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Global reduction of solar power generation efficiency due to aerosols and panel soiling

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Air pollution and dust prevail over many regions that have rapid growth of solar photovoltaic (PV) electricity generation, potentially reducing PV generation. Here we combine solar PV performance modelling with long-term satellite-observation-constrained surface irradiance, aerosol deposition and precipitation rates to provide a global picture of the impact of particulate matter (PM) on PV generation. We consider attenuation caused by both atmospheric PM and PM deposition on panels (soiling) in calculating the overall effect of PM on PV generation, and include precipitation removal of soiling and the benefits of panel cleaning. Our results reveal that, with no cleaning and precipitation-only removal, PV generation in heavily polluted and desert regions is reduced by more than 50% by PM, with soiling accounting for more than two-thirds of the total reduction. Our findings highlight the benefit of cleaning panels in heavily polluted regions with low precipitation and the potential to increase PV generation through air-quality improvements.

In 2018, solar photovoltaic (PV) electricity generation saw a record 100 GW installation worldwide, representing almost half of all newly installed renewable power capacity, and surpassing all other power-generating sources in added generation capacity[1–3]. Global total PV capacity now exceeds 500 GW (ref. [1]). With decreasing production costs, increasing PV module efficiency and continued government support, solar PV is anticipated to provide 16% of total global electricity generation by 2050 (with ~4.6 TW in solar PV capacity)[4]. PV generation in China, India, Africa and the Middle East is projected to account for 10% of global electricity generation and 60% of global PV electricity generation by 2050[4]. Current installation rates are exceeding projections, however, indicating that the 2050 projections may also be exceeded.

While emerging markets see great potential for solar PV development, these regions often have high concentrations of particulate matter (PM) in the atmosphere, a threat to PV generation efficiency[5]. The North China Plain and the Indo-Gangetic Plain both feature high aerosol optical depths (AODs), mainly due to anthropogenic air pollution[6,7]. Dust is the main cause of high PM loadings over the Arabian Peninsula and northern Africa[8]. Atmospheric aerosols scatter (dust, sulfate, nitrate and organic carbon) and absorb (black carbon) shortwave radiation, reducing the amount of irradiance reaching the surface. Li et al.[9] found that atmospheric aerosols in the North China Plain reduce annual average surface solar resource by 25–35%, that is, a loss of up to 1.5 kWh m^{-2} d^{-1} in generation[9]. Recent studies indicate that air quality improvements in China may generate an increase of up to US$10 billion in solar generation revenue annually by 2040[10,11]. In addition, soiling of solar panels, caused by the accumulation of dust and dirt on the panel surface, limits the penetration of insolation to PV cells, and thus reduces the efficiency of electricity generation[12–14]. Local studies in India and on the Arabian Peninsula consistently report more than a 30% decrease in solar PV efficiency due to panel soiling after 3–6 months without cleaning[15–17]. A recent study by Bergin et al.[18] estimates a reduction of ~17–25% in surface solar resources across India, China and the Arabian Peninsula, with roughly equal contributions from ambient PM and particles deposited on PV surfaces that are cleaned monthly[18]. Solar irradiance predictions are starting to incorporate more accurate aerosol representations for the purpose of solar PV resource estimates and generation forecasts[19].

Precipitation removes dust and dirt accumulated on PV surfaces, especially in monsoon regions such as China and India. Our study considers precipitation as a natural removal mechanism for particles deposited on PV surfaces. We provide a global picture of the impact of PM on PV generation efficiency, which considers both atmospheric aerosols and surface soiling of panels. We quantify the PM impact for both fixed and tracking panels with PM removal by precipitation alone, and further investigate the benefit of cleaning panels.

Our work integrates NASA's Clouds and the Earth's Radiant Energy System (CERES)-SYN1deg (an observation-constrained global irradiance dataset) and Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2, a weather/aerosol reanalysis dataset) with PVLIB-Python, a solar PV performance model, to calculate the global reduction of solar PV electricity generation efficiency due to aerosols. We examine (1) the global distribution of solar resources and PV electricity generation and how they are modified by the impact of PM; (2) the total PM impact divided into atmospheric aerosol attenuation and panel soiling; (3) regional-mean impacts of atmospheric aerosol attenuation, panel soiling and clouds in order to identify the relative importance of PM and clouds; (4) the magnitude of PM impacts on fixed, one-axis tracking (OAT) and two-axis tracking (TAT) panels; and (5) the benefits of cleaning PV panels on a quarterly or monthly cycle or maintaining them in a constantly clean state, compared with relying entirely on removal by natural precipitation (no cleaning). Finally, we discuss policy implications for air pollution mitigation and PV deployment.

Average aerosol impacts

A 12 yr average of observation-based surface point-of-array irradiance (POAI) from 2003 to 2014 shows abundant annual aver-

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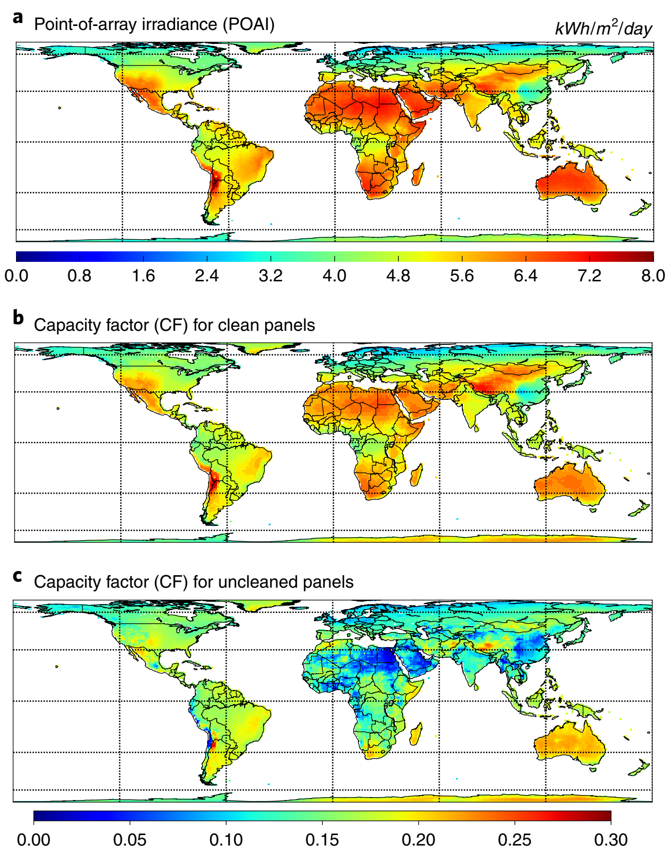

Fig. 1 | Average global surface solar resources and PV electricity generation, 2003–2014. a, POAIs at the surface for fixed panels under the all-sky condition (with aerosols and clouds). **b**, CFs of fixed-panel PV systems are shown for panels with no aerosol deposition, which receive the POAIs as shown in **a**. **c**, Panels covered by aerosol deposition without being cleaned receive lower POAIs than clean panels due to soiling. A large reduction in PV efficiency due to soiling is indicated in **b** and **c**.

age solar resources in subtropical regions (between 0° and 30° latitude) in both the Northern and Southern hemispheres (Fig. 1a). Western China, the Middle East, northern Africa, southern Africa, Australia, the western United States and the west coast of South America all feature POAIs larger than 7 $kWh\,m^{-2}\,d^{-1}$. Due to clouds, equatorial regions have 15–40% lower solar resources than subtropical regions with POAIs of 4.5–6 $kWh\,m^{-2}\,d^{-1}$, with India and Brazil at the high end of that range. High-latitude regions, for example, Europe, the northern United States and Canada, have an annual average POAI of less than 4 $kWh\,m^{-2}\,d^{-1}$, approximately half that of the resource-abundant regions. This spatial pattern of solar resources is largely driven by the amount of available insolation (high insolation in low latitudes and low insolation in high latitudes) and cloud cover (high cloud cover in equatorial regions and in regions affected by monsoons reduces surface insolation). We find POAIs to be slightly higher (5–10%) than previously reported[20], although with almost identical spatial patterns, because we evaluate the maximum radiation incident on a fixed, optimally tilted panel rather than on a horizontal surface. By converting irradiance into electricity, we calculate that most resource-abundant regions have average PV capacity factors (CFs) of between 0.2 and 0.25 (Fig. 1b). The CF is defined as the actual annual generation divided by the total generation that would occur if the PV panels generated electricity at the nameplate capacity all year round. Solar PVs over western China and the west coast of South America feature particularly large CFs of between 0.25 and 0.3, the highest efficiency in the world. PV CFs in other regions fall between 0.1 and 0.2.

When including the soiling impact over an entire annual cycle, assuming removal only by precipitation, PV CFs decrease by more than 30% in the most resource-abundant regions (Fig. 1c). Due to substantial dust deposition, northern Africa and the Middle East feature CFs lower than 0.1, more than 60% lower than those of clean panels. Other resource-abundant regions, for example, the western United States, southern Africa and Central Asia, feature CFs decreased by more than 25% (a drop to 0.15–0.2 from 0.2–0.25) due to soiling. Some low-resource regions, for example, eastern China and northern India, also see CF reductions of about 0.1 due to soiling.

When panels are left uncleaned by anything except natural precipitation, the overall impact of PM on PV efficiency is dominated by soiling (over atmospheric aerosol attenuation). Total PM reduction of CFs is more than 0.2 in northern Africa and the Middle East, 0.1–0.2 in western and northern China, northern India and the west coast of South America, and 0.05–0.1 in Southeast Asia, Central Asia, southern Africa and the western United States (Fig. 2a). After separating the total PM reduction of CF into atmospheric aerosol attenuation and soiling effects, we find that at least 80% of the total impacts can be attributed to the soiling effect except in the highly polluted North China and Indo-Gangetic plains (Fig. 2b,c). Due to precipitation in these regions, soiling reduces CFs by less than 50%. However, atmospheric aerosol attenuation in these two regions is the highest in the world, with CFs reduced by up to 0.06 (more than 60% of the total PM impact). Reductions due to atmospheric aerosols are caused by high anthropogenic air pollution over these two densely populated regions, consistent with the findings in Li et al.[9].

High soiling impacts occur in desert regions and in highly polluted regions. Desert regions, such as northern Africa and the Arabian Peninsula, feature particularly high reductions of PV generation due to soiling, as a result of a combination of low precipitation rates (Supplementary Fig. 8) and high dust deposition rates (Supplementary Fig. 7). These two factors result in a rapid accumulation of dust on PV panels in those areas, where there is almost no rainfall to clean them naturally. In heavily polluted northern China, air-pollution-driven sulfate and black carbon deposition on panels causes a large soiling impact (Supplementary Fig. 7). The moderate precipitation rate over northern China is not sufficient to remove this particulate accumulation. Northern India is similarly influenced by air pollution, with large contributions from sulfate, organic carbon and black carbon aerosols. Despite the high annual precipitation, northern India features half a year without rain, leaving PV panels accumulating particulate matter for months before being removed. However, because of severe air pollution, PV generation in both northern China and northern India is similarly influenced by atmospheric aerosols and soiling. Although the western United States and the west coast of South America have lower PM deposition rates than northern China and northern India (Supplementary Fig. 7), their very low precipitation levels remove little soiling from PV panels, resulting in large soiling impacts (Supplementary Fig. 8).

Comparing the spatial distribution of soiling reduction (Fig. 2c) with that of solar resources (Fig. 1a,b), we find that resource-abundant regions are generally more susceptible to reduction of PV efficiency due to soiling. Most resource-abundant regions are in subtropical desert areas where relative humidity is low and dust aerosol concentrations are high. PV generation in these areas is greatly enhanced by cleaning the PV panels, a topic that will be explored later in this paper.

Regional-mean impacts of aerosols and clouds

We calculate the regional-mean PM and cloud impacts on PV generation efficiency for major countries in the world. Here, PM and cloud impacts are defined as an increase in PV CFs when aerosols

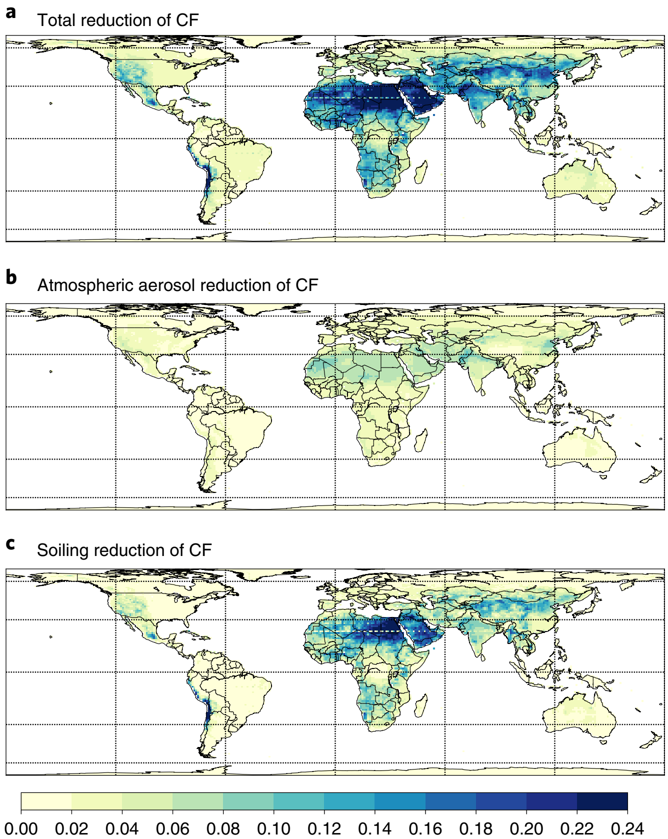

Fig. 2 | Average reduction of PV CFs due to the effect of aerosols, 2003–2014. a, The combined effect of atmospheric aerosols and soiling (resulting from aerosol deposition on PV panels). **b**,**c**, The effects due to atmospheric aerosols alone (**b**) and soiling alone (**c**). The effect due to atmospheric aerosol attenuation is much less than the effect of soiling. Supplementary Fig. 1 shows the atmospheric aerosol reduction in CF, with more detail at low CFs (0–0.06).

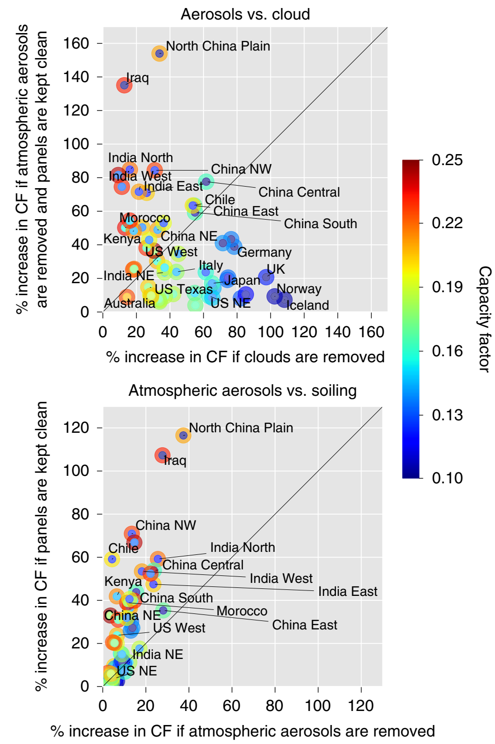

Fig. 3 | Comparison of regional-average percentage increase in PV CFs for fixed panels under various conditions. a, Comparison of the increase in CF if atmospheric aerosols are removed and panels are kept clean versus if clouds are removed (that is, total aerosol versus cloud impact). **b**, Comparison of the increase in CF if PV panels are kept clean versus if only atmospheric aerosols are removed (that is, soiling versus atmospheric aerosol impact). The colour of the inner circles represents the CF with total aerosol impacts (attenuation due to both atmospheric aerosol and soiling); outer circles show CFs without aerosol effects (atmospheric aerosols are removed and PV panels are kept clean). Regions are based on countries, except for the United States, China and India, which are further divided into subregions of major electricity grids (Supplementary Figs. 2–4). PMs in the resource-abundant polluted or desert regions such as the North China Plain and the Middle East have a larger impact than do clouds in clean cloudy regions such as Iceland and Norway. The colour contrast between the inner and outer circles indicates the huge impact of aerosols over some of the regions that would otherwise have abundant solar resources.

or clouds are removed. For the three countries of greatest interest, that is, the United States, India and China, we further divide each country into subregions according to their major electricity grids (Supplementary Figs. 2–4).

Clouds are a dominant factor impacting surface irradiance and PV generation over most regions, but PM plays a more important role over desert and heavily polluted regions. The North China Plain and Iraq would more than double their PV efficiency if aerosols were removed. PV generation in Algeria, northern, eastern and western India, and northwestern China would increase by 70–90% in the absence of aerosols. In general, total PM impacts are two times greater than cloud impacts over northern China and northern India, and five times greater over the Arabian Peninsula and northern Africa. Over eastern, central and southern China and Chile, relatively high precipitation rates reduce the total PM impact to around 60% (that is, removal of PM would increase PV efficiency by 60%), making it comparable to cloud impacts in these regions. Similar PM and cloud impacts are also found in lightly polluted dry regions, such as northeastern China (50%) and the western United States (40%).

When panels are left uncleaned and only precipitation removal of soiling is considered, soiling impact appears to play a larger role than atmospheric aerosol attenuation in most regions. Over the North China Plain and Iraq, keeping panels clean would more than double the PV efficiency, while removing atmospheric aerosols would increase efficiency by about 30%. In most resource-abundant regions, keeping panels clean leads to twice as large an increase in PV efficiency as removing atmospheric aerosols. This indicates that, in the short term, cleaning PV panels in resource-abundant regions would greatly increase efficiency and eliminate more than two-thirds of the total PM impact. Nevertheless, in the long run, reducing anthropogenic aerosols would decrease aerosol deposition rates and thus also reduce the soiling effect. Over most high-PM-impacted regions, where solar resources are also abundant, totally removing PM would double PV efficiency (Fig. 3). Over desert regions, by frequently cleaning the PV panels, more than two-thirds of such benefits could be achieved.

Aerosol impacts on tracking panels

Tracking technology enables solar PV panels to receive more direct radiation from the Sun and increases PV efficiency. OAT panels change their tilt angle from east to west during the day to maximize the level of solar irradiance they receive daily. TAT panels follow the Sun seasonally as well as diurnally and receive the maximum direct radiation. The magnitude of the benefit due to tracking depends on

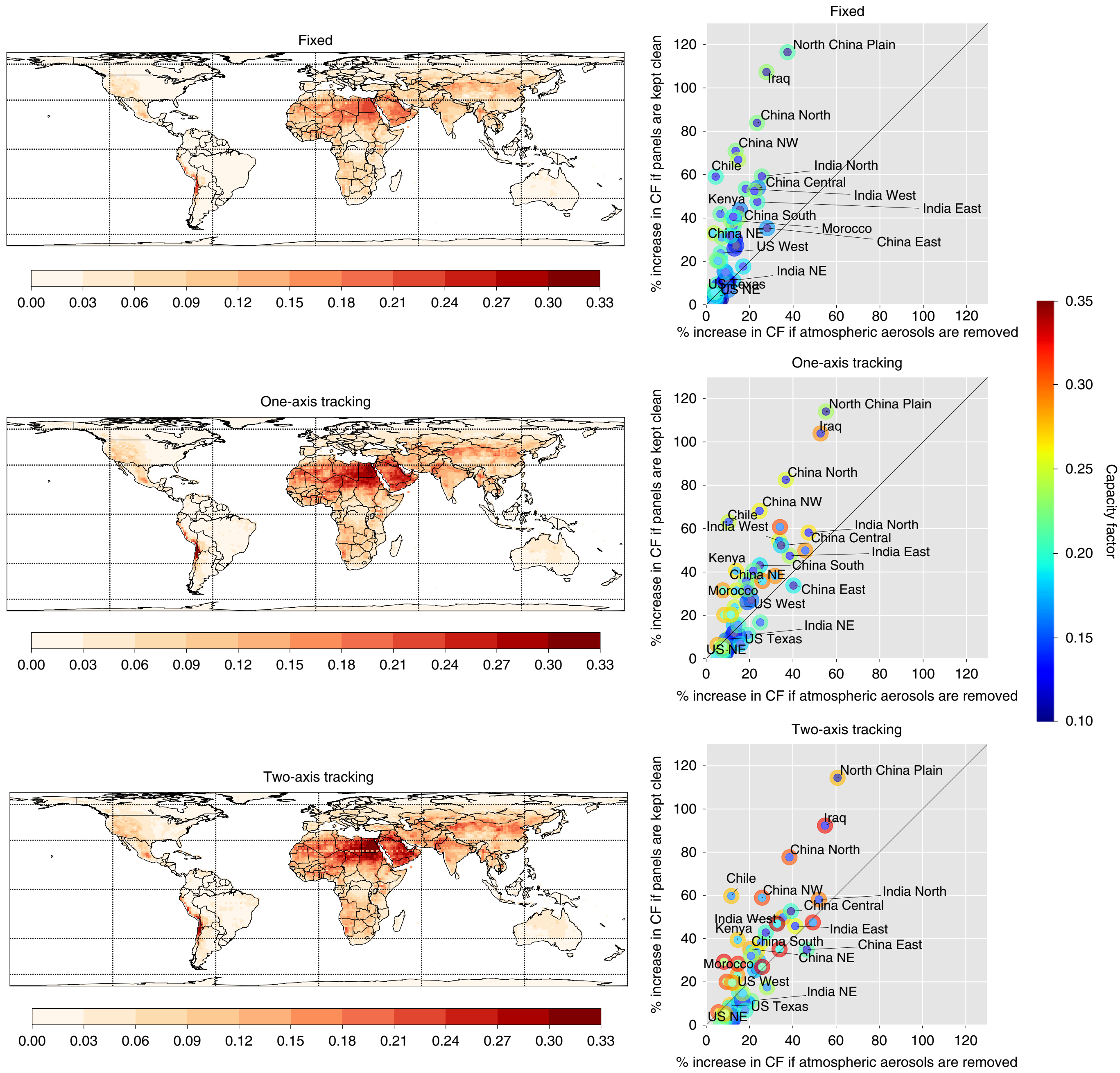

Fig. 4 | Comparison of aerosol impacts on PV CFs for fixed and tracking panels. a–c, Increases in PV CFs if atmospheric aerosols are removed and the PV panels are kept clean (that is, total aerosol impact) for fixed (**a**), OAT (**b**) and TAT (**c**) panels. **d–f**, Increases in PV CFs if the PV panels are kept clean compared with if atmospheric aerosols are removed (that is, soiling versus atmospheric aerosol impact) for fixed (**d**), OAT (**e**) and TAT (**f**) panels. The colour of the inner circles represents the CF with total aerosol impacts (attenuation due to both atmospheric aerosols and soiling); the colour of the outer circles represents CFs with no aerosol impact (atmospheric aerosols are removed and panels are kept clean). Regions are based on countries, except for the United States, China and India, which are further divided into subregions of major electricity grids (Supplementary Figs. 2–4).

OAT versus TAT, location and soiling levels. In equatorial regions, fixed panels provide more than 90% of the efficiency of TAT panels in the same location; in subtropical regions, OAT panels are more than 90% as efficient as TAT panels. TAT panels increase PV CFs by more than 50% in high-latitude regions where seasonal variation of surface irradiance is large.

While tracking panels bring large benefits to PV efficiency versus fixed panels, the impacts of PM become much larger. PM reduces the CF of TAT panels by almost twice that of fixed panels (Fig. 4a–c). Atmospheric aerosol attenuation is much larger on tracking panels than on fixed panels, with the CFs of tracking panels reduced five times more than the CFs of fixed panels (Supplementary Fig. 5). Nevertheless, the increase of soiling impacts on tracking panels is less; soiling reduces CFs of TAT panels only 50% more than that of fixed panels. In terms of percentage impacts, tracking panels have a larger percentage reduction in CFs from the presence of atmospheric aerosols due to increased aerosol optical path-length, but a similar percentage reduction due to soiling. Tracking allows PV panels to receive more direct radiation, which is also more susceptible to PM impacts than diffuse radiation. Therefore, tracking panels, which

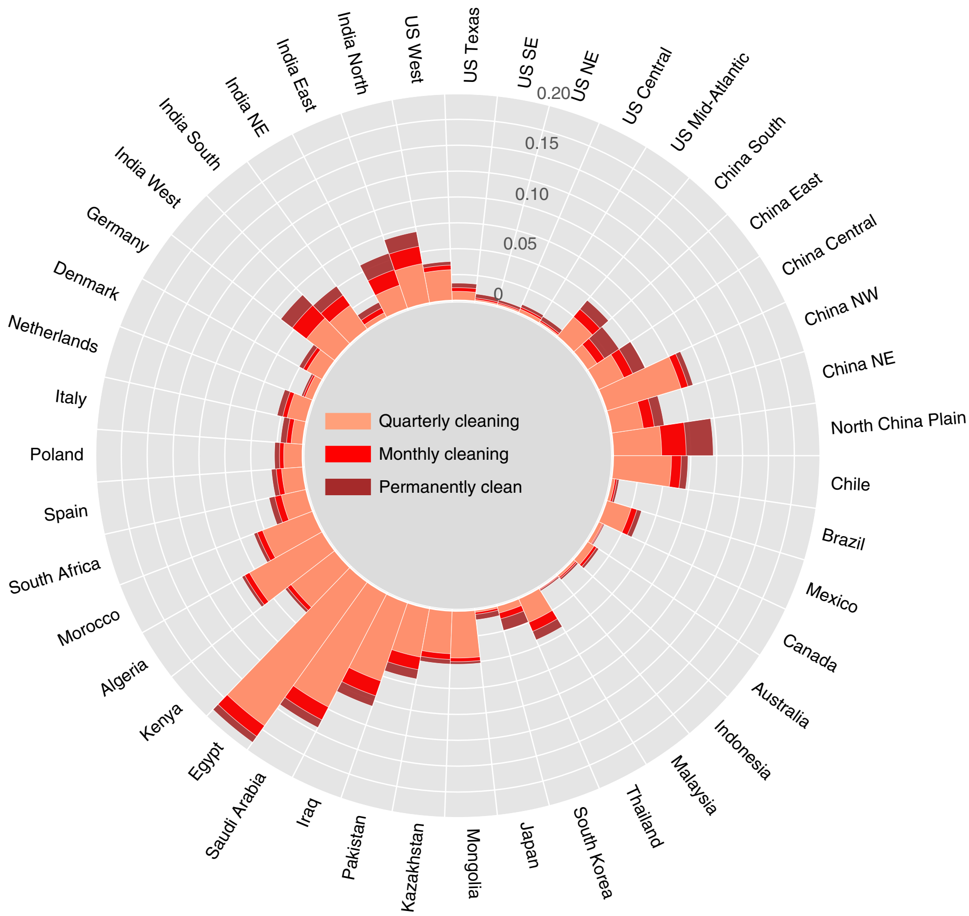

Fig. 5 | Increase in PV CFs resulting from panel cleaning in various world regions relative to panel soiling removal by precipitation only. Light pink boxes (inner) represent the benefit of quarterly cleaning compared with no cleaning over 12 years (precipitation-only removal). Red (middle) boxes represent the benefit of monthly cleaning compared with quarterly cleaning. Dark brown boxes (outer) represent the benefit of maintaining permanently clean panels compared with monthly cleaning.

use a larger proportion of direct radiation, experience a greater percentage impact from atmospheric aerosols than fixed panels. For the soiling effect, it may appear that aerosol deposition tends to be stronger on fixed panels because tracking panels frequently change their tilt angle, and thus have a smaller effective area to receive aerosol deposition in the vertical direction due to gravitation. However, our model, which takes into account both gravitational and turbulent deposition fluxes, shows that turbulent mixing is the dominant force of aerosol deposition on solar panels. Turbulent mixing results in effectively similar aerosol deposition fluxes in all directions. As a result, for most regions, soiling level is similar when comparing tracking panels with fixed panels. Nevertheless, although tracking technology has little impact on soiling level, the effect of PM on the PV efficiency of tracking panels is almost twice that for fixed panels. Therefore, air pollution mitigation and panel cleaning brings a much larger increase in PV efficiency for tracking than for fixed panels and increases the desirability of using tracking. In fact, tracking technology provides the greatest benefits in clean, high-latitude areas, as well as in the most heavily polluted, resource-abundant regions if panels are kept clean.

Benefits of cleaning panels

The above analysis quantifies the soiling effect when deposited aerosols are only removed by precipitation. Here we explore the effect of cleaning in improving PV generation relative to precipitation-only removal, which in our analysis follows PM accumulation over 12 yr from 2003 and 2014. The benefits of quarterly cleaning, monthly cleaning and permanently clean panels in addition to precipitation removal are quantified.

The largest benefit of cleaning is found in desert areas, for example, northern Africa, the Middle East and western China (Fig. 5). Quarterly cleaning results in an average CF increase of 0.18 in Egypt, followed by 0.15 in Saudi Arabia, 0.08 in Algeria and 0.07 in northwestern China. The percentage increases are particularly large in Egypt (~400%) and Saudi Arabia (~150%) (Supplementary Fig. 6). High soiling effects in desert regions primarily result from desert dust deposited on the panels, combined with low precipitation rates. In the scenario of precipitation-only removal, soil on panels is hardly removed in desert regions. Therefore, even quarterly cleaning provides huge benefits relative to no cleaning. However, it is important to choose panel-cleaning technologies that are appropriate for a region. Existing dry-cleaning technology with silicone rubber brushes can provide water-free cleaning for PV panels located in high-solar-resource, low-water-availability desert locations[21].

In comparison, the additional benefit of monthly or higher-frequency cleaning is relatively small. However, in China and India, even though quarterly cleaning improves PV efficiency by ~50%, the additional benefit of having permanently clean panels is comparable (~50%). In the North China Plain, quarterly cleaning increases PV CFs by 0.047 (50%); monthly cleaning gives an additional increase of 0.025 (25%); and permanently clean panels give a further increase of 0.025 (25%).

Our findings suggest that a little cleaning effort (quarterly cleaning) greatly increases PV efficiency in desert regions where precipitation rates are low and soiling is rarely removed by rain. Over highly polluted regions, frequent cleaning, in addition to precipitation, would also greatly reduce the soiling effect. The benefit of cleaning PV panels at various frequencies should be compared to the costs of applying surface coatings to PV panels that repel aerosols or utilizing self-cleaning technologies for panels. Further cost–benefit studies at local levels can provide developers with valuable information on the cleaning technology most worthy of investment.

Discussion

Our study reveals that PM, through both atmospheric aerosol attenuation and deposition on the panels, greatly reduces solar PV electricity generation efficiency in most solar-resource-abundant regions. In heavily polluted areas (for example, northern China and northern India) and desert regions (for example, northern Africa, the Middle East and western China), PM reduces PV efficiency by more than 50%. Removing PM in these regions would more than double the efficiency of PV electricity generation. PM, with an average impact more than three times that of clouds (Fig. 3a), plays a more important role in modulating PV efficiency in most resource-abundant regions. Compared to atmospheric aerosol attenuation, however, panel soiling plays a dominant role in most regions, accounting for more than two-thirds of the total aerosol impact (Fig. 3b). Most resource-abundant regions are in the dry subtropics where aerosols are mostly dust and about four times or greater impact occurs from panel soiling than from atmospheric aerosols. This study focused on the impact of aerosols on PV panels comprised of crystalline silicon cells, the most widely available and installed technology on the market. Further investigation is needed into the impacts of aerosols on thin-film panels and the differences in spectral impacts from dust compared to other aerosol species.

By exploring the benefit of cleaning the panels in addition to precipitation-only removal, we find that quarterly cleaning greatly increases PV efficiency, especially in northern Africa and the Middle East. In these desert regions, due to very low precipitation rates, even quarterly cleaning provides a huge benefit relative to no cleaning, with PV efficiency more than doubled (Fig. 3b). In heavily polluted regions such as the North China and Indo-Gangetic plains, more frequent cleaning cycles provide substantial further benefits to PV efficiency because they constantly clean off the rapidly accumulating soiling due to high pollution levels. In most heavily polluted, resource-abundant regions, the CFs of tracking panels increase dramatically when panels are cleaned.

This study advances the understanding of the effect of aerosols on PV generation by investigating the global impacts from atmospheric aerosols and soiling at regional and subnational levels, including precipitation removal of soiling as the baseline natural removal process, and evaluating the benefits of cleaning panels at various frequencies. Our findings indicate that soiling of PV panels may be the biggest threat to their electricity generation. PM in solar-resource-abundant polluted or desert regions such as the North China Plain and the Middle East have a larger impact than clouds in clean, cloudy regions such as Iceland and Norway. In the short term, cleaning panels can dramatically reduce the impact that aerosols have on PV efficiency, especially for tracking panels and rooftop installations in highly polluted urban regions. However, the soiling effect and atmospheric aerosol attenuation are intertwined. Reducing atmospheric aerosols would reduce aerosol deposition, and thus also decrease the soiling effect. Therefore, in the long run, mitigating air pollution and restoring desertified land would reduce both atmospheric aerosols and the rate of aerosol deposition on the panels, and thus enhance PV generation in both highly polluted areas and desertifying regions, most of which have abundant solar resources. Developing renewable energy would further facilitate this virtuous cycle.

Methods

We apply the PVLIB-Python model to simulate PV electricity generation at each 1° latitude × 1° longitude continental grid box globally. PVLIB-Python takes irradiance data as input and provides alternating current (a.c.) power as output. We further calculate PV CFs (the a.c. output divided by the designed maximum output power) to measure PV efficiency. We use surface solar irradiance from the NASA CERES-SYN1deg dataset from 2003 to 2014, which provides both all-sky (both clouds and aerosols are included) and all-sky-no-aerosol (only clouds are included without aerosols) scenarios. The effect of atmospheric aerosol attenuation is calculated by taking the difference between the two scenarios. The soiling effect is estimated by the attenuation of irradiance due to PM accumulated on top of the panel, that is, soiling. We calculate the total mass of each of the four PM species, dust, sulfate, organic carbon and black carbon, accumulated on the panel. For the rate of accumulation, we apply deposition rates of each PM species from the MERRA-2 reanalysis dataset also from 2003 to 2014. For the rate of removal, we include precipitation as the only removal mechanism. The removal rate is a function of both the precipitation intensity (also from MERRA-2) and the aerosol species. In our simulation, due to their hydrophilic properties, sulfate and organic carbon are easier to remove by precipitation than dust and black carbon. We build on the work of Bergin et al.[18] and apply the optical properties of each PM species (absorption coefficient, scattering coefficient and backscattering ratio), together with the total mass, to calculate the reduction in POAI due to soiling and its impact on PV electricity generation efficiency. We also explore the benefit of quarterly (every 3 months), monthly and weekly (every 7 days) cleaning cycles to reduce soiling and improve PV generation efficiency, in addition to the precipitation-only removal. A total of 13 global experiments are designed, spanning 2003 to 2014, to calculate PV CFs at 1° latitude × 1° longitude with 3 h temporal resolution. Calculating the 2003–2014 average CFs from these 13 experiments, we explore the impact of atmospheric aerosols, soiling (with only precipitation removal) and clouds on PV efficiency, PM impacts on tracking panels, and the benefit of cleaning PV panels in addition to precipitation.

PVLIB-Python solar PV system model. PVLIB-Python version 0.3.3 is an open-source toolbox to perform advanced data analysis and research on PV system performance modelling and operations[22]. In this study, we apply PVLIB-Python to calculate the total output power from a solar PV system using observed irradiance and weather data. PVLIB-Python allows performance modelling of the entire PV system, including specific PV module and inverter model characteristics at user-defined times and locations[23,24]. The model takes input of surface solar irradiance, calculates the POAI (the irradiance received by a panel at any angle tilt), further takes the input of weather data (for example, temperature) to calculate the direct current (d.c.) output power, and finally applies the inverter for a.c. output power. In this process, both PV cell efficiency (solar energy converted to d.c. electricity) and inverter efficiency (d.c. to a.c. electricity) are considered. We applied the wrapper developed by Li et al.[9], which enables parallel computing for a large number of grid-point locations and time steps using the PVLIB-Python model, and increases the computing efficiency to allow for our global analysis.

In this study, a Canadian Solar CS5P 220 M is used as the PV module, with a maximum output power of 220 W and a peak efficiency of 12.94%. An ABB MICRO-0.25-I-OUTD-US 208Vac inverter, with a designed efficiency of 96%, is applied in the model. The overall peak PV system efficiency is 12.42%.

Atmospheric aerosol and cloud data. This study applies the observational data of surface irradiance from CERES–SYN1deg edition3A from 2003 to 2014 for both the effect of atmospheric aerosols and clouds. CERES-SYN1deg provides 3 h average surface direct and diffuse irradiance globally at a resolution of 1° latitude × 1° longitude. These data are computed using the Langley Fu-Liou radiative transfer model calculations constrained by aerosols, clouds and other atmospheric data (for example, temperature, pressure, water vapour, ozone). AODs are retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS) and assimilated using the Model for Atmospheric Transport and Chemistry for aerosol properties and vertical profiles at daily temporal resolution. Cloud properties are derived from MODIS and five geostationary satellite imagers[25,26]. Surface shortwave irradiance in the CERES-SYN1deg dataset has been evaluated by Rutan et al.[27] with observations at 37 globally distributed land sites from the Baseline Surface Radiation Network, Global Monitoring Division and Atmospheric Radiation Measurement. For China, the AODs used by CERES-SYN1deg have been extensively evaluated by Li et al.[9] over 50 sites against surface observations from the China Aerosol Remote Sensing Network and show good agreement[9]. Rutan et al.[27] found that, compared with these surface observations, irradiance in CERES-SYN1deg outperforms other satellite-derived datasets, such as the International Satellite Cloud Climatology Project Radiative Flux Data, the Global Energy and Water Exchanges – Surface Radiation Budget dataset 3.0 and MERRA-2, with substantially less-than-average biases. Surface irradiance computed in CERES-SYN1deg for all-sky, clear-sky (with aerosols, no clouds) and all-sky-no-aerosol (no aerosol, with clouds) conditions are used to further calculate the attribution of irradiance reductions to aerosol and clouds.

Weather data and PM deposition rates. Near-surface (2 m) temperature, wind speed and pressure (3 h average) from MERRA-2 for 2003–2014 are used as input to the PVLIB-Python model. These three parameters are required to simulate the PV module temperature that affects conversion efficiency from radiation to electricity. In addition, land surface precipitation data from MERRA-2, at 1 h temporal resolution, are also used to calculate the removal rate for the panel soiling effect. MERRA-2 is a NASA atmospheric reanalysis dataset, which assimilates satellite observational data of temperature, pressure, humidity, precipitation, radiance, ozone, aerosol data, and so on, among which the aerosol data are from MODIS and the Multi-angle Imaging Spectroradiometer[28]. MERRA-2 leverages advanced modelling and assimilation systems, and provides high-resolution weather data (temperature, wind speed and pressure) that, when compared with observations, accurately represents seasonal mean climate[29,30]. MERRA-2 precipitation shows low bias, high correlation and a realistic diurnal cycle compared with observations from the Global Precipitation Climatology Project (GPCP) version 2.2[31].

Dry deposition rates of dust, sulfate, organic carbon and black carbon PM from MERRA-2 are used to calculate the accumulation rate of soiling on PV panels. Aerosols in MERRA-2 are simulated with the Goddard Chemistry, Aerosol, Radiation and Transport (GOCART) model[32]. Dry deposition of PM is part of the aerosol removal mechanism in the GOCART model. The GOCART aerosol module accurately simulates AODs, aerosol concentrations and aerosol–radiation interactions[32–35]. The fact that MERRA-2 assimilates AODs mainly from MODIS and AERONET makes it highly consistent with the CERES-SYN1deg dataset, which also uses MODIS and AERONET to simulate aerosols and aerosol–radiation interactions. This consistency enables a direct comparison of the atmospheric aerosol effect, which uses the CERES-SYN1deg dataset, with the soiling effect, which is calculated using the PM deposition rates from MERRA-2.

Estimating the soiling impact. In this study, the soiling impact is defined as the attenuation of surface irradiance due to PM accumulated on the surface of the PV panel. To quantify the soiling impact, we first calculate the total mass of each of the four PM species, dust, sulfate, organic carbon and black carbon, that contribute to soiling, considering both the accumulation and removal processes. For the rate of accumulation, we apply deposition rates of each PM species from the MERRA-2 reanalysis dataset. We consider two components of aerosol deposition flux: gravitational deposition and deposition due to turbulent mixing. The gravitational flux is vertical and is reduced on tilted panels due to their smaller effective area. In contrast, the turbulent flux is assumed to be the same in all directions and thus does not change for a tilted versus a fixed panel. For the rate of removal, precipitation is the only removal mechanism. Given the different hydrophilic properties of the four PM species, sulfate and organic carbon are easier to remove by rainfall than dust or black carbon in our simulation. The removal rate is a function of both the 1 h precipitation rate (p) and the aerosol properties:

(1) When $p < 1\,\mathrm{mm\,h^{-1}}$, no aerosol removal occurs.
(2) When $1 < p < 3\,\mathrm{mm\,h^{-1}}$, sulfate is entirely removed and half of the organic carbon is removed.
(3) When $3 < p < 5\,\mathrm{mm\,h^{-1}}$, sulfate is entirely removed and half of all other aerosols are removed.
(4) When $p > 5\,\mathrm{mm\,h^{-1}}$, all aerosols are removed.

We then use the optical properties of each PM species (absorption coefficient, scattering coefficient and backscattering ratio), together with the total mass, to calculate the reduction in POAI due to soiling and its impact on PV electricity generation efficiency. We estimate the influence of PM deposition on the radiative balance of a surface, using a similar method to that of Bergin et al.[18]. The irradiance received by the PV cell is calculated by:

$$\mathrm{POAI_{out}} = \mathrm{POAI_{in}} \times \mathrm{e}^{-\tau}$$

where $\mathrm{POAI_{in}}$ is the incoming irradiance before reaching the cell, and τ is the optical depth of the soil on the panel, defined by:

$$\tau \sum_{i=1}^{4} \left(E_{\mathrm{abs},i} + \beta_i E_{\mathrm{scat},i}\right)\mathrm{PM}_{\mathrm{F},i}$$

where $E_{\mathrm{abs},i}$ is the absorption coefficient, $E_{\mathrm{scat},i}$ is the scattering coefficient, β_i is the backscattering ratio, and $\mathrm{PM}_{\mathrm{F},i}$ is the mass of the soil layer per unit area on the panel. i represents an aerosol species. The optical properties are the same as used by Bergin et al.[18] consistent with observations. For dust, $E_{\mathrm{abs}} = 0.02\,\mathrm{m^2\,g^{-1}}$, $\beta = 0.02$ and $E_{\mathrm{scat}} = 1.00\,\mathrm{m^2\,g^{-1}}$. For organic carbon, $E_{abs} = 0.00\,\mathrm{m^2\,g^{-1}}$, $\beta = 0.30$ and $E_{\mathrm{scat}} = 4.00\,\mathrm{m^2\,g^{-1}}$. For black carbon, $E_{\mathrm{abs}} = 8.00\,\mathrm{m^2\,g^{-1}}$, $\beta = 0.30$ and $E_{\mathrm{scat}} = 0.00\,\mathrm{m^2\,g^{-1}}$. For sulfate, $E_{\mathrm{abs}} = 0.00\,\mathrm{m^2\,g^{-1}}$, $\beta = 0.30$ and $E_{\mathrm{scat}} = 4.00\,\mathrm{m^2\,g^{-1}}$. Further experiments are needed to determine how aerosols deposited on a surface may have different absorption and scattering properties than atmospheric aerosols.

$\mathrm{POAI_{out}}$ is then used as input to the PVLIB-Python model to further calculate the a.c. output power and CF. We also simulated the soiling effect with quarterly, monthly and weekly cleaning cycles, including precipitation removal in all three cases, to explore the potential to increase PV efficiency by cleaning panels in addition to precipitation removal.

Soiling effect, in this study, is quantified assuming no removal mechanisms other than precipitation. According to this study, precipitation removes more than 70% of the soiling on panels in most regions (except in northern Africa and western China) when no other removal mechanism is considered (Supplementary Fig. 9). In monsoon regions such as eastern China, northern India and the eastern United States, precipitation plays an important role in removing soiling even when monthly or quarterly cleaning is implemented (Supplementary Fig. 10). By only including precipitation and not wind, we potentially underestimate the natural removal rate of aerosols and overestimate the effect of soiling on the panels. However, observations in desert and heavily polluted regions have shown that wind influences aerosol deposition much more than aerosol removal; the net effect of wind is to increase soiling of solar panels due to increased dry deposition[36–38]. The effect of wind on dry deposition is already accounted for in the MERRA-2 dataset used in this study.

Furthermore, the simple radiative transfer model applied in this study only assumes a single layer of particles, without considering multiple scattering between particles. With high concentrations of particles on PV surfaces in some regions in the scenario with precipitation-only removal, our method may underestimate the soiling impact by neglecting multiple scattering.

Experimental design. We designed 13 experiments spanning 2003 to 2014 over the globe to calculate PV CFs at 1° latitude × 1° longitude with 3 h temporal resolution. We explore the impact of atmospheric aerosols, soiling (with only precipitation removal) and clouds on PV efficiency on fixed panels using four scenarios: (1) all-sky (both aerosol and clouds are present in the atmosphere) with soiling; (2) all-sky without soiling (both aerosol and clouds are present in the atmosphere but PM deposition on the panel is not included); (3) all-sky without aerosols or soiling (only cloud is present); (4) clear sky (no clouds but with aerosols) with soiling. The impact of panel soiling on PV CF is calculated by $\mathrm{CF_2} - \mathrm{CF_1}$ (the difference between all-sky without soiling and all-sky with soiling), and similarly for atmospheric aerosols ($\mathrm{CF_3} - \mathrm{CF_2}$) and clouds ($\mathrm{CF_4} - \mathrm{CF_1}$). Total PM effect is defined by the sum of the soiling impact and atmospheric aerosol attenuation, which is effectively $\mathrm{CF_3} - \mathrm{CF_1}$. The second set of six experiments explore atmospheric aerosol and soiling impacts on tracking panels through two major scenarios, OAT and TAT, each with the above-mentioned scenarios 1–3. The third set of three experiments quantifies the impacts of cleaning on the soiling effect by conducting the all-sky with soiling scenario with (A) quarterly, (B) monthly and (C) weekly cleaning cycles with precipitation removal. The benefit of cleaning is defined by the difference between scenarios A, B or C and scenario 1. We analyse the 2003–2014 average PM impact at each 1° latitude × 1° longitude for its spatial distribution, and further calculate the regional-mean impact by taking an area-weighted average. The United States, India and China are further divided into subregions according to the major electricity grids in each country, as shown in Supplementary Figs. 2–4, respectively.

Data availability

The datasets generated and analysed during the current study are available from the corresponding authors on reasonable request.

Code availability

The custom code generated during the current study is available from the corresponding authors on reasonable request.

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Author contributions

X.L., M.H.B. and D.L.M. designed the research. X.L. prepared the data and performed the PV performance simulations. X.L., D.L.M. and M.H.B. analysed the results. X.L. and D.L.M. wrote the manuscript. All authors discussed the results and contributed to the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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