANALYSED

As the advantages and disadvantages of the possible configurations are quite broad, 10 different types of thermodynamic cycles were assessed in our study. They include 4 simple recuperated cycles, 4 recompression cycles and 2 partial cooling cycles. Each of them was modelled with and without reheat (RH) or intercooling (IC) if applicable. A summary is exposed in the following table.

Table 2: ***sCO2 cycles description***

<table>
<tr><th>sCO2 cycles</th><th>Cycle description</th></tr>
<tr><td>
</td><td>The Supercritical Simple Recuperated cycle is a simple recuperated Brayton cycle adapted to the supercritical region. It is aimed at overcoming (to the extent possible) the inherent limitations presented by a standard/classic Brayton cycle, such as the very high compression work and large heat transfer areas due to a low specific volume. Taking advantage of the thermo-physical properties of carbon dioxide in the supercritical region, not only is compression work drastically reduced, but the resulting system is also much more compact and less sensitive to pressure drops.</td></tr>
<tr><td>
</td><td>The Supercritical Simple Reheating Recuperated cycle.
The introduction of reheating enables a twofold improvement of cycle performance: expansion work increases and the thermal stresses due to the high pressures and temperatures at turbine inlet are largely reduced.</td></tr>
<tr><td>
</td><td>The Supercritical Simple Intercooling Recuperated cycle.
This cycle is an evolution of the Supercritical Simple Recuperated cycle, with the addition of intercooled compression, originally proposed for nuclear applications.</td></tr>
</table>

	*The Supercritical Simple Reheating and Intercooling Recuperated cycle.* This cycle includes those recuperative cycles that are characterized by a multi-stage intercooled compression and a reheated (therefore two-stage) expansion.
	*The Supercritical Recompression* cycle is named after the re-compressor located in parallel with the main compressor. The flow is therefore split in two for the compression process. The first stream flows into the cooler where its temperature is reduced to a value close to the critical temperature. The second stream is not cooled but compressed directly in the re-compressor. The benefits of this layout are twofold. First, the pinch point problem in the low temperature recuperator is attenuated due to the change in heat capacity that is brought about by the dissimilar mass flow rates on the high (reduced flow) and low pressure (full flow) sides of the equipment. Second, the thermal duty of the cooler is also reduced, hence reducing the size of this equipment.
	*The Supercritical Reheating Recompression cycle* is a mere evolution of the Recompression cycle, characterized by the addition of a single reheat. This cycle is specifically designed for sodium-cooled fast reactor applications where reheating takes place in a Na-to-CO2 heat exchanger
	*The Supercritical Intercooling Recompression cycle* is a split-flow, highly-recuperative cycle characterized by a multi-stage compression process. This configuration is very similar to the Recompression cycle but with the addition of intercooling in the main compression line.

	*The Supercritical Intercooling and Reheating Recompression cycle.* The general layout is aimed at enhancing the performance of the Recompression cycles by merely adding multi-stage intercooled compression and reheated expansion processes.
	*The Supercritical Partial Cooling cycle with Intercooling and Reheating.* The general layout is aimed at enhancing the performance of the Partial Cooling cycles by merely adding multi-stage intercooled compression and reheated expansion processes.
	*The Supercritical Partial Cooling cycle with Intercooling.* It is a modification of the Partial condensation with precompression cycle, very similar to the Supercritical Recompression layout but with the addition of a cooler and a pre-compressor before the flow-split. The interest of the Partial Cooling cycle is a higher specific work and a very low sensitivity of global efficiency to deviations of pressure ratio from the optimum value.

The cost data for the sCO2 cycles equipment was derived from a publication[2]. The cost data for primary heat exchanger (PHX), indirect power block costs and the other subsystems of a particle CSP system are derived from DLR internal data3.

[2] **Weiland, N. T., et al. (2019).** sCO2 Power Cycle Component Cost Correlations From DOE Data Spanning Multiple Scales and Applications. ASME Turbo Expo 2019: Turbomachinery Technical Conference and Exposition.
[3] **Heller, L. G., Stefan; Buck, Reiner** (in press). SCO2 Power Cycle Design without Heat Source Limitations: Solar Thermal Particle Technologyin the CARBOSOLA Project. 4th European sCO2 Conference for Energy Systems, Prague, Czech Republic.

5 METHODOLOGY FOR CYCLE SELECTION

The design point efficiencies of the cycles were simulated using Ebsilon Professional v.14 with an ambient temperature of 19°C. The sizing of all solar components (heliostat field, receiver, thermal energy storage) were done using a defined oversizing (solar multiple = 2.5) and storage size (12 h full load equivalent). The annual input to the storage system, and therefore to the power cycle, was approximated with estimated annual average efficiencies of these solar components. More Details on the models, boundary conditions and parameters can be found in an accepted manuscript[4].

With the described model, an optimization process was performed in order to identify the cycles that fulfil the COMPASsCO2 goals. The objective functions of this model are the power block efficiency and the Levelized Cost of Electricity (LCOE).

The main parameters that were varied for the sensitivity analysis were:

Table 3: ***Parameters ranges***

Parameter	Unit	Range
Turbine inlet temperature (TIT)	[°C]	550…700
Compressor inlet pressure	[bar_a]	45…80
Recuperator terminal temperature difference	[K]	5…60
Main cooler and IC conductance area product (U*A)	[W_t/K]	… 17.5
Recompression fraction	[%]	20…45

The cycle and power plant costs are calculated based on component cost correlations and subsystem cost estimates, respectively. Meanwhile, the LCOE is derived by estimating the annual power production of the plant.

[4] **Heller, L. G., Stefan; Buck, Reiner** (in press). SCO2 Power Cycle Design without Heat Source Limitations: Solar Thermal Particle Technologyin the CARBOSOLA Project. 4th European sCO2 Conference for Energy Systems, Prague, Czech Republic.

6 CYCLE SELECTION

The following graph exposes different values of LCOE versus the power block efficiency for each cycle and with different turbine inlet temperatures (TIT). Even though the TIT is fixed at 700°C or above in this project, it is still interesting to include other cycles with lower TIT to observe its influence on the LCOE. The model used assumes a cost increase of the primary heat exchanger by a factor 4.2 between TIT=550°C and 700°C.

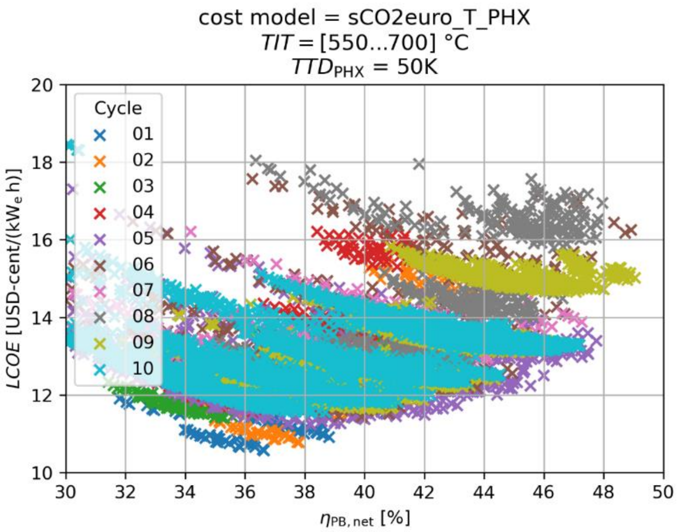


*Figure 1: **LCOE vs PB efficiency for each cycles and for a range of TIT***

As the COMPASsCO2 project will focus on a $TIT = 700°C$, only the corresponding points can be kept, therefore obtaining the following graph.

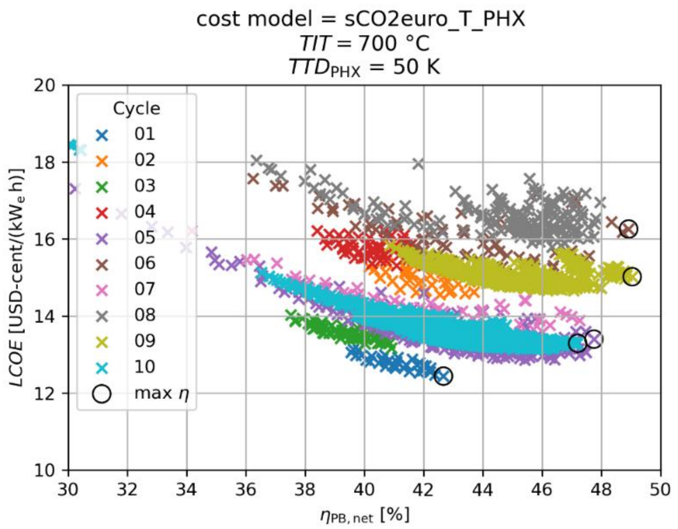


*Figure 2: **LCOE vs PB efficiency for each cycle and for TIT = 700°C***

Table 4: ***Parametric analysis main results***

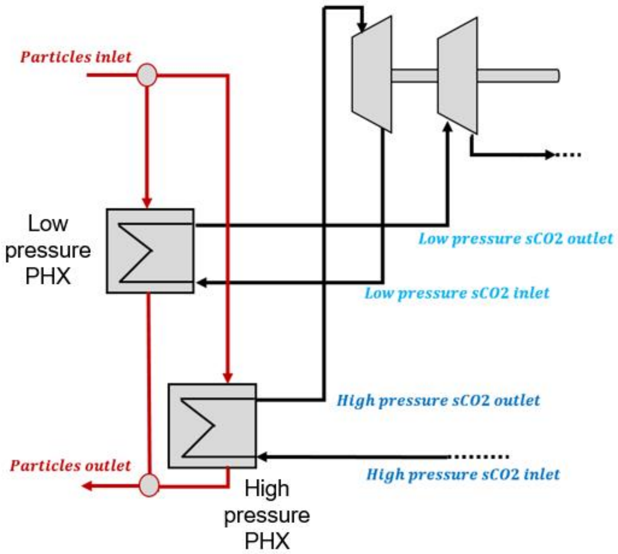
Cycle	LCOE [USD-cent/kW$_e$ h]	$\eta_{PB,net}$ [%]	$T_{PHX,sCO2,in}$ [°C]	$T_{PHX,sCO2,in,RH}$ [°C]
01	12.4	42.7	442	-
05	13.4	47.8	504	-
06	16.3	48.9	577	620
09	15.0	49.0	532	583
10	13.3	47.2	438	493

As the results highlight, the cycle that possesses the highest power block efficiency (49.0 %) is the partial cooling with reheat and intercooling (configuration 9) and the cycle configuration with the lowest LCOE is the simple cycle (configuration 1), although its net efficiency (42.7%) is not much different that state-of-the-art Rankine cycles.

Globally, lower TITs lead to lower LCOE values. But because in COMPASsCO2 applications are searched for TIT ≥ 700°C and the main focus is not on cost reduction but on material development to push the boundaries of cycle efficiency, the choice fell on the configuration 9 that possesses the highest power block efficiency while having a lower LCOE compared to the other high-efficiency cycles. Furthermore, the results of COMPASsCO2 will hopefully lead to significant cost reductions of high-temperature components so that these technologies become economically superior.

7 PROCESS PARAMETERS OUTCOMES

The process parameters related to the configuration 9 are shown on the following sketch and table of the PHX or particle/sCO_2 heat exchanger, which is the key component to be designed and tested in COMPASsCO2.



Parameters	Particles (high pressure PHX)	Particles (Low pressure PHX)	sCO2 (high pressure PHX)	sCO2 (low pressure PHX)
PHX inlet temperature [°C]	900	900	532.8	583.4
PHX outlet temperature [°C]	582.8	633.4	700	700
PHX inlet pressure [bar]	/	/	265.3	110.4
PHX outlet pressure [bar]	/	/	260	108.2
Mass flowrate [kg/s]	355.9	288.3	632.6	632.6

Figure 3: ***Process parameters related to the configuration 9***

The parameters values that lead to these process parameters are exposed hereunder.

Table 5: ***Parameters values related to the Figure 3 process parameters***

Parameter	Unit	Value
Pre-compressor inlet pressure	[bar]	45
Main compressor inlet pressure	[bar]	80
Recuperator TTD	[K]	5
Pre-cooler U*A	[MW_{th}/K]	3.3
Intercooler U*A	[MW_{th}/K]	5.6
Recompression fraction	[%]	44

8 DISCUSSION OF THE RESULTS

The literature review revealed other cycles than those considered in our optimization process which can achieve higher net power block efficiency. However, as the Technology Readiness Level (TRL) is still quite low for such concepts, data were missing to properly simulate them. If this kind of technology reaches higher TRLs, more data will be available to target a techno-economic optimum including such type of plants.

The evaluated cycles provide a set of parameters which are very challenging for the material development, which is in-line with the main scope of the project COMPASsCO2. In further project results, especially towards the end of the project, the techno-economic competitiveness of the overall plant will be assessed in detail considering the developed materials and any improvement of the Brayton cycle technology published by other researchers or companies.

9 LITERATURE REVIEW

*Table 6: **Literature review list***

Title	Supercritical CO2 Brayton cycles for solar-thermal energy	Exergetic analysis of supercritical CO2 Brayton cycles integrated with solar central receivers	Techno-economic Analysis of Alternative Solarized s-CO2 Brayton Cycle Configurations	Impact of Solar Tower Design Parameters on sCO2-based Solar Tower Plants
sCO2 cycles	recompression	simple, recompression, partial cooling, intercooling	simple, recompression, others	Recompression + reheating
Year of publication	2013	2015	2016	2016
Turbine inlet temperature		550 °C-850 °C	600 °C-700 °C	605 °C
Main findings	necessary developments identified; salt-sCO2 PHX design and material concerns briefly discussed; indirect system preferable for larger TES systems	Exergetic optimum at TIT=700 °C-750 °C	large effect of temperature difference over PHX; simple recuperated cycle most cost-effective	lowest LCOE for biggest storage temperature spread; very competitive LCOE
Authors	Brian D. Iverson a,b,⇑, Thomas M. Conboy b, James J. Pasch b, Alan M. Kruizenga	Ricardo Vasquez Padilla a,⇑, Yen Chean Soo Too a, Regano Benito b, Wes Stein a	Ho, Carlson, Garg, Kumar	Buck, Giuliano

Title	Supercritical Carbon Dioxide Power Cycle Design and Configuration Optimization to Minimize Levelized Cost of Energy of Molten Salt Power Towers Operating at 650°C	Thermo-Economic Assessment of Supercritical CO2 Power Cycles for Concentrated Solar Power Plants	Thermo-Economic Optimization of an Air Driven Supercritical CO2 Brayton Power Cycle for Concentrating Solar Power Plant with Packed Bed Thermal Energy Storage	Benchmarking supercritical carbon dioxide cycles against steam Rankine cycles for Concentrated Solar Power
sCO2 cycles	simple, recompression, partial cooling	many, steam	Recompression + reheating	recompression, partial cooling, combined, steam
Year of publication	2019	2019	2019	2015
Turbine inlet temperature	630 °C	750 °C and others	600 °C-850 °C	600 °C
Main findings	large effect of storage temperature spread; lowest LCOE for partial cooling; LCOE of simple and recompression comparable; lowest LCOE for highest PHX approach temperature	large effect of storage temperature spread; lowest LCOE for partial cooling->simple->recompression ;no clear advantage over steam cycle; part-load modelling	very competitive LCOE but with questionable cost model; small system (10MWe) economically viable; lowest LCOE at 825 °C	superheated steam cycle more cost-effective and efficient
Authors	Neises, Turchi	Crespi	Silvia Trevisan*, *Rafael Guédez, Björn Laumert*	V.T. Cheang ⇑, R.A. Hedderwick, C. McGregor
Place of publication	/	Thesis, Uni. De Sevilla	https://doi.org/10.1016/j.solener.2020.10.069	https://dx.doi.org/10.1016/j.solener.2014.12.016

Title	Parametric Analysis of Particle CSP System Performance and Cost to Intrinsic Particle Properties and Operating Conditions	sCO2 Power Cycle Design Without Heat Source Limitations: Solar Thermal Particle Technology in the Carbosolar Project	Optimizing the Supercritical CO2 Brayton Cycle for Concentrating Solar Power Application	Planning for Successful Transients and Trips in a 1 MWe-Scale High-Temperature sCO2 Test Loop
sCO2 cycles	recompression	simple, recompression, partial cooling, steam	recompression, partial cooling	Recompression
Year of publication	2019	unknown	2018	2018
Turbine inlet temperature	715 °C	550 °C-650 °C	600 °C-715 °C	715°C
Main findings	sCO2 cycle costs twice as high as desired (even when neglecting indirect cost); lowest LCOE for highest hot tank temperature and large storage (>15h)	in terms of LCOE: particle systems better than salt; simple cycle better than recompression and partial cooling (these two similar); RH and IC increase LCOE; steam similar to best sCO2 setup; low sCO2 cycle efficiency at economic optimum; equipment cost dominated by PHX	efficiency (50%) and cost (600 USD/kWe) targets of sCO2 power blocks currently not met; lower TIT (~650 °C vs. 715 °C) could lead to significant cost reductions of turbine, storage, PHX, piping, recuperator	Many of the challenges coming from low-temperature shaft end seals in a high-temperature turbine (high thermal gradients)
Authors	Kevin J. Albrecht, Matthew L. Bauer, Clifford K. Ho	Heller, Glos, Buck	Rajgopal Vijaykumar, Matthew L. Bauer, Mark Lausten, and Abraham M. Shultz	Timothy C. Allison, Douglas Carl Hofer, Jeff Jeffrey Moore, Joseph M. Thorp
Place of publication	https://doi.org/10.1115/ES2019-3893	The 4th European sCO2 Conference for Energy Systems	The 6th International Supercritical CO2 Power Cycles Symposium	https://doi.org/10.1115/GT2018-75873

Title	A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors	Performance Improvement Options for the Supercritical Carbon Dioxide Brayton Cycle	Energy Analysis of the S-CO2 Brayton Cycle with Improved Heat Regeneration	sCO2 Power Cycle Component Cost Correlations From DOE Data Spanning Multiple Scales and Applications
sCO2 cycles	Simple, Recompression, Indirect	Simple	Recompression	Recompression
Year of publication	2004	2007	2018	2019
Turbine inlet temperature	Depends on the cycle	480°C	500-850°C	550°C
Main findings	see the article for details	Options to improve the cycle efficiency: increasing HEX size, raising of the cycle high end pressure and optimization of the low end temperature and/or pressure to operate as close to the critical point as possible	The presented a modified version of a recompression Brayton cycle with partial cooling has different key outcomes that are summed up in the article	While a considerable number of vendor quotes and estimates have been considered in this study, there are several components for which the number of quotes available were insufficient to generate a suitable cost correlation
Authors	V. Dostal, M.J. Driscoll, P. Hejzlar	A. Moisseytsev, J.J. Sienicki	Muhammad Ehtisham Siddiqui, Khalid H. Almitani	Nathan T. Weiland, Blake W. Lance, Sandeep R. Pidaparti
Place of publication	/	/	https://doi.org/10.3390/pr7010003	/

Title	Review of Supercritical CO2 Power Cycle Technology and Current Status of Research and Development	Commissioning of a 1MWe Supercritical CO2 Test Loop	Supercritical Carbon Dioxide Applications for Energy Conversion Systems	On the Conceptual Design of Novel Supercritical CO2 Power Cycles for Waste Heat Recovery
sCO2 cycles	Different types considered	Recompression	Recompression with regeneration	Different types considered
Year of publication	2015	2018	2015	2020
Turbine inlet temperature	Depends on the cycle	700°C	455°C	600°C
Main findings	The main benefit of the sCO2 cycle is the small size of the overall system and its application includes not only the next generation of nuclear reactors byt also conventional water-cooled reactors, coal power plants and several renewable energy sources	/	The sCO2 recompression cycle efficiencies are much higher than the Brayton's one	A promising cycle can be obtained by the combination of two elementary Brayton cycles which are superimposed
Authors	Yoonhan Ahn, Seong Jun Bae, Minseok Kim, Seong Kuk Cho, Seungjoon Baik, Jeong Ik Lee, Jae Eun Cha	J. Moore, S. Cich, M. Day, T. Allison, J. Wade, D. Hofer	Damiano Vitale Di Maio, Alessandro Boccitto, Gianfranco Caruso	Giovanni Manente, Mario Costa
Place of publication	http://dx.doi.org/10.1016/j.net.2015.06.009	/	http://doi.org/10.1016/j.egypro.2015.11.818	https://doi.org/10.3390/en13020370

Title	Innovative power generation systems using supercritical CO2 cycles	Thermo-Economic Assessment of Supercritical CO2 Power Cycles for Concentrated Solar Power Plants	Supercritical Carbon Dioxide Cycles for Gas Fast Reactor	Supercritical CO2 Cycles for Gas Turbine Combined Cycle Power Plants
sCO2 cycles	Different types considered	Different types considered	Different types considered	Different types considered
Year of publication	2017	2019	2011	2010
Turbine inlet temperature	750°C	Depends on the cycle	500-850°C	/
Main findings	A lot more needs to be done before a full coal-based sCO2 cycle can be developed and commercialized with confidence	The assessment is quite difficult because of the low TRL of the sCO2 technologies therefore a set of assumptions were made and the main conclusions are available in the thesis	The most promising cycle for gas fast reactor seems to be the partial-cooling cycle	sCO2 cycle can generate more power than existing steam cycles for gas turbine application. It also leads to reduced plant footprint, simplified and flexible operation and installation
Authors	Qian Zhu	Francesco Crespi	Martin Kulhanek, Petr Hajek	Timothy J. Held
Place of publication	https://doi.org/10.1093/ce/zkx003	/	/	/

10 REFERENCES

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2. **Ho, C. K., et al. (2016).** "Technoeconomic Analysis of Alternative Solarized s-CO2 Brayton Cycle Configurations." Journal of Solar Energy Engineering **138**(5).
3. **Buck, R. and S. Giuliano (2018).** "Impact of solar tower design parameters on sCO2-based solar tower plants." 2nd European sCO2 Conference 2018: 30-31 August 2018, Essen, Germany: 160-167.
4. **Neises, T. and C. Turchi (2019).** "Supercritical carbon dioxide power cycle design and configuration optimization to minimize levelized cost of energy of molten salt power towers operating at 650 °C." Solar Energy **181**: 27-36.
5. **Crespi, F. M. (2019).** Thermo-economic assessment of supercritical CO2 power cycles for concentrated solar power plants. Department of Energy Engineering
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