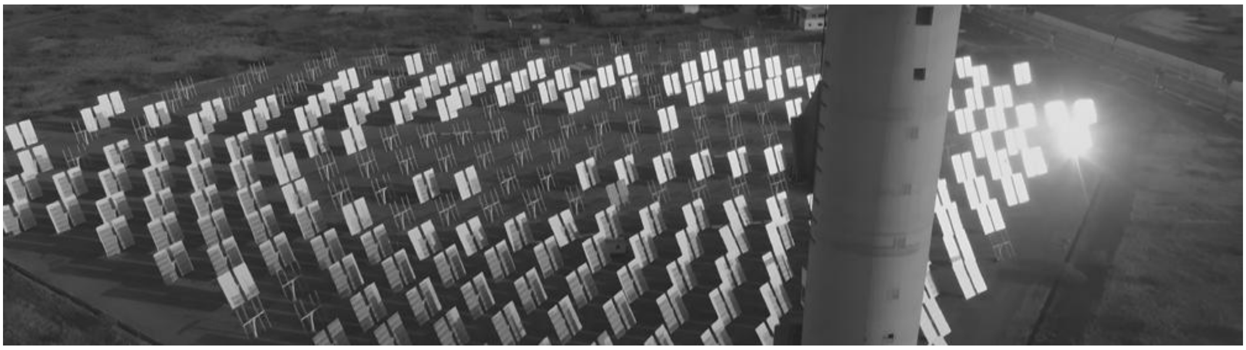
Book of

ABSTRACTS

EU-Solaris 2nd Doctoral Colloquium 2025, Almería, Spain



Foreword

I have fond memories of the first Summer School organized by the *Plataforma Solar de Almería* in 1998. It consisted of two modest one-week courses, supported by European funding and attended by participants from various countries across Europe.

At the time, I could not have imagined that the Concentrating Solar Thermal (CST) community would go on to regularly organize such events, in collaboration with our long-standing scientific partners. Today, we all recognize the significant value of these gatherings and have worked collectively to maintain this important tradition—now a well-established and cherished part of our community's calendar.

Initiatives such as Sol-LAB, along with various transnational access programs to major European research facilities—including projects like SFERA and, more recently, SOLARIZE—have played a key role in providing the necessary support to sustain these annual events, particularly the Doctoral Colloquium and the Summer School. These efforts are fueled by the commitment and enthusiasm of Europe's leading R&D centers dedicated to advancing CST technologies.

The spirit of these initiatives is closely aligned with the mission of EU-SOLARIS ERIC: *"To strengthen the cohesion of the R&D community in CST."* We remain committed to ensuring their continuity in the years ahead, ideally within an even broader international framework.

In the meantime, I extend my warmest wishes to all participants for an enriching and enjoyable experience—and, more broadly, a pleasant stay in my hometown, Almería. As a reminder, Almería will also host the *SolarPACES Conference* this coming September, the world's foremost event for the CST research community.

We hope to see many of you there!

With warm regards and a heartfelt welcome to Almería,
On behalf of the EU-SOLARIS ERIC team.

Dr. Diego Martínez Plaza

Managing Director

EU-SOLARIS ERIC

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Advances on the design of linear Fresnel solar concentrators

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The design of linear Fresnel solar concentrators poses a complex challenge due to the high number of decision variables and relatively few constraints [1]. These characteristics define a multivariate problem with a multi-objective nature, where optical, thermal, and economic factors are key to assessing overall performance, often involving trade-offs relations [2,3]. Rather than pursuing a single optimal solution, the developments in this work offer insights into the broader generalization of this design challenge. The strategy was to decompose the problem into smaller, more manageable, and targeted sub-problems, each addressed independently. Specifically, it presents results related to: (i) the development of an optical method, surrogate to time-intensive ray-tracing simulations; (ii) the curvature design of primary mirrors, comparing different shapes and design approaches; (iii) the secondary optic design; and (iv) the assessment of cost-effectiveness relations of optimal geometric configurations.

The developed analytical optical method is based on a vector analysis and linear integration of the effective source profile. It yields computations that that do agree very well with ray-tracing simulations, with energetic calculations of annual efficiency only 2.6% lower than those from ray-tracing [4]. Related to the curvature design of primary mirrors, geometrically, cylindrical mirrors does not significantly deviate to the parabolic ones (ideal shape), when designed for the same conditions. For this reason, they are indistinguishable from the receiver perspective and have the same performance of efficiency and flux distribution [5]. Moreover, a set of curvature calculation approaches does not yield significant divergent values of annual efficiency: deviations were up to 1.4% lower than the maximum value [6].

Concerning secondary optics, the developed results shows that Compound Parabolic Concentrator (CPC) and Compound Elliptical Concentrator (CEC) edge-ray designs yield optics very closer to those maximizing efficiency and flux uniformity but also providing a clear advantage in terms of tolerance to optical errors. Moreover, CPC and CEC optics show a clear trade-off between efficiency and tolerance to errors, where the former shows higher values of tolerance while the latter presents a better efficiency [7].

On optimal geometric configurations, Fig. 1 illustrates the trade-off between annual efficiency (ECF) and specific direct cost of the solar field (Γ), comparing different configurations. These results show that optimal non-uniform designs (where geometric parameters such as width, shift, and radius vary – the NUN case) are more cost-effective solutions than variable radius configurations (but with constant width and shift – the VAR case), as shown in Fig. 1a, although the difference is not that big.

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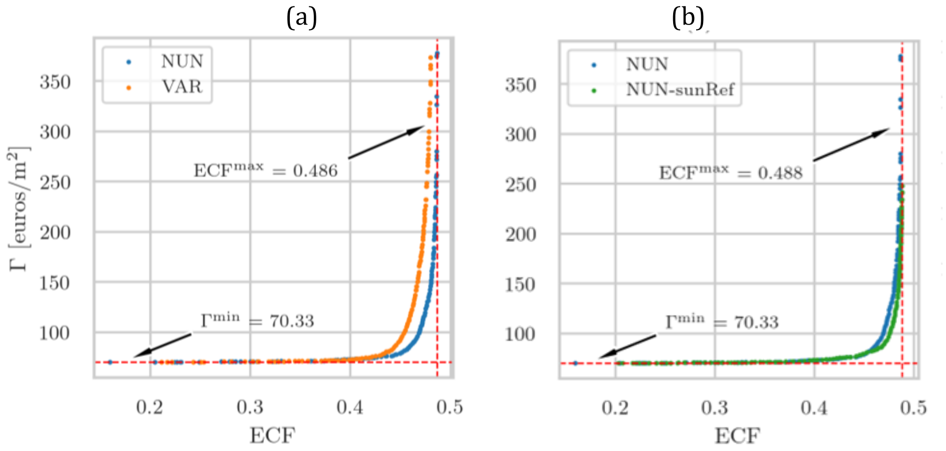

Fig. 1: . Pareto Fronts of optimal solutions for different linear Fresnel configurations.

Furthermore, Fig. 1b shows that predefined curvature radius criteria, such as the sun reference (the NUN-sunRef case) yield outcomes nearly identical to optimization-based solutions. Consequently, the curvature radius can be decoupled from other design parameters, significantly reducing computational complexity without compromising performance.

The insights presented here are valuable for advancing the design of linear Fresnel solar concentrators. Although primarily aimed at the context of solar thermal electricity generation – where an evacuated tube serves as the absorber element – the findings presented here may also be applicable to the context of other applications of solar concentration.

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Differentiable ray tracing for solar simulator Synlight

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How much light will reach my experiment? This is one of the crucial questions when working with a solar simulator like Synlight in Juelich, which often ended up only vaguely answered. This is because the currently available models for the flux distribution prediction do not provide an accuracy required for the design phase of a solar reactor or receiver [1]. These issues stem from various sources, but most notably from deformation of reflectors, likely caused by their own weight and heat. One potential way to improve the situation is a more accurate modelling of the inaccuracies through differentiable raytracing, which is being worked on in this PhD thesis.

The first main task of this approach is to use flux measurements to reconstruct reflector or the misalignment of the light source by deriving optical parameters from the measurement data. To solve this inverse task a gradient (in the direction of the deformations) comparing the measurement with the equivalent data of the ray tracing simulation was built. By constantly comparing this gradient, it is now possible to determine precise deformation parameters for the simulation, ultimately reconstructing the same flux distribution as in the measurement. In order to calculate this gradient, a differentiable raytracer for Synlight needed to be built, which introduced a set of new and interesting challenges.

If a general differentiable ray tracing method is used, as is more common in computer graphics, a major challenge is the seeming discontinuity in ray paths, as they either hit an object, or not. This makes ray tracing not differentiable by applying automatic differentiation [2] without regards to geometry. This was solved for many general problems by various methods, such as sampling the gradient along ray paths that intersect with these edges [3]. Still, these methods are a field that is being very actively researched, and remain difficult to implement, often taking assumptions that are not applicable in cases like the Synlight ray tracing. Thus, investigating more constrained problems remains a worthwhile task. This can be done by developing a method avoiding geometry boundaries, while still resulting in a suitable gradient, and implementing it in a differentiable ray tracer. Using the gradients produced by the ray tracer, it can then be demonstrated that deformations from measurements can be reconstructed using gradient-based optimization techniques. After this, results from the raytracing software can be compared to flux measurements to evaluate the accuracy of the software built.

To draw a conclusion, a short outlook over further planned developments in the project will be given. These most importantly include scenarios modelling multiple lamps simultaneously. On top of that, generalization ideas of the model to expand its applicability to further facilities will be presented.

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Secondary concentrator design for point focus systems

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Secondary concentrators are optical devices similar to a funnel and located directly in front of the aperture of a solar receiver with the purpose to increase the concentration of solar radiation between the entry and the exit aperture [1].

There are three reasons why to use them:

1. Operation at temperature well above 800°C. The high losses due to thermal radiation (see Figure 1) can be reduced by minimizing the area of the receiver aperture, requiring an increase of the solar flux beyond the ability of the heliostat field [1].

2. Modular designs. When for any reason the receivers must be built considerably smaller than the extension of the focal spot, a modular design can be chosen with the secondary concentrators covering the gaps between the apertures of the receivers [1] (see Figure 2).

3. Beam-down systems (see Figure 3). For optical reasons, the solar ray in the focal plane on the ground cannot reach a useful concentration and therefore needs a "boost" provided by a secondary concentrator [1].

Fig. 1: Receiver operating at 1200°C in the SSPS tower of the Plataforma Solar de Almería in Tabernas (Spain).

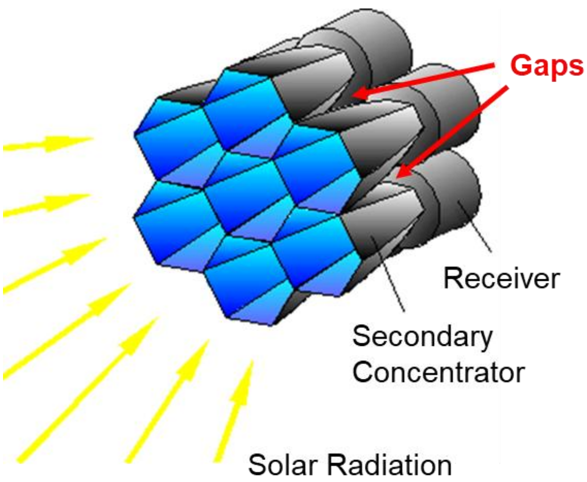

Fig. 2: Example for modular solar receivers with secondary concentrators.

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Fig. 3: The beam-down CSP in Yumen Xinneng/Xinche (China).

Concentrating solar technologies (CSP) are renewable energy systems for exploiting incident beam solar irradiation with high exergy efficiency values. These systems provide the possibility for producing useful heat at high temperatures that can be utilized by highly efficient power cycles or producing directly solar fuels. However, the levelized cost of electricity (LCOE) for the CSP remains higher than the other renewable technologies like PV and onshore wind energy. Therefore, to expand the use of CSP systems, certain critical design aspects must be considered: i) reducing the material used, ii) increasing efficiency, iii) reducing wind loads, iv) reducing thermal stresses that can lead to component failure, v) increasing safety levels by minimizing various risks, and vi) developing novel and efficient storage techniques for long-term (seasonal) operation. A direct response to the aforementioned critical challenges facing CSP is beam-down CSP design [2].

The concept of beam-down concentrating solar technology is based on the use of two reflection stages to concentrate solar radiation near the ground. This allows the heat transfer fluid to flow close to the ground, reduces the need to pump these fluids to high altitudes, and also allows for large installations like chemical processing plants that would be too large to be installed on top of a tower.

Furthermore, this technology offers the possibility of using fluidized beds and chemical reactors in the receiver that require a vertical beam to produce solar fuels or other chemical products. This idea is particularly attractive for the production of solar fuels that can facilitate seasonal storage, a key aspect for the future development of renewable energy [2].

The aforementioned advances in beam-down technologies indicate their significant potential to accelerate the integration of CSP in the global energy sector [2].

Finally, the conjunction of beam-down tower systems with the application of secondary concentrators is studied within the framework of the European project SUNSON (No. 101083827). This project promotes net-zero emission electrification through an intelligent combination of advanced concentrated solar power (CSP) with an ultra-high temperature storage system for power generation using a thermophotovoltaic cell and pursues a technological breakthrough in the compact concentration of solar energy and the conversion of renewable energy sources to generate electricity with a highly modular and scalable approach that increases its efficiency and profitability. My doctoral thesis will be dedicated to the optical design of such a system.

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Molten carbonate salts doped with nanoparticles for corrosion mitigation in CSP/CST technologies

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Introduction

Nanosalts are dispersions of nanoparticles in pure or mixed molten salts. It has been shown that some of the thermophysical properties of the salts are enhanced in relation to the base molten, particularly their thermal conductivity and heat capacity [1, 2]. This result, makes them a promising solution to enhance the power generation efficiency of next generation concentrated solar power (CSP) technology. However, the use of these nanosalts in a CSP plant faces many challenges [2], namely their behavior in contact with structural materials that must be addressed to provide the choice of cost-effective steels. This work aims to present the results of the study of the corrosion of AISI 430 stainless steel in contact with molten LiNaK carbonate salts doped with MgO and SiO2 nanoparticles.

Methodology and results

Three mixtures of molten salts were prepared, one only with the eutectic mixture of lithium, sodium and potassium carbonate salts (32.1:33.4:34.5 m/m), and two new mixtures of these molten salts, doped with 1% MgO nanoparticles (99% purity, 20 nm); and 1% SiO_2 nanoparticles (99.5% purity, 10~20 nm, non-porous) from SkySpring Nanomaterials, were homogenized with the eutectic mixture in a mechanical mill for 5 min in a clean room. The undoped mixture also contains magnesium as an impurity.

The corrosion tests were carried out in a muffle furnace at 650 ºC the AISI 430 steel being in direct contact with each of the mixtures for 24, 240 and 1000 hours, under static conditions and atmospheric air.

As demonstrated in Figure 1, the corrosion rate of the mixture with 1% SiO2 exhibits a higher rate over time in comparison to the other two salt mixtures, with this difference being more pronounced in the initial times. With regard to the mixture with MgO, the corrosion rate tends to stabilize after 240h at a lower rate than the mixture without doping (221 ± 4 vs 326 ± 52 mm/year at 1000h).

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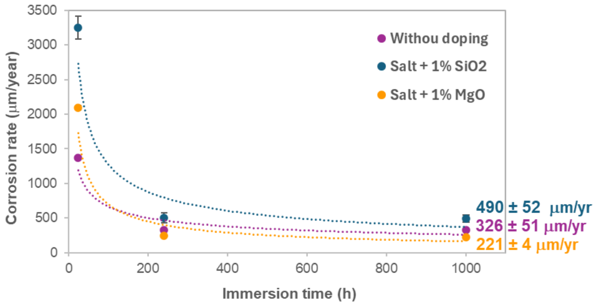

Fig.1: Corrosion rate of AISI 430 immersed in different mixtures LiNaK carbonate salt at 650 °C.

SEM surface images (Fig. 2) demonstrate that the morphological structures of the oxides formed after 1000 hours are different, depending on the type of nanoparticles used on doping the salt. However, by analyzing the respective XRD diffractograms (at 1000h), the oxides identified were the same ($Li_5Fe_5O_8$, $LiFeO_2$ and MgO).

At 240 hours, in the case of the mixture without doping and with 1% MgO, the formation of $LiCrO_2$ was also observed, in addition to $Li_5Fe_5O_8$, $LiFeO_2$ and MgO.

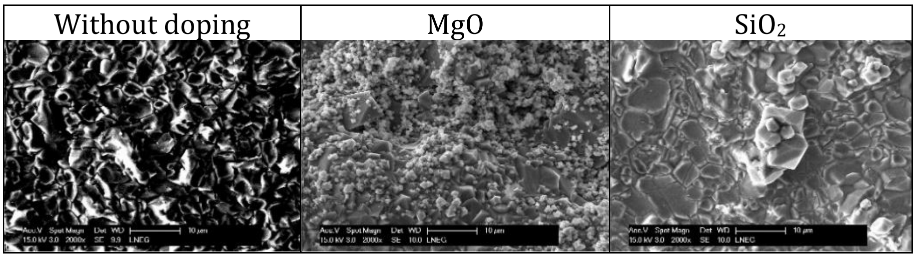

Fig.2: SEM images obtained with SE detector of the oxide scales formed on AISI 430 after immersion different mixture LiNaK carbonate salt at 650 °C after 1000 h.

These results show that magnesium oxide nanoparticles appear to have a significant impact by reducing the corrosion rate of AISI 430 stainless steel (from 326 to 221 with 1% MgO nanoparticles), which is not the case for silica.

Acknowledgments

The authors greatly appreciated the financial support FCT - Fundação para a Ciência e a Tecnologia, I.P., from project NEWS4CSP (2022.05021.PTDC) (https://doi.org/10.54499/2022.05021.PTDC).

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Fouling of silicone-based heat transfer fluid on heated surfaces

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Silicone-based heat transfer fluids (HTFs) are interesting materials due their improved properties compared to organic HTFs, such as BP/DPO. Their wider range of operation (-30 – 425 °C), higher operation temperatures, less degradation and less production of hydrogen, environmental compatibility, less toxicity and no fouling at regular operating temperatures make these fluid promising materials for efficient and safer industrial operation [1, 2].

The mobile pump and heat transfer fluid test facility (MoPuW) at DLR [3] has been utilized to assess the performance of silicone oil under prolonged high-temperature conditions. Continuous operation at 450 °C revealed unexpected deposition of a black material on wetted surfaces of metal samples within the tubing system. The origin of these particles was found to be the surface of the electrical heater which was covered with a material consisting of black particles and a highly viscous substance, presumably highly polymerized oil.

The objective of this PhD project is to investigate the conditions that lead to fouling of silicone-based heat transfer fluid on heated surfaces. One goal is to model the dynamic formation of fouling using CFD simulations to enable the prediction of fouling in practical applications.

To fulfil the goal, generation of the fouling material is provoked on an electrically heated surface. Flow and heating conditions are measured to associate the fouling material formation over time at defined operating status. Subsequently, the deposits of fouling material are analyzed in order to estimate its material properties related to heat transfer. The possible variation of fouling material properties due to the change of heterogeneity of the material over time will be addressed as well. These changes on the thermal properties are expected to affect directly the insulation effect of the fouling material, changing the surface temperature, which in turn has a significant impact on the fouling process. The temperature of the heated surface is the pivotal parameter in determining the formation of fouling material due to its relation with the degradation reactions. To measure surface temperatures an experimental fouling simulator setup was developed. This setup serves to determine the thermal fouling resistance, R_f [4]:

$$R_f = \left(\frac{T_{surface} - T_{bulk}}{\dot{q}}\right)_t + \left(\frac{T_{surface} - T_{bulk}}{\dot{q}}\right)_{t_0}$$

Where $\dot{q}$ is the heat flux in the heater surface, $T_{surface}$ is the surface temperature of the heater, T_{bulk} is the bulk temperature of the fluid, t represents a given time and t_0 is an initial time [3].

R_f can then be modelled and utilized to predict the fouling material formation over time in a local section with defined flow and thermal conditions [5, 6]. Figure 1 shows various fouling behaviors that have been documented in literature [5]:

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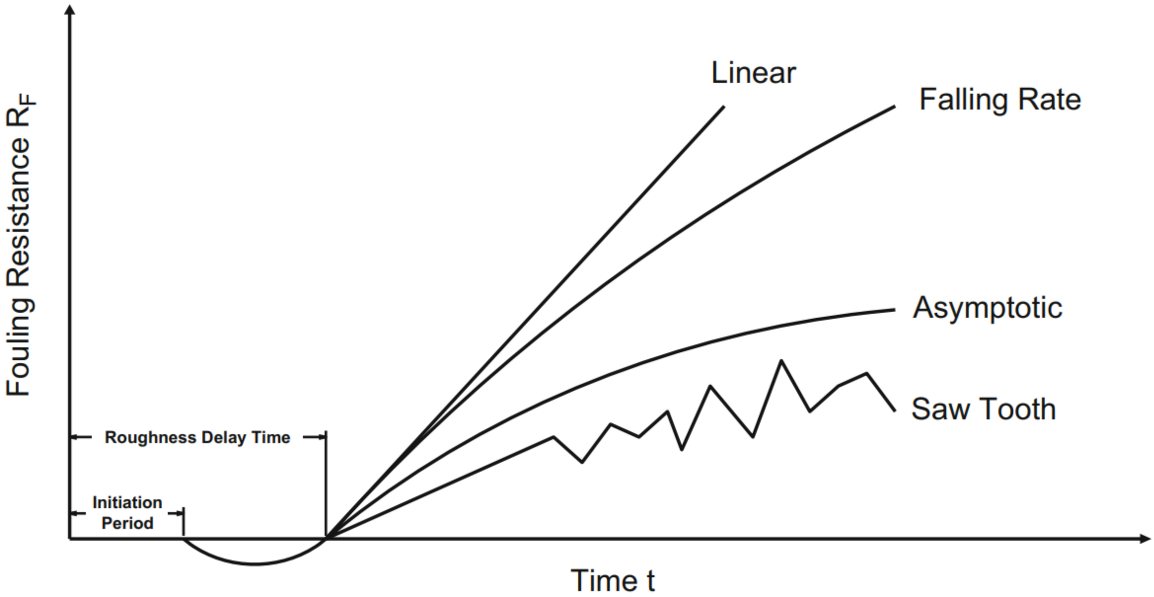

Fig. 1: Observed trends in fouling resistance.

The fouling thermal resistance model will be implemented using computational fluid dynamics (CFD) techniques to predict the formation of fouling over time. The previously build fouling simulator setup will be used as the baseline for these simulations, with the objective of validating the change and evolution of fouling deposits over time. Surface temperature, fluid bulk temperature, heat flux, and mass flow will be used to validate the future simulations.

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High Temperature Attrition and Erosion due to Particle Impact at the CentRec® Receiver

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Three heat transfer fluid (HTF) materials are currently under development for the third generation of concentrating solar power (CSP) tower technology. The materials under consideration are high-temperature molten salts, gas-phase HTF and ceramic particles. Ceramic particles offer several advantages, including their high chemical stability, high temperature resistance and potential applications in Thermal Energy Storage (TES). Nevertheless, the mechanical interactions with the particles are considered to be the primary challenge in this field [1].

DLR is developing a centrifugal particle receiver, which is called CentRec®. This device is composed of two principal components: the first component is the inner tube, where the particles move while receiving solar radiation, and the second component is the collector ring, where the particles are ejected and become distributed to the rest of the system. At the moment of ejection from the inner tube to the collector ring, two interactions can take place [2].

The first interaction is attrition, which is the interaction between two particles. This interaction can happen at most twice per day for each particle. or 730 impacts per year. The second interaction at the CentRec® is erosion, which is the interaction between the particle and the steel that the collector ring is made of, which is Inconel 617. The consequence of this interaction is the removal of material from the ring and its deformation.

In order to investigate the attrition effect, two types of particles developed by Saint-Gobain were evaluated: The Gen 3 particles and the Gen 4 particles. To increase their solar absorptance, the particles were coated. The Gen 3 particles were covered with the DECHEMA coating, while the Gen 4 particles were covered with three different coatings, developed by DLR, DECHEMA, and CIEMAT, respectively. The results indicate a loss of mass for the Gen 3 particles, while no mass loss was observed in the Gen 4 particles (see Figure 1a)). However, this does not imply that degradation was not occurring for the latter. The analysis of solar absorptance before and after the attrition test (Figure 1b) indicates a loss of coating. The most pronounced degradation of solar absorptance was observed on the DECHEMA coating, CIEMAT ending the test with the highest solar absorptance and DLR being the most stable coating.

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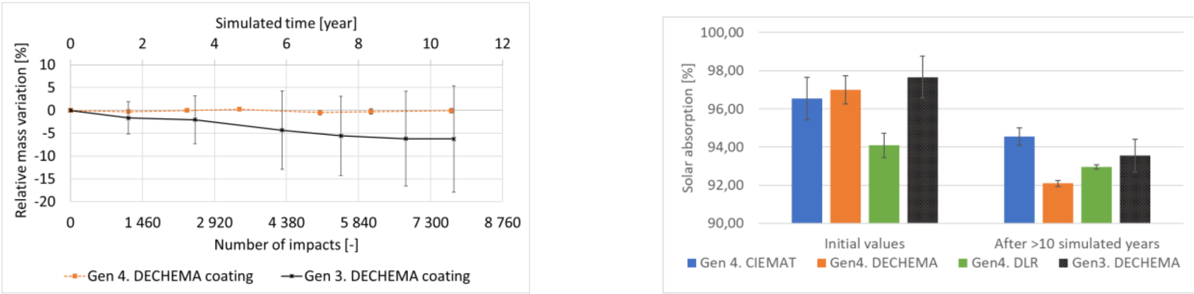

Fig. 1: a) Relative mass variation depending on the number of impacts (bottom-x axis) and simulated years (top-x axis). b) Solar absorptance of the coated particles in initial state and after receiving more than 7300 impacts (corresponds to 10 years of operation).

To mitigate the erosion effect on the collector, *Forschungzentrum Jülich* has developed three different coatings. These include a CoNiCrAlY coating, an oxide layer strengthened with a CoNiCrAlY coating and a ceramic coating. These coatings are tested under conditions similar to the CentRec® receiver. To this end, the study will test two samples of each coating and two uncoated samples. The sample holder (see Fig 2) was designed in such a way that one sample receives the erosion treatment, while the second one is protected from the falling particles. Still, the protected sample receives the same thermal treatment as the eroded sample and from the final comparison of both, the erosion effect can be eliminated. The experimental methodology comprised the use of the UV/VIS/NIR spectrophotometer Lambda 1050 from PerkinElmer to measure the optical changes in the coating, the confocal microscope from Zeiss to determine height and big surface changes, the M205C microscope from Leica for visual inspection by high-resolution images, the NewClassic ML balance from Mettler Toledo and the Surfcom 130A surface roughness measuring instrument from Zeiss to detect small surface changes.

a) b) c)

Fig. 2: a) Sketch of the sample holder with the two respective samples. b) Erosion and temperature sample placement on the support. c) Temperature sample placement on the back of the support.

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Comprehensive durability assessment of advanced solar reflector materials: Results from UV, CASS, and outdoor exposure testing

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The optical performance and durability of solar reflectors are fundamental to the operational stability and cost-effectiveness of Concentrating Solar Thermal (CST) systems, given their direct impact on optical efficiency and overall system cost [1]. The most widely used reflectors in the industry are second-surface silvered-glass structures, composed of a silver layer backed by a copper layer and protected with lead-based paints [1]. As the solar industry shifts toward more environmentally responsible alternatives, a new generation of reflector materials is emerging, featuring copper-free layer stacks, lead-free protective coatings, and cost-effective glass substrates with higher impurity levels [2]. However, the long-term performance of these alternatives under outdoor exposure and accelerated aging tests remains unknown.

The work presented in this thesis investigates the degradation mechanisms of novel silvered-glass solar reflectors subjected to weathering agents such as UV radiation, humidity, salt spray and temperature. Several durability tests were conducted throughout the year on novel materials featuring variations in silver layer thickness, copper content, coating systems, and glass compositions. The experimental campaign included 3000 h of UV exposure using an Atlas UVA 340 chamber, 960 h of CASS test, and a three-month outdoor exposure campaign. In parallel, a separate set of laminated samples, developed during a research stay in DLR-Oldenburg using silver- and silver-aluminum-based stacks, was tested under UV and damp heat tests. Additionally, one-year outdoor exposure data were analyzed to assess solarization effects in reflectors manufactured with high- and low-iron glass.

The results demonstrated that the majority of materials initially exhibited similar optical performance, with differences in solar hemispherical reflectance below 0.1 percentage points. However, reflectors with higher glass impurity content showed slightly lower initial reflectance.

During accelerated aging tests, reflectors with thinner silver layers experienced a gradual loss in reflectance due to tarnishing. CASS tests revealed a strong correlation between coating quality and optical degradation: copper-free samples with lead-based paints and optimized silver thickness exhibited the best corrosion resistance, while copper-free samples with water-based coatings failed prematurely. The three-month outdoor exposure supported these findings, with visible corrosion observed in the most sensitive configurations.

Laminated samples tested under UV and damp heat conditions showed minimal reflectance degradation. Regarding solarization, significant effects were observed in all samples, with more

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pronounced degradation in reflectors with higher iron content. However, the phenomenon stabilized after approximately 500 hours of exposure.

Fig. 1 presents an example of the degradation results for copper-free with a lead-based coating, copper-free with waterborne paint coating and the state-of-the-art reflectors after 3000 hours of UV exposure.

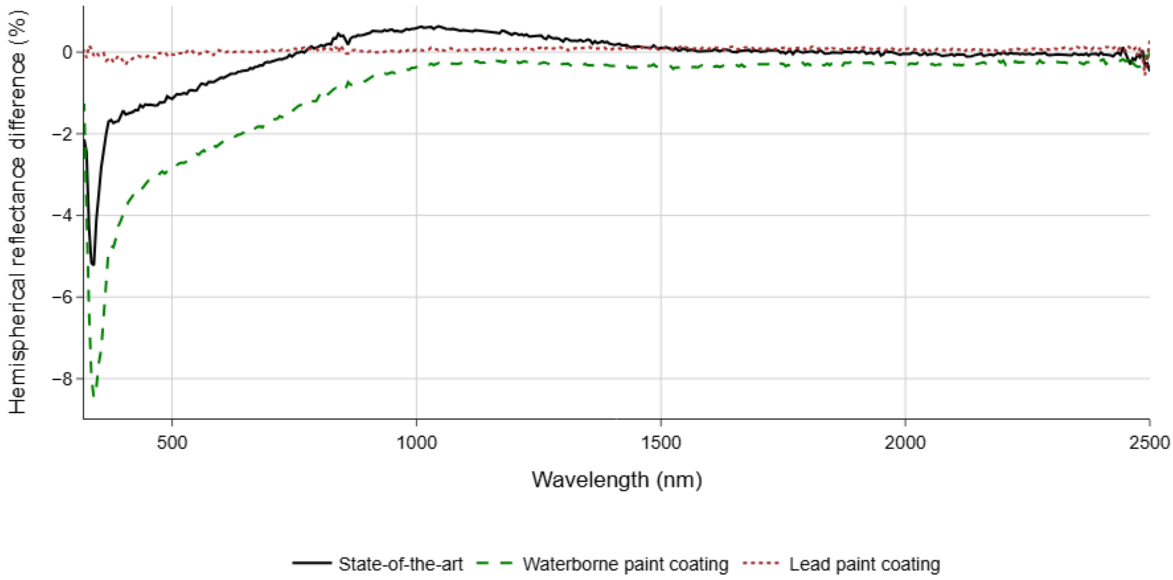

Fig.1: Hemispherical reflectance difference results for copper-free with lead-based coating, copper layer and lead-based coating and state-of-the-art reflectors after 3000 h of UV exposure.

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Characterization of the soiling effect on PV and CST systems operating in arid environments

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The fast growing of solar fields around the world is accompanied by a best understanding of the main parameters that affect these renewable systems, as irradiance, temperature and soiling. The last one is a natural and random phenomenon that influences the performance of concentrating solar thermal (CST) and photovoltaic (PV) systems. The most attractive sites for the installation of solar plants are those with high levels of irradiance, which generally are arid and semiarid environments with high concentration of sand, dust and other pollutant agents. The effect of soling in those sites can be 5 or 6 times more in CST than in PV, explained by the differences in the optical properties of the surfaces of each technology [1]. For that reason, the continuous monitoring of the soiling effect in solar systems is highly recommendable. This monitoring is performed with different low cost and simple sensors, depending on the solar technology installed. Additionally, these sensors might contribute to find a forecasting method that allow predicting the combined losses due to soiling in future hybrid plants, including both PV and CST technologies. An important section of this thesis consists in the analysis of the response of optical soiling sensors with the goal of advancing in the knowledge and availability of simple, low-cost and reliable soiling measurement equipment for solar systems and to stablish a relationship with the electrical behavior in PV devices operating in arid regions.

The soiling sensors studied in this work were installed and tested at the CIEMAT-Plataforma Solar de Almería (PSA). The first one (figure 1 left), developed by CIEMAT, allows to determine the soiling ratio (SR) based on the relationship between the electrical response of a PV cell with a cover glass exposed to soiling and other one with a cover glass always protected (and consequently clean). The SR is correlated with laboratory measurements of optical properties like transmittance of PV or CST glass covers and reflectance of CST concentrators [2]. The second one (figure 1 right) is a sensor developed by Tekniker, based on IR light scattering measurement on various surface types [3]. The results of the two sensors were validated by using two different approaches, a commercial soiling sensor and a traditional soiling station that consists in two identical PV devices, one of them regularly manually cleaned and the other left to naturally soil. Soiling losses are calculated by the comparison of the electrical output of both devices.

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Fig.1: Left: Soiling sensor by CIEMAT-PSA. Right: Soiling sensor by Tekniker.

A campaign of soiling data acquisition with both innovative sensor was performed. As example, the results are displayed in figure 2, which shows the relationship between the SR of the sensor by CIEMAT with the traditional soiling sensor station (left) and the commercial sensor (right). A trend is observed with an evident dispersion of the data due to different factors possibly like climatological conditions and location.

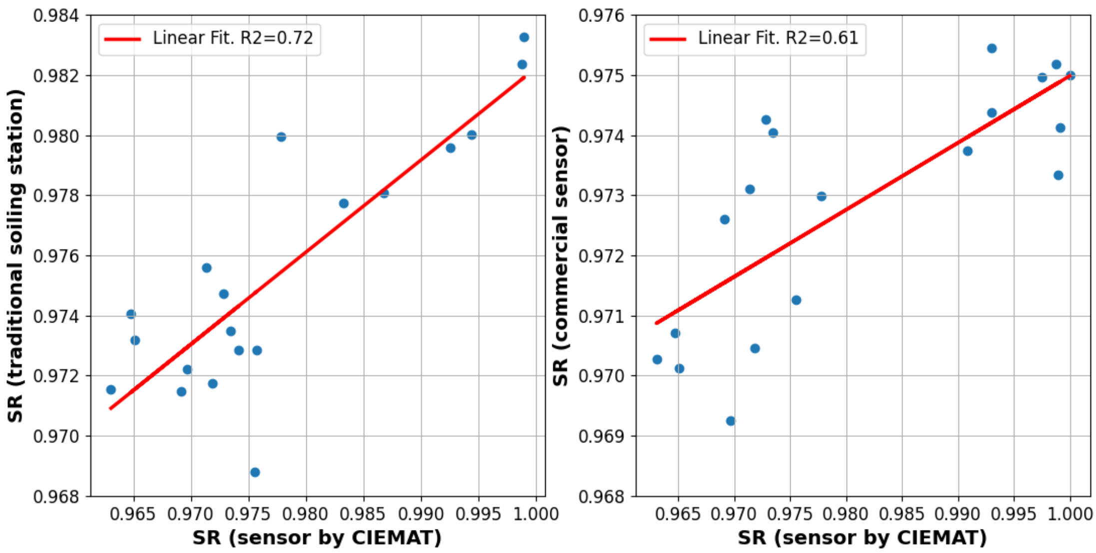

Fig.2: Correlation between SR of CIEMAT sensor and traditional soiling station (left) and commercial sensor (right).

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Techno-economic analysis of a membrane distillation systems for brine concentration

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Zero Liquid Discharge (ZLD) is an advanced water treatment process designed to maximize water recovery and reduce its discharge making the valorisation of the solid content possible [1]. In desalination, ZLD is particularly important for harvesting valuable minerals, making better use of the resource, thereby making desalination more sustainable. Membrane distillation (MD) is a thermally driven separation process suitable for its integration with reverse osmosis (RO) to concentrate RO brine to salt saturation points as a previous step of valorisation [2]. MD systems use various module configuration to optimize performance efficiency. The module design affects heat transfer, mass transport, and overall water recovery. To improve energy efficiency, configurations with internal heat recovery are selected, Spiral-Wound module (SW) and Vacuum Multi-Effect module (VME) configurations [3,4].

In previous work presented in the last edition (1st EU-Solaris Doctoral Colloquium) a VMEMD was characterised taking account different inputs range, such as operation temperature, feed flow rate or feed salinity. In the present work, a techno-economic comparison between two different MD module, one with V-AGMD configuration, using a SW module and the other with VMEMD configuration using a VME module, both of them characterised at the facilities of Plataforma Solar de Almería (PSA), was carried out for a case study consisting of treating RO brine from an RO process used to supply the water requirements of a limestone mining plant placed in Puerto Colombia (Colombia).

The simulation results show that VMEMD significantly increases the water production of the process, raising the recovery ratio of the desalination process from 46.51 % (RO) to 81.00 % (RO+VMEMD without batch operation), while the V-AGMD improves this performance to 50.15 % (RO+V-AGMD without batch operation). As a result, the concentrated brine obtained by VMEM is higher than SWM. In terms of Levelized Cost of Water (LCOW), the cost of the water produced from the RO brine was 0.038 USD $\$\cdot L^{-1}$ while the SWM was 0.053 USD $\$\cdot L^{-1}$ which means that treating brine from RO with VME module is 29.71 % cheaper than with SW module when the batch operation it is not considered.

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Sustainable brine management via solar multi-effect evaporation systems.

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The growing demand for reverse osmosis (RO) desalination plants has raised concerns about their potential environmental impact, particularly with regard to the discharge of large quantities of brine into aquatic environments. Consequently, the effective disposal of brine remains a significant unresolved challenge from technological, economic, and environmental perspectives. One of the key objectives of this PhD research plan is to provide a sustainable solution to ensure the sustainability of the desalination process, leading to the maximization of freshwater and approaching zero liquid discharge (ZLD) by brine concentration as a previous step of its valorization for no brine disposal.

For brine concentration, variants of RO, such as osmotically-assissted reverse osmosis (OARO) and high-pressure reverse osmosis (HPRO), have been developed in the last years though both are emerging and have limite maturity use, besides high system complexity, capital costs and energy demands. Alternatively, solar thermal concentrators are gaining pretty attention, being membrane distillation (MD), the most accepted technology, compared to multi-stage flash distillation (MSF) and Multi-effect distillation (MED), due to its modularity, being more adaptable to small-scale applications.

Thus, initially, in this research plan, three different solar multi-effect evaporation systems have been proposed for its evaluation at the facilities of Plataforma Solar de Almería (PSA). Multi-effect configuration is based on the recovery of latent heat of condensation as latent heat of evaporation in consecutive effects, increasing the concentration factor and energy efficiency compared to that in a configuration with one single effect. Specifically, the first one will be a vacuum multi-effect membrane distillation (VMEMD) with four desalination effects with an effective membrane area of 6.72 m^2; the second one, a film-Vacuum-Multi-Effect-Distillation (FVMED) system, a fully polymer-based implementation of Multi-Effect Distillation (MED), with the advantages of plastic materials and size; and finally, the third one, a passive multi-effect MD unit developed under the framework of the european project MEloDIZER (101091915). A techno-economic analysis will be carried out for a real case study.

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Control and optimisation techniques for efficient and sustainable integration of desalination technologies in CSP plants

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Reverse osmosis (RO)-based desalination is considered the most promising solution to mitigate water scarcity, a challenge currently affecting over one-third of the global population. However, the main drawback of this technology lies in its high energy demand, which is still predominantly reliant on conventional energy sources. To ensure sustainable development, the integration of renewable energy sources is essential.

Among these, solar energy stands out as the most suitable candidate to be coupled with desalination. Concentrated Solar Power (CSP) technology emerges as the most promising alternative due to its dispatchability capacity thanks to thermal energy storage systems [1]. CSP enables thermal energy storage in a more cost-effective manner and with reduced environmental impact compared to photovoltaic systems, which rely on battery storage.

The primary objective of this PhD research Project is to demonstrate the feasibility of integrated high temperature CSP (based on solar tower and Brayton cycle) and desalination systems, based on RO technology and membrane distillation (MD), leveraging advanced optimization and control techniques [2,3,4]. The MD subsystem aims to concentrate the brine from the RO unit, thereby maximizing water recovery and facilitating subsequent processing of dissolved minerals (i.e. brine valorization). This also mitigates the environmental impact associated with brine discharge into marine ecosystems [5].

To achieve this objective, the following research lines have been defined: (i) Evaluation and characterization of the RO+MD pilot plant developed within the AgroConnect project, located at IFAPA (Instituto Andaluz de Investigación y Formación Agraria, Pesquera, Alimentaria y de la Producción Ecológica), an agricultural research centre near to the University of Almería. This includes the design and implementation of low-level control strategies and validation of the brine concentration process using MD. (ii) Evaluation, characterization, and development of optimization strategies for the CSP+RO plant at the Plataforma Solar de Almería. (iii) Development of a comprehensive simulation tool for the integrated CSP+RO+MD system that allows evaluation of the proposed control and optimization techniques.

To automate and optimize the RO+MD plant at IFAPA, a SCADA system has been developed using FUXA, a web-based process visualization software. This SCADA integrates sensors and actuators from both processes. Figure 1 shows the SCADA interface for the MD subsystem.

As for control strategies, the initial phase consists on identifying the startup dynamics of the MD plant and on the implementation of conventional PID controllers to regulate the cold and hot water flow rates and temperatures of the MD modules.

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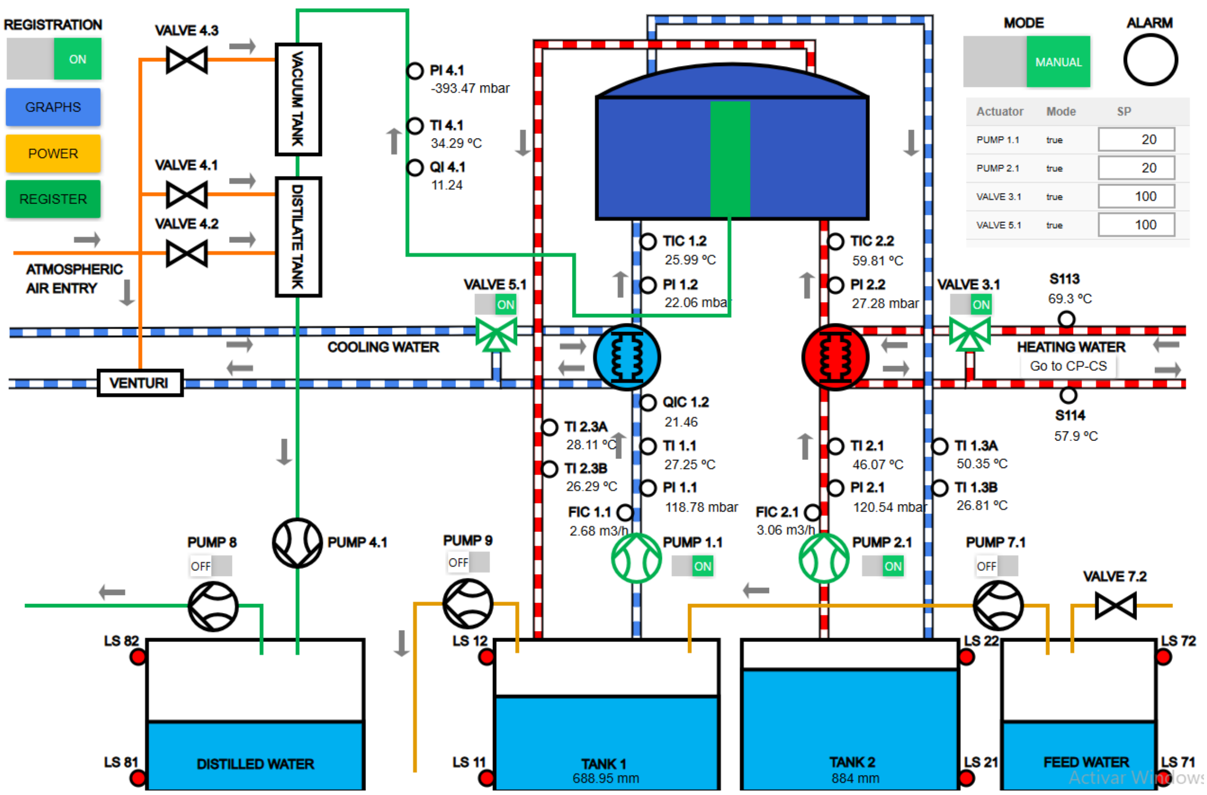

Fig.1: SCADA made in FUXA of the membrane distillation unit located at IFAPA.

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Study of strategies to enhance the profitability of solar thermal power plants in the Spanish electricity market through the development of a parabolic-trough plant simulation model.

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Electricity grids are experiencing rapid changes in these last years due to the high penetration of renewable energies in the energy mix at the expense of fossil fuels. Non-dispatchable energies lead to imbalances between generation and demand that are reflected in energy prices. This is the case of the Spanish grid, where photovoltaic production grew from 8852 GWh in 2019 to 43609 GWh in 2024 [1], resulting in a decrease of the prices in hours of good solar resource. Concentrating solar power (CSP) leverages energy storage to operate in the energy market delivering energy when it is most needed rather than maximizing energy yield, helping to match generation and demand.

To contribute to the study of the role that (CSP) can have in the present and future it has been developed a simulation tool for parabolic trough power plants. A flexible and hierarchical approach has been adopted to enable easy modification of plant parameters, dimensions and operation criteria. In view of this, the model has been coded in Python language, following an object-oriented programming methodology, like existing models [2]. The plant is divided into three main blocks (solar field, thermal storage system and power block) as shown in Figure 1.

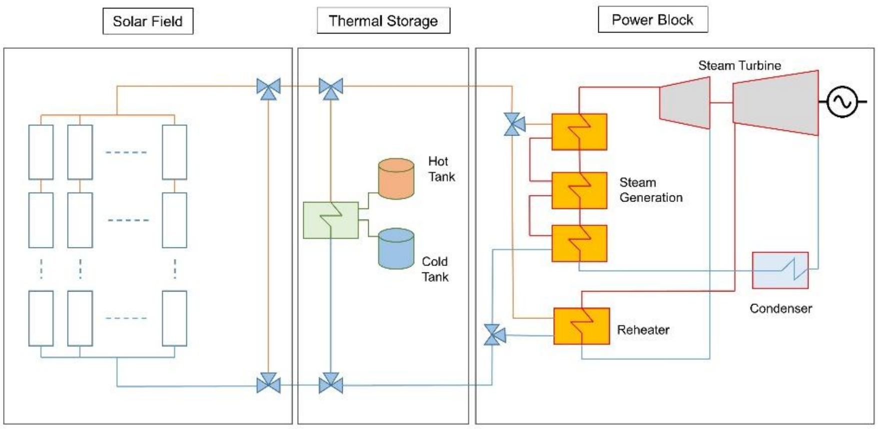

Fig.1: Plant model scheme.

The tool has been validated with data from a commercial plant installed in Spain reaching annual values of RMSE below 8 MW and WMAE below 18% in terms of net electric power.

Once validated, two improvements have been made to the model. On the one hand, a soiling model has been developed for the mirrors and tubes of the parabolic-trough collectors. It is based on

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meteorological values and is undergoing steady progress thanks to an ongoing test campaign on the Plataforma Solar de Almería.

On the other hand, advanced features have been included to analyse different dispatch and scheduling strategies. In a first approach, a transfer function is analytically defined to convert daily energy market prices into power set-point values. In a second approximation, genetic algorithms are used to obtain the hourly schedule of set-point values from market prices. The mass flow rate of heat transfer fluid required by the power block is calculated from the set power at each time step.

Using this feature, several days in the summer and fall of 2024 have been simulated to analyse different arbitrage strategies for the plant to supply energy to the grid. Energy prices in the daily Spanish market are used as input to determine the power supply scheduling that optimizes daily plant revenues.

Preliminary results indicate that a profit increase of 7-60% can be achieved, while energy production decreases by only 2.5-8%. Figure 2 shows an example of plant operation resulting from the proposed strategy based on energy prices (b) compared to standard operation (a). In this example, energy production is extended during night hours with higher prices, thus increasing the expected plant profit by 13.2% despite a lower electricity yield (-5.1%).

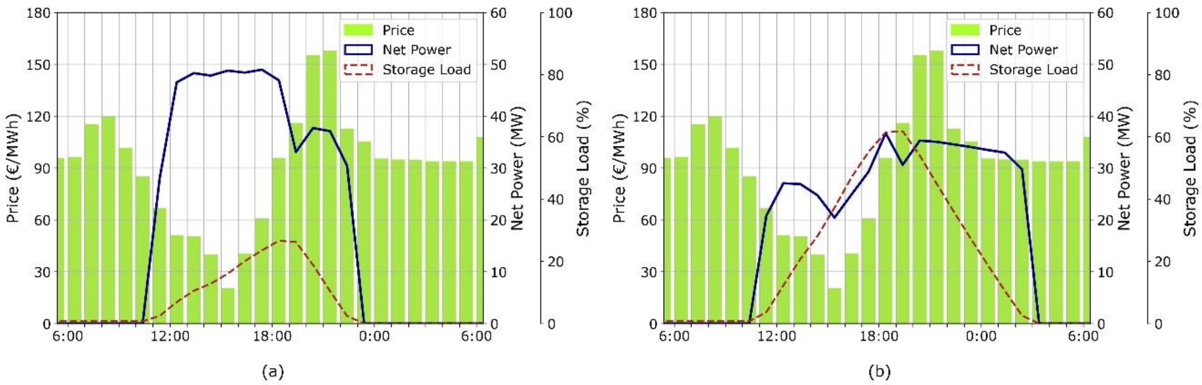

Fig.2: Simulation of operation strategies in 23-09-2024, (a) standard operation, (b) operation based on Spanish daily energy market.

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Towards flexible CSP power block

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The increased momentum of the energy transition and high shares of variable renewable energy in electricity grids have put significant emphasis on dispatchable and flexible electricity generation. In this context, concentrating solar power (CSP) systems present vast potential when their flexibility is improved, as they are already capable of dispatchable electricity generation thanks to thermal energy storage (TES). Central receiver (CR) technology is one of the most promising CSP systems for commercial-scale electricity generation, and the steam Rankine cycle is the most widely used cycle so far [1].

Focusing on the steam Rankine cycle within the scope of CR, the flexibility concept, the improvement areas of the power block, and cost and price implications will be discussed through this submission. In this context, minimum load, load change ramp rate, and start-up behaviour of the power block are regarded among the key flexibility characteristics. Addressing these parameters as the starting point, the authors aim to tackle flexibility in a wholistic approach by raising the following questions:

1. How do the flexibility related parameters impact the performance estimations in quasi-dynamic simulations for different grid conditions?
2. How can the minimum load be reduced, and how does it affect the performance of the CSP system in load-following scenarios?
3. How can the steam Rankine cycle and its components be interpreted from a flexibility and cost perspective?
4. How can the techno-economic assessment frameworks and key performance indicators (KPIs) be improved to capture the performance of CSP regarding flexibility?

To reflect on these questions, the major outcomes of the research conducted and reported so far [2], [3] will be presented together with the latest results of the ongoing research.

As a glimpse of the methodology to answer the first two questions, performance estimation studies are conducted using the in-house developed Python based CR model, complemented by EBSILON® *Professional* for power block simulations. The transient effects are accounted for in the model as time and energy penalties.

Then, various design and simulation tools, along with inputs from industry, are incorporated to study the Rankine cycle by analyzing its components to better interpret their flexibility and cost implications.

Finally, the best practices for techno-economic assessments (TEA) and traditional KPIs are re-evaluated to contribute to more accurate quantification, and subsequently, a better understanding of the true value of CSP plant performance under changing electricity market conditions.

Funded by the European Union

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This study has received funding from the EU TOPCSP Project under the grant agreement number 101072537.

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sCO_2 and CO_2 mixture cycles off-design operation in CSP plants

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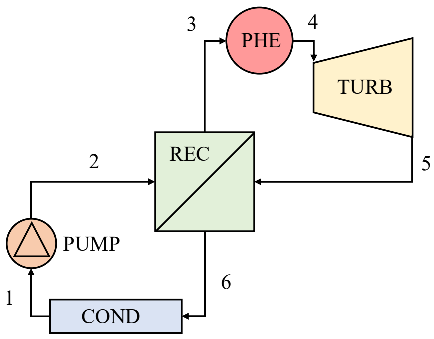
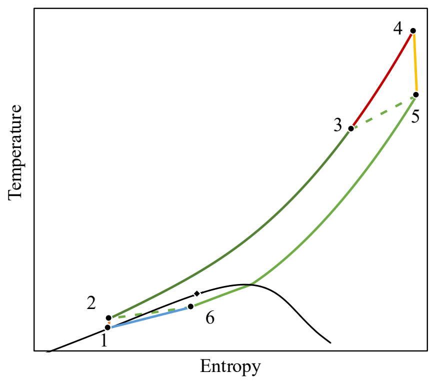
Concentrated solar power (CSP) plants are a promising renewable energy technology due to the high dispatchability provided by the low-cost thermal energy storage technology (TES). However, the electricity cost of CSP plants is higher than that from PV and wind plants [1]. The electricity cost reduction can be pursued by reducing the cost of equipment and increasing the plant efficiency. The closed supercritical CO_2 (sCO_2) cycles offer a thermal efficiency advantage over both the steam Rankine and helium Brayton cycles at high TIT [2] and could be a promising alternative for the next generation of CSP plants [3]. Using dopants with high critical parameters and moving from supercritical to transcritical cycles at the same minimum cycle temperature, the efficiency can be improved. CO_2-based mixtures have been extensively compared with pure sCO_2 cycles, showing both thermal efficiency [4] and techno-economic [5] improvement. New tower CSP plant designs have an installed capacity of around 100 MW and use dry cooling systems. Therefore, both sCO_2 and CO_2 mixture cycles performance will be significantly affected by the ambient air temperature changes. This, together with the limitations of power cycle and CSP plant operation, makes power cycle off-design performance a challenging task both in terms of control and efficiency optimization.

In this study I aim to investigate the influence of air temperature on operating conditions of the simple recuperated power cycle using sCO_2 and CO_2+$SiCl_4$ mixture [6] (Fig.1. shows the layout and T-s diagram). Different ways of power cycle control will be discussed in order to remain within safety limits, along with their influence on the operation parameters of the power cycle and CSP plant.



(a)



(b)

Fig.1: Layout (a) and T-s diagram (b) of a simple recuperated mixture cycle. PHE – primary heat exchanger; TURB – turbine; REC – recuperator; PUMP – pump; COND – air cooled condenser.

In order to appropriately simulate performance, an off-design steady-state model of the simple recuperated cycle was developed in MATLAB. Main cycle components were calculated with high-fidelity models constructed based on data available in the literature and previous research. Turbine, compressor, and pump were modeled using the dimensionless performance maps from the literature. Recuperators and air-cooled condensers/coolers were designed with an in-house code, after which their performance was calculated in off-design conditions. The primary heat

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exchanger was discretized and modeled with a simplified approach based on the results of a commercial rigorous model.

Aknowledgments

This paper is part of the TOPCSP project that has received funding from the European Union's HORIZON MSCA Doctoral Network, Project number 101072537.

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Typical Year of Atmospheric Extinction of Solar Radiation of the Plataforma Solar de Almería. Validation of Extinction Models and Maps in areas of interest for thermoelectric solar tower plants

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Introduction

A significant source of radiative losses in thermoelectric solar tower plants is solar extinction. This phenomenon is caused by the absorption and scattering of solar radiation by aerosols and water vapor. Given the large area of land usually occupied by these plants, the distance between the heliostats and the receiver (slant range, SR) often exceeds 1 km. Along this path, aerosols and water vapor are frequently present, contributing to solar radiation losses. Consequently, considering solar extinction is essential for determining the best locations for solar tower plants. To achieve this goal, experimental data are necessary to validate the models. The Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas" (CIEMAT) developed a solar extinction measurement system based on two digital cameras and a Lambertian target and it has been operating since June 2017. The system is acquiring solar extinction data every minute for a distance of 741.63 m. This database has allowed the generation of a Typical Solar Extinction Year (TSEY) for the Plataforma Solar de Almería (PSA) [1]. A typical year is defined as the collection of the most representative meteorological data in a location. The elaboration of them implies a minimum of five years of data. This typical year has been used to validate a solar extinction model at PSA [2]. This model can be used to obtain atmospheric extinction at any location of interest. Furthermore, a solar extinction map of Spain will be created as a part of the national project "More Efficient Heliostat Fields for Solar Tower Plants: The HELIOSUN Project". This is the third objective of the PhD programme.

Validation of a Solar Extinction Model at PSA

The solar extinction model uses the Aerosol Optical Depth (AOD) at 550 nm and the SR (742 m) as inputs. This model was developed by Polo et al [2]. AOD is defined as an integrated extinction coefficient from the ground to the Top of Atmosphere (TOA).

Simulated databases from June 28, 2017 to July 20, 2023 was generated using this model. The AOD at 550 nm was obtained from Aerosol Robotic Network (AERONET) and satellite data. Specifically, data were obtained from the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2) model and the Moderate Resolution Image Spectroradiometer (MODIS). The use of a radiative transfer code such as LibRadtran has facilitated the obtaining of these simulated values. Four databases have been generated and synthetic TSEYs were calculated, according to each source of AOD information. A comparative analysis has been carried out with the experimental TSEY (Table 1).

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Table 1. TSEY elaborated using Polo et al model vs Experimental TSEY from PSA.

	Polo et al model (Simulated TSEY)				Experimental TSEY
	AERONET	MERRA-2	MODIS (Aqua)	MODIS (Terra)	
Average value	6 ± 2 %	7 ± 2 %	7 ± 2 %	7 ± 2 %	6 ± 2 %
Distance	741.63 m				

The results obtained with the model are in agreement with the experimental TSEY, highlighting the outcomes derived from AERONET data. The rigorously validation process enables the estimation of solar extinction worldwide, thereby allowing the identification of optimal locations for thermoelectric solar tower plants.

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Modeling of a fluidized-bed heat exchanger for integration in a solar power plan

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This PhD thesis is part of the European Powder2Power and national SHIP4D projects, which aims to develop a new generation of concentrating solar power (CSP) plants capable of operating at temperatures above 600 °C, and ideally between 700 and 750 °C. Unlike conventional systems that rely on liquid or gas heat transfer fluids, this concept uses solid particles both as a heat transfer medium and a thermal energy storage material. These particles are heated by concentrated solar radiation in a receiver, stored at high temperatures, and then used to transfer heat to a working fluid through a specially designed heat exchanger. This component, referred to as HX2, is at the heart of the thesis.

The studied heat exchanger features a complex geometry, where tube bundles carrying the working fluid are immersed in a fluidized bed of hot particles. The working fluid—such as supercritical CO_2 operating at temperatures above 600 °C—flows inside the tubes, while the moving particles ensure efficient heat transfer by conduction and convection. The main objective of this thesis is to develop an intermediate-scale numerical model capable of accurately simulating the thermal exchanges within this system, accounting for the complex two-phase flow regimes in the fluidized bed.

The research begins with a global heat balance model to provide initial performance estimates. This is followed by more detailed 3D simulations using an Euler-Euler approach implemented in the Neptune_CFD solver—a high-performance code designed for multiphase flow simulations. Heat transfer within the tube walls is modeled using the Syrthes software, which is coupled to Neptune_CFD. Special attention is devoted to analyzing how the layout of the immersed tubes influences heat transfer efficiency. Validation of the simulation results is planned through experimental campaigns conducted within the Powder2Power project, using a pressurized air/particle fluidized-bed heat exchanger operating at high temperature.

Once validated, the model will be applied to simulate the final power plant configuration, where supercritical CO_2 is heated in the HX2 component. The study will include a parametric analysis of the heat exchanger geometry, fluidization velocity, particle properties, and inlet conditions of the working fluid. Ultimately, the thesis will deliver practical design recommendations for optimizing design and efficiency of future heat exchangers for particle-based solar power plants.

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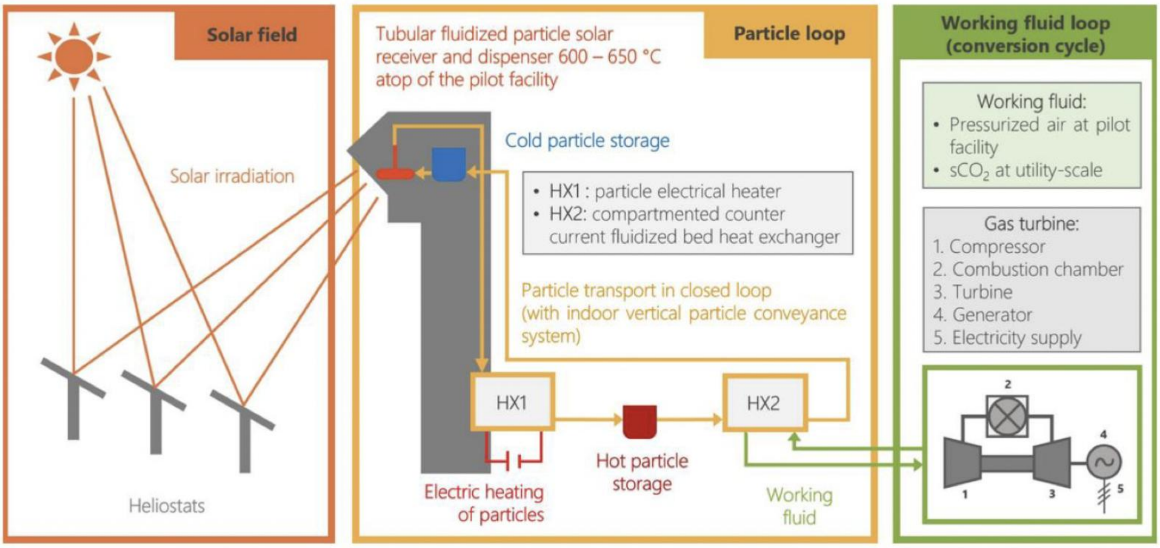

Fig.1 : Schematic of the P2P power plant at Themis.

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Acknowledgements.
This project has received funding from the European Union's Horizon Europe research and innovation programme under the grant agreement No 101122347 and benefited from State aid managed by the National Research Agency under France 2030 with the reference "ANR-22-PESP-0005".

Experimental characterisation of a drilling waste treatment plant by an indirect thermal desorption method

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ABSTRACT

This study aims to experimentally characterize the energy efficiency of an indirect heating, hybrid thermal desorption treatment of Oil-Based Drilling Waste (OBDWs) from drilling platforms. The treatment focuses on recovering base oil from drilling residues while ensuring that cuttings are disposed of with minimal oil content. The analysis evaluates the energy consumption from each heat sources and process zones, quantifies overall and zone-specific losses, and assesses the impact of key variables on performance through sensitivity analysis. The objective is to identify opportunities for improve energy and material management.

The results show that, during a 5-day campaign treating OBDWs, initially composed of 70.62 % solids, 21.56 % water, and 7.82 % base oil with 99.6 % separation efficiency, the indirect dual heating Thermal Desorption Treatment Unit (TDU) had an overall treatment energetic efficiency of 59.24 %. The TDU had a utilization rate of 427.024 kW input energy, achieved by an energy contribution of 87.12 % from diesel combustion and 12.88 % from electrical resistances. In terms of process energy distribution, 20.6 %, 49.4 %, and 5.0 % of the input energy were allocated to cuttings, water, and base oil, respectively, of which 15.76 % represented losses leaving the drying system in the form of hot solid cuttings and hot water, added to 22.3 % through flue gases and 2.7 % from surface heat losses.

A sensitivity analysis of specific treatment parameters showed that changes in certain variables may lead to proportional changes in process efficiency. The analysis shows that combustion excess air, HTF heat demand, and base oil specific heat vary inversely with process efficiency, while ambient temperature varies directly with efficiency.

This characterization may guide enhancements in the energy efficiency of this and similar treatment processes, understand and address undesired outcomes, and support the transition to a more sustainable treatment method.

Keywords: Drilling waste, drill waste treatment, thermal treatment methods, indirect thermal desorption

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Simulating Convective Losses from Rotating Cavity Receivers

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Note: *Results presented here were also submitted for evaluation to SolarPACES 2025.*

Introduction

The centrifugal particle receiver concept (CentRec) developed by the German Aerospace Center (DLR) Institute of Solar Research uses a fast-rotating, down-tilted cylinder in which particles flow in a controlled manner on the side wall under the influence of gravity. Since CentRec is a novel concept, there is limited research on the effects of wind velocity and rotation on convective losses or strategies on how to reduce them. To address this gap, concepts shown in Fig. 1 were evaluated using CFD simulations.

The baseline case has a 925 mm deep conical radiation shield around the aperture with a cone angle of 45 degrees. The long cone doubles this depth while the flat plane rids the cone completely. The spoiler is a shallow structure following the contour of the cone up to 140mm above the housing wall level, surrounded by a 15-degree circular segment wall tangent to the housing. Wind walls are solid blocks measuring 2 x 8 x 0.5 m.

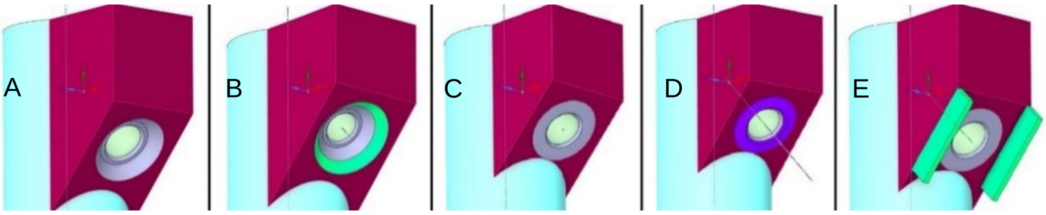

Fig.1 Tested cases. A) Baseline; B) Long cone; C) Flat Plane; D) Spoiler; E) Wind walls.

Boundary Conditions and Methodology

The receiver was modelled as a 45° down-tilted, 6.2 m deep, cylindrical cavity measuring 4.4 m in diameter, with a 3.1 m wide aperture. Inner walls were diffuse and grey with $\varepsilon = 0.8$. The back and side walls were at uniform temperature of 1273 K and rotating at 28 rpm. All other surfaces were adiabatic and stationary. The receiver was perched on a 10 m diameter tower. The aperture centre was 10 m below the top of the tower and 7.5 m away from the tower axis.

The presented results are obtained using the k-ω SST turbulence model implemented in ANSYS Fluent 2023 R1. Steady-state simulations were performed, and wall functions were used. Simulations with finer meshes ($y+ < 1$) did not yield any notable difference in the results.

EU-Solaris 2nd Doctoral Colloquium 2025, Almería, Spain. June 2-4, 2025

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Preliminary Results

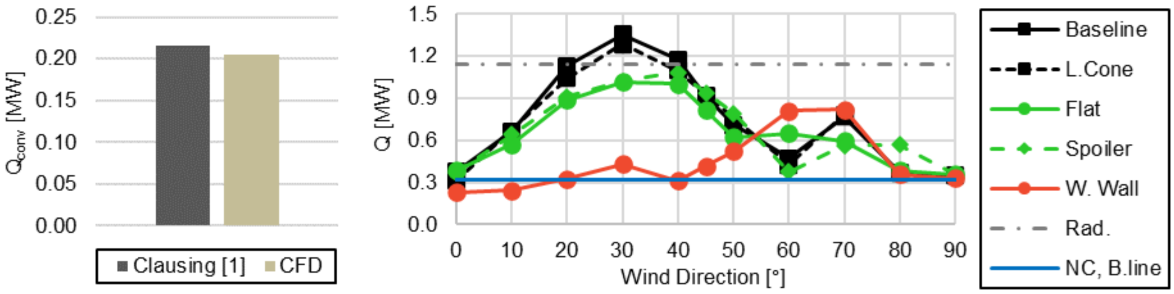

Fig.2 Left: Convective heat loss for natural convection from a static cavity.
Right: Convective heat losses for the five concepts under 15 m/s wind, along with radiative and natural convection losses from a rotating cavity for reference.

Reynolds and Richardson numbers were calculated to be $7.97*10^5$ and 0.415 using the aperture diameter and film temperature. Since cases are in the mixed convection regime and there are no relevant experimental results in the literature for rotating cavities, the CFD model is verified using a well-tested correlation [1] for calculating free convection from static cavities. The result presented in the left-hand plot of Fig. 2 shows excellent agreement, indicating correct modelling of buoyancy-driven flow.

Under head-on winds, all concepts work similarly, but as the sideways component of the wind becomes more prominent, walls perform significantly better. They work by guiding the airflow from top to bottom along the housing wall while preventing air from escaping from the sides, forming a cushion of air that shields the aperture. Without this cushion, conical apertures scoop the wind, increasing the convective losses substantially. Using a flat panel or a spoiler to generate an air curtain provides only a partial remedy.

As the wind becomes more sideways, the wind walls start scooping the air, which increases convective losses. However, these losses are still comparable to the baseline case and much lower than their radiative counterpart. The spoiler creates an air curtain as intended and gives the best result for the side-dominant wind directions, while the flat panel offers adequate shielding as well. Both baseline and long cone cases show a distinct secondary peak at 70 degrees, while other concepts level between 60 and 80 degrees before sinking to natural convection levels at 90 degrees. The secondary peak happens as the air hitting the aperture ring is split, and a jet of fast-moving air is introduced in the receiver.

Ongoing analyses will focus on the effect of spoiler, wind wall and housing shape while increasing the number of tested wind directions and speeds. Then active systems such as air curtains will be investigated, and hybridisation options will be explored, as our findings show different methods work the best for different wind directions.

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Optimization of a solar receiver with movable redox structures

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Decarbonizing the aviation sector is one of the large environmental goals of this century. To this end syngas (H_2 / CO) the input for e.g. kerosene production needs to be produced through a renewable pathway. Two-step thermochemical reduction-oxidation (redox) cycles are one promising approach to directly convert solar energy to storable chemical energy and deliver the reactants for subsequent Fischer-Tropsch synthesis of aviation fuels. While alternative redox materials are still under research, Ceria (CeO_2) has emerged as the standard redox material due to its high cycling stability and fast reaction kinematics [1].

The ceria is reduced in a first step which requires low oxygen partial pressures ($p_{O2} \sim 1$ mbar) and high temperatures ($T_{red} > 1400$ °C). The latter can be provided by concentrated solar radiation. In the second step the redox material is re-oxidized at lower temperature ($T_{ox} < 1100$°C) thereby reducing an atmosphere of H_2O/CO to the desired products H_2/CO and closing the loop. Solar-to-fuel efficiencies of 4.1 % have been demonstrated in recent years [2]. The biggest potential for improvement was identified in the optimization of the temperature swing operation between reduction and oxidation e.g. by introducing heat recuperation and in the temperature distribution over the redox material [2].

The R2Mx receiver concept addresses these challenges by employing movable redox material that cycles between separate reduction and oxidation reactors [3]. This enables continuous operation of the reduction reactor without cyclic heating of inert reactor components. Furthermore, it opens up new opportunities for solid-to-solid heat recuperation. In a recent study [4] Brendelberger further proposes to use cylindrical redox material assemblies (RMAs) distributed over a receiver cavity with multiple apertures. Hence the RMAs receive radiation from all directions with a high ratio of indirect radiation that promises to lead to a more uniform temperature distribution.

The placement and movement of the RMAs in the multi-aperture receiver open up a large parameter space for the optimization of the design and the operational strategy. Especially interesting is the reduction reactor as this is where the concentrated solar radiation is absorbed to create the temperature profile determining the reduction reaction. To examine this system in more detail a numerical model of a MW-scale reduction reactor will be developed. The model will focus on the description of the solar radiation absorbed in the reactor and the thermal radiation exchange within the reactor. It further considers conduction to the ambiance and the reduction reaction through effective material properties. A special challenge is posed by the transient behavior of the individual RMAs. Reactor test stands that are currently under development to demonstrate different features of the R2Mx concept can provide data for model validation.

An outline of the numerical model will be presented. Initial results of the solar concentrator layout that determines the solar radiation profile delivered to the different apertures of the receiver are included.

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Modeling and control of a next-generation, fluidized particle-based solar receiver at MW scale

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Fluidized solid particles in concentrated solar power have shown the potential to induce higher global efficiencies compared to conventional heat transfer fluids [1]. By maintaining their physicochemical stability at higher temperatures than synthetic oils and molten salts (600–750°C), they reduce storage issues and reach more efficient conversion cycles.

In the context of the European project *Powder2Power*, aiming to demonstrate the feasibility of such a CSP central tower plant prototype at MW-scale (TRL7) [2], this work focuses on the tubular solar receiver in a two-pronged approach. First, by thermally modeling the receiver as a function of the incident solar flux distribution and the particle mass flow rate through the tubes. Second, by implementing a control strategy using deep reinforcement learning, trained both by simulated results of the model and experimental data. Special attention will be given to transient states, as they will determine the appropriate response of the control system to maximize thermal efficiency while ensuring a safe operation.

The studied receiver is an original 2 MWth pilot consisting of 40 vertical tubes subjected to concentrated radiation over a 3 m height. Particles flow upwards from the dispenser to the hot store (see Fig. 1), driven by a controlled pressure gradient and additional air injections. Because the concentrated solar field on the receiver is not perfectly uniform, the resulting temperature distribution is non-homogeneous (see Fig. 2). This can alter air velocity inside the tubes, reducing the particle flow rate in some regions and potentially triggering self-reinforcing feedback loops that lead to hot spots (>900 °C), which compromise the integrity of the tube array. Other fluidization regimes characteristic of this particular fluidized bed system must also be taken into account.

A finite element model will simulate heat and temperature distributions under varying conditions, distinguishing the thermal dynamics of tubes and particles. Initially, experimental results of a single-tube mock-up from [3] will be considered to design a basic single-tube model. Later, a model considering the 40-tube array will be developed.

Data acquired during the first experimental campaign at Thémis Solaire Innovation (TSI, Targasonne) in summer 2025 will support both validation of the full-receiver model and training for the intelligent control system. The developments arising from this research will be implemented during a year-long operational test in 2027 at the TSI site.

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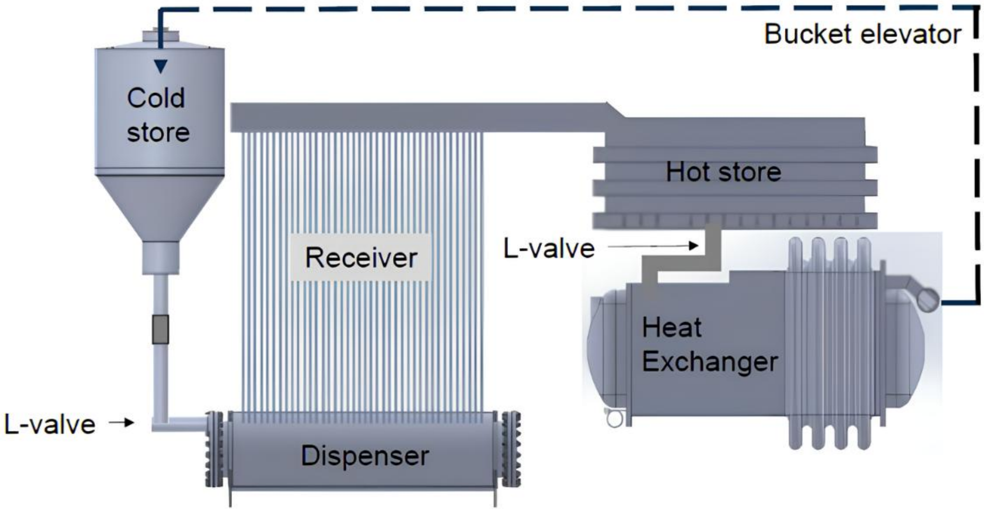

Fig. 1: Schematic layout of the Powder2Power particle loop [4].

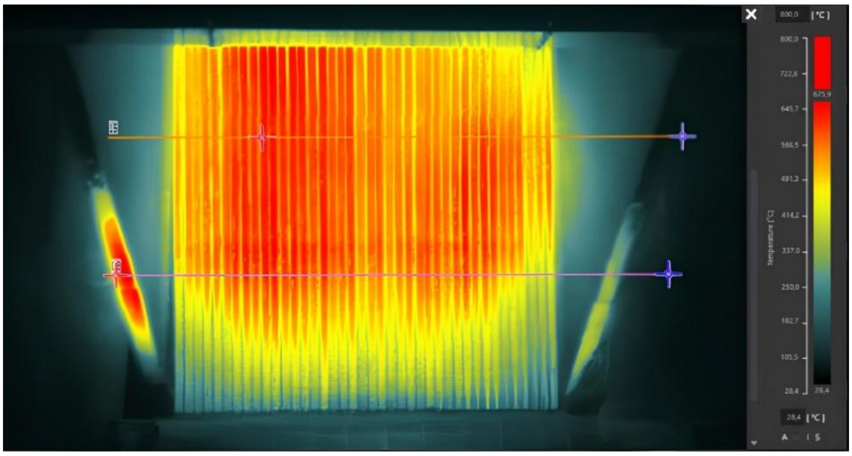

Fig. 2: Infrared temperature measurement of the receptor during the first experimental campaign of European project *Next-CSP*, predecessor of Powder2Power [4].

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Thermo-Mechanical Study of Silicon Carbide (SiC) for Fluidized Bed Solar Receivers

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1. Introduction

Research has grown significantly over the past decade, with global capacity projected to reach 58 TWh by 2035 [1]. Many CSP technologies are still in early development, but fluidized bed solar receivers show potential for improving thermal efficiency and reducing costs. The SiCSun project aims to enhance CSP systems by integrating fluidized bed technology into solar receivers, improving heat transfer and performance. This study focuses on the thermo-mechanical behavior of a silicon carbide (SiC) tubular solar receiver, chosen for its ability to withstand temperatures above 1000°C, and evaluates its mechanical durability under these conditions.

2. Experimental Setup

The experimental study focuses on evaluating the thermo-mechanical behavior of a silicon carbide (SiC) tubular receiver implementing a particle fluidized bed as heat transfer. The setup includes a 1 meter long SiC tube with a diameter of 48 mm, placed within a cavity designed to minimize heat losses to the surrounding air. This receiver is exposed to a concentrated solar flux of 600 kW/m^2.

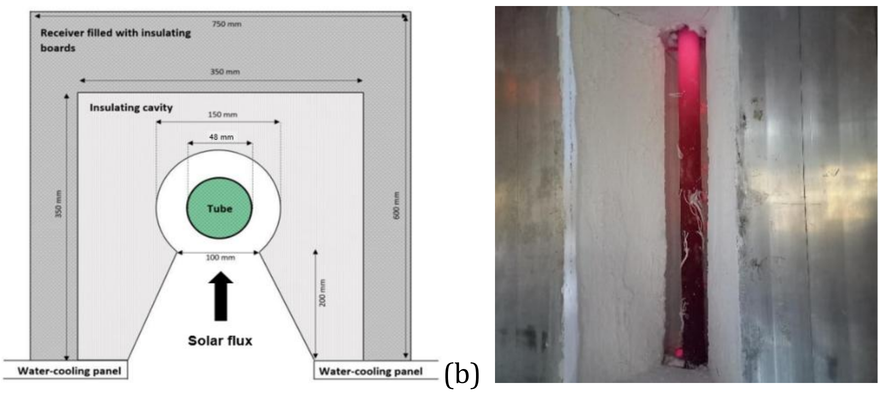
(a)  (b)

Fig. 1: Schematic (a) and photo (b) of a Tubular Receiver in an Insulated Cavity Exposed to Frontal Solar Flux

Inside the tube, fluidized particles absorb heat from the SiC walls, enhancing thermal transfer. Previous studies show that a flow rate of 242 kg/h ensures turbulent fluidization, promoting stable heat transport [2]. This study focuses on SiC's thermodynamic performance as a receiver material. Experiments will be conducted at ambient and 300°C inlet particle temperatures, with results compared to a prior study using a different receiver material [3]. The investigation will analyze thermal deformations and thermo-mechanical stresses to evaluate SiC's performance and structural integrity under high solar flux and temperature, considering its fragility.

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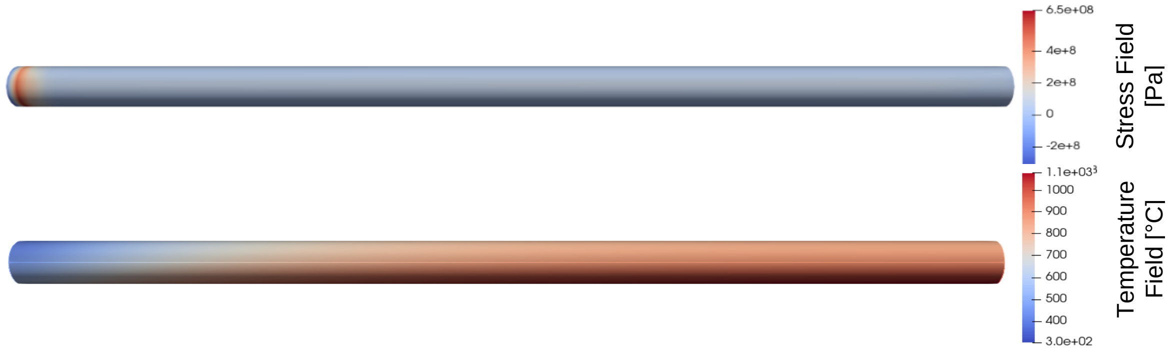
3. Thermo-mechanical analysis

Numerical simulations were conducted to assess the thermo-mechanical behavior of the SiC tube before the experimental campaign, aiming to define its operational limits and optimize the experimental environment. Using Code-Aster with SALOME, the 1-meter tube was exposed to 600 kW/m^2 solar flux.strategy.

Fig. 2: Numerical Simulation of a Tubular Receiver, temperature and stress distribution under solar flux exposure



The analysis focused on temperature distribution and mechanical stress, with results showing temperatures exceeding 1000°C, causing a displacement of about 1 cm, but remaining within SiC's elastic limits. These findings confirm SiC's mechanical resilience. A broader parametric analysis, including variations in inlet temperatures, flow rates, and solar flux, refined the experimental strategy by optimizing heat uniformity and assessing stress, deformation, and failure probability.

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3D CFD Analysis of an Open Volumetric Air Receiver and Comparison with 10 kWth Solar Tests

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1. Introduction

The design and optimization of Open Volumetric Air Receivers (OVARs) require detailed numerical modeling to complement experimental campaigns and improve performance predictions. This work presents a Computational Fluid-Dynamics (CFD) study of the thermal behavior of ceramic foam absorbers coupled with a funnelling-cup, with a focus on heat transfer efficiency of the system under varying operating conditions. The modeling strategy builds on previously validated lab-scale work [1, 2] and is extended here to simulate the absorber-cup configuration under concentrated solar irradiation in 3D. The model is benchmarked against 10 kW_{th} experimental tests conducted at the Plataforma Solar de Almería (PSA) within the Horizon Europe ASTERIx-CAESar project [3].

2. Experimental and Numerical Methodologies

The experimental setup includes a single ceramic foam absorber and cup integrated into a thermal air loop designed to replicate full-scale receiver operation. Ambient air is forced through the absorber by a blower, then flowing sequentially through the receiver pipe, air/water heat exchanger, and flow meter. The setup is placed at 50 mm behind the focal plane of PSA's SF60 solar furnace, where a shutter controls the incident solar flux. Each foam and cup was tested under three solar input levels and three target air temperatures. The foam used has a porosity of 0.85, cell diameter of 1470 μm, window diameter of 490 μm, and strut thickness of 210 μm, and the cup is made of composite N610-DF13-4500/FW12. Quasi-steady state periods were selected for numerical comparison.

A 3D CFD model of the absorber (120 mm x 120 mm aperture) and cup (60 mm outlet diameter) was developed in STAR-CCM+, replicating the experimental conditions. A continuum approach was used, including radiative transfer (Rosseland approximation), forced convection, and local thermal non-equilibrium (LTNE). Simulations were performed for solar fluxes between 360 and 630 kW/m^2. The numerical methodology includes:

1. Governing equations: Navier-Stokes, fluid/solid energy, turbulence and radiation.
2. Mesh sensitivity analysis to ensure numerical accuracy.
3. Boundary conditions: Inlet air mass flow, outlet pressure, and thermal losses.
4. Validation by direct comparison with experimental measurements.

3. Preliminary Results

The validation of the model is based on three thermocouples located near the cup exit, positioned approximately in the same axial plane. The model integrates the experimentally measured solar flux profile (Fig. 1, a)).

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Figure 1 b) and c) qualitatively show the evolution of the solid and fluid temperatures, highlighting strong gradients within the absorber-cup system. Consequently, comparison is focused at the outlet, where temperature fields are more homogeneous.

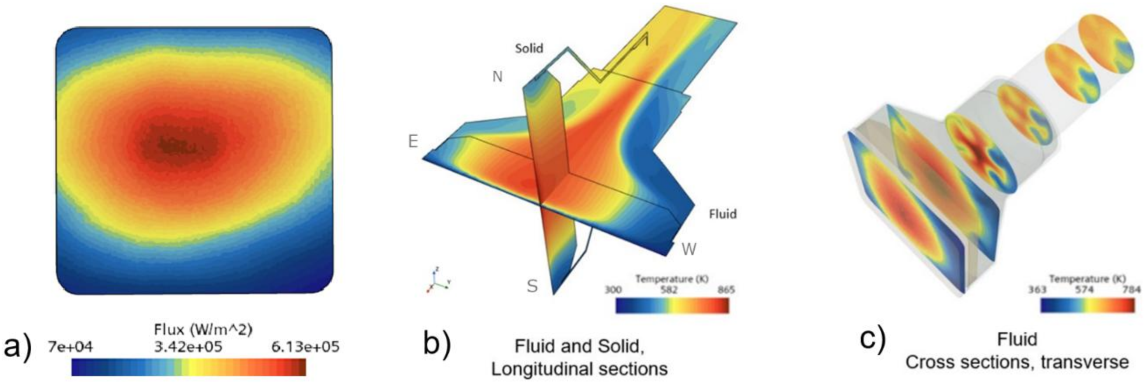

Fig. 1: a) Incident solar flux profile; b) solid (N-S) and fluid (E-W) temperature profile; c) Fluid tem-pera-ture sections within the absorber and cup

Table 1 shows experimental temperatures of three sensors (TK4, TK5, and TK6), their average (TK456), and numerical predictions for a selected steady state period. Simulations were conducted using the average experimental mass flow rate $\dot{m}_{a,avr}$, with upper $\dot{m}_{a,max}$ and lower $\dot{m}_{a,min}$ bounds to assess deviations within the quasi-steady state period. The difference between the average experimental TK456 value and the average numerical result for $\dot{m}_{a,avr}$ is less than 2%. Moreover, numerical results also present the significant temperature variation within the given plane due to the solar flux profile and the mass flow variation, ranging from 478 K to 748 K. These values align well with the measurements from the three available thermocouples (TK4, TK5 and TK6).

Table 1. Comparison of cup outlet temperatures (in K): experimental sensors vs. numerical results

	Experimental Data				**Numerical Data**			
	TK4	**TK5**	**TK6**	**TK456**	$T(\dot{m}_{a,avr})$ 13.7 g/s	$T(\dot{m}_{a,max})$ 14.1 g/s	$T(\dot{m}_{a,min})$ 13.1 g/s	
Average	**524**	**652**	**624**	**600**	**610**	**601**	**621**	K
Maximum	532	658	632	607	735	724	748	K
Minimum	511	647	617	592	484	478	492	K

The thermal efficiency of the absorber-cup system was assessed using both experimental and numerical data. Based on the average experimental outlet temperature (600 K from TK456), the efficiency is estimated at 83.1%. The corresponding numerical simulation, predicting 610 K, yields an efficiency of 85.7% confirming the model's reliability under the evaluated conditions. The same methodology was applied to simulate absorber-only performance, achieving 90.6% efficiency with an average outlet temperature of 627 K.

4. Outlook

The validated numerical model serves as a powerful tool inferring detailed insights about the system's behaviour that would otherwise be challenging to obtain through experimentation. The full study will include an in-depth analysis of the absorber thermal efficiency under different operational scenarios, including solar flux and working temperatures. Future work will aim to simulate

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a full-scale receiver, aligned with the design and performance goals foreseen for implementation within the ASTERIx-CAESar project.

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Development of a concentrator photovoltaic-electrochemical system for water splitting with waste heat integration

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As the world shifts towards reducing fossil fuel usage and achieving global climate goals, green hydrogen is emerging as a key factor to the energy transition, serving not only as a versatile chemical for various industrial processes but also as a CO_2-neutral fuel and energy vector. A promising approach to producing hydrogen from solar energy involves harnessing electricity from photovoltaic (PV) cells to power electrolyser cells (ECs), which yield hydrogen via water splitting.

Industrial photovoltaic-electrochemical (PV-EC) setups usually combine solar fields with large centralised EC stacks. However, research trends show that PV-EC systems can achieve higher efficiencies when adapted to operate under concentrated sunlight [1]. These concentrator photovoltaic-electrochemical (CPV-EC) systems require active cooling due to the high irradiance the PV is exposed to and the fact that most commercial water electrolysers are designed to operate above their thermoneutral voltage, where they also generate excess heat.

The present work focuses on the development of a CPV-EC solar-to-hydrogen system, which will be designed for use in conjunction with solar concentrators. In addition to CPV modules and a water electrolyser, this particular system will include a thermally coupled process (TCP) intended to increase the overall efficiency by integrating the waste heat in the cooling streams back into the process. The objective of this study is to develop and evaluate concepts of potential CPV-EC-TCP systems with the aim of identifying, modelling and then experimentally characterising a promising system choice.

In order to find applicable combinations of CPV modules, ECs and TCPs, literature and market reviews were carried out for each of these components, which contributed to the identification of suitable available options. By considering the boundary conditions of the different components, especially their temperature sensitivities and required heat flows, first combinations of CPV module, EC and TCP were defined and compiled into innovative solar-to-hydrogen system concepts of various categories. Given that this selection was too broad for each system to be modelled, it was narrowed down based on the following reasoning:

For CPV applications, there is a general consensus among solar researchers that multi-junction cells are the best choice [2]. Preliminary experiments carried out as part of this project in the German Aerospace Center's (DLR) High-Flux Solar Simulator (HFSS) confirmed this statement, as GaInP/GaAs/Ge triple-junction modules were found to be practically the only PV modules available on the market that can be readily applied to higher concentrations with efficient outcomes.

For the EC, high-temperature options were excluded from the selection due to their lower Technology Readiness Levels (TRLs) and the high electricity input required to meet the demand for high-temperature heat in the framework of this CPV application. Among the low-temperature options PEM ECs were chosen, as they offer the best dynamic operation capabilities and high

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efficiencies at high current densities, as well as already being commercialised up to MW-scales [3].

The selection of TCPs that can make use of the low-temperature waste heat of the triple-junction CPV and PEM EC was narrowed down to thermoelectric generators, organic Rankine cycles and Kalina cycles.

As a next step, steady-state 0D models of the subcomponents were set up and combined into a process model to help identify the most efficient TCP options. The subsequent phase of this project will focus on one promising selected system and involve transient modelling in order to reach an optimised reactor design that can be experimentally characterised under concentrated irradiation.

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Modeling of Radiative Heat Transfer in Redox Material Assemblies for Solar Fuel Production

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The utilization of concentrated solar radiation for the production of sustainable fuels and chemical commodities is a promising pathway for promoting the decarbonization of the industry and transport sector. Two step thermochemical reduction-oxidation (redox) cycles can be driven within a receiver-reactor installed on a solar tower to produce hydrogen or syngas. Metal oxide redox materials (e.g. CeO_2) within the reactor are reduced at high temperatures ($T_{red} \geq 1400$ °C) and low oxygen partial pressures ($p_{O_2} \leq 10$ mbar). In the second step of the process the reduced material is cooled down ($T_{ox} \leq 1000$ °C) and brought into contact with an oxidizer such as water vapor or carbon dioxide, generating hydrogen or carbon monoxide respectively and returning the redox material to its initial oxidized state.

The reduction extent of the metal oxide and thereby the process efficiency strongly depends on the heat input provided to the redox material and the resulting temperature profile within the structure. For state-of-the-art receiver-reactors the active material is incorporated as reticulated porous ceramic (RPC) elements mounted on the inner reactor cavity walls [1]. This reactor design allows for a direct solar irradiation of the redox material from only one site, resulting in large temperature gradients within the structure and thereby significantly limiting the overall reduction extent and process efficiency. The novel R2Mx reactor concept allows the incorporation of redox material with different monolithic geometries and types of irradiation [2]. Redox material assemblies (RMA's) with cylindrical shape can be implemented into the reactor and are primarily irradiated by indirect thermal radiation from the inner reactor cavity walls. In order to obtain a better understanding of the resulting heating process during the reduction step and for an adapted RMA geometry development, it is necessary to investigate the radiation absorption and the internal radiative heat transfer within the redox structure.

For modeling the radiative heat transfer inside RPC redox structures several approaches are reported, including the Rosseland diffusion approximation, Monte Carlo ray tracing (MCRT) and the P1 model [3, 4]. In order to utilize the accuracy of MCRT while reducing the computational cost of the overall thermal simulation, generalized radiation exchange factors can be pre-calculated by a MCRT model and afterwards used in an effective thermal simulation [5]. Such radiation exchange factors describe the qualitative heat exchange by radiation between different redox material elements inside the RPC structure, as well as with the surrounding reactor environment. For the new RPC geometry with diffuse irradiation a MCRT model with effective material properties is developed to simulate the radiative heat exchange and calculate resulting radiation exchange factors [6]. Resulting temperature profiles within the structure are an important characteristic for the two-step redox process efficiency and RMA development. The MCRT model is presented and the effect of the resulting radiation exchange factors on the heating profile is analyzed.

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Catalyst development for high temperature SO_3 splitting in the solar-aided sulfur thermochemical cycle

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1. Introduction

The hybrid Sulfur cycle (HyS), also known as the Westinghouse cycle, presents a promising and sustainable method for hydrogen production via solar-driven water splitting. Two reactions are combined within this cycle, a thermochemical and an electrochemical, respectively. The first set of reactions (1, 2) is an endothermic step, in which sulfuric acid decomposes into sulfur dioxide, water and oxygen, under high temperature conditions. The oxygen can be obtained and released as a byproduct while SO_2 and H_2O participate in the electrochemical reaction. In this reaction, SO_2 in water produces sulfuric acid and hydrogen gas.

The sulfuric acid splitting consists of two endothermic steps:

$$\mathrm{H_2SO_4(g)} \rightarrow SO_3\mathrm{(g)} + \mathrm{H_2O(g)} \quad \Delta H = +98 kJ/mol \ (1)$$

$$SO_3\mathrm{(g)} \rightarrow {}^{1}\!/_{2}\ \mathrm{O_2(g)} + SO_2\mathrm{(g)} \quad \Delta H = +99\ kJ/mol \ (2)$$

While the initial dissociation of sulfuric acid is thermodynamically favorable ensuring a full, non-catalytic conversion, the subsequent SO_3 splitting constitutes a reversible reaction that requires a catalyst to achieve an acceptable conversion. To enable this reaction under high temperature (850°C) conditions, Concentrated Solar Technologies (CST) are employed to provide the necessary thermal energy, essentially coupling solar energy with the process studied. In this context, various metal-based oxides, primarily copper, iron and aluminum based catalytic materials either unsupported or supported on alumino-silicate structures have been developed and evaluated with respect to their physicochemical and catalytic properties.

2. Materials and Methods

Non-precious, metal-based catalysts were synthesized through two different, cost effective and technically simple synthesis routes: Dry Mixing (DM) and Dissolution-Evaporation-Precipitation (DEP). The DM route involved mixing metal oxides in powder form, while DEP is a wet synthesis method in which metal precursors are dissolved in water, mechanically stirred, followed by gradual evaporation of the solvent and drying to obtain the wet solid matter. In both cases, a sintering protocol was implemented to produce catalytically active phases. Single or mixed copper, iron and aluminum based oxides, specifically CuO, Fe_2O_3, $CuFe_2O_4$ and $CuAl_2O_4$, were synthesized for the high temperature reaction (850°C), considered the most promising catalytically active phases [1,2]. In most cases, aluminum or silicate supports were incorporated. The materials were structured into near-spherical granules (1-2 mm), calcined at 1000°C and characterized by X-Ray Diffraction (XRD), Scanning Electron Microscopy (SEM) coupled with Energy Dispersive X-ray Spectroscopy (EDS), BET surface area analysis and mechanical (crushing) strength (CS) measurements before and after the reaction. The catalytic performance of these materials was evaluated in a quartz tube reactor at 850°C, using sulfuric acid (95-98%

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concentration) as the feed. The reaction temperature was monitored with thermocouples and real time SO_2 measurements were performed using a UV-Vis spectrometer.

3. Results and discussion

Tab. 2 summarizes the most promising catalytic performance materials of the current experimental study. The SO_3 conversion of the iron oxide (Fe_2O_3) is also presented as a benchmark material. The crushing strength values are acceptable for all the samples.

Tab. 2: Catalytic results and CS measurements

Catalytic Material	SO_3 conversion (%)	CS (N)	
		Fresh	Used
Fe_2O_3	42.0	20.9	30.0
Cu-Al (1:1)$_{\_DM}$	65.0		
Fe-Cu (1:1)$_{\_DEP}$	65.8	-	-
Fe-Cu (1:1)/kaolin$_{_DM}$	66.2	17.6	22.1
Fe-Cu-Al (1:1:1)$_{\_DM}$	70.0	14.5	24.9

The addition of copper to iron and iron-aluminum based samples led to enhanced catalytic behavior, achieving up to 70% SO_3 conversion. This can be attributed to the existence of $CuFe_2O_4$, $CuAl_2O_4$ and CuO, all of which being catalytically active phases of the fresh catalysts. Following the on-stream exposure, copper sulfates are detected on all the samples (used), based on the XRD results. BET surface area for all the samples before and after the reaction is negligible. All the catalytic materials exhibit enhanced crushing strength measurements after the on-stream exposure, attributed to sintering phenomena occurring during the reaction. X-ray mapping combined with XRD results indicate that the reaction is taking place on the surface of the catalytic particle. All these efforts provide critical insights towards the development of efficient catalytic particles in granular form, enabling high-temperature H_2SO_4 dissociation coupled with CST technologies.

4. Acknowledgements

This work has received funding by the European Commission through the HORIZON EUROPE project “HySelect” under grant agreement number 101101498.

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Development and Properties of Materials as Disproportionation Catalysts for Sulphur Dioxide

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Solar radiation can only be concentrated for power production during day time with clear sky when direct radiation is available but energy is needed 24 hours per day. Therefore, it is important to integrate a thermal energy storage (TES) into concentrating solar power (CSP) systems. In CSP the state-of-the-art TES is molten salt. Its storage capacity is limited by its heat capacity. To increase the storage capacity, a sulphur-based thermochemical cycle is introduced, where the energy is stored in the chemical bonds of sulphur. Sulphur as energy storage material has many advantages over molten salts. It has more than 20 times the storage capacity. In addition, sulphur is stable under ambient conditions which allows for long-term storage at low cost [1].

The solid sulphur cycle concludes three steps. In the first step, the heat from a CSP plant is utilised to decompose sulphuric acid at temperatures ranging from 650 to 850°C, resulting in the formation of sulphur dioxide (SO_2). Subsequently, the SO_2 is mixed with water and reacts in a disproportionation reaction, resulting in the generation of elemental sulphur and sulphuric acid. In the last step, sulphur can be burned in air thereby undergoing an exothermic reaction. The heat that is produced can be utilised in the generation of electricity in a gas-turbine [2]. The product of this step is SO_2 which is then used to produce sulphuric acid in a well-established process in the industry. The current work is focussing on the second step, the optimization of SO_2 disproportionation.

Previous studies by *Wong* et al. on SO_2 disproportionation showed that this reaction has slow reaction kinetics. For this reason, a variety of common heterogeneous and homogeneous catalysts were tested. Dissolved iodide showed the best catalyst activity up to this point [2]. However, for industrial applications the reaction rate of the SO_2 disproportionation catalysed by iodide is still too slow as enormous reactor volumes would be required to process SO_2 streams for generating sulphur at relevant scale.

The goal of this work is to discover the relevant properties the catalyst requires to support the SO_2 disproportionation reaction more efficiently. In the first step, further catalyst screening will be done. It is assumed that because of the similar redox potentials of iodine/iodide and sulphur dioxide/sulphur, the redox potential may be a relevant property of the SO_2 disproportionation catalyst [3]. In the context of a heterogeneous catalyst reaction, the *Claus* reaction has a certain degree of similarity to the SO_2 disproportionation. A literature survey on this reaction revealed that basic sites are required for the adsorption of SO_2 on the catalyst [4]. It can therefore be assumed that this might also hold for SO_2 disproportionation.

These potentially relevant properties were considered to select candidates for the catalyst screening process. For metal oxides the electron-donating power is given by the optical basicity [5]. To ensure optimal comparability and accessibility of the data pool, the initial candidates considered were metal oxides.

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Quantum Espresso [6,7] will be used to understand this reaction, providing data like surface energy, adsorption/desorption energy and activation energy.

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Development of a solar-thermochemical reactor for sustainable production of high-purity nitrogen using concentrated solar power

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Due to the fluctuating availability of energy from renewable sources and global goals towards climate neutrality, the necessity of energy storage is constantly growing. A highly discussed candidate is hydrogen due to its high gravimetric energy density. However, hydrogen poses problems due to its high diffusivity and its low density [6,11]. Indeed, together with nitrogen, hydrogen can be reacted to ammonia which is liquid at milder conditions and thus can be stored and transported much easier (at ambient pressure, ammonia only needs to be cooled to approximately 225K to liquefy, instead of 20K for hydrogen [7,9]). Fertilizer industry is one the most important demander of ammonium [1]. Besides the nourishment of the world's growing population, fertilizer is required for producing bio-fuels which cover 6% of global energy needs [5] and serves as fuel for ships.

The synthesis of ammonia from nitrogen and hydrogen ($N_2 + 3H_3 \rightleftharpoons 2NH_3$) is commonly carried out in the Haber-Bosch process which requires nitrogen of very high purity [2]. In order not to destroy the catalyst involved, only oxygen impurities in the range of a few ppm can be tolerated [4]. State of the art nitrogen production processes that achieve the required purity, such as the cryogenic air separation by Thomson-Linde process, require much energy and have a large carbon dioxide footprint and are therefore willed to be replaced by more sustainable processes [8,10,12].

Thermochemical air separation has been studied in recent years and can present an alternative route for nitrogen production as it can be operated under milder reaction conditions and with the use of renewable energy sources [3,6]. In a recent study our institute demonstrated the general achievability of a remaining oxygen impurity of less than 10 ppm in nitrogen by a thermochemical process using a perovskite metal oxide for air separation [6]. However, the integration of renewable energy sources into this process is still outstanding.

Therefore, in this study, we develop a novel reactor concept /design for thermo-chemical air separation that uses concentrated solar power as energy source for heating the perovskite to the required reaction temperature. Besides, fundamental improvements of heat integration into the process and more performant concepts for heat exchange between different reaction steps are developed and implemented in the reactor. Special attention is paid to the scalability of the reactor in order to take the next step towards an industrial employment.

Similar to the recent study, air from ambient will be pre-purified by a pressure-swing adsorption process (PSA) which extracts the majority of the oxygen from the air but is not economically favorable to achieve the required purity of the nitrogen [6,10]. Thus, the thermo-chemical air separation process follows upon the PSA step and provides nitrogen of high purity. A summarizing overview of the considered air separation process and its integration into adjacent processes is given in Fig.1.

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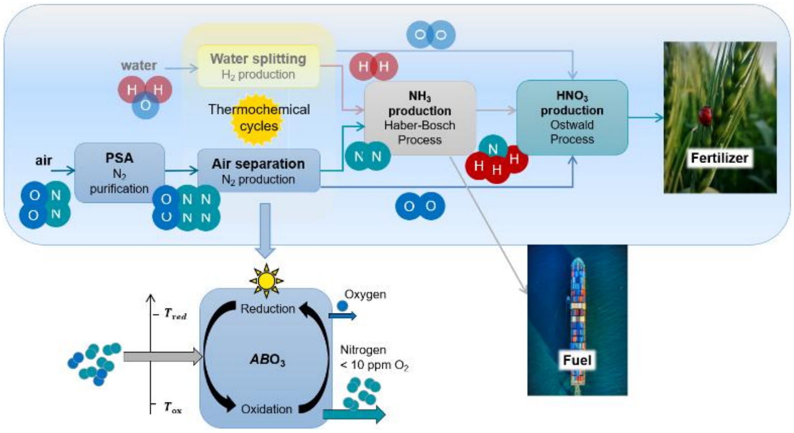

Figure 3: Overview of the interaction and integration of the here considered air separation process into adjacent processes [6]

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Experimental investigation of the Sulphur Dioxide Depolarized Electrolysis with commercial components

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Hydrogen is gaining momentum as a promising green energy carrier and different production routes are being intensely investigated [1]. The hybrid sulphur cycle (HyS), or Westinghouse process, was developed as an alternative for the production of sustainable hydrogen [2]. It consists of two main steps: a thermochemical (sulphuric acid decomposition to sulphur dioxide, water and oxygen in high temperatures, ~ 850°C) and an electrochemical (sulphur dioxide depolarized electrolysis - SDE). This electrolytical process, includes the oxidation of SO_2 to H_2SO_4 in the anode and the hydrogen evolution reaction in the cathode. The standard equilibrium potential of the overall electrochemical reaction is 0.158 V, significantly lower than the one of direct electrolysis (1.23 V) [3]. This difference makes this hybrid approach worth investigating, as the same amount of hydrogen can be produced with lower electricity consumption, consequently lowering the cost. The heat for the thermochemical step can be sustainably and efficiently provided, when it comes from concentrating solar technologies (CST) [4]. The current work is investigating the electrochemical part. So far, research on SDE investigated the use of different catalyst materials and operating conditions, with most common catalysts being gold, platinum and palladium-based [5].

This work aims to experimentally investigate the performance of SDE in the lab-scale (Fig. 1) under different operational conditions, using commercial components designed for PEM electrolysers, in order to produce insights and describe dependencies, useful for the process understanding towards a scale-up and the establishment of a baseline. This baseline will serve as a reference for comparison to the performance of SDE with custom modified components in future tests. The experiments utilize graphite monopolar plates and catalyst coated membranes (CCM), featuring a platinum loaded catalytic layer with a loading of 0.6 mg Pt/cm^2 at the anode side and 0.3 mg/cm^2 at the cathode, dispersed in carbon black, coated on Nafion™ 212. The pressure chosen for the long-term operation tests is close to ambient. The applied potential, operating temperature, concentrations and flowrates of the electrolytes are parameters of investigation. Results are extracted in single cell setups of active geometric surface areas from 5 to 100 cm^2. SO_2 consumption and H_2 production are evaluated in correlation with the electricity consumed, with specific energy consumption being used as a metric, while SO_2 cross-over from anolyte to catholyte and the parasitic actions in which it results, namely its reduction to H_2S and elemental sulphur is also assessed.

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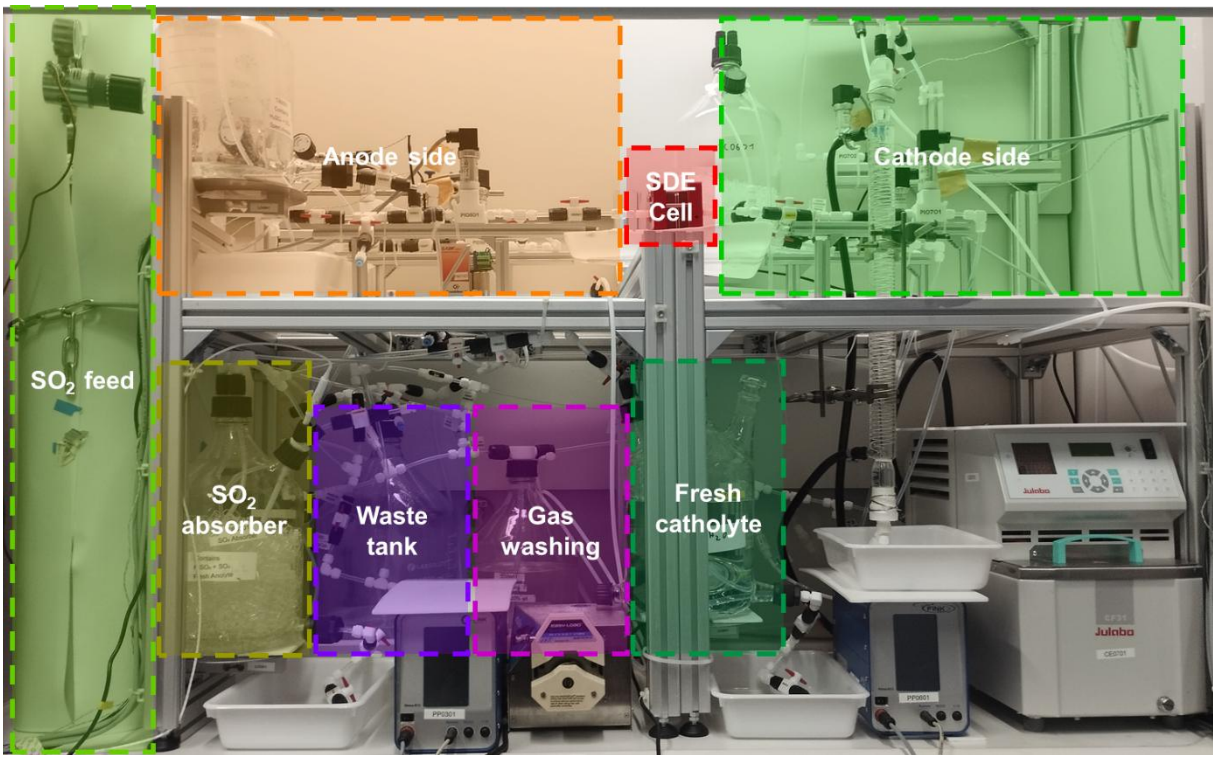

Fig.1: Sulphur dioxide depolarized electrolysis experimental setup in DLR.

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