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Air Pollution and Soiling Implications for Solar Photovoltaic Power Generation: A Comprehensive Review

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Abstract

Solar photovoltaic (PV) is a promising and highly cost-competitive technology for sustainable power supply, enjoying a continuous global installation growth supported by the encouraging policies and commercial markets. However, air pollution and soiling of PV modules prevail worldwide, potentially casting a shadow on solar PV power generation. This study presents a comprehensive review of the documented impact of air pollution and PV soiling on solar resources and techno-economic performances of PV systems. Both air pollution attenuation and soiling could significantly reduce the solar PV power generation globally, and soiling losses contribute to most of the total power reduction in most regions except in high-polluted areas. In addition, considering the natural soiling processes, the influencing parameters of soiling such as environmental and configurational factors and their correlation to dust deposition on PV surface are discussed. Furthermore, this study introduces the impact of air pollution elimination on surface solar radiation and solar PV power generation. Given the current novel coronavirus disease 2019 (COVID-19) pandemic, studies related to its effects on the solar PV sector are discussed in the present review. The reported soiling mitigation approaches and technologies are systematically compared. Finally, the current research challenges are stated, and suggestions for future works in improving the penetration of solar PV applications are provided to help promote solar power generation towards the carbon neutrality all over the world.

Keywords

Solar photovoltaic power generation, Air pollution, Soiling, Solar radiation, Soiling mitigation approaches, COVID-19 lockdown

1. Introduction

In 2019, the annual global primary energy consumption grew by 7.67 EJ (+1.3%), below half the growth rate in 2018 (+2.8%). Meanwhile, the carbon emissions growth slowed to +0.5%, far lower than its ten-year average rate of +1.1% [1]. To a certain extent, the global energy trends owing to the strong growth of renewable energy with an annual increased capacity of more than 200 GW [2]. In the first quarter of 2020, the novel coronavirus disease 2019 (COVID-19) has catalyzed a decrease in global demand for oil and coal of 5% and 8%, respectively [2]. Renewable energy was the only electricity source with increasing demand during this period, which is widely perceived as the most prominent and promising alternative for conventional fossil fuels to mitigate the so-called global energy ‘trilemma’ [3–5]. Over the past decades, shares of renewable energy in power generation continued to increase worldwide to decarbonize the power sector [6]. A growing number of countries are making efforts towards the renewable energy transition. For instance, renewable energy prosumers are being mainstreamed in all EU Member States [7]. In China, the renewable energy industry is a fundamental way of implementing the energy supply revolution strategy [8,9]. Among all renewable energy resources, solar energy is at the center of the constellation of power generation technologies, given its inexhaustibility [10], environmental sustainability [11–13], and easy accessibility with few costs in vast regions across the globe [10,14]. The annual technical potential of solar energy is up to 1500–50000 EJ, sufficient for the annual global primary energy demand as the most abundant resource of renewable energy [15,16]. As shown in Fig. 1, the Arabian Peninsula, northern, southwestern and eastern Africa, Australia, and western South America have the highest solar potential with an annual average global horizontal irradiance at over 2200 kWh/m^2.

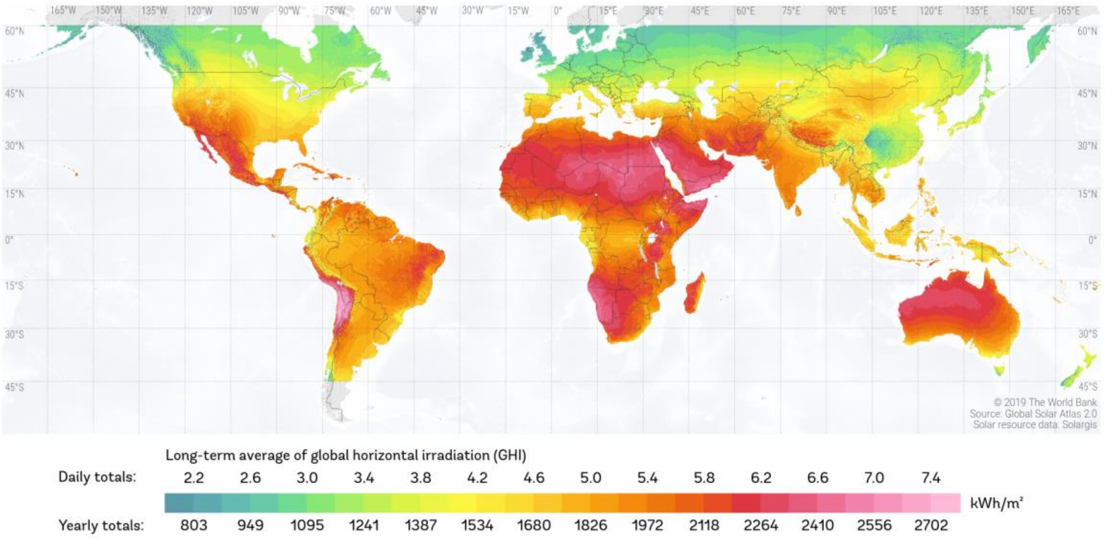

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Fig. 1. The spatial distribution of global horizontal radiation (GHI) [17].

Solar photovoltaics (PV) is the primary technology of solar energy utilization, accounting for approximately 99% of global installed solar power capacity, which shows promising potential towards a carbon-free power supply in the following decades [2,18–20]. During 2009–2019, global total solar PV capacity increased from 23 GW to 627 GW, with new installations of 115 GW in 2019 (see Fig. 2) [2]. The demand for solar PV is expanding as the most competitive option for commercial and residential power supply in a growing number of countries or regions around the world. This tendency was primarily attributable to the continuous improvement in PV technologies and reduction in PV module costs with the support of worldwide governmental policies and investments [21,22]. The cost of PV modules reduced about 22.5% for each doubling in the cumulative PV production capacity over the last 40 years [23]. The price of commercial PV-generated electricity has been quoted at below US$ 2 c/kWh [24]. Solar power is expected to be the cheapest source of power supply in the future. Moreover, the global PV projects would experience an increasing expansion after 2022, given the continuous policy supports and cost reductions with the predicted annual additions of almost 165 GW during 2023–2025 [25]. Solar PV power plays an increasingly prominent role in power supply with an anticipated global capacity of 4.6 TW accounting for 16% of the total global power generation by 2050 [26].

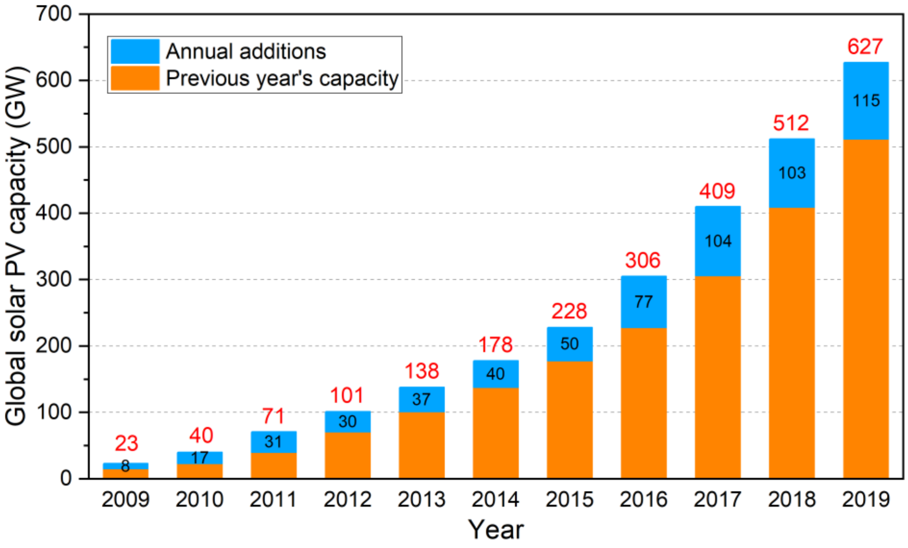

Fig. 2. Solar PV global capacity and annual additions from 2009 to 2019 [2].

The intensity of solar radiation reaching the PV surface plays a significant role in determining the power generation from the solar PV modules [5,27]. However, air pollution and dust prevail worldwide, especially in regions with the rapid growth of solar PV markets such as China and India, where solar PV power generation is significantly reduced [28]. Fig. 3(a) shows the influence of air pollution on the atmospheric transparency. As shown in Fig. 3(c), atmospheric pollutants have the potential to attenuate solar radiation reaching the PV surface through reflection, scattering and absorption, which is a threat to solar power production. In addition, soiling of PV modules caused by deposition of contaminants (e.g. dust, industry emissions and engine exhausts) on the PV surface is another severe challenge, particularly in arid and semi-arid regions with a high concentration of airborne dust such as the Arabian Peninsula and northern Africa [24,29–31]. An exemplary example of soiling on the PV surface is shown in Fig. 3b. As a barrier between PV modules and solar radiation, soiling can reduce solar transmittance through the covers of PV, resulting in significant degradation of PV generation efficiency, as presented in Fig. 3(c).

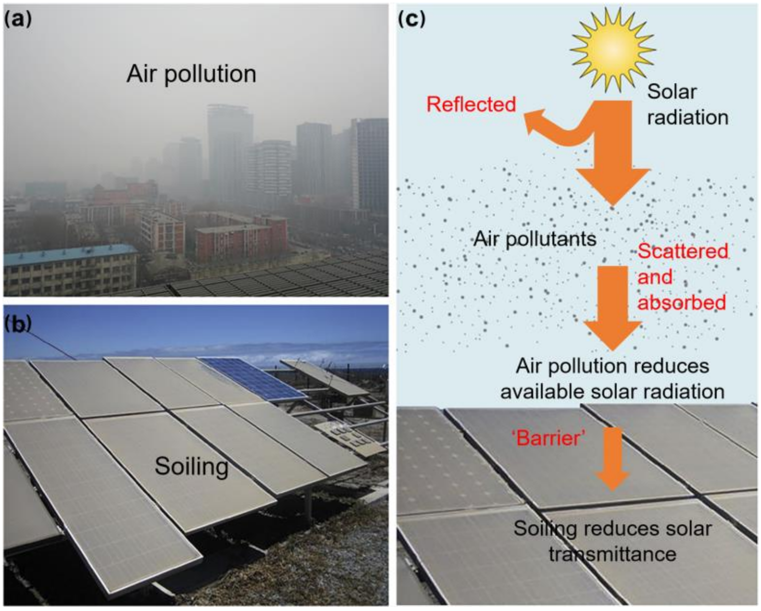

Fig. 3. Examples of (a) air pollution [32], (b) PV modules soiling [33], and (c) how air pollution and soiling lead to decreased solar radiation reaching PV surface.

Overall, both air pollution and soiling have a significant impact on solar PV power generation. Previous studies have reviewed the related works on the soiling of solar PV modules, for example, Ilse et al. [24] provided an overview of soiling processes on PV modules from microscopic and macroscopic levels. A techno-economic assessment of soiling losses in the 2018 twenty top solar PV markets and mitigation strategies was subsequently presented [34]. Maghami et al. [31] divided the shading of PV modules due to soiling into hard shading and soft shading. They further summarized the influences of shading on PV performance. Focusing on soiling mitigation, Kazem et al. [35] discussed the status of cleaning approaches for PV panels. Similarly, the soiling impacts and mitigation measures in Nigeria were summarized by Chanchangi et al. [30]. Besides, Tawalbeh et al. [36] conducted a comprehensive analysis of the efficiency and environmental impact of solar PV systems. However, there is a limited study to comprehensively introduce the impact of air pollution on solar PV power generation. Therefore, this study aims to provide an insight into air pollution and soiling implications as well as the effects of elimination of air pollution and soiling mitigation strategies on solar PV power generation around the world. The rests of this study are organized as follows: the reduction of solar resources and power generation as well as the benefits of elimination of air pollution to the solar PV sector are discussed in Section 2; Section 3 presents the natural soiling processes, soiling impact on PV performance and approaches for mitigation of soiling; Finally, the current research gaps and challenges, future research needs, and key findings are summarized respectively in Section 4, 5, and 6.

2. Air pollution and solar photovoltaic power generation

Air pollution has a significant influence on solar PV energy potential as air pollutants reduce the amount of solar radiation reaching PV surface. This section discusses the long-term solar resources variability, the impact of air pollution on solar PV power generation at various scales, and the benefits of cleaner air from air pollution control and COVID-19 lockdown measures to solar resources and the PV sector.

2.1 Long-term variation of solar resources

Surface solar radiation determines the local solar resources as a critical factor for energy generation of solar PV systems, which has not been constant but has undergone ‘global dimming’ and ‘global brightening’ periods.

2.1.1 Global dimming and brightening

‘Global Dimming’: Numerous early studies found a general decrease in the amount of surface solar radiation at most radiation sites from the early 1960s to the 1980s, referred to as ‘global dimming’ [37–39]. Gilgen et al. [40] described the shortwave irradiance data in the Global Energy Balance Archive database. They found that surface solar radiation decreased significantly in large regions in North America, Europe, Asia and Africa, with a relative reduction of 2% per decade between the 1950s and 1980s. Stanhill and Moreshet [41] analyzed the data from the World Radiation Network, indicating that surface solar radiation in 1985 fell by 5.3% of 9 W/m^2 compared with that in 1958. Meanwhile, a similar average reduction was observed based on the spline-fitted latitudinal distributions of available measurements. An annual decrease of 0.63% (45.2 ± 4.3 MJ/m^2) in surface solar radiation at Bet Dagan (Israel) is reported between 1956 and 1987, and the reduction reached 0.91% per year [42]. The global analyses at different sites further confirmed the decreasing trend of surface solar radiation over the same period [43]. In addition, a similar trend in the solar radiation at the Earth’s surface was found in polar regions. For instance, Dutton et al. [44] observed an overall decrease in the annual surface solar radiation at the South Pole from 1976 to 1987 with an unexpectedly 15%

reduction during the late austral summer. Based on worldwide observational records, these pioneering works identified that the solar radiation reaching the Earth's surface has not been constant but presented an almost consistent downward decadal variation around the world since the late 1950s.

'Global Brightening': On the contrary, studies since the 1990s based on updated records noted that a trend reversal had been found since the 1990s and the downward trend of surface solar radiation gradually faded in the 1980s, referred to as 'global brightening' [37,38,45,46]. In the global context, Wild et al. [37] studied the variation of surface solar radiation from 1990 onward, finding that the 'global dimming' did not persist into the 1990s over large locations based on the updated records. They reported that a widespread recovery appeared since the late 1980s with an average decadal increase of 6.6 W/m^2 from 1992 to 2002, and the reversals were particularly evident in Europe, America, and Australia. The authors then conducted a detailed study in a broader range using the updated records from 2000 to 2005, and pointed out that the global brightening beyond 2000 would be continued at most sites across the globe [38]. Similarly, based on the available satellite records of surface solar radiation, Pinker et al. [47] observed a global daily increase of 0.16 W/m^2 from 1983 to 2001, which was combined by a decrease before 1990 and a sustained increase after that. Similar trend reversals of surface solar radiation on specific locations are also reported during the same period [48–53]. For example, Zhou et al. [48] found that surface solar radiation increased 0.78 W/m^2 per decade across China in 1994–2015 based on the data from two satellite retrieves (i.e. CERES-EBAF and GEWEX-SRB). And it is consistent with the trend (0.92 W/m^2 per decade) observed from surface measurements during the same period. Long et al. [51] reported a decadal increase of surface solar radiation of 6 W/m^2 across the continental United States between 1996 and 2007. In summary, a worldwide trend reversal on surface solar radiation compared to the prior 'global dimming' has been observed since the 1990s.

However, the 'global brightening' in surface solar radiation did not fully complement the preceding 'global dimming' at many locations [39,54,55]. For example, Yang et al. [56] homogenized a dataset with 119 sites to assess the long-term trend of surface solar radiation in China. A significant dimming of 20.23 ± 1.55 W/m^2 was noted between 1958 and 1990 but diminished from 1991 to 2005 (2.77 ± 0.17 W/m^2 per decade) and reversed to a brightening of 7.36 ± 2.12W/m^2 between 2005 and 2016. The results indicated that surface solar radiation levels in recent years are still below that in the 1960s in China. Besides, surface solar radiation has been consistently declining at a few sites such as India [57,58].

2.1.2 Causes for global dimming and brightening

Theoretically, both external changes in extraterrestrial solar radiation at the top-of-the-atmosphere and internal changes in the atmosphere transparency can affect the solar radiation reaching the Earth's surface. Extraterrestrial solar radiation is primarily influenced by the Sun and the Earth's orbital patterns. Generally, the orbital of the Earth remains constant on the decadal scales [39]. A quasi-periodic variation of solar output has been confirmed (i.e. the about 11-year Schwabe Solar Cycle), but it is negligible compared with the changes in surface solar radiation observed from the ground measurements [39,59]. Thus, the so-called 'global dimming and brightening' may be originated from internal changes in the atmospheric transparency, mainly caused by the variations in cloud characteristics, atmospheric aerosols and water vapor [49,60,61].

Wild [39] reviewed the potential causes of 'global dimming and brightening' and demonstrated that the atmospheric water vapor has a minor effect on the decadal variations in surface solar radiation. Yang et al. [62] affirmed Wild's statement by analyzing the long-term dataset (1958–2016) in China. They estimated that the contribution of water vapor during the dimming period was only 2.2%. Therefore, changes in clouds and aerosols are considered the possible leading causes for the global phenomenon with potential interactions. Meanwhile, the decadal variations were found under both cloudy and cloud-free conditions. Consequently, the changes in atmospheric aerosols due to anthropogenic air pollution were the dominant cause in severely polluted regions over the past decades [39,62–64].

Atmospheric aerosols can modify the incident solar radiation by either directly scattering (e.g. nitrate, sulfate and organic carbon) and absorbing (e.g. black carbon and brown organic carbon) solar radiation or indirectly changing the cloud cover, lifetime and optical properties of clouds through aerosol-cloud interaction effect [28,65–68]. Furthermore, heating of absorbing aerosols in the atmosphere may lead to the evaporation of cloud droplets, resulting in reduced cloud cover (i.e. semi-direct effect of aerosols) [69]. In general, all these effects of aerosols have a significant impact on surface solar radiation. For instance, Wang et al. [70] found that the aerosols variations caused by anthropogenic emissions changes may explain the decadal variations of surface solar radiation from dimming to brightening in Europe and China. Similar conclusions are also found by Streets et al. [63] and Allen et al. [71]. In addition, studies also qualitatively proved the above statement that atmospheric aerosols had a vital influence in the 'global dimming and brightening' based on various climate models [72–75]. All these findings and results indicated that the global phenomenon is an anthropogenic change, mainly originated from aerosol emissions. Sweerts et al. [76] claimed that surface solar radiation would possibly return to the historical levels if aerosol emissions fall to the levels of the 1960s in China.

2.2 Impact of air pollution on solar PV power generation

Currently, the global growth of solar PV markets is exceeding projections. It is projected that the PV installations in China, Middle East, Africa and India will supply 10% of the global electricity generation and exceed 60% of the total PV power generation around the world by 2050 [26]. However, the growing atmospheric aerosols loads caused by anthropogenic air pollution significantly attenuate surface solar radiation, which casts a shadow on solar PV power generation. In recent years, the quantitative impact of air pollution on PV systems has been evaluated. Simulation models are adopted to estimate the effect of surface solar radiation changes caused by air pollution on the PV performance, with a perspective of solar engineering from global to urban scales. Moreover, field experiments on PV systems in different capacities are also conducted to study the impact of air pollution on PV power generation, mainly focusing on high-polluted countries and regions with continuously expanding PV markets.

2.2.1 Impact of air pollution on solar PV power generation at global and regional levels

Several outstanding studies provided a global picture of the air pollution impact on solar PV power generation based on the historical data. A global assessment of the atmospheric aerosol impact on PV power generation was presented by Li et al. [28] by combining the solar PV performance model (PVLIB-Python) with long-term satellite-observation data from CERES-SYN1deg. The estimated average reduction of PV capacity factors (CFs, defined as the ratio between a PV panel's actual annual power generation and its possible maximum annual generation under the conditions of the name-plate capacity) due to atmospheric aerosol attenuation are presented in Fig. 4. Overall, the highly polluted Northern China Plain and Indo-Gangetic Plain suffered from the highest atmospheric aerosol attenuation with PV CFs reductions of 0.031–0.06 (34%–45%) and 0.03–0.073 (25%–46%), respectively.

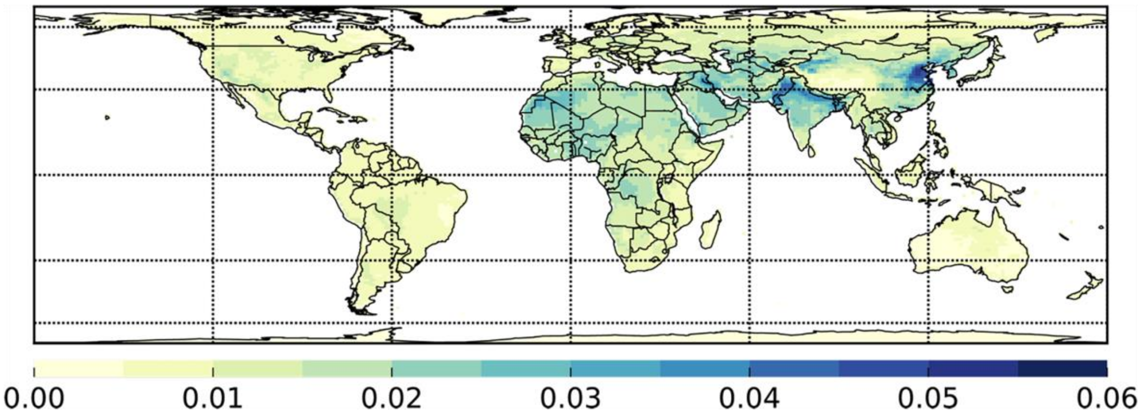

Fig. 4. 2003–2014 annual average reduction of PV CFs due to atmospheric aerosols [28].

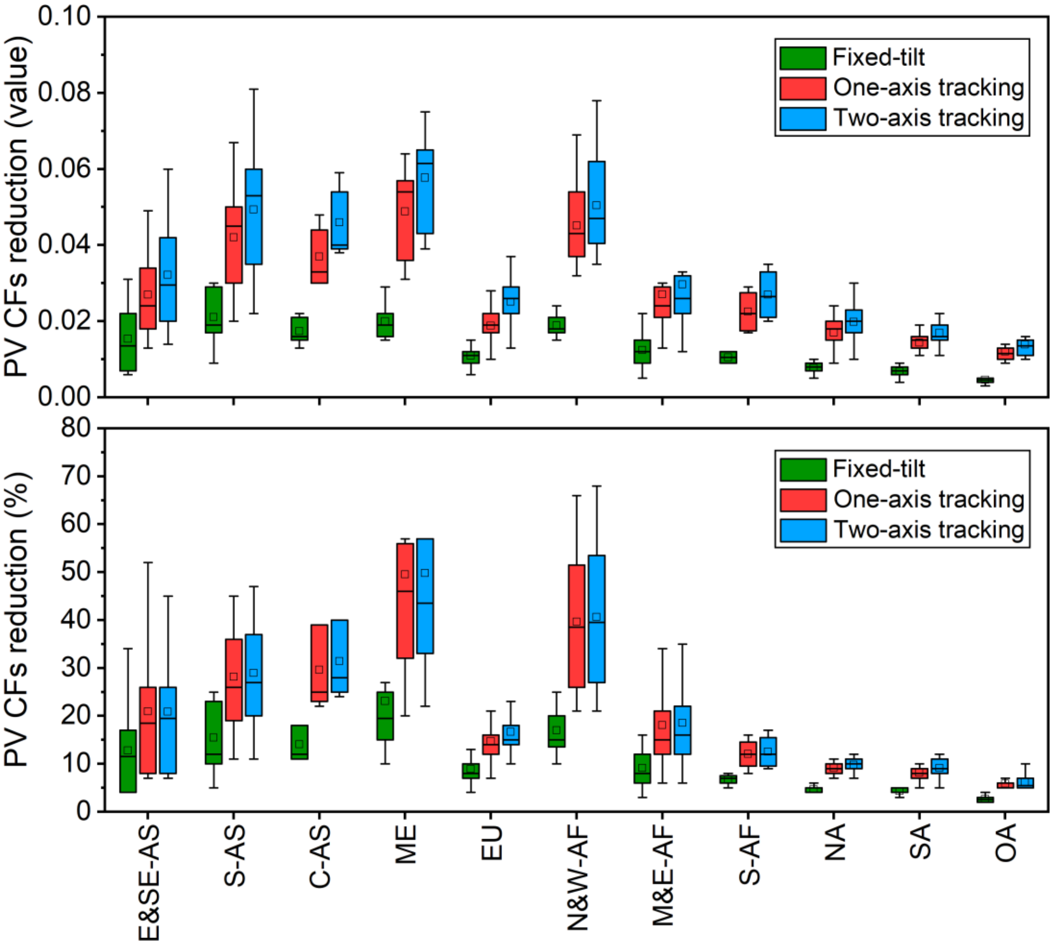

Fig. 5. Average reduction of PV CFs due to atmospheric aerosols during 2003–2014 sorted by region: East and Southeast Asia (E&SE-AS), South Asia (S-AS), Central Asia (C-AS), Middle East (ME), Europe (EU), North and West Africa (N&W-AF), Middle and East Africa (M&E-AF), Southern Africa (S-AF), North America (NA), South America (SA), Oceania (OA) [28].

In terms of the regional impacts of air pollution on solar PV power generation, Fig. 5 shows the estimated average aerosols-induced reduction of regional-mean PV CFs for fixed-tilt, one-axis tracking, and two-axis tracking PV modules during 2003–2014. It is noteworthy that the impact of atmospheric aerosols on both one-axis and two-axis tracking PV modules is much more significant than that on fixed-tilt PV modules because the atmospheric aerosol attenuation causes much more losses in received solar irradiance for tacking PV modules compared to fixed ones. Specifically, the estimated reduction of PV CFs is 0.003–0.031 (2%–34%) for fixed-tilt PV modules and 0.009–0.081 (5%–68%) for tracking PV modules. In terms of the spatial distribution of atmospheric aerosols impact, Middle East features more PV CFs losses with average reductions of 0.017 (23%), 0.037 (50%), and 0.046 (50%) for fixed-tilt, one-axis tracking, and two-axis tracking PV modules, respectively. In contrast, Oceania shows a lower average PV CFs reduction of below 0.015 (7%) than other regions. In addition, Bergin et al. [77] estimated the influence of atmospheric particulate matter (PM) related to biomass and fossil fuel combustion on PV performance. The global modeling and field experiments results showed 10%–15% decreases in available energy for solar power generation across the Arabian Peninsula, eastern-central China and northern India due to ambient black carbon, organic carbon, ions and dust. Besides, the long-term trend, seasonal cycle and spatial pattern of PV productivity over the Euro-Mediterranean domain have been substantially influenced by natural and anthropogenic aerosols [78]. The reductions could be up to 20% over the Mediterranean regions of Syria-Iraq and Africa in summer. However, Central Europe is the most affected area in this region, with a higher sensitivity of PV power generation to atmospheric aerosols.

By country, the ten top solar PV markets in 2019 account for over 80% of global cumulative PV capacity [2]. China, the United States, Japan, Germany and India remained the leading countries and continued to be the leaders. With supports of policies, the annual growth rates of PV capacity in other countries, such as Vietnam, Spain and the Netherlands, are expected to reach more than 20% for the coming five years [79]. The estimated reductions in CFs of fixed and tracking PV due to atmospheric aerosols in these countries are shown in Table 1. Focusing on the largest solar PV market, China eclipsed all other countries for PV capacity, accounting for 32.6% of global PV markets with PV installations of 205.2 GW in 2019 and expected to increase to 486 GW by 2024 [2,79]. However, solar PV potential is being attenuated by severe air pollution over much of China as a heavily polluted country. The atmospheric aerosols reduced CFs of fixed-tilt, one-axis tracking, and two-axis tracking PV respectively by 4%–34%, 8%–52%, and 8%–45% in China (see Table 1). In addition, Li et al. [64] quantified the impact of atmospheric aerosols on PV systems in China in the context of regional electricity grids and provinces. The results revealed that the annual average point-of-array irradiance (POAI) is reduced by 20%–25% due to atmospheric aerosols over northern and eastern China, and a decrease of up to 80% in the direct POAI occurred in the Eastern Grid from 2003 to 2014. Furthermore, Sweerts et al. [76] found a consistent decrease in the national average PV CFs since 1965 based on the Global Solar Energy Estimator model and the observed radiation data from 119 sites over China (see Fig. 6). They pointed out that the nation-wide PV potential is reduced by 11%–15% on average in China between 1960 and 2015. Furthermore, a tremendous annual loss of 14 TWh with US$ 1.9 billion financial losses was observed by comparing the PV power generation under solar radiation levels in 1960–1965 (baseline) and 2011–2015 based on China’s total PV capacity in 2016.

Table 1. Impacts of air pollution on PV CFs in the major solar PV markets.

Country	PV capacity (GW) [2,79]		PV CFs without aerosols [28]			Reduction of PV CFs [28]					
	2019	2024	Fixed-tilt	One-axis tracking	Two-axis tracking	Fixed-tilt		One-axis tracking		Two-axis tracking	
China	205.2	486.0	0.164–0.246	0.184–0.287	0.202–0.326	0.006–0.031	4%–34%	0.016–0.049	8%–52%	0.019–0.06	8%–45%
United States	76.1	178.9	0.131–0.207	0.138–0.25	0.175–0.287	0.006–0.01	4%–6%	0.009–0.024	8%–14%	0.014–0.03	9%–15%
India	42.0	111.9	0.184–0.219	0.205–0.267	0.224–0.296	0.017–0.03	12%–25%	0.03–0.061	19%–45%	0.035–0.073	20%–46%
Japan	63.0	95.1	0.163	0.181	0.201	0.014	10%	0.023	16%	0.028	17%
Germany	49.7	78.6	0.138	0.154	0.178	0.013	12%	0.02	20%	0.028	22%
Australia	16.0	40.2	0.225	0.282	0.308	0.005	3%	0.013	5%	0.015	5%
South Korea	10.9	28.5	0.187	0.21	0.238	0.024	17%	0.037	24%	0.044	25%
Vietnam	6.5	23.7	0.169	0.192	0.201	0.013	11%	0.024	18%	0.028	19%
Spain	10.6	27.7	0.193	0.226	0.258	0.01	6%	0.02	12%	0.024	13%
Netherlands	6.6	23.5	0.137	0.15	0.176	0.013	13%	0.019	20%	0.028	23%
France	9.9	22.0	0.159	0.179	0.207	0.011	8%	0.018	13%	0.024	15%
Brazil	4.5	15.9	0.192	0.224	0.234	0.008	4%	0.015	7%	0.016	8%
Italy	20.6	31.9	0.18	0.208	0.238	0.013	9%	0.024	15%	0.031	17%
United Kingdom	13.3	-	0.123	0.13	0.154	0.009	9%	0.013	23%	0.019	16%
United Arab Emirates	2.0	8.8	0.236	0.297	0.323	0.022	24%	0.059	57%	0.068	57%
Saudi Arabia	0.5	7.2	0.247	0.32	0.347	0.021	25%	0.056	56%	0.064	57%
Israel	2.1	8.0	0.214	0.266	0.293	0.016	15%	0.036	29%	0.043	29%

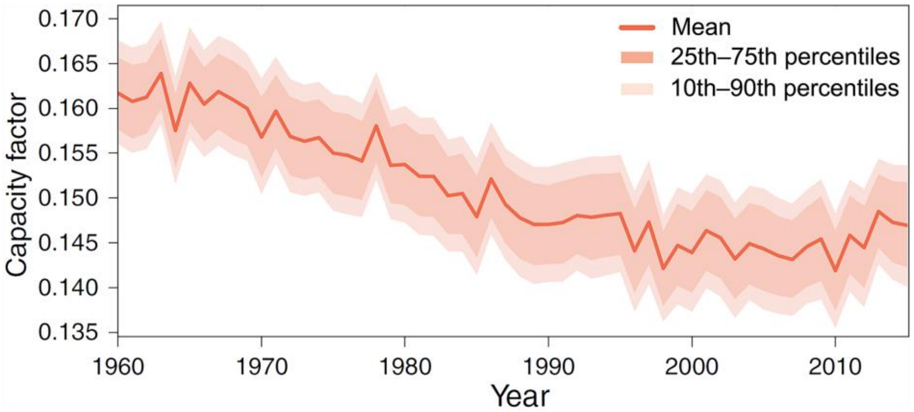

Fig. 6. Changes in average PV CFs in China since 1960 [76].

2.2.2 Impact of air pollution on solar PV power generation at the urban level

The rapid growth of the population in urban areas, with an expectation of 2.5 billion in 2050, increases energy consumption [80]. In recent years, a growing number of cities have integrated renewable energy technologies into the energy sector, especially solar PV technologies, to achieve a sustainable energy supply and low-carbon environment [81–84]. However, urban air pollution has been an urgent environmental issue faced by many cities due to urbanization and industrialization along with the combustion of fossil fuels, which inversely affects the solar PV potential.

In China, distributed solar PV (DSPV) has been widely integrated with buildings in megacities, but air pollution occurred more frequently in these cities [85–87]. Losses in DSPV electricity generation for typical buildings in cities due to aerosol pollution were summarized by Zhang et al. [88] as presented in Table 2. They have further evaluated the aerosol pollution impact on the efficiency of DSPV electricity generation based on observational data from nine megacities. It is found that the annual reduction of electricity generation is up to 7.4–13.5 TWh from 2014 to 2018, equivalent to an economic loss of CNY 377–676 million. Wu et al. [89] estimated the annual PV electricity generation without ambient fine particulate matter (PM2.5) for 2017 and 2018 in Hangzhou using an improved model of the degree of grey slope incidence. They found that the haze-induced losses were 5.25% ± 1.19% and 6% ± 1.16%, respectively, compared to the actual generation. Meanwhile, PV electricity generation decreased by up to 8.77% ± 0.9% due to the adverse effects of urban haze in Tianjin from 2018 to 2019. A method was presented to simulate the impact of PM2.5 concentrations on the daily power output of PV modules [90]. The results indicated that PM2.5 reduced the PV power output by 6.5% (6.36 W/m^2), 7% (6.99 W/m^2), and 30.3% (29.91 W/m^2) of the maximum generation in Beijing under PM2.5 concentrations of 35–75 μg/m^3, 75–115 μg/m^3, and >115 μg/m^3, respectively, with a mean decrease of 25.6% (25.27 W/m^2) due to the impact of PM2.5. Besides, the PV electricity generation in western China accounts for more than 40% of total domestic generation. However, severe air pollution over this region reduced the annual electricity generation by 54.75–113.15 kWh/m^2 between 2014 and 2018 [91].

Table 2. Losses in DSPV electricity generation for typical buildings due to aerosol pollution [88].

City	Building type	PV form	Installed capacity (kW)	Power losses (kWh)	Losses ratio (%)
Chongqing	Laboratory building	Roof PV panel	125.1	5249.3	6.0

Hefei, Anhui	Commercial office building	Roof PV panel	300.8	2666.6	3.5
Heyuan, Guangdong	Office building	PV glass wall	312.0	5114.7	3.8
Qingdao, Shandong	Office building	Roof PV panel	69.0	3591.5	6.4
Xuzhou, Jiangsu	Office building	Roof PV panel	55.0	3393.1	4.2
Zhuhai, Guangdong	Office building	PV curtain wall, PV glass wall	228.1	6259.6	3.8

India installed an estimated 9.9 GW solar PV additions in 2019, next to China and the United States, for a total capacity of 42.8 GW [2]. It is expected to reach 100 GW of PV installations by 2022, including 40 GW of rooftop PV capacity [2,92]. India faces a significant reduction in solar PV power generation resulting from increasing air pollution as similar to China. Peters et al. [93] derived an empirical model to estimate the energy yield losses of PV modules due to air pollution based on measured data in Delhi. They found that the annual electricity generation would be reduced by 40 ± 10 kWh/m^2 for a PV module with a conversion efficiency of 20% due to an 11.5% ± 1.5% decrease in solar irradiance caused by air pollution. Furthermore, the authors extended the model to other 16 cities across the globe to assess the impact of air pollution on PV modules with estimated annual losses in electricity generation ranging from 24 to 144 kWh/kW (see Table 3) [94]. Meanwhile, the results indicated that a more drastic reduction of PV power generation occurred in cities located in India, China, and the Arabian Peninsula, which supports the findings of Bergin et al. [77]. The annual losses of PV installations per gigawatt due to air pollution could be up to US$ 20 million and US$ 16 million, respectively, in Delhi and Kolkata, India.

Table 3. Losses in global tilted irradiance (GTI) for fixed PV panels with optimal angle and PV power generation (PV_{out}) due to urban air pollution [94].

Location		GTI (kWh/m^2)	GTI losses (kWh/m^2)	Relative GTI losses (%)	PV_{out} losses (kWh/kW)
Americas	Mexico City	2295	90 ± 7	3.9 ± 0.3	71 ± 5
	Los Angeles	2267	50 ± 5	2.2 ± 0.2	39 ± 4
	Bogotá	1526	29 ± 3	1.9 ± 0.2	24 ± 2
Asia	Manama	2284	178 ± 11	7.8 ± 0.8	137 ± 9
	Ulan Bator	2031	167 ± 20	9.2 ± 1.0	144 ± 18
	Kolkata	1804	173 ± 14	9.6 ± 1.0	132 ± 11
	Dhaka	1774	160 ± 16	9.0 ± 0.9	123 ± 12
	Jakarta	1721	74 ± 5	4.3 ± 0.4	57 ± 4
	Beijing	1634	149 ± 16	9.1 ± 1.0	121 ± 13

	Singapore	1630	33 ± 3	2.0 ± 0.2	25 ± 3
	Shanghai	1428	117 ± 10	8.2 ± 0.9	94 ± 8
	Hanoi	1356	80 ± 3	5.9 ± 0.6	62 ± 2
Africa	Addis Ababa	2174	89 ± 17	4.1 ± 0.8	71 ± 14
	Kampala	1941	114 ± 6	5.9 ± 0.6	89 ± 0
Europe	Pristina	1599	58 ± 5	3.6 ± 0.4	47 ± 4
	London	1195	29 ± 2	2.4 ± 0.2	24 ± 2

In addition, Chile possesses good conditions for the solar PV market within Latin America, with solar PV accounted for 8.2% of total domestic generation in 2019 [2,95]. Santiago de Chile hosts abundant solar irradiance of 5.12 kWh/m^2/day while frequently suffers from air pollution [96]. Del Hoyo et al. [97] reported an annual global solar radiation reduction of around 3.5% in Santiago compared with a hypothetical atmosphere without aerosols. Accordingly, the power generation for monocrystalline silicon (mono c-Si) and amorphous silicon (a-Si) PV modules in Santiago decreased respectively by 7.2% and 8.7%, with a maximum average reduction between 11.2% and 11.7% in winter, as shown in Fig. 7. Solar PV energy is in a vital position in the energy policies of South Korea [98,99]. However, its solar PV power generation has declined significantly over the past years due to the local air pollution and the transport of atmospheric aerosols from continents. For instance, Son et al. [100] analyzed the recorded data of the hourly electricity generation of two PV power plants in Seoul during 2015–2017. The PV electricity generation was found to be reduced by over 10% under atmospheric conditions of PM2.5 and PM10 concentrations of 35 μg/m^3 and 80 μg/m^3, respectively. Moreover, the maximum electricity generation capacity of both PV power plants could be reduced by more than 20% when the concentrations of PM2.5 and PM10 increase to 75 μg/m^3 and 150 μg/m^3, respectively. Besides, the daily reduction in power generation for a polycrystalline silicon (poly c-Si) PV module was about 2%–48% due to the presence of atmospheric aerosols in Niamey (Sahel zone) as reported by Neher et al. [101]. Subsequently, the authors found that the aerosols reduced the daily solar PV power generation by 13%–22% in five other cities in West Africa [102].

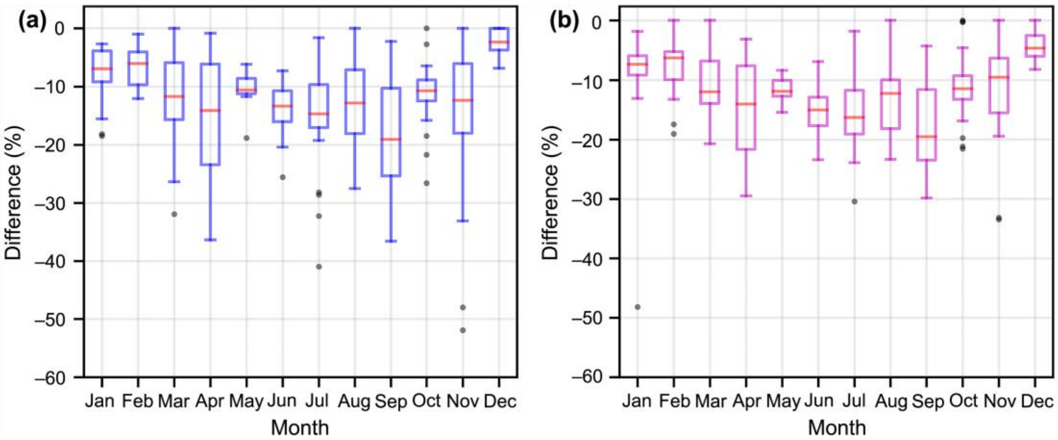

Fig. 7. The monthly differences between estimated power generation without aerosols and measured power generation for (a) mono c-Si, and (b) a-Si PV modules [97].

In summary, all the above studies investigated the adverse impact of air pollution on solar PV resources and PV performances from global to regional levels, which illustrated significant reductions in solar PV power generation and huge potential revenue losses. It is therefore suggested that attenuation by atmospheric aerosols should be considered as a vital factor in large-scale solar PV planning.

2.2.3 Impact of air pollution events on solar PV power generation

Besides the studies mentioned above focusing on the long-term impact of air pollution on solar PV power generation, several studies attempted to analyze the impact of air pollution events on the local PV system performance. A high pollution episode occurred in June 2013 due to fires in Riau Province, Indonesia, which strongly affected other neighboring countries in Southeast Asia, including Singapore, Malaysia, Brunei, and southern Thailand [103]. Solar PV resources and power generation have been significantly affected during this pollution episode. For example, a heavy haze took place in Singapore with the 24-h average pollutant standards index (PSI) of up to 246 in mid-June 2013 [104,105]. Nobre et al. [105] compared the global irradiance and normalized power output of a PV system for clear and haze days, as shown in Fig. 8. It is found that the power output reduced by 12.8%, along with a relative decrease of 13.9% in global irradiance. The authors further pointed out that the overall losses in power output of ten PV systems across Singapore ranged from 15% to 25% caused by this haze event. A similar air pollution episode was found in Kuala Lumpur, Malaysia, resulting in a significant decrease of 17.8% in electricity generation of a PV module with a maximum power output of 210 W during the period from September to October 2015 [106]. Perry and Troccoli [107] reported an overall 7% decrease of PV power output with a maximum reduction of up to 27% caused by a wildfire happened in Canberra, Australia. Gómez-Amo et al. [108] studied the impact of a wildfire episode on the power generation of a PV power plant located in Burjassot, Spain. The peak and average daily decreases of PV electricity generation caused by smoke were found to be up to 51% and 34%, respectively.

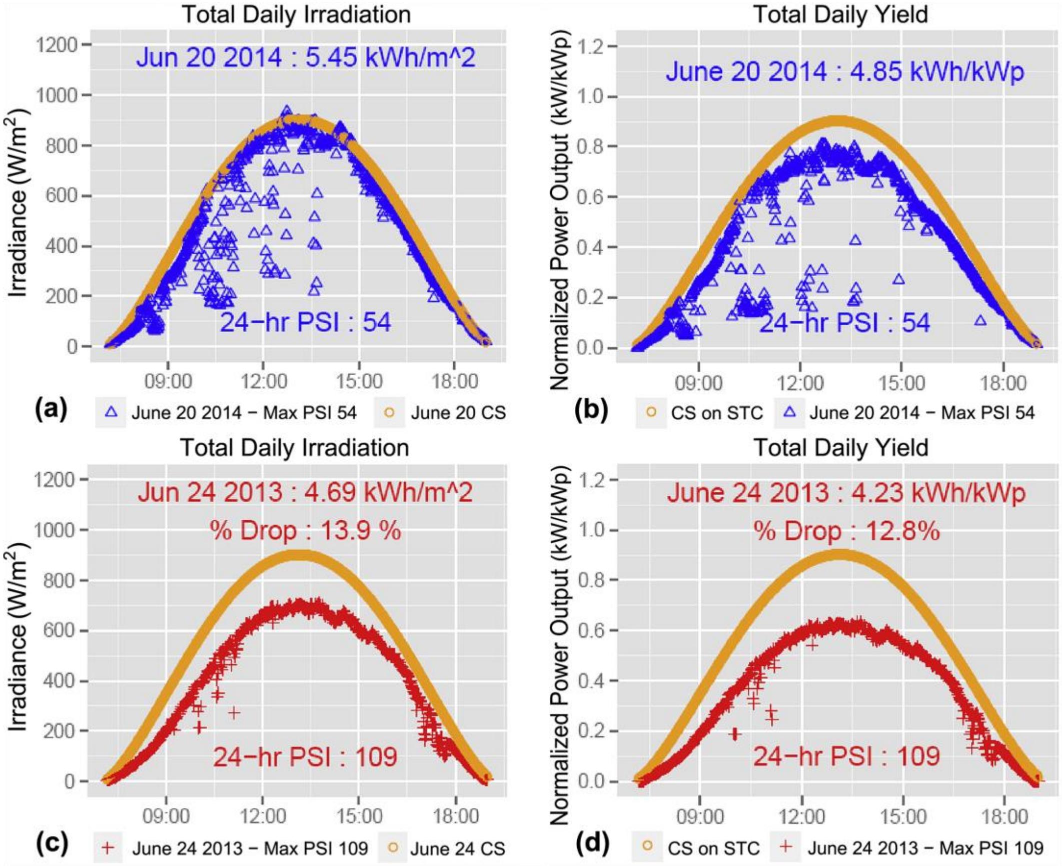

Fig. 8. The global horizontal irradiance and normalized power output of a c-Si PV system in a clear-sky day with 24-h PSI of 54 (June 20, 2014) and in a haze but cloudless day during the pollution episode with 24-h PSI of 109 (June 24, 2013) [105].

2.2.4 Impact of air pollution on the future solar PV power potential

With a continuous worldwide expansion on solar PV installations, it is important to study the impact of air pollution on the future evolution of solar PV energy potential. Therefore, the climate modeling considering future aerosol emissions scenarios has been widely to assess the future energy potential of PV systems over the world [109,110]. As shown in Fig. 9, Zou et al. [111] found an overall decreasing trend of 0.67 kWh/m^2 per year of the global solar PV electricity generation from 2006 to 2100, based on the Model for Interdisciplinary Research on Climate (CMIP5 models) in the RCP8.5 (high-emissions) scenario. On the other hand, the analysis indicated that the significantly decreasing atmospheric aerosols in the future would result in an increase in solar PV power generation in Europe, East Asia, Central America, and Central Africa, which agrees with the findings by Wild et al. [112]. The near-future availability of solar PV power generation in Europe and Africa was assessed by Gaetani et al. with the ECHAM5-HAM aerosol-climate model [113]. The results indicated that anthropogenic aerosol emissions have a statistically significant impact on solar PV productivity. For instance, the simulated annual reduction in PV electricity generation was approximately 7% and 6%, respectively, in eastern Europe and northern Africa. In comparison, a significant increase was occurred in western Europe (10%), southern Tropical Atlantic (6%), and eastern Mediterranean (3%) due to the abatement of aerosol emissions, as shown in Fig. 10(c). Additionally, an increase in the potential PV productivity is expected over Europe from 2021 to 2050 considering the significant decrease in sulfate aerosol emissions concerning the reference period 1971–2000, particularly in the central European countries such as Germany, Hungary and the Czech Republic, with a significant increase of above 10% in summer [114].

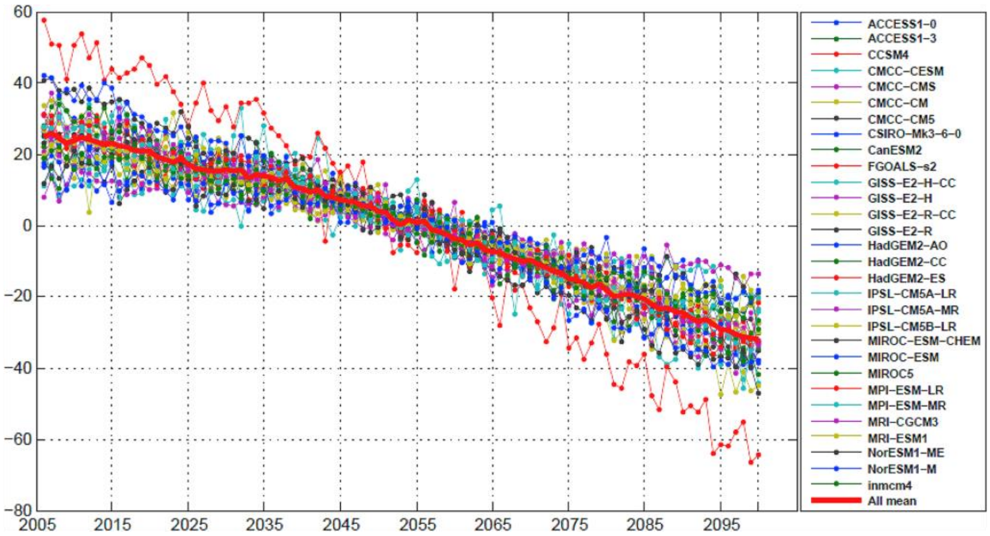

Fig. 9. Global annual average anomaly potential PV electricity generation during 2006–2100 in CMIP5 models in RCP8.5 scenario [111].

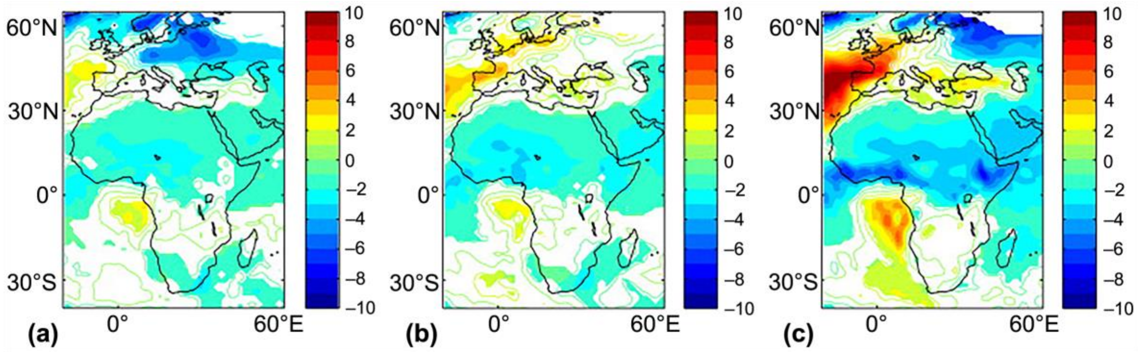

Fig. 10. The differences in ECHAM5-HAM modeling for annual PV electricity generation for (a) 2030GHG–2000, (b) 2030CLEMFR–2000, and (c) 2030MFR–2000 aerosol emissions (Shading means a 95% significant difference) [113].

2.3 Elimination of air pollution for solar PV power generation

Eliminating air pollution through effective policies and measures can reduce anthropogenic aerosol emissions, consequently increasing solar radiation reaching the surface with a potential increase in solar PV power generation. Additional power generation achieved by eliminating air pollution means higher economic benefits [76]. Furthermore, the elimination of air pollution can contribute to possible co-benefits for the building energy savings, ecosystem health, physical and mental health of human beings, and other welfare [115–117].

2.3.1 Air pollution control policies and measures

Air pollution can be resulted from the open burning of biofuels and the combustion of fossil fuels and primarily coal. China produces large quantities of atmospheric pollutant emissions associated with coal consumption as the world's largest consumer of coal [118]. The serious adverse effects of air pollution continue to prompt China to implement aggressive clean-air policies and anti-pollution measures to limit fossil fuel consumption and reduce atmospheric aerosol emissions. In 2013, China released the Air Pollution Prevention and Control Action Plan reducing around 25%, 20%, and 15% of PM2.5 emissions in Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta regions, respectively, in 2017 benchmarked with 2012 [119]. A series of stringent measures have been implemented for the achievements of the clean air action plan, such as phase-out indigenous coke ovens [120], stringent controls on sulfur dioxide (SO_2) emissions from coal-fired power plants through mature desulfurization techniques [121], updates on industrial boilers [122], and shift from coal to gas and renewable energy [123–125]. Since 2013, nation-wide PM2.5 concentrations have decreased significantly along with the reductions of SO_2 and NO_x that benefited greatly from these policies and measures [122,126,127]. In addition, China promised to peak carbon emissions by around 2030 and to be carbon neutral by 2060 [128].

Given the previous and current success of pollution-control policies and measures in China, Sweerts et al. [76] believed that aerosol emissions would continue to decrease. They pointed out that air pollution elimination would result in an annual increase between 51–74 TWh in PV electricity generation potential based on the expectation that China's solar PV capacity will be at least 400 GW by 2030. Assuming that the Chinese feed-in tariff (FIT) for PV is phased out by 2030, the cost savings from the potential solar power gains could reach US$ 4.6–6.7 billion per year. The authors further concluded that potential increases could be approximately 1% of total domestic electricity generation in 2030 with the growth of solar PV share in the electricity mix. Fig. 11 illustrates the breakdown effects of eliminating emissions from energy, industrial, residential and commercial (RCO), and transport sectors on national-mean surface solar irradiance in China. The elimination of emissions from multiple sectors significantly increases surface solar irradiation compared with adopting a single sector approach. Based on China's PV deployment in the future, the increases in solar PV power generation from the cleaner atmosphere would be 49–73 TWh in 2030 and 85–158 TWh in 2040 [129]. For the 2040 PV capacity scenario, the increased power generation would lead to an additional annual revenue of US$ 6.9–10.1 billion considering the degression of FIT, which could compensate for 13%–17% of the costs of pollution controls in all sectors.

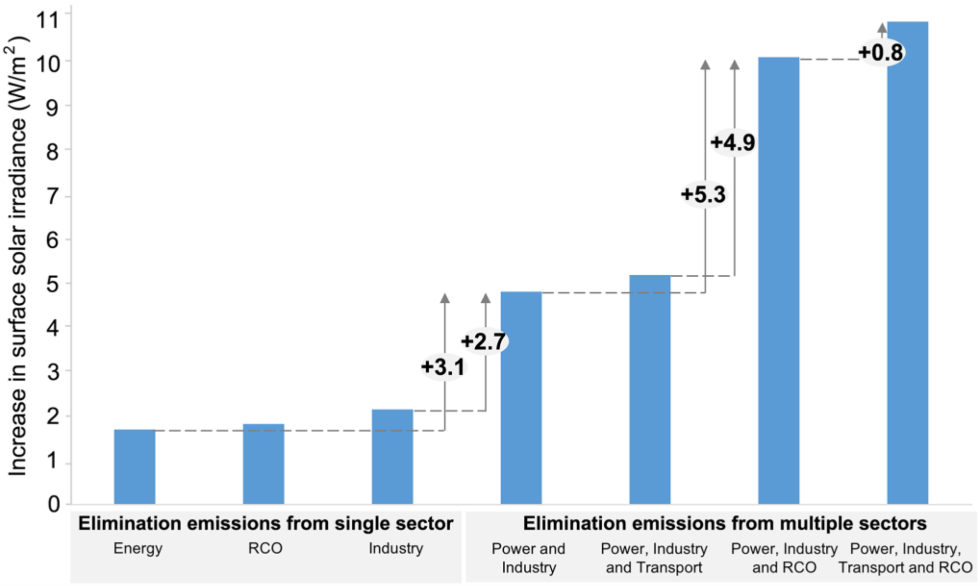

Fig. 11. National-mean increase in surface solar irradiance from eliminating SO_2, black carbon, and organic carbon emissions [129].

2.3.2 COVID-19 lockdown measures

The COVID-19 has been swiping the globe since the end of 2019. In response to this global emergency, governments worldwide have implemented government-enforced lockdown measures that would counter the spread of the COVID-19 pandemic [130,131]. Fig. 12 shows the lockdown restriction from January to August 2020 in 577 cities affected by COVID-19 worldwide. About 75% of the cities were locked down in March 2020, and about 50% ended in May 2020, with an average lockdown period of 57 days [132]. Economic activities associated with transport, mobility, manufacturing, tourism, and agriculture were almost at a standstill due to the governmental restrictions in many countries [133]. The global energy demand in 2020 was estimated to decrease by up to 6% compared to that in 2019 [134]. Meanwhile, the progress of the solar PV sector was inevitably hindered by this global crisis, especially in the deployment of distributed PV. For instance, Zhang et al. [135] tracked the economic footprint of COVID-19 lockdown in the solar PV sector of Japan based on comprehensive records of 1.6 million financial transactions and 44374 PV installations. The results indicated that the monthly demand and value-added reduced respectively by 78.69% and 67.69% in the distributed PV market when the lockdown period exceeded two months.

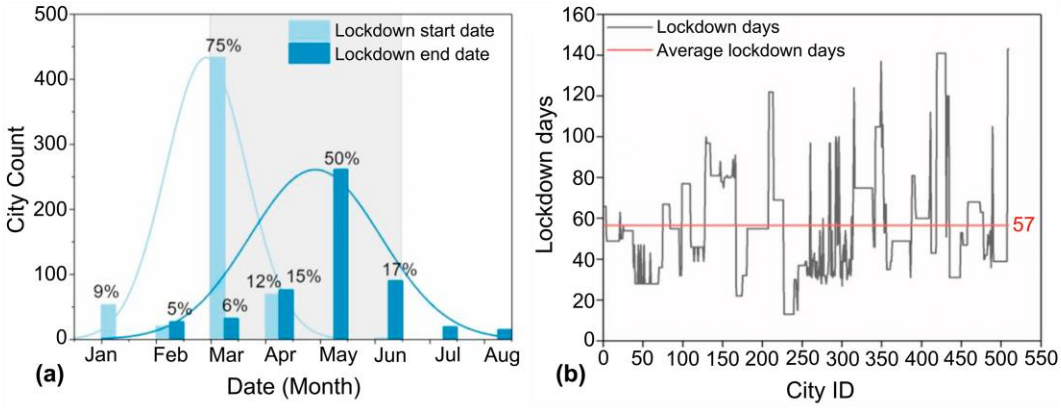

Fig. 12. COVID-19 lockdown periods in 577 cities worldwide from January to August 2020 [132]. (a) The probability distribution of start and end dates of lockdown and (b) the number of days under lockdown.

On the other hand, the COVID-19 pandemic offers opportunities for governments to promote renewable energy that will accelerate global solar PV projects [79,133,136,137]. Moreover, the COVID-19 lockdown measures could potentially bring about unexpected benefits to the environment and health. Among them, these measures have significantly reduced the anthropogenic emissions of air pollutants and consequently improved the air quality [138–141]. For instance, satellite and ground station data from 34 countries demonstrated that the lockdown reduced the population-weighted concentrations of PM2.5 and nitrogen dioxide (NO_2) by up to 31% and 60%, respectively [142]. The changes in air pollutants concentrations are expected to improve the atmospheric transparency, allowing more solar radiation to reach the Earth’s surface and, consequently, increasing solar PV power generation.

China is the first country to launch lockdown restrictions to contain the pandemic. Over China, about one-third of cities were placed under draconian control, and 95 cities imposed lockdown measures such as prohibitions of group gatherings and unnecessary commercial activities, and restrictions on public and private transportation [143]. As shown in Fig. 13(a), the lockdown did reduce the air pollution: the daily air quality index (AQI) declined by 12.2% compared with cities without lockdown [144]. Focusing on Wuhan, the first locked-down city, as an example, Choi and Brindley [145] found that the columnar NO_2 and aerosol optical depth (AOD) at 550 nm during the lockdown period declined respectively by 75% and 15.6% compared with the same term in 2019, resulting in a 19.3% increase in the average broadband direct normal irradiance (DNI), as illustrated in Fig. 13(c). Furthermore, Fig. 13(b) shows the average simulated spectral DNI over Wuhan: a significant blue-shift was observed in the DNI spectrum during the lockdown period, which improves the spectral matching with PV cell, thereby increasing the efficiency for a triple-junction PV cell with an estimated increase of 29.7% in maximum power point, as shown in Fig. 13(d).

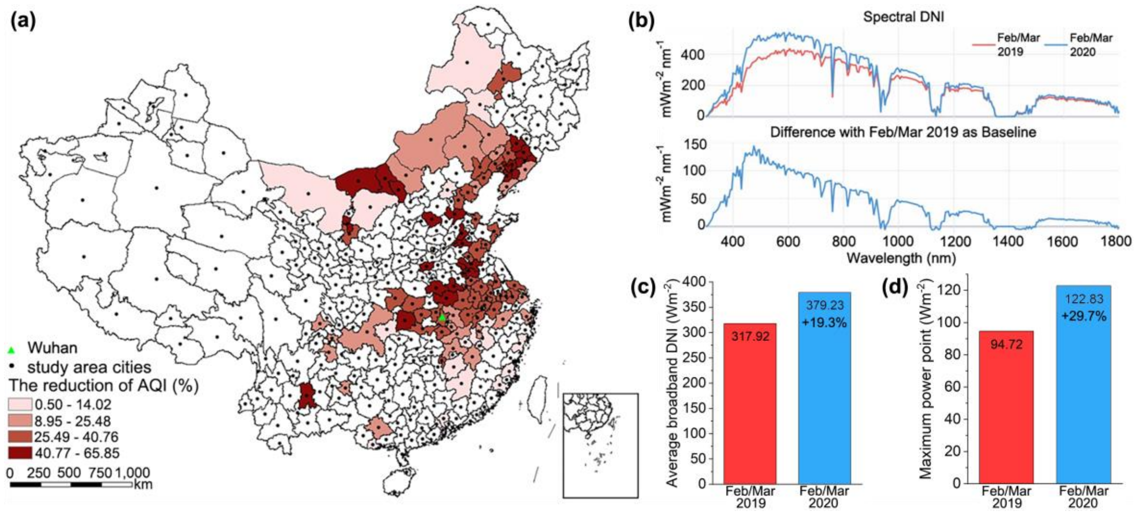

Fig. 13. The effects of lockdown on air quality, solar irradiance, and solar energy generation. (a) Reduction of AQI in locked-down cities over China [144]. Estimated (b) spectral DNI, (c) surface broadband DNI, and (d) maximum power point for a triple-junction PV cell over Wuhan during Feb/Mar 2019 and 2020 [145].

From 16 March to 14 April 2020, the average AQI of India declined by 15%–44% due to lockdown compared with the same period in previous years [146]. Peters et al. [147] found that surface solar radiation increased by 8.3% ± 1.7% in late March 2020 and by 5.9% ± 1.6% in April 2020 in Delhi, because of the air quality improvement due to India’s COVID-19-related restrictions (see Fig. 14). They reported that the energy production of solar PV installations in Delhi will continue to increase as long as the air pollution level is kept low. A similar report in Malaysia shown that the reduction of air pollutants due to lockdown allows more sunlight to reach PV modules, which increases the generation of solar power [148]. Solar PV power generation in other high-polluted cities with COVID-19-related restrictions such as London, Los Angeles, Mumbai and Kolkata was expected to increase as the lockdown-induced drop in the levels of air pollution [147]. In addition, the PV power output in Germany, the United Kingdom, and Spain increased significantly, with generation records peaked respectively at 32.2 GW, 9.68 GW, and 6.3 GW during the spring of 2020, which was mainly attributed to the cleaner air as a result of the lockdown restrictions [149].

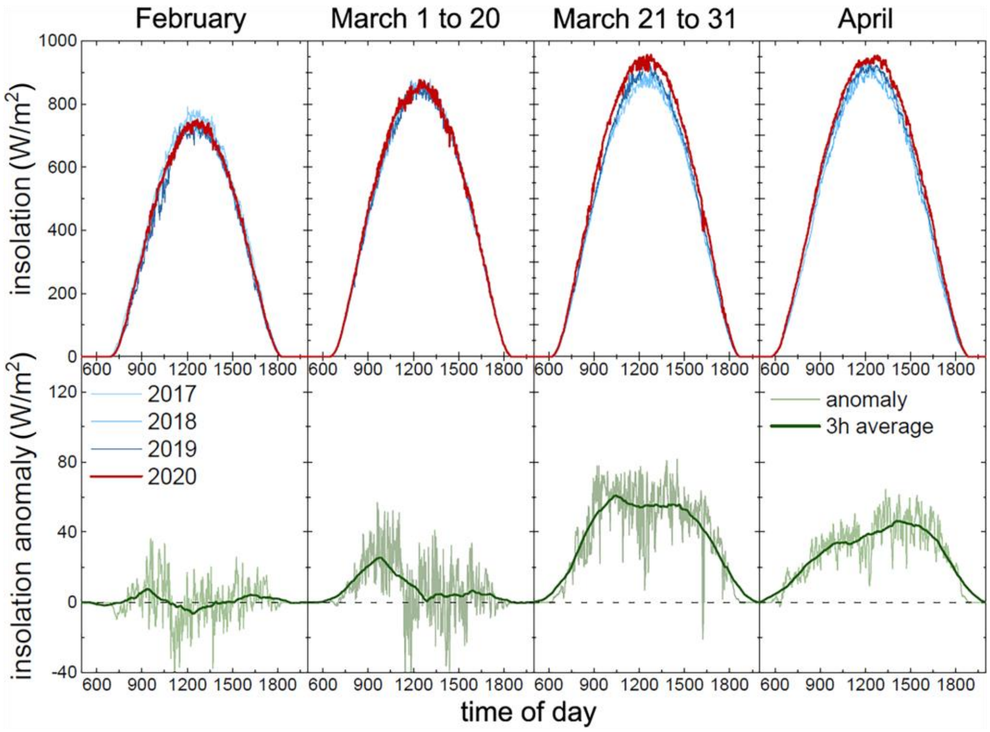

Fig. 14. The clear-sky solar radiation and solar radiation anomaly in the years 2017 to 2020 in Delhi, India [147].

3. Soiling and solar photovoltaic power generation

In addition to air pollution attenuation, the airborne dust and grime deposited on the front surface of PV modules, referred to as ‘soiling’, is an inevitable environmental hazard resulting in a drastic reduction in PV power generation around the world. This section discusses the natural soiling processes considering various influencing factors and highlights the impact of soiling on solar PV power generation. Meanwhile, the soiling mitigation approaches are summarized and compared.

3.1 Influencing factors of natural soiling processes

Soiling on the front surface of PV modules is a complex process due to various factors. For PV modules and PV power plants, soiling is mainly determined by environmental factors, including airborne dust concentration, meteorological factors such as wind speed, frequency and strength of rainfall, ambient temperature, relative humidity and dew [24,31,150]. Apart from the environmental factors, configurational characteristics of the PV modules (e.g. installed tilt angle and orientation, and the front surface properties) can also significantly influence the soiling processes [24,151,152]. Meanwhile, the time variation of these factors should be considered as a significant factor in the soiling processes.

3.1.1 Environmental factors of natural soiling processes

Airborne dust concentration and properties: Dust is generally referred to as the solid particles with a diameter less than 500μm, such as aeolian sandy soil particles, pollen, dander, and PMs generated from fossil fuels combustion, vehicle emissions and construction debris, which depends on the site of PV modules [30,35,153]. Airborne dust concentration is considered as the major domination of soiling. Micheli and Muller [154] presented an analysis of 20 solar PV soiling stations across the United States. The results indicated that the annual average daily concentration of PM2.5 and PM10 showed significant correlations with the soiling rate, both having a determination coefficient (R^2) of 0.82. It means that PM pollution potentially resulting in high soiling rates.

In addition, the physical and chemical properties of dust vary greatly with sources, resulting in varied soiling rates on the PV surface from location to location. In general, dust deposition is primarily affected by gravitational forces, macroscopic intermolecular forces (i.e. Van der Waals forces), capillary forces, and electrostatic forces [30,155]. As shown in Fig. 15, Ilse et al. [24] stated that the capillary forces dominate the adhesion between dust particles and PV surface for all particle sizes, followed by Van der Waals forces. In comparison, the effects of gravitational forces and electrostatic forces can be neglected for the relevant size range of particles. Similarly, Isaifan et al. [156] reported that the capillary forces dominate the adhesion between dust particles and PV surface, sharing 98% of total forces under high relative humidity, while Van der Waals forces play a dominant role under dry environmental conditions. On the other hand, Chanchangi et al. [30] reported that the inertial and gravitational forces are major determinants of adhesion for dust particles with larger sizes, while the Van der Waals forces primarily influence dust particles with smaller sizes. According to Sarver et al. [157], the intermolecular attractions show a reverse trend with the dust particle sizes below 10 μm. For example, compared to coarse dust particles larger than 5 μm, fine dust particles with a diameter less than 1 μm present a higher tendency for adhesion to cover the PV surface uniformly. Therefore, the increase of sunlight scattering or absorption and the decrease of transmittance would result in optical losses [158,159].

Besides, the morphology of dust particles is also an important influencing factor for optical losses caused by deposited dust on PV surfaces. Tanesab et al. [160] pointed out that soiling dominated by porous dust particles allows more sunlight to reach the PV surface. Meanwhile, they concluded that dust particles with angular and diagonal shapes caused less optical losses than elliptical and spheroid dust particles.

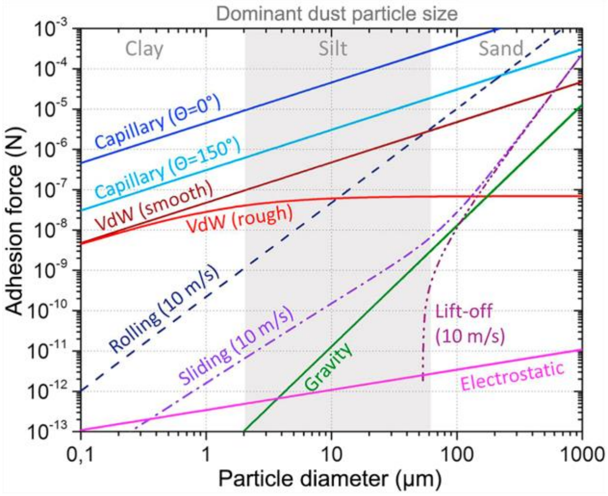

Fig. 15. The typical particle adhesion forces and threshold values [24].

Rainfall: Rainfall greatly affects the soiling processes since sufficient rainfall can clean the soiled PV modules, while light rain may cause more soiling problems. Micheli et al. [161] found that the rainfall shows an obvious statistical correlation to the soiling rates. Similarly, Caron and Littmann [162] studied the region-specific soiling trends in California, indicating that the rainfall significantly effects the soiling. Specifically, the soiling rate reduced from 10.5% per month to less than 1% in the Central Valley due to the frequent rain between mid-October and November 2010. However, a brief and light fall of rain can cause the wet deposition of airborne dust particles, which may aggravate the soiling of PV modules. For example, Valerino et al. [163] noted that light rain events (below 5 mm/h) did not clean the soiled PV modules but accelerated the deposition of dust particles, resulting in a higher soiling rate.

Wind: Wind is an important factor that affects the deposition and removal of dust particles on the PV modules, with both positive and negative effects on the soiling processes that rate the balance between dust deposition and resuspension. On the one hand, wind may reduce soiling rates as it can blow away the deposited dust from the surface of PV modules. Jiang et al. [164] modeled the effect of wind blowing on the suspension of accumulated dust particles. They found that wind can effectively remove the dust particles larger than 1 μm, but ineffective for smaller particles. On the other hand, wind can spread the airborne dust particles as a transporting carrier that increases soiling rates. Wind speed plays an essential role for soiling in this regard. Said et al. [165] concluded that more airborne dust particles were deposited on the PV surface with the increasing wind speed, which agrees with the findings of Goossens and Van Kerschaever [166].

Relative humidity and ambient temperature: The environmental relative humidity and ambient temperature significantly influence the adhesion forces between dust particles and the surface of PV modules. Chanchangi et al. [30] and Jamil et al. [158] stated that dust particles are easier to be transported by wind in an arid or semi-arid climate with low relative humidity and high ambient temperature. In addition, high relative humidity can aggravate the soiling rates of the PV modules as it increases adhesion forces. Specifically, Said and Walwil [167] found that the adhesion force is increased by approximately 80%, with the relative humidity increasing from 40% to 80%, as shown in Fig. 16. Figgis et al. [168] summarized that the adhesion force between dust particles and the PV surface increases when the relative humidity reaches 30%–50%. When the relative humidity exceeds 60%–70%, the adhesion force would further strengthen.

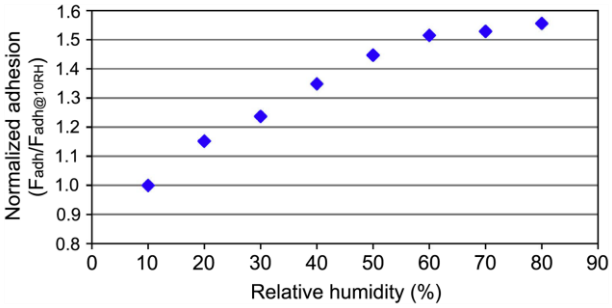

Fig. 16. The influence of relative humidity on adhesion forces of dust particles (48 µm silica bead) to a PV surface [167].

The water vapor condensation on the surface of PV modules is another important factor for the soiling rates. The temperature of the PV surface cools below the ambient temperature as a result of radiative cooling during the night and dawn. Meanwhile, the relative humidity increases with the decrease of the water vapor saturation concentration due to the ambient temperature reduction. The surface temperature is then below the dew point temperature, resulting in water vapor condensation on the surface of PV modules. Consequently, the adhesion of dust particles is significantly enhanced through the increase of cementation, particle caking and capillary forces, as presented in Fig. 17 [24,169–171]. For example, Ilse et al. [172] found that dew formed frequently in Qatar, resulting in cementation of nanoscopic needles of the clay mineral palygorskite with significant increases of dust particles adhesion. Furthermore, similar dew formation on PV modules is found in various desert sites [157].

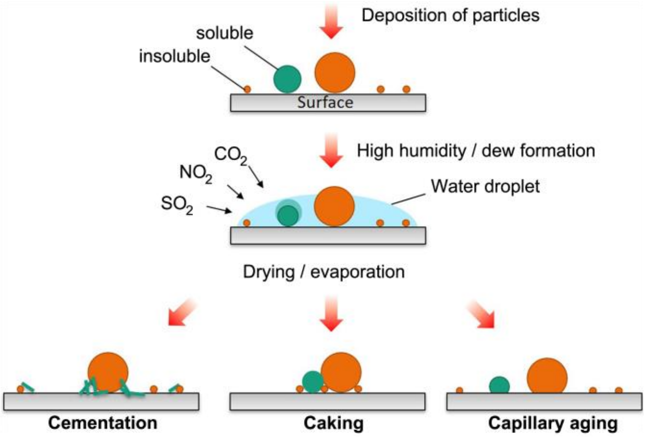

Fig. 17. Soiling mechanisms for increases of dust particles adhesion to surfaces through cementation, particle caking and capillary forces [24].

Bird droppings and biofilms: Bird droppings are generally counted for the soiling since they completely block the incident sunlight from reaching the PV surface. In contrast with the dust particles, bird droppings only influence a few solar cells, leading to the emergence of hot spots on a PV module [173]. In addition, bird droppings also accelerate the dust deposition processes with the adhesiveness for airborne dust particles [150]. Besides, it has been shown that biofilms such as fungi, bacteria, algae, lichen and mosses, may cause serious microbial soiling of PV modules, especially in tropical and moderate climates [174,175].

3.1.2 Configurational factors of natural soiling processes

Surface properties of PV modules: The properties of the front surface of PV modules, e.g. the cover material and coating, also significantly affect the soiling processes. Kalogirou et al. [176] studied the influences of soiling on a-Si, mono, and poly c-Si PV modules and concluded that the glass cover is less affected by soiling compared to the Tedlar cover. Similarly, Jiang et al. [177] indicated that the poly c-Si PV module covered by epoxy is faster to be soiled by dust particles than that covered by glass via controlled experiments. In addition, glass covers are coated with various coatings such as surface passivation coating and anti-reflection coating to improve the optical properties. However, these coatings may lead to dust accumulation as they increase the particles adhesion to the PV surface [153,178].

Tilt angle and orientation: The tilt angle and orientation of the PV modules greatly influence the soiling processes. A numerical experiment on a PV module was conducted by Lu and Zhao [179] to investigate the mechanisms of dust deposition based on the discrete particle model and the shear stress transport k–ω turbulence model. The results indicated that the tilt angle and orientation of PV modules greatly affected the deposition rates and behaviors. The peak deposition rates were observed with the dust particles diameter of 150 μm for all cases as shown in Fig. 18. It is found that the maximum deposition rates were 14.28%, 13.53%, 9.78%, and 6.79%, respectively, for the PV modules at 25°, 40°, 155° (i.e. –25°), and 140° (i.e. –40°).

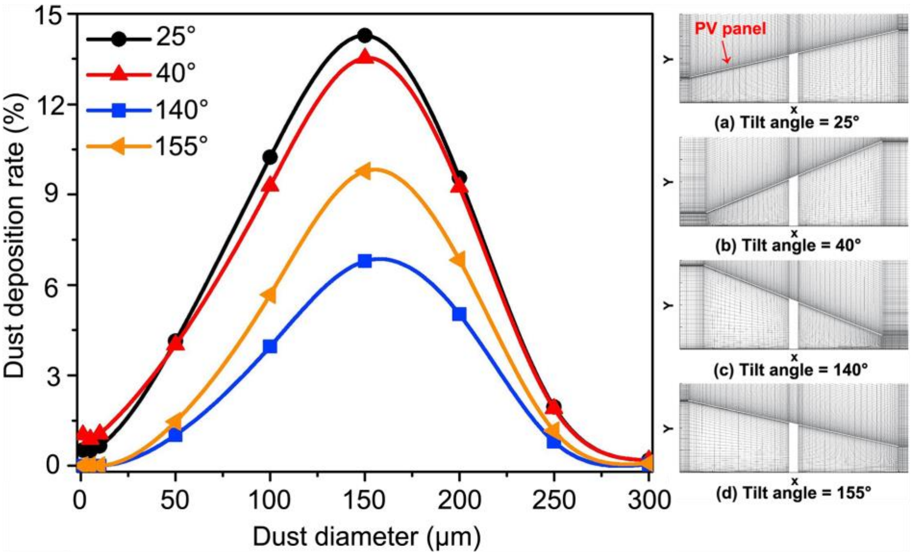

Fig. 18. Dust deposition rates on the PV modules with tilt angles of 25°, 40°, 155° and 140°, respectively [179].

Besides, many field experiments were conducted to study the impact of tilt angle and orientation on the soiling of PV modules. Xu et al. [180] found that the light transmittance increases from 0.76 to 0.97 with the tilt angle changing from 0° to 90° when the dust deposition density is 6.82 g/m^2. Sun et al. [181] pointed out a 19%–47% decrease in the average dust deposition density for each 30°increase of tilt angle (0°– 90°) in terms of PV modules with different surfaces properties. In the case of the desert location, Elminir et al. [182] observed that the dust deposition density ranges from 15.84 g/m^2 (at a tilt angle of 0°) to 4.48 g/m^2 (at a tilt angle of 90°). The corresponding reductions of transmittance were between 52.54% and 12.38%, respectively. Furthermore, they found that more dust particles accumulated on the PV modules installed at northeast orientation due to the emissions of local cement factories transferred by the northeast wind. As shown in Fig. 19, Ullah et al. [183] also reported similar findings in Lahore, Pakistan. It is found that the daily soiling rate decreases by about 0.011% per degree with the PV modules tilting from horizontal to vertical. Heydarabadi et al. [184] reported that a maximum dust accumulation is reached when the PV modules were oriented to the south at a tilt angle of 30° and 90° for particles with diameter larger than 10 μm and less than 1 μm, respectively. Similarly, Qasem et al. [185] found a non-uniformity of 0.2% of spectral transmittance at 90° tilt and 4.4% for the PV modules with a tilt angle of 30°. In addition, higher soiling rates occurred for PV modules installed at a fixed tilt angle in comparison with one-axis or two-axis tracking PV modules [186]. Overall, the above studies demonstrated that soiling rates decrease as the tilt angle of PV modules increases from 0° (i.e. horizontal surface) to 90° (i.e. vertical surface) because large size dust particles tend to roll down and detach from the PV surface under the influence of gravitational forces.

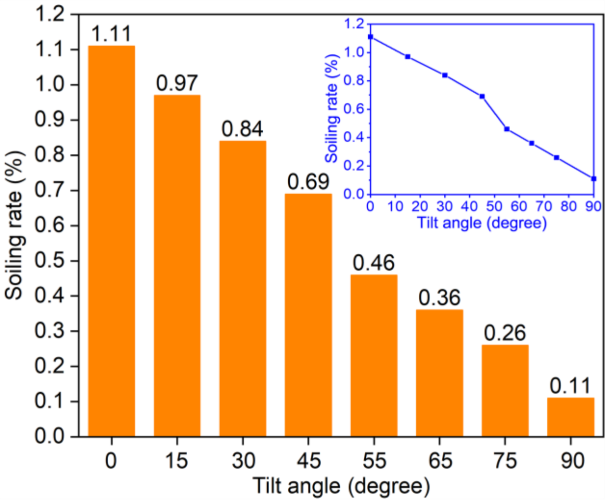

Fig. 19. Average daily soiling rates on the PV surface at different tilt angles [183].

3.2 Impact of soiling on solar PV power generation

Soiling caused by airborne dust particles and grime is a global environmental hazard that decimates the solar PV industries by reducing solar irradiation reaching the surface of PV modules. Soiling generally results in a drastic reduction of solar PV power generation with heavy financial losses. It is found that the daily PV power generation losses exceed 1%, and monthly PV efficiency significantly decreases by up to 80% due to soiling [35,173]. As presented in Fig. 20, the effect of soiling accounts for more than 80% of the total reduction of PV CFs over most of the world. In comparison, less than 50% of the total reduction can be attributed to the soiling of PV modules in the regions of Indo-Gangetic plains and North China with heavy air pollution [28]. It is noteworthy that the reduction of PV CFs is more significant in arid and semi-arid regions with high solar irradiance, especially in the subtropical desert areas such as the Middle East and North Africa.

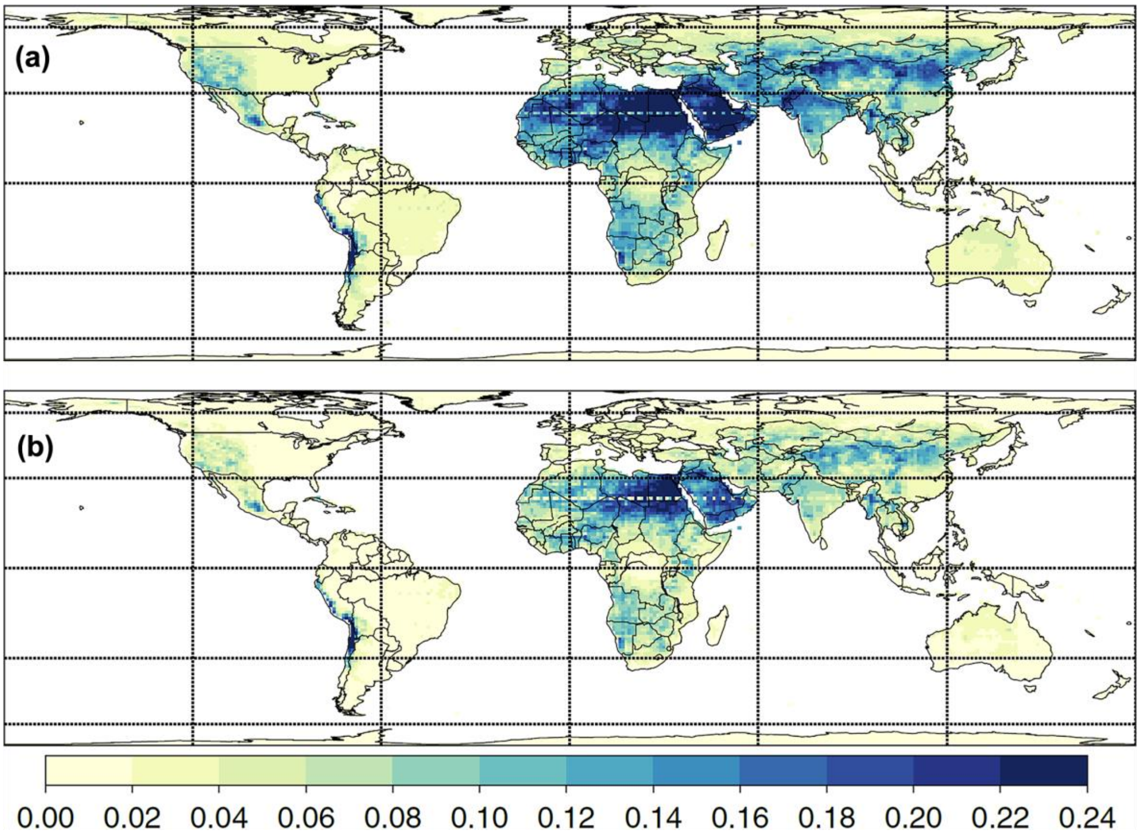

Fig. 20. 2003–2014 annual average reduction of PV CFs due to (a) atmospheric aerosols and soiling, (b) soiling of PV modules [28].

3.2.1 Impact of soiling on solar PV power generation by field and outdoor experiments

Over the past years, an increasing number of studies were carried out to investigate the impact of natural soiling on solar PV power generation with the exponential increase of solar PV installations worldwide. Ilse et al. [34] quantitated the impact of soiling on the 20 top PV markets, accounting for approximately 90% of global PV capacity in 2018. The estimated solar PV power generation reduced by at least 3%–4% in 2018 due to the soiling of PV modules, equivalent to a total revenue loss of more than € 3–5 billion. Furthermore, the soiling-induced reduction of global solar PV power generation could increase to 4%–7% by 2023. Table 4 summarizes the field and outdoor experiments on the impact of soiling on PV power generation. It is found that the power losses and efficiency reduction of PV modules due to soiling accumulate with time and vary with environmental factors, installation parameters and PV modules design. In general, soiling causes more losses in PV power generation in the Middle East, with a maximum power output reduction of more than 50% and PV efficiency reduction of about 40%. While soiling reduces less PV power output between about 1% and 8% in Europe. Most studies focused on the impact of soiling on the crystalline silicon PV modules and further studies are needed to investigate the impacts of soiling on other types of PV modules.

Table 4. Summary of the reported impact of soiling on solar PV power generation.

Location	Climate	Type and the front surface of PV	Tilt angle (°)	Duration of study	Dust deposition density (g/m^2)	Parameter of PV modules	Reduction (%)	Ref.
				Middle East				
Sharjah, UAE	Desert	Poly c-Si, glass	45	2 weeks	N/A	PV efficiency	10.95	[187]
			25				14.11	
			0				37.63	
			25	5 months	5.44	Power output	12.7	
Aswan, Egypt	Desert	Poly c-Si, glass	45	10 months	N/A	Power output	25.5	[188]
			30				31	
			20				38	
			15				43	
Tehran, Iran	Semi-arid	Mono c-Si, glass	N/A	70 days	6.0986	Power output	21.47	[189]
Shiraz, Iran	Semi-arid	Mono c-Si, glass	45	8 months	N/A	Power output	11.7	[190]
			30				12.1	
			15				15.8	
			0				33.4	
Limassol, Cyprus	Temperate	Mono c-Si, glass	45	7 months	12	Power output (monthly)	17.4	[182]
Limassol, Cyprus	Temperate	a-Si, Tedlar	31	12 weeks	N/A	Power output	8	[176]
		Poly c-Si, Tedlar					14	
		Mono c-Si, Tedlar					15	
Dhahran, KSA	Desert	Poly and mono c-Si, glass	26	6 months	6.184	Power output	>50	[191]
Dhahran, KSA	Desert	Mono c-Si, glass	26	45 days	5	Power output	6	[167]
						Short-circuit current	13	
Sohar, Oman	Desert	Poly c-Si, glass	27	3 months	111.11	PV efficiency	18	[192]
						Open circuit voltage	7	
						Short-circuit current	10	
Qatar	Desert	a-Si	N/A	100 days	N/A	PV efficiency	7.1	[193]
		Mono c-Si					9.5	
Baghdad, Iraq	Desert	Mono c-Si, glass	30	1 day	0.21	PV efficiency	5.87	[194]
				1 week	0.4		10.57	
				1 month	0.64		15.78	
Bahrain	Desert	Poly c-Si, N/A	26	16 months	N/A	Electricity generation (monthly)	8.72	[195]
				South Asia				

Tripura, India	Tropical	Mono c-Si, glass	23.8	6 months	N/A	PV efficiency	9.07–15.59	[196]
						Open circuit voltage	0.26–0.59	
						Short-circuit current	8.97–16.66	
Islamabad, Pakistan	Subtropical	Poly c-Si, glass	60	30 days	3.179	Power output	7.95	[197]
			34.5		4.618		11.55	
			15		5.522		13.8	
		Mono c-Si, glass	60		3.179		11.13	
			34.5		4.618		16.16	
			15		5.522		19.33	
Lahore, Pakistan	Semi-arid	Bifacial poly c-Si, N/A	30	2 weeks	N/A	Short-circuit current	15	[183]
Lalitpur, Nepal	Temperate	Poly c-Si, glass	27	5 months	9.6711	PV efficiency	29.76	[198]
East & Southeast Asia								
Hong Kong, China	Subtropical	CIS thin-film, glass	0	3 months	N/A	PV efficiency	16.116	[199]
Xi’an, China	Continental	Poly c-Si, glass	30	8 days	5.06	Power output	6.31	[200]
					7.58		9.51	
					12.64		20.62	
Hangzhou, China	Temperate	Poly c-Si, glass	20	1 week	0.644	Power output	7.4	[201]
Phitsanulok, Thailand	Tropical	a-Si, glass	N/A	30 days	0.268	Electricity generation	3.5	[202]
		Poly c-Si, glass					2.6	
Selangor, Malaysia	Tropical	Poly c-Si, glass	5	3 weeks	N/A	Power output	2.72	[203]
Singapore	Tropical	N/A, glass	20	5 weeks	N/A	PV efficiency	2	[204]
North Africa								
Ouargla, Algeria	Desert	Mono c-Si, glass	30	8 weeks	4.3619	Max. power output	8.41	[205]
						Open circuit voltage	0.51	
						Short-circuit current	6.1	
Europe								
Puglia, Italy	Temperate	Poly c-Si, glass	25	3 months	N/A	Power output	1.1–6.9	[206]
Canary Islands, Spain	Subtropical	c-Si, glass	22.5	5 months	N/A	PV efficiency	13–27	[33]
Athens, Greece	Temperate	Poly c-Si, glass	30	2 weeks	0.1	Power output	2	[207]
				8 weeks	1		6.5	
Athens, Greece	Temperate	Poly c-Si, glass	30	1 hour	0.63	PV efficiency	0.1	[208]
						Power output	2.3	
Gdansk,	Continental	Mono c-Si, N/A	37	N/A	0.862 µm	Short-circuit	13.3	[209]

Poland					thickness	current		
Évora, Portugal	Temperate	Mono c-Si, glass	15	Dust event	1.067	Max. power output	8	[210]
				North America				
California, US	-	N/A	<5 6–19 >20	145 days	N/A	PV efficiency (daily)	0.18 0.052 0.053	[211]
Santa Clara, US	Temperate	N/A	N/A	108 days	N/A	PV efficiency	22	[212]
				South America				
Santiago, Chile	Semi-arid	Poly c-Si, glass Mono c-Si, glass Thin-film, glass	32	30 months	N/A	Electricity generation (daily)	0.19–0.83 0.19–0.79 0.23–0.62	[213]
				Australia				
Perth, Australia	Temperate	a-Si, N/A Poly c-Si, N/A Mono c-Si, N/A	32	1 year	N/A	Max. power output	9.12–9.99 8.42–8.89 8.48–12.18	[159]

3.2.2 Impact of soiling on solar PV power generation by indoor experiments

Indoor experimental studies were also conducted to clarify the impact of soiling on solar PV power generation. Jiang et al. [177] found that the PV output efficiency degraded from 0 to 26%, with the dust deposition density growing from 0 to 22 g/m^2 using a test chamber and a sun simulator. Additionally, the results showed that the PV output efficiency decreased more at higher and lower solar radiation intensity. Similarly, Muñoz-García et al. [214] performed a series of experiments used a climatic chamber (see Fig. 21) to simulate the soiling processes under desert climate conditions, which indicated that the cumulated dust deposition density of 1.30−1.63 g/m^2 could reduce the electricity generation by 4.73%−6.90%. An experiment conducted by Rao et al. [215] demonstrated the influence of soiling on the current-voltage characteristics of PV modules, and 45%–55% losses in the PV power output were noticed due to a 7.155 g/m^2 dust density.

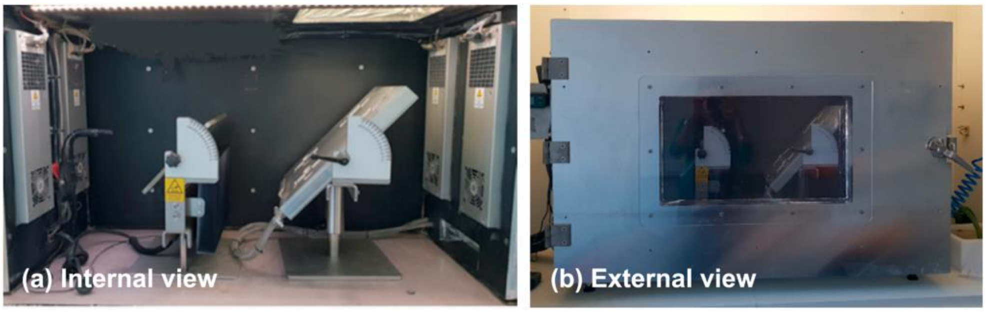

Fig. 21. Indoor soiling chamber [214].

Table 5. Comparison of the impact of collected dust samples on a PV module under laboratory conditions [216].

	Voltage (V)		Ampere (A)		Power (W)	
Dust weight	100 g	200 g	100 g	200 g	100 g	200 g
No dust	20	20	5.3	5.3	106	106
Barke	17.3	16.8	4.3	4.1	74.39	71.4
Buraimi	18	17.65	4.9	4.7	88.2	77.66
Liwa	17.5	16.9	4.45	4.25	77.875	71.83
Masqat	17.45	16.85	4.35	4.2	75.9	70.77
Saham	16	16.03	4.42	4.02	70.72	64.44
Sohar	15.9	15.1	4.35	4.15	69.165	62.66

Dust species have a significant impact on the power generation of PV modules. Kazem and Chaichan [216] collected dust samples from six cities in Northern Oman to assess the soiling impact on the PV modules under laboratory conditions (25°C, 45% relative humidity, and 850 W/m^2 light intensity). Table 5 illustrates the impact of distributed dust of 100 g and 200 g on the voltage, current, and output power of a 0.9 m^2 PV module, showing a 35%–40% power reduction due to soiling. Darwish et al. [217] simulated the reduction of PV efficiency and power output at a fixed solar radiation of 600 W/m^2 due to different dust particle species, i.e. natural dust, calcium oxide (CaO), manganese dioxide (MnO_2), iron oxide (Fe_2O_3) and carbon. The dust of carbon shows the most significant impact on the PV performance with power output and efficiency decreased from 57.82 W to 0.135 W and from 13.2% to 0.03%, respectively, as the density of carbon dust increasing from 0 to 20.27 g/m^2 (see Fig. 22).

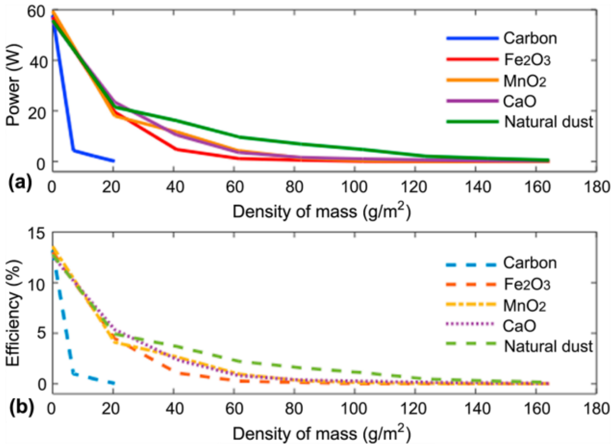

Fig. 22. The impact of dust particle species and dust deposition density on (a) PV power output and (b) PV efficiency [217].

3.2.3 Impact of soiling on solar PV power generation by modeling studies

Modeling studies have been conducted to study the impact of soiling on the PV modules.

For example, Zitouni et al. [218] developed three models, i.e. the multiple linear regression model, response surface methodology model and artificial neural network model, to predict the losses in electricity generation due to soiling. The results showed that the soiling reduced the daily electricity generation by 0.03 kWh and 0.61 kWh, respectively, during the rainy and dry periods in Morocco. The total losses reached up to 82.5 kWh that accounted for 28% of the maximum generation capacity throughout the whole test period. Similarly, Pulipaka et al. [219] quantified the impact of the dust particle sizes on the losses in solar PV power generation based on regression. Further, they predicted the energy outputs of a soiled PV module by neural networks. You et al. [220] modeled the soiling-induced efficiency losses of PV modules in Doha, Hami, Malibu, Sanlucar la Mayor, Taichung, Tokyo and Walkaway. It is found that Tokyo has the lowest efficiency loss of below 4%, while the PV efficiency is reduced by more than 80% in Doha.

3.3 Soiling mitigation approaches for solar PV power generation

Soiling of PV modules reduces the solar PV power generation and the lifespan of PV modules given the corrosion, discoloration and delamination effects due to the chemical nature of deposited dust particles. It is therefore crucial to clean the soiled PV surfaces to mitigate the soiling effects. Soiling mitigation approaches can be categorized into restorative and preventive approaches, as shown in Fig. 23, including natural cleaning, manual cleaning, mechanical cleaning, anti-soiling coating, and electrodynamic dust shield.

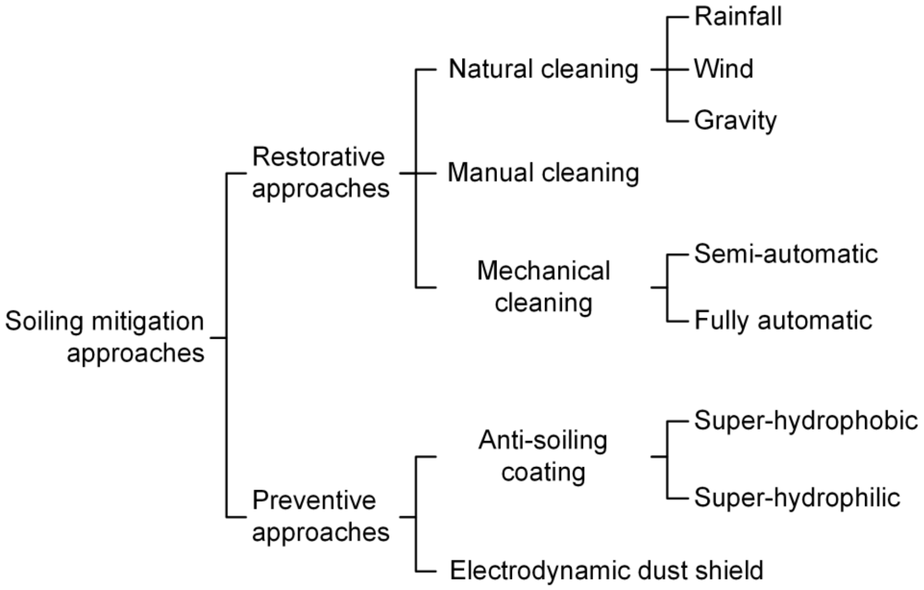

Fig. 23. Overview of soiling mitigation approaches classified by category.

3.3.1 Restorative soiling mitigation approaches

Natural cleaning: Rainfall, wind and gravity generally act as the natural cleaner for soiled PV modules [30]. Sufficient rainfall can effectively clean the soiled PV surfaces, although the power generation decreases on rainy days. Natural cleaning by rainfall is more effective in removing the deposited dust particles from the surfaces in locations with lighter soiling rates, such as Europe. For instance, 2.2 mm of rainfall has a 50% probability to completely clean the soiled PV modules in southern Europe [221]. The west coast of South America and the Western United States have low dust deposition rates; however, the extremely small rainfall is difficult to restore the PV surfaces to their original conditions, which aggravates the impact of soiling to a certain extent [28]. The tilt angle has a significant influence on the natural cleaning, as the horizontal position of PV modules is not conducive to rainfall cleaning compared to the inclined one. Meanwhile, increasing the tilt angle from 0° to 90° promotes the deposited dust particles detaching from the surface due to gravity [184]. In addition, wind can remove dust particles of large sizes from the surface, especially for PV modules in high installations [31]. Jiang et al. [164] concluded that wind effectively removes large dust particles greater than 1 μm in diameter. However, wind cleaning is ineffective for small-size dust particles as the large needed wind velocity for particle resuspension.

Manual cleaning: Manual cleaning approaches are effective methods to clean soiled PV modules using brushes with special bristles or soft cloth, or chemical additives. Manual cleaning with a reasonable cleaning schedule is almost the optimum soiling mitigation strategy for small-scale PV power plants [34,150]. This approach can effectively remove cementations and hard soiling, such as bird droppings and biofilms from the front surface of PV modules by labor. However, manual cleaning can potentially lead to the artificial abrasion of the front surface of PV modules, resulting in damage to durability and optical transmittance of the cover [222,223]. Miller et al. [222] stated that examined the abrasion of PV coating and cover glass and found that a natural fiber bristle (i.e. hog bristle) can reduce the abrasion damage during cleaning processes. Besides, the labor cost for manual cleaning is generally quite high, particularly for large-scale PV power plants. Moreover, since the PV modules generally require to be washed with pressurized water before brushing, manual cleaning is unsuitable for water shortage regions such as arid and semi-arid locations with severe soiling [150,158].

Mechanical cleaning: Mechanical systems for PV module cleaning are generally operated by fully automatic or semi-automatic devices through brushing, wiping and blowing. Both brushing and wiping operate the brushes and wiper to move either vertically or horizontally on the PV surface based on the electromechanical approach [30]. For instance, Khan et al. [224]

developed an automatic cleaning mechanism for micro solar PV systems, as shown in Fig. 24, mainly consisting of mechanical systems, electrical systems, an electro-mechanical control unit, and a cleaning wiper. The experimental results indicated a 35% increase in the PV efficiency with the proposed mechanical cleaning system. In addition, the blowing approaches use air nozzles with vortex generators to remove soiling from the surface but also to reduce the surface temperature of PV modules [30,225]. Similar to manual cleaning, the PV surfaces may be subject to artificial abrasion during cleaning processes [222].

Currently, mechanical cleaning is still dominated by semi-automatic approaches. The fully automatic cleaning market accounted for only 0.13% of the global solar PV capacity in 2018, which is expected to increase to 6.1 GW in 2022 since the fully automated robots for cleaning have been integrated into the design of PV plants [34].

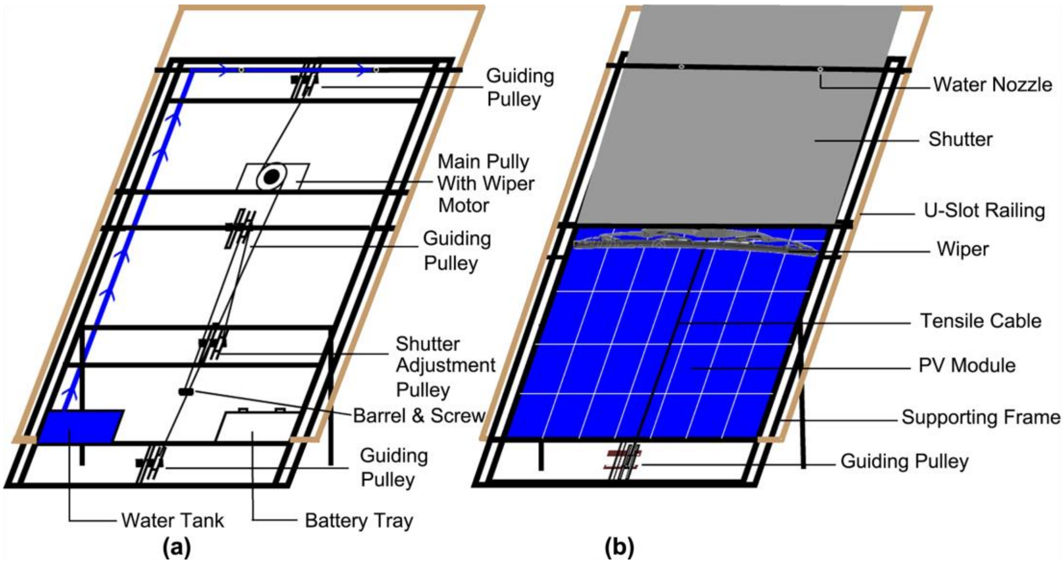

Fig. 24. An automatic cleaning mechanism designed by Khan et al. [224].

3.3.2 Preventive soiling mitigation approaches

Anti-soiling coating: The anti-soiling coating is a self-cleaning approach applied to the front surface of PV modules to reduce dust deposition and accumulation. It should be highly transparent, anti-reflective, high-temperature-resistant, ultraviolet (UV) resistant, durable, low cost, and easily industrialized [34,157]. In recent years, super-hydrophobic and super-hydrophilic materials have been widely adopted to mitigate the soiling of PV modules [226,227].

The super-hydrophobic coating has low wettability and high water drops mobility. Water drops on the super-hydrophobic surface have a water contact angle larger than 150°, as shown in Fig. 25(a) [228]. It promotes the water drops to roll off the surface with dust particles when tilting the super-hydrophobic surface at an angle. The super-hydrophobic coating can prevent dust particles from accumulating on the PV modules and significantly reduce the PV efficiency decrease [155]. Furthermore, the super-hydrophobic coating with nanostructures can enlarge the water contact angle for a better anti-soiling effect [158,229,230]. However, Quan and Zhang [231] found that both ordinary hydrophobic and super-hydrophobic coating can significantly reduce dust deposition by dust impinging and dust removal experiments. They indicated that the strength of hydrophobicity has little impact on the anti-soiling effect. Moreover, the lifespan of super-hydrophobic is relatively short, and its performance can be significantly degraded over time by UV irradiation and other environmental factors [30,34].

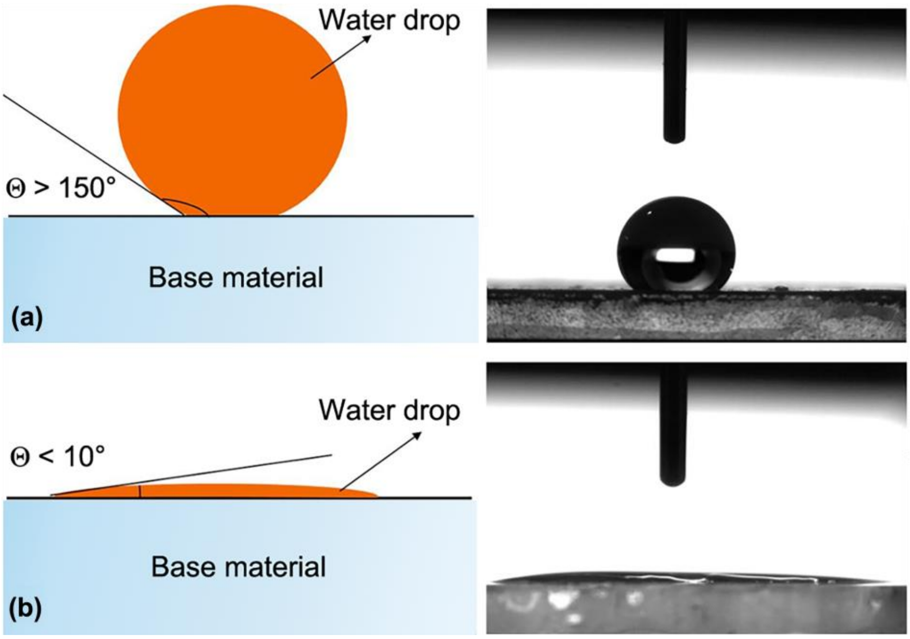

Fig. 25. Water drops on (a) super-hydrophobic and (b) super-hydrophilic surfaces [228].

On the contrary, super-hydrophilic coating strongly attracts to water. The water contact angle of water drop on the super-hydrophilic surface is extremely small (or even close to 0°), as presented in Fig. 25(b), allowing water to spread onto the PV surface [228,232]. Consequently, the deposited dust particles can move along with the water film and eventually be carried off the surface of PV modules. In general, the super-hydrophilic coating is composed of Titanium dioxide (TiO_2) nano-film, which can chemically break down the organic particles when exposed to UV light (photocatalytic effect) [158,228]. Thus, the super-hydrophilic surface is considered more effective than the surface with a super-hydrophobic coating. For example, an outdoor experiment conducted by Son et al. [233] demonstrated that the mono c-Si PV coated with the nano-patterned super-hydrophilic coating without chemical functionalization is reduced by 1.39% in efficiency after 12 weeks, which is smaller than that of the PV modules with fluorinated super-hydrophobic coating and bare glass packaging by 2.62% and 7.79%, respectively.

Electrodynamic dust shield: Electrodynamic dust shield (EDS), also known as electrodynamic screen, is a promising soiling mitigation technique that can repel or transport dust particles off the PV surface by creating a dynamic electric field [234,235]. Specifically, electrodynamic traveling waves are generated by the dynamic electric field by applying alternating high voltages to the parallel electrodes on a substrate (see Fig. 26). The electrically charged dust particles are then lifted off the surface by the Coulomb force and carried to the edge of EDS through the electrodynamic traveling waves [157,235–237]. Experimental studies have confirmed that the dust removal efficiency of EDS is more than 90% in dry ambient conditions [238–240]. However, the application of EDS in field conditions is limited by environmental issues such as the reduced dust removal efficiency with increasing relative humidity and duration of dust particles on the surfaces [241]. For instance, Javed and Guo [242] found that the dust removal efficiency of a two-phase, standing-wave EDS dropped from 22% to 9% when the relative humidity increased from 10% to 80%. Guo et al. [243] noticed that the average EDS efficiency decreased from 40% to 14% over four days. In addition, the required high-voltage electricity supply and high initial cost also make the EDS difficult for large-scale applications.

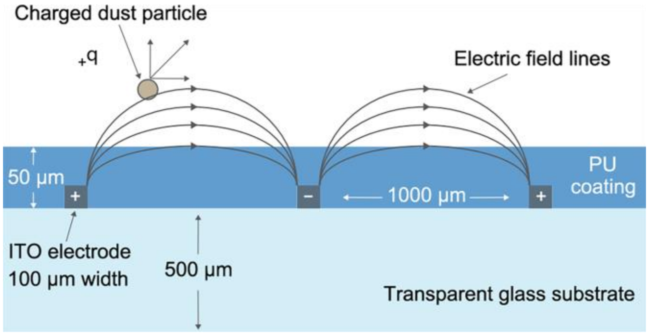

Fig. 26. Cross-sectional schematic diagram of an EDS [157].

3.3.3 Comparison of soiling mitigation approaches

Table 6 summarizes the advantages and disadvantages of the above restorative and preventive soiling mitigation approaches. It is found that no approach fits all site-specific soiling problems, considering the techno-economic factors such as the soiling removal efficiency, technical reliability, and the costs of labor and other sources. Even though preventive approaches, such as anti-soiling techniques, are reported to be effective in mitigating the soiling of the PV modules, the cleaning need cannot be eliminated. In summary, both manual cleaning and mechanical cleaning are still the optimal approaches for soiling mitigation.

Table 6. Comparison of different soiling mitigation approaches for the PV modules.

Soiling mitigation approaches	Advantages	Disadvantages
Natural cleaning	• No cost	• Dependent on geographical environment and weather conditions • Ineffective for small size dust particles [164]
Manual cleaning	• Nearly 100% soiling removal efficiency [150] • Low capital cost [34]	• High labor cost • Unsuitable for water shortage regions [150] • Surface abrasive damage [222,225]
Mechanical cleaning	• > 95% soiling removal efficiency (fully automatic) [34] • Automatic activation of cleaning with electromechanical controller [158,224] • Low or no labor cost [34] • Reducing the surface temperature [30,225]	• High initial cost • High costs of operation and maintenance [35] • Surface abrasive damage [158,222]
Anti-soiling coating	• Passive soiling mitigation approach • No need for external labor and other sources • Enlarging periods between cleanings [34]	• Reducing the PV efficiency [35] • Not eliminating the need for cleaning [34] • Dependent on rainfall or dew
• Super-hydrophobic coating	• Better anti-soiling effect with nanostructures [158,229,230]	• Short lifespan [30] • Uncertain durability due to UV irradiation [34]
• Super-hydrophilic coating	• Highly durable [30] • More effective than super-hydrophobic coating [233]	• Causing more soiling accumulation when the coating is deteriorating [30,158]
EDS	• > 90% dust removal efficiency in dry ambient conditions [238–240] • Fast cleaning action [158]	• Inefficient for cementation and wet dust particles [34,241] • Less effective with high relative humidity [242] • High-voltage electricity supply [235] • High initial cost[34]

4. Current research gaps and challenges

Based on the comprehensive literature review, it can be found that air pollution and soiling do threaten solar resources and solar PV power generation over many areas with rapid growth of PV capacity. Currently, there are still some research gaps and challenges. Most of the previous studies focused on the impact of air pollution and soiling on crystalline-silicon PV modules, which are currently the most widely installed PV technologies on the global markets. Systematic investigations on the degradation of power generation due to air pollution and soiling are essential for the other PV technologies such as thin-film PV modules. Besides, only limited studies have been conducted to quantify the reduction in solar PV power generation due to air pollution, which is far from comprehensive to reveal the impact of air pollution on the solar PV sector. In addition, soiling is still a severe challenge for solar power generation around the world, and research on the impact of COVID-19-related measures on the solar energy field is quite scarce.

5. Recommendations for future works

Solar PV is a highly cost-competitive clean power generation technology. Throughout the past decade, a higher annual solar PV capacity was installed than any other renewable and non-renewable power generation technologies worldwide. With the supports of governmental policies and investments in the solar PV sector, the global solar PV market will consistently increase with a rapid growth in the future. Therefore, based on the comprehensive review on air pollution and soiling implications for solar PV power generation, the recommendations for future works are suggested as below:

1) The previous studies reveal that air pollution and soiling significantly reduce solar PV power generation worldwide. Further studies are needed to develop an insight into the impacts of different air pollutants and dust species on the spectral, electrical, and thermal characteristics of various solar PV technologies over the major solar PV markets. In addition, it will be helpful to investigate the solar power generation potential under future aerosol emission scenarios for the optimal applications of solar energy, especially in the emerging solar PV markets such as Vietnam.

2) Shifting high-polluted power generation devices to solar-powered technologies will contribute to air cleaning. In turn, great benefits from a cleaner atmosphere are expected for the solar PV sector as well as health, environment and economy. Therefore, further analyses of energy-environment-economy interdependencies on air pollution elimination and the solar PV sector are needed for the formulation of improved renewable energy policies to achieve a carbon-neutral energy framework in the near future.

3) Although the COVID-19 lockdown restrictions decelerated the development of the global solar PV market, the pandemic promotes the shift progress to renewable energy. Moreover, these restrictions have improved air quality, increasing solar PV power generation in some regions. As the COVID-19 pandemic is still developing globally, continuous studies are significant to be conducted to quantify the impact of COVID-19-related measures on the solar PV sector. Besides, more efforts are needed for sustainable and renewable energy transition strategies in the post-COVID-19 world.
4) Soiling is still a crucial factor affecting solar PV power generation, although there are various mitigation strategies. In future works, the optimal cleaning frequency is needed to be determined by comprehensively assessing the technical and economic benefits for specific locations. Innovative anti-soiling coating materials and EDS techniques need further in-depth research and developments to tackle soiling. Moreover, further investigation is needed into the soiling monitoring and theoretical soiling modeling, particularly in arid and semi-arid locations with low rainfall.

6. Conclusions

Air pollution and soiling prevail worldwide, casting a shadow on solar PV power generation. This study provides a comprehensive review on the adverse impacts of air pollution and soiling on solar PV power generation, considering the key impact factors. Meanwhile, the benefits of eliminating air pollution to the solar PV sector and the mitigation strategies to tackle the soiling problems are discussed. Important conclusions are summarized as follows:

1) Both air pollution attenuation and the soiling of PV modules could significantly reduce PV power generation and cause huge financial losses in most regions with abundant solar resources. The reduction of PV capacity factors is between 2% and 68% due to the atmospheric aerosol attenuation. Soiling losses varied in different regions ranging from about 1% to more than 50%. In general, more losses in PV power generation due to air pollution and soiling is observed in the Middle East than in other regions.
2) Air pollution reduces solar power generation by attenuating solar radiation reaching the PV surface through reflection, scattering and absorption, while soiling reduces the solar transmittance through the covers of PV modules and degrades the solar power generation efficiency. In general, the soiling of PV modules plays a leading role in the reduction of PV power generation around the world, except in the highly polluted regions such as Indo-Gangetic plains and North China, when compared with the impact of air pollution.
3) Elimination of air pollution by governmental policies and measures is beneficial to increase

surface solar radiation and, consequently, increasing the power generation of PV modules. In addition, reducing air pollution, especially the concentrations of particulate matter, would also decrease the soiling of PV modules.

4) The COVID-19 pandemic inevitably hindered the progress of the solar PV sector. However, COVID-19 lockdown restrictions notably reduce the levels of air pollution over many regions, improving the atmospheric transparency that allows more solar radiation to reach the PV surfaces, which increases the solar PV power generation, especially in the cities with severe air pollution.

5) Soiling of PV modules is a complex process determined by the various interactive parameters, including environmental factors and configurational characteristics of the PV modules. At present, the soiling problems are far from solved.

6) Manual cleaning and mechanical cleaning are the most effective and reliable strategies to remove the soiling from PV modules among multiple restorative and preventive soiling mitigation approaches, although the costs of these measures are high. Besides, preventive approaches such as anti-soiling coatings can assist the cleaning measures by enlarging the periods between cleanings.

Declaration of competing interest

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

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