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Preliminary Results of the EU SolarSCO2OL Demonstration Project: Enabling the Integration of Supercritical CO_2 Power Blocks into Hybrid CSP-PV Plants

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ABSTRACT

This paper presents an update on the status of the EU-funded H2020 project SOLARSCO2OL, with the main target and accomplished project objectives and deliverables. SOLARSCO2OL is dedicated to demonstrating a 2 MW supercritical CO_2 (sCO_2) cycle utilizing heat derived from molten salts within a solar facility, namely the Evora Molten Salt Platform (EMSP), in Portugal. SOLARSCO2OL will be the first MW scale EU sCO_2 power block that will be coupled with an existing molten salt parabolic trough collector system featuring high-temperature molten salt thermal energy storage (TES). The demo plant will include a molten salt electric heater, boosting the salt temperatures before they enter into the salt-to-sCO_2 primary heater, ensuring a Turbine Inlet Temperature (TIT) of 565 °C. Successful demonstration of sCO_2 power block and molten salt loop components at MW scale, along with complete system integration, marks a pivotal stride toward more competitive and efficient CSP plants in the short term, capitalizing on existing commercially viable molten salt CSP plants. Driven by an industry-oriented consortium, SOLARSCO2OL seeks to advance this concept's marketability by 2030. This is explored through feasibility studies for scaling up, environmental and social analyses, and encouragement of business cases within the EU. The project was initiated in October 2020 but experienced a suspension from March 2022 to February 2023 due to financial constraints. This paper focuses on the engineering, design and integration aspects of the new demonstration plant now located in Evora, Portugal. The initial phase, centered around design optimization, has been successfully completed, and the project's current focus is on tasks like manufacturing, prototype testing, detailed engineering, procurement, and installation. The concluding phase will be the operation of the demo. The demonstration campaign is projected to conclude by the end of 2025.

INTRODUCTION

Molten salt (MS) solar towers with two-tank TES systems employing the nitrate-potassium 40-60% salt mixture as heat transfer fluid (HTF) and storage media, coupled to super-heated steam cycles, can be considered the most advanced state-of-the-art and commercial concentrating solar power (CSP) technology. This technology has proven cost-competitive and reliable in a number of installations worldwide [1], yet CSP is in general still perceived as not cost-competitive enough on the basis of levelized cost of electricity (LCOE) when compared to other renewable technologies such as wind and solar PV, in spite of the benefit of CSP being able to provide energy on demand due to its inherent energy storage capability. In order to make the technology more competitive, policy-makers and researchers have identified that advances on the technology side that can increase the conversion efficiency of the system, and significant cost reductions at component and system level are needed, including the development of strategies and technologies for hybridization with other more cost-competitive renewable technologies [2]. One option to increase efficiency, and thereby possibly cost-competitiveness, is to collect and store energy at higher temperatures, from 700°C and above. Commercial MSs are limited to a maximum operating temperature of 580°C, due to the risk of salt decomposition above 585°C. In turn, moving up in temperature would require the use of new HTFs and TES systems. Multiple technologies are under development to address this issue, including the use of novel chloride salts [3], liquid sodium [4], solid particles [5], and ceramics and rocks using air as HTF [6]. Similarly, moving to temperatures higher than 650 °C would also demand the use of other types of power cycles different than steam cycles. In this context, sCO_2 cycles can represent a viable alternative for CSP. These cycles have the advantage of being able to operate in a broader temperature range than steam cycles and reach higher efficiencies [7], while at the same time being tenfold more compact, which in turn can represent an opportunity for cost reduction. In addition, sCO_2 cycles have also been identified to reach high efficiencies already at medium-size scales of 15 MW and above [6], which can also facilitate the deployment of smaller-scale CSP plants, easier to finance. However, the reliability of sCO_2 cycles is yet to be proven, and, similar to new TES and HTFs, research is undergoing at multiple fronts including turbomachinery aerodynamic design and manufacturing, optimized heat exchanger design, cycle control and dynamics, and the use of high-temperature non-corrosive materials. There is yet limited research worldwide targeting the demonstration of integrated sCO_2 cycles and components, with most projects at kW scale in the laboratory and only a handful of MW scale. Among the projects at MW scale, the 10 MW US DoE STEP program is one of the most ambitious ones, where an integrated sCO_2 cycle will be demonstrated operating at 700°C with heat provided by natural gas [8]. No public documented project development or commercial operation of sCO_2 cycles coupled to CSP, or HTFs used in CSP, are found yet to date, with only few R&D demos have been announced: EDF's Shouhang pilot where a 10 MW cycle is intended to be coupled to a MS tower [9]; the US DoE Gen3 program where a MW-scale particle CSP system will be designed for future coupling to a MW-scale sCO_2 cycle [10], and the recently publicized Heliogen's pilot project targeting the coupling of a CSP tower facility with a sCO_2 cycle. None of these projects in Europe (EU) in spite of EU being home to worldwide leading turbomachinery and heat exchangers OEMs, as well as home to multiple CSP technology developers and having set clear CSP cost targets [11]. Substantial technological development is thus yet needed both on the CSP and the sCO_2 fronts in order for integrated CSP-sCO_2 systems to reach market maturity. Each technology shift and development entails new unknown risks and will have several consequences on the future development of the integrated system, notwithstanding challenges related to the coupling of both from a control and operational perspective. Developing the needed technologies in a stepwise approach can represent a more viable and lower-risk alternative, financially speaking, for the sustainability of the CSP industry.

This paper presents the results from the ongoing SOLARSCO2OL project, which aims at demonstrating a first-of-a-kind EU MS driven MW scale sCO_2 cycle. In doing so, technological advancements are proposed in relation to the demo design, operating strategies, alongside techno-economic and life-cycle analyses for up-scaled and advanced systems with higher operating temperatures. This paper builds on the previous publications from the author that focused on the first year results [12], [13]. The project builds upon existing know-how on commercial MS technology and focuses mainly on demonstrating the reliability and performance of a cost-effective and scalable sCO_2 cycle, with key component and system equipment designed and supplied by partners within the project consortium in the EU. Specifically, in this paper an overview of the project and time-plan is provided first, followed by the targeted upscaled integrated system, the specific demo-pilot cycle design, and boundaries.

THE SOLARSCO2OL DEMONSTRATION PILOT

The SOLARSCO2OL demonstration pilot plant integrates a 2 MW gross sCO_2 simple Brayton cycle with a molten salt system that includes an electric heater and storage TES, and the 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 the grid-connection point and utilities.

Originally, the SOLARSCO2OL pilot was planned to be demonstrated at the premises of an existing solar complex near Cordoba in the south of Spain, composed of a 50 MW CSP plant and a 6.1 MW dual-axis tracking PV plant, as presented in [12], [13]. 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 the preparation of detailed engineering work, for which the first P&IDs have been issued, including auxiliary systems and respective list of equipment and procurement work had begun. Simultaneously, after the cycle thermodynamic definition, the technology supplier partners within the consortium have worked on the conceptualization and design optimization of their respective components to be installed in the pilot. Baker Hughes and Franco Tosi Meccanica have issued the design of the sCO_2 compressor and turbine, respectively, supported by thermodynamic, fluid mechanics, and thermo-mechanical studies. In doing so, they were 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 to define optimal control strategies. The latter was also being supported by MAS Europe, which is in charge of the control software and identifying related instrumentation equipment for the pilot. Similarly, Lointek 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 supported by Ikerlan and CERTH in specific relation to component optimization via CFD analysis.

On March 31, 2022, the consortium opted for a suspension of activities primarily due to budgetary constraints and internal reorganization at La Africana Plant, now under the ownership of La Africana Energy with reduced involvement from MAGTEL. This prompted the exploration of alternative solutions for the SOLARSCO2OL demonstration campaign. After assessing various options, the Evora Molten Salt Platform (EMSP) in Evora, Portugal (http://www.emsp.uevora.pt/) emerged as the new designated demo location. Potential additional costs associated with integrating the demonstration campaign into this new location were managed through co-investment from the site owner and a budget redistribution among the partners. The EMSP is owned by the University of Evora (UEVORA) and co-managed with the German Aerospace Center (DLR). Thus, UEVORA and DLR were welcomed into the consortium as responsible demo partners. To facilitate the re-engineering of the demo plant, Build to Zero (B2Z) also joined the SOLARSCO2OL consortium. Resuming activities hinged on several criteria: the commitment level of the new demo site offered by UEVORA and DLR, its alignment with project objectives, the feasibility of testing the MW scale SOLARSCO2OL sCO_2 power cycle, and unanimous agreement among beneficiaries regarding budget redistribution.

Evora Molten Salt Platform (EMSP)

Figure 1 shows the EMSP, the facility that hosts a molten salt parabolic trough collector (PTC) system and a high temperature molten salt thermal energy storage (TES) system. Pre-existence of these systems would enable the SOLARSCO2OL consortium to save costs, while at the same time the demonstration of the technology at the premises of the EMSP would further enhance the visibility of the site and guarantee continuation in the operation of the facility while being extended to accommodate innovative components, thereby making the EMSP even more unique and positioning it as the first installation in EU and worldwide to host a MW-scale hybrid PV-CSP-sCO_2 system. The pilot is designed to fully demonstrate and simulate the typical behavior, operational strategies, and flexibility of a CSP plant. The EMSP solar field includes four parabolic trough collectors connected in series, for a total length of 700 m and equipped with innovative heat collecting elements, reaching a total thermal power output of 3.5MW and a molten salts temperature up to 560°C, including a complete TES system (HPS2).

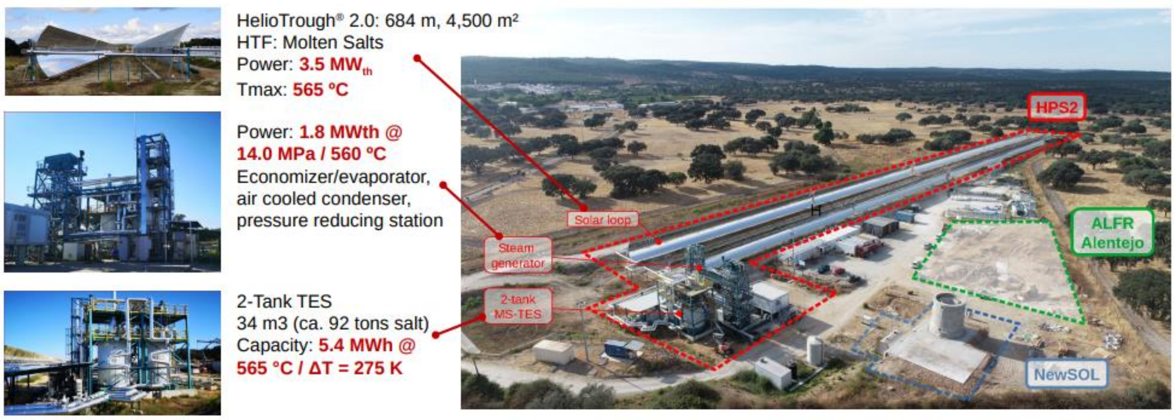

Figure 1:Evora Molten Salt Platform

Thermodynamic Cycle Definition of SOLARSCO2OL Demo

As shown in Figure 2, the cycle to be demonstrated is a simple recuperated Brayton cycle that consists of six key thermodynamic states and five major components. The six thermodynamic states defined are shown in Figure 2 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 the best compromises between reaching high performance and the available project budget. Table 1 summarizes the main design efficiencies and thermal and electric powers of the main components of the cycle. The design of the thermodynamic cycle and the main components have been defined and preserved even if the location has been changed.

Table 1: Design Point – SOLARSCO2OL sCO_2 Power Cycle

Cycle Efficiency	-	0.22	Total Efficiency	-	0.20
MS Mass Flow Rate	kg/s	22.0	Primary Heater Thermal Power	MW	6.80
sCO_2 Mass Flow Rate	kg/s	21.0	Cold Sink Thermal Power	MW	5.30
Turbine Efficiency	-	0.83	Turbine Electric Power	MW	1.96
Compressor Efficiency	-	0.67	Compressor Electric Power	MW	0.47
Recuperator Effectiveness	-	0.80	Recuperator Thermal Power	MW	8.70
Electro-mechanic efficiency	-	0.92	Net Power	MW	1.38

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 showed that the stability of the compressor would be assured. Based on these cycle specifications, Build to Zero (B2Z) has worked 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 2025, at different loads and under different weather conditions, accounting in total for at least 500 operating hours from which data will be analyzed.

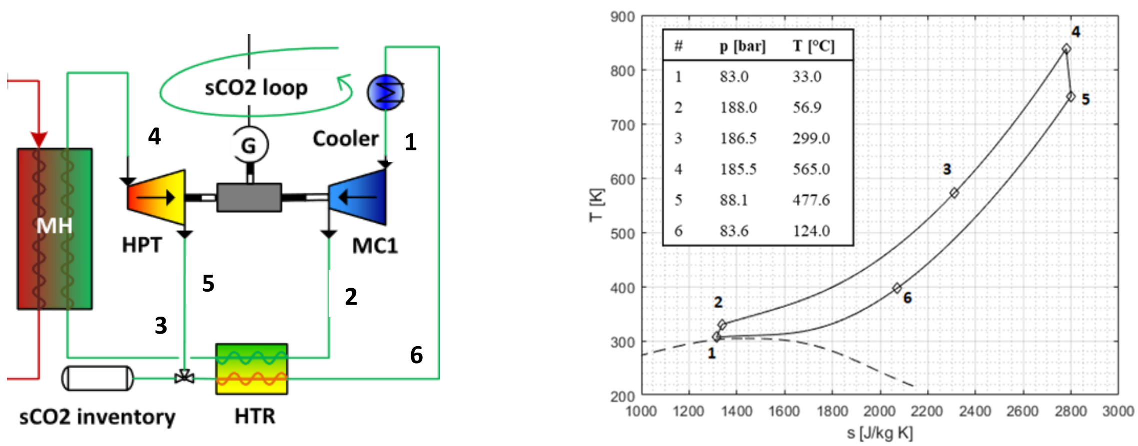

Figure 2: Thermodynamic states of the sCO_2 Cycle in the SOLARSCO2OL Demo

SOLARSCO2OL DEMO plant layout

The integration of the EMSP with the sCO_2 power cycle has posed a central engineering challenge. The sCO_2 cycle demands 6.8 MWth thermal input at the primary heater, sourced from 22 kg/s of molten salt at 580 ºC, as detailed previously. The EMSP boasts two identical molten salt tanks operating at matching conditions, with 580ºC temperature and -15/+50 mbar pressure. Both tanks are equipped with similar flanges, connections, 2x100% molten salt pumps, recirculation valves, and lines. The pumps in each tank differ in capacity due to their distinct roles: the cold pumps, handling higher pressure drops (>700 m) in the parabolic trough loop, have a larger capacity to manage fluid circulation (300-500 ºC) at a flow rate of ~12-14 kg/s. However, this is inadequate to meet the 22 kg/s demand for SOLARSCO2OL, necessitating reliance on TES and operational adjustments. Conversely, the hot pumps, facilitating the circulation of hot salts through the near steam generator and returning to the cold tank, possess lower capacities. They cannot achieve the required flow rate to the sCO_2 exchanger, resulting in partial loads. To address this disparity and ensure comprehensive operation for SOLARSCO2OL, a viable solution involves substituting one cold pump with a hot pump. This adjustment maximizes molten salt flow through the solar field, utilizes TES inventory effectively, and achieves the requisite flow rate in the sCO_2 exchanger.

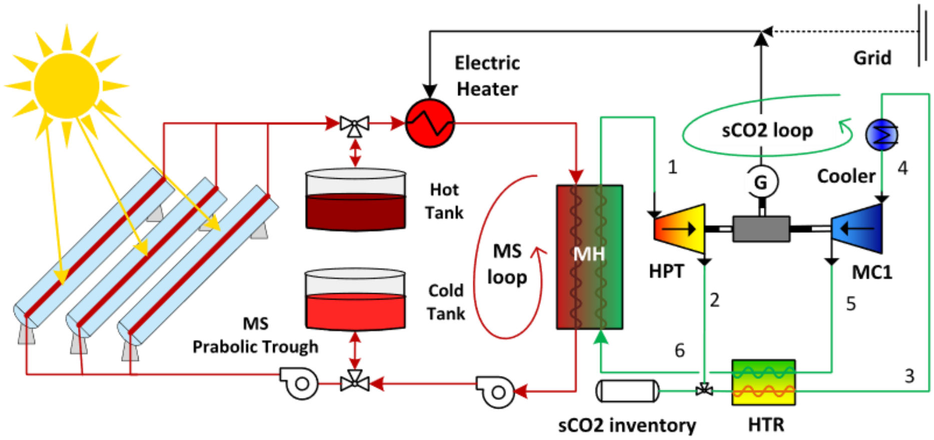

Figure 3: SOLARSCO2OL demo layout schematic

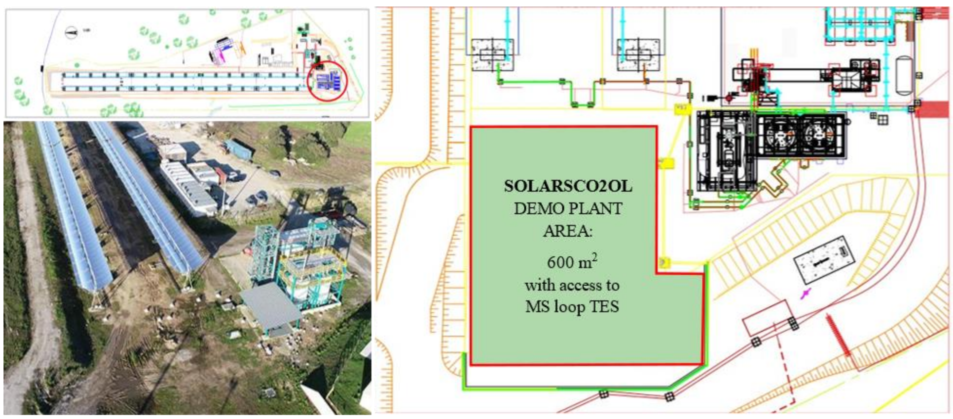

Figure 4: Integration of SOLARSCO2OL demo in EMPS

The molten salts pumps used in this EMSP are of the submerged type, ensuring there are no leaks or freezing issues near the impeller. The pump employed is a vertical VS1 model, which has been successfully operating in the MS PTC loop without any incidents or leaks. To incorporate the SOLARSCO2OL demo, all the piping and equipment undergo butt-welding with high standards of NDTs to assure zero leakages in the molten salts. Both the piping and equipment have a self-draining design that allows gravity to empty them into a drain tank. The CO_2 inventory system includes the traditional inventory components, including a cryogenic liquid CO_2 tank, a cryogenic piston pump for transporting the liquid CO_2 through an electric evaporator, and a buffer tank for CO_2 storage, that is used to regulate pressure and make-up the CO2 loop when required. The system leaks are from the primary vents of the Dry Gas Seals (DGS). The preliminary sizing of the cryogenic reservoir is around 6000 liters, while the buffer tank is sized at 1500 liters, which is the total volumetric content of the CO_2 loop. The maximum capacity of the output flow is 30 Nm^3/h. The sizing of the CO2 inventory is currently pending in the project, awaiting a more accurate estimation of CO_2 losses from the turbomachinery suppliers.

Figure 3 illustrates the simplified schematic of the pilot plant, encompassing key components such as the high-pressure turbine, main compressor, cooler, recuperator, main primary heater, molten salt tank, and electric heater, delineated by black, green, and red lines for electricity, CO_2, and molten salts, respectively. Figure 4 outlines the area earmarked for SOLARSCO2OL integration within the EMSP. The proposed integration involves situating the collector field in series with an electric heater downstream. At the nominal point, leveraging the solar field to elevate the "Solar Salt" temperature to approximately ~500°C is recommended, further augmented to ~580°C via a 3.5 MW electric heater. This setup optimally utilizes both molten salt tanks within the EMSP, offering advantages in terms of CAPEX requirements, demo plant capabilities, and representing SOLARSCO2OL technology effectively. This configuration minimizes alterations to the existing EMSP plant, operates with molten salt reservoirs at intermediate temperatures (490-500ºC) in the hot tank, and mitigates the impact of solar fluctuations on field operation—rendering it a more realistic representation of CSP technology aligned with SOLARSCO2OL's objectives. This initiative marks one of the initial pre-commercial electric heating systems designed explicitly for molten salt applications at the MW scale, showcased in a European research facility. It provides crucial performance data to the scientific and industrial Power-to-Heat (PtH) and CSP communities. The system operates during sunlight hours, drawing electricity from the grid. The investigation into PV production profiles as input to the heater explores potential operating modes in a hypothetical future hybrid CSP-PV scenario. On-site infrastructure, including grid connection points and utilities, will be upgraded to accommodate the pilot's requirements.

Operational Modes

The new SOLARSCO2OL demo, including the TES and SF side of EMSP, has been modeled to estimate the possible operational modes scenarios where both MS and sCO_2 cycles can be operated during the testing period of 500 h. The maximum EH thermal power that can be installed on site is lower than 3.5 MWe, due to limitations of the available medium voltage grid and substation extension that is expected to be done. Swapping one cold pump from the cold tank to the hot tank is the option that allows a nominal flow rate of 22 kg/s from the hot tank to SOLARSCO2OL equipment, and back to the cold tank, although with very limited run time (because of the small TES capacity). As a first tentative, the solar field would first preheat the system up to 480-500ºC recirculating the salts from the cold tank to the hot tank and back to the solar field, thanks to the connection that is left between hot and cold tanks. Once the hot tank is filled with the expected temperature, the operation of the power cycle will start while maintaining the solar field outlet at 500ºC to increase the operating time. The temperature boost from 500ºC to 580ºC is then feasible with the electric heater with a power below 3.5 MW. The temperatures on the cold and hot tanks have been assumed equal to 380 and 490 ºC.

Table 2 summarizes the main operational possible scenarios. The table indicates that due to limitations in the existing cold and hot MS pumps within EMSP, the sCO_2 cycle can't sustain a nominal load throughout the entire day. This constraint implies that achieving the original 100% load is feasible, but within a shorter timeframe, directly influenced by the solar field performance and weather conditions. However, by reducing the sCO_2 cycle load through flow adjustments on both sCO_2 and MS sides, a sustained operation at 60-70% load during daylight hours becomes viable. This operational level aligns with the demonstration campaign's objectives, validating the technology and sCO_2 implementation within CSP configurations.

The total operational time across different load levels will be distributed within available months, based on the solar field's expected performance. This strategy ensures adaptability to varying scenarios and optimizes the operational approach.

Table 2: Operational possible scenarios

Load sCO_2 Cycle	MS Mass Flow Rate	sCO_2 Mass Flow Rate	EH Thermal Power	PTC Thermal Power	MS-sCO_2 HX Thermal Power	Recup. sCO_2 Thermal Power	Compressor	Turbine	Operation Time
%	kg/s	kg/s	MW_t	MW_t	MW_t	MW_t	MW_e	MW_e	h
100	22.2	21.01	3.1	3.7	6.8	8.7	0.51	1.77	1.5
90	19.8	18.91	2.7	3.3	6.1	7.8	0.44	1.70	2.6
80	17.6	16.81	2.4	2.9	5.4	6.9	0.39	1.51	4.3
70	15.4	14.56	2.1	2.6	4.7	6.0	0.35	1.25	steady

Specifically, three operating modes have been identified: start-up, nominal, and shutdown:

- **Startup:** the system's startup begins with the molten salt loop. Before introducing salts into the system, heat tracing warms up the piping and equipment to prevent freezing risks. As sunlight hits, hot and cold tank salts circulate through the PTC solar field, elevating the cold tank's temperature to 450 ºC while keeping the salts within the EMSP via a tank-to-tank bypass line. The duration varies based on initial temperatures. When a temperature of 450 ºC is achieved, the bypass closes, and the hot tank fills with solar field molten salts, aiming for a 500ºC outlet temperature. Once the hot tank reaches its target temperature, salts are pumped to the electric heater to reach 580ºC, then to the primary heat exchanger. The colder salts (at 380ºC) return to the cold tank, closing the molten salt loop. These salts are then pumped back to the solar field, constrained by the cold tank pump flow (11 kg/s). The mass flow rate ranges from 15 to 22 kg/s, based on desired molten salt flow and power cycle load levels. For the sCO_2 cycle, the sCO_2 is preheated, before introducing the molten salts, incrementally increasing pressure and temperature while adjusting valve settings. Specifically, during startup, the cryogenic deposit releases liquid CO_2, which undergoes expansion through a gasifier, transforming into gas at 83 bar and 33 ºC, that fills the 1500 liters buffer tank. Following this, the set point for the compressor suction pressure is increased to achieve the nominal pressure by extracting CO2 from the buffer tank. Load increase on both molten salt and sCO_2 sides aligns with pressure and flow adjustments for steady conditions. Upon achieving stability, the startup sequence concludes, activating controllers for normal operation until the shutdown period. This phased startup ensures a controlled introduction of molten salts and CO_2 into the system, optimizing temperature, pressure, and flow for smooth operation and a safe transition to steady conditions.
- **Normal operation:** in normal operation, CO_2 pressure control occurs at the compressor suction side. A setup comprising two valves — one for CO_2 makeup to compensate for losses and the other for releasing excess gas in case of malfunction — maintains optimal pressure. The fixed-speed compressor sends high-pressure CO_2 to the turbine, regulating flow through the inlet control valve. To keep the compressor within its operational range, the anti-surge/spillback line is utilized. The hot molten salt pump manages the required flow, adjusted by the motor's Variable Frequency Drive (VFD), directing salt to the electric heater. The temperature control system heats the salt to the necessary set temperature. This flow aligns with heating the sCO_2 to the designated temperature based on the set load. During sunlight hours, the cold pump and solar field loop operate, ensuring the outlet temperature aligns with the hot tank range. If lower, salts can be redirected to the cold tank and recirculated until reaching the desired setpoint. The cooler regulates sCO_2 temperature, maintaining it below 35 ºC. This control involves managing water levels (wet/dry) and fan speeds. Supporting and auxiliary systems remain active and automated during normal operation to ensure seamless functioning.
- **Shutdown:** during the shutdown, the plant adopts two distinct standby modes: hot and cold. In the hot standby mode, the plant pauses temporarily with the intention of a swift restart. Consequently, the molten salt system remains filled without draining to facilitate this quick resumption. Electric heat tracing safeguards the piping and components by maintaining the salt temperature above 280 ºC, effectively preventing freezing. Meanwhile, the sCO_2 cycle is deactivated, settling into a specific stable condition while the cooling system remains operational for immediate use if needed. In contrast, during extended plant shutdowns, the cold standby mode is implemented. Here, the molten salt system is emptied back into the storage tanks using a dedicated drain tank positioned below ground level. The design of all pipes ensures a slope towards this tank, preventing any accumulation of salt. Immersed heaters within the drain tank or large tanks act as

safeguards against low temperatures. Additionally, the drain pump redirects salts to the cold tank, guaranteeing availability for subsequent preheating of the solar field. The sCO_2 system stabilizes in this state. Attention is directed towards potential CO_2 condensation in case temperatures drop below the dew point, necessitating the removal of any condensate from the system. Cooling operations are halted during this phase of shutdown.

TECHNO-ECONOMIC ANALYSIS OF THE HYBRID PV-CSP REPLICATION LAYOUT

The upscaled concept of SOLARSCO2OL for replication studies is presented in Figure 5. The plant under investigation is characterized by a state-of-the-art PV plant hybridized with a molten salt-driven CSP plant with a two-tank TES system and a sCO_2 power block. The hybridization between the two plants is realized by employing a molten salt electrical heater that allows storing the electricity produced in excess by the PV field as thermal energy. The integration of the EH can potentially enhance the cost-competitiveness of the hybrid plant by increasing its flexibility and augmenting its capacity factor. In the CSP plant, a tubular molten salt receiver is employed to convert the power collected by the heliostat field into thermal power with operating temperatures ranging between 295 and 565 °C [14]. The molten salts are directly stored in a two-tanks TES. Electric heat tracing is considered as the main freeze protection system so that the molten salts stay above the solidification point during low irradiance periods. The TES decouples the sCO_2 power block electricity production from the intermittent solar-based heat production. During the discharge phase, the molten salts flow in a molten salt-to-sCO_2 heat exchanger, guaranteeing a TIT of 550 °C. The sCO_2 power block, represented as a box in Figure 5, is one of the main focus areas of this analysis. Eight different power block configurations have been outlined modifying the simple recuperated sCO_2 Brayton cycle, including intercooling, reheating, and recompression. Dry cooling has been considered for all the configurations. The use of molten salts as HTF and TES media coupled to sCO_2 cycles can in turn be seen as an intermediate step to enable market entry of the sCO_2 technology at lower risks by building upon mature and bankable CSP systems. Combining conventional molten salt systems with sCO_2 in CSP plants has also been shown to have the potential to increase the cost-competitiveness of CSP when compared to the use of traditional steam cycles [15]–[18]. The design of the plant had been defined as solving a multi-objective optimization problem aiming at minimizing the Levelized Cost of Electricity (LCOE) and maximizing the Capacity Factor (CF) of the plant. The decision variables adopted in this problem are the solar multiple (SM), the hours of storage, the ratio of PV capacity over CSP capacity, the ratio of the electric heater capacity over the CSP capacity, and the power block type.

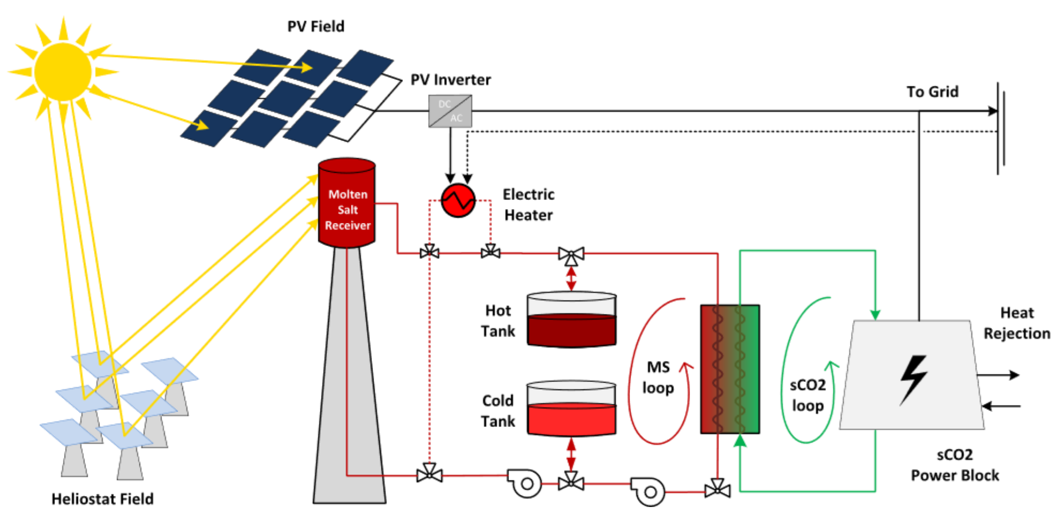

Figure 5: Layout of the hybrid PV+CSP system

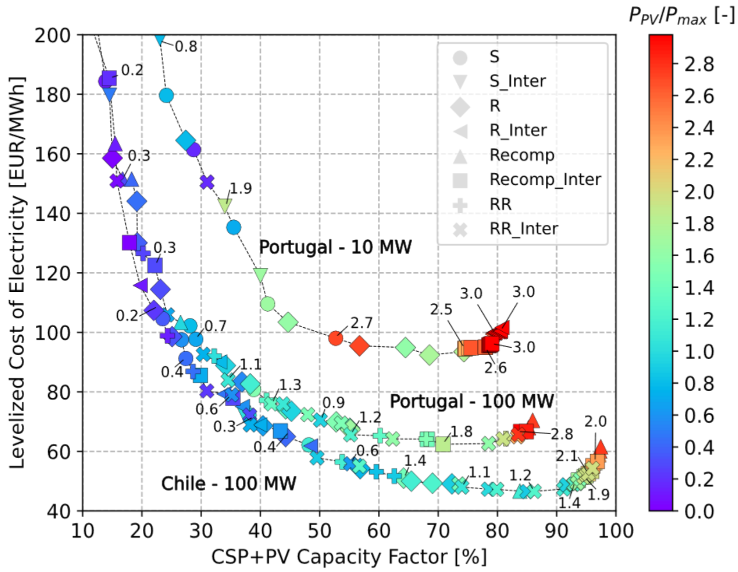

Figure 6: Scale (100 MWe – 10 MWe, Portugal) and location (Portugal – Chile, 100 MWe) comparison

The main technical and economical assumptions adopted for the hybrid plant, the methodology for modeling the plant performance, and the dispatch strategy have been addressed and reported in [19]. First, the hybrid solar plant has been optimized for a European good solar resource location (Evora, Portugal) and considering a CSP capacity of 100 MWe. Then, the impact of the scale has been investigated by adopting a CSP capacity of 10 MWe. In the end, the location effect has been analyzed for a 100 MWe plant located in Likana, Chile. Figure 6 shows the trade-offs between minimum LCOE and maximum CF for the eight power cycle layouts investigated in this study, utilizing distinct markers to differentiate between the different power block layouts. The color bar in Figure 6 represents the influence of the PV installed capacity over the CSP one. The trade-off converges within an optimal region, resulting in an LCOE of 65 EUR/MWh and a CF of 75%. Increasing the $PPV/Pmax$ ratio leads to a decrease in LCOE and an increase in CF. This trend holds until reaching the optimal region, where the $PPV/Pmax$ ratio that minimizes the LCOE of the plant ranges from 1.3 to 2.1, depending on the power block configuration being considered. On one side, the largest $PPV/Pmax$ ratios lead to the highest CFs (>70 %), with a slight increase in the LCOE.On the other side, the smallest $PPV/Pmax$ ratios lead to relatively low CFs and high LCOEs. This highlights the importance of hybridizing these technologies: low-cost PV systems make CSP more cost-competitive, while the dispatchability of CSP allows reaching high capacity factors and firm production. The sCO_2 power block with recompression and intercooling is the layout that leads to the minimum LCOE (62.4 EUR/MWh), while a simple recuperated cycle yields the highest CF (78%) with a similar LCOE (65.7 EUR/MWh). Considering that the percentage difference in LCOE among the layouts investigated is less than 5%, with similar CFs, a simple recuperated Brayton cycle can be preferred at this size and with these operating temperatures since it is the simplest and cheapest layout, and easier to design and control during the operation. However, the selection of more efficient power blocks, with higher sCO_2 return temperatures offers the possibility to integrate cogeneration or the integration of bottom cycles that can lead to extra flows of revenues. Figure 6 shows also the impact of the scale on the trade-off moving from 100 to 10 MWe. The scale effect leads to a reduction in cycle efficiency and doubles the specific cost of the power block. The increase in the specific costs that characterize more efficient power block types does not reflect directly on the CAPEX of the plant. This is due to the change of the solar field and the TES as a function of the PB efficiencies and return sCO_2 temperatures. On one

hand, for a given SM, a more efficient power block leads to a smaller solar field compared to a simple recuperated power block configuration. Indeed, a smaller heat duty is required to the power block for the same power output. On the other hand, more efficient power blocks are generally characterized by higher sCO_2 temperatures, resulting in more expensive TES due to lower temperature differences. Figure 6 shows that a PV/CSP ratio of 2.3 minimizes the LCOE of the plant (89.1 EUR/MWh), yielding a CF of 79 %. This result highlights that hybrid PV-CSP systems are cost-competitive also at small scales and in a good European location. Figure 6 shows that higher PV/CSP ratios (2.2 – 2.7) are favored at 10 MWe pointing out that the hybridization with PV becomes even more influential at smaller scales. Consequently, the role of the electric heater becomes relevant with EH/CSP capacities above 1 and utilization factors ranging from 12 to 21 %.
As expected, when moving to Likana, Chile, the higher solar resource availability leads to better system performance characterized by higher CFs and lower LCOEs. Specifically, the minimum LCOE is equal to 46.5 EUR/MWh corresponding to a CF of 85%. Although the power block configuration including reheat, recompression, and intercooling minimizes the LCOE of the plant, there is no significant difference between the LCOEs achieved with a simple recuperated cycle (48.3 EUR/MWh). This suggests that a simple power block configuration can be preferred due to lower CAPEX, simpler design, and smoother operability. Due to the high solar resource availability, the PV/CSP ratio that optimizes the system is smaller than one (0.9) resulting in a share of CSP production of 71 %. PV/CSP ratios around 1 are preferred in this location and no excess of PV production is obtained. Consequently, the molten salt electric heater is not selected by the optimizer in this location. Compared to the hybrid plant located in Evora, CSP has a more relevant role in Likana both in terms of capacity and electricity production.

CONCLUSIONS

This paper provides an overview of the advancements accomplished in the SOLARSCO2OL Demo project, emphasizing the engineering aspects of the pilot plant, strategic operational planning, and the techno-economic evaluation of the upscaled SOLARSCO2OL concept. The project's motivation and anticipated impact underscore the potential enhancements offered by innovative sCO_2 cycles and their active integration with solar PV through adaptable electric heaters. This integration has shown promise in augmenting the techno-economic performance of CSP plants employing state-of-the-art solar tower technologies using molten salts as heat transfer fluid and storage medium. Demonstrating the success of this cycle's integration into a mature CSP technology, even at a smaller scale (e.g., 2 MW), serves as a pivotal step towards the future upscaling and market entry of sCO_2 cycles. Moreover, this progression anticipates the evolution of higher-temperature CSP systems once the relevant technologies reach advanced stages of maturity. The demo cycle, a simplified Brayton cycle with a gross installed capacity of 2 MW and an aimed nominal thermodynamic efficiency of 22.1%, solidified its main component designs by the end of the first project year. However, recent months have been dedicated to re-engineering efforts necessitated by the relocation of the demo to the EMSP site. Modifications proposed for the EMSP aim to seamlessly integrate the sCO_2 power cycle while preserving inlet conditions and aligning with the original component designs. The re-engineering endeavors at the EMSP site demonstrated the technical feasibility of installing the new demo plant in this location, ensuring it can function under the same boundary conditions as envisaged during the project proposal's interconnected demo plant phase. The modifications outlined in this document are expected to yield similar results to those initially anticipated at the La Africana site. Key milestones achieved in the pre-engineering phase include defining a new co-located demo plant at EMSP, validating heat and mass balances in both molten salt and supercritical CO_2 systems, establishing updated process flow diagrams (PFDs) and basic piping and instrumentation diagrams (P&IDs) encompassing the entire system, outlining the design conditions of the entire plant, identifying primary auxiliary components, and formulating an operational philosophy outlining main control loops and operational scenarios within the available EMSP equipment (Solar Field and Thermal Energy Storage). Additionally, a revised plant general arrangement was issued utilizing available information from suppliers and EMSP. Furthermore, partners estimate that employing a similar simple Brayton cycle configuration with analogous component designs could potentially yield a thermodynamic efficiency surpassing 30.5% at 10 MW scales. A more complex reheat-recompressed cycle configuration could elevate efficiency to 41.4%. Moreover, techno-economic analyses indicate that at 100 MW scales, a hybrid PV-CSP plant integrating flexible molten salt electric heaters and a reheat-recompressed sCO_2 power block could achieve Levelized Cost of Electricity (LCOE) values of 66.3€/MWh for a typical Southern-EU location, falling substantially to 43€/MWh for locations akin to Chile.

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