Photovoltaic technologies: problems, technical and economic losses, prospects

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Abstract

Photovoltaic technologies directly convert sunlight into electricity and are one of the most common renewable energy sources. Solar power is the most efficient and economical way to generate electricity. To continue to reduce the cost of this technology and increase profits, the solar industry is constantly looking for ways to maximize efficiency and minimize the losses and costs associated with the energy production process. Nevertheless, photovoltaic systems, including solar panels, tend to accumulate dust and dirt particles. As a result, the fraction of incident light decreases and this leads to a decrease in energy conversion efficiency to 50%. At the moment, a universal solution to the problem of pollution of photovoltaic systems does not exist due to their location-specific and seasonal fluctuations, differences in local energy costs, as well as the availability and cost of resources.

Keywords 1

Photovoltaics, solar energy, soiling, concentrated solar power, dust cleaning

1. Introduction

In 2020, the share of wind power plants (WPP) and solar power plants (SPP) in the structure of electricity production has doubled – to 6.8% (3.3% in 2019) with a total electricity production of 148.9 billion kWh (Fig.1, Table 1). The installed capacity of these renewable energy sources (RES) during the year increased by 1.9 GW (+ 41% compared to 2019) [1].

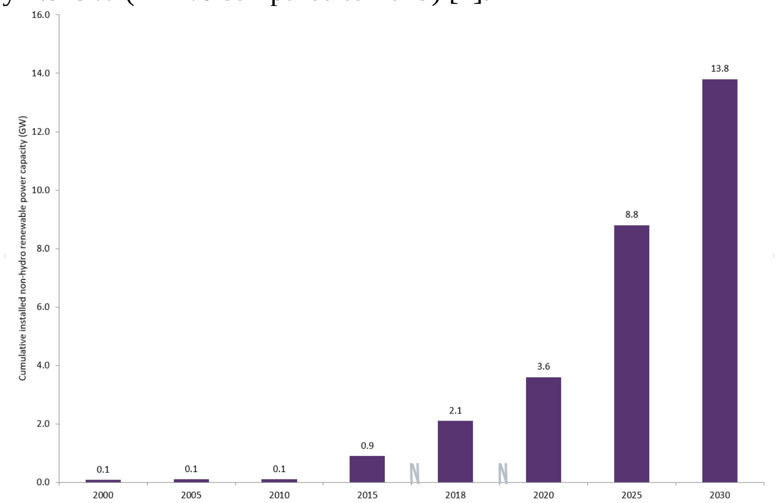

Figure 1: Power market: Ukraine, cumulative installed renewable power capacity (GW), 2000–2030 [2]

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The installed capacity of SPP increased the most, the peak production of which in the spring-summer period falls on the hours of daytime consumption reduction (from 12:00 to 17:00), which requires flexible tools to balance them. The balancing of RES, mainly SPP, during the day was last year and remains today the main problem of integration of RES into the energy system of Ukraine.

Table 1
Dynamics of installed capacity volumes and share in the total production of wind farms and power plants

	2019	**2020**	**Δ**
Installed power, MW (%)	3555.4	5362.6	+1807.2 (+50.8%)
Volumes and share in total production, billion kWh (%)	3.1	6.8	+3.7 (4.6%)

At the same time, in 2020 the transmission system operator (TSO) and distribution system operators (DSO) issued a total of technical conditions for connection to the united energy networks of Ukraine of the new generation of RES with an installed capacity of 1374.95 MW, of which 1035.7 MW – to OSP networks, where SPP accounts for 78%. That is, the growth of RES capacity will continue and, accordingly, will increase the share of RES in the structure of electricity production [3].

Also, in Ukraine there is a law "On the electricity market" (Law "On the electricity market" from 13.04.2017, № 2019-VIII) in terms of penalizing electricity producers at the "green" rate for daily generation imbalances in the network relative to the accepted and agreed with a "guaranteed buyer" forecast from the manufacturer. Responsibility for the accuracy of forecasting rests with the producer "… In order to limit the impact of support for electricity producers on the "green" tariff on electricity prices…"[4].

Producers of "green energy" are fined for deviating from the approved forecast – by 10% for SPP. For large producers with a share of 5% or more in the total energy balance of the country, respectively, the tolerance will be 5%. The Law defines (see paragraph 11 of the section on transitional provisions) that

The share of compensation to the guaranteed buyer (from) producers at the "green" tariff, the cost of settling the imbalance of the guaranteed buyer is [5, 6]:

- until December 31, 2020 – 0 percent;
- from January 1, 2021 – 10 percent;
- from January 1, 2022 – 20 percent;
- from January 1, 2023 – 30 percent;
- from January 1, 2024 – 40 percent;
- from January 1, 2025 – 50 percent;
- from January 1, 2026 – 60 percent;
- from January 1, 2027 – 70 percent;
- from January 1, 2028 – 80 percent;
- from January 1, 2029 – 90 percent;
- from January 1, 2030 – 100 percent.

According to an IEA report under the PV-power Systems Program, the use of mesoscale meteorological models "does not appear to improve forecasting quality." Post-processing of data (mainly spatial averaging and error correction) can relatively reduce the inaccuracy of the local estimate by 15-25%, but still for short- and medium-term forecasting it will be at least 25-30%.

2. The main methods for making forecasts of electricity generation during the operation of solar power plants

Cloudless sunny weather has a positive effect on the growth rate of energy generation. But on cloudy days, there is a high density of cloud masses, which causes a decrease in the amount of production of this type of resources. The most urgent solution to this problem is the need to forecast the amount of electricity that a particular solar station can produce [7,8]. High-quality forecasting enables manufacturers and operators of grid companies to competently manage the performance indicators of solar panels, thus effectively introducing "green" energy into the overall energy system of the country.

This procedure should, first of all, take into account the amount of solar radiation that the stations will receive. This indicator can be influenced by many different factors, including meteorological and climatic conditions, namely, daylight hours, rainfall, wind speed and much more.

During choosing a forecasting method, a specialist needs to take into account what data he should receive as a result of calculations. If he needs to find out the total production of electricity or change the volume of production, then he will need various mathematical methods and approaches. Next, we will talk about two basic techniques that allow to make a forecast of the production of this type of resource for up to 6 hours or a day in advance.

2.1. Methods for making a forecast of sun activity for up to 6 hours

Currently, the main methods for determining solar activity are the total sky imagery and the study of photos from space [9] (Fig.2). These methods provide an opportunity to make short-term forecasts up to 6 hours and make the following assumptions for the future generation of electricity from solar stations for a period of at least a day.

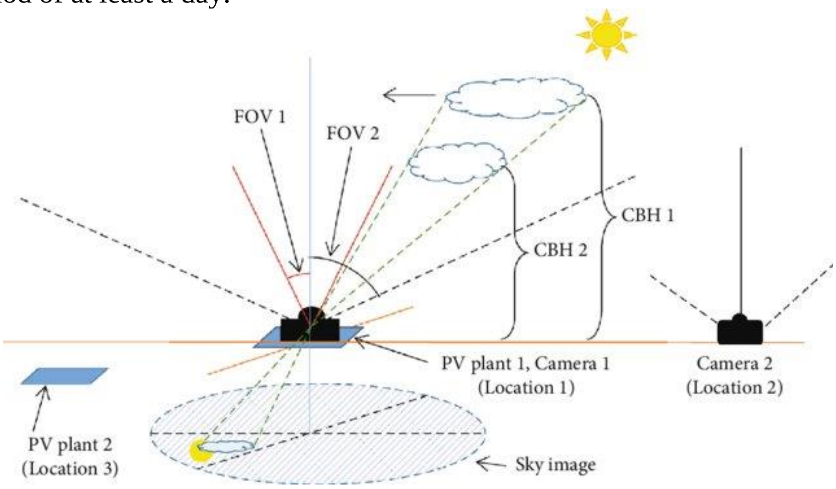

Figure 2: Camera locations, different FOVs of a camera [9]

This method is used to make forecasts of future volumes of electricity production by "green" plants in almost real time. This method makes it possible to predict with high accuracy the generation of electricity half an hour in advance.

To make a forecast, a specialist must perform the following operations:

- to get pictures of the sky in the area where the power plant is installed – for this, it is necessary to take pictures from the earth's surface;
- to analyze the received information, identify thin and thick clouds;
- to evaluate the vector of movement of cloud masses – for these purposes, a sequence of a small number of images will be required;
- knowing the location of the clouds, information about the vector of their movement, it is necessary to calculate the irradiation power and create a forecast for the generation of electrical energy.

Specialized meteorological stations provide the necessary information regarding the size, structure and movement of cloud masses. It is these data that make it possible to make accurate predictions even for a small-time horizon.

As for forecasting for a longer period, its accuracy is noticeably reduced. The main reason is that it is very difficult to determine the movement of clouds and the change in their geometric shape. Currently, there is still no exact mathematical model that allows to determine the formation of cloud fields.

Alternatively, you can use images of cloud masses taken from the surrounding area, and then make a forecast that will take into account the vector of movement of cloud masses. The technician should also be aware that clouds in different layers have different properties. For example, low clouds can move faster than high clouds. In the photo, the clouds located in the lower layers can cover the high ones.

2.2. Analysis of cloud conditions by studying images from space

This method practically repeats the algorithm of the previous method. Except that instead of the images of the sky and cloud fields taken from our planet, the photographs taken from satellites installed in space will be used. This information can be transmitted by optical photography or by using infrared sensors.

The main advantage of this method is to obtain cloud scales over a large area. It should be noted that satellite imagery is of high quality and allows to cover almost the entire area of the Earth. As for the previous method, Total sky imagery is suitable for implementation in a certain area. A reliable measurement of the reflectance makes it possible to accurately calculate the cloud index. According to the applied formula, this indicator depends on the optical depth of the cloud. This method has been studied quite deeply, and therefore has become widely used in the study and marking of solar resources on the map (Fig.3). Thus, insolation is determined for a specific area [9].

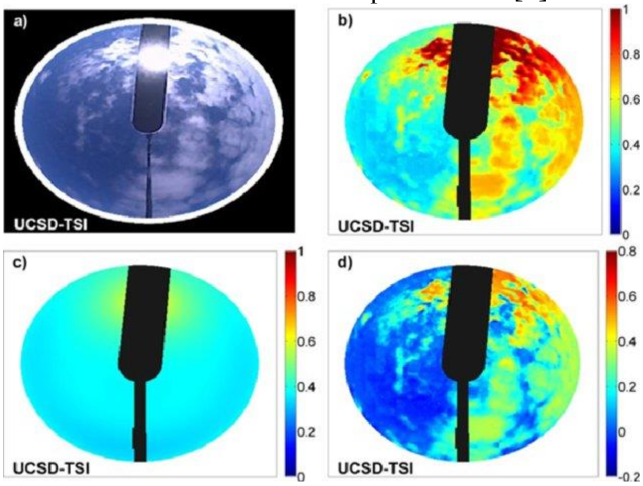

Figure 3: Clear Sky RBR generated [10]

Among the disadvantages of the method is the fact that most ordinary space satellites send data exclusively through the visible spectrum, and therefore, morning forecasts are often less accurate. The main reason is the lack of accumulation of the necessary information. Experts are trying to cover this gap with images obtained using infrared radiation. You also need to understand that the spatial resolution of space satellites is several times less than that of images of cloud fields taken from the earth's surface. This method allows to photograph large clouds, while small formations remain unnoticed, which negatively affects the accuracy of the insolation calculation. The frequency of transmission of information is much less than in the first method. In addition, it should be taken into account that processing satellite data requires much more time from specialists, which also affects the accuracy of forecasting.

The use of satellites makes it possible to create an accurate forecast up to 6 hours, which in most cases exceeds the performance of numerical methods for determining the weather.

At the moment, solar energy around the world has begun to practice forecasting the production of "green" energy for a short time, starting with one day and ending with a week. So far, this type of forecasting does not have a clear system, since the results show a large error. Therefore, the longer the forecast period will be covered, the more reliable the result will be.

Do not forget about factors that are indirectly related to natural features, one of the most common is the level of dustiness of solar panels. As a rule, this indicator increases if there is hot weather without rain for a long time. The rain will wash away the dust from the panels and increase the generation of electrical energy accordingly. This factor should also be taken into account when making a forecast.

The best way to predict solar energy production is to average the forecasts that are provided by various weather services.

Today, forecasting the indicators of solar energy production is done by several large companies located in countries where solar energy is developed. Everything is just beginning in Ukraine, there is a lot of work ahead, the result of which will be the emergence of its own forecasting systems. In the near future, forecasts will help not only take into account the weather conditions of our country, but also adapt to changes in local legislation.

3. Reduction of solar energy production due to air pollution with dust and particulate matter

Pollution can easily cause electricity loss of more than 1% per day and is a specific phenomenon that depends on local climatic conditions [11]. The predominant type of pollution can vary significantly depending on the location: deposits of mineral dust, bird droppings, biofilms of bacteria, algae, lichen, mosses or mushrooms, plant debris or pollen, engine exhaust gases, industrial emissions, as well as agricultural emissions, for example, feed dust (Fig.4) [12, 13, 14].

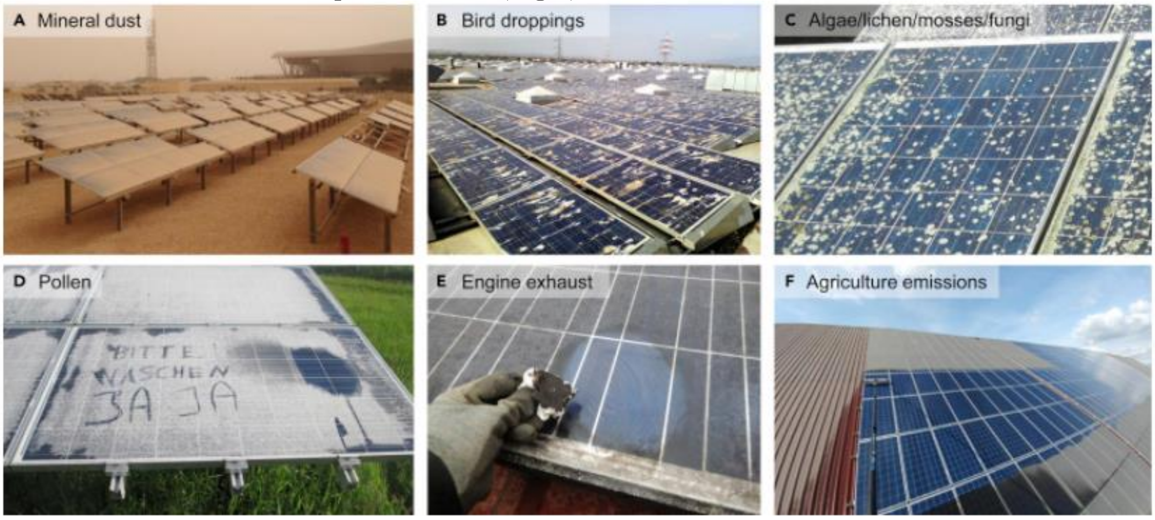

Figure 4: Examples of Soiling [15]

As a result of natural processes and human activities, dust is formed, which is present in the air in the form of solid suspended particles (PM). The properties of the dust particles vary depending on the location. Dry desert areas are characterized by electrostatically attracted inorganic materials, in coastal areas – salt and dirt caused by rain. Industrial and cooler areas are dominated by wind-borne organic mud, evaporated rain deposits, and atmospheric pollutants from fossil fuels [16, 17]. In China, Africa, India, peak losses can vary by 10-70%; in Europe – 1-7%. Table 2 shows the different properties of dust particles on different continents [18].

Table 2
Comparison of dust samples in some places [19]

Location	Major elements	Major Oxides	Origin
Hangzhou (30.25° N, 120.16° E), China	Si, Ca, Al, Fe, K, Mg, Na	SiO_2, Al_2O_3, Cao, Fe_2O_3	Sand, potash feldspar, straw burning, mechanical wear
Perth (56.39° N, 3.43° E), Australia	Si, Ca, Al, Fe, K	CaO, SiO_2, $KAlSi_3O_3$	Acidic and sandy soils from deserts
United Arabic Emirates		SiO_2, Fe_2O3, CaO	Human activities, wind-blown dust coming from the Arabian Peninsula

Doha (25.29° N, 51.51° E), Qatar	Ca, Si, Fe, Mg, Al	$CaCO_3$, $CaMg(CO_3)_2$, SiO_2	Calcite, dolomite, building, local soil
Cairo (30.04° N, 31.24° E), Qatar	Si, Ca, Al, Fe, Mg, K, Na	SiO_2, $CaCO_3$	Cement industry, desert, fossil fuel combustion
Northern Poland	Si, Al, Mg, Fe, K, Ca, P, S	SiO_2, Al_2O_3, MgO	Sand, frictional elements of mechanical components

The HÜBTAM laboratory analyzed in a scanning electron microscope particle taken from the surfaces of solar panels and determined the content and number of particles forming dust. The figures show the monthly change of elements with a powder content of more than 5% of the number of elements [20].

In the figures 5-7, the particles contain oxide forms of elements that occur in nature, such as Si, C, Ca, O, Al, and F. In particular, the height of the oxygen element is indicated in Figure 6 shows. As can be seen from the results, between the end of the winter season and the transition of the spring period, the transitions of heavy elements carried by dust also increase. This transition also increases the tendency of contaminants to adhere to the surfaces of the panels. Change of item depending on months below 5% is given in Table 3.

Table 3
Amount of element in % March-December

Element Name	March	April	May	June	July	August	September	October	November	December
S	0	1.12	4.09	0.22	0	0.34	0.43	0	0	0
Mg	2.12	3.6	1.56	1.49	0.57	0.19	0.43	1.11	0.23	0.56
Fe	1.54	1.30	0.42	0.47	0.76	0.22	0.27	0.57	0.58	0.23
Na	1.49	0	1.93	1.09	0.01	0.06	0.42	0.07	0	0
In	0	0.83	1.40	0	0	0	0	0	0	0
K	1.09	0.23	0	0.36	0.12	0.11	0.2	0.11	0.16	0.03

The size of the deposited particles on the photoelectric surfaces is generally in the range of 1-50 microns. The diameter of the dust particles is less than 10 microns and less than 2.5 microns corresponds to PM_{10} and $PM_{2.5}$, respectively. Solid particles ranging from $PM_{2.5}$ to PM_{10} never wash even after heavy rain. Smaller PMs are distributed more evenly than larger dust particles due to the larger specific surface area. Particles larger than PM_{10} are highly localized and tend to precipitate more than smaller particles. However, they are more likely to be washed away after heavy rain. The reflection, scattering, and absorption of incident light on the photocells depend significantly on the particle size [21].

The deposition of dust on photovoltaic surfaces is influenced by factors such as the material of the upper surface of the photovoltaic module and the inclination angle of the panel, the speed and direction of the wind, and the presence of moisture on the surface.

The upper surface of the photoelectric module includes glass for traditional modules and various transparent acrylic materials based on polymer for lightweight structures. The acrylic material has a larger dust build-up than the glass cover. Vertically mounted acrylic glazing showed 16% more precipitation. It has also been reported that the surface of the photoelectric module made of glass attracts less dust than the surface made of Tedlar [22]. On very smooth surfaces, the adhesion forces between the dust particles and the surface are extremely high, and even at very high wind speeds (up to 100 km/h or more), fine particles are not removed from such surfaces.

Increasing the tilt angle of the photoelectric module affects the stability of the dust particles. It has been found that dust accumulation decreases with increasing inclination angle. Thus, a two-sided photovoltaic system with a vertical plane will produce higher power than a single-facial and horizontally positioned photovoltaic system. However, the cleaning cost for this type of photovoltaic module may be higher. The inclined photovoltaic tracking system has a smaller angle of incident losses compared to the horizontal photovoltaic system. A soil-coated tracking photovoltaic system shows only up to 6% loss, while a horizontally positioned photovoltaic system without tracking can experience losses of up to 10% [23].

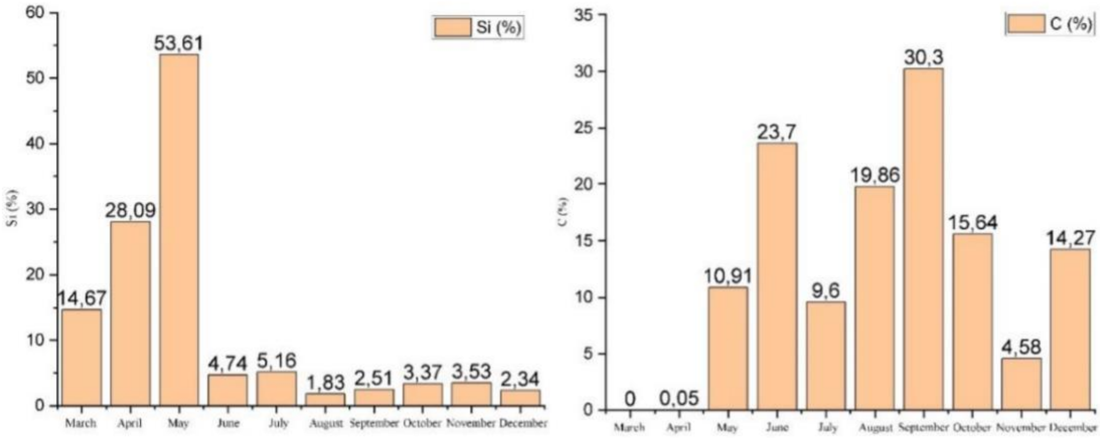

Figure 5: Monthly change of elements Si and C [20]

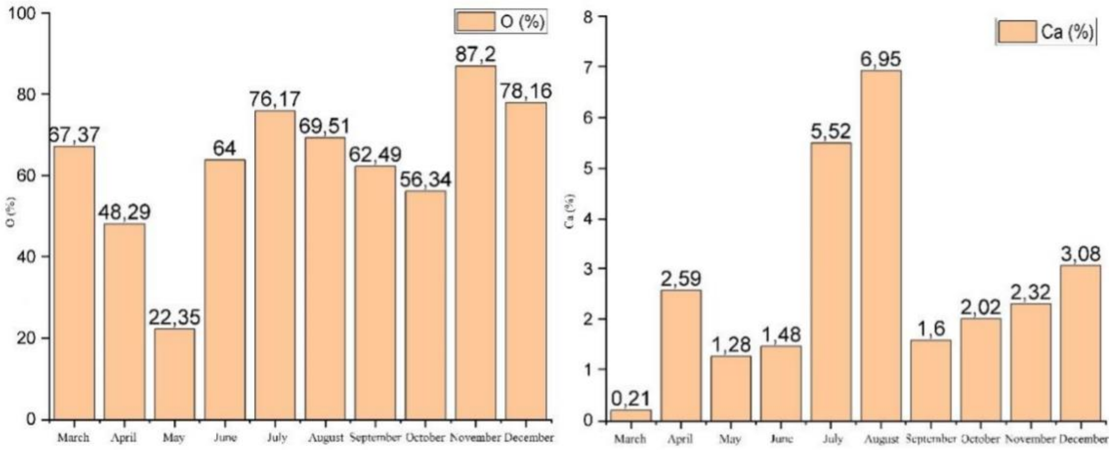

Figure 6: Monthly change of O and Ca elements [20]

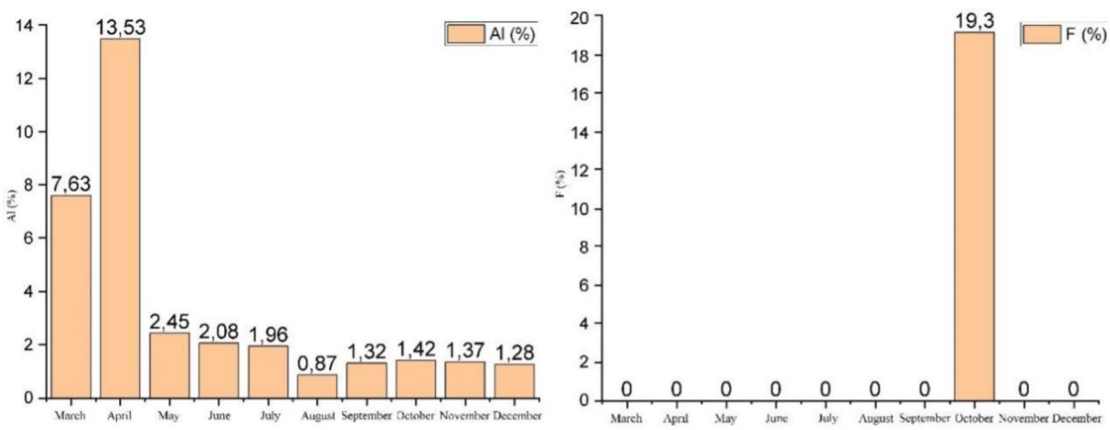

Figure 7: Monthly change of Al and F elements [20]

Wind speed and direction affect dust deposition on photovoltaic surfaces. High wind speed can remove dust from the surface of photovoltaic panels, while low wind speed contributes to dust accumulation. The sedimentological effect of wind on the work of photocells is small but is systematic. The study of dust deposition on the photovoltaic collector was carried out using wind tunnel simulations and field experiments, and the authors concluded that the wind direction and orientation of the collector affect dust deposition. Wind speed above 2 m/s has less effect on the distribution of dust deposits. At a speed of 25 m/s and relative humidity of 40%, the wind can carry away about 80% dust particles with a diameter of ≥50 μm, about 50% particles with a size of 25 μm, and < 5% particles with a size of 10 μm. In another work, it has been demonstrated that particles of 10 μm or less can only be removed at an air velocity above 25 m/s. The wind at a speed of 0.57 m/s could attach 1334 μg/cm^2 of dust to the surface of the photovoltaic panel with an inclination of 29° and a north direction of 10° east [24].

The presence of moisture on the surface of the photoelectric module creates an adhesion force between the particles that causes the particles to adhere to the surface of the photoelectric module. The deposition and accumulation of dust are highly dependent on the bonding force between the photovoltaic surfaces and the dust elements. These include gravitational, capillary, electrostatic, and Van der Waal coupling forces. The presence of humidity in the atmosphere helps to increase the adhesion force. Under high humidity conditions, capillary forces provide 98% adhesion [23]. For a dry atmosphere, Van der Walla forces prevail. Increasing humidity from 40% to 80% increases adhesion by about 80%. Small precipitates significantly accelerate the dust deposition process. However, heavy rain can remove contaminants from the surface of photovoltaic panels.

4. Effects of Pollution and Techno-Economic Loss Assessment

Contamination of photovoltaic modules has a negative effect on their characteristics. Incident solar radiation, short-circuit current, idling voltage, and filling factor are four parameters that determine the output power of photovoltaic modules. Generally, deposited dust reduces light transmission and therefore reduces incident solar radiation. The short circuit current is directly proportional to the incident light. Consequently, the power reduction is apparent when using dusty photovoltaic modules. Reducing incident radiation can slow the temperature rise of the photovoltaic system; thus, this does not greatly affect the idling voltage. With a high ash content such as 0.4 mg/cm^2, the density of ash deposition on poly-Si photovoltaic surfaces reduces the output power by 30% compared to a similar transparent photovoltaic panel in Greece. Relatively small ash deposition (i.e. 0.06 mg/cm^2) reduced 2.5% of the generated electricity. The output power of the contaminated concentrating photovoltaic system is more adversely affected because the incident sunlight is scattered in the other direction and therefore a large number of beams are lost and not received.

To assess the global impact and cost of pollution, the optimum between clean-up costs and pollution revenue loss between clean-up activities was identified for the top twenty photovoltaic markets. According to the data and estimates of the articles [15], pollution led to a reduction in global solar energy production by at least 3-4% in 2018, which led to a loss of income in the world of at least 3-5 billion euros (Fig.8).

Based on the assumptions made, global pollution losses could rise significantly to 4-7% of annual electricity generation, leading to economic losses of more than 4-7 billion euros by 2023. This development is mainly due to the increased deployment of photovoltaic systems under high insolation conditions. Additional factors that increase the impact of pollution are an increase in the efficiency of photovoltaic modules and a projected increase in the share of solar installations on roofs (from ~ 29% in 2018 to ~ 35% in 2023) [25]. Other factors, such as improved air quality in some parts of the world, can reduce anthropogenic sources of pollution, although air quality policies are usually in place for a long time [26]. On the other hand, rising temperatures and changes associated with climate change can cause an increase in global soil dryness and the risk of droughts and forest fires, worsening PV and CSP pollution due to higher concentrations of aerosols and other factors. uneven precipitation [27].

At this stage, an overview of panel surface cleaning methods is considered necessary.

5. Cleaning of contaminated photovoltaic modules

As already mentioned, removing dust from photovoltaic modules is important for increasing output power (Fig.9).

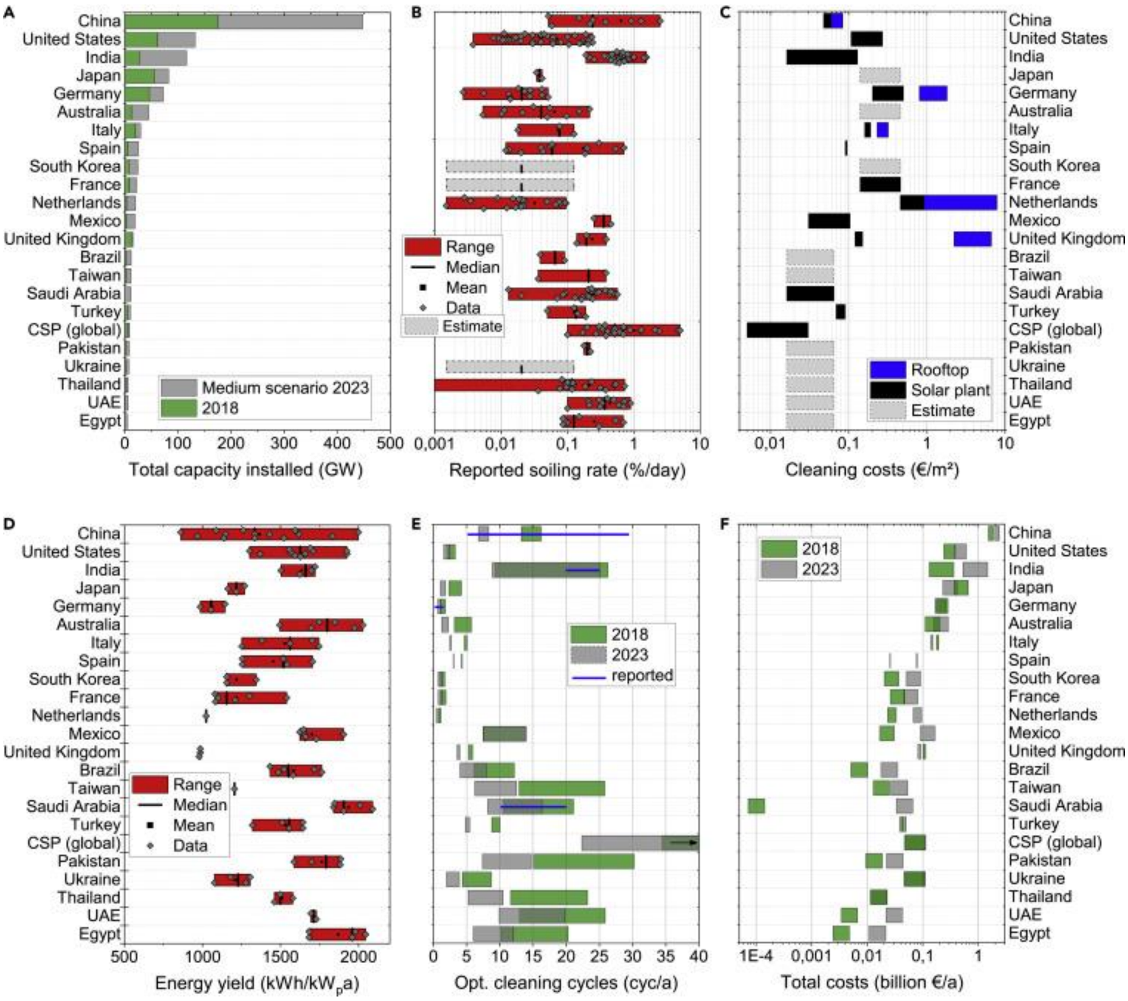

Figure 8: Effects of pollution on solar power generation [15]: (A) – installed photovoltaic capacity by 2018 and average estimate by 2023, sorted by the country for the top 22 and global CSP capacity; (B) – relevant pollution indicators; (C) – specified cleaning costs per cleaning and square meter; (D) – typical energy output in kWh/kW_p; (E) – estimated range of an optimal number of annual cleaning cycles (columns) and actual range of typical annual cleaning cycles; (F) – minimum expected financial losses due to contamination calculated on the basis of optimal cleaning cycles

5.1. Passive pollution protection

The removal may be natural, mechanical, or chemical. Natural methods of dust removal are based on wind energy, gravity, and rainwater. Of course, precipitation is free, but it is seasonally variable, which makes this method unreliable. Moreover, after cleaning, rinsing the surface, and drying the glass is required, otherwise, the glass will become an ideal surface for depositing dust particles [28]. In the early morning, late evening, night, and on a rainy day, the photovoltaic module can be rotated to a vertical or inclined position to remove dust; however, these methods are not very effective. In addition, rotation of the array of photovoltaic modules is not feasible. Mechanical methods include cleaning, blowing, vibration, and ultrasonic treatment. A broom or brush is typically used for a cleaning method that is driven by a machine. Due to the small size and strong adhesion of dust, this method is not very effective. For blowing methods, the wind from the blower is used, but this requires a lot of energy [29].

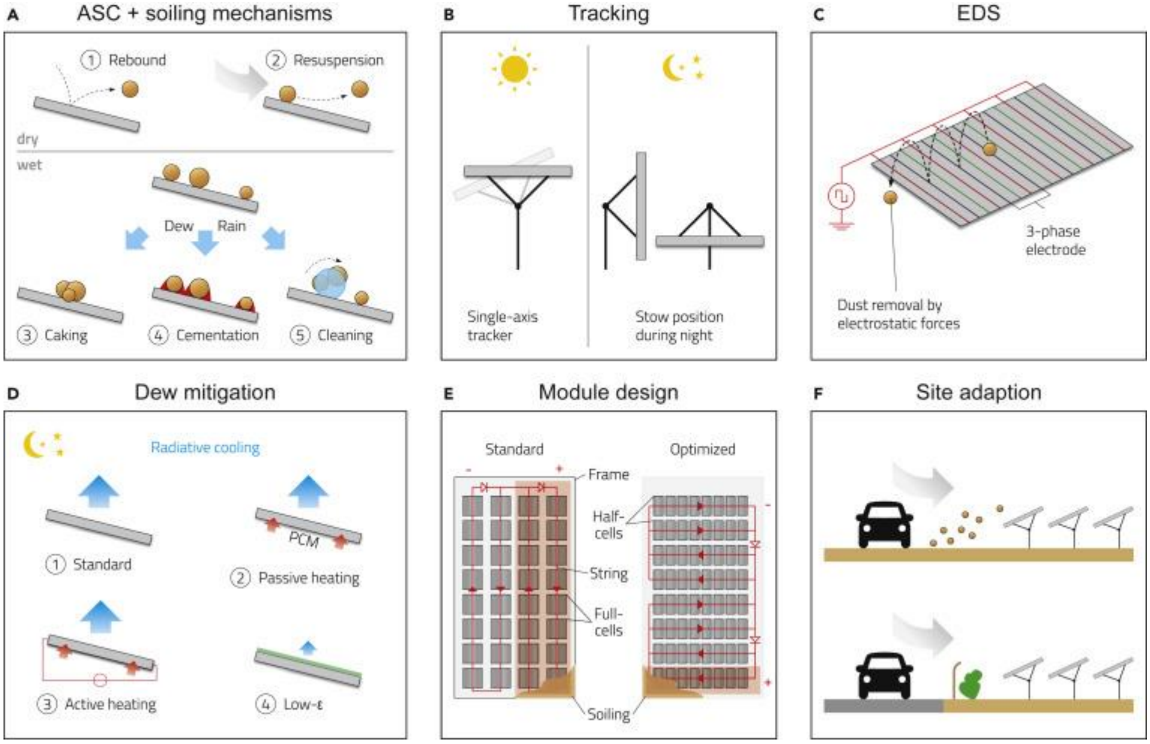

Figure 9: Schematic Illustration of Soiling Mitigation Technologies [15]: (A) – important soiling mechanisms which could be addressed by anti-soiling coatings (ASCs); (B) – single-axis tracking and optimization of night stowing position; (C) – working principle of EDS (standing wave version); (D) – dew mitigation by low-ε coatings and active and passive heating; (E) – PV module design approaches for soiling loss reduction: the red overlay indicates lost cell strings dew to soiling; (F) – site adaption

5.2. Electrodynamic Shield (EDS)

Transparent electrodynamic shields (EDS), also called electrodynamic dust shields, repel dust particles, creating a time-varying (dynamic) electric field above the surface. The basic electrodynamic shield (EMF) consists of a transparent or thin layer of electrodes of direct or complex shape, deposited on a substrate. The electrodes are coated with a thin transparent dielectric sheet which is glued to the electrodes with an adhesive to insulate the electrodes from the air. EDS is activated by means of alternating high voltage supplied to electrodes. Both standing and traveling waves can be used on EDS. Standing waves move dust-up and down, and traveling waves move dust horizontally. A traveling wave system requires a complex electrical circuit and high voltage (> 800 V) [30]. For the production of photovoltaic energy on a utility-scale, a standing wave design is suitable. It has been demonstrated that 98% of the dust from a transparent conveyor consisting of transparent indium and tin oxide electrodes printed on a glass plate can be removed using this approach while electrostatic traveling waves are generated by a four-phase rectangular applied voltage. To replace the expensive indium and tin oxide, a glass plate with repellent sand and a high-voltage single-phase rectangular power supply system based on the power supply were later used. This system generated an inverted motion of sand particles that were carried down by gravity. The effectiveness of the EDS approach can be reduced over time and, in cyclical operation, at low dust levels [31]. Moreover, dust particles that settle on photovoltaic systems over a longer period of time are less sensitive to the EDS removal process.

5.3. Cleaning

So far, no passive pollution protection technology (e.g. surface coatings) has completely eliminated the need for cleaning. In addition, there is no universally recommended method of cleaning, as cost-effectiveness and efficiency vary depending on local conditions, available resources, and frequency of cleaning. In general, cleaning methods can be divided into manual, semi-automatic, and fully automatic. The market for fully autonomous cleaning, which is only 0.13% of the current global solar power capacity, will grow from 1.9 GW to 6.1 GW in 2022 [32].

Robotic cleaning uses an object-based sensor that can remove dust from photovoltaic systems to maximize the output of photovoltaic solar panels (Fig.10). PVCleaner Robot V1.0. T. is the first robotic device for cleaning photovoltaic systems [33]. Robot vacuum cleaner E4 - Water Free (DCR) (Ecoppia Empowering Solar, Herzliya, Israel) is able to clean 99% of the contaminants. This anhydrous microfiber wipes clean the surface of the photoelectric module, and the downward movement of this DCR depends on gravity. E4 - Energy Independent DCR (manufactured by Ecoppia Empowering Solar) does not depend on energy, since it consumes energy from batteries during the cleaning process. DCRs work well at a tilt angle from 5° to 35°. The SMR - 640AD model (Miraikikai Inc, Hayashi - Cho, Takamatsu, Kagawa, Japan) is portable, can move in any direction, is easy to handle, and is powered by a lithium-ion battery, has an 80% reduction potential. from the cost of cleaning. PV - ROB12 (Zero One Mechatronics) uses air and water as a medium and requires an AC power supply for operation [34]. All of them are suitable for traditional photovoltaic systems but are crucial for vertical integrated photovoltaic facades of buildings (BIPV). For offices in the UAE, an anhydrous robotic dust cleaning system was developed. This robot had its own battery, which for work was charged from solar panels. This system consisted of soft brushes made of microfibre at the extreme ends, four wheels, a hail sensor, a control system, and a three-step engine [35].

Figure 10: Robotic solar panel cleaner

The choice of optimal treatment technology is influenced by a variety of factors, including the type of contamination and deposition rate, water availability, site availability, and system configuration (e.g. tracking versus fixed angle of inclination, installation of roof or ground), as well as labor costs, necessary equipment, and supply contract terms. Efforts are also being made to determine the optimal cleaning schedule based on the determination of the degree of pollution and weather, as well as dusty forecasts.

5.4. Anti-pollution coating (self-cleaning)

Hydrophobic and hydrophilic are two types of self-cleaning coatings available to protect against contamination and protect the photovoltaic system from dust deposition. The water wetting angle (WCA) above 90° is known as hydrophobic and below 90° is hydrophilic. WCA above 150° is called superhydrophobic and below 5° is called superhydrophobic [36]. High surface energy materials have wettability and are suitable for hydrophilic/super hydrophilic surfaces. Low surface energy materials such as silanes, silicones, nanoparticles, and polymers are used because of their water-repellent properties for hydrophobic surfaces. Hydrophilic coatings reduce contamination by photocatalytic reaction, and superhydrophobic coatings allow water droplets to roll down and remove dirt from the surface. Self-cleaning activities are predominant in nature. For example, lotus leaves, rice leaves, and butterfly wings exhibit superhydrophobicity, while pitcher, shark skin, fish scales, and snail shells have super hydrophilic properties [37]. A popular super-hydrophilic film is TiO_2, which has hydrophilicity and photocatalytic activity. However, TiO_2 reduces glass transmittance and rapidly loses hydrophilicity by restoring the angle of contact with water in the dark. Composite films TiO_2/ SiO_2 can overcome all these limitations [38].

6. Estimating Costs of Pollution Reduction Technologies

The research [15] provides approximate calculations of the estimate of positive net present value (NPV) for which pollution reduction technologies become economically feasible.

In order to estimate the maximum allowable process costs, photovoltaic plants of a communal scale, the optimal number of cleaning cycles, purchase prices for electricity in the amount of 0.03 euro/kWh and a 10-year payback period for investments in technologies at a discount rate of 5% are taken into account.

The economic benefits of reducing pollution resulting in fewer cleaning cycles can easily increase with higher cleaning costs (e.g., installation on the roof and in remote locations) or in areas with severe pollution.

The estimates provided can be compared with assumptions about the potential to reduce pollution and the current costs of various technologies (Table 4). Automated cleaning systems, ASC, optimized photovoltaic module design and tracking solution are expected to achieve an acceptable utility-wide cost range. On the contrary, electrodynamic shields and heating solutions seem too expensive or technology is underdeveloped.

Table 4
Pollution reduction potential and costs of selected pollution reduction technologies [15]

Mitigation Technology	Potential Optimum Reduction of Soiling Rates	Costs	Potential Limitations	Most Reasonable Application Scenario
Fully automated cleaning	>95%	2.4–8.2 €/m^2	integration in plant design	PV utility scale, ground mounted
Anti-soiling coatings **• Applied by glass manufacturer** **• Retro-fit**	≪80% (literature review) <20%–50% (authors estimate) 32% reported for commercial coating	<2 €/m^2	performance dependent on location and season, degradation by cleaning and environmental stresses	utility scale, residential, ground-mounted and rooftop, BiPV, CSP + extra benefit from AR property
Tracking	<40%–60%	n.a.	integration in plant planning, additional costs	utility scale, ground mounted, state of the art in CSP
Electrodynamic screen/shield (EDS)	≪98% (laboratory) 32% reported for 2-	<30 €/m^2	expensive, large-scale application needs to be proven	BiPV, island systems, street lighting, rooftop, CSP

	year study in Saudi Arabia			
Heating **• PCM** **• Active cell heating** **• PVT**	<20%–60%	<80 €/m^2 (PCM) n.a.	expensive, large-scale application needs to be proven	BiPV, island systems, street lighting, rooftop installations + extra benefit from cooling during day for PCM + PVT
Optimized PV module design and orientation	<65%	≤0 €/Wp	integration into mass production	utility scale, rooftop installations
Site adaption	unknown, site specific	n.a.	little experience, research needed	utility scale PV and CSP

Based on the technical and economic assessment, it can be concluded that automated cleaning machines, ASC, inverted-lay tracker modifications and optimized photovoltaic module designs are potentially applicable on a large scale in the medium term. For these technologies, reduced pollution can result in significantly lower cleaning costs, hence the estimated investment costs become reasonable, especially in highly contaminated areas [39-45]. But it is worth noting that economic conditions are very difficult, since reducing the pollution level by 50% can lead to additional costs only in the range of 2 euros/m^2 for PV, for example. Accordingly, earlier stage technologies, such as EDS and night heating, are currently too expensive and insufficiently tested in the field, but their development is far from exhausted and should be continued.

Moreover, more research is still needed on the effectiveness of all proposed technologies depending on location, their possible environmental impact and the long-term reliability of CSP photovoltaic modules or mirrors, as well as operating methods to ensure efficient and safe use of the technology.

7. Conclusions

Pollution can become a serious problem for photovoltaic systems worldwide, which is even more worrying due to the rapid expansion of the photovoltaic system market. Mitigation strategies should be implemented to eliminate or mitigate its effects and should be tailored to the specific conditions and configurations of each photovoltaic facility. In addition, the complexity and variability of pollution still make forecasting difficult. For these reasons, it must be constantly monitored.

Pollution can also be assessed directly on the basis of photovoltaic data or environmental parameters, without the need for special pollution monitors.

An economic analysis was presented to estimate the maximum allowable monitoring costs. The results show that the allowable costs of monitoring pollution vary depending on the size of the system and the effectiveness of the pollution reduction strategy.

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