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SUPERCRITICAL CARBON DIOXIDE/ALTERNATIVE FLUID BLENDS FOR EFFICIENCY UPGRADE OF SOLAR POWER PLANT

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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 CSP 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 potentialities of N_2O_4 and $TiCl_4$ were already demonstrated from theoretical point of view. 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 kW_{th}) 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 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. 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.

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.

From preliminary analysis, it comes out that CO_2-N_2O_4 and CO_2-$TiCl_4$ mixtures as working fluids in PBs are promising thanks to

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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.

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.

The consortium comprises 9 partners with the key complementary expertise, including 5 top level European universities, one innovative SME and three world leading companies.

CURRENT STATUS OF CONCENTRATING SOLAR POWER

CSP technology uses a series of mirrors to concentrate the direct solar radiation and to convert it into high temperature heat that is subsequently converted into electric power through a conventional power cycle. Currently there are about 5 GW of installed CSP plants mainly based on Parabolic Trough technology (3.7 GW) and on Solar Tower technology (0.6 GW). Parabolic trough collectors (PTC) use one-axis tracking systems and concentrate the radiation onto a receiver tube (linear concentrators) in which a heat transfer fluid (HTF) flows. The majority of the CSP plants based on PTC uses synthetic oil as HTF, thus limiting the maximum temperature slightly below 400°C. A standard re-heated steam cycle with maximum temperature around 370°C is thus the most commonly adopted power conversion technology with a net power block efficiency of about 37-38%. The use of solar salts as HTF in PTC is another interesting option that has been under development for several years and that will be applied in some of the new CSP plants in China. Solar salts can achieve temperatures up to 565°C guaranteeing a PB conversion efficiency of about 39-42%. Solar Tower (ST) systems use heliostat to concentrate the solar radiation onto a central receiver in which solar salts are used as HTF or in which steam is directly produced for the steam cycle. The first option (i.e. ST) is nevertheless preferred as it allows for the direct integration of high capacity thermal energy storage systems that enable a higher solar share or potentially continuous operation without fossil fuel backup. The standard PB conversion technology is also based on a steam cycle with similar performance as the previous ones.

Current and forecasts on CSP costs are reported in Table 1, showing how ST is expected to have the strongest LCOE reduction. The capacity factor represents the PB operating hours with respect to the yearly hours.

Table 1: Global weighted average CSP investment cost, capacity factor and LCOEs, 2015 and 2025 [1]

	Investment Cost ($/kW)		**Capacity Factor**		**LCOE ($/kWh)**	
	2015	**2025**	**2015**	**2025**	**2015**	**2025**
PTC	5550	3700	41%	45%	0.15-0.19	0.09-0.12
ST	5700	3600	46%	49%	0.15-0.19	0.08-0.11

The main driver to attain lower costs is the operating temperature, which can be combined with the use of supercritical cycles for further performance enhancement and cost reduction. Indeed, a higher operating temperature implies higher conversion efficiency of the PB which brings about a smaller area of the solar field (lower primary energy demand for the same electricity output). This would result in substantial capital cost reduction, as the solar field of a CSP power plant with thermal energy storage accounts for about 40-50% of the total capital cost [1]. Moreover, higher operating temperatures enable a higher temperature change across the thermal energy storage system, resulting in a much lower inventory of heat transfer fluid (molten salts in standard technology) and smaller footprint of the storage tanks (the storage size is on energy base, and consequently is inversely proportional to the temperature difference across the receiver).

The cost of the storage system, which accounts for between 10% and 15% of the total cost of the plant [1], can therefore be largely reduced.

SUPERCRITICAL CO_2 POWER CYCLES 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 [2–4]. 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 [2]. Experiments performed by this institution confirmed that the addition of butane to the CO_2 increases the critical temperature with benefits for the cycle efficiency. On the contrary, adding SF6 has the opposite effect (the critical temperature decreases). The proven concept was later protected under US Patent 20130033044A115 but, in spite of the evident interest in the concept and the successful

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experimental demonstration, no further activity has been reported in recent years. Moreover, the experimental activity carried out by Sandia focused more on the compressor performance near the critical point, than to demonstrate the concept as a whole (i.e., the expected performance of the cycle using CO_2 blends at high heat rejection temperatures) nor the stability of the working fluid at the high temperatures that are sought in sCO_2 applications. Finally, the maximum temperature considered in this work was around 400 °C, as it aimed at geothermal and biomass applications only, and this is far from the temperatures achievable in ST plants.

Another innovative concept making use of CO_2 mixtures in sCO_2 power cycles at high pressure and temperature is the oxycombustion-based system developed by NetPower in collaboration with Toshiba, where a mixture of carbon dioxide and steam (plus traces of other gases) is expanded in the turbine [5]. Nevertheless, this concept was not aimed at modifying the critical point of the mixture but rather at achieving very high turbine inlet temperatures that would otherwise not be possible. Another important feature of the proposed technology is that it enables non-chemical, cost-effective carbon capture. Recently, Czech Technical University in Prague started to investigate the adoption of CO_2 blends as working fluid for temperatures up to 550°C [6]. 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 the Table 2. From the table, 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 Università degli Studi di Brescia and Politecnico di Milano [7,8], 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. Titanium tetrachloride is a relatively low cost, non-carcinogenic fluid, with zero Global Warming Potential (GWP) and Ozone Depleting Potential (ODP), currently employed in high temperature industrial processes. In fact, it is remarkably stable**,** as also confirmed by a previous experimental thermal stability analysis carried out at temperatures up to 550 °C [9]. At room temperature, it appears as a colorless liquid. However, it reacts violently with water, even with the small amounts contained in humid air, to generate heat and corrosive gases containing hydrogen chloride. In the presence of water, it is also corrosive for many metals. However, all these unfavorable characteristics of $TiCl_4$, become less critical with high dilution with CO_2 [10].

Thermodynamic and transport properties of N_2O_4 have been calculated in the past years, [11–13]. Nitrogen dioxide and nitric oxide are considered greenhouses gases because they promote the formation of ozone, but it seems very unlikely that very reactive NO and NO_2 will reach the troposphere. N_2O_4 was also proposed as working fluid in Brayton cycles in the past years [14,15]. At ambient conditions, N_2O_4 is unstable and decomposes into NO_2 (nitrogen dioxide) which in turn can decompose into oxygen and nitric oxide (NO) depending on the pressure and temperature. In the following calculations it is always considered the system $N_2O_4/NO_2/NO/O_2$ at chemical equilibrium and, for simplicity, we will indicate it from now on as N_2O_4.

Table 2: Recent research activities on CO_2 mixtures with the main features

Research Institute	Years	Fluid	Temperature Range	Activity
UNIBS [16,17]	2012 2014	Mixtures of CO_2 and hydrocarbons: benzene and toluene	400 °C	A thermodynamic analysis of supercritical and trans-critical cycles
UNIBS – POLIMI [7,8,18–20]	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
UNIBS [21]	2017	Mixtures of carbon dioxide and n-butane, sulphur hexafluoride, toluene	<350 °C	Thermodynamic evaluation of the performances of different Brayton cycles.
SANDIA[2]	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 in Prague [6]	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

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The power cycles were modelled calculated using Aspen Plus V9.0 [24] with the Peng-Robinson Equation-Of-State (EOS) [25] as CO_2-N_2O_4, CO_2-$TiCl_4$ and pure N_2O_4 cannot be modelled in RefProp EOS [26]. A k_{ij} equal to 0.0745 was assumed for $TiCl_4$ while equal to zero for N_2O_4 as discussed in previous works. Table 3 summarizes the main design parameters adopted for the cycles modelling. For further information, the reader can refer to the previous publication [7,8]

Table 3: Main assumptions for the power cycle simulation both at 700°C and 550°C maximum temperatures

Parameter	Value
Turbine inlet pressure (bar)	250
Minimum temperature (°C)	51
$\Delta p/p$ Hp/Lp side of regenerator	0.01/0.015
$\Delta p/p$ Primary Heat Exchanger	0.015
$\Delta p/p$ heat rejection Heat Exchanger	0.02
Compressor/Pump polytropic efficiency	0.89
Turbine isentropic efficiency	0.93
Mechanical/Electrical efficiency	0.99/0.99

A preliminary assessment was carried out in previous works [7,8] and the main results are reported in Table **4** and Table 5.

Two different locations were considered, Seville and Las Vegas as they have different latitude and irradiation which both affect the solar plant performance and electricity production.

Results are reported in terms of energy and efficiency for the most relevant sections of the plant (i.e. the optical and thermal processes are not explicated as they are in common between all the cases and no development has been performed in these components.

E_{sun} stands for the solar energy available on the solar field;

E_{gross} is the gross electric energy generated by the PB neglecting heat rejection auxiliaries;

E_{netPB} is the net electricity generated by the power cycle;

E_{net} is the net electricity generated by the solar plant including the solar field auxiliaries' consumptions;

η_{net_PB} and $\eta_{overall}$ are the PB net electric and overall plant efficiencies.

Table 4: Yearly energy assessment for a solar plant placed in Seville and Las Vegas with maximum power cycle temperature equal to 550°C [7]**.**

T_{max} 550°C	**Seville (TES 8 hours)**					**Las Vegas (TES 10 hours)**				
	Steam cycle	Pure CO_2	N_2O_4	N_2O_4+CO_2	$TiCl_4$+CO_2	Steam cycle	Pure CO_2	N_2O_4	N_2O_4+CO_2	$TiCl_4$+CO_2
E_{sun} [GWh]	609.1	609.1	609.1	609.1	609.1	807.6	807.6	807.6	807.6	807.6
E_{gross} [GWh]	115.4	115.7	116.9	122.8	123.6	143.9	146.2	147.3	155.1	156.2
E_{netPB} [GWh]	114.0	114.5	115.7	121.7	122.5	142.6	144.0	145.0	152.9	154.1
η_{net_PB} [%]	38.5	39.9	39.3	42.1	42.6	38.5	39.8	39.3	42.0	42.5
E_{net} [GWh]	112.7	111.3	114.4	119.5	119.6	140.9	139.5	143.4	149.9	150.0
$\eta_{overall}$ [%]	18.5	18.3	18.8	19.6	19.6	17.4	17.3	17.8	18.6	18.6

Table 5: Yearly energy assessment for a solar plant placed in Seville and Las Vegas with maximum power cycle temperature equal to 700°C [7]

T_{max} 700°C	**Seville (TES 8 hours)**				**Las Vegas (TES 10 hours)**			
	Pure CO_2	N_2O_4	N_2O_4+CO_2	$TiCl_4$+CO_2	Pure CO_2	N_2O_4	N2O4+CO_2	$TiCl_4$+CO_2
E_{sun} [GWh]	627.58	627.6	627.6	627.6	832.1	832.07	832.1	832.1
E_{gross} [GWh]	125.3	135.7	135.9	137.2	161.0	169.4	170.1	172.1
E_{netPB} [GWh]	124.3	134.7	135.0	136.2	159.2	167.4	168.2	170.3
$\eta_{net\_PB\_y}$ [%]	48.3	46.0	47.8	48.5	48.1	46.1	47.8	48.5
E_{net} [GWh]	120.11	133.5	131.8	132.4	153.4	165.9	164	165.2
$\eta_{overall}$ [%]	19.14	21.3	21.0	21.1	18.4	19.9	19.7	19.9

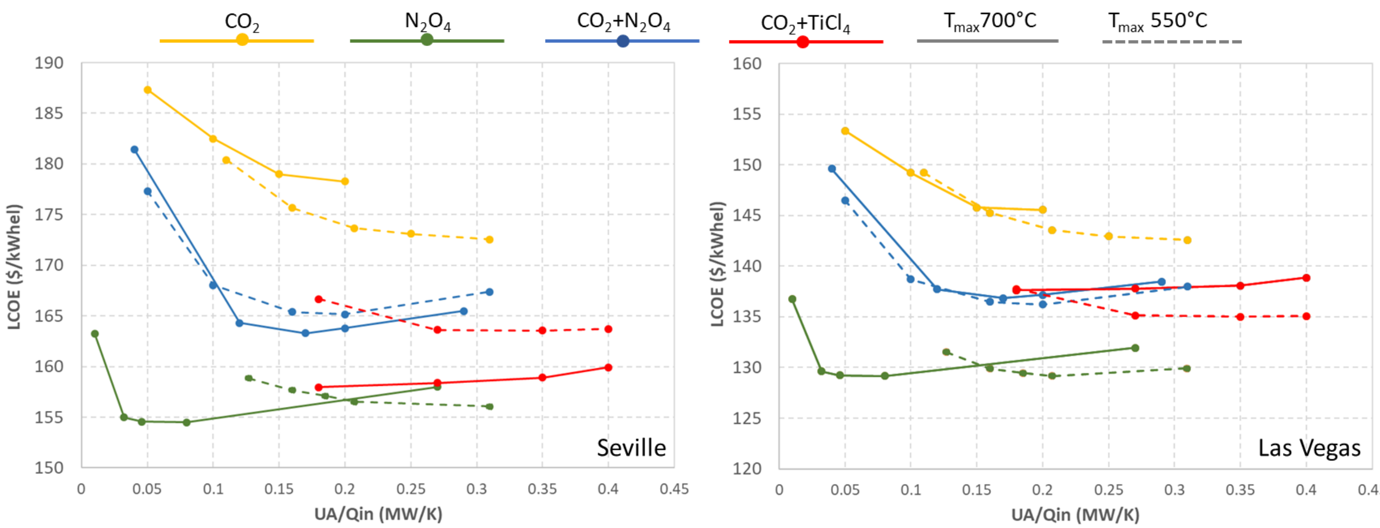

Figure 1. LCOE for the different working fluids and maximum temperatures in Seville and Las Vegas as function of the recuperative heat exchanger area [7]

Table 6: Power block specific costs for the different cases considered at different maximum temperatures together with the reference cases [7,8]

Maximum temperature 550°C – Solar salts as HTF					
	Steam cycle	Pure CO_2	N_2O_4	N_2O_4+CO_2	$TiCl_4$+CO_2
PB specific costs [$/kW]	1400	1303.4	793.8	976.8	1043.0
Maximum temperature 700°C – Liquid Sodium as HTF					
	Steam cycle	Pure CO_2	N_2O_4	N_2O_4+CO_2	$TiCl_4$+CO_2
PB specific costs [$/kW]	-	985.2	687.4	802.7	847.7

Table 5 pointed out that the cycle efficiency of the proposed innovative fluids can be as high as 47.8% for CO_2 -N_2O_4 and 48.5% for CO_2-$TiCl_4$. Preliminary studies showed that these numbers can be improved by 1% assuming larger UA [7,8]. In addition, a simple regenerative cycle configuration can be adopted reducing the plant complexity. Table 6 summarizes the CAPEX of the PB for the different cases investigated outlining the potentialities to reduce the specific costs around 700$/kW which corresponds to a reduction close to 50% and 20% with respect to conventional steam cycle and sCO_2 power blocks [27].

In terms of yearly electricity production (see

Table **4** and Table 5), the innovative fluids outperform the more conventional ones with an overall efficiency increase by 5%. The resulting LCOE (see Figure 1) which combines the thermodynamic and cost advantages of the innovative fluids is around 130 $/MWh for a plant located in Las Vegas (US) and 155 $/MWh for a plant located in Seville (US) compared to 147 $/MWh and 184 $/MWh of a steam cycle.

From the thermodynamic and economic results, CO_2-N_2O_4 and CO_2-$TiCl_4$ mixtures as working fluids in PB are promising thanks to the high efficiency, small turbomachinery and simple plant lay-out which bring about a substantial specific cost reduction. However, the power cycle performance for the innovative cycles were based on simple thermodynamic models such as the Peng-Robinson equation of state, calibrated on a few available experimental data.

The SCARABEUS project will address these aspects combining theoretical modelling with experimental campaign.

THE SCARABEUS PROJECT

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

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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 [25] or Soave-Redlich-Kwong [28] 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) [29] or perturbed chain statistical associating fluid theory (PC-SAFT) [30] which accounts for species molecular structure and their interaction.

As already pointed out in previous research activities [8,10], 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.

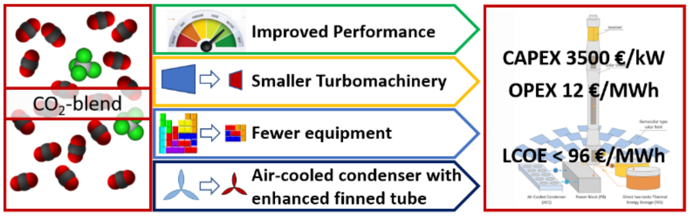

Figure 2. SCARABEUS approach and cost targets for a large scale solar tower plant

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 SCARABEUS CONSORTIUM

Politecnico di Milano [31] 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.

Technical University of Wien [32]has been working on sCO2-cycles within the frame of two national projects where a transcritical sCO2-test rig with a thermal power of 300kW thermal power has been constructed. This rig is currently operational and will be used in SCARABEUS.

Kelvion thermal solutions [33] 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.

Exergy [34] is an industrial company manufacturing turbomachinery and will work with City on design of the turbomachinery and will perform the associated cost analysis

University of Seville [35], 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 sCO2 cycle and turbomachinery design and optimization and of CSP technology (acquired through close collaboration with industry).

City University of London [36], 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.

Quantis[37] will perform the technology assessment from a life cycle perspective (environmental life cycle assessment and life cycle costing).

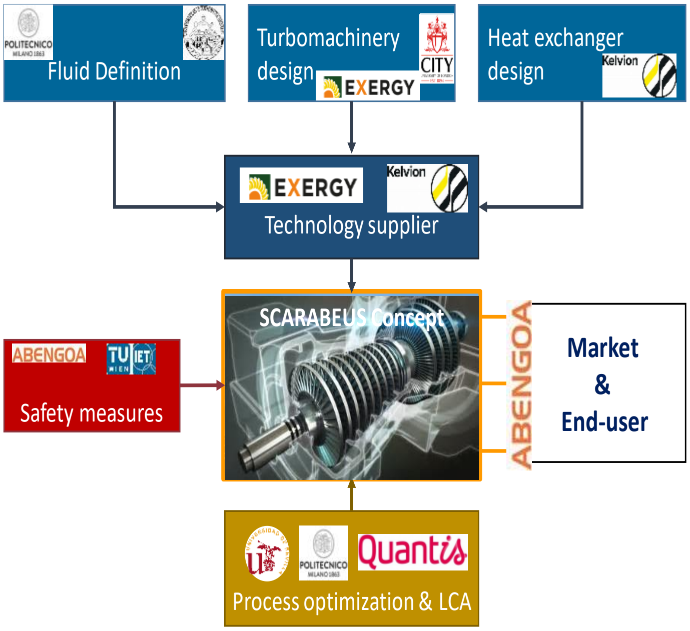

Figure 3. Value chain for the SCARABEUS project

Abengoa Energia [38] is one of the world leading companies in CSP, spanning its activities over the whole value chain: ownership, EPC, 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

University of Brescia [39] has a laboratory for evaluating the stability of working fluids and holds a strong thermodynamic background on mixtures. They will support the assessment of the best candidate mixture as well as perform the corresponding stability tests.

The SCARABEUS value chain is summarized in Figure 3

CONCLUSIONS

This paper discussed the potentialities of the blended CO_2 as working fluids in power block. Previous work demonstrated that the adoption of CO_2-N_2O_4, CO_2-$TiCl_4$ can boost the efficiency above 49% assuming a maximum temperature equal to 700 °C while reducing the complexity and costs of the power section. SCARABEUS projects will start from these preliminary results and will demonstrate that the application of supercritical CO_2 blends can reduce the LCOE of a Concentrated Power plant below 100 €/MWh_{el}. The project will also demonstrate the innovative fluids at relevant scale for 300 hour in a CSP-like operating environment.

NOMENCLATURE

CAPEX	Capital Expenditure
CSP	Concentrated Solar Power
HTF	Heat Transfer Fluid
LCA	Life Cycle assessment
LCOE	Levelized Cost of Electricity
OPEX	Operating Expenditure
PB	Power Block
ST	Solar Tower
TES	Thermal Energy Storage
E_{sun}	Solar energy available on the solar field
E_{gross}	Gross electric energy generated by the power block
E_{netPB}	net electricity generated by the power cycle
E_{net}	net electricity generated by the solar plant;
η_{net_PB}	PB net electric efficiency.
$\eta_{overall}$	overall solar plant efficiency.

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