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SCARABEUS: Supercritical Carbon Dioxide/Alternative Fluid Blends for Efficiency Upgrade of Solar Power Plants

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Abstract. The future of Concentrated Solar Power technology relies on significant cost reduction to be competitive against both fossil fuel power stations and renewable technologies as photovoltaics and wind. Most of the research activity on concentrated solar power focuses on supercritical CO_2 cycles to increase the solar plant efficiency together with a cost reduction. Recently, several research groups have started investigating the blending of CO_2 with small amounts of additives to boost the thermodynamic cycle performance. The SCARABEUS project aims at developing and demonstrating CO_2 blends in concentrating solar power plant with maximum temperatures of 700°C, power cycle efficiency above 50% and cost of electricity below 96 €/MWh. The innovative fluid and newly developed components will be validated at a relevant scale (300 kWth) for 300 h in a CSP-like operating environment.

INTRODUCTION

Concentrated Solar Power (CSP) plants are set to play an important role in the energy supply mix in the twenty first century. Unfortunately, the Levelized Cost of Electricity (LCoE) of CSP (currently about 150 €/MWh) has not attained the level targeted (100 €/MWh) except for few installations in exceptionally good locations. As of today, many ongoing research projects aiming at enhancing the efficiency of the power block (PB) and reducing the associated costs are based on supercritical CO_2 technology. However, relatively high ambient temperatures, typical in regions characterized by high solar irradiation, remain the Achilles heel of supercritical CO_2 cycles as the efficiency of these systems drops dramatically in warm environments where ambient temperature is close to or higher than the critical temperature of CO_2 (31°C), hence not allowing to adopt condensation cycles with expectedly higher efficiencies. This issue stems as an intrinsic critical hurdle for the future commercialization of CSP plants, which may be difficult to overcome by any means with the technology currently in use or with standard supercritical CO_2 technology.

To address this limitation, the SCARABEUS project [1] proposes a modified working fluid whereby carbon dioxide is blended with certain additives to enable condensation at temperatures as high as 60°C whilst, at the same time, still withstanding the required peak cycle temperatures.

The SCARABEUS project aims at developing and demonstrating an innovative power cycle based on blended CO_2 for CSP applications, yielding higher efficiency and lower cost. As reported in Table 1, the application of supercritical CO_2 blends has the potential to increase the thermomechanical conversion efficiency from the current 42% to above 50%. In addition, capital expenditure (CAPEX) and operating expense (OPEX) can be reduced by 30% and by 35% respectively with respect to state-of-the-art steam cycles, thus exceeding the reduction achievable with standard supercritical CO_2 technology.

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TABLE 1. CSP power plant performance comparison

Parameter	State-of-the-art Steam cycle	sCO_2 targets		SCARABEUS project	
Maximum cycle temperature (°C)	550 [2]	550	700	550	700
Condensing cycle	Yes	No	No	Yes	Yes
Power block net conversion efficiency	40-43% [3]	41%	47% [4,5]	>43% [6]	>50% [6]
Overall solar to electric efficiency	22% [7]	22%	24%	24% [6]	>26% [6]
Power block - Capital cost (€/kW)	1100-1300 [8]	900	1000 [9]	750 [6]	700 [6]
LCOE (€/MWh)	150	150	128 [10]	<110 [6]	<96 [6]
Carbon footprint (kgCO2eq/MWh)	27 [11]	25	22	<24	<18

The primary objective of the SCARABEUS project is to demonstrate that using blended-CO_2 is the only route currently possible to meeting the very ambitious economic performance of next generation CSP plants. There are two main areas of research in this project: the first is the identification of the optimal additive which would reduce the size and increase the efficiency of the PB. The second is the development of tailored heat exchanger designs, particularly for the air-cooled condenser, to operate with the innovative fluid as these are key enabling components for the proposed technology. The project will demonstrate the innovative fluid and newly developed heat-exchangers at a relevant scale (300 kW_{th}) for 300 h in a CSP-like operating environment.

SUPERCRITICAL CO_2 POWER CYCLE AND CO_2 BLENDS

Supercritical CO_2 systems have been extensively researched in recent years, both theoretically and experimentally. The potential of sCO_2 relies on the following features: (i) liquid or liquid-like (i.e. low compressibility) state of the working fluid during compression, which drastically reduces the associated work, and (ii) low expansion ratio of the cycle and low isentropic exponent of the working fluid (CO_2), which largely increase the potential to recuperate heat within the cycle. A number of experimental loops, based either on the Recompression and Simple Recuperated cycle layouts, have been constructed in the last ten years to demonstrate the feasibility of the concept [12,13]. The idea of blending the CO_2 to modify the critical properties of the working fluid dynamically has been explored in the past, mainly by Sandia National Labs in United States for low temperature heat sources [12].

Recently, Czech Technical University in Prague started to investigate the adoption of CO_2 blends as working fluid for temperatures up to 550°C [14]. The activity is theoretical and provides an estimation of the potential enhancement of the PB performance due to the presence of additives. Previous and on-going research activities in the area of CO_2 blends undertaken by various research groups worldwide are reported in Table 2. Two different lines of research can be outlined: blending with hydrocarbons (with limited operating temperature) and adoption of gases to increase the ideal gas effect.

There is just one activity, performed by University of Brescia and Politecnico di Milano [6,15], investigating the adoption of blending fluids capable of increasing the critical temperature and withstanding temperatures up to 700°C. In the framework of this collaboration, two promising fluids have been identified for blending: $TiCl_4$ and N_2O_4. It comes out that CO_2-N_2O_4 and CO_2-$TiCl_4$ mixtures as working fluids in PBs are promising thanks to the high cycle efficiency, small turbomachinery and simple plant lay-out which bring about a substantial specific cost reduction. A simple regenerative cycle with the proposed innovative blends can reach a cycle efficiency as high as 48.6% for CO_2-N_2O_4 and 49.7% for CO_2-$TiCl_4$ compared to an efficiency of 48% for a complex recompression cycle with pure CO_2.

TABLE 2. Recent research activities on CO2 mixtures with the main features

Research Institute	Years	Fluid	Temperature Range	Activity
University of Brescia [16,17]	2012 2014	Mixtures of CO_2 and hydrocarbons: benzene and toluene	400 °C	A thermodynamic analysis of supercritical and trans-critical cycles
University of Brescia – Politecnico di Milano [6,15,18–20]	2016 2018	Binary mixtures of CO_2 with Di-Nitrogen Tetroxide (N_2O_4) and Titanium Tetracholride ($TiCl_4$)	400 °C to 700°C	Thermal stability tests up to 500 °C for $TiCl_4$. Thermodynamic modelling and overall cycle assessment
University of Brescia [21]	2017	Mixtures of carbon dioxide and n-butane, sulphur hexafluoride, toluene	<350 °C	Thermodynamic evaluation of the performances of different Brayton cycles.
SANDIA [12]	2011 2013	Binary mixtures of carbon dioxide and Sulphur Hexafluoride (SF6) and different hydrocarbons.	50 °C to 160 °C	Experimental evaluation of the compressor performances with mixtures of carbon dioxide and SF6 and n-butane. A Patent.
KAIST [22]	2011	Binary mixture of $CO_2$and: argon, xenon, nitrogen, oxygen.	580 °C	Evaluation of performance of supercritical Brayton cycles for Sodium-cooled Fast Reactors
Czech TU [14]	2016 2017	Binary mixture of CO_2 and: He, O_2, N_2, Ar, CH_4 (methane), H_2S (Hydrogen Sulfide), CO	550°C	Thermodynamic evaluation of some Brayton cycles
Xian Jaotong University [23]	2018	Binary mixture of CO_2 and hydrocarbons/organic fluids	<330°C	Parametric analysis and optimization based on thermodynamic and economic performance of the system

THE SCARABEUS PROJECT

The SCARABEUS project scheduled work plan includes activities covering the whole value chain needed to prove thermodynamic, economic and environmental benefits of the proposed technology. It is broken down in seven work packages covering four years of work, starting on April 2019.

As mentioned in the introduction section, the primary objective of the SCARABEUS project is to demonstrate that using blended-CO_2 is the only route currently possible to meeting the very ambitious economic performance of next generation Concentrated Solar Power plants. Within SCARABEUS, a solar tower and an indirect cycle concept are considered: the heat transfer fluid (HTF) collects thermal power in the receiver and transfers it to the working fluid of the power cycle in dedicated heat exchangers. The indirect cycle concept is selected because it does not require a new receiver development and enables the utilization of conventional thermal energy storage (TES) technologies. In this latter regard, it is noted that thermal energy storage is an essential feature to fully exploit the advantages of CSP over PV and wind energy technologies.

The first step of the project will be to identify the most promising candidate fluids (dopants) to be added to the CO_2. This phase will be based on a thorough literature review, starting from the relevant research activities summarized in Table 2, and on fluid compatibility analyses developed, both for the compounds already investigated and for new fluids that will be explored. Upon identification of the most promising candidates, a theoretical model to describe the thermo-physical properties of the working blends will be developed based on experimental data from literature and from the proprietary database of the applicants. The modelling will start from the simplest cubic equation of state formulation as Peng-Robinson [24] or Soave-Redlich-Kwong [25] with the calibration of mixing rules parameters passing through Volume Translated Peng Robinson (VTPR) or exploring predictive models as UNIQUAC Functional-group Activity Coefficients (UNIFAC) [26] or perturbed chain statistical associating fluid theory (PC-SAFT) [27] which accounts for species molecular structure and their interaction.

As already pointed out in previous research activities [28,29], the correct modelling of the thermo-physical properties behavior of the CO_2 blend is mandatory to accurately predict the fluid behavior around the critical point and the resulting cycle performance.

The theoretical description of these CO_2 blends will then be incorporated into a thermodynamic modelling environment to analyze the performance of the power plant. Simultaneously, dedicated experiments of CO_2-blends heat transfer properties will be carried out to perform and optimize the designs of the recuperative heat exchanger and air-cooled condenser. The complete performance model with an accurate characterization of the working fluid will enable the selection of the optimal CO_2 blends that yield the best performance of the PB. Based on this information, a more specific aerodynamic design, performance characterization and cost assessment of turbomachinery, recuperative heat exchanger and air condenser will be carried out. At the same time, a more refined performance model of the PB with the capability to simulate both design point and off-design behaviour of the SCARABEUS power plant with blended-CO_2 will be developed and, with this tool, an optimization of the entire plant will be performed (including solar field and thermal energy storage system).

One of the main outcomes of the modelling activities carried out in the project will be the specifications of the two working fluids yielding the best power plant performance. The thermal stability of these fluids will be investigated through dedicated experiments to ensure that decomposition at high temperature does not take place, neither in the short (immediate decomposition) nor in the long terms (after 2000 hours at high temperature). This will demonstrate the capability of the fluid to withstand temperatures up to 700°C in the presence of metallic materials and lubricants. Additionally, vapor-liquid equilibrium measurements will be carried out to determine the Andrew's curve of the CO_2 blends. Afterwards, the Andrew's curve will be used to calibrate the thermodynamic models to verify the description of the behaviour of CO_2 blends, which is a necessary requirement to ensure the validity of the results provided by the performance models. In parallel, all the pieces of information produced by the project will be integrated in a thorough market analysis whereby the economic objectives of the project will be demonstrated. To this end, multi-variable cost estimators and financial models will be developed and integrated with the optimization tools.

Ultimately, resolving the outlined challenges leads to a lower cost of electricity (LCoE), yielding a technology that becomes cost competitive against photovoltaic systems and even fossil fuel technologies. The target LCoE to achieve this twofold objective is in the range between 50 and 100 €/MWh. Figure 2 summarizes the very large impact of SCARABEUS on the economic performance of CSP plants: 3500 €/kWel CAPEX and 12 €/MWhel OPEX (accounting for the contribution of the power block only) are the final economic targets of the project. Moreover, the drastic reduction of CAPEX and OPEX is even more pronounced if considered in the context of the current objectives of the SunShot initiative of the US Department of Energy [https://www.energy.gov/eere/solar/sunshot-2030], which is presently targeting 900 USD/ kW_{el} (CAPEX of the power block) and 2 USD/ MWh_{el} (OPEX of the power block, excluding fixed OPEX by capacity) for the next generation of sCO2 power cycles to be deployed by 2030.

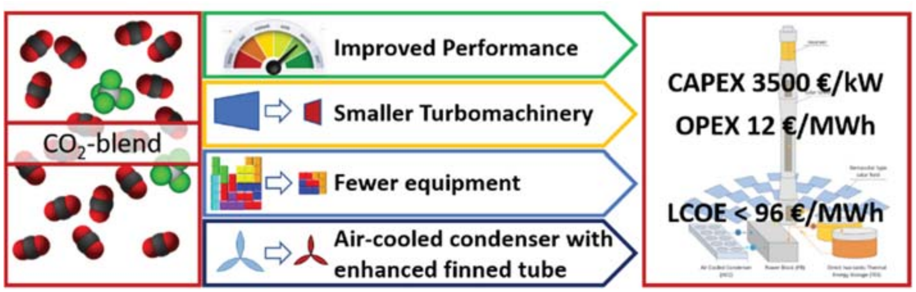

FIGURE 1. SCARABEUS approach and cost targets for a large scale solar tower plant [1]

These ambitious objectives are tackled by SCARABEUS, a project conceived to bring about greater strides than would be obtained if steam turbine or combined gas/steam turbine technologies were used. This progress is built upon innovations on: (i) improvement of the PB performance, boosting the net heat to electricity efficiency to above 50%; (ii) reduction of the complexity of the PB since only one recuperator and one primary heat exchanger are necessary as opposed to more than ten heat exchangers typically adopted in a steam cycle; (iii) reduction of the size of turbomachinery compared to steam turbines of similar power output, bringing about large reduction in capital costs; (iv) innovation in heat exchanger design and manufacturing, aiming at the best compromise between thermal effectiveness and manufacturability.

THE SCARABUES CONSORTIUM

The SCARABEUS consortium comprises 9 partners from 6 European countries (Italy, Spain, French, United Kingdom, Austria, and Switzerland) with the key complementary expertise, including 5 top level European universities, one innovative SME and three world leading companies. The SCARABEUS value chain with the primary role of each partner is shown in Fig. 2.

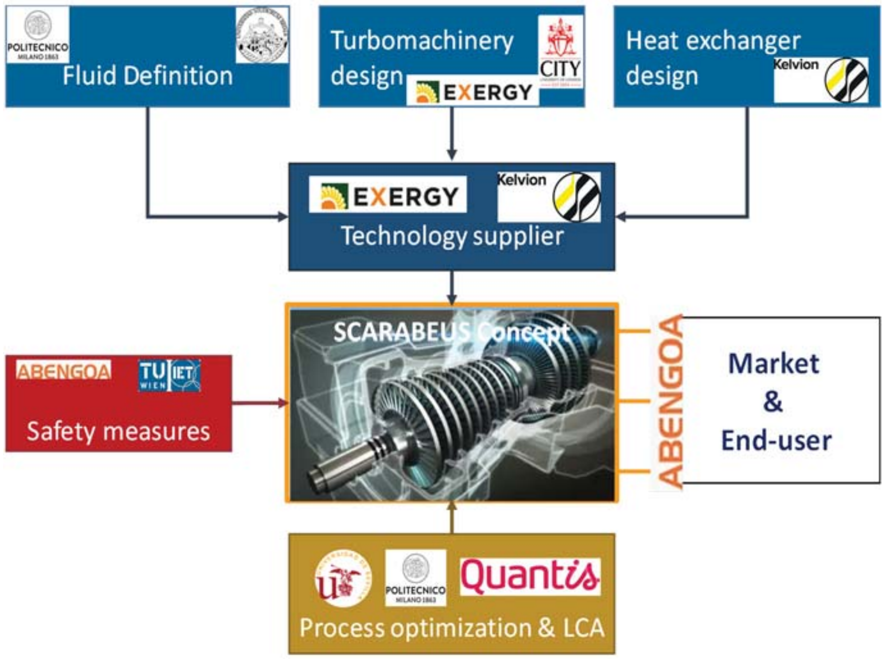

FIGURE 2. SCARABEUS project value chain

Politecnico di Milano will lead and coordinate the project and will be responsible for the dissemination of the project results. In addition, it will define the thermodynamic properties of the CO_2 mixture through vapour-liquid equilibrium measurements.

University of Brescia has a laboratory for evaluating the stability of working fluids and holds a strong thermodynamic background on mixtures. It will support the assessment of the best candidate mixture as well as perform the corresponding thermal stability tests.

University of Seville, one of the most active institutions in the field of supercritical carbon dioxide technology in Europe, will capitalize on its expertise in the area of sCO_2 cycle and turbomachinery design and optimization and of CSP technology (acquired through close collaboration with industry).

City University of London, has expertise in the design of turbomachinery including the effect of variable gas properties and will be responsible for the design and analysis of the turbomachinery components.

Exergy is an industrial company manufacturing turbomachinery and will work with City on design of the turbomachinery and will perform the associated cost analysis.

Quantis will perform the technology assessment from a life cycle perspective (environmental life cycle assessment and life cycle costing).

Kelvion thermal solutions has one of the world's largest product portfolios in the field of heat exchangers (plate, shell and tube and finned tubes heat exchanger; modular cooling tower systems) and will be responsible for the conceptual design and optimization of the air-cooled condenser and the recuperative heat exchanger.

Technical University of Wien has been working on sCO_2-cycles within the frame of two national projects where a trans-critical sCO_2-test rig with a thermal power of 300kW thermal power has been constructed. This rig is currently operational and will be used in SCARABEUS.

Abengoa Energia is one of the world leading companies in CSP, spanning its activities over the whole value chain: ownership, engineering, procurement and construction, operation, servicing. The company will provide the end-user's perspective and will support the benchmarking of SCARABEUS in comparison to state-of-the-art commercial plants. They will also be responsible for the SCARABEUS technology exploitation.

CONCLUSIONS

The potentiality of the blended CO_2 as working fluids in CSP power block is discussed in this work. The adoption of SCARABEUS in solar tower plants will yield higher conversion efficiencies than commercial technologies both at design and off-design operating conditions. The expected design efficiency is >50% compared to 47% for pure sCO_2 cycles and 43% for steam power plants. SCARABEUS projects will start from these preliminary results and will demonstrate that the application of supercritical CO_2 blends can reduce the complexity and costs of the power section, thus reducing the LCOE of a Concentrated Power plant below 100 €/MWhel. The project will also demonstrate the innovative fluids at relevant scale for 300 hour in a CSP-like operating environment.

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