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Overview of surface engineering technology to improve the energy efficiency in concentrated solar power (CSP) plants

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A B S T R A C T

Thermal energy storage (TES) technologies have been selected as key enabling technologies to mitigate climate change and to assess renewable energy deployment. Thereby, TES technologies are not considered a side system anymore but a technology with a high potential by itself. However, their energy efficiency and performance has a limitation in the material available for their final application. In this scenario, surface engineering is the clue to improve the thermal performance of TES systems under working boundary conditions by improving several aspects as corrosion protection, thermal barrier, optical absorbance, etc. This review explores the pivotal role of coatings in advancing Concentrating Solar Power (CSP) plants, crucial for harnessing clean and sustainable energy. Covering various coating techniques, including vapor deposition, laser deposition, sol-gel, thermal spray, and others, the study evaluates their applications, advantages, and limitations. Notably, thermal spray emerges as a cost-effective and adaptable solution for corrosion resistance, while sol-gel and vapor deposition showcase versatility with distinct advantages. The innovative focus on coatings enhancing TES system properties reveals promising outcomes, offering valuable insights for advancing CSP technology. In conclusion, coatings prove indispensable for maximizing the efficiency and viability of CSP plants, solidifying their significance in the transition towards cleaner and sustainable energy solutions.

1. Introduction

Nowadays, the population is increasingly aware of the environmental and social impacts of fossil energy sources [1].The demand for clean, safe and sustainable energy has become a global necessity. In this context, renewable energies are increasingly being used. In fact, in 2022, 3481 GW of power were generated from renewable energies worldwide [2]. Considering the renewable technologies to produce electricity, solar and wind power have become the most developed and well-known in recent years.

1.1. Concentrating solar power (CSP) plants

Within the field of solar energy, concentrating solar power (CSP) plants have emerged as a promising and efficient technology that is cost-effective at this moment. This relevance has meant that in 2022 a total of 6.3 GW was generated worldwide from concentrated solar power plants [2] since these plants have the capacity to highly reduce greenhouse gas emissions.

Concentrated solar power (CSP) plants are based on the principle of concentrating direct solar radiation at one point using disks or lenses [3]. However, in order to maximize its effectiveness and make it more efficient, continuous advances have been required. An example of this was the emergence of thermal storage systems (TES) to harness the energy even in times when there is no sun [4]. TES system is based on the storage of sensible, latent, or thermochemical heat for later usage [5]. Further than the incorporation of TES units, specialized coatings have been applied to improve the efficiency and durability of the plants. All the CSP plants implemented in the world in 2022 incorporate TES systems in order to make them more efficient and reduce the kWh cost [6].

1.2. Surface engineering

Coatings can be used in CSP technology to reduce corrosion in all system components and enhance plant performance by improving effectiveness properties [7,8]. Similarly, surface engineering can help to increase the economic viability of CSP systems.

This review's main goal is to state an overview of the state-of-the-art

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surface engineering studies and developments applied to CSP plants and outstand some of the main potential added value that this discipline can contribute to CSP improvement.

2. SCOPE and structure of the review

The scope of this review is to summarize the different applications of coatings in CSP plants organized according to application techniques. In addition, the advantages, and limitations of each type of coating technology to be applied in CSP will be detailed, in order to create a perspective of the maturity level of each technique for each application.

There are several techniques available to create a proper coating for such a function but are those listed below which are relevant to be implemented in CSP plant components.

- **Vapor Deposition Techniques.** This application can be realized from vapor by chemical reaction (CVD, Chemical Vapor Deposition) [9] or by condensation of a vaporized form of a solid material (PVD, Physical Vapor Deposition) onto various surfaces [10].
- **Laser Deposition Techniques.** Laser deposition is a group of different techniques that use a laser beam to melt a coating material onto a surface. The most commonly used method is laser-sintering [11] and laser cladding [12].
- **Sol-gel.** It is a method to produce solids from small molecules. These molecules are converted into a colloidal solution (sol) which is transformed into an integrated state (gel) [13].
- **Thermal Spray.** Is a technique that consists of projecting small particles melted at high temperatures or even cold (cold spray) that are successively attached to a surface [14]. There are different thermal spraying processes. The most prominent are flame spraying (FS), atmospheric plasma spraying (APS), electric arc spraying, and high-velocity oxygen-fuel (HVOF).
- **Other Deposition Techniques.** There are other more simple methods such as dip-coating, in which a thin uniform layer of coating is deposited on a substrate by immersing the substrate in a solution [15]; spray, which consists of pulverizing the coating with a gun or sprayer [16]; paint, which consists of depositing the coating with a brush [17]; and slurry, which consists of a mixture of particles divided over a liquid that is applied to the substrate [18].

The coating created by the previously described technique can protect the CSP components or can make them more efficient in performing as a key combination under these aspects.

- **Corrosion resistance.** In this type of plant, high-temperature fluids, such as molten salts (e.g., nitrates, carbonates, chlorides), are used to store heat and generate electricity [19]. At these elevated temperatures, the salts can corrode alloys and metals in heat exchangers, piping, and thermal storage systems. The application of coatings reduces the level of corrosion and degradation of materials, both caused by molten salts and elevated temperatures.
- **Selective coatings for solar receivers.** Dark coatings and/or with high absorbance can be used to increase the amount of heat captured in CSP plants [20]. This increases the energy conversion efficiency, making them a more attractive option with a lower LCOE [21].
- **Improve effective properties.** Coatings with high conductivity can be applied to modify the properties of TES systems. This is because, at the operating temperatures in CSP plants, most heat transfer occurs by radiation [22,23]. Therefore, by modifying properties such as conductivity and emissivity, TES systems with excellent performance can be achieved [23–25].

A graphical scheme regarding the review structure and scope is shown in Fig. 1.

3. Implementation in CSP plants

3.1. Corrosion resistance

One of the main problems in CSP plants is the high corrosion media they have due to the use of molten salts at high temperatures. This fact causes corrosion different parts and components of the system, such as piping, heat exchangers, etc. Must be designed to reduce or control this effect. The same applies to the implementation of thermal energy storage (TES) systems. The use of molten salts for energy storage causes severe damage to the molten salt storage tanks. Therefore, two types of corrosion can be distinguished in CSP plants: due to molten salts and due to high temperatures.

On one hand, molten salt corrosion is a common problem in CSP plants using high-temperature fluids. This issue increases as the operational working temperature rises and depends on the type of molten salts (e.g., nitrates, carbonates, chlorides, etc.) [19,26]. These salts are

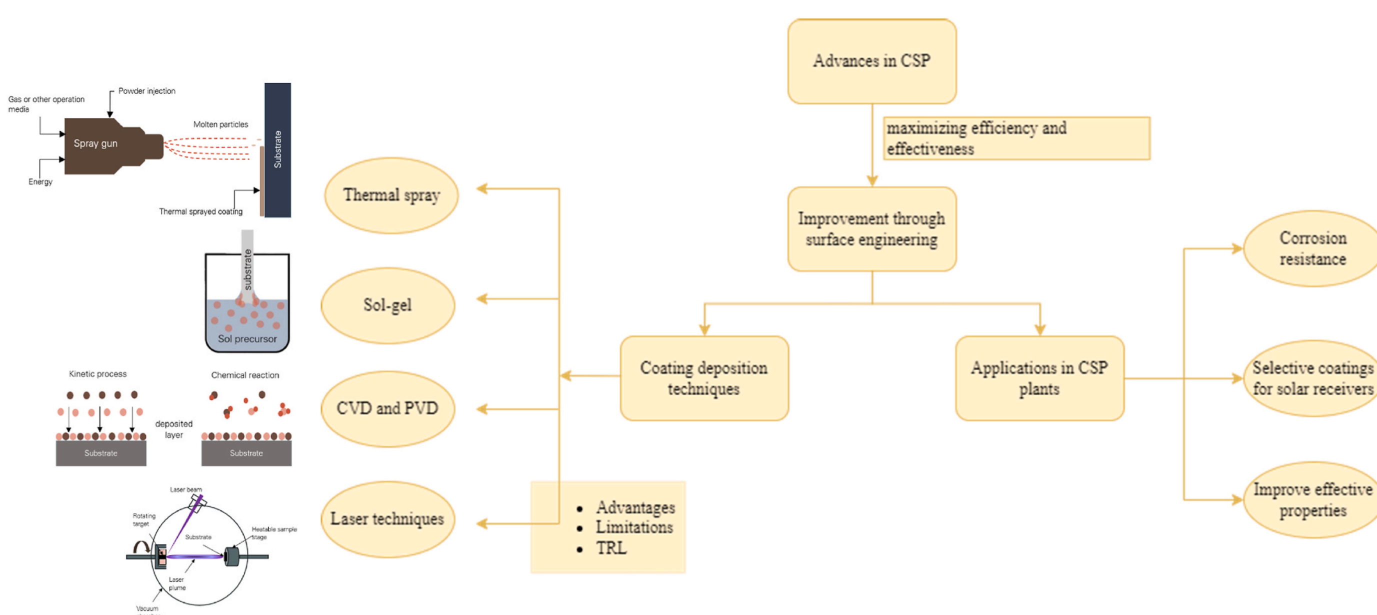

Fig. 1. Scheme and graphical abstract of the review structure & scope.

reduced forming oxides that increase the corrosive capacity and this effect is higher in the presence of impurities (Na, V, S, K, and Cl) [27,28]. For all these reasons, this type of corrosion is a complex issue that depends on the chemical composition of the salt and the substrate, the corrosion mechanism, and thermodynamics [29]. Numerous studies have been carried out to evaluate the corrosion mechanisms induced by these salts on different metallic elements such as alloys and steels. Although corrosion caused by salts cannot be prevented at present, it can be considerably reduced by choosing suitable, resistant materials [8]. They must be resistant materials, have adequate adhesion to facilitate their application, and have a uniform structure to avoid the formation of pores and cracks [8,30].

On the other hand, coatings also help to protect critical parts of CSP plants. They also serve to improve performance, increase service life, and thus reduce costs. This is why these coatings are used to protect absorbers and receivers, as they reduce corrosion and protect the surface from abrasion and dust [7]. Since the 1990s, numerous studies have been carried out to evaluate the corrosion mechanisms induced by different metallic elements such as alloys and steels. Although high-temperature degradation and hot corrosion in gas and steam turbines were initially studied [31,32], these allowed further research to be carried out on CSP plants.

In general, there are several coating application techniques to prevent salt corrosion and protect absorbers and receivers. The most prominent are slurry, thermal spray, sol-gel, and vapor deposition procedures (PVD and CVD) and the main relevant results are described in the following section taking into account advantages and disadvantages and details about the technical readiness level (TRL).

3.1.1. Slurry

It is not new that the formation of aluminium oxides on the surface of materials allows them to be protected from corrosion, especially from corrosion by molten nitrate salts [33].

However, in recent years, there has been an increased interest in aluminizing as a coating technique to prevent corrosion. This is because it is a simple, low-cost, and flexible procedure in terms of the surfaces on which it can be applied [34]. For this reason, in general, the slurry process for applying coatings is performed with aluminium. In this process, a suspension of Al particles in a liquid is applied on the surface of the desired material. It is then heat treated in an Ar atmosphere [34,35]. Such is the development of this technique that an improvement of the process has been patented [36] by carrying out the treatment in situ and making it more adaptable. With this improvement, it is possible to produce thin films obtained by a solution of a metal in a liquid containing alkali-stabilized silica.

Regarding the aluminizing of slurry to prevent salt corrosion in solar thermal plants, several studies have been carried out. Initially, they had some disadvantages compared to other deposition methods. However, in 2015 a study showed that these limitations could be overcome by controlling the powder composition and the process [34]. From this point on, the investigations carried out were increasingly successful. Most of them were performed in solar salt ($NaNO_3$–KNO_3) on stainless steels or ferritic-martensitic steels, as this is the most common in CSP plants. Soleimani Dorcheh et al. [35] stated research with P91 and SS304. In this case, the test showed the proper performance of these coatings in contact with solar salt at 600 °C for 2500 h. This is mainly caused by the formation of Na(Fe, Al)O_2 as a protective layer (passive corrosion). The investigations carried out by Audigié et al. about aluminized and nickel-aluminized coatings on P91 and P92 are also noteworthy [37,38]. In both studies, P91 and P92 were tested at temperatures up to 580 °C for 1000 h, and 2000 h, respectively. Despite the formation of cracks presented, these did not act as corrosion pathways. Furthermore, these tests showed that the coatings protect the material from mass variations and spallation.

Finally, Grégoire et al. performed a comparative study was carried out between different materials used in CSP plants (P91, SS 316L, and Inconel 600) [39]. The aim was to relate the alloying elements (Fe, Cr and Ni) to avoid corrosion using this type of coating in NaCl–KCl. The main conclusions of this study are that the aluminide coatings with high Ni content proved to be less resistant to the salt mixture tested than the Fe-rich ones.

In summary, slurries for corrosion resistance application in CSP plants are recommended as a proper solution for their usage in order to improve the effectiveness of plant performance over the years. However, these types of coating are still an option with a lot of potential to be explored since it is not cost-efficient yet. Table 1 summarizes the advantages and limitations as well as the TRL of the slurries for corrosive resistance in the TES field.

3.1.2. Thermal spray

The first studies on the use of thermal spray to deposit coatings were intended for fuel cells, incinerators, and boilers [44–47]. This made it possible to evaluate the behaviour of different coatings in environments with harsh conditions and scalable to those of concentrating solar power plants at a later date. For fuel cells, the coatings consisted of compounds of different metals (e.g., FeCrAl, AlCoFeCr, NiCrFeNbMoTiAl) deposited on carbon steels and stainless steels. They were fabricated by several variants of thermal spray such as HVOF or APS. Hence, their behaviour in various salts such as V_2O_5–K_2SO_4, V_2O_5–Na_2SO_4, and molten carbonates was evaluated.

In terms of boilers and heat exchangers, studies such as those performed by Hidalgo et al. [48] on the use of nickel-chromium coatings deposited by flame and plasma spray and those by Singh et al. [49] on different metallic films by HVOF to protect T22 steel stand out. Furthermore, a study was carried out on the use of different metal alloy films to protect pipelines and heat exchangers from erosive conditions and high temperatures in 2008 [50] with satisfactory implementation. Finally, for incinerators, the investigations of Guilemany et al. on Ni and Fe alloys deposited by HVOF are noteworthy [51,52] also showed proper implementation in this field. From them, it was shown that Ni alloys are effective in chlorine environments. However, those based on iron gave somewhat worse results.

On the other hand, comparisons have also been made between different thermal spray techniques. In particular, Pontarollo et al. compared the use of cold spraying with HVOF coating deposition, which was better studied at the time [53]. Thanks to this research, the results showed that Inconel 625 CGS coatings were much more resistant to corrosion, which was a breakthrough in terms of the use of this technique for different industrial applications. Continued experimentation with this type of spray allowed analysis of the microstructure and fatigue behavior [54]. After some time, tests on molten salts were started.

In this context, the preparation and cold spray application of a FeAl film was achieved [55]. The uniform and anti-cracking structure on 316 L stainless steel was tested in molten carbonates for CSP plants. Similarly, in 2014, studies on molten salts were also carried out, in this case on V_2O_5–Na_2SO_4. Specifically, T22 carbon steel was coated with a Ni–Cr alloy by FS [56]. However, the results were not as expected since the corrosion was not avoided. In the same year, an arc ion plating (AIP) was tested to fabricate a FeAl layer on 310S stainless steel [57]. From this research, it was concluded that the structure of the coating is fundamental avoiding the formation of pores and cracks, a fundamental cause of the appearance of corrosion.

Other techniques for applying corrosion protection coatings have also been tried in solar thermal power plants. An example of this was the deposition of different alloys and MCrAlX by HVOF and APS [58]. These were evaluated in molten carbonates at 600 °C, which was a major step forward in this type of technology. Thanks to the results obtained, the degradation of the materials used in TES systems can be controlled and minimized. Similarly, different FeAl-based HVOF intermetallic coatings were tested in sodium sulfate (850 °C) [59]. However, the applied layers were cracked and oxidized, which allowed rust to form at the interface. Finally, more recently, T22 steel was coated with Inconel 625 by

Table 1
Summary the advantages and limitations as well as the TRL of the slurries for corrosive resistance in TES field.

		References
ADVANTAGES	- **Cost.** Low-cost technique, and it is very low-cost if only one layer has to be deposited. - **Dimensions and thickness.** Thin layers of 50–100 μm are applied and can easily coat surfaces such as pipes. - **Application temperature and durability**. The performance at 600 °C during 700 h, and 550/580 °C during 2000 h are the best results obtained. - **Tunneability to the application**. Good anti-corrosion performance has been demonstrated in KNO_3–$NaNO_3$ and NaCl–KCl. - **Compatibility with other techniques**. Possibility of co-deposition with electroplating, PVD, CVD, or electrodeposition. - **Adaptation to surfaces**. Tested on different materials: P92, P91, 304SS, SS 316L, Inconel 600, T22 and high purity nickel. - **Environment**. There are cases in which solutions based on water and organic polymers are used, which makes it more ecofriendly.	[37–39] [39,40] [35,37–41] [35,37–39] [34,38] [34,35, 37–41] [34,37–39]
LIMITATIONS	- **Dimensions and thickness**. Some research has demonstrated the need to apply several layers to ensure total and uniform coverage, which would increase the thickness used. - **Pretreatment** at 300–350 °C for minutes or hours is required. - **Post curing** process with Ar is required at 700 °C-10 h or 1050/1100 °C-35 min. - **Defects**. Possibility of interdiffusion that causes changes in the structure and irregularities in the adhesion. In addition, if the 'bisque' formed is not properly removed, flakes may appear, affecting the integrity of the system. Finally, impurities in the Ar stream or metals dissolved in salts can act as oxidants modifying corrosion kinetics. - **Environment.** If phosphates, chromates, or halides are used, it is toxic to human health and harmful to the environment. - **Research**. Need for further studies for the optimization of the technique, tests with cyclic thermal behavior and with a greater variety of salts.	[39,40] [34,35, 37–41] [34,35, 37–41] [34,35,37, 38,41] [34] [34,35, 37–41]
TRL	There are currently a few patents for this type of technology. In 1975, a slurry coating process was patented to coat a metal surface with another metal in particulate form [42]. This process is particularly suitable for very thin coatings (less than 1 mm) and can be used to prevent corrosion. Also, a chromium VI-free anticorrosion coating was developed in 2001 that includes a binder and a corrosion inhibitor [43]. This mixture can contain a suspension of silica particles, clay, and zinc-aluminium phosphate to form a slurry that is applied to the surface to be protected. Currently, there are pilot-scale comparative tests of these coatings on different steels (P92 and T22) [40]. The samples were exposed to a temperature range of 600–620 °C. The results showed that the aluminide coated materials had very high strength. However, it is important to note that these investigations are not specific to prevent corrosion in this type of plants. Therefore, further research and development will be necessary to adapt these solutions to the specific requirements of CSP plants. On balance, these patents suggest that the potential of slurry aluminide coating is promising in CSP plants. These coatings could be the future of this type of plant by improving the efficiency of TES systems. In addition, these coatings could be applied to other plant components and provide complete protection.	

compact plasma spray [60]. The material was tested in solar salt, commonly used in CSP systems. With the coating, the formation of very fine flakes of corrosion arose only on the external surface.

In summary, thermal spraying is a technique that has been widely developed for a long time and with excellent results against corrosion in general and against corrosion in the solar field in particular. It is also economical and effective on a large scale, thanks to its versatility in terms of materials. Table 2 summarizes the advantages, limitations, and TRL of thermal spray coatings for corrosive resistance in TES field.

3.1.3. Sol-gel

Sol-gel coatings, thanks to their stability and resistance, are positioned as a good candidate for reducing corrosion in CSP plants. This technique has evolved over the years and different materials and nanomaterials have been tested to improve it [71]. Of these, the most noteworthy are Al_2O_3, Fe_2O_3, SiO_2, ZrO_2, TiO_2 and CeO_2. For this reason, reviews of the use of sol-gel coatings on different metals (steel, copper, magnesium, magnesium, aluminium, and alloys) began to be carried out, as they have a great anti-corrosive effect [72–74]. In addition, they proved to be resistant to water and abrasion.

On the other hand, an important aspect of this type of film is the subsequent heat treatment to achieve sintering. Therefore, Díaz-Parralejo et al. studied the effect of this temperature on the structure and properties of the coating [75]. The material chosen was yttria-stabilized zirconium oxide due to its high wear resistance. The results showed that the optimum choice of this temperature allows the film to be adapted to the required needs.

Its usage in different solar applications is particularly noteworthy for producing solar selective coatings. However, this application also requires high corrosion resistance. An example of this is the study on AISI SS 321 of a multilayer coating of SiO_2, TiO_2, and Ag–TiO_2 [76]. Regarding zirconia-based coatings, the most outstanding works are those of Encinas-Sánchez et al. and Pérez et al. tested on solar salt [77–80]. These investigations were carried out on various materials used in CSP plants (AISI 304, P91, and ferritic-martensitic 9Cr–1Mo Steel) at 500 °C and showed good results after 1000 h. As a result, it was possible to compare the coating performance of the three materials. In environmental terms, considerable advantages were obtained by using steel with lower Cr–Ni content. In addition, the use of 9Cr–1Mo steel showed great potential for use in CSP plant tanks and piping. Following this line of research, an attempt was made to evaluate the relationship between these films and their deposition parameters [81]. This was a breakthrough since it allowed the production of coatings with more specific parameters required in this type of installation.

In summary, the usage of sol-gel for corrosion resistance application in CSP plants is recommended due to its flexibility in terms of substrates and environments. However, the requirement to apply several layers may limit its application on certain materials. Table 3 summarizes the advantages, limitations, and TRL of sol-gel coatings for corrosive resistance in TES field.

3.1.4. Vapor deposition techniques

Vapor deposition for applying coatings can be physical (PVD) or chemical (CVD). In the 1990s, the use of different variants of CVD coatings was studied [85]. Specifically, CVD, plasma-assisted CVD (PACVD), and metal-organic PACVD (MO-PACVD) film applications were analysed. This research was carried out for both monolayer and multilayer coatings and on numerous substrates (e.g., steel, hard metals, alloys). This made it possible to evaluate the anti-corrosion and wear behaviour. Similar multilayer titanium coatings were analysed years later by Zhang et al. which also confirmed the high hardness, substrate adhesion, and toughness of these films [86]. Likewise, Fe–Al coatings were analysed due to their characteristics such as service life and their effectiveness in protecting materials [87]. Cyclic tests were carried out on Fe–9Cr–1Mo and 304L steel at 800 °C. Thanks to this, the good performance of this type of film against corrosion and resistance to environments with water vapor was proved.

Regarding PVD process, various investigations have led to the development of numerous new coatings that meet the needs of both medium and high temperatures [88]. Although the first studies were not carried out specifically for this type of plant. However, the required

Table 2
Summary of the advantages, limitations, and TRL of thermal spray coatings for corrosive resistance in TES field.

		References
ADVANTAGES	- **Cost.** Some studies show a decrease in production and maintenance costs due to the use of this type of coatings. - **Dimensions and thickness.** It is a quite variable technique that can go from the application of one layer, multilayer or graded. Therefore, the thickness varies from microns to mm/cm. It currently allows a high production volume and is viable for pipe coating. - **Application temperature and durability.** Temperatures up to 300–850 °C. Resistance tested with good results up to 1000 h. - **Tunneability to the application.** Tested on a wide variety of salts (molten carbonates, Na_2SO_4–V_2O_5, K_2SO_4–V_2O_5, NaCl–KCl–Na_2SO_4, $NaNO_3$–KNO_3). In addition, some studies have shown corrosion reduction from 2500 μm/year to 34 μm/year. - **Pretreatment.** Generally, for thermal spraying, it is necessary to prepare the surface beforehand to ensure the correct adhesion. - **Adaptation to surfaces.** Due to the wide variety of thermal spray techniques, different metals (e.g., SS 304-310-316), alloys and non-metallic materials (e.g., composite, biological, or ceramic materials) can be coated. - **Environment.** It is a sustainable technique that could be even more eco-friendly if clean fuels are consumed, less energy-intensive processes are used, and the materials employed are recycled.	[53–57,61] [45,47,53–65] [45,47,53–65] [47,55–61,63,65] [62] [45,47,53–65] [66]
LIMITATIONS	- **Cost.** In many cases, the coating is annealed at high temperatures to improve resistance. This practice increases the cost considerably. Also, flame and plasma techniques are more expensive. - **Compatibility with other techniques.** There are no clear examples of research where thermal spray is combined with other deposition techniques. - **Post curing.** If annealing is necessary, it can also reach temperatures of over 800 °C. - **Defects.** Some coatings have shown porosities or cracks, which may allow corrosion to penetrate. - **Research.** Need for further studies for the optimization of the technique and tests with cyclic thermal behavior.	[46] [57] [53,55,57,62] [55,58,63,67]
TRL	Results show the high potential of this technique and suggest that thermal spray deposition allows obtaining highly resistant coatings [61]. These, in addition to allowing the protection of pipelines and other CSP plant equipment, are viable for the protection of the tanks of the TES systems. Furthermore, this technique is optimal for various types of salts. Still, further studies are needed that are more adapted to the operating conditions (saturated salts, presence of impurities, different thermal gradients). There are patents related to thermal spray coatings to prevent corrosion, but they are not directly related to their use in CSP plants. However, this shows that steps have already been taken in this type of deposition technique. An example of this is a compact thermal spray powder suitable for forming a compact ceramic coating and noted for its durability [68]. Furthermore, an alloy coating (5–7 wt% nickel, 8–10 wt% molybdenum, 1.5–3 wt% chromium, 7–9 wt% phosphorus, 0.5–1.5 wt% boron) having excellent corrosion resistance and a coating method for the application thereof were also invented [69]. Thanks to this composition and the fact that it can be deposited by different thermal spray techniques, this coating is also resistant to seawater and reduces maintenance costs. Finally, there is a coating patent that is suitable for both metallic and non-metallic surfaces [70]. This consists of various alloy layers of MCrAlM' in which M is nickel, cobalt, iron or mixtures thereof. M′ is yttrium, zirconium, hafnium, ytterbium or mixtures thereof. These layers are useful for prolonging service life under severe conditions.	

Table 3
Summary of the advantages, limitations, and TRL of sol-gel coatings for corrosive resistance in TES field.

		References
ADVANTAGES	- **Cost.** Low initial cost technique, even if several layers are applied. - **Dimensions and thickness.** Coating thicknesses of a few microns and with ease for industrial scalability and process automation. Good adaptability to tanks and pipelines. - **Application temperature and durability.** Applications in solar salt at 500 °C for 1000–2000 h. However, the higher the number of layers, the lower the durability of the coating. - **Tunneability to the application.** Good corrosion resistance in $NaNO_3$–KNO_3 with low corrosion estimation per year. - **Compatibility with other techniques.** Compatible with various synthesis methods and with numerous application techniques such as dip-coating, electrodeposition, spraying, and brushing. In addition, if different synthesis methods are combined to create hybrid organic-inorganic coatings, it allows the combination of the properties of both. - **Adaptation to surfaces**. Tested on 304SS, 430 SS, SS 316L, SS 321SS, P91, carbon steel, aluminium, copper, and magnesium. - **Pretreatment.** Synthesis and processing are generally performed at low or room temperature. - **Environment.** This is an eco-friendly technique that uses impurity-free and residue-free compounds with low synthesizing temperatures.	[71,75,77,78,81] [71,73,79,80] [76–80] [76–80] [71–73] [71–81] [73] [71,72,76,78]
LIMITATIONS	- **Dimensions and thickness.** Some compounds require a higher thickness which makes adhesion to the substrate more difficult. - **Post-curing.** Heat treatment can range from 200 °C to 850 °C, which increases power consumption. From 1000 °C for sintering, coating degradation may occur. - **Defects.** The existence of diffusion through the coating is caused by the destabilization of the thin film. In addition, if zirconia-based coatings are used, the monocyclic phase of the zirconia may worsen the performance over long operating times. - **Research.** Need for further studies for the optimization of the technique, tests with cyclic thermal behavior and with a greater variety of salts.	[71,72,74] [73] [77,79,80] [71,72,74,77]
TRL	Overall, the various patents and research papers developed so far suggest that sol-gel coatings can be an effective option. They prevent corrosion on metals and in solar concentrator plants thanks to the barrier effect. Both in Europe and Asia there are patents for this method to prevent corrosion of metal surfaces. The European method consists of an acid-catalyzed sol-gel coating that is combined with a polyaniline solution prior to coating a metal substrate [82]. The coating is then cured and, if desired, can be activated under alkaline conditions. However, this patent was abandoned. In Japan, on the other hand, a broader method was established, which refers to any field in which a metal or metal alloy needs to be protected against general corrosion [83]. This provides better control over corrosion resistant film properties, organic matter removal and porosity reduction. More recently, the work of Encinas-Sánchez on ZrO_2-3%mol Y_2O_3 sol-gel coatings for concentrating solar power plants with thermal storage is noteworthy [84]. The research work demonstrates that sol-gel coatings have great potential for use in current concentrating solar power plants.	

properties (corrosion and high-temperature resistance) are scalable for use in CSP plants. Similarly, the use of nitride coatings by physical vapor deposition on $X_{155}CrMoV_{12}$ steel began to be tested [89]. Of all the coatings used, the titanium-based was confirmed as a valuable alternative to chromium, with anti-corrosion properties. Also, the use of Al–Ti and Al–Mn coatings has been studied [90]. Already in the early 2000s, the properties of these systems were promoted by the fact that, by using very thin coatings, a higher corrosion resistance was achieved than with conventional films. More recently, tests with YSZ coatings and a Ni-YSZ nanocomposite coating on Inconel 690 have begun [91]. These coatings had a poorly porous and resistant structure due to the formation of NiO during annealing.

The application of PVD coatings for different purposes in CSP plants has also been studied in recent years. Concerning molten salt behavior, in 2015, a multilayer metallic coating was used as a model [92]. It was composed of NiV–Al and was deposited on P91 steel simulating the operating conditions in this type of plant. This mimicked continuous operation, but also common variations between day and night. In this way it was possible to demonstrate durability against corrosion under thermal stress conditions.

In summary, vapor deposition techniques have proven to be suitable due to their ability to generate different coating thicknesses as a measure to reduce corrosion. Nevertheless, their use in this type of plant is more developed in the selective solar absorber area. Table 4 summarizes the advantages, limitations, and TRL of PVD and CVD coatings for corrosive resistance in TES field.

3.1.5. Other deposition techniques

Further than these types of corrosion-reducing coating deposition techniques, there are less cost-effective ones or with lower TRL that have been developed in recent years. One method was proposed to protect carbon steel against high-temperature molten salt corrosion in CSP applications [96]. It consisted of the formation of a calcium carbonate layer subjected to different temperatures (isothermal, cycling conditions up to 500 °C) and atmospheres (humid air, dry air, inert atmosphere). In this work, various methods of preparing the protective carbonate layer were employed to explore the possible differences between them. Graphite powder was added to the salts of the TES system, sprayed on carbon steel (sprayed with a gun and using an ethanol-graphite solution), and in situ formation on the material. In general, this proposal was aimed at finding a solution to reduce technology capex costs. Continuing with the use of graphite as an anticorrosion method, in another study samples of Carbon steel A516 Gr70 were coated with Graphite 33 from Kontakt Chemie spray [97]. Then, corrosion is greatly reduced at almost 400 °C. This decrease can be accentuated if the amount of deposited graphite is optimized.

On the other hand, diffusion coatings applied to steels by pack cementation or slurry deposition were tested. This type of process is not a technique in itself. Rather, it involves the diffusion of chemical elements into the surface layer of the base material, which alters its properties without adding a separate layer [98]. This test was carried out comparing steels (T91 and VM12) with and without coating to protect them from molten solar salt at constant temperature [99]. Of the two coatings tested (Chromium pack cementation and Aluminium-silicon slurry coating), Al–Si was the most interesting.

Finally, there are investigations on multilayer Ni coatings with fractal texture on various alloys (SS310, SS316, SS347, and In800H) [100]. In this case, the electrodeposition method (monolayer and bilayer) on molten carbonate salt (32 % Li_2CO_3+33 % Na_2CO_3+35 % K_2CO_3) at 750 °C was used. Both depositions were adequate, however, the stability time is doubled with the double-layer coatings. Likewise, work was also carried out on the behavior of Inconel 625 and NiCrMoAl deposited by laser cladding in molten NaCl–KCl, and NaCl–KCl–K_2SO_4. This allowed us to characterize the corrosion mechanism and its stages. The second coating, performed better against chlorides thanks to Al_2O_3.

In addition to these investigations, different anti-corrosion coatings

Table 4
Summary of the advantages, limitations, and TRL of PVD and CVD coatings for corrosive resistance in TES field.

		References
ADVANTAGES	- **Cost.** The use Fe or Al coatings on metals reduces the cost of the technology. CVD more cost-effective than PVD. - **Dimensions and thickness.** Layers from 2 to 4 μm (monolayer) to 30–50 μm (multilayer systems). Thicker layer coatings, in general, have greater resistance. Moreover, these coatings are applicable to various parts of CSP plants and PACVD technique is easily industrially scalable. - **Application temperature and durability.** The behaviour in a temperature range of 500–565 °C in salts and up to 800 °C for other applications. In general, they show good durability against thermal fatigue. - **Tunneability to the application.** Tests to simulate continuous operations and also day-night cyclic changes for solar salt. - **Adaptation to surfaces**. Studies have been carried out on numerous materials such as Inconel 690, P91, Fe–9Cr–1Mo, SS 304L, $X_{155}CrMoV_{12}$. Also, on metals such as Cu, Ni, Au, Cr, Mo, Ti, Ag and on glass. - **Pretreatment.** In case of MO-PACVD technique the deposition temperature drops to 140 °C. - **Post curing.** thermal post-treatment is not required If the coating temperature is lower than the tempering or aging temperature. **Environment.** The PVD is more ecofriendly as it does not use volatile chemicals and does not produce damaging by-products.	[88,92] [85–87, 90] [87,88,92] [92] [85–92] [85] [85] [10]
LIMITATIONS	- **Compatibility with other techniques.** There is no evidence of joint application with other deposition techniques. However, hybrid application of CVD and PVD is feasible. - **Pretreatment.** Deposition temperatures for CVD techniques range from 900 to 1100 °C, 450–550 °C for PACVD. - **Post curing.** If annealing is present, corrosion resistance is increased in exchange for heat treatment at 600 °C. - **Defects.** If tests are performed on industrial grade solar salt, the degree of corrosion increases dramatically. Moreover, microscopic defects have been found in some work that should be monitored. - **Environment.** The CVD technique can cause environmental damage in case of using harmful volatile products or generating by-products that are not properly treated. - **Research**. Need for further studies for the optimization of the technique, tests with cyclic thermal behaviour and with a greater variety of salts.	[93] [85] [85] [89,92] [9] [88,92]
TRL	In general, the development of PVD and CVD coatings for corrosion prevention in CSP plants has reached a significant level of maturity. However, these are mostly focused on improving the optical properties of the receivers with the addition of corrosion protection. Currently, there are no patents dedicated exclusively to this application. However, in recent years, research has been carried out on the prevention of corrosion in metals and alloys. A PVD deposited aluminium alloy base material plated film was developed in China [94]. The plated film includes the insulation layer and a corrosion resistant coating. In addition, it is more environmentally friendly. More recently, a multilayer system with corrosion and wear protection has been invented in Germany [95]. The anti-corrosion layer consists of a metal nitride or a metal carbonitride containing at least titanium and magnesium as metal. On the other hand, the anti-wear layer is formed by at least one non-metallic diamond-like carbon layer. This system is formed by a PVD process and/or a PACVD process.	

exist in the industry, although they are not especially dedicated to CSP plants. In 2004, coating compositions were developed for metal parts based on metal particles in aqueous dispersion deposited by spraying, soak-draining, or soak-centrifugation [101]. Although they are effective in the 180–350 °C range, they could be applied to other parts of the system subjected to less severe conditions. A few years later, anti-corrosion paints and coatings with nanoparticles were produced [102]. They are manufactured from various resins dissolved in organic or inorganic solvents. More recently, in 2019, on an anti-corrosive phosphate coating modified by Si [103]. The preparation method can be diverse (dip coating, curtain coating, brush coating, or spray coating).

3.2. Selective coatings for solar receivers

The amount of sunlight captured by materials and converted into heat is crucial to the efficiency of CSP plants. Coatings can be applied to various components, such as mirrors, receivers, and absorbers, to improve their thermal properties and increase the amount of heat captured. Several techniques generally used for the fabrication of thin films are used for the manufacture of solar absorber materials. These include CVD, PVD, sol-gel, etc.

Due to the importance of absorbers in solar thermal plants, they have been studied in order to optimize the overall efficiency of solar thermal power plants with selective absorbers [104]. Thanks to this type of study, it has been shown that 65 % efficiency is achievable in these plants. Hence, the behaviour of the optical properties of the coating of a CSP receiving plant on its thermal efficiency has been modeled [105].

Current solar receivers are usually coated with a high sunlight absorption layer applied on the bare surface in order to improve their ability to absorb and convert light into heat. However, these coatings must exhibit several characteristics [7].

- Chemically and structurally stable for the operational temperatures (500–1000 °C).
- Long life cycle (20 years minimum).
- Comply with regulations and restrictions (for health, safety or environmental reasons)
- Cost-effective, comfortable to apply, and retains adhesion for a long period.

Numerous materials have also been tested for use as selective absorbers. The most prominent of these are nanocomposites [106], transition oxides, nitrides, and nitride oxides [4,107]. The same is true for multilayer coatings, which allow for improved properties depending on the compound in each layer [108].

Selective solar coatings have always been classified into different types [107]: intrinsic, semiconductor-metallic, multilayer, cermets, or metal-dielectric composites and textured surfaces. However, there is no clear distinction between categories. Therefore, in this review, they are classified according to the application technique.

3.2.1. Sol-gel

As discussed above, sol-gel coatings are very useful in solar thermal power plants. In addition to their good corrosion resistance, they can also be used as selective black coatings to improve the absorbance in CSP plants. A good example of this is the low-cost chromium-free selective multilayer surfaces [109]. It has excellent stability at more than 300 °C that exceeds that obtained with common coatings in the market. In addition, its Cu–Co–Mn–Si–O composition allows an absorbance of 0.95 and a thermal emissivity of 0.12 at 100 °C. Therefore, receiver tubes coated with this coating are attractive for applications such as solar thermal power plants, cogeneration, and even generate cooling with waste heat through trigeneration. Following these investigations, it was found that using $CuMnCoO_x$ thin coating in different preparation conditions can improve absorption (92–93 %) [110]. In fact, this ability is enhanced by using an acid-based sol-gel dip coating. Hence, the film has high thermal stability and surface adhesion.

On the other hand, there is clear evidence that using the sol-gel technique in combination with other methods makes it possible to produce effective and more environmentally friendly selective coatings. Evidence of this is the creation of selective adsorbent coatings based on titanium oxide combined with carbon in particle or nanotube form [111]. Sol-gel and dipping techniques were combined in a layer-by-layer system of TiO_2/CB and TiO_2/CNT. The coating developed in this work achieved excellent results with optimum selective properties. In addition, the system performed well against corrosion.

In addition to this, research has begun in recent years on a specific type of CSP plant that uses a particulate system in a gravity-driven tower as a receiver. Concerning this topic, in 2023, the use of desert sand coated with metal oxides ($CuMn_2O_4$, $CuCr_2O_4$, and $MnFe_2O_4$) was investigated [112]. This study highlighted the potential of this system in the future of CSP plants.

In summary, the use of sol-gel coatings as selective solar absorbers is a versatile and effective option. In addition to improving the optical properties of the absorbers, it also protects against corrosion. However, it is an energy-intensive and less environmentally friendly technique. Table 5 summarizes the advantages, limitations, and TRL of sol-gel coatings applied in solar receivers in TES field.

3.2.2. Deposition vapor techniques

On the one side, CVD is a reproducible method on a large scale and is suitable for several materials and surfaces. It is a process widely used in the industry to manufacture all types of coatings. In particular, the use of this technique for the production of selective solar absorbers is among the oldest. As early as the 1970s, Seraphin et al. fabricated a multilayer coating based on semiconductors with a total absorbance of 0.85 [123]. In this work, the feasibility of the system for temperatures around 500 °C was reviewed. This coating system had a composition of $SS/Cr_2O_3/Ag/Cr_2O_3/Si/Si_3N_4/SiO_2$ where Si was the absorber layer, and the antireflective layers were Si_3N_4 and SiO_2.

In addition, the CVD process has been improved and optimized. One example is atomic layer deposition. This is a variant of CVD where the desired material is formed from gaseous precursors in chemical reactions [124] and can be applied in selective solar absorbers that operate up to 700 °C with cylindrical microcavities [125]. These voids are uniformly coated with Pt nanoparticles and Al_2O_3. Then, higher absorbance values (0.92) were achieved. Al_2O_3 deposited by ALD was used in another study on improving the thermal stability of a multilayer solar selective absorber [126]. The designed structure, $Cu/Al_2O_3/Cr/SiO_2/Cr/SiO_2$, allowed to eliminate diffusion. Although stability was only reached for a little more than 70 h, 0.95 absorptance was achieved at 500 °C.

On the other side, the PVD technique has also been extensively used to produce selective absorbers. Thereby, the most common are sputtering and thermal evaporation. Solar absorber coatings were developed by sputtering, which were capable of coating large surfaces [127]. For this purpose, copper, glass, and polymers were coated with a mixture of chromium, chromium oxide, and chromium nitride. The durability of the absorbers was found to be satisfactory according to IEA requirements for flat plate collectors. PVD films have evolved from chromium oxides to multilayer systems that include elements such as Zr, Al, and Ti [128]. Furthermore, the toxicity of chromium (VI) led to experimentation with coatings with less or no chromium. An example of this is the optimization of a zinc oxide coating that acts as a protective layer against humidity and provides absorbance values above 0.95 [129]. Similarly, shortly thereafter, a new coating based on $Mo–Si_3N_4$ and stable at 600 °C was created [130]. The good absorbance and characteristics made it a competent and viable option for CSP plants.

Research on ternary, quaternary, and multilayer coatings stands out. Zou et al. and Gong et al. use these chromium-aluminium-based composite coatings on stainless steel [131,132]. Both studies demonstrated the good stability of these films deposited by cathodic arc plating at high

Table 5
Summary of the advantages, limitations, and TRL of sol-gel coatings applied in solar receivers in TES field.

		References
ADVANTAGES	- **Cost.** If it is optimized and efficiency is increased, it can be a low-cost technique. - **Dimensions and thickness.** This can range from 30 to 600 nm. There are investigations in which it has been possible to coat long pipes (2 m) with good results, however, it is not common. - **Tunneability to the application.** Solar selective absorbers with good adhesion, stability, and good selective properties (absorbance of 0.85–0.95 and emissivity of 0.12–0.15) are obtained. This makes it possible to improve the collectors of CSP plants, as well as to use them in cogeneration and trigeneration. - **Compatibility with other techniques**. It is mostly combined with dip-coating; however, electrodeposition can also be used. - **Adaptation to surfaces**. It has good results for stainless steel. - **Post curing**. There is evidence of the use of fast and efficient curing, using induction heating, which improves the efficiency. - **Environment**. It is a technique that generates less waste.	[109,113] [109,112, 113] [109–114] [109–111, 113,114] [110,111, 113] [109] [114]
LIMITATIONS	- **Dimensions and thickness.** As several layers are normally deposited to improve the optical properties, the thickness of the coating increases. As the most common way to apply it is by dip coating, this can make scalability to the industrial level difficult. - **Application temperature and durability.** The thermal stability of this type of coating has been tested at around 300 °C. - **Pretreatment.** Strong agitation for a couple of days before deposition may also be necessary for the formation of the solvent. - **Post curing.** On many occasions, thermal curing at 400–500 °C for minutes or hours is needed for solvent evaporation. - **Defects.** Long formation times with the possibility of the appearance of pores. Higher energy consumption. - **Environment.** Precursor reagents must be controlled. This method also has a worse LCA. - **Research.** Need for new studies for the optimization of the technique, tests at higher temperatures and more variety of materials.	[111,113] [109, 111–113] [109,111, 113] [114] [110,114] [114] [110,112, 114]
TRL	The sol-gel technology to produce solar selective absorbers is at a high level of maturity. It has been used in several practical applications and there are several patents for producing coatings based on this method. In 2003, such a coating was developed based on a metallic layer with high solar absorption efficiency [115]. In addition, this layer was protected by a sol-gel deposited layer to reduce mechanical, thermal, and environmental damage. This invention had a high absorbance. Over the years, more research has been carried out in this field. One example is the development of an organic-inorganic sol-gel method [116] with an absorbance of 0.90 and an emissivity close to 0. It also has a high thermal stability at 600 °C. Another case is the research on a multilayer system (metal layer, absorber layer, and sol-gel anti-reflective layer) with excellent optical properties, high-temperature resistance, and low production cost [117]. Another multi-layer system (with high absorption and one with low emission) is stable in harsh environments [118]. Also noteworthy is the patent created by Tekniker [119] where they use the sol-gel method to create a glass and TiO2 coating for solar reflectors with anti-soiling properties. As regard co-deposition coatings, the combination with sputtering [120] and dip-coating [121] stands out. In general, these are simple methods, which produce coatings with good thermal and oxidation resistance, stability, and long service life. On the other hand, more recently, a method was developed to produce an anti-reflective coating (MoSi2–SiO2) for high temperatures [122]. It is a convenient and easy method with good results and high potential in the field of CSP plants.	

temperatures, which are improved by using multilayer systems. Several investigations were also carried out with aluminium oxides deposited by an electron beam [133]. The good results ensured even at 700 °C considerable absorbance levels. The good performance of these compounds allowed the introduction of other elements such as W as a black reflecting layer [134]. Similarly, continuing with the use of W in the films, another work was carried out on multilayer sputter-deposited coatings on SS and silicon substrates [135]. In addition, this system prevents the inward diffusion of oxygen.

Finally, the addition of zirconium by Usmani and Dixit [136]. They fabricated an absorber-reflector tandem of ZrO_x/ZrC–ZrN/Zr deposited by magnetron sputtering on SS and copper. However, the invention was much better in inert atmospheres or in vacuum. The work of Meng et al. is also noteworthy in this field. In 2017, a coating based on zirconium and aluminium ($Cu/Zr_{0.2}Al_{0.8}N/ZrN/AlN/ZrN/AlN/Al_{34}O_{62}N_4$) deposited by dual ion beam assisted deposition (DIBAD) process was designed [137]. Two years later, the thermal stability of the system was improved by adding some Si [138].

In summary, vapor deposition techniques (CVD and PVD) are recommended for this type of application due to their technological maturity and good optical properties. However, the requirement for heat treatment may limit their application in certain materials. Table 6 summarizes the advantages, limitations, and TRL of CVD & PVD coatings applied in solar receivers in TES field.

3.2.3. *Dip coating*

Dip coating is a deposition method that allows the formation of very thin coatings on different surfaces. It has different applications, including use in CSP plants to form selective solar absorber layers. As mentioned above, this technique can be combined with other techniques, generally sol-gel, to achieve better and more effective coatings [111]. In addition to the use of titanium-based coatings using the mixture of these two techniques, studies on $CuMn_2O_4$ ceramic films are also noteworthy [150]. The combination of these two forms of deposition has proven to be sustainable and low-cost. Moreover, this study revealed the good performance of the material with an absorbance of 0.91 and an emittance of 0.12. Consequently, is a promising option for flat-plate CSP plants.

Regarding this type of materials, it has been proven that, in general, these copper-manganese oxide ($CuMnO_x$) thin films are selective, competent, and with adequate thermal stability for solar plants [151]. In addition, they can be used on different surfaces such as aluminum, stainless steel or glass, which are very common materials in these installations. They form homogeneous, crack-free layers which, when heat treated, form a black absorber coating with good spectral properties. Moreover, the efficiency of CSP plants is closely related to the operating temperature of the system. This is why the receivers must withstand high temperatures while maintaining high photothermal conversion. This has been achieved with a nickel-doped cobaltite thin film (Ni_x-Co_3-xO_4; $0 \leq x \geq 1$) on stainless steel substrates [152]. In this way, absorbances of 0.92–0.94 are achieved, which show that they are very good solutions for high-temperature applications.

Adding these two ideas, coatings of (Cu–Ni–Mn) oxides were studied for the same application. A coating ($Cu(Mn_{0.748}Ni_{0.252})_2O_4$) was developed in 2020 by immersion technique as well [153]. This acts by reducing the intensity of reflected light to create a temperature barrier (up to 500 °C for 250 h). This results in a high absorbance of 0.95, which would allow a great improvement in the efficiency of this type of plant.

In summary, the use of solar absorbing coatings applied by dip coating is an economical and simple solution. Although it is not as developed as other techniques, it has huge potential. Table 7 summarizes the advantages, limitations, and TRL of dip-coatings applied in solar receivers in TES field.

3.2.4. *Spraying methods*

The use of the spray technique to coat surfaces is one of the simplest

Table 6
Summary of the advantages, limitations, and TRL of CVD & PVD coatings applied in solar receivers in TES field.

		References
ADVANTAGES	- **Cost.** If coatings are based on cheap metals, the cost of production is reduced. Also, using the PVD cheaper than CVD. - **Dimensions and thickness.** They can vary from a few microns to a few nanometers. Multi-layer systems are usually used, which are adaptable to high production. In addition, there is research in which they have been tested at pilot scale on 2–3 m samples. - **Application temperature and durability.** The range extends from 450 °C to 850 °C. However, most tests show stability around 500 °C for hundreds of hours. - **Tunneability to the application.** Coatings with high absorbances (0.85–0.96), low emissivity (0.02–0.18), with self-cleaning capacity, resistance to degradation and corrosion. - **Adaptation to surfaces**. It adapts to numerous surfaces such as copper, stainless steel, aluminium, and various alloys. - **Environment.** The use of PVD generally does not cause contamination.	[128,139] [123,125–138] [123,125–138] [123,125–138] [123,125–138] [10]
LIMITATIONS	- **Compatibility with other techniques**. There is no evidence of joint application with other deposition techniques. However, hybrid application of CVD and PVD is feasible. - **Pretreatment.** For the application of some coatings, they must be applied with heating at 100–300 °C. - **Post curing.** These coatings may require curing at elevated temperatures for several hours. - **Defects**. Small superficial microscopic defects may appear. In addition, ADL is usually not suitable because deep microstructures are needed to obtain spectrally selective absorption properties. - **Environment**. CVD is worse environmentally speaking than PVD, and if they contain chromium or heavy metals, they are even more polluting. - **Research.** Need for new studies for the optimization of the technique at higher temperatures.	[93,126] [88,123,127, 133,136] [123,129,133] [125,126] [9] [128,136]
TRL	The use of vapor deposition techniques has been widely studied and commercialized for many years to produce selective solar coatings. It can therefore be said to be an established and mature technology. Numerous studies [140–142] have been carried out to develop coatings using these techniques that are viable for various applications such as solar collectors, solar panels for domestic needs, or thermoelectric power plants. Capable of operating in corrosive environments and with good optical properties. There are also several works combining dip-coating and sol-gel [120]. There are several patents for coatings and methods of producing them using CVD and PVD techniques. One example is the multilayer metal-based systems from the United States [143,144]. These coatings include Ti and Mo compounds that provide high stability (550–650 °C) and favor their use in CSP plants. As well as the gradient Cr–CrNO/SiNO structure of anti-reflective coatings [145]. Studies on these coatings have also been carried out in China. The multilayer coatings of oxides of Si, Ti, Al or a combination of these have a high absorbance and low emittance, as well as good stability at temperatures above 600 °C [146]. Also noteworthy is the creation of a system of ceramic nanoparticle layers (transition metal nitride-boride-cabide and mixtures of these) that is not only viable for CSP plants, as well as for photovoltaic or solar steam generation [147]. Finally, WIPO also holds several patents on metallic multilayers applicable with PVD, CVD or PECVD [148, 149]. These stand out for their high heat conversion efficiency and their robustness to mechanical and thermal stresses.	

Table 7
Summary of the advantages, limitations, and TRL of dip-coatings applied in solar receivers in TES field.

		References
ADVANTAGES	- **Cost.** Low-cost technique with long-term stability and reproducibility. - **Dimensions and thickness.** The layers have a thickness of nm. This allows it to be easily scalable at industrial level, especially when depositing a single layer. - **Application temperature and durability.** This method shows stability in a range of 250–500 °C for almost 250 h. However, there are studies where this stability increases up to 800 °C. - **Tunneability to the application.** They are thermally stable, corrosion-preventing coatings with good optical properties (absorbance of 0.80–0.95 and emissivity of 0.07–0.14). It is a good method for high temperature selective solar applications. - **Adaptation to surfaces**. It is effective on various materials such as stainless steel, aluminium or glass. - **Environment**. It is a technique with low toxicity and minimal waste.	[150–152] [111, 150–153] [111, 150–153] [111, 150–153] [111,150, 151] [111]
LIMITATIONS	- **Compatibility with other techniques.** There are only studies where hybrid methods of sol-gel deposition and dipping are used. - **Pretreatment.** Strong agitation for a couple of days prior to deposition may also be necessary for the formation of the solvent. - **Post curing.** It is necessary to let the coating dry at 65–75 °C for 1 h. It is then heat treated at 400–500 °C to control the thickness and structure. - **Defects.** When the coating is deposited by immersion, it is possible that the roughness of the layers is variable and has to be controlled by annealing. - **Research**. Need for new studies for the optimization of the technique and tests at higher temperatures.	[111,150] [111] [111, 150–152] [111] [150,153]
TRL	The use of the dip-coating technique is widespread at the industrial level due to the ease of the process. However, as for its use to improve absorbance in CSP plants, it is not as common as the use of other deposition methods. So, it is common to see this technique combined with any of the others. In terms of patents on the market, there are some in which this technique is used to produce solar selective absorbers. Its use can be combined with another deposition method such as sol-gel. As mentioned above, there is research [121] in which the combination of these two techniques allows the creation of coatings with excellent selective properties very useful in this type of plants. On the other hand, if a hybrid method of sol-gel, dip-coating and sputtering is used, an ideal multilayer system for stainless steels with high thermal stability (500–600 °C) can be achieved, combining all the advantages of each of the techniques [120]. Another case is the patent for a multilayer system deposited by layer-by-layer self-assembly of nanoparticles, polymers and combinations thereof [154]. These layers can be deposited by dip-coating and is a very useful solution for producing solar concentrating mirrors.	

and cheapest methods on the market. An example of this is the case of the tandem structure of copper oxide nanowire and cobalt oxide nanoparticles [155]. If the coating is spray deposited, absorbance values of 0.88 are obtained. Likewise, Karas et al. tested the synthesis of a cobalt-copper and copper-manganese oxide [156]. The coating was a mixture of black oxide nanoparticles deposited on Inconel 625. The results showed that the film was viable at 750 °C. At the same temperature, a manganese-iron oxide nanoparticle-pigmented coating is stable [157]. The films in question have good optical properties (absorbance of 0.93) and high energy conversion efficiency (0.89) after being in operation for 700 h in various thermal cycles of day and night.

On the other hand, the spray application of a commercial polymer (polyethylene-3,4-dioxythiophene:polystyrene sulfonate) on a stainless steel substrate has been investigated [158]. In addition, the effect of layer thickness and optical properties has been studied. In this way, the feasibility of this polymer as a selective solar coating was demonstrated. Concerning the combination of other techniques with spray deposition, work was carried out on a TiN/TiC–Ni/Mo film coating stainless steel fabricated by a hybrid method of spray and laser cladding [159]. The good performance of the selective coating also allows it to resist corrosion and aging.

In addition to all this, there is a recent study in which coatings inspired by the morphology of stony corals are produced [160]. This type of film is adjustable in scale (nanoscale, microscale, and macroscale). This structure allowed to reach absorbance values of 0.98 and stability at 850 °C for almost 2000 h. The scalability of the system on a commercial solar thermal receiver was also demonstrated, thus demonstrating the feasibility and efficiency of the study.

In summary, the use of spray coatings for solar receivers is effective, provided that the materials allow it. That is why it is not a widely used technique in this area. Table 8 summarizes the advantages, limitations, and TRL of sprayed coatings applied in solar receivers in the TES field.

Table 8
Summary of the advantages, limitations, and TRL of sprayed-coatings applied in solar receivers in TES field.

		References
ADVANTAGES	- **Cost.** Low-cost, easy, and fast energy-efficient manufacturing. - **Dimensions and thickness.** Typically, only a few microns thick. These coatings can be applied individually or in multilayer systems to facilitate large-scale manufacturing. - **Application temperature and durability.** 650–750 °C for periods of 200–1000 h. - **Tunneability to the application.** The use of spray coatings as selective solar absorbers has achieved absorbance values of 0.84–0.96, with low emissivity of 0.04–0.36 and high energy conversion efficiency. In addition, they have proven to be resistant in high-temperature environments in day-night cyclic tests. - **Adaptation to surfaces**. They perform well on stainless steel, aluminium, and Inconel 625.	[156–158] [156–158] [156,157, 159,160] [156–162] [156,157, 159,161]
LIMITATIONS	- **Compatibility with other techniques.** In general, compatibility with different deposition techniques will depend on the materials involved (coating and surface) and the desired properties. There are not many studies where it is combined with other techniques, however, its use with laser cladding proves its effectiveness. - **Pretreatment.** Sometimes a pretreatment of the surface at temperatures close to 100 °C is required. - **Post curing.** It may also be necessary to evaporate the solvent with which the spray is deposited and a drying/baking after the application of the spray at 500 °C. - **Defects**. Cracks or pores may appear in the coating, which may require the application of several layers. - **Environment.** If toxic substances are used to produce the coating, they may be harmful to the environment. - **Research.** Need for new studies for the optimization of the technique.	[159] [157] [157] [160] [163] [158–160, 162]
TRL	The use of spray-deposited solar selective absorber coatings is a fairly old, easy-to-use and low-cost technique. This is why it is a highly mature technology for which there are numerous patents. A clear illustration is a spray-applied coating known as SOLKOTE HI/SORB-II [164]. This coating was produced in 1980 to fulfil the needs of solar thermal applications. Its durability on the market is due to its resistance to water and high temperatures, UV rays and good optical properties. The use of these coatings is prominent in countries such as China. China holds several patents on such spray-applied coatings. In 2011, it patented a method for producing a superconducting flat plate coated with a layer to improve its solar energy absorption [165]. This method was economical and scalable to industrial level and application on materials such as aluminium, copper, steel and alloys. Also, in 2017, two processes were patented for the production of solar selective films based on $FeMnCuO_4$ [166] and TiO_2 [167] respectively. Both possessed high absorption capacity and low emissivity. The first coating also had high thermal stability and was suitable for mass production due to its low cost. The titanium-based coating was weather and dirt resistant. Similarly, the World Intellectual Property Organization (WIPO) has patented several techniques and systems related to high-temperature solar energy, in which the use of spray-coatings is also used [168]. Among them, a system based on nickel and silicon oxide with good spectrally selective behavior at 600 °C stands out [169]. And also, another one that includes a silicon polymer and transition metal oxide nanoparticles dispersed in it [170].	

3.2.5. *Laser deposition*

There are currently several coating deposition processes using lasers. In 2014, studies were conducted on solar absorbers by laser sintering on stainless steel [171]. The coating contained micro and nanoparticles of tungsten and allowed good control of surface morphology while forming a thermally stable and oxide protective layer. Another example is the case of Karoro et al. who reported nanostructured Co nanocylinders-Al_2O_3cermets produced by electrodeposition and laser [155]. These coatings were optimized and achieved absorbance values of 0.98.

Among the various laser-based techniques, laser cladding is one of the best for creating selective solar coatings. In this field of research, the works of Pang et al. carried out in recent years are important. TiN/TiC–Ni/Mo cermet coatings with the desired optical properties were planned and produced [172]. In addition to demonstrating the feasibility of this type of system, the potential of this technique in the world of absorber coatings was also demonstrated. Linked to this work, another research was presented which highlights the high thermal stability of this coating at elevated temperatures [173]. In addition, the results showed that the addition of TiC and Mo greatly improves the absorbance obtained with the material. This same coating was also deposited by combining two different techniques: spray and laser cladding [159] as mentioned above. This allowed us to improve the absorbance slightly and increase the weathering resistance. On the other hand, a monolayer cermet coating doped with oxide on 316 L substrate, whose structure is Ni/TiN–La_2O_3, was studied [174]. This solution showed outstanding optical properties, high hardness, and corrosion resistance.

In summary, laser-deposited coatings are recommended for this application due to their robustness and optical properties. This is a more novel and expensive set of techniques due to its requirement for specific equipment. Table 9 summarizes the advantages, limitations, and TRL of laser deposition coatings applied in solar receivers in the TES field.

3.2.6. *Other deposition techniques*

More recently, studies have been carried out on the application of selective solar coatings using other techniques such as electrodeposition. An example of this is the creation of a fractally textured film of copper oxide and copper-manganese oxide on Inconel 625. Tests showed very promising values for CuMnO [179]. The results were obtained through simulations and experimentation, with a high degree of agreement between the two methods. In another investigation [180], the morphology and the effect of the optical properties of these coatings were studied in a range of 450–850 °C. This allowed the creation of degradation curves and stability maps for both films. In addition, the presence of minimal changes in structure and properties when subjected to different

Table 9
Summary of the advantages, limitations, and TRL of laser deposition coatings applied in solar receivers in TES field.

		References
ADVANTAGES	- **Dimensions and thickness.** Thicknesses of a few microns can be scalable to an industrial level. - **Tunneability to the application.** Investigations showed coatings with high hardness, corrosion resistance, anti-reflective and good optical properties (absorbance of 0.80–0.90 and emissivity of 0.03–0.12). - **Adaptation to surfaces.** Suitable for stainless steel, and aluminum. - **Pretreatment.** It is only necessary to prepare the coating and deposit it. A second coat may be necessary to obtain the desired surface morphology. - **Post curing.** High-temperature annealing is performed to improve the optical properties. - **Defects.** The work carried out with these coatings shows that they are coatings with a good finish, without defects and with very low or negligible porosity.	[159, 171–174] [159, 171–174] [155,171] [171,172] [159, 172–174] [172–174]
LIMITATIONS	- **Cost.** This is a novel technique that may require greater investment due to the use of specialized equipment and adequately trained professionals. Some particular studies show the possible feasibility of manufacturing them economically. - **Application temperature and durability.** Tests have been made where they are viable at 350–650 °C. However, these tests are done for short periods. - **Compatibility with other techniques.** Only co-deposition with spray and electrodeposition have been tested. - **Environment.** Some research has resorted to doping the coating with rare earths, which can have a serious impact on the environment. - **Research.** Need for new studies for the optimization of the technique and tests at higher temperatures.	[159,174, 175] [159, 171–174] [155,171] [174] [171]
TRL	Techniques that use lasers to deposit coatings are increasingly emerging techniques. The most commonly used are laser sintering and laser cladding. In the United States, a method was developed to create a spectrally selective coating by laser sintering [176]. In addition, this sintered layer could be textured to give it the desired roughness. On the other hand, methods for synthesizing solar selectively absorbing coating through laser cladding have been patented in China. One of them is a multilayer system, including photoluminescent layers doped with ((K, Na) NbO_3) with an excellent optical performance and adequate thermal resistance [177]. Within this field, the co-deposition of laser cladding with spray also stands out [178]. This combination allows the development of high-performance, high-temperature stable, easy handle, and low-cost selective coatings.	

temperatures was verified, thus preserving an efficiency of 90 %.

On the other hand, there is also evidence of the use of the pack cementation process to produce, in this case, selective solar absorbers [181]. VM12 was coated with Cr–Mn oxides, which have self-curing behavior and good optical and thermal properties. All this is due to the diffusion mechanism that creates and transforms the coating compounds. Another novel example is the creation of a coating applied to quartz sand for use in CSP plants with integrated TES systems [182]. The applied coating consists of silica and nanoparticles of $Cu_{0.5}Cr_{1.1}Mn_{1.4}O_4$ and $CuCr_2O_4$. Therefore, the feasibility and potential of this technique are enormous, as it is a cheap and easy way with a high yield. Finally, the use of a black $CuCr_2O_4$ pigment doped with Mn to form compounds with the formula $CuCr_{(2-x)}Mn_xO_4$ is noteworthy [162]. The application of this pigment to the tower receivers in the CSP plants allows absorbance levels to be raised to values above 0.98, since the presence of Mn eliminates reflective peaks.

3.3. Improve effective properties

In general, thermal conductivity is a very important parameter in thermal storage systems. High values of this parameter imply higher energy storage and improved efficiency. The improvement of this property has been studied through composite and microencapsulated materials; however, the use of coatings is also an interesting option. The application of coatings in TES systems is not widespread in the research world. However, the work of Trevisan et al. on the use of coatings in packed beds is noteworthy. In them, a methodology is developed to evaluate the thermal effect of the coating on the behavior of the TES unit (emissivity-conductivity) [23]. This demonstrates the relationship between the coating emissivity and conductivity of the TES system and the influence of the coating on the particle size of the TES unit. Furthermore, the use of different layers of different materials within the same unit would allow better control of the loading process and thermocline degradation. In addition to this study, two other investigations were also carried out to evaluate the performance of metallic [24] (Inconel, Nitinol, and stainless steel) and inorganic [25] (HIE-Coat 840MX, Pyromark 2500, Pyro-Paint 634-ZO, MgO and TiO2) coatings applied in the form of paint or powder on this system by applying different thermal cycles. Of all these materials, Nitinol, SS 304, HIE-Coat 840MX, and Pyro-Paint 634-ZO obtained the best results. They showed stabilities at very high temperatures (1000 °C) and good thermal cycling behavior. Inconel 738 and TiO2 coatings are potential candidates for application if they are thermally pretreated. Finally, Inconel 738, Inconel 625, Pyromark 2500, and MgO coatings are ruled out for this use under these tested conditions.

4. Dicussion

Taking all these aspects into account, coatings emerge as a cost-effective and efficient remedy to improve efficiency in CSP plants. The optimal technique selection depends on the precise requirements, plant materials, and operating parameters. Continuous advances in the development of new coating techniques and compositions adapted to the specific requirements of CSP plants highlight the steady progress in this field. Despite these advances, further research is still needed to optimize these techniques, explore their cyclic thermal behavior, and evaluate their performance in a larger spectrum of salts and corrosive environments. These improvements would overcome current limitations and extend applicability to a wider range of substrates and environments. Similarly, future research can be focused on the development of more sustainable and eco-friendly materials to reduce the environmental impact of coating techniques. As well as working on the viability of these at the industrial level, in order to make their implementation effective in large-scale CSP plants. The economic feasibility of less developed techniques could also be explored in order to evaluate their potential on a large scale. In addition, this work also leads to research in new fields and new combinations of materials to further improve the efficiency and durability of coatings.

To sum up, Table 10 shows details about the techniques used to produce the coatings as well as the materials applied as coatings for their potential to improve TES in CSP plants. In addition, the properties of those coatings under study as well as their application functionality in the plants are added as part of this information.

5. Conclusions

This review summarizes the different coatings applications in CSP plants organized according to application techniques as well as the advantages and limitations of each type of coating technology to be applied in CSP plants taking into account the maturity level of each technique (Vapor Deposition Techniques, Laser Deposition Techniques, Sol-gel, Thermal Spray within others) for each application in CSP (Corrosion resistance, Selective coatings for solar receivers, and to improve

Table 10
Details about the coating techniques, material used as coating, properties and application of these coating in several components of CSP plants.

			Properties			Application in CSP plants	
Deposition Method	Substrate Materials	Coating Materials	Corrosion Resistance	Temperature Resistance	Optical Properties	Anticorrosion Barrier	Solar Absorber
Thermal spray	*Stainless Steel:* (304, 310, 316L) *Alloy Steel:* (T22) *Alloys, Composites* *Biological materials, Ceramics*	*Alloys:* (Al, Fe, Fe–Al, Ni, Ni–Cr, MCrAlM′) *Inconel 625*	Na_2SO_4–V_2O_5 K_2SO_4–V_2O_5 NaCl–KCl–Na_2SO_4 $NaNO_3$–KNO_3	300-850 °C	–	✓	–
Sol-gel	*Stainless Steel:* (316L, 430, AISI 304, AISI 321) *Alloy Steel:* (P91) *Carbon Steel Alloys* *Non-ferrous metals:* (Cu, Mg, Al)	*Ceramic0 p:* (Al_2O_3, Fe_2O_3, SiO_2, ZrO_2, ZrO_2–Y_2O_3, TiO_2, Ag–TiO_2, CeO_2) *Multilayer:* (Cu–Co–Mn–Si–O, Cu–Co–Mn–O, TiO_2/Carbon particles) *Metal oxides:* ($CuMn_2O_4$, $CuCr_2O_4$, $MnFe_2O_4$)	$NaNO_3$–KNO_3	Up to 500 °C	Absorptivity (0.85–0.95) Emissivity (0.12–0.15)	✓	✓
CVD and PVD	*Stainless Steel:* (304L) *Alloy Steel:* (P91) *Alloys* *Non-ferrous metals:* (Cu, Ni, Au, Cr, Mo, Ti, Ag) *Inconel 690, $X_{155}CrMoV_{12}$*	*Alloys:* (Ti, Fe–Al, Al–Ti, Al–Mn, NiVAl) *Ceramics:* (ZrO_2–Y2O3, Ni–ZrO_2–Y_2O_3) *Multilayer:* (SS/Cr_2O_3/Ag/Cr_2O_3/Si/Si_3N_4/SiO_2, Cu/Al_2O_3/Cr/SiO_2/Cr/SiO_2, ZrO_x/ZrC–ZrN/Zr, Cu/$Zr_{0.2}Al_{0.8}N$/ZrN/AlN/ZrN/AlN/$Al_{34}O_{62}N_4$)	$NaNO_3$–KNO_3	500-565 °C	Absorptivity (0.85–0.96) Emissivity (0.02–0.18)	✓	✓
Slurry	*Stainless Steel:* (316L, 304) *Alloy Steel:* (P91, P92,T22) *Inconel 600: High-purity nickel*	*Aluminides:* (Al, Ni–Al)	KNO_3–$NaNO_3$ NaCl–KCl	Up to 600 °C	–	✓	–
Dip-coating	*Stainless Steel* *Non-ferrous metals:* (Al) *Glass*	*Ceramics:* ($CuMnO_x$) *Oxides:* (Cu–Ni–Mn, Ni–Co) *Non-ferrous metals:* (Ti)	–	250-500 °C	Absorptivity (0.80–0.95) Emissivity (0.07–0.14)	–	✓
Laser techniques	*Stainless Steel* *Non-ferrous metals:* (Al)	*Ceramics:* (Al_2O_3) *Multilayer:* (TiN/TiC–Ni/Mo, TiC–Mo, Ni/TiN–La_2O_3)	–	350-650 °C	Absorptivity (0.80–0.90) Emissivity (0.03–0.12)	–	✓
Spray coatings	*Stainless Steel* *Inconel 625*	*Oxides:* (Cu, Co, Mg–Fe) *Polymers:* (polyethylene-3,4-dioxythiophene:polystyrene sulfonate) *Multilayer:* (TiN/TiC–Ni/Mo)	–	650–750 °C	Absorptivity (0.84–0.96) Emissivity (0.04–0.36)	–	✓

effective properties).

Overall, coatings demonstrate multifaceted potential within CSP plants. In addition to serving as a protective layer against corrosion, these elements are also essential for optimizing solar energy absorption and improving thermal storage properties. This dual role significantly increases the efficiency and sustainability of these energy systems, situating coatings as integral components in improving the performance and durability of these plants.

With regard to their application as a corrosion barrier, in general, all deposition techniques are low-cost methods with optimal results. Among these methods, the thermal spray technique stands out as the most prominent due to its cost-effectiveness and applicability for large-scale use. Its adaptability to achieve various thicknesses makes it a versatile option, proven effective on a range of substrates, both metallic and non-metallic, and in several corrosive environments. However, in some thermal spraying methods, it is necessary to prepare the surface beforehand to ensure the correct adhesion of the coating or a subsequent annealing, which increases energy consumption. Another promising technique for this type of application is sol-gel, as it also shows satisfactory results with a wide variety of substrates in different environments. However, a major drawback is that some applications require multiple layers, which increases the possibility of coating flaking off. Achieving this balance between a number of coats and adhesion is crucial, as lower thickness means lower durability compared to other technologies. Vapor deposition techniques offer coatings with layers ranging from a few microns to greater thicknesses. This makes it possible to increase the range of CSP plant elements to which these can be applied. Nevertheless, their requirement for high-temperature heat treatments, especially CVD, might pose restrictions on certain substrates and processes. From an alternative perspective, the use of slurry deposition can be environmentally friendly, although its effectiveness and durability may present challenges compared to other well-established techniques. Industrial scale-up of this technique is not as straightforward although its potential is promising.

In terms of their application as selective solar absorbers, these coatings play a crucial role in maximizing the capture of sunlight and its conversion into heat, which has a direct impact on the efficiency of CSP plants. In particular, sol-gel shows remarkable versatility and allows the generation of more efficient coatings with good optical and corrosion-resistant properties. However, this technique is also energy-intensive and has a higher carbon footprint compared to other methods. In contrast, vapor deposition techniques (CVD and PVD) are widely used and have a high technological maturity, offering optimal optical properties and elevated temperature robustness against high temperatures. Nevertheless, as in its application against corrosion, the required heat treatment could pose restrictions on certain materials. Dip coating, although less widespread, has the potential for high-temperature applications and offers cost-effective selective properties. Spray technique, despite its economic advantages, has favorable results, but is limited to a more restricted range of materials. Finally, laser deposition shows the ability to create robust, selectively absorptive coatings with suitable optical properties. However, this is a novel technique that may require greater investment due to the use of specialized equipment and adequately trained professionals.

Finally, the use of coatings to improve the properties of TES systems is a novel application with enormous potential. It has been shown that improving thermal conductivity is essential in this type of system and the use of coatings for this purpose is a promising but not widely explored option. Some of the coating materials studied such as Nitinol, SS 304, HIE-Coat 840MX, and Pyro-Paint 634-ZO show positive results at elevated temperatures and thermal cycles. The most suitable techniques to achieve proper coatings for CSP plants are thermal spray, sol-gel, and cold spray. The specific studies about corrosion resistance are promising results to achieve high potential results.

CRediT authorship contribution statement

Sergi Dosta: Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Lorena Betancor:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Camila Barreneche:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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