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Review

A Review of Conventional and Innovative-Sustainable Methods for Cleaning Reflectors in Concentrating Solar Power Plants

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Abstract: The severe soiling of reflectors deployed in arid and semi arid locations decreases their reflectance and drives down the yield of the concentrating solar power (CSP) plants. To alleviate this issue, various sets of methods are available. The operation and maintenance (O&M) staff should opt for sustainable cleaning methods that are safe and environmentally friendly. To restore high reflectance, the cleaning vehicles of CSP plants must adapt to the constraints of each technology and to the layout of reflectors in the solar field. Water based methods are currently the most commonly used in CSP plants but they are not sustainable due to water scarcity and high soiling rates. The recovery and reuse of washing water can compensate for these methods and make them a more reasonable option for mediterranean and desert environments. Dry methods, on the other hand, are gaining more attraction as they are more suitable for desert regions. Some of these methods rely on ultrasonic wave or vibration for detaching the dust bonding from the reflectors surface, while other methods, known as preventive methods, focus on reducing the soiling by modifying the reflectors surface and incorporating self cleaning features using special coatings. Since the CSP plants operators aim to achieve the highest profit by minimizing the cost of cleaning while maintaining a high reflectance, optimizing the cleaning parameters and strategies is of great interest. This work presents the conventional water-based methods that are currently used in CSP plants in addition to sustainable alternative methods for dust removal and soiling prevention. Also, the cleaning effectiveness, the environmental impacts and the economic aspects of each technology are discussed.

Keywords: sustainable cleaning; CSP reflectors; soiling; dust removal; mirror washing

1. Introduction

Renewable technologies are not sustainable if water impacts are not fully analyzed and addressed [1]. The Mediterranean and desert environments have high Direct Normal Irradiance (DNI) which favors the adoption of CSP technologies as a source of green energy production. Sustainable CSP technologies should integrate the environmental concerns into the operation and maintenance (O&M) of the solar plant by selecting approaches that reduce carbon emission, any possible sources of pollution and water use. The cooling tower and the washing of the mirrors use up water heavily but with the deployment of air-cooled condensers or hybridized coolers [2], the washing of reflectors will become the main consumer of water. According to [3], the annual consumption of water in wet parabolic trough plants goes in its majority to the cooling tower, approximately 94% , with only 4% consumed by mirror washing. In the case of dry cooling, cleaning reflectors consumes up to 62% of the total consumed water. However, it must be noted that a larger solar field is needed because dry cooling results in a less efficient power block and thus necessitates more water for cleaning additional reflectors.

Because the mirrors are back silvered and the light traverses the reflector twice, CSP reflectors are more affected by dust than PV panels and thus need adapted sustainable dust removal strategies. The size of the solar field is designed by taking into account the DNI, the optical and thermal efficiencies of the plant, the power needed by the power cycle and the storage capacity. Larger storage capacity induces an expanded solar field and thus additional cleaning costs. The surface of the reflectors should be clean to avoid the absorption and scattering effect of deposited dust particles. The location of the CSP site and weather conditions are among the main factors impacting the soiling rate. Many soiling studies shed light on the loss of reflectance in many regions [4–10]. To obtain a high cleaning efficiency, it is essential to be informed about the size of particles deposited on the surface, its composition, and the nature of the forces involved in the dirt deposition, settlement and adhesion [11].

Deciding on the best cleaning methods is an economical decision based on the cost of cleaning versus the loss of energy resulting from soiled reflectors. Also, the dust removal methods must be environmentally friendly, sustainable with low water consumption in addition to having high dust removal efficiency for restoring full initial reflectance. Many methods are being developed as potential solutions to prevent dust adhesion or for enhanced cleaning effectiveness. The conventional water-based methods are currently applied in CSP plants; however these methods rely principally on water as the main cleaning solution.

New sustainable cleaning concepts are being investigated by researchers and new initiatives are developing innovative alternatives. The cleaning methods can be classified as preventive where the focus is on developing surfaces that are dust repellent [12], or curative, that deal with removing the dust that already deposited.

This review covers the cleaning systems of three main types of CSP technologies, that is parabolic troughs, heliostats and linear Fresnel reflectors. The conventional methods already known and commonly used in CSP plants are presented. Details about these methods relying on contact and non-contact cleaning methods and the various degrees of automation used in CSP plants are provided. Then we shed light on optimisation methods which aim to improve the cleaning effectiveness of these conventional cleaning techniques. In addition to presenting promising lower water consumption methods, other alternatives focusing on eliminating any need for water in the cleaning process are reviewed. By preventing dust from settling on the mirrors, soiling prevention techniques are great options to tackle soiling of reflectors. Also, the cleaning cost and the quality of water used for washing reflectors are discussed.

The ultimate purpose of this literature revision is to support researchers and plant operators to adopt more sustainable O&M protocols.

2. Conventional Methods

Water is the main cleaning agent used in conventional washing methods. It is either used alone by spraying high pressure water on the surface of soiled reflectors or in combination with a contact cleaning tool used for brushing, wiping or scrubbing the surface of soiled reflectors.

2.1. Non-Contact Cleaning

This method consists in spraying high pressure water onto the dirty surface. According to [13–15], this method is quite effective in removing dust. However, it fails to completely remove all the dust cemented to the mirrors because of the resistance of dust particle to the action of water jetting.

The cleaning effectiveness of this method is affected by parameters such as the distance between the high pressure system and the cleaned surface, the nozzle characteristics and diameter, the angle of impingement and the applied jetting pressure. Although increasing the inlet pressure of water enhances the cleaning effectiveness [16], this solution is not advantageous because of its consumption of additional water volumes. According to the same author [17], varying the angle of impingement applies tangential forces on soil particles which can improve the cleaning effectiveness and thus enhance the reflectance restoration.

2.1.1. High Pressure Spraying

Applying high pressure water spraying results in obtaining a reflectance of 80% to 90% [14]. By applying this method on both glass and acrylic mirrors, it was found that mirrors can recover 98% of their initial reflectance, whereas acrylic mirrors restore just 92% reflectance [11]. According to [18], this method requires 0.19 gallons of water per square meter of aperture area and increases the reflectance by three percentage points.

2.1.2. Deluge Spraying

This method relies heavily on water by using a deluge-type spraying. According to [18], this method is four times faster than the high pressure method and consumes 0.23 gallons per square meter of aperture area. As a result of applying this method, one percentage point increase in reflectance is obtained.

2.2. Contact Cleaning

Although high pressure water is effective in removing a great deal of deposited dust, it leaves some dust that builds up with repetitive cleaning cycles [14]. Contact cleaning consists either in brushing, wiping or scrubbing the soiled surface. This method is effective in restoring full initial reflectance. According to [13], using a soft wipe was successful in recovering full initial reflectance unlike non contact cleaning methods. Despite its high cleaning effectiveness, contact cleaning can harm the surface of the reflectors by causing scratches or delamination over many cleaning cycles. As a result of applying different brush hardness and sand samples on polymer mirrors, it was recommended using a soft brush and water for benign cleaning [19]. A combination of scrubbing and rinsing is effective for highly adhered dust particles; however before applying any cleaning device, water spray should be first applied to remove loose dust [15]. Figure 1 shows a kit of cleaning tools used in washing soiled CSP mirrors as used in [20].

2.3. Application in Real CSP Plants

The level of automation of cleaning systems influences the effectiveness, the speed and the cost of cleaning. The vehicles and apparatus used for applying water-based methods should be adapted to the shape of CSP reflectors because this difference dictates constraints to the movement of the cleaning tools. Also, the layout and the distribution of the reflectors in the solar field impacts the cleaning effectiveness and the cleaning speed.

Figure 1. The set of cleaning tools used for washing exposed mirrors in PSA comprises high pressure nozzle, soft scubbing brush, steam washer, tanks for both demineralized water and detergents [20].

2.3.1. Manual

Manual cleaning remains an option either when its cost is cheaper than other alternatives or when other cleaning options are ineffective, thus requiring the human intervention. This method was reported in [21] when confronted with very dirty parts of the reflectors. Manual cleaning using a brush and demineralized water was applied on the lower edge of the mirrors every two or three years [18]. This type of cleaning is time consuming and requires great effort, however its use is justified when the cost of labor is cheap or when the number of reflectors is low.

2.3.2. Semi-Autonomous

This is the most used option in current CSP plants [2,22]. The procedure for semi-autonomous cleaning of dirty reflectors consists either in washing a row of reflectors and then coming back to the adjacent row, or simultaneously cleaning two rows facing each other. One of the earliest semi-autonomous vehicles is a tractor-pulled trailer used in SEGS III-VII plants in the USA [18]. Generally, the type of cleaning vehicles used in CSP plants are trucks equipped with a tank and pump unit in addition to the necessary cleaning tools, that is nozzles for water jetting at a range between 30 bar and 200 bar and brushes, squeegee, or sponge for contact cleaning. Figure 2a,b show routine cleaning of parabolic troughs and heliostats in Noor II and III.

(**a**)

(**b**)

Figure 2. Semi-automatic cleaning in CSP plants (courtesy of ECILIMP Termosolar [23]). (**a**) Semi-automatic cleaning of parabolic troughs in Noor II; (**b**) Semi-automatic cleaning of heliostats in Noor III.

Habitually, only one arm is needed for heliostat cleaning, while two arms are needed for washing the upper and lower parts of the parabolic troughs. The cleaning tools may adopt different designs. For example Mr.Twister used a double rotating arm with two sets of swivel assemblies with four nozzles, while the deluge type spraying vehicle has fixed nozzles on each side of the truck to simultaneously spray the rows of mirrors facing each other [18].

The vehicles used for washing can be dedicated exclusively to spraying pressurized water or may include also a contact cleaning tool. For example, three modes for cleaning (brushing with low-pressure water, cleaning using only high-pressure water, cleaning with cleaning brushes using high pressure water) were adopted in [24]. In Shams-1 solar plant, the semi-automatic cleaning vehicle first wets the soiled mirrors using sprayers of water, then cleans using rotating brushes, and finally rinses using sprayers located at the back of the vehicle [2].

These vehicles performance is evaluated based on their water and fuel consumption, the time required for cleaning, and the number of operators needed. The disadvantages of these heavy trucks are the deterioration of the paved roads and potential sprinkling of dust on the already cleaned reflectors. Also, any error from the operator could lead to breaking or deteriorating the mirrors or the receiver tube even though these vehicles are generally equipped with sensors for detecting obstacles.

Another type of semi-autonomous devices for heliostat cleaning was developed by [25]. Even though this equipment automatically cleans one side of the heliostats row and reverses its trajectory to clean the other side of the row thanks to path detecting sensors, it still needs an operator for its positioning.

Several type of semi-autonomeous vehicles are available on the market. Table 1 presents conventional semi-automatic cleaning vehicules used in CSP plants.

Table 1. Conventional semi-automatic cleaning vehicules used in CSP plants.

CSP Plants		Cleaning Vehicule	Cleaning Frequency and Rate	Water Quality and Consumption	Other Cleaning Considerations	References
Solar plant	ISCC Ain Beni Mathar	Truck equipped with spraying nozzles and soft rotating brushes some casual manual cleaning	Each reflector is cleaned once per month	Intermediate demineralization produced using RO of raw water of wells	Cleaning time includes day shifts as well as night cleaning	[26]
Technology	Parabolic trough					
Location	Ain Beni Mathar, Morocco					
Solar field (m^2)	183,120					
Solar plant	Kramer junction solar power plant	Twister and deluge trucks	-	Demineralized water approx 0.7 L /m^2	-	[18]
Technology	Parabolic trough					
Location	Boron, California		-A week cycle of high pressure with two weekly deluge in between			
Solar field (m^2)	200,000		-Three night of 30 MW field			
Solar plant	Gema solar plant	High pressure water truck and robot (Hector)	Depending on the soiling level	–	The use of a soiling map to identify zones with varying soiling level	[22]
Technology	Heliostats					
Location	Andalucia, Sevilla					
Solar field (m^2)	304,750					
Solar plant	NOOR I	High pressure water truck with brush	-Depending on the target reflectance of the solar field	Demineralization water	Two shifts : -From sunset to 10 PM - From 10 PM to sunrise	[27]
Technology	Parabolic trough					
Location	Ouarzazate, Morocco					
Solar field (m^2)	1,308,000		-The solar field is cleaned in a week			
Solar plant	NOOR III	High pressure water truck with brush	Depending on the target reflectance of the solar field	Demineralized water expected (0.5 L/m^2)	Not yet operational	[28]
Technology	Heliostat					
Location	Ouarzazate, Morocco					
Solar field (m^2)	1,321,197		-Vehicle speed less than 10 Km/h			

Table 1. *Cont.*

CSP Plants		Cleaning Vehicule	Cleaning Frequency and Rate	Water Quality and Consumption	Other Cleaning Considerations	References
Solar plant	GlassPoint Solar EOR	Automated roof washing system	During the night	Wash water is reused	-	[29]
Technology	Enclosed Trough					
Location	South of Oman					
Solar field (m^2)	17,280					
Solar plant	Sierra SunTower	Semi-automated system with high-pressure spray nozzles	-1200 m^2/h -3 h for the entire field	-	-	[30]
Technology	Heliostat					
Location	Lancaster, CA, USA					
Solar field (m^2)	13,836					
Solar plant	Shams solar plant	Semi automatic cleaning truck with spraying nozzle and round brush	-Field cleaned once every 6 days -1.5 m^3 of demineralized water to clean a single loop	Expensive raw water produced by a desalination plant	-	[2]
Technology	Parabolic trough					
Location	Emirates, Madinat Zayed					
Solar field (m^2)	627,840					
Solar plant	Ivanpah	Semi automatic cleaning vehicles	Bi-weekly	-	Depending on the location of the dirt relative to the tower (truck and tractor)	[31]
Technology	Heliostat					
Location	US, Primm, NV					
Solar field (m^2)	2,600,000					

2.3.3. Autonomous

Here, the human intervention is discarded by relying on automatic cleaning apparatus programmed to perform the cleaning [22,32]. The robots are generally equipped with a navigation system and optical sensors to avoid harming the reflectors. Unlike the parabolic trough reflectors, flat surfaces like heliostats and linear Fresnel mirrors allow for more flexible cleaning and are adapted for such fully automated cleaning solutions. For heliostat cleaning robots, the surface needs to be in the horizontal position or light inclination. Hector and Paris cleaning vehicules [33,34] are examples of unmanned commercially available equipments with the first dedicated to cleaning heliostats and the second adapted to trough cleaning.

Several solutions for automatic cleaning are particularly adapted for linear Fresnel [35]. Many Companies are proposing ready to market robots which are claimed to have low water consumption [22] and consume minimal energy [36]. However, purchasing a float of robots involves a high acquisition and maintenance cost. Also, an operator might be needed to monitor the process.

Another unconventional idea is to use unmanned aerial vehicle (UAV) or drones for cleaning as proposed in [37] where the cleaning task is achieved by using many pusher propellers that are suspended to the main body of the drone in opposite direction. Another configuration for autonomous cleaning patented by [38] consists in a solar collector equipped with an array of sprinklers with in-ground body and rotary heads which are positioned at the perimeter of the reflector.

For advantageous autonomous cleaning, a system comprising a counterbalance device coupled to the wiping device placed over the top end of the reflector was proposed in [39]. The cleaning force is executed by the counterbalance device which moves the wiper twice per day along the soiled surface.

Cleaning the mirrors directly from their frames will enable fast and reliable automatic cleaning. An approach based on a cleaning device moving on the rails positioned at the transverse ends of the collectors modules is proposed in [40]. The performance of such guide railed devices are still not practically tested and their investment cost is unknown.

2.4. Optimization of Conventional Methods

To improve the cleaning effectiveness of these water-based conventional methods, several improved techniques and optimized cleaning parameters are proposed. This section presents approaches for an optimal water-based washing.

2.4.1. Optimized Strategies

Due to constraints such as the limited number of cleaning vehicles (only a couple semi-automatic cleaning vehicles in a plant) and to the almost fixed speed of cleaning of each mirror, CSP plant operators must decide on the optimum strategy to obtain the best cleaning in the shortest time with the best cleaning effectiveness.

The duration of the cleaning task is adding to the cleaning cost. The optimization of the rate of cleaning, which is the time required for cleaning each reflector and the trajectory adopted to move from a reflector to another, is among the possible ways of improvement. A strategy developed by [31] consisted in optimizing routes and trajectories using a navigation system and an iterative algorithm that allowed 15% savings in cleaning time. Also, mastering the movements of the vehicles (stopping points, stabilizing, positioning the telescopic arms) are main concerns to the O&M of Ivanpah Solar Power plant [31].

As the soiling is not evenly distributed in every zone of the solar field, special techniques can be applied to different zones depending on their level of dirtiness. For example, Gemasolar power plant [22] developed a soiling map that indicates the level of soiling in every part of the solar field. This unevenness of soiling was also mentioned in [15], where harsh cleaning using chemical cleaning acid is performed in the zones near the power tower. The cleaning strategy of NOOR I solar plant, located in Ouarzazate, consists in partitioning the solar field into eight sectors with their reflectance monitored daily [27]. The cleaning of the entire solar field of this plant lasts for six nights with the cleaning order favoring the areas with the greater loss of reflectance. Another strategy adopted by [31] consists in accounting for two sectors in the solar field, near tower and far from tower, where two distinct cleaning vehicles are used. The first area located near the tower is cleaned by a tractor vehicle while the other area, referred to as being far from tower, is cleaned by a truck vehicle.

Scheduling the cleaning task according to a fixed time strategy makes it less reactive to maximizing the profit while maintaining a high reflectance. Flexible cleaning, on the other hand, depends on conflicting sets of parameters and is not simple to be continuously optimized. To tackle seasonal variations of soiling, a Condition-Based Cleaning strategy explained in [41] claims to reduce 5 to 30% of the cleaning cost compared to time rigid strategies.

2.4.2. Parameter Optimization

Optimal parameters of pressure and temperature are critical for water spraying methods. By investigating different ranges of both pressure and temperature, it was found that a pressure of 125 bar and temperature of 47.5 °C is the optimum combination for effecive dust removal [42]. Using hot water for washing is considered a good option, within certain limits to avoid risk on the personnel, when it enhances dust removal, reduces the time of cleaning and is economically justified [15].

The design parameters of the device used to spray water are also important to ensure an effective spraying and scrubbing effect. For example the nozzles arrangement impacts the water jet velocity [43] and tilting water-jet impingement by 15° from the horizontal increases the scrubbing effect.

2.4.3. Combining Cleaning Strategies

It may be beneficial to implement a two level method for cleaning soiled reflectors as pointed in [15]. This study suggests that non contact cleaning fails over many cleaning cycles to perfectly clean the mirrors thus leaving some dirt that accumulates and hardens in the long run. In this case, a complementary method is recommended to address the shortcomings of the routine washing strategy. Depending on its cost and need in the cleaning process, such methods can be used several times a year or in alternation with the main method.

3. Special Cleaning Agents

Natural cleaning, detergents and suppression of dust represent special cleaning mechanisms. The cleaning effectiveness of water-based washing methods can be enhanced using additives and detergents. Also, natural cleaning, weather parameters such as winds and rainfall, can either reduce the cleaning frequency or, at the opposite way, aggravate the soiling of reflectors. To reduce the cleaning frequency and preserve a good reflectance level, special simple measures such as dust control and suppression are among common practices adopted in CSP plants.

3.1. Additives and Detergents

Cleaning using additives, surfactants and detergents can be needed to remove dust from very dirty mirrors or after several cleaning cycles based solely on water. The cleaning solution effectiveness is determined by the surface chemistry between the cleaner and the dirty surface [44]. Only 98% of initial reflectance is obtained by cleaning with high pressure tap water and a surfactant to prevent water spotting [13]. Despite this, it was recommended in this study because it is nonabrasive and cheaper compared to other potential cleaning methods. To be a viable cleaning solution, detergents must not pollute the environment, reduce the surface tension, be easily mixed and used in the cleaning device and do not threaten to harm the surface over many cleaning cycles [14].

To compare potential cleaners, [44] performed a wetting study consisting of applying a certain volume of the cleaner and measuring the corresponding contact area of the wetted surface. The effect of various types of surface-active agents (surfactants) on sand particles was investigated by [45].

This study reported that a mixture of anionic and cationic surfactants is the most successful on sand particle regardless of the surface charge. In an experiment conducted by [46], various cleaning methods applied on mirrors exposed in la Plataforma solar de Almería revealed that alcohol-based detergent is very effective in removing dust.

The use of detergents is not necessarily beneficial for cleaning, for example it was found that its use was not advantageous when a high pressure water spray was applied with enough number of passes [42]. Also, this study concluded that there is no need for detergents when brushes coupled with a high pressure spray is the applied cleaning method. For enhanced detergent and water cleaning, hot detergent solutions were investigated in [13]. This study concluded that this method was not able to improve the water spraying effectiveness. When the result of cleaning using these additives is poor, harsh chemical cleaning can be used. For example, a 3% hydrofluoric acid wash was applied on the reflectors near the cooling tower [18]. This type of cleaning however is aggressive and was subsequently eliminated and substituted with periodic scrubbing.

3.2. Weather Cleaning

Abundant rain or wind blowing can be beneficial to remove dust from mirrors. For example, rainfall cleaning can reduce the need for artificial cleaning frequency during winter [47]. Also, the snow settling and sliding on the surface achieves perfect cleaning. Adversely, unfavorable weather conditions such as little rain mixed with dust can quickly deteriorate the state of the surface and may require a special cleaning compaign with additional need for scrubbing. To avoid this situation, adequately orienting the reflectors helps to avoid painful and costly cleaning [47].

Dry seasons and rainy seasons require different cleaning frequencies. Generally, intensive cleaning is mostly required during summer when electricity price is high. It was concluded by [20] that during rainy periods, the high-pressure demineralized water method is equally good as the cleaning using demineralized water and a brush. Also, scrubbing is needed when morning or night dew participates to strengthening the bonding between the particles matter and the reflectors.

3.3. Dust Control and Supression

Simple measures performed by the O&M staff can alleviate the soiling of reflectors. As explained by [14], the orientation of the mirrors could reduce or increase the amount of settling dust. For example, inverting the mirrors or putting them in stow position reduces the soiling, whereas horizontal position facing up is disadvantageous.

Another simple technique to prevent the soiling of solar reflectors consists in using dust fences to minimize fugitive dust. For example, by installing wind fences a reduction of 60 % of fugitive dust is obtained at a height of one and two meters [48].

The saltation of dust particles caused by the dryness of soils accentuates dust emission in CSP plants. This issue can be handled by a practical easy method consisting of spraying water on soils and paving the roads inside the CSP plants [49,50].

4. Innovative Water Saving Cleaning Methods

Due to water scarcity in the areas where CSP plants are deployed, novel cleaning solutions are prioritizing low water consuming technologies or opting for dust removal using other agents other than water. This section presents these technologies and discusses their strengths and short comings.

4.1. Lower Water Consumption

These low water consuming techniques rely on mechanisms aiming at weakening the bonding between the dust and the reflectors surface with the help of reduced amounts of water.

4.1.1. Ultrasonic Cleaning

This non-contact cleaning technique, also named acoustic cleaning, uses ultrasonic waves that generate cavitation bubble into liquids. This is achieved through piezoelectric materials that change their form under the effect of electric charge [32]. Under a high frequency (>20,000 Hz) electric field, piezoelectric ceramic materials vibrate generating ultra-sonic waves. These waves make the liquids cavitate, generating imploding bubbles in the cleaning solution. When these bubbles implode in the close area of a solid surface, asymmetric implosion takes places, delivering microscopic high velocity jets that removes attached particles on said surface. This cleaning mechanism is one of the most efficient cleaning methods in the market.

Within the framework of the WASCOP project [51], this cleaning principle has been applied for heliostats maintenance. For this purpose, a resonant sweeping wiper using agitation and cavitation with a very thin water layer as the cleaning solution is being tested. Also, a method based on this same principle for cleaning Fresnel and heliostat collectors, using piezoelectric transducers producing the ultrasonic wave emitted in the cavity, was proposed in [52]. The water consumption of this cleaning device is said to be 0.025 L/m^2 when the collector is horizontally oriented. When the system is used under oblique orientation, the water layer drops down and therefore, a constant water flow is needed in order to maintain the layer. In this case, cleaning results above 99% of cleaning efficiency need higher water consumption, but still lower than traditional methods such as pressure water jets. With the aim of achieving TRL 5, said device is being tested on a real heliostat field in CIEMAT PSA. The device is focused on the cleaning of a single facet of 3000 × 1000 mm, working under oblique configuration and manually swept. Deionized water consumption can be regulated by means of nozzles and sweeping speed controlled by measuring the process cleaning process time. The goal of the experiment is to measure the water consumption needed in order to obtain more than 98% of relative reflectance in comparison with traditional cleaning methods such as pressured water jets. The graph in Figure 3 shows the evolution of the cleaning consumption both for ultrasonic cleaning (US) and water pressured jets (WPJ) during the testing campaign. It can be appreciated, that the water consumption drops in both cases as the campaign goes on. This is because of the fact that both systems are being tuned in order to obtain more than 98% of reflectance with minimum water consumption. As it can be appreciated, after 6 weeks period, both systems are giving lower water consumption than during the initial tests, but ultrasonic cleaning needs 7 times less water than pressured water. Similarly, an ultrasonic vibration cleaning using water as a solvent to clean soiled mirrors is adopted in [13].

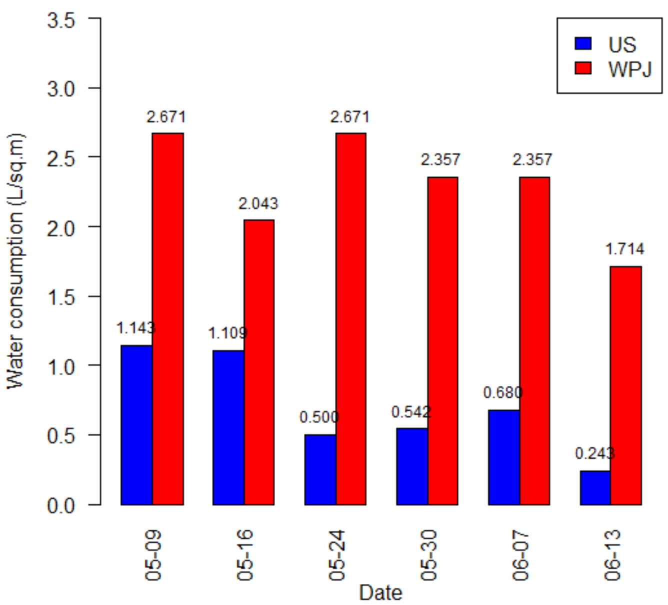


Figure 3. The results of the ultrasonic cleaning conducted in May and July 2018 in PSA.

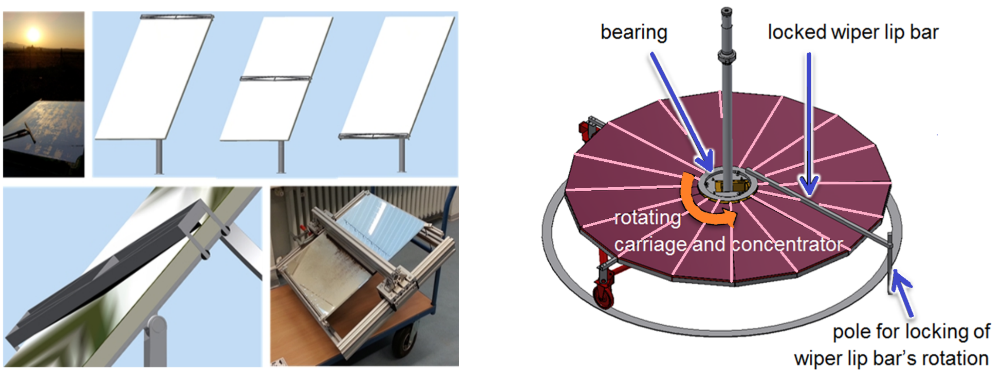
4.1.2. Automated Wiper Lip Cleaning Methods

Previous studies [53] have shown that water-soluble particles are cemented onto the surface of solar reflectors during alternating dry and humid periods as encountered in desert areas. The cleaning effort and water consumption to remove cemented particles is significantly higher than cleaning a surface with not cemented particles. Therefore, it seems desirable to clean the mirrors after every dew formation or rain. Then simple cleaning methods with low water consumption like wiper systems can be applied. To avoid high labor costs automated systems would be required [54].

Dew is a major source of water in arid regions where it could provide up to 40% of the annual water deposition [55]. Using a dew-based cleaning method was proposed in [56] where wipers, cleaning angles and surface wetting time were varied and tested. This study revealed that a 99.3% cleaning efficiency is obtained using normal single wiper, versus 98.9% results from applying industrial wiper.

However in the absence of dew and rain, additional water supply is needed. Within the WASCOP project, an innovative concept for heliostats cleaning that partly uses dew for cleaning is proposed. This concept consists in installing a lip moving by gravity and guided at the edges of a heliostat's mirror panel, see Figure 4a. To be able to bring the wiper lip back to its starting position only by gravity it must be possible to reduce the elevation angle significantly below horizontal orientation. Then no additional drive is needed. However, a system to control the wiping speed while sliding down during cleaning would be required and might be costly.

For heliostats with approximately round concentrators (with common vertical primary axis) it is possible to realize a wiper cleaning system which is driven by the azimuth drive [54]. The concept is illustrated in Figure 4b (patent pending). The wiper lip is fixed on a bearing in the center of the heliostat. During cleaning, the bar holding the wiper lip is stopped from rotating with the concentrator by a pole positioned next to the heliostat. Thus, the concentrator rotates under the fixed wiper lip and is cleaned. If the wetness caused by dew or rain is not sufficient additional water is sprayed on the mirrors through the wiper lip bar or from the pole besides the heliostat. The benefits of the cleaning system are that labor cost is reduced significantly and that it could ,thus, be run more often than common cleaning systems. Hence, the average cleanliness and consequently the efficiency of the solar power plant would be increased. Furthermore, less water is required.



(**a**) (**b**)

Figure 4. Wiper lip system. (**a**) Dew-based technology (lip system); (**b**) Wiper lip bar fixed at a central bearing and stopped from rotating with the concentrator by a fixed locking pole.

4.2. Dry and Semi-Dry Cleaning

Dry cleaning methods represent sustainable solutions to be deployed in arid environments. In this section, promising mechanical, electromechanical and electric methods are presented.

4.2.1. Mechanical and Electromechanical Methods

A new system dedicated to heliostat cleaning is being developed by BrightSource Industries, based on a waterless, automated mechanical cleaning solution replacing the conventional process, see Figure 5. Key aspects of the technology include a dry-cleaning automated process that requires no water on a regular basis. Sufficient and even pressure on the reflector surface is maintained by a small DC motor. To optimize the performance, the heliostat's installed PV cell is used as a power source in addition to sophisticated integration with the solar power plant's control system. The system will enable more frequent cleaning that will increase annual electricity production while reducing operating costs.

Figure 5. Images of 1st (**right**) and 2nd (**left**) generation integral cleaning devices installed on a heliostat in BrightSource Solar Energy Development Center (SEDC).

The current design features a 3rd generation of a heliostat cleaning device which is based on the studies and tests performed on the previous generations. Those tests resulted in improved cleanliness of the heliostat over time. In the testing phase, it was found that three heliostats with installed integral cleaning device showed steady reflective values of $\sim 90\%$, while the performance of a reference heliostat without the device is gradually degraded between each manual cleaning operation. The Implementation of such automatic cleaning devices can provide immediate solution post dust storm events. Another electromechanical cleaning method acts by weakening the dust bonding to the reflectors by vibrating or shaking the surface. A cleaning technique based on this principle was mentioned in [13]. Also, a method converting high frequency electrical currents to mechanical vibrations was proposed in [57] where generators and piezoelectric or magnetostrictive transducers, placed on the dirty collector, produce oscillations that are transmitted to the dirty surface. Once the dust is detached, it is then repulsed by tilting the surface or by wind action removal.

4.2.2. Electrostatic Methods

Electrostatic methods act on dust removal by charging a transparent conductor sheet using a high voltage [58]. By applying phased voltage pulses, the electrodes charge the dust particles which are then removed by three-phase alternating electric field [59]. To perform this task, an electro-dynamic screens (EDS) designed by laminating a transparent dielectric film containing parallel electrodes can be retrofitted to collectors in operation or implemented in the manufacturing phase of reflectors [60]. Figure 6 shows the layers needed for retrofitting a second surface CSP mirror [59].

This self cleaning method consumes low energy and its cleaning effectiveness is said to remove more than 90% of soiling in just two minutes. This performance is only valid when the deposited particles diameter is greater than 2 μm and the relative humidity is lower than 50% . The shading effect of the electrodes which causes a loss of reflectance is a main disadvantage of this method. An optimum design was found in [61] reporting that an electrode width superior to 25–50 μm, with a center-to-center spacing of 700 to 800 μm permits the best cleaning efficiency with minimum reflectance loss [59]. This technology is believed to significantly reduce the need for cleaning. For example, based on the calculation of a 250 MW plant using lab scale data inputs and assuming the cost of production, a 74% water reduction is obtained by applying EDS technology[62].

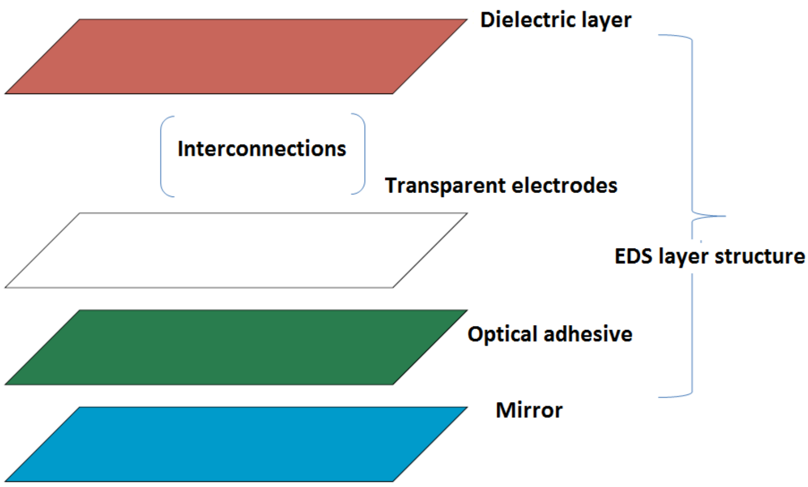


Figure 6. The components layers of EDS technology retrofitted on a second surface mirror [59].

5. Soiling Prevention

Less frequent cleaning is needed when effective dust preventing solutions are adopted in the CSP plants. This can be achieved by developping mirrors with advanced anti-soiling coatings and using dust barriers that are strategically deployed in the solar field.

5.1. Anti-Soiling Coatings

These methods alleviate the soiling issue by reducing the cleaning frequency [63–65]. To prevent the soiling, different strategies modifying the surface energy (wettability) of top layer CSP can be adopted. Hydrophobic (water repellent) or Hydrophilic (water attracting), process have good cleaning attributes. In the first case, the contact angle of the surface which is greater than 90° promotes water droplets which are prone to sliding and enables the removal of the dust in the trajectory. In the second case, the contact angle less than 90° promotes a thin water over the surface and thus prevents the accumulation of dust.

However, the contact angle of a surface can be modified to generate the superhydrophobic (contact angle $\geq 160°$) and superhidrophilic coating ($\leq 10°$), to maximize the cleaning behaviour for CSP reflectors. To prepare superhydrophobic [66] coatings there are different methods based on silica, combined with some fluoropolymers or polyurethane of polisiloxane binder applied using spin and spray technique, while other methods [67] are based on Al_2O_3, TiO_2 and ZnO top coatings using the Ion Layer Gas Reaction (Spray-ILGAR) technique. To prepare super hydrophilic coatings there are different materials such as WO_3 and TiO_2. These materials also present the photocatalytic functionality causing the decomposition of organic materials under solar irradiation. Currently, the most frequently used material is the TiO_2. The hydrophilicity of a TiO_2 surface can be induced by UV-irradiation. Electrons and holes produced by UV irradiation are trapped by surface and O^{-2} ions, producing Ti^{+3} and oxygen vacancies, respectively. Thus resulting in the adsorption of water molecules at the defect sites and the forming of hydrophilic domains. Among the possible shortcomings of these techniques the subsequent loss of reflectance and the lack of durability of the coatings.

5.2. Dust Barriers

Dust barriers are promising options for preventing the dust particles from entering the solar field. This solution is different from security fences and wind-breaks conventionally used in most CSP plants. Dust barriers must target particles ≤250 µm that are mainly responsible for reflectance loss [68]. Using fluid dynamics and air flow, a solid wind barrier designed optimally can successfully avert 86% of large dust particles [69]. Although seemingly a simple solution, multiple considerations impact the effectiveness of such systems such as their distance to the reflectors, their location in the solar field, and the shape of these designed obstacles. Cranfield University proposed different shapes of dust barriers with optimized porosity, see Figure 7, that are being tested in PSA.

Figure 7. Dust barriers installed in PSA.

6. Other Aspects

In arid and semi arid environments, water quality and its subsequent re-use are among the important aspects to be taken into account for selecting the cleaning strategy. The quality of water is essential to guarantee a benign cleaning without any deterioration of the surface of the mirrors. After washing reflectors, alternatives for collecting, recycling and reusing the washing water are presented. Since the use of any cleaning solution is dependent on its cost, the different considerations influencing the costs involved in this task are explained.

6.1. Water Treatment

Depending on the location of the site selected for CSP deployment, raw water can come from wells, dams or desalination plants. A low water quality is detrimental for cleaning. To avoid spotting, tap water use is excluded and at least some form of treatment is required [14]. Also, the water dedicated to mirror washing should respect certain requirements to avoid problems like degradation and staining.

In desert locations where water is desalinated, washing water is reverse osmosized for mirrors washing [2]. Generally, the elimination of magnesium and calcium ions is recommended and a value below 5 ppm is advised [15]. Using a washing water hardness of 12 ppm is good enough to achieve similar reflectance to using hardness lower than 5 ppm (only a 0.5% is the difference between the two cases) [42]. Following this same study, using deionized water can be costly and should be thoughtfully studied. Also, using additives such as sheeting agents added to the rinse water is beneficial for reducing the water droplets left on the reflectors and accelerates the drying [15]. Unfortunately, in current CSP plants a great deal of washing water spills on the ground and is seldom recovered.

6.2. Water Collection and Re-Use

The washing water could be recovered by semi-autonomous cleaning vehicles using a collection tray as proposed in [70], or by cleaning robots equipped with sucking devices that could be recuperated later for treatment.

Separating clean water from contaminants is a delicate task as these contaminants contain a mixture of substances including dust, salts, and detergents. Investing in a post treatment plant can be water saving but costly. In an attempt to recover and reuse this water, a nanostructured inorganic filtration membranes is developed in [2] to decontaminate the washing water. In the frame work of MinWaterCSP [71], Waterleau [72] developed an on-truck water treatment system that suits the composition of water generated by the trucks cleaning CSP mirrors. This system illustrated in Figure 8 comprises components for performing operation such as sedimentation, cartridge micro filtration, activated carbon filtration in addition to the phase of ion exchange or reverse osmosis.

Concerning water reuse, it was proposed to use wastewater generated from the washing activity in dust reduction [49], this strategy of wetting dry soils minimizes saltation of particles and contributes to compacting the ground. Recycling water of enclosed trough systems is performed in [29] where it is recycled back to the gutter system so it can be later reused.

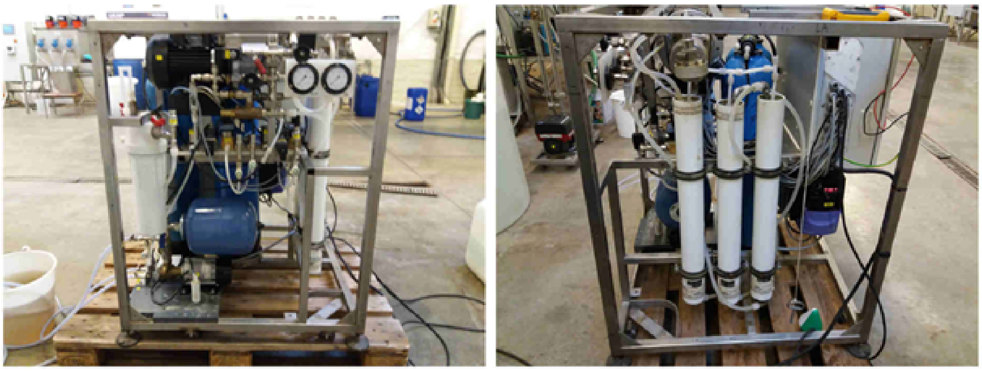


Figure 8. On-truck water treatment unit for mirror water reuse (courtesy of waterleau [72]).

6.3. Cost of Cleaning

The effectiveness of a cleaning method is judged by its capacity to regain high reflectance with minimal environmental impacts and reduced water consumption with of course minimal deterioration over cleaning cycles. From an economic point of view, cheap and affordable cleaning systems enabling less frequent cleaning frequency and short cleaning rates are of great importance. The cleaning should be initiated when the economic value of the energy gained by cleaning justifies the cleaning cost [15]. However, due to the complexity of this decision, the cleaning is performed when the cleanliness is below 96% cleanliness level [47]. The frequency of cleaning is determined, among other factors, by the seasonal soiling rate and the economical value of the generated power. Severe weather conditions, such as dust storms, decrease dramatically the reflectance and require instant intensive cleaning.

The cleaning cost involves fixed costs for acquiring the cleaning devices and various variable costs. The variable cleaning costs increase with a reduced frequency interval. They involve the cost of water and its treatment (if any), the cost of fuel or energy and the salaries of the staff involved in the cleaning task. It is estimated that \$0.21/m^2 is the yearly cost of washing at KJC combining the deluge and Twister [18].

The Equations (1) and (2) [73], present the cost of cleaning using cleaning vehicles:

$$C_{O\&M} = C_{Labor} + C_{Fuel} + C_{Water} + C_{maintenance} + C_{Replacement} \quad (1)$$

$$C_{total} = \frac{C_{capital} + F_{PVA} * C_{O\&M}}{M} \quad (2)$$

where C_{total} is the total cost required for the cleaning task in (\$/m^2), $C_{capital}$ is the investment for purchasing the cleaning vehicles, F_{PVA} is the present value of the annuity and M is the total field area.

New cleaning technologies must be competitive both in cost and efficiency. However, it is not easy to compare the economic benefits of innovative technologies as each method has its production and O&M costs. A levelized cost of mirror cleaning variable was proposed by [74] to compare different cleaning technologies. This indicator is defined in [74] as follows :

$$LCOMC = \frac{C_{Annual}}{E} \quad (3)$$

where C_{Annual} is the annual cost of acquiring, installing, operating and maintaining cleaning technologies and E is the expected yearly produced energy that takes into account the loss of reflectance associated with the corresponding technology. For the case of EDS technology, it is argued that attaning a cost of around \$10/m^2 or less is financially competitive compared to a deluge type cleaning [74]. This calculation took into consideration also the use of deluge cleaning as a complementary method with spaced cleaning frequency.

The economic gain of selling electricity produced by the CSP plant dictates the frequency of cleaning. It is recommanded to perform more frequent cleaning for countries with lower wage salaries like Morocco, while countries like Spain are encouraged for less frequent cleaning due to the impact of the cleaning staff salaries on the achieved profit [75]. Also according to this same study, opting for an optimal cleaning strategy increases the economic gain by 2.6 %.

6.4. Receiver Tube Cleaning

Parabolic trough technologies focus the incident irradiation on the receiver tube. When this component is soiled, the optical efficiency of these concentrators drops. This dirtiness, measured by the decay in transmittance, is even higher in troughs located in proximity of the cooling tower where high humidity cause the dust to adhere strongly to the receiver tube surface [76]. The cleaning of the receiver tubes is tricky as it is vulnerable and difficult to reach. Therefore, any cleaning that is susceptible of scratching or degrading the anti-reflective coating has to be excluded. These tube suppliers advice to adopt a certain cleaning method to preserve this component. It is recommended to clean the receiver using a pressure below 20 bars and demineralized water with a quality under 1 μS/cm while holding the nozzle at a cleaning distance greater than 40 cm from the tube [76]. To find the adequate cleaning method for receiver cleaning, many designs of the cleaning nozzle, in addition to various distances from the tube are attempted in [77]. This study dismissed using a brush and sponge for contact cleaning and favored fiber cloth instead. Also, it suggested that the cleaning trucks should have their cleaning jets facing the effective part of the tube.

Concerning the cleaning devices, special vehicles spraying the tube from different positions and with different orientations were proposed in [78]. To decrease the soiling rate, the frequency of washing and the risk associated with repetitive cleaning, the receiver tubes can also benefit from anti-soiling coating technologies.

7. Discussion

Sustainable water saving cleaning and cooling technologies will not only allow CSP plants to gain more attraction and produce cleaner electricity, but also will decrease the growing tension between the use of this scarce resource for industrial purposes versus agriculture and drinking water needs. The research on cleaning must further focus on how to keep the reflectors clean rather than how to clean them when dirty. The first path leads to technologies that equip the solar surfaces with mechanisms and features for dirt prevention and thus maintain high reflectance, although this requires considerable upfront costs. While the second choice only deals with the cleaning issue once the solar field is deployed in the selected area and then tries to optimize the cleaning according to the site specific conditions. This second approach is limited and requires a dedicated cleaning staff and additional costs during the operation of the plant.

Dust prevention and cleaning of reflectors are essential for CSP plants to be profitable. They require balancing conflicting objectives such as minimizing the cost of cleaning and water consumption while maximizing the yield and the economic profit. The perfect cleaning solution would guarantee cheap and fast cleaning with no need for water and with low investment and operation costs. Unfortunately, to this date no technology fulfils all these criterion. Table 2 shows the advantages and disadvantages of many available cleaning approaches.

As CSP plants are opting for dry cooling instead of wet cooling, reflectors washing becomes the activity that most consumes water. Thus the urgent need for innovative sustainable cleaning concepts of CSP reflectors. The most used cleanings systems in today's CSP plants are cleaning trucks equipped with high pressure nozzles and scrubbing brushes. These systems are the most mature as vehicles are well controlled especially when sensors are present to prevent mirrors breakage. The decision to add detergents or use heated water is weighed against the resulting improved effectiveness, their additional cost and their environmental impact. Even when an optimized cleaning strategy is adopted, water remains an essential element for washing. For these conventional methods to be a viable option, recovering of washing water, either for later use in other activities of the CSP plant or for subsequent washing of reflectors, is crucial.

Table 2. The characteristics of various available cleaning solutions.

Cleaning Methods Characteristics	High Pressure	Scrubbing Brushes	Combined High Pressure and Scrubbing Brush	Optimized Strategies (Alternation of High Pressure and Brush)	Ultrasonic Cleaning	Dust Barriers	Antisoiling Coating	EDS
Cleaning capability	Average	High	High	High	High	Average	Average	Average
Water saving	Low	Low	Low	Low	High	Average	Average	Average
Energy or fuel consumption	Average	Average	High	Average	Average	-	-	-
Cleaning Operators	Average	Average	Average	Average	Low	-	-	Low
Speed of cleaning	Average	Low	Low	Low	Average	-	-	High
Frequency of cleaning	High	High	High	High	Average	Low	Low	Average
Technology readiness	High	High	High	High	Low	Average	Average	Low
Replacement of components	Average	Average	Average	Average	Unkwon	Low	Unkown	Unkown
Investment Cost	Average	Average	Average	Average	Unkown	Low	Unkown	Unkown

8. Future Research

Promising alternative to conventional high water consuming methods are being developed. Coatings applied on the surface of the reflectors are gaining attraction as they prevent dust deposition and reduce the cleaning frequency. However they have to withstand the test of time by demonstrating durability during the expected life time of the plant. Also, as this technology does not totally eliminate the need for cleaning, it must be used in conjunction with other cleaning technologies. In this case, if this additional cleaning is in contact with the coated surface, the durability of the coating must be further enhanced. Similar economic and environmental concerns raise with ultrasonic cleaning solutions that although consume little water and eliminate the need for contact cleaning, their TRL remains low and their cost and effectiveness must be further tested and proved. Concerning the automated wiper lip cleaning methods it must be proven that the wiper would not scratch the glass of the mirrors. Regarding the low scratching rates of car windscreens by wipers it is accepted that the scratching will be low as long as it can be ensured that no soil cements on the mirrors.

Concerning dry cleaning methods, they dislodge dust with shaking, vibrating or applying a high voltage on the targeted surfaces. Barriers to the development of these dry methods could be either their prohibitive cost, their unproved performance or their non readiness to large field deployment. For example the cost of the EDS technology is not well known, as it is still in the laboratory scale and its cost adds up to the already expensive cost of mirrors.

Another aspect to take into account while evaluation a cleaning solution is that not all cleaning technologies perform equally well all the time. Effectiveness may be high at certain optimum conditions and less effective under other environmental conditions. The EDS self-cleaning solutions are only very advantageous for a certain range of particles and for certain humidity range, see Section 4.2.2.

Advanced learning algorithms can be of great benefit for detecting the soiling level in large CSP solar field which make them a powerful tool for selelecting optimized cleaning strategies. The level of soiling of the solar field can be obtained based on the analysis of color pixel of soiled solar surfaces. Such methods require advanced machine learning algorithms capable of classifying the dirt on the mirrors. An investigation performed by [79] used the color and intensity data of digital photographs as indicators to detect soiling. Another method based on convolutional neural networks was proposed to forecast soiling level in [80]. This algorithm uses as inputs RGB images of a soiled surfaces and environmental parameters. Also, soiling prediction using artificial neural networks was attempted by [81]. However, the problem with these methods is that they need extensive reflectance and environmental data measurements.

9. Conclusions

High DNI sites are synonymous with severe dusty environments. With the deployment of air-cooled condensers or hybridized coolers in CSP plants, the washing of reflectors will become the main consumer of water. Opting for an adequate cleaning system requires weighting the economical benefits of its implementation (investment and maintenance cost) versus the expected gain in the CSP plant yield. Although water-based methods present the enormous disadvantage of using a scarce resource, they remain by far the most used methods. However, the cost of purchasing water for the washing of reflectors must be increased and penalized so other sustainable cleaning strategies are favoured.

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Nomenclature

Acronyms	
LCOMC	Levelized cost of mirror cleaning ($/KWh)
PVA	The present value of annuity
CSP	Concentrating Solar Power
DNI	Direct Normal Irradiance
EDS	Electro-dynamic screens
O&M	Operation and Maintenance
ppm	Parts per million
PSA	Plataforma Solar de Almería
RH	Relative humidity (%)
TRL	Technology Readiness Levels
UAV	Unmanned aerial vehicle
US	Ultrasonic cleaning
WASCOP	Water Saving for Concentrated Solar Power
WPJ	Water pressure jets
Roman symbols	
C	The cost of cleaning
E	The expected yearly produced power (KWh/year)
F	Financial factor
M	The total field reflective area (m^2)

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