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First Year of the EU SolarSCO2OL Demonstration Project - Enabling Hybrid Supercritical CO_2 CSP Plants integrated with PV

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ABSTRACT

The EU funded H2020 SOLARSCO2OL project aims to demonstrate a 2 MW supercritical CO_2 (sCO_2) cycle with heat provided by molten salts in a relevant industrial operational environment at the premises of an existing solar complex in Spain, composed of a 50 MW Concentrating Solar Power (CSP) plant and a 6.1 MW dual-axis tracking PV plant. The new pilot plant will consist of a purposely designed molten-salt storage system including a molten salt electric heater, a storage tank, and the salt-to-sCO_2 primary heater connected to the sCO_2 cycle. In specific relation to the turbomachinery, the project aims to demonstrate the reliability and the technical performance of all key components present in a simple Brayton sCO_2 cycle, including the balance of plant and control systems. Ultimately, the overarching goal of the project is to serve as a stepping-stone towards hybrid sCO_2 based CSP and PV plants able to provide cost-efficient, flexible, modular, scalable, and dispatchable solar power. Besides the specific demonstration objectives, and related component development and verification, the project aims to investigate the techno-economic performance of advanced hybrid CSP-PV layouts combining electric heaters and sCO_2 cycles at higher temperatures, as well as the social and environmental acceptability of the proposed solutions. The project started in October 2020 and will span for a period of 4 years, with three clear phases: design optimization (up to months 18-24); manufacturing, prototype tests, detailed engineering, procurement, and installation (up to month 36); and operational experience, analysis and conclusive recommendations during the last year. The anticipated budget for the project is 15.5 M€, and it has received a grant of 10M€ from the European Commission. The SOLARSCO2OL consortium is formed by 15 partners from industry and academia with complementary expertise in the fields of CSP and turbomachinery. In this paper, an overview of the project objectives, deliverables, and time plan is presented together with a condensed first-year summary including preliminary results from the conceptualization and design phases for the demonstration plant and its components.

INTRODUCTION

According to the JRC CSP platform, with increased efficiency of component and price reduction, it could be feasible to produce 11 % of Europe's (EU) electricity by means of CSP by 2050. In the European Commission's (EC) energy strategy, CSP is mentioned as a potential dispatchable renewable energy source (RES) with increasing potential market when coupled with flexible, high performant and low CAPEX power conversion units. In this respect, sCO_2 has been studied for several years as a future technology to overcome the steam-based cycle in efficiency and power density, as an enabling technology to promote CSP worldwide [1]. SOLARSCO2OL presents sCO_2 cycles as a key enabling technology to facilitate a larger deployment of CSP plants, by enhancing their performance (efficiency, flexibility, annual yield) and reducing their energy costs. Compared to organic and superheated steam-based Rankine cycles, sCO_2 cycles can achieve higher efficiencies over a wider temperature range, including the temperatures reached by traditional molten salt CSP technologies, making it possible to consider them even as a retrofitting alternative. The integration of sCO_2 power blocks can lead to lower CAPEX, lower OPEX, avoidance of water as operating fluid, smaller system footprints, and overall higher operational flexibility start-ups and load variations. SOLARSCO2OL aims to demonstrate the first MW scale EU sCO_2 power block, thereby bridging the gap with other R&D initiatives in the subject worldwide [2][3][4]. The research work to be performed within SOLARSCO2OL is aligned with the EU CSP SET Plan goals [5] and R&I activities enlisted for CSP, and thus the project is of high relevance for the development of a more cost-efficient next-generation CSP technology.

SOLARSCO2OL advancing state of the art of CSP

Molten salt solar towers employing the so-called "solar salt" as HTF at a hot-salt temperature of about 570 °C can be considered the most advanced state-of-the-art and commercial technology. The set EU target of achieving a levelized cost of electricity (LCOE) inferior to 100 €/MWh for an annual direct normal irradiance (DNI) of 2050 kWh/m^2 [5], requires significant cost reductions, coupled with the new development of heat transfer fluids (HTFs), thermal energy storage (TES) technologies and power systems able to reach thermal efficiencies superior to 50%. A molten-salt solar tower is not the only possible path for next-generation CSP; however, the operating flexibility, energy-storage efficiency, and industry familiarity with this design makes it a leading contender. Evolving from 570 °C to 700 °C or even higher temperatures will necessitate a new HTF to be developed, owing to solar salt's decomposition around 600 °C. Furthermore, an advanced power cycle more amenable to CSP requirements than steam-based turbines must be employed to achieve the LCOE objective. Each technology shift will have several consequences on the CSP system. Deploying a new CSP technology operating at approximately 700°C would entail a level of risk that makes financing such a technology difficult. Instead, developing the necessary technologies in a step-wise approach, by first demonstrating system concepts and power technologies at 600 °C and later evolving to higher-efficiency systems at 700°C, offers a lower-risk path. Furthermore, financing high-risk technologies and projects that can approach one billion euros is highly challenging, and progressing towards the EU SET goals in steps that CSP industry members can support and implement is essential for the health of the industry and the commercial viability of newly developed technologies. SOLARSCO2OL leverages on existing molten-salt know-how and bankability from key CSP industrial actors, and introduces two critical innovations that can facilitate the transition towards the next generation of CSP in a step-wise approach. Specifically, the project proposes the replacement of steam cycles by sCO_2 cycles and the integration of molten salt electric heaters for active hybridization with PV; both of which will be demonstrated at MW-scale in a relevant environment, whilst still analyzing the techno-economic performance of other future advanced CSP layouts with innovative HTFs and TES systems from a simulation perspective.

THE SOLARSCO2OL HYBRID CSP-PV REPLICATION LAYOUT

The reference SOLARSCO2OL hybrid CSP-PV layout consists of a conventional molten salt tower CSP plant in which the solar field is supported in parallel by an electric heater fed with electricity from a co-located PV plant, as shown in Fig 1. This plant includes a 2-tank TES system used to store salts at 580°C such that a recompressed sCO_2 cycle with a reheat can operate at a turbine inlet temperature of at least 565°C, and thus been able to reach efficiencies of 50% at nominal conditions. The thermal energy storage included in the CSP plant is also employed to store electricity produced from the PV field. Thus, the electric heater can be used to charge the thermal energy storage when electricity is produced in excess from the PV field, or when it is not profitable to sell electricity to the grid. This electricity-feeding integration concept can be extended at the grid level by allowing the heater to be fed with electricity from the grid in times when electricity prices are cheap, or even negative. Similar to conventional CSP plants, the heat stored in the hot tank can be withdrawn at a later stage and used to drive a thermal power block to produce electricity on demand. The thermal power block in the SOLARSCO2OL reference layout consists of a recompression-reheat sCO_2 cycle, where CO_2 is heated up to 565°C. The main components of the recompression-reheat sCO_2 cycle are shown in Fig. 1. The choice of this cycle was based on previous research studies that estimated that thermal efficiencies of 50% would be attainable even at 565°C inlet temperatures [1], these were confirmed in a preliminary thermodynamic analysis, for which thermodynamic states of the cycle are also shown in the T-S diagram included at the right of Fig.1.

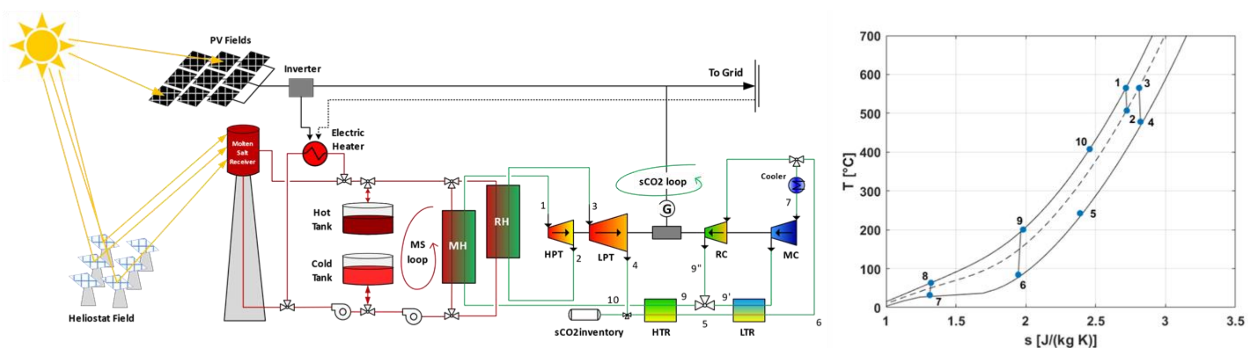
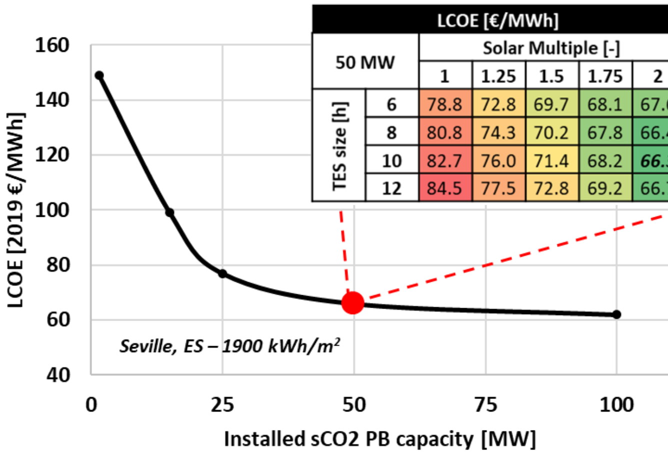


Fig. 1 SOLARsCO2OL Hybrid CSP-PV Layout with recompressed-reheat sCO2 power block

Preliminary Techno-economic Analysis of Replication Layout

A preliminary techno-economic analysis of the replication layout has been performed using KTH's in-house DYESOPT tool [6]. In this techno-economic study, the combined net output of the plant is set such that it meets a baseload nominal value equal to the installed capacity of the sCO_2 power block. The operating strategy of the plant is set such that electricity from PV is prioritized and injected to the grid directly during the day, and also to provide auxiliary power to the solar field in the CSP plant. The CSP is operated such that it is dispatched around the PV (respecting power block operational constraints), such that during a day with high irradiance, the plant is mainly storing energy during the day and producing electricity later during dark hours. In this strategy, excess electricity from PV can be used to store thermal energy in the hot tank via the electric heater, whenever available, and for as long as the hot tank is not full. The analysis was carried for a location nearby Seville with a DNI of approx. 1900 kWh/m^2/year, which characterizes a typical Southern-EU location with acceptable meteorological conditions for deployment of solar plants, and for a location nearby Calama in north of Chile with excellent DNI conditions of approximately 3400 kWh/m^2/year.

The performance indicator used in this study was the LCoE, calculated with a methodology and technical models developed by the authors in previous studies [7][8]. The study has been performed considering an operational lifetime of 25 years and a construction period of 2 years. A weighted average capital costs (WACC) of 5% as interest rate has been assumed, similar conditions to CSP and PV projects developed in Ouarzazate, Morocco. On the sCO_2 cycle side the isentropic efficiency of the compressors and the turbines has been assumed to be 89% and 85%, respectively, and a conservative value of 85% effectiveness has been used for the heat exchangers. Cost figures for the sCO_2 cycle were extracted from recent published studies from DoE [9]. Other key assumptions include cost figures of 120€/m^2 for the solar field, 0.49€/kg for the molten salts, and a global figure of 1€/W$_{dc}$ for the PV plant. In modeling the PV plant and respective balance of system, a typical PV module with 18% efficiency and a DC-AC ratio of 1.2 has been considered. The results of the preliminary techno-economic analysis are summarized in Fig. 2. In the left side the optimum LCoE is plotted against the installed capacity of the hybrid plant (i.e. same MW installed for both PV and sCO_2 cycle in this example). The optimum LCoE is defined as the lowest value resulting from a sensitivity analysis done to the storage capacity and the solar field size, as shown on the table in the middle. Results highlighted correspond to a 50 MW installed capacity. The table to the right summarizes LCOE values found for both locations, and for competing configurations including a co-located hybrid plant (PV and CSP share connection point, but there is no electric heater), a CSP- sCO_2 only plant, and a conventional CSP plant with a steam cycle.



LCOE [€/MWh]						
50 MW		Solar Multiple [-]				
		1	1.25	1.5	1.75	2
TES size [h]	6	78.8	72.8	69.7	68.1	67.6
	8	80.8	74.3	70.2	67.8	66.4
	10	82.7	76.0	71.4	68.2	***66.3***
	12	84.5	77.5	72.8	69.2	66.7

LCoE [€/MWh]		
Layout (50 MW plant)	1900 kWh/m^2	3400 kWh/m^2
CSP sCO_2 + PV (+ El. Heater)	**66.3**	**42.8**
CSP sCO_2 + PV (co-located)	**69.2**	**44.4**
CSP sCO_2 (no PV)	93.7	77.9
CSP steam cycle	105.1	85.5

Fig. 2 SOLARsCO2OL Hybrid CSP--PV Layout with recompressed-reheat sCO2 power block

The results confirm that systems with an installed capacity greater than 15 MW are already able to remain below the targeted 100 €/MWh, highlighting the capabilities of the system of being deployed more cost-effectively at smaller scales than traditional steam-based alternatives. Moreover, it is observed that even small systems of 2 MW (similar to the SOLARSCO2OL demo) are able to reach competitive values of approx. 150 €/MWh. It is shown that for larger capacities (> 50 MW) the plant is able to reach LCoE values below 70 €/MWh, with larger systems (100 MW) closer to 60 €/MWh inclusive. To the right of the figure, the table shows the influence of the location, for which the same optimum 50MW configuration identified for Seville has been modelled also in Calama (not optimized for it). The results highlight that in locations with a higher DNI, as Calama (Chile), LCoE values of approx. 45 €/MWh could be reached, which is in line with recent competitive bids observed in Chile for hybrid CSP-PV configurations . Furthermore, it was observed that the same optimum configuration with 10 hour storage capacity would in all cases exceed a capacity factor above 55%, reaching values closer to 75% in the case of Chile. Here it is worth underlining that capacity factor for the hybrid plant is defined as the total annual yield divided by the potential yield that the plant would provide if operating 100% of the time, at 100% load, with load defined as the nameplate capacity of the sCO_2 power block. The optimum hybrid CSP sCO_2-PV plant configuration with 50 MW and 10 hours of storage is estimated to cost 270M€, with an annual OPEX of 0.35 M€ approx., and for the reference location (Seville) the share of energy produced by the CSP plant was 65.7%.

The table on the right of Fig. 2 also shows that, regardless the location, the shift from steam cycles to sCO_2 would represent a significant reduction in LCoE (by approx. 8-10%). This is possible provided that the recompressed sCO_2 cycle would operate at nominal conditions with an efficiency of approximately 50%, whereas the conventional superheated steam cycle is capped to 43%, both with a similar CAPEX in order of magnitude. It is also shown that hybridization with PV (just by simple co-location with smart control) can already lead to a LCOE reduction of 25% or more. At last, the analyses presented in this section were performed during the first stages of the project to assess the feasibility of the proposed concept, and are now being extended to include more detailed correlations both from technical and economic standpoints, together with more detailed dynamic control strategies as part of the WP1 of the project. This updated version of the techno-economic model will be used to assess replication case studies for a potential site in Seville, but also in Ouarzazate, Morocco, using data from the Noor III plant as a reference in collaboration with Masen, a partner of the project. Furthermore, additional advanced CSP layouts involving other HTFs and TES with higher temperature are also being investigated from a techno-economic modeling perspective.

THE SOLARSCO2OL DEMONSTRATION PILOT

Results presented in the previous section make clear that the successful design, development and demonstration of the main sCO_2 power block components at MW scale (turbomachinery and heat exchangers), and the electric heater would represent an important step towards more cost-competitive and efficient CSP plants in the near term, leveraging from already commercial molten salt technologies. In turn, the SOLARSCO2OL demo is a purposely-designed independent pilot that integrates a 2 MW gross sCO_2 simple Brayton cycle with a molten salt system that includes an electric heater and storage tank, besides all required balance of plant and instrumentation for control. The pilot is grid connected and able to operate on demand for experimental purposes, leveraging also from existing infrastructure on site in relation to grid-connection point and utilities. Fig. 3 shows a simplified schematic of the pilot plant (left) including all main components namely the high-pressure turbine (HPT), the main compressor (MC), the cooler, the recuperator, the main primary heater (MH), the molten salt tank and the electric heater, with black lines denoting electricity, green CO_2 and red molten salts, respectively.

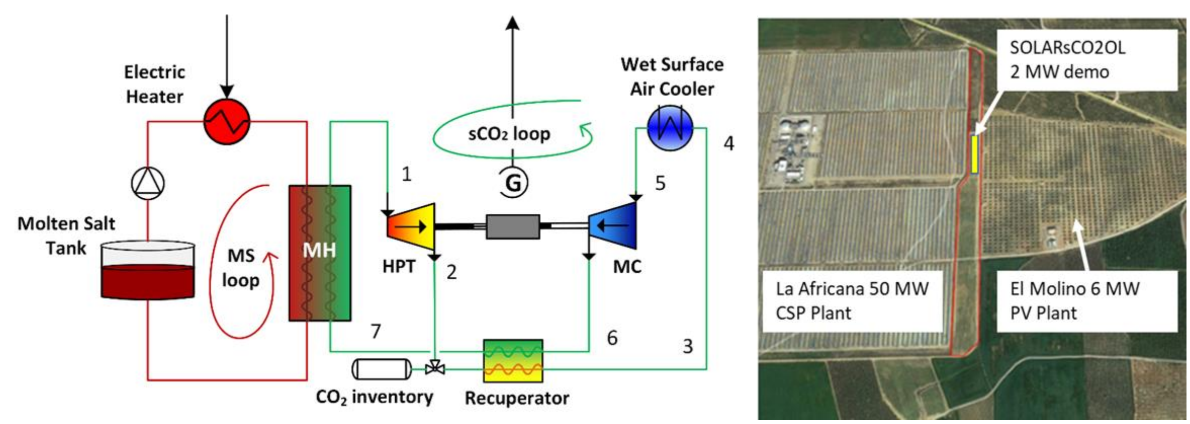


Fig. 3 Left: Simplified Schematics of the SOLARsCO2OL Pilot; Right: Pilot location in existing power plant in Spain

The SOLARSCO2OL pilot is planned to be demonstrated at the premises of an existing solar complex nearby Cordoba in south of Spain, composed of a 50 MW CSP plant and a 6.1 MW dual-axis tracking PV plant. The pilot would be erected in an area situated between both power plants, and with easy access to road and utilities, including access to an existing grid-connection point. Both existing solar power plants have been constructed and operated by Magtel, a partner of the project, which also owns the land and is in charge of site preparation work, procurement of the balance of plant system equipment, and of the operation of the demo once commissioned. Fig. 3 shows the reserved area on site for the pilot plant. Early since project start permitting process and civil work has started, building upon existing facilities. During the first year, and under the guidance of Abengoa, KTH, UNIGE and RINA-C, all the SOLARSCO2OL partners have locked the cycle thermodynamic configuration (shown in the next section) and initiated preparation of detailed engineering work, for which first P&IDs have been issued, including auxiliary systems and respective list of equipment and procurement work has begun.

Simultaneously, after the cycle thermodynamic definition, the technology supplier partners within the consortium have worked during the first year on the conceptualization and design optimization of their respective components to-be installed in the pilot. Baker Hughes and Franco Tosi Meccanica have issued first conceptual design of the sCO_2 compressor and turbine, respectively, supported by thermodynamic, fluid mechanics and thermo-mechanical studies. In doing so, they have been supported by UNIGE and Abengoa in characterizing the expected off-design operation of the turbomachinery, and in understanding the expected dynamic behavior of the integrated system in order to define optimal control strategies. The latter also being supported by MAS Europe, which will be in charge of the control software and identifying related instrumentation equipment for the pilot. Similarly, Lointek has worked in detail on the optimization of the heat exchangers in the power block, and SEICO on the design of the molten salt electric heater. In their quest, both Lointek and SEICO are being supported by Ikerlan and CERTH in specific relation to component optimization via CFD analysis.

Thermodynamic Cycle Definition of SOLARSCO2OL Demo

As shown in Fig. 3, and mentioned in previous sections, the cycle to be demonstrated is 2 MW gross simple recuperated Brayton cycle that consists of six key thermodynamic states and five major components. The six thermodynamic states defined are shown in Fig. 4 alongside a representative T-s diagram. These thermodynamic conditions lead to a targeted nominal thermodynamic efficiency of 22.1%. To achieve so, the hot and cold temperatures of the molten salt are set to 580°C and 380°C. The definition of the thermodynamic states resulted from finding best compromises between reaching a high performance and the available project budget. In doing so the design isentropic efficiencies for the compressor and turbomachinery were set to 67% and 83%, respectively, and the target recuperator effectiveness was set to 80%.

CO2 Thermodynamic States – SOLARSCO2OL Demo		
#	P [bar]	T [°C]
1	188.0	57.0
2	186.5	301.5
3	185.5	565.0
4	88.1	481.0
5	83.6	125.0
6	83.0	33.0

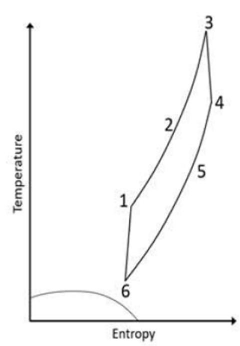


Fig. 4 Thermodynamic states of the sCO2 Cycle in the SOLARsCO2OL Demo

In the following sections, details about the preliminary designs of each of the key components of the power cycle and the electric heater are provided. In summary, a minimum recuperator effectiveness target of 80% was selected to ensure higher efficiency of the cycle, as it was shown to be one of the parameters with greatest influence; whereas desirable, an increase in effectiveness would have represented a larger heat exchanger area and thus higher costs. Similarly, the efficiencies of the turbomachinery components were settled based on preliminary calculations made by partners and are expected to increase along with the installed capacity of the cycle, as aerodynamic performance would be enhanced in larger equipment. The definition of the pressure lines accounts for estimated drops in the heat exchangers (derived from conceptual designs), and the maximum and minimum pressure values were carefully selected to guarantee the rotor-dynamic stability of the turbine and the stability of the compressor at the inlet, by allowing a safety margin with regards to the critical point. In specific relation to the later, a conservative value of cold temperature at 33°C was considered. By doing so, preliminary calculations at off-design using UNIGE's own-developed software [10] showed that the stability of the compressor would be assured. Based on these cycle specifications, Abengoa has worked in great details with all partners to design the balance-of-plant and auxiliary systems required to guarantee an adequate performance of the demo, alongside the definition of specific operating routines to consider during start-up, stand-by, and normal testing operation. The aim of the project is to perform tests on site throughout 2024, at different loads and under different weather conditions, accounting in total for at least 500 operating hours from which data will be analyzed.

Furthermore, and in order to show the impact of installed capacity and related component scaling-up on the thermodynamic performance of the cycle, the partners carried a thermodynamic analysis of a 10 MW gross cycle with same configuration considering respective up-scaled optimized components, and it was determined that at such scales isentropic efficiencies of 78% and 90% could be achieved for the compressor and turbine, respectively, following a similar design approach, which coupled to an enhanced recuperator effectiveness of 90% would yield a thermodynamic efficiency of 31.5%. At 10 MW-scale the cycle could be further improved with reheat, recompression (and respective intercooling), and would be expected to reach already a thermodynamic efficiency of 41.4%, at same pressure and temperature levels. Stressing the potential of the cycle even at relative small-scales, and the value of demonstrating a scalable design of the components already in the 2 MW SOLARSCO2OL Demo. The following section shows a summary of each of the preliminary designs attained for the main components of the power block, with main considerations undertaken by the respective partners.

PRELIMINARY DESIGN OF DEMO COMPONENTS

Compressor

The CO_2 thermodynamic properties near critical point shows large gradients. Therefore, the preliminary design of the compressor required a dedicated detailed aerodynamic analysis of the inlet guide vane (IGV) and the first impeller in order to understand impact on overall compressor performance and to ensure no local conditions with liquid CO_2 occurred at nominal condition. Compressor inlet temperature control is an important parameter that must be taken in account carefully during the design phase to meet compressor requirements. Cooler control shall guarantee that, in all operating conditions, steady state and transient, the inlet temperature is such that there is no CO_2 liquid formation to operate the compressors without any limitations.

Another challenge of designing a supercritical CO_2 compressor is the fluid density, comparable with liquid CO_2. The extreme power density (power to inertia ratio) for this application requires special attention on mechanical verification of the main compressor components, on the compressor rotor dynamic behavior and on the evaluation of the thrust load acting on compressor thrust bearing. On the other hand, the extreme power density allows the selection of a smaller size compressor, providing benefits in terms of footprint and equipment cost, but at the expense of potentially increasing manufacturing complexity as it is much smaller than typical process centrifugal compressors. Moreover, in case it is necessary to vent the compressor due to dry gas seal (DGS) failure, supercritical CO_2 might cross the condensation line, entering in the dome where liquid and gas coexist, and worst yet clogging might occur if the vented CO_2 reaches 5 bar, therefore a dedicated analysis was carried out to investigate the consequences of DGS vent lines clogging and the respective mitigation actions needed from a design point.

Considering the challenges raised above, and the experience from the sCO2Flex project [11], Baker Hughes deployed own internal tools and methods to propose a conceptual design of the SOLARSCO2OL compressor able to meet the cycle requirements and ensure a stable operation at relatively high efficiencies. The result from the preliminary design phases concluded in a 3 stage centrifugal compressor machine, with a nominal speed exceeding 12000 rpm, and an operating range from 60% to 105% speed. This selection was built with the aim to keep impeller diameters such that they are obtained from linear downsizing within the Baker Hughes standard range to ensure that standard manufacturing processes can be applied. The train shaft line is composed by a variable speed drive electric motor, the gearbox and the centrifugal compressor. A cross section of the preliminary design of the compressor is shown in Fig. 5, followed by normalized power and polytrophic efficiency curves in Fig. 6, plotted as a function of normalized loads and also displaying the expected influence of rotational speed (also normalized).

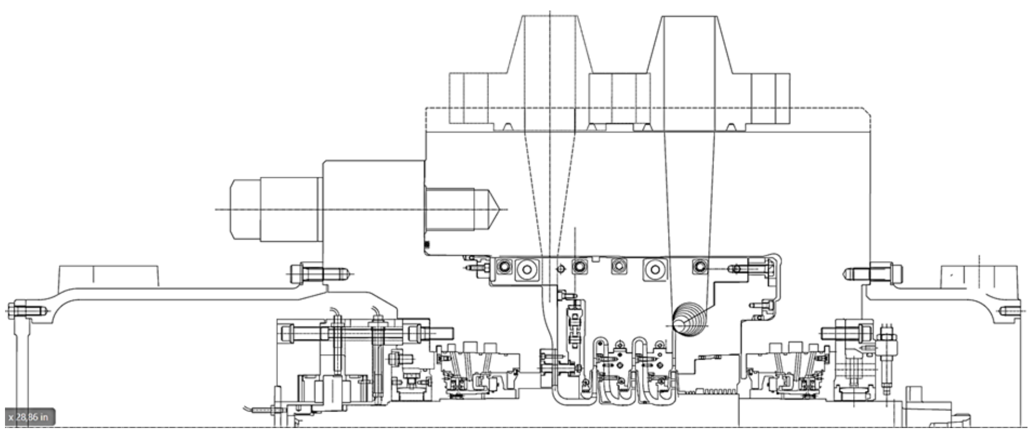


Fig. 5 Cross section of the SOLARSCO2OL Demo compressor preliminary design

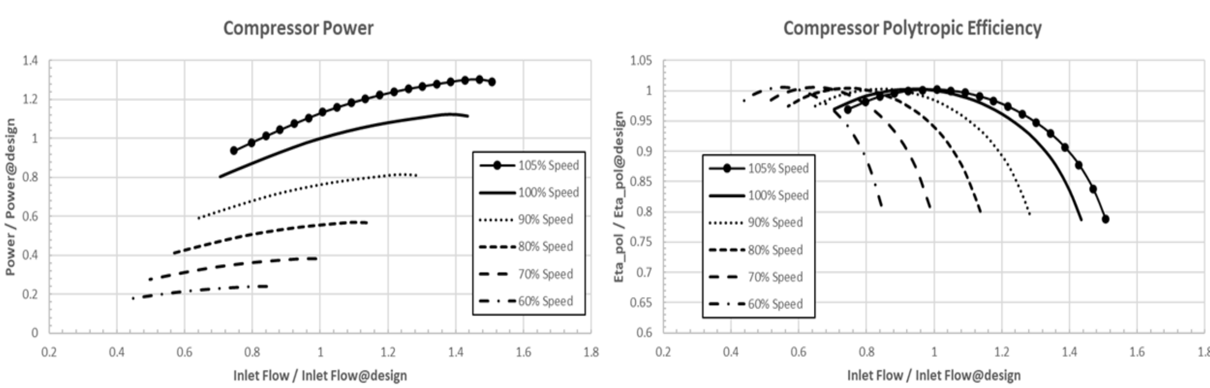


Fig. 6 Normalized power and efficiency curves of the SOLARSCO2OL Demo Compressor Preliminary Design

Turbine

The SOLARSCO2OL project requires a sCO_2 turbine of particular challenges as the power size is possibly the smallest that can be ever commercialized, with all inherent aerodynamic and manufacturing issues, plus the need to deliver a scalable design, and at the same time demonstrate that even with current HTF technologies (limiting the turbine inlet to 565°C) the efficiency and the overall costs can justify a commercial future for the technology. In turn, one of the targets of the preliminary design led by FTM was to take already into consideration solutions addressing these challenges and looking ahead into the next generation of sCO_2 turbines, leading to a design scalable to 10 MW and more, and able to operate at inlet temperatures of at least 650°C. In doing so, proprietary gas turbine design tools by FTM [12] were deployed and it was determined that a turbine configuration with one radial stage and possibly two axial stages, as shown in Fig. 7, was the best compromise to keep an even low power extraction per stage and mitigate potential rotor-dynamic stability issues. This radial plus axial design approach would enable the possibility to scale to higher power sizes, whilst keeping the same range of aero-thermodynamic features and the same range of mechanical stationary and dynamic load ranges.

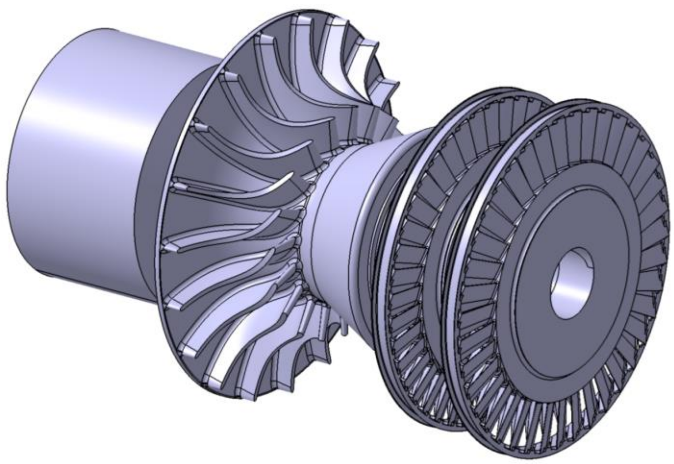


Fig. 7 3D Representation of the Preliminary Design of the SOLARSCO2OL Turbine

A purposely developed 1D code was used to investigate different stages geometries and to get the preliminary operating curves. The nominal steady operating conditions for the selected preliminary turbine design has been checked by mean of CFD calculations with satisfactory agreement. To do so, gas properties were taken from NIST Refprop 10.0. ANSYS CFX was used for CFD simulations, and ANSYS mechanical for all thermo-mechanical calculations. It has been recognized that high temperature (and corrosion resistant) materials are needed not only for future enhanced thermodynamic conditions up to 650°C at turbine inlet, but also to withstand high stationary mechanical loads. Fig. 8 shows the estimated performance curves of the turbine, both in terms of power (left), and expansion ratio and efficiency (right) as a function of normalized volumetric flows. These will be the basis for the definition of off-design performance maps. These performance curves show that it is expected for the turbine to operate in a range within 50% to 120% load, with an efficiency varying between 74% and 85% respectively. A theoretical nominal efficiency value of 86% is calculated, which should suffice to reach the targeted 83% when accounting for aerodynamic phenomena not widely studied, and currently being investigated. In this context, first CFD analyses from the preliminary design reveal that clearance leakages can play an important role in the performance of the turbomachinery, as expected due to its small size. Furthermore, and similar to the compressor design work, considerations have also been taken to address the design of the DGS, and required auxiliary balance of plant system.

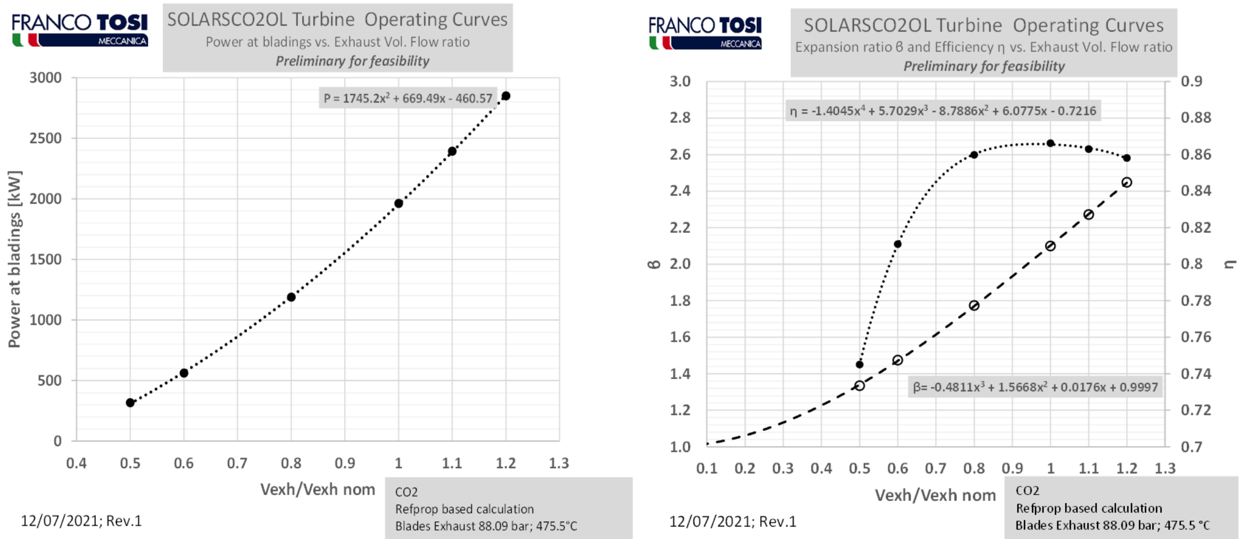


Fig. 8 Estimated Performance Curves of the SOLARSCO2OL Turbine

Heat Exchangers

Thermodynamic boundary conditions and requirements for the heat exchangers were specified as a result of the thermodynamic cycle definition, subsequently Lointek led the preliminary thermal and hydraulic design of the primary heater and the recuperator in the sCO_2 power cycle. For both heat exchangers a Hairpin-type shell-and-tube configuration was selected. The selection was the result of multiple analyses and previous manufacturing and operational experience from Lointek. Amongst others, one of the advantages of such configuration is the enhanced heat transfer due to the counter flow arrangement between the fluid in the shell, and the one in the tubes. Sensitivity analyses to geometrical and material specifications of the tubes and shell elements of the heat exchangers were carried using proprietary and commercial tools. The results of these preliminary designs are now being used in subsequent CFD and FEM studies for both validation and further optimization, with the support of Ikerlan and RINA.

For the primary heater, given the temperature gradient required it was decided to split the component into two heat exchangers placed in series. Fig 9 shows the expected temperature profiles in the molten salts and in the CO_2 throughout both shells, in red and blue respectively. Although designs are similar, the colder heater is strategically chosen to have a larger thermal duty, to reduce possible risks that arise at higher temperature. Increasing redundancy by having two heaters was also strategically chosen from a reliability standpoint [13].

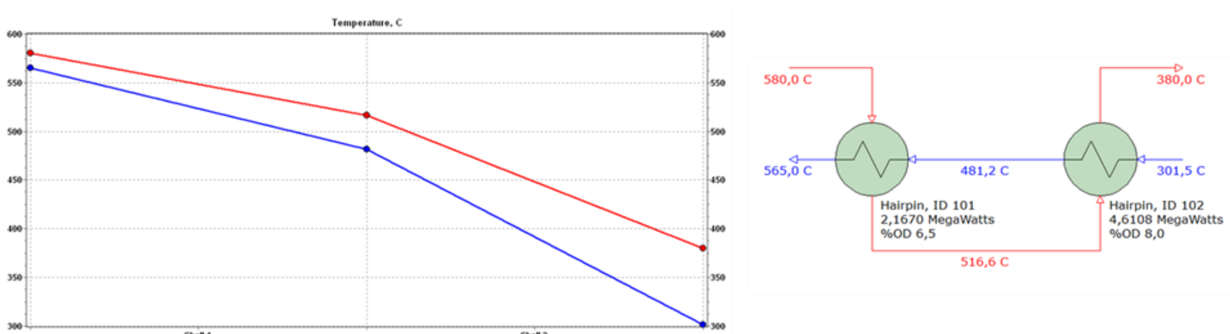


Fig. 9 Temperature Profile Output of the Preliminary Design of the SOLARSCO2OL Demo Primary Heater

As mentioned earlier, the recuperator was designed with the target to meet an effectiveness of 80%, which resulted in a single hairpin-type heat exchanger of approximately 5 meters length, with a shell diameter of approximately 43 cm (external), leading to estimated pressure drops of 5% and 1% on the shell and tube sides, respectively (as shown in Fig. 4). For the CO_2 cooler, specific design configurations are still being assessed by the consortium, thus far favoring dry-cooling alternatives, either a fully adiabatic or a wet-surface air cooler. Adiabatic coolers have the advantage of being less CAPEX intensive, but on the contrary demanding more electricity (and thus OPEX), larger footprints and also being more sensitivity to ambient conditions.

Molten Salt Electric Heater

The design of a molten salt electric heater is currently considered by the project to have TRL 4-5, as an electric heater of MW scale purposely designed for molten salt applications has not been commercially documented. Even if the resulting electric heater shows similarities to other proven heaters with other media and application, this equipment faces thermal and structural challenges in molten salts service that will have to be proven and properly studied in SOLARSCO2OL. Traditional molten salts used in CSP applications (with a 60% sodium nitrate and 40% potassium nitrate mixture) might undergo various degradation processes.

Within the operating temperature range the Nitrates partially convert to Nitrites, releasing oxide ions which then become available for further reactions. Above the maximum operating temperature sodium oxides can also form. The effects of this degradation are the possible formation of solid phases within the melt that can foul heating surfaces, as well as potential weakening of the materials of construction through corrosion mechanisms. Solid phases occur due to degradation products and as the result of the various reaction mechanisms of these products with the impurities in the salts, dissolved atmospheric gases, and with the metals used for pressure containing parts and internals. Corrosion, on the other hand relates to the potential formation of sodium ferrite salts, a non-adhering oxide on the material surface, as well as with possible leeching of Chromium, Molybdenum and Manganese from the surface layers of the alloy materials, and dissolving them into the nitrate melts as metal oxide ions. The formation of sodium ferrite salts is observed at temperatures greater than 600°c, and creates an oxide layer on some steels which spalls from the steel surface as an oxide scale, thus exposing more material to corrosion and as such, accelerating the corrosion rate. Leeching, on the contrary, creates depletion zones of these alloying elements below the oxide layers of the metal. This creates a non-homogenous material with a variation of mechanical properties such as thermal expansion coefficient, which makes the materials prone to damage if the equipment is exposed to thermal cycling during the testing regime.

In turn, the design of molten salt electric heaters requires a detailed temperature control strategy, departing from a good understanding of the flows and heat transfer phenomena, subject to the given heater geometry, which is also to be optimized. One key challenge is that electric heaters, in general, do not heat flows consistently, as the fluid passes along the trajectory governed by the heater internals. In most services this uneven heat input is not of consequence as the fluid mixes downstream of the heater into a medium with nearly consistent temperature. For this service a far finer tolerance is required on the temperature deviation from the maximum operating temperature, so in short hot spots in stagnant flow paths have to be eliminated.

Given the above challenges, and the set cycle boundary conditions, SEICO prepared a preliminary design of the electric heater using proprietary heater design tools, resulting in a single in-line once-through design with a shell casing of 1 meter diameter and 4 meters long. A simplified CAD of the preliminary internal design showing the wetted parts is shown in Fig. 10.

The resulting design considers 546 baffled active elements and 14 stages. This preliminary design is now being assessed via CFD and FEM studies in collaboration with CERTH, in order to analyze thermal performance and mechanical integrity, and potentially leading to future optimized configurations. Future configurations might potentially lead to new design of internals, distribution of elements between stages, determination of optimum element heat flux per section, element sensor location and final control methodology prior to locking a final design. It is worth highlighting that CFD simulations of electric heaters are very complex due to the geometry involved, whilst some simplifications often used for a tube bank may not yield the correct results. The plan is to fine tune the internal design and the control of the heater elements with the intent of providing a far smoother increase in the heat energy addition to the fluid as it passes through the Electric heater whilst ensuring the heating elements do not exceed the degradation temperature limits highlighted previously.

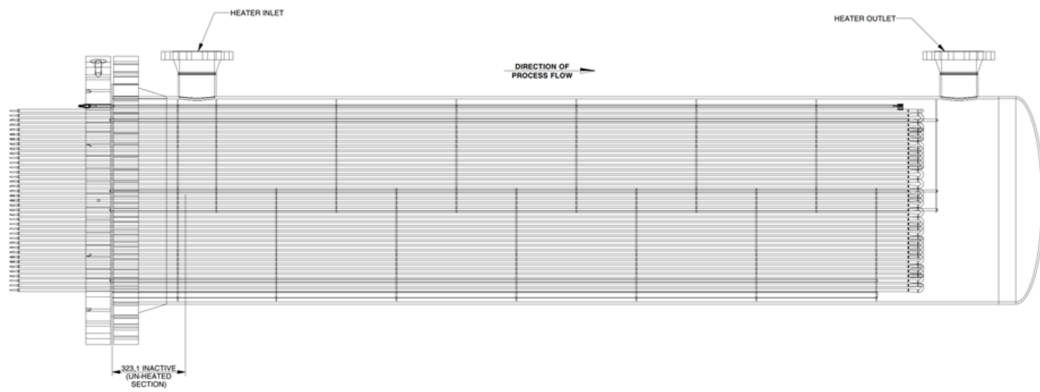


Fig. 10 Simplified CAD of the Preliminary Design of the Molten Salt Electric Heater

CONCLUSIONS

Progress made after the first year of the SOLARSCO2OL Demo project has been summarized in this paper, with focus placed on introducing the preliminary design of the demo pilot plant, the thermodynamic cycle to be demonstrated and its main components, as they now enter the subsequent optimization phases via numerical studies. The motivation for the project and its expected impact have also been highlighted, showing that enabling new sCO_2 cycles and active hybridization with solar PV via flexible electric heaters can already enhance the techno-economic performance of the CSP plants, yet with current state-of-the-art solar tower technologies deploying molten salts as heat transfer fluid and storage media. In this way the successful demonstration of the cycle and integration into a mature CSP technology, even at smaller scales (i.e. 2 MW), can be seen as a stepping stone towards up-scaling and market entry of sCO_2 cycles in the near future, and of higher temperature CSP systems in the later future, once the respective CSP technologies have reached a higher level of maturity.

The demo cycle will be a simple Brayton cycle with an installed capacity (gross) of 2 MW and a targeted nominal thermodynamic efficiency of 22.1%. A three-stage centrifugal compressor has been chosen, together with a 3-stage turbine consisting of an inlet centrifugal stage and two axial ones. These components are estimated to achieve limited isentropic efficiencies of 67% and 83%, respectively, given the limitations imposed by the small size and the related aerodynamic losses (e.g. cavity and clearance loses). Hairpin-type shell-and-tube heat exchangers have been designed for the demo for the primary heater and the recuperator, targeting an effectiveness of at least 80% for the latter. The partners have worked in great details to guarantee that designs are scalable and to facilitate manufacturing process. In doing so, the partners estimate that for a same simple Brayton cycle configuration with similar component designs it would be possible to reach a thermodynamic efficiency exceeding 30.5% at 10 MW-scales, with the possibility to be increased up to 41.4% in a more complex reheat-recompressed cycle configuration. Moreover, techno-economic studies show that at 50 MW scales the hybrid PV-CSP plant integrating flexible molten salt electric heaters and a reheat-recompressed sCO_2 power block could potentially reach LCOEs of 66.3€/MWh for a typical Southern-EU location, well-below the EU CSP set targets, and further down to 43€/MWh for locations like in Chile.

The 15 partners of the SOLARSCO2OL project, namely RINA Consulting, KTH, UNIGE, Abengoa, Masen, Baker Hughes, Franco Tosi Meccanica, OCMI-OTG, CERTH, Ikerlan, Mas Europe, SEICO, ESTELA, Lointek and Magtel, are committed to its successful implementation. The project is on track, following the preliminary design and conceptualization phase, the project is now entering in the optimization of the system via numerical investigations, which shall continue until months 18-24, depending on the sub-system or component. Soon after this phase the designs will be locked and manufacturing will began, whilst in-parallel site works are expected to start including procurement and installation of auxiliary and utilities equipment. By month 36 the pilot is expected to be commissioned, and will subsequently undergo an experimental testing protocol of at least 500 hours including different operating modes, spread throughout the fourth year of the project (October 2023 – October 2024) in order to capture the impact of weather variations on the performance of the cycle, and the system as a whole.

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