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Perspective

Techno-Economic Assessment of Soiling Losses and Mitigation Strategies for Solar Power Generation

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Soiling consists of the deposition of contaminants onto photovoltaic (PV) modules or mirrors and tubes of concentrated solar power systems (CSPs). It often results in a drastic reduction of power generation, which potentially renders an installation economically unviable and therefore must be mitigated. On the other hand, the corresponding costs for cleaning can significantly increase the price of energy generated. In this work, the importance of soiling is assessed for the global PV and CSP key markets. Even in optimized cleaning scenarios, soiling reduces the current global solar power production by at least 3%–4%, with at least 3–5 billion € annual revenue losses, which could rise to 4%–7%, and more than 4–7 billion € losses, in 2023. Therefore, taking into account the underlying physics of natural soiling processes and the regional cleaning costs, a techno-economic assessment of current and proposed soiling mitigation strategies such as innovative coating materials is presented. Accordingly, the research and development needs and challenges in addressing soiling are discussed.

INTRODUCTION

Soiling can easily cause more than 1% power loss per day[1–4] and is a site-specific phenomenon, strongly influenced by local climatic conditions.[1,5–11] The predominant type of contamination could change considerably depending on the location: mineral dust deposits[1] (Figure 1A), bird droppings (Figure 1B), biofilms of bacteria, algae, lichen, mosses, or fungi[12–14] (Figure 1C), plant debris or pollen[15] (Figure 1D), engine exhausts or industry emissions (Figure 1E), and agricultural emissions such as feed dusts (Figure 1F).

For PV modules, soiling on the front glass mainly results in optical losses due to light absorption or backward scattering,[2,16] depending on the area shaded by soiling particles and also on the dust compositions and particle size distributions.[2,8,16,17] Compared to PV, soiling-induced losses are 8–14 times greater for CSP because most of the forward scattered light, which could still generate electricity in PV, does not hit the CSP receiver due to limited collector acceptance angles. Similar applies to concentrator photovoltaics (CPVs), which also use lenses or mirrors. However, as CSP only accounts for about 1.1% of global installed solar power capacity, and CPV being less than 0.1%, the focus of this study is set on conventional PV.[18–20]

The physics of dust deposition and adhesion are complex due to the many influencing factors, ranging from weather, site, and system specifications to surface

Context & Scale

The light-collecting surfaces of solar power systems cover areas of more than 3,000 km^2 worldwide, with PV modules accounting for the majority. An often-neglected problem is the contamination of these surfaces, so-called "soiling," which leads to significantly reduced energy yields, especially in high-insolation arid and semi-arid climates. Indeed, an inadequate soiling mitigation strategy in high solar-potential and soiling-prone locations such as China, India, or the Middle East can cancel out in few weeks the impressive progress in solar cell and CSP efficiency made in recent decades.

Currently, there is no one-solution-fits-all to the problem of soiling due to its site-specific and seasonal variability, differences in local energy costs, and the availability and costs of resources required for cleaning, such as water or labor. Indeed, frequent cleaning can increase the energy generation costs and water consumption dramatically, leading to a need for water-less and inexpensive soiling mitigation technologies. Our analysis nano-characteristics as well as their time-variability (e.g., diurnal or seasonal weather changes).[1] Airborne dust concentration is considered the major determinant of soiling,[1,6,7,21] together with rain frequency, as rain is quite effective at cleaning soiled surfaces if sufficiently abundant.[1,6,22] On the other hand, rain can also cause negative effects, e.g., by wet deposition of aerosol particles that have been washed out of the atmosphere.[23] Wind speed is also an important parameter, as it influences the particle deposition mechanisms and rates the balance between deposition and resuspension.[24–26] Tilt angle of the PV modules and CSP mirrors should be considered since soiling rates are greater on flatter surfaces.[2] Relative humidity and dew strongly enhance dust adhesion to surfaces through capillary forces, particle caking, and cementation.[1,17,27,28] These moisture-related adhesion mechanisms are considered important, even in deserts: radiative cooling of the glass surfaces at night allows surfaces to cool below the ambient air temperature. They frequently reach the dew point, and thus, dew precipitates on the collector surfaces.[1,27]

indicates that in addition to optimized cleaning plans, automated cleaning machines, anti-soiling coatings, tracking system modifications, PV module design, improved soiling monitoring, and site adaption can be economically feasible and effective solutions to reduce the negative impact of soiling. Other technologies like electrodynamic screens or dew mitigation need further research and development to improve functionality and become economically relevant for large-scale application.

On top of reversible optical losses, soiling can cause permanent degradation of PV modules and mirror materials. In cases of omitted cleaning, cemented dust layers, lichens, and fungi can become practically irremovable, whereas harsh cleaning can lead to the scratching or abrasion of typical anti-reflective coatings (ARCs) or glass corrosion.[13,29,30] In addition, mechanical loads during cleaning or thermal shocks when a hot element is cleaned with cold water may lead to breakage of solar cells and glasses or expansion of micro cracks. Further, potential induced degradation (PID) in PV can be enhanced by soiling,[31,32] and partial shading due to non-uniform soiling can lead to the formation of hot spots. In CSP, increased dust loads can lead to accelerated degradation of receivers by particle melting, failure of bearings, ball joints, and others.

However, within this study, only the optical and corresponding yield losses due to soiling are considered for the investigation of the global impact of soiling. Currently, cleaning is the state-of-the-art to tackle soiling. Cleaning economics also determine the economic viability of other mitigation technologies. Therefore, the techno-economic feasibility of potential technologies is investigated based on an evaluation of their efficiency in soiling loss reduction and potential costs. The most promising available strategies are thus identified and recommendations provided for further research.

IMPACT ON GLOBAL SOLAR POWER PRODUCTION AND ENERGY COSTS

In order to estimate the global impact and cost of soiling, the optimum between cleaning costs and revenue losses due to soiling between cleaning events was determined for the twenty top PV markets (about 90% of global installed PV capacity in 2018[33]) and the global CSP market. Accordingly, an extensive dataset was compiled from literature and interviews with stakeholders, including regional soiling rates (Figure 2B and Tables S1–S3), local cleaning costs (Figure 2C and Table S1), and simulated local energy yields (Figure 2D and Table S4). From these, the optimum number of cleaning cycles per year was calculated for each country (Figure 2E). The calculations were performed considering the reported installed capacity[33] and regional feed-in-tariffs[34] from 2017 to 2018, as well as a medium growth scenario and an average electricity price of 0.03€/kWh for 2023. In addition, the total costs of soiling being the sum of optimized annual cleaning costs and the remaining revenue losses were determined (Figure 2F). Further details of the methodology are provided in the Experimental Procedures and the Supplemental Information.

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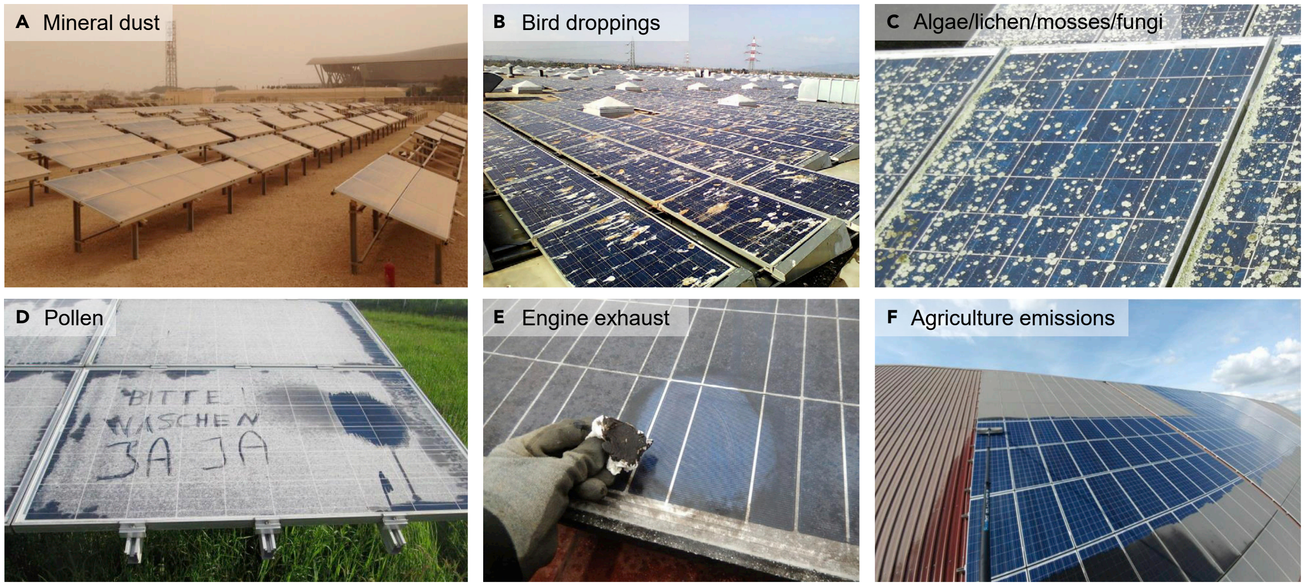

Figure 1. Examples of Soiling

Overview of different soiling types with exemplary photographs of soiling by (A) mineral dust in a desert area, (B) bird droppings, (C) algae, lichen, mosses or fungi and (D) pollen in wet and moderate climates, (E) engine exhaust from an industrial area, and (F) agricultural emissions.

According to the data presented in Figure 2, soiling is estimated to have reduced global solar power production by at least 3%–4% in 2018, causing global revenue losses of at least 3–5 billion €. This conservative estimate does not consider additional costs of non-optimized PV cleaning schedules (e.g., in residential application) and cleaning rooftop installations (3–8 times costlier than cleaning ground-mounted PV), which accounted for about 29% of global installations in 2018.[33] This assumption is less pronounced for CSP, as this technology is only profitable in large plants where cleaning is typically performed in a more cost-optimized manner. Higher incentives of power purchase agreements that were contracted earlier than 2018 were not taken into consideration. Such projects tended to have higher prices for generated electricity, which would increase the optimum cleaning frequency and the related cleaning expenses. Secondary effects such as increases in loan rates due to the uncertainty of yield forecasts because of the unpredictability of soiling could also have a financial impact but were not evaluated here.

Based on the assumptions made, global soiling losses could rise significantly to 4%–7% of annual power production, causing more than 4–7 billion € economic losses by 2023. This development is mainly driven by an increased deployment of PV in high insolation and also in highly soiling-affected regions such as China and India, as well as the mentioned low predicted electricity price, which reduces the incentive for cleaning.[35,36] Additional factors that increase the impact of soiling are rising PV module efficiencies and a predicted increasing share of rooftop installations in PV (from about 29% in 2018 up to about 35% in 2023[33]). They have not yet been considered in the calculations. Other factors such as improved air quality in some parts of the world[37–41] could reduce anthropogenic sources of soiling, although air-quality policies typically operate over long time scales. On the other hand, the increase in temperature and the changes associated with climate change might cause a rise in the global soil aridity[42] and the risk of droughts[43] and wildfires, worsening PV and CSP soiling because of the higher concentration of aerosols and the more irregular precipitation patterns.

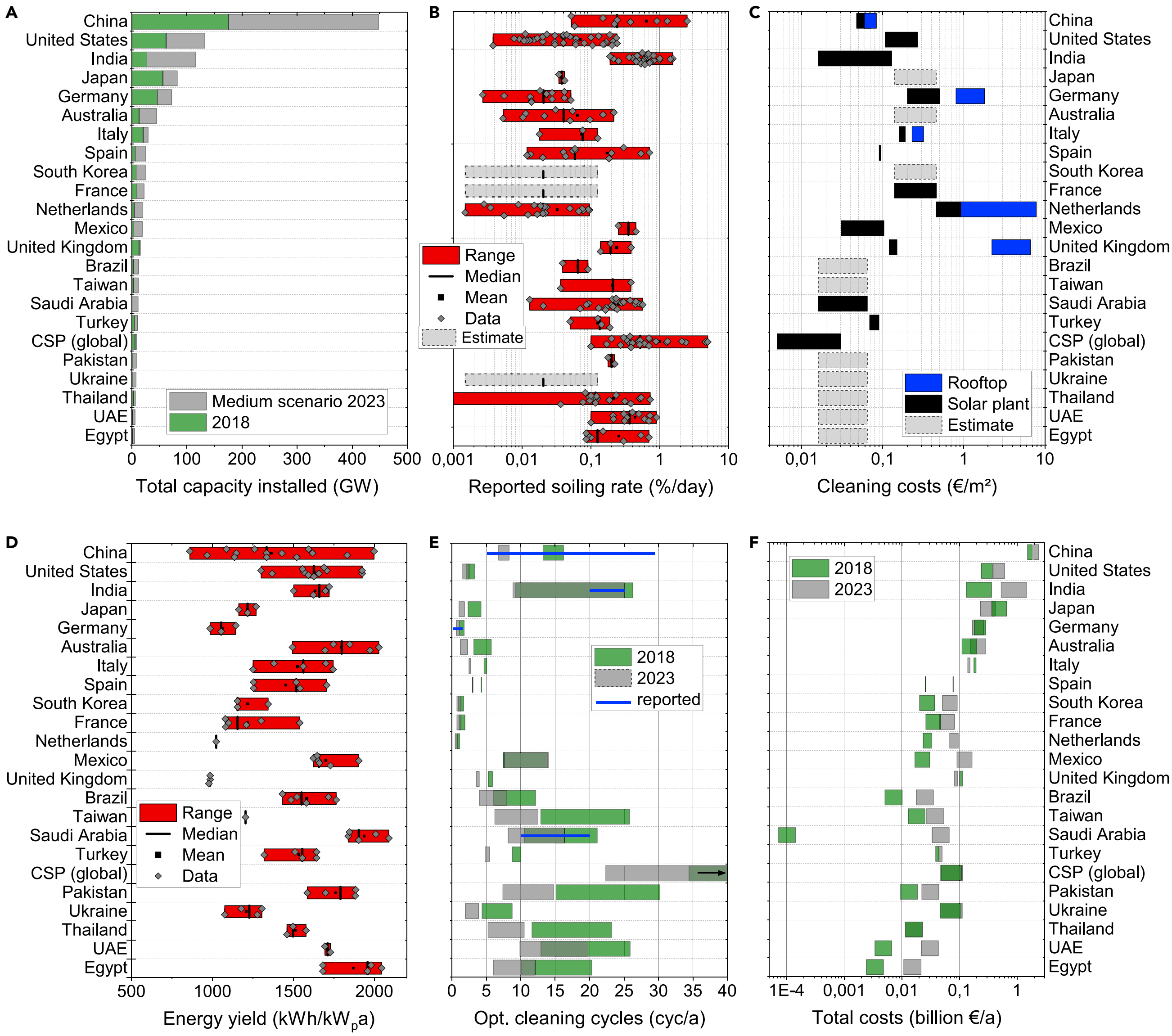

Figure 2. Impact of Soiling on Solar Power Generation

(A) PV capacity installed by 2018 and medium estimate for 2023, sorted by country for the top 22, and global CSP capacity.

(B) Corresponding soiling rates reported in literature; see Tables S2 and S3.

(C) Reported cleaning costs per cleaning and square meter.

(D) Typical energy yield in kWh/kW$_p$ for representative locations, see Table S4.

(E) Calculated range of optimal number of yearly cleaning cycles (bars) and actual range of typical yearly cleaning cycles reported in literature (blue lines, see Model Validation). The arrow indicates that for CSP, the numbers are out of range and (up to 85 in 2018 and 55 in 2023).

(F) Minimum expected financial losses due to soiling calculated from optimum cleaning cycles.

TECHNICAL EVALUATION OF SOILING MITIGATION TECHNOLOGIES

The previous section described the severity of soiling across the solar-energy industry. Here, soiling mitigation and cleaning strategies as reported in various studies and reviews[2,44–51] are re-assessed to gain new insights into physical constraints and technology developments. New innovative approaches are suggested and evaluated.

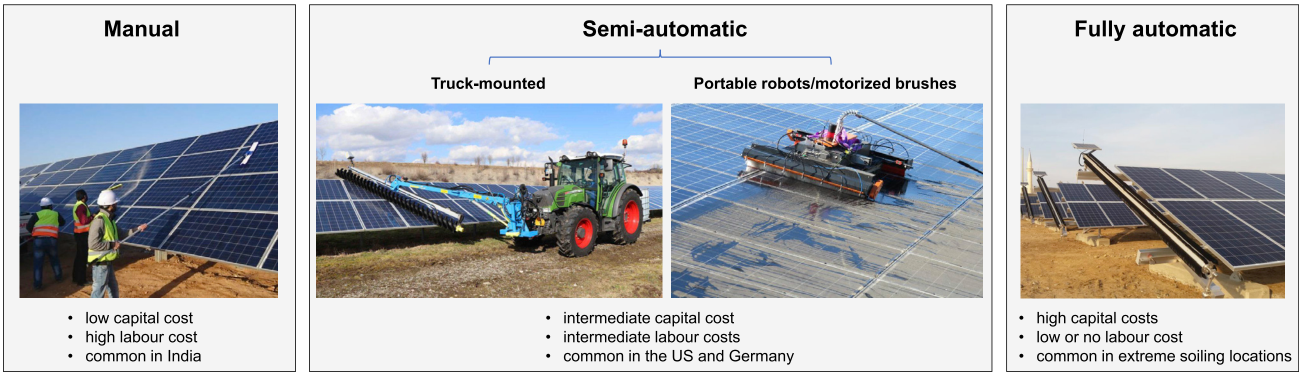

Figure 3. Overview of Different Cleaning Technologies Sorted by Category: Manual, Semi-automatic (Including Truck-Mounted Solutions and Portable Robots), and Fully Automatic

Cleaning

So far, no passive anti-soiling technology (e.g., surface coatings) completely eliminates the need for cleaning. Furthermore, there is not a universally recommended cleaning method, as the economics and effectiveness change with local conditions, available resources, and cleaning frequencies. In general, cleaning methods can be categorized into manual, semi-automatic, and fully automatic (Figure 3). A further distinction can be made between dry cleaning technologies on the one hand that are currently only available for PV and not CSP and are mostly applied in regions with water scarcity such as desert environments, and wet cleaning technologies on the other hand, that are generally preferred due to their increased cleaning efficiency and lower damage potential.[13] Despite this, the fully autonomous cleaning market, which represents only 0.13 % of the current global solar capacity, is expected to grow from about 1.9 GW today to 6.1 GW in 2022,[52] thanks to the recent developments of dry, fully automated robots, which can be already integrated into the plant design.

There are many factors influencing the decision on optimal cleaning technology, including soiling type and deposition rates, water availability, accessibility of the site, and system configuration (e.g., tracking versus fixed tilt angle, roof versus ground mounted) as well as labor cost, equipment required, and feed-in contract conditions. Efforts are being made to also identify optimal cleaning schedule based on soiling rate detection and weather as well as dust forecasts.

Anti-soiling Coatings

Anti-soiling coatings (ASCs), applied to the front glass of PV modules or CSP mirrors, aim to reduce soiling and the demand for cleaning. Ideally, ASCs are highly transparent, anti-reflective, durable, non-toxic, applicable at industrial scale, low cost, and, of course, self-cleaning and are considered as a "holy grail" by the soiling community.[2]

Five dry and wet soiling mechanisms (Figure 4A), especially important for ASC performance in arid regions, have been identified through outdoor and laboratory testing.[1,17,24,27,53–55] They are (1) rebound (particles bouncing off the surface upon impact), (2) resuspension (delayed removal of particles by wind), (3) caking (rearrangement and compaction of particles during dew events), (4) cementation

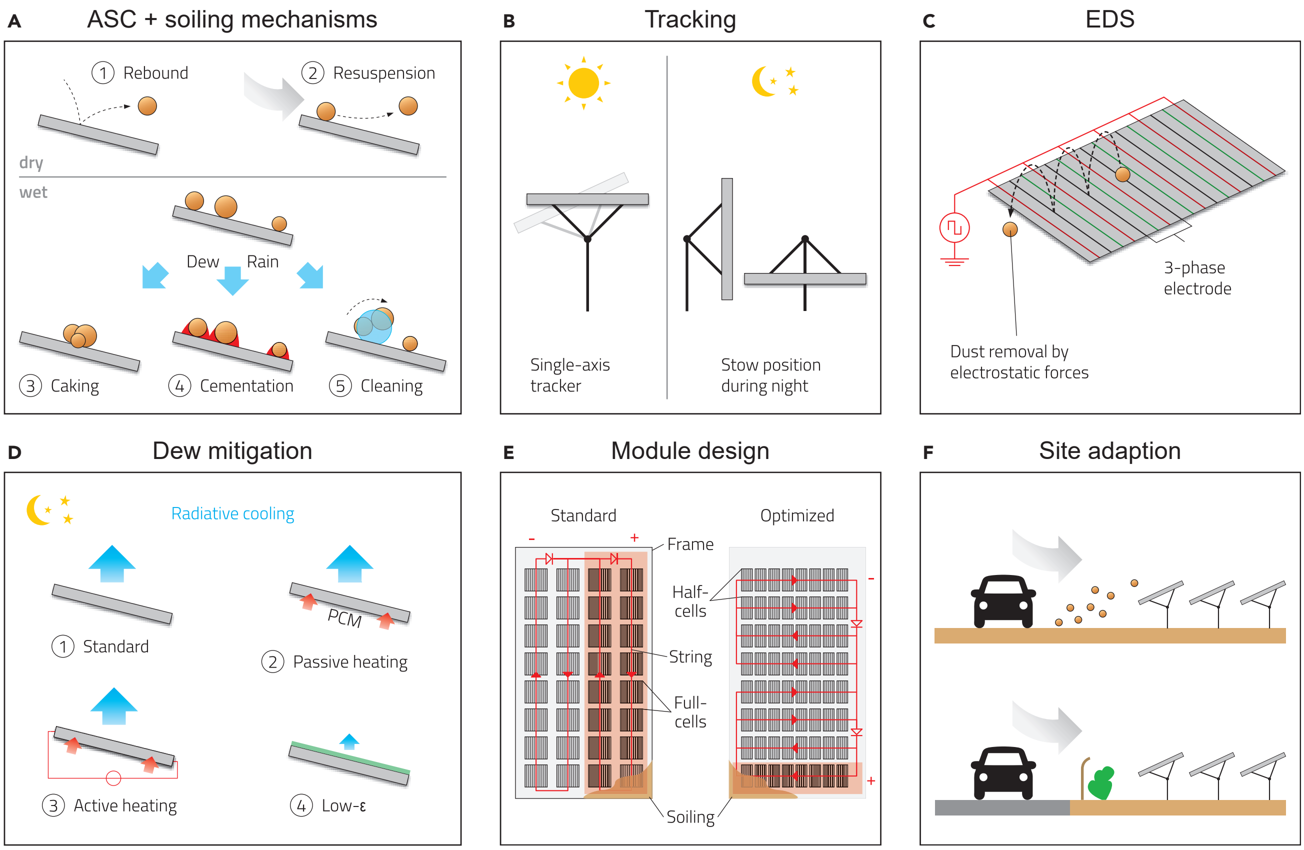

Figure 4. Schematic Illustration of Soiling Mitigation Technologies

(A) Important soiling mechanisms which could be addressed by anti-soiling coatings (ASCs).

(B) Single-axis tracking and optimization of night stowing position.

(C) Working principle of EDS (standing wave version).

(D) Dew mitigation by low-ε coatings and active and passive heating.

(E) PV module design approaches for soiling loss reduction: the red overlay indicates lost cell strings dew to soiling.

(F) Site adaption.

(formation of chemical and/or solid bridges between particles and surfaces after dew cycles), and (5) water cleaning (particles washed off by rain or strong dew). To reduce soiling, rebound, resuspension and water cleaning should be enhanced, cementation should be avoided, and the optical loss (projected area) of caked particles should be minimized by "herding" dust into agglomerates via coating hydrophobicity.[28,56] However, limitations arising from physical phenomena must be considered:

- Location: factors affecting soiling rate and coating performance can change dramatically with location, as well as with diurnal and seasonal variation of weather conditions. Consequently, coatings need to be tailored to specific site conditions.
- Particle adhesion physics: dust particles smaller than 10–20 μm diameter are essentially irremovable by wind because they are immersed in a thin viscous part of the boundary layer, which attenuates flow velocity and turbulence.[1,55] Furthermore, when dew occurs, particles typically become more tightly adhered to the surface.[27] The particle size distribution of surface soiling differs by location, with a volume fraction of particles < 20 μm generally in the range of

35%–90%.[1,26] Consequently, small particles remain stuck to the PV or mirror surfaces and, over time, comprise an increasing fraction of the soiling layer and optical losses.

- Durability: coating performance tends to degrade over time due to abrasion (by cleaning or sand storms),[13,29] particle settlement and cementation,[17] UV irradiation, temperature cycles, or even by rain or condensed water.[57,58] There are two components to this degradation: a permanent degradation due to the physical damage or removal of the ASC itself and a temporal degradation due to the contamination of its outermost surface by the environmental matter, which obstructs its anti-soiling properties. Indeed, this latter type can also have permanent effects if not properly and timely addressed.[17,30] The durability and long-term performance of coatings are currently difficult to predict, and the community has been working to identify standard methodologies to test them in advance, e.g. IEC 62788-7-3 or VDI 3956-1.

ASCs have seen limited market deployment, as they do not eliminate the need for cleaning but offer longer periods between cleanings. Nevertheless, the attraction of a passive anti-soiling solution is great, so that development continues, with many promising approaches.[2–4] Soiling rate reductions of more than 80% have been reported from outdoor exposure studies; however, over longer periods, average anti-soiling performances are typically much lower (e.g., 20%–50%) and could even be worse than uncoated glasses depending on coating type, local climatic conditions, and status of degradation.[28,59–73]

Tilt Angle and Solar Trackers

Field studies consistently show that soiling rates significantly decrease at steeper surface tilt angles.[2,47,74] In addition, new insights indicate that, for several locations at least, soiling could be similar or even greater during the night than during the day,[1,75] suggesting soiling mitigation by vertical or inverted overnight stowing[76] (see Figure 4B). Experiments conducted on glass coupons in Doha, Qatar, showed an average soiling loss reduction of 41% for vertical stowing and of 50% for inverted stowing during the night.[77] In addition, about 60% reduction in soiling loss was reported in India for PV modules inverted upside down during non-sunshine hours,[78] and more than 98% for non-tracked vertical mounted bifacial modules.[79]

An analysis of the top 13 PV solar tracking companies indicated that a 90° or 180° stowing technique could not be currently applied, as the tilt angle range for typical tracker designs are either $\pm 45°$ or $\pm 60°$. With the solar tracker market share of utility-scale PV plants estimated to rise from about 20% in 2016 to 40% in 2020,[35] the concept of extending the tracker tilt range for night stowing appears a potential cost-effective soiling mitigation strategy. In contrast, the grand majority of CSP heliostats do have the inverted stow option, and parabolic troughs are typically stored in $-15°$ toward the ground. However, some heliostat concepts do not allow inverted stow positions, and changing its design was considered not convenient for one example due to increased construction cost that was estimated not to be compensated by the reduced cleaning cost.[80] Accordingly, the technical feasibility of tracker adaption must be examined individually. Nevertheless, steep stowing positions of traditional PV tracking systems during the night have already been reported to decrease soiling by more than 30%.[81]

Heating of Surfaces Preventing Water Condensation

Dew has been identified as a crucial factor in soiling in many places, both for PV and CSP, by increasing cementation, decreasing particle rebound and causing distinct soiling patterns.[1,27,53] Condensation typically peaks before dawn, when the relative humidity is high, and PV modules are colder than the ambient air temperature because of their infrared radiative emission to the sky (so-called radiative cooling). PV modules are reported to cool significantly below ambient temperature so that the dew point temperature is reached frequently, especially in clear sky conditions.[1,53] Additionally, condensation may also occur at temperatures above the dew point due to capillary and hygroscopic condensation.[27,53] Soiling rates are reported to be considerably higher on days with dew occurrence as compared to dry days.[82] Accordingly, new approaches were proposed for soiling mitigation by preventing condensation through active and passive surface heating[17,27] (see Figure 4D). This includes heat generation by controlled current supply to solar cells, adapted application of photovoltaic thermal hybrid solar collectors[83] or using latent heat from phase-change materials (PCM), typically proposed for PV cooling during the day.[84] In addition, low-emissive (low-ε) coatings could significantly reduce the radiative cooling and therefore the occurrence of dew. Active heating with relatively high power indicated up to 65% soiling reduction,[17,27] but so far no results, models, or practical conclusion on the economic feasibility of heating approaches to reduce soiling exist. However, in combination with positive effects of PV module cooling during the day (higher energy yield, reduced PV module degradation due to lower daily temperature difference), heating modules at night might offer potential for soiling mitigation in situations with high cleaning and maintenance costs (e.g., remote locations, street lighting, and building-integrated PV) in arid environments.

Electrodynamic Screens

Transparent electrodynamic screens[47] (EDSs), also called electrodynamic dust shields[85] or cleaning systems,[86–88] repel dust particles by creating a time-varying (dynamic) electric field over a surface.[2] The fields are often generated by interdigitated electrodes embedded in a protective film, supplied with alternating high voltages (Figure 4C). EDSs have been successfully demonstrated in the lab and are often proposed as an anti-soiling strategy for PV and CSP. However, they have proved difficult to translate to the field, where harsh conditions interfere with the electronic systems, and dust becomes cemented to the surface by moisture.[2,45,47,85] Some common issues have been reported, including reduced effectiveness in cases of high relative humidity,[2,89] long particle duration on the surface,[2,85] and low surface tilt angle.[89] A recently launched commercial device reported 32% soiling rate reduction in Saudi Arabia,[87] but large-scale implementation has not occurred yet due to its relatively high cost of around 30 €/m^2 (PV module prices are actually in the range of 30–90 €/m^2). There are attempts to mass-produce EDS systems to lower their cost. However, the cost reduction potential and effectiveness in a variety of weather conditions and durability still need to be demonstrated for market adoption. Therefore, in the near future, EDSs are likely to be limited to applications where high system costs are acceptable.

PV Module Design

PV module design and materials can themselves be tailored to reduce impacts of non-uniform soiling patterns. Examples are use of half-sized PV cells, configuration of cell strings and bypass diodes, and frameless modules to avoid dirt collection at edges. Partial shading, due to dust accumulating preferentially on one part of a PV module, can degrade power output significantly more than the same amount of dust spread uniformly. Indeed, shading only 50% of a single solar cell can trigger the bypass diode of this string (see schematic in Figure 4E), which could lower the power production of a typical 3-string module by one third. Considering that soiling generally accumulates on the bottom frame, a dense strip of dust covering the bottom row of cells could theoretically cause complete power loss if the module was unfavorably oriented. In contrast, for modules using half-sized PV cells, the risk of this situation can be reduced by parallel sub-strings of cells.[90,91] Half-cell modules could have up to 65% higher power than an equivalently shaded full-cell module, but this also strongly depends on the cell interconnection layout, the shading pattern, and module orientation. Further, under partial shading conditions, half-cell modules could have a lower temperature due to changed reverse-biased heat dissipation.[92] Actually, there are already commercial PV modules with favorable module design available in the market. With lower electrical losses and the higher optical gains, the half-cell modules are expected to show almost similar or even lower costs in production per Watt peak compared to full-size modules.[93]

Site Selection, Adaption, and Monitoring

The possibility of soiling mitigation through selection and modification of the plant site has received little attention from PV researchers. However, lessons can be drawn from experience with CSP systems,[45] which are more strongly affected by soiling than PV. First, soiling (daily loss rate, rain frequency, and dust characteristics) should be analyzed at each potential site during resource assessment measurement campaigns using full-size PV modules or CSP soiling measurement devices at their intended tilt or tracking pattern and orientation. It is not yet possible to accurately predict soiling only from climate information, although some studies could show underlying principles of soiling dependencies on other weather parameters.[1,10,24,75,94–96] In addition, soiling rates can vary dramatically for sites only 5–10 km apart or even within the same site.[97] The closer a site is to a dust generation source, the greater is its soiling risk.[1] Industrial dust sources such as cement plants, agriculture and livestock farms, and dirt roads or high traffic roads can be avoided by site selection. If such sources are unavoidable, their impact can be mitigated by design and layout of the solar plant to facilitate cleaning, e.g., choosing row spacing and length to allow efficient use of truck-mounted systems or automated cleaning machines. In addition, preventive measures can reduce the impact of fugitive local dust sources e.g., by water spray, vegetation, paved roads, dust barriers, or increased height of installation (see Figure 4F).[45] Chemical soil stabilizers have been used in some US PV plants and reduced dust emission by orders of magnitude.[98] Wind and dust barriers have the potential to reduce soiling as shown by wind tunnel and FEM dust transport simulations,[99,100] but their effectiveness has to be proven in operating environments[45] and might need to be tailored to the specific site, as strong wind could both worsen or ameliorate soiling.[26]

Monitoring is an essential soiling mitigation tool, as it helps to detect extreme soiling conditions and to adapt the cleaning schedule depending on the interannual variability of the climatic conditions, or to other exceptional soiling events, such as road or building works. For large PV systems, ideally also soiling non-uniformity is mapped to identify sections that are economically worth cleaning. The current IEC 61724-1 standard[101] recommends to monitor soiling where the expected annual losses are higher than 2% with at least two soiling sensors for PV sites of more than 5 MW. There are numerous soling sensor concepts, including two-sensor systems (at PV-cell or module level), where one of the sensors is cleaned regularly (manually or automatically), and more recent developments toward maintenance-free sensors.[50,102–106] In CSP, it is recommended to monitor soiling on a daily basis by handheld devices[107] that are operated

Table 1. Economics of Soiling Mitigation

Assumed Reduction in Soiling Rate	Reduction of Optimum Number of Annual Cleaning Cycles	Remaining Cumulative Yield Loss	Allowed Costs for Mitigation Technology to Achieve Positive NPV
−100%	−100%	0%	5.00–7.90 €/m^2 (average) 1.00–18.70 €/m^2 (min-max)
−80%	−55%	45%	2.50–4.20 €/m^2 (average) 0.60–10.40 €/m^2 (min-max)
−50%	−29%	71%	1.30–2.20 €/m^2 (average) 0.30–5.50 €/m^2 (min-max)
−20 %	−11%	89%	0.50–0.80 €/m^2 (average) 0.10–2.00 €/m^2 (min-max)

Estimate of maximum allowed technology costs to achieve a positive net present value (NPV), calculated for different theoretical soiling rate reductions and assuming utility-scale PV plants, optimum cleaning cycles, power purchase prices of 0.03 €/kWh,[36] and a 10-year payback period for technology investment at 5% discount rate.[113]

by solar field technicians. One of the challenges here is to select the minimal number of measurement points to sufficiently predict the average solar field cleanliness.[108,109] A tendency to make soiling measurements less labor intensive is also predominant in CSP soiling sensor development.[107]

A qualitative survey of the soiling distribution at a plant can also be conducted through visual terrestrial or aerial (drone and satellites) inspection of the field or by advanced solar field performance analysis (e.g., monitoring on module-level), with new methods being continuously developed.[50,110–112]

Cost Estimates for Soiling Mitigation Technologies

From the data presented in Impact on Global Solar Power Production and Energy Costs, rough estimates for a positive net present value (NPV), at which soiling mitigation technologies become economically feasible, were calculated assuming different efficiencies for the reduction of soiling rates, see Table 1.

The values vary greatly between different countries and site conditions, as indicated by the range of global minima and maxima. Economic benefits from soiling mitigation leading to reduced numbers of cleaning cycles could easily increase with higher cleaning costs (e.g., rooftop installations and remote locations) or in areas with extreme soiling.

The provided estimates can be compared with our assumptions for soiling rate reduction potential and current costs of the different technologies; see Table 2. The automated cleaning systems, ASCs, optimized PV module design, and tracker solution are assumed to reach a feasible cost range at utility scale. In contrast, electrodynamic screens and heating solutions appear too expensive, or the technology is not mature enough.

CONCLUSIONS AND RECOMMENDATIONS

Due to its large impact on the maintenance and economics of solar-energy plants, there is growing interest in soiling mitigation in the solar power industry and research community, with the publication rate on the topic increasing exponentially since 2008.[3,4] However, the amount of research is small compared to other fields of solar technology such as PV cell development or CSP plant design. To place these topics into perspective, the increase in crystalline PV cell efficiencies achieved

Table 2. Soiling Reduction Potential and Costs for Selected Soiling Mitigation Technologies

Mitigation Technology	Potential Optimum Reduction of Soiling Rates	Costs	Potential Limitations	Most Reasonable Application Scenario
Fully automated cleaning	>95%	2.4–8.2 €/m^2 [49,114]	integration in plant design	PV utility scale, ground mounted
Anti-soiling coatings ● Applied by glass manufacturer ● Retro-fit	<<80% (literature review) <20%–50% (authors estimate) 32% reported for commercial coating[72]	<2 €/m^2	performance dependent on location and season, degradation by cleaning and environmental stresses	utility scale, residential, ground-mounted and rooftop, BiPV, CSP + extra benefit from AR property
Tracking	<40%–60%	n.a.	integration in plant planning, additional costs	utility scale, ground mounted, state of the art in CSP
Electrodynamic screen/shield (EDS)	<<98% (laboratory) 32%[87] reported for 2-year study in Saudi Arabia	<30 €/m^2	expensive, large-scale application needs to be proven	BiPV, island systems, street lighting, rooftop, CSP
Heating ● PCM ● Active cell heating ● PVT	<20%–60%	<80 €/m^2 (PCM) n.a.	expensive, large-scale application needs to be proven	BiPV, island systems, street lighting, rooftop installations + extra benefit from cooling during day for PCM + PVT
Optimized PV module design and orientation	<65%	≤0 €/W_p	integration into mass production	utility scale, rooftop installations
Site adaption	unknown, site specific	n.a.	little experience, research needed	utility scale PV and CSP

over the past two decades (about 10% relative) will be eliminated by a few weeks of soiling in arid regions. Yet the soiling problem is far from solved, although there are multiple mitigation approaches.

Based on a techno-economic assessment, we identified automated cleaning machines, ASCs, tracker modification with inverted stowing, and optimized PV module designs as potentially applicable on a large scale in the medium term. For these technologies, the reduced soiling rates can lead to sufficiently lower cleaning expenses, so that the estimated investment costs become reasonable, especially in areas with high soiling rates. However, the economic conditions are very challenging, as, e.g., a soiling rate reduction of 50% might only allow additional costs in the range of 2€/m^2 for PV. Accordingly, earlier-stage technologies like EDS and night-time heating are currently too expensive and insufficiently validated under field conditions, but their development is far from exhausted and should be continued. In addition, more research is still needed on the location-dependent effectiveness of all suggested technologies, their possible impacts on the environment and on the long-term reliability of the PV modules or CSP mirrors and also operating practices to assure effective and secure use of the technologies.

Together with the technological approaches, soiling mitigation can start at the site selection and plant design stage. Studies on this aspect are particularly lacking, suggesting that more research is needed on soiling monitoring (including resource assessment campaigns), soiling modeling, and integration into meteorological models.

In addition, there is a particular need for passive anti-soiling solutions for difficult to reach locations, such as rooftops and remote sites, which would also allow higher investment costs. Here, ASCs can be a useful complement to an active cleaning program by extending the period between cleanings. Innovative materials and new concepts continue to be developed, targeting new functionalities such as self-healing, promotion of condensation run-off, or retro-fit application. Key remaining challenges include durability and effectiveness in different climate conditions.

EXPERIMENTAL PROCEDURES

Estimation of Global Soiling Impact

Since soiling rates vary significantly with location, technology, site specifics, season and time of the day, a statistical analysis of in excess of 100 publications reporting soiling rates for PV modules and CSP plants for different regions of the world was used to estimate regional losses and their variability, see Figure 2B. A detailed overview of the literature results is presented in the Supplemental Information; see Tables S1–S3. Only data from outdoor exposure experiments performed at typical tilt angles were considered because soiling increases dramatically for low tilt angles. From the dataset of each country, the median value was chosen for calculation. For countries with no data available from literature, estimates from soiling rates from nearby countries were used.

In comparison to soiling rate studies, there are only a few scientific reports on common cleaning economics and costs with regard to PV soiling.[9,22,51,115–126] The outcomes of these studies are difficult to compare, as they mostly report on soiling economics for a particular site (sometimes without optimization), use complex model approaches that are not easy to reproduce or are based on limited or outdated data. Therefore, information on cleaning costs has been compiled from industry partners and stakeholders, indicating huge differences between the different countries and different sites and plant sizes (see Figure 2C). For the calculations, both minimum and maximum values for utility plants were used. In the case that no reliable data was available, cleanings costs were estimated based on costs in countries with comparable economic development and labor conditions.

The specific yield for PV systems was simulated with the project design software PV*SOL premium 2018 for a 67 kW_p PV system with 200 PV modules from Canadian Solar Inc. (CS6U-335P) and an inverter from SMA (Sunny Tripower 8000TL-20). From this, the energy yield was determined at fixed, optimum tilt without soiling losses for one year for several locations for each country (see Figure 2D) and the average yield per country was used for the calculations. The yield data and details for the simulated locations are provided in the Supplemental Information (see Figure S1 and Table S4).

In order to estimate the financial losses due to potential yield losses from soiling, the incentives from power purchase agreements in 2018 were determined for each country; the data is provided in Table S1. For 2023, average electricity prices of 0.03 €/kWh and 0.05 €/kWh were assumed for PV and all countries and for CSP, respectively.

From the collected datasets, the optimum number of cleaning cycles per year, *cyc*, and the corresponding total costs were calculated by cost optimization as follows for each of the top 22 countries (PV) and global CSP. The average number of days between cleanings, *n*, was determined as

$$n = \frac{365}{cyc}. \quad \text{(Equation 1)}$$

The soiling rate *SR* is defined as an increase of soiling loss per day. This means that for a soiling rate of 0.5 %/day, the soiling loss on the first day will be 0.5 %, on the second day it will be 1%, and on the third day 1.5 %, respectively. In this study, the soiling rate was assumed to be constant between cleaning events, which is typically the case for desert environments. Accordingly, the total, cumulative soiling loss factor between cleaning cycles S_{loss} can be calculated by

$$S_{loss} = \sum_{k=1}^{n} k \times SR = SR\frac{n^2+n}{2}, \quad \text{(Equation 2)}$$

with the index k accounting for all days without cleaning, see also Figure S2 in the supplemental material. Equation 2 assumes a linear soiling derate independently of the value of the soiling loss, up to a maximum loss of 100%. Some authors have been suggesting the use of an exponential function that asymptotically tends to the maximum loss of 100%.[116] However, in this work, linear soiling profile modeling has been preferred, as it directly employs the soiling rate metric, which is widely available in the literature and often reported to match experimental results (see also Table S2).[17,22,127] From the soiling loss, the annual yield loss Y_{loss} can be determined by multiplication with the installed capacity C, the specific annual yield Y_{spec}, and the total number of cleaning cycles per year:

$$Y_{loss} = C \times Y_{spec} \times S_{loss} \times \mathrm{cyc} = 365\ C \times Y_{spec} \times\ SR \times \frac{n+1}{2}. \quad \text{(Equation 3)}$$

The solar power generation and supply to the grid is generally rewarded by incentives I, as commonly reflected by feed-in tariffs or bid prices, in units of €/kWh. By multiplication of the lost annual yield with the assumed local incentives, the annual financial loss F_{loss} due to soiling of a system can be estimated:

$$F_{loss} = Y_{loss} \times I. \quad \text{(Equation 4)}$$

On the other hand, the annual cleaning costs are determined by

$$U = u \times C \times \frac{1}{A} \times cyc = u \times C \times \frac{1}{A} \times \frac{365}{n}. \quad \text{(Equation 5)}$$

u is the cleaning cost per cleaning in $€/m^2$, and A is the module/mirror area efficiency. For PV, module characteristics of 300 W_p and an area of 1.64 m^2 were assumed, yielding A = 0.183 kW_p/m^2. For CSP, exemplary values of the plant Noor Ouarzazate III were taken (150 MW, 7400 heliostats with an area of 178.5 m^2 each), resulting in $A = 0.114\ kW/m^2$.

The total soiling-related costs T is the sum of cleaning costs and financial losses due to reduced energy yield.

$$T = F_{loss} + U. \quad \text{(Equation 6)}$$

Accordingly, the optimized number of cleaning cycles was calculated by determination of the minimum of the total costs $T'(n) = 0$, which yields

$$cyc_{opt} = \frac{365}{n_{opt}} = 365\sqrt{\frac{Y_{spec} \times SR \times I \times A}{2u}}. \quad \text{(Equation 7)}$$

It should be noted that here, the specific yield Y_{spec} needs to be converted to a daily value (annual yield divided by 365). Similar approaches to calculate the optimum cleaning number also resulted in a dependence on the square root of the lost incentives divided by twice the cleaning costs.[123,125]

As described above, a minimum and maximum optimum number of cleaning cycles was determined for minimum and maximum utility-scale plant cleaning costs and used for calculation of the financial losses for each of the top 22 countries (PV). The global soiling loss was calculated as sum from the top 22 countries:

$$\frac{\sum_{i=1}^{22} Y_{loss,i}\left(n_{opt,i}\right)}{\sum_{i=1}^{22} C_i Y_{spec,i}}. \quad \text{(Equation 8)}$$

Accordingly, also the global soiling costs were calculated as sum of top 22 countries

$$\sum_{i=1}^{22} T_i. \quad \text{(Equation 9)}$$

Tables with detailed data and references are provided in the Supplemental Information. As Figure 2 demonstrates, the available data, such as soiling rates, are often limited and can vary considerably within a country. This also increases the uncertainty of the rough estimates for the global impact of soiling.

Calculation of the Potential Cost Range for Soiling Mitigation Technologies

The estimated financial losses for each country in the previous section were used to determine the potentially feasible costs range for soiling mitigation technologies assuming specific reductions of soiling rates (see Table 1). For this, the soiling rate in Equation 7 was adapted to the reduced soiling rate $SR_{mitigate}$. The country-specific optimum numbers of cleaning cycles were recalculated and used for determination of the adapted total soiling-related costs $T_{mitigate}$ (see Equation 6). From this, the difference between the total costs for non-mitigated (only cleaning) and mitigated soiling was calculated for each country and divided by the capacity-related area, yielding the potential annual cost savings of soiling mitigation per m^2 $CS_{mitigate}$.

$$CS_{mitigate,i} = T_i - T_{mitigate,i.} \quad \text{(Equation 10)}$$

The maximum allowed technology investment costs V_{max}, so that a NPV $\geq$ 0 € is achieved after a 10-year payback period and a discount rate of 5%, were calculated for each country i according to the minimum and maximum cleaning costs by:

$$V_{max,i} = \sum_{l=0}^{9} \frac{CS_{mitigate,i}}{(1+l)^l} \approx CS_{mitigate,i} \times 8.11 \quad \text{(Equation 11)}$$

A payback period of 15 years is typical for financing PV plants in moderate climates by bank lenders.[128] However, for soiling, especially desert environments become relevant, and no reliable data on long-term durability of mitigation technologies is available yet. Accordingly, 10 years were chosen, corresponding to the typical product warranty of PV modules. Discount rates for PV have been reported to be typically in the range of 4%–9% (depending on the country).[113] The average values of V_{max} as displayed in Table 1 were determined as the (non-weighted) mean of all $V_{max,i}$, and the global minimum and maximum values were also provided.

In summary, the calculations in this study indicate the cost range for which investments into soiling mitigation technologies might become profitably compared to standard cleaning approaches. Opportunity investments, such as adding PV capacity to an existing installation, are not considered in this analysis. However, against the background of ultra-low module and system prices, such investments could become reasonable to even replace the cleaning itself, at least in low-soiling environments (see Example S1).

Model Validation

The model results largely build on reported soiling rates and cleaning costs (see Tables S1 and S2). Model validation by correlation with further field data is challenging, because only rare data is available, and there is a large uncertainty because soiling rates and cleaning costs vary considerably already within one country. However, the first attempt of validation can be made by comparing the calculated optimum number of cleaning cycles with typical numbers reported from the field. Some data could be derived from literature and interviews

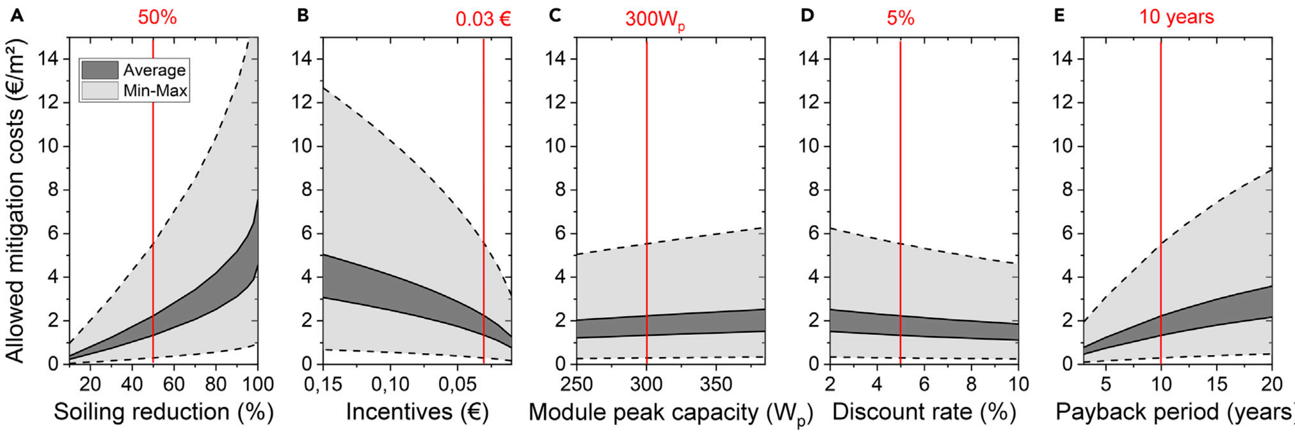

Figure 5. Sensitivity Analysis of Selected Parameters Influencing the Estimates for Allowed Mitigation Costs

(A) Soiling rate reduction.

(B) Incentives for power generation and supply to the grid.

(C) PV module peak capacity.

(D) Discount rate.

(E) Payback time for calculation of NPV.

for China,[124] India,[114] Germany, and Saudi Arabia[129] and is plotted as blue lines in Figure 2E. As stated above, the data vary significantly. However, it can be concluded that the model estimates match the expected numbers for different regions quite well.

A second approach for validation is a comparison between the calculated allowed costs for soiling mitigation of 80%–100% (2.5–7.9 €/m^2, see Table 1) and the costs for automated cleaning robots (2.4–8.2 €/m^2 which match very well [49,114] see Table 2). Automated cleaning robots are increasingly gaining relevance in high-soiling areas,[52] which is also suggested by the data obtained within this study and demonstrates that the heuristic approach used has the potential to reflect the actual soiling economics.

However, in order to provide a better overview of factors influencing the outcomes, a sensitivity analysis has been performed for soiling rate reductions (Figure 5A), incentives (Figure 5B), PV module peak capacity (Figure 5C), discount rates (Figure 5D), and payback time period (Figure 5E). Only one parameter was changed during each analysis, and the standard parameters used are indicated by red lines in Figure 5. The graphs show the average costs as well as absolute minimum and maximum as derived for minimum and maximum cleaning cost estimates for the different regions (see Equation 8). A more in-depth analysis for selected countries is also provided in Figure S3.

From Figure 5, it can be concluded that the cost estimates are mainly determined by the assumed soiling rate reduction of the respective technology and the incentives for power supply to the grid, followed by the assumed payback period of the initial investment. PV module peak capacity and discount rate have only a minor impact on the final results.

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.joule.2019.08.019.

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AUTHOR CONTRIBUTIONS

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Supplemental Information

Techno-Economic Assessment of Soiling Losses and Mitigation Strategies for Solar Power Generation

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Table S1: Supplemental data used for calculation of optimum cleaning cycles and yield losses in Figure 2 and section "Impact on global solar energy production and energy costs"

Country	Total Capacity 2018 [GW][1]	Total Capacity 2023 [GW][1]	Median Soiling Rate [%/day]	Specific annual yield [$kWh/kW_p/a$]	Cleaning costs, lower limit [€/m²]	Cleaning costs, upper limit [€/m²]	Feed-in-Tariff 2017/18 [€/kWh]
China	175.1	448.1	0.240	1366.2	0.048	0.071	0.11[2]
United States	62.1	132.4	0.040	1628.7	0.107	0.268	0.05[b]
India	27.3	116.1	0.617	1636.5	0.016	0.129	0.03[3]
Japan	55.9	82.4	0.038	1217.1	0.140[+]	0.460[+]	0.16[3]
Germany	45.9	72.6	0.021	1062.5	0.200	0.500	0.09[3]
Australia	12.6	45.2	0.040	1798.3	0.140[+]	0.460[+]	0.19[3]
Italy	19.9	29.5	0.076	1528.1	0.160	0.190	0.11[2]
Spain	5.9	25.4	0.059	1454.7	0.090	0.095	0.06[+]
South Korea	7.7	24.8	0.020[+]	1218.5	0.140[+]	0.460[+]	0.05[+]
France	8.9	22.3	0.020[+]	1219.1	0.140	0.460	0.06[2]
Netherlands	4.2	20.1	0.020	1024.2	0.457	0.915	0.08[4]
Mexico	3.6	19.0	0.350	1703.2	0.030	0.104	0.03[3]
United Kingdom	13.0	15.7	0.193	984.2	0.120	0.150	0.07[3]
Brazil	2.3	12.5	0.065	1583.6	0.016[+]	0.064[+]	0.07[3]
Taiwan	2.7	12.1	0.208	1205.2	0.016[+]	0.064[+]	0.13[3]
Saudi Arabia	0.0	11.4	0.222	1937.9	0.016	0.064	0.05[+]
Turkey	5.1	10.6	0.135	1534.9	0.069	0.090	0.10[3]
CSP (global)	5.6[5]	9.2[5]	0.535[+]	2781.3[6]	0.0050	0.03	0.12[+]
Pakistan	1.7	8.4	0.200	1763.5	0.016[+]	0.064[+]	0.12[3]
Ukraine	2.0	8.0	0.020[+]	1209.9	0.016[+]	0.064[+]	0.15[7]
Thailand	2.7[8]	6.2[9]	0.117	1512.6	0.016[+]	0.064[+]	0.15[3]
United Arab Emirates	0.7	6.1	0.367	1711.4	0.016[+]	0.064[+]	0.05[3]
Egypt	0.7	5.0	0.125	1869.7	0.016[+]	0.064[+]	0.09[3]

[+] Estimate

Table S2: Supplemental overview of PV soiling rate data points shown in Figure 2 and used for calculation of median values in Table S1

Country, City	Soiling Rate [%/day]	Reference
Australia	0.0211	Ghiotto et al. [10]
Australia, Perth	0.1500	Tanesab [11]
Australia, Geraldton	0.0103	Morley et al. [12]
Australia, Nyngan	0.0113	Morley et al. [12]
Australia, Broken Hill	0.0053	Morley et al. [12]
Australia, Alice Springs	0.2148	Ilse et al., unpublished
Australia, Alice Springs	0.0967	Ilse et al., unpublished
Australia, Alice Springs	0.0543	Ilse et al., unpublished
Australia, Alice Springs	0.0500	Ilse et al., unpublished
Australia, Alice Springs	0.0307	Ilse et al., unpublished
Brazil, Paraná	0.0906	Michels et al. [13]
Brazil, São Paulo	0.0389	Shirakawa et al. [14]
China, Shenzhen	0.3750	Ju et al. [15]
China, Taiyuan	1.2857	Liqun et al. [16]
China, Dunhuang	0.2400	Dross et al. [17]
China, Dunhuang	0.2200	Dross et al. [17]
China, Dunhuang	0.1500	Dross et al. [17]
China, Ningxia	0.9100	DDS – Dust Detection System [18]
China, Nanjing	0.0583	Liu et al. [19]
China, Nanjing	0.0518	Liu et al. [19]
China, Xi’an	2.5000	Guan et al. [20]
Egypt, Minia	0.7000	Hegazy [21]
Egypt, Minia	0.5333	Hegazy [21]
Egypt, Helwan	0.1000	Elminir et al. [22]
Egypt, Helwan	0.0905	Elminir et al. [22]
Egypt, Helwan	0.0857	Elminir et al. [22]
Egypt, Aswan	0.3	Chen [23]
Egypt, Aswan	0.15	Chen [23]
Germany, Cologne	0.0132	Becker et al. [24]
Germany	0.0055	Kürvers [25]
Germany	0.0411	Kürvers [25]
Germany	0.0027	Ilse et al., unpublished
Germany	0.0274	Ilse et al., unpublished
Germany	0.0228	Solarpflege.de [26]
Germany	0.0513	Solarpflege.de [26]
Germany	0.0274	Solarpflege.de [26]

Country, City	Soiling Rate [%/day]	Reference
Germany	0.0137	Solarpflege.de [26]
Germany	0.0411	Solarpflege.de [26]
Germany	0.0137	Solarpflege.de [26]
Germany	0.0183	Solarpflege.de [26]
India, Tripura	0.2143	Bhattacharya et al. [27]
India, Bangalore	0.6014	Bohra et al. [28]
India, Bangalore	0.4079	Bohra et al. [28]
India, Bangalore	0.6514	Bohra et al. [28]
India, Bangalore	0.4714	Bohra et al. [28]
India, Bangalore	0.99	Bohra et al. [28]
India, Bangalore	0.6271	Bohra et al. [28]
India, Bangalore	1.5543	Bohra et al. [28]
India, Bangalore	0.8214	Bohra et al. [28]
India, Delhi	0.3583	Nobre et al. [29]
India, Bangalore	0.6667	Thangaraj et al. [30]
India, Bangalore	0.5667	Thangaraj et al. [30]
India, Bangalore	0.7000	Thangaraj et al. [30]
India, Bangalore	0.7333	Thangaraj et al. [30]
India, Vellore	1.4286	Amarnadh et al. [31]
India, Vellore	1.0000	Amarnadh et al. [31]
India, Vellore	0.8100	Amarnadh et al. [31]
India, Vellore	0.7143	Amarnadh et al. [31]
India, Bombay	0.6578	Ilse et al., unpublished
India, Bombay	0.4900	Ilse et al., unpublished
India, Bombay	0.5329	Ilse et al., unpublished
India, Bombay	0.1900	Ilse et al., unpublished
India, Bombay	0.2533	Ilse et al., unpublished
India, Bombay	0.6865	Ilse et al., unpublished
India, Bombay	0.6067	Ilse et al., unpublished
India, Bombay	0.5557	Ilse et al., unpublished
India, Bombay	0.4693	Ilse et al., unpublished
India, Bombay	0.4546	Ilse et al., unpublished
Italy	0.0180	Belluardo et al. [32]
Italy	0.0763	Belluardo et al. [32]
Italy, Puglia	0.1255	Pavan et al. [33]
Japan, Miyazaki	0.0417	Nishioka et al. [34]

Table S2: Supplemental overview of PV soiling rate data points shown in Figure 2 and used for calculation of median values in Table S1

Country, City	Soiling Rate [%/day]	Reference
Japan, Miyazaki	0.0344	Hirohata et al. [35]
Mexico, Hermosillo	0.4500	Cabanillas and Munguia [36]
Mexico, Hermosillo	0.2500	Cabanillas and Munguia [36]
Netherlands	0.0958	Tzikas et al. [37]
Netherlands	0.0913	Tzikas et al. [37]
Netherlands	0.0775	Tzikas et al. [37]
Netherlands	0.0750	Tzikas et al. [37]
Netherlands	0.0663	Tzikas et al. [37]
Netherlands	0.0495	Tzikas et al. [37]
Netherlands	0.0203	Tzikas et al. [37]
Netherlands	0.0035	Tzikas et al. [37]
Netherlands	0.0015	Tzikas et al. [37]
Netherlands	0.0228	Tzikas et al. [37]
Netherlands	0.0220	Tzikas et al. [37]
Netherlands	0.0213	Tzikas et al. [37]
Netherlands	0.0200	Tzikas et al. [37]
Netherlands	0.0186	Tzikas et al. [37]
Netherlands	0.0167	Tzikas et al. [37]
Netherlands	0.0151	Tzikas et al. [37]
Netherlands	0.0122	Tzikas et al. [37]
Netherlands	0.0089	Tzikas et al. [37]
Netherlands	0.0055	Tzikas et al. [37]
Netherlands	0.0028	Tzikas et al. [37]
Pakistan, Taxila	0.2222	Ali et al. [38]
Pakistan, Taxila	0.1778	Ali et al. [38]
Saudi Arabia, Dhahran	0.4444	Said et al. [39]
Saudi Arabia	0.0929	Karmouch and Hor [40]
Saudi Arabia	0.0866	Kamouch and Hor [40]
Saudi Arabia, Dhahran	0.2778	Adinoyi et al. [41]
Saudi Arabia, Dhahran	0.2000	Rehman and El-Amin [42]
Saudi Arabia, Jeddah	0.3000	DDS – Dust Detection System [18]
Saudi Arabia	0.0204	Alamoud [43]
Saudi Arabia, Thuwal	0.54	Hermann[45]
Saudi Arabia, Thuwal	0.50	Hermann[45]
Saudi Arabia, Thuwal	0.45	Hermann[45]
Saudi Arabia, Rumah	0.210	Jones et al. [44]
Saudi Arabia, Rumah	0.233	Jones et al. [44]
Saudi Arabia, Rumah	0.167	Jones et al. [44]
Saudi Arabia, Rumah	0.567	Jones et al. [44]
Saudi Arabia, Rumah	0.373	Jones et al. [44]
Saudi Arabia, Rumah	0.130	Jones et al. [44]
Saudi Arabia, Rumah	0.013	Jones et al. [44]
Saudi Arabia, Rumah	0.070	Jones et al. [44]
Saudi Arabia, Rumah	0.207	Jones et al. [44]
Saudi Arabia, Rumah	0.240	Jones et al. [44]
Saudi Arabia, Rumah	0.233	Jones et al. [44]
Saudi Arabia, Rumah	0.163	Jones et al. [44]
Spain, Malaga	0.2000	Piliougine et al. [46]
Spain, Malaga	0.0400	Piliougine et al. [47]
Spain, Gran Canaria	0.5333	Schill et al. [48]
Spain, Navarre	0.0133	García et al. [49]
Spain, Malaga	0.0548	Zorrilla-Casanova et al. [50]
Spain, Almería	0.0118	Ilse et al., unpublished
Spain, Almería	0.0600	Ilse et al., unpublished
Spain, Almería	0.0429	Ilse et al., unpublished
Spain, Almería	0.0586	Ilse et al., unpublished
Spain, Almería	0.0200	Ilse et al., unpublished
Spain, Madrid	0.3000	Vivar et al. [51]
Spain, Madrid	0.1833	Vivar et al. [51]
Spain, Madrid	0.7111	Vivar et al. [51]
Taiwan, Taichung	0.0363	Chen et al. [52]
Taiwan, Kaohsiung	0.3800	DDS – Dust Detection System [18]
Thailand	0.1237	Ketjoy et al. [53]
Thailand	0.1167	Ketjoy et al. [53]
Thailand	0.0987	Ketjoy et al. [53]
Thailand	0.0943	Ketjoy et al. [53]
Thailand	0.1858	Ketjoy et al. [53]
Thailand	0.1213	Ketjoy et al. [53]
Thailand	0.0965	Ketjoy et al. [53]
Thailand	0.1005	Ketjoy et al. [53]
Thailand	0.517	Lee et al. [54]
Thailand	0.517	Lee et al. [54]

Table S2: Supplemental overview of PV soiling rate data points shown in Figure 2 and used for calculation of median values in Table S1

Country, City	Soiling Rate [%/day]	Reference
Thailand	0.727	Lee et al. [54]
Thailand	0.313	Lee et al. [54]
Thailand	0.233	Lee et al. [54]
Thailand	0.077	Lee et al. [54]
Thailand	0.000	Lee et al. [54]
Thailand	0.117	Lee et al. [54]
Thailand	0.000	Lee et al. [54]
Thailand	0.377	Lee et al. [54]
Thailand	0.083	Lee et al. [54]
Thailand	0.0363	Chen et al. [52]
Thailand, Angthong	0.5400	DDS - Dust Detection System [18]
Turkey, Istanbul	0.1433	Durusu et al. [55]
Turkey, Istanbul	0.05	Durusu et al. [55]
Turkey, Istanbul	0.1885	Durusu et al. [55]
Turkey, Istanbul	0.126	Durusu et al. [55]
UAE, Abu Dhabi	0.9000	Al-Sabounchi et al. [56]
UAE, Abu Dhabi	0.7222	Al Hanai et al. [57]
UAE, Abu Dhabi	0.6000	El-Nashar [58]
UAE, Abu Dhabi	0.3333	El-Nashar [58]
UAE, Masdar	0.2103	Brito et al. [59]
UAE, Masdar	0.2133	Brito et al. [59]
UAE, Masdar	0.3024	Brito et al. [59]
UAE, Masdar	0.3100	Brito et al. [59]
UAE, Dubai	0.5	Chen [23]
UAE, Dubai	0.7	Chen [23]
UAE, Dubai	0.4	Chen [23]
UAE, Dubai	0.1	Chen [23]
UK, Brighton	0.3857	Ghazi et al. [60]
UK, Brighton	0.1929	Ghazi et al. [60]
UK, Brighton	0.1381	Ghazi et al. [60]
USA, Arizona	0.0149	Cano et al. [61]
USA, Arizona	0.0130	Cano et al. [61]
USA, Arizona	0.0130	Cano et al. [61]
USA, Arizona	0.0117	Cano et al. [61]
USA, Arizona	0.0110	Cano et al. [61]

Country, City	Soiling Rate [%/day]	Reference
USA, Arizona	0.0092	Cano et al. [61]
USA, Arizona	0.0107	Cano et al. [61]
USA, Arizona	0.0077	Cano et al. [61]
USA, California	0.21	Mejia et al. [63]
USA, Arizona	0.061	Naeem [64]
USA, Arizona	0.02	Tamizh et al. [65]
USA	0.0167	Gostein et al [66]
USA	0.1667	Gostein et al [66]
USA, Oregon	0.2353	Smith et al. [67]
USA, New Mexico	0.0300	Micheli et al. [62]
USA, California	0.1000	Micheli et al. [62]
USA, California	0.0600	Micheli et al. [62]
USA, California	0.0400	Micheli et al. [62]
USA, California	0.0400	Micheli et al. [62]
USA, Arizona	0.0200	Micheli et al. [62]
USA, California	0.0800	Micheli et al. [62]
USA, Arizona	0.0500	Micheli et al. [62]
USA, California	0.2400	Micheli et al. [62]
USA, California	0.1300	Micheli et al. [62]
USA, California	0.1600	Micheli et al. [62]
USA, Colorado	0.0400	Micheli et al. [62]
USA, Texas	0.1500	Micheli et al. [62]
USA, California	0.0300	Micheli et al. [62]
USA, Florida	0.0300	Micheli et al. [62]
USA, Colorado	0.0400	Micheli et al. [62]
USA, Arizona	0.0600	Micheli et al. [62]
USA, California	0.1879	Ilse et al., unpublished
USA, California	0.2033	Ilse et al., unpublished
USA, California	0.0443	Ilse et al., unpublished
USA, California	0.1057	Ilse et al., unpublished
USA, California	0.0229	Ilse et al., unpublished
USA, Oregon	0.0038	Ryan et al. [68]
USA, Arizona	0.0111	Hammond et al. [69]

Table S3: Supplemental overview of CSP soiling rate data points shown in Figure 2 and used for calculation of median values in Table S1

Country, City	Soiling Rate [%/day]	Reference
USA	0.35	Kolb 2007 [70]
USA, Kramer Junction	0.49	Cohen et al. [71]
USA, 7 sites	0.4 0.33 0.17 0.2 0.27 0.55 0.88 1.27	Deffenbaugh et al. [72]
Abu Dhabi: al Wagan & Jabel Hafeet	2.4 4.6 2.1 5.0	Tahboub et al. [73]
Spain, PSA Morocco, stone desert Morocco, sand desert	0.3 0.6 1.3	Wolfertstetter et al. [74]
Spain, PSA	0.52	Wolfertstetter et al. [75]
Spain, PSA Missour Morocco	0.51 0.71	Wolfertstetter et al. [76]
Spain, PSA	0.1 0.7	Fernández García [77]
South Africa	0.37 0.70	Griffith et al. [78]
Spain, Madrid	0.38	Vivar et al. [51]

Figure S1: Overview of locations used for estimation of average specific yield in Figure 2

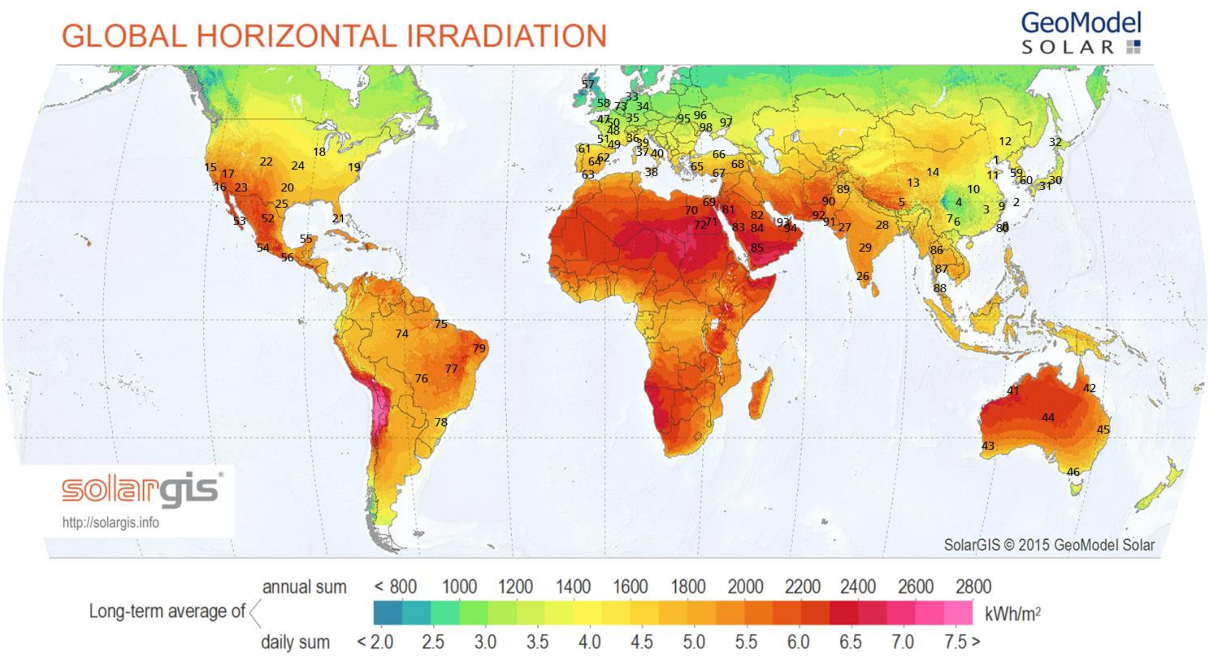


Table S4: Overview of locations used for estimation of average specific yield in Figure 2

#	Country	City	Optimum tilt angle [°]	Specific annual yield [kWh/kW$_p$/a]
1	China	Beijing	32	1335
2	China	SHANGHAI	22	1148
3	China	Changsha	17	968
4	China	Chengdu	16	861
5	China	Lhasa	28	1832
6	China	Kunming	25	1430
7	China	DALI	27	1594
8	China	Xiamen	17	1262
9	China	JINGDEZHEN	21	1087
10	China	Zhumadian	22	1137
11	China	Weifang	29	1335
12	China	CHANGCHUN	39	1521
13	China	Golmud	34	1998
14	China	XINING	33	1618
15	United States	SAN FRANCISCO INTL AP	29	1658
16	United States	LOS ANGELES INTL ARPT	26	1707
17	United States	LAS VEGAS MCCARRAN INTL AP	31	1925
18	United States	CHICAGO OHARE INTL AP	30	1369
19	United States	WASHINGTON	33	1301
20	United States	DALLAS-FORT WORTH INTL AP	26	1627
21	United States	MIAMI INTL AP	24	1566
22	United States	DENVER INTL AP	35	1690
23	United States	PHOENIX SKY HARBOR INTL AP	30	1924
24	United States	KANSAS CITY INT'L ARPT	32	1556
25	United States	SAN ANTONIO KELLY FIELD AFB	24	1593
26	India	COIMBATORE/PEELAMED	14	1698
27	India	Ahmedabad	25	1721
28	India	PATNA	24	1503
29	India	Nagpur Sonegaon AFB	23	1624
30	Japan	Tokyo	30	1164
31	Japan	Osaka	27	1217
32	Japan	Sapporo	34	1270
33	Germany	Hamburg	37	987
34	Germany	Berlin	37	1055
35	Germany	Stuttgart	35	1145
36	Italy	Milano (UNI 10349)	31	1252
37	Italy	Roma (UNI 10349)	32	1561
38	Italy	Catania (UNI 10349)	30	1746
39	Italy	Bologna (UNI 10349)	32	1380
40	Italy	Bari (UNI 10349)	32	1701
41	Australia	Broome	19	1974
42	Australia	Cairns	16	1697
43	Australia	Perth	29	1848
44	Australia	Alice springs	24	2028
45	Australia	Brisbane	25	1748
46	Australia	Melbourne	31	1495
47	France	LE HAVRE/OCTEVILLE	34	1080
48	France	Bourges	33	1210
49	France	Montpellier	35	1539
50	France	PARIS/ORLY	33	1083
51	France	Bordeaux	34	1302
52	Mexico	MONTERREY INTL ARPT	20	1624
53	Mexico	LA PAZ INTL AIRPORT	22	1904
54	Mexico	COLIMA	18	1660
55	Mexico	Merida	19	1647

Table S4: Overview of locations used for estimation of average specific yield in Figure 2

#	Country	City	Optimum tilt angle [°]	Specific annual yield [kWh/kW$_p$/a]
56	Mexico	Salina Cruz	16	1729
57	United Kingdom	GLASGOW AIRPORT	40	987
58	United Kingdom	LONDON CITY AIRPORT	36	979
59	South Korea	Seoul	31	1156
60	South Korea	Pusan	31	1345
61	Spain	Lugo	31	1254
62	Spain	Barcelona	35	1542
63	Spain	Sevilla	30	1705
64	Spain	Madrid	31	1518
65	Turkey	IZMIR/CIGLI(CV/AFB)	29	1644
66	Turkey	Bafra	29	1320
67	Turkey	Mersin	28	1555
68	Turkey	Erzurum	31	1511
69	Egypt	Cairo	22	1683
70	Egypt	Siwa	27	2046
71	Egypt	Luxor	22	1958
72	Egypt	Dakhla	23	1980
73	Netherlands	AMSTERDAM/SCHIPHOL	35	1024
74	Brazil	MANAUS/PONTA PELADA	6	1486
75	Brazil	BELEM/VAL DE CAES	4	1523
76	Brazil	CUIABA/MARECHAL RON	17	1580
77	Brazil	Barreiras	15	1764
78	Brazil	Curitiba	23	1432
79	Brazil	Campina Grande	5	1716
80	Taiwan	Taizhong	18	1205
81	Saudi Arabia	TABUK (SAUD-AFB)	26	2091
82	Saudi Arabia	Hafr Al-Batin Airp.	23	1839
83	Saudi Arabia	Madinah	23	1847
84	Saudi Arabia	RIYADH/KING KHALID	22	1903
85	Saudi Arabia	WADI AL DAWASER	21	2009
86	Thailand	Lampang	19	1579
87	Thailand	Bangkok	14	1498
88	Thailand	Surat Thani	6	1461
89	Pakistan	Islamabad	29	1587
90	Pakistan	Quetta	28	1882
91	Pakistan	Hyderabad	24	1700
92	Pakistan	Panjgur	26	1885
93	UAE	Abu Dhabi/Bateen	21	1728
94	UAE	AL AIN INTNL ARPT	22	1694
95	Ukraine	Lvov	34	1076
96	Ukraine	Kiev	35	1179
97	Ukraine	Lugansk/Voroshilovgr	36	1278
98	Ukraine	Nikolaev	34	1307

Figure S2: Supplemental illustration on the calculation methodology of energy yield losses in methods section "Estimation of global soiling impact"

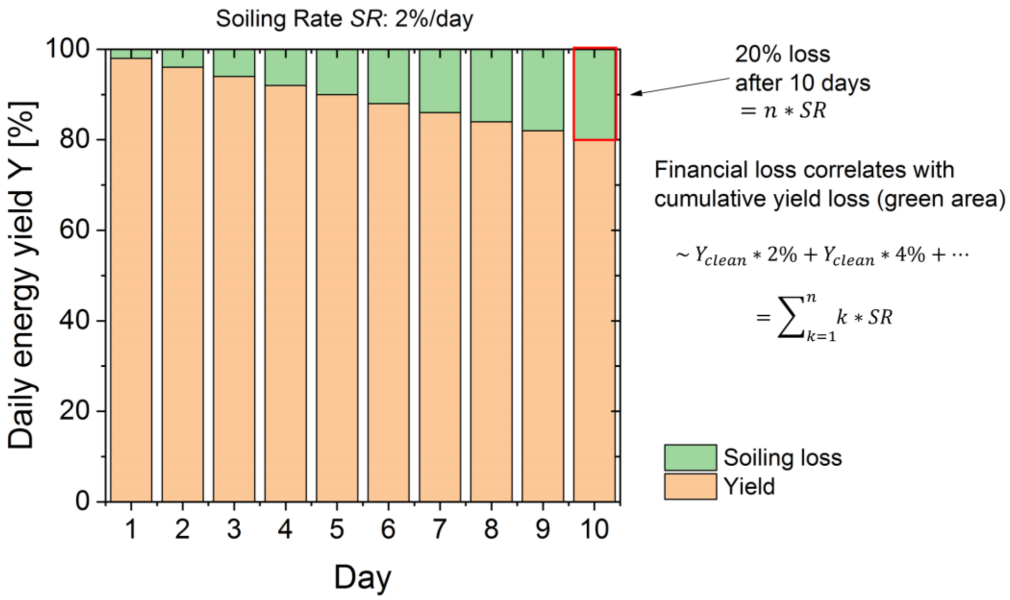


Fig. S2 schematically represents the assumptions and calculation methodology used to derive the energy yield losses in the methods section "Estimation of global soiling impact". The example graph shows the daily energy yield assuming a soiling rate of 2% loss per day, which is cumulative and would lead to an absolute soiling loss of 20% after 10 days (see green bars in the graph). Accordingly, the cumulative soiling loss for all days can be calculated by the sum of the soiling loss of each individual day, yielding equation (2) in the methods section, which is also shown in Fig. S2.

Example S1: Example calculation for opportunity investment for PV cleaning by increasing the PV plant capacity

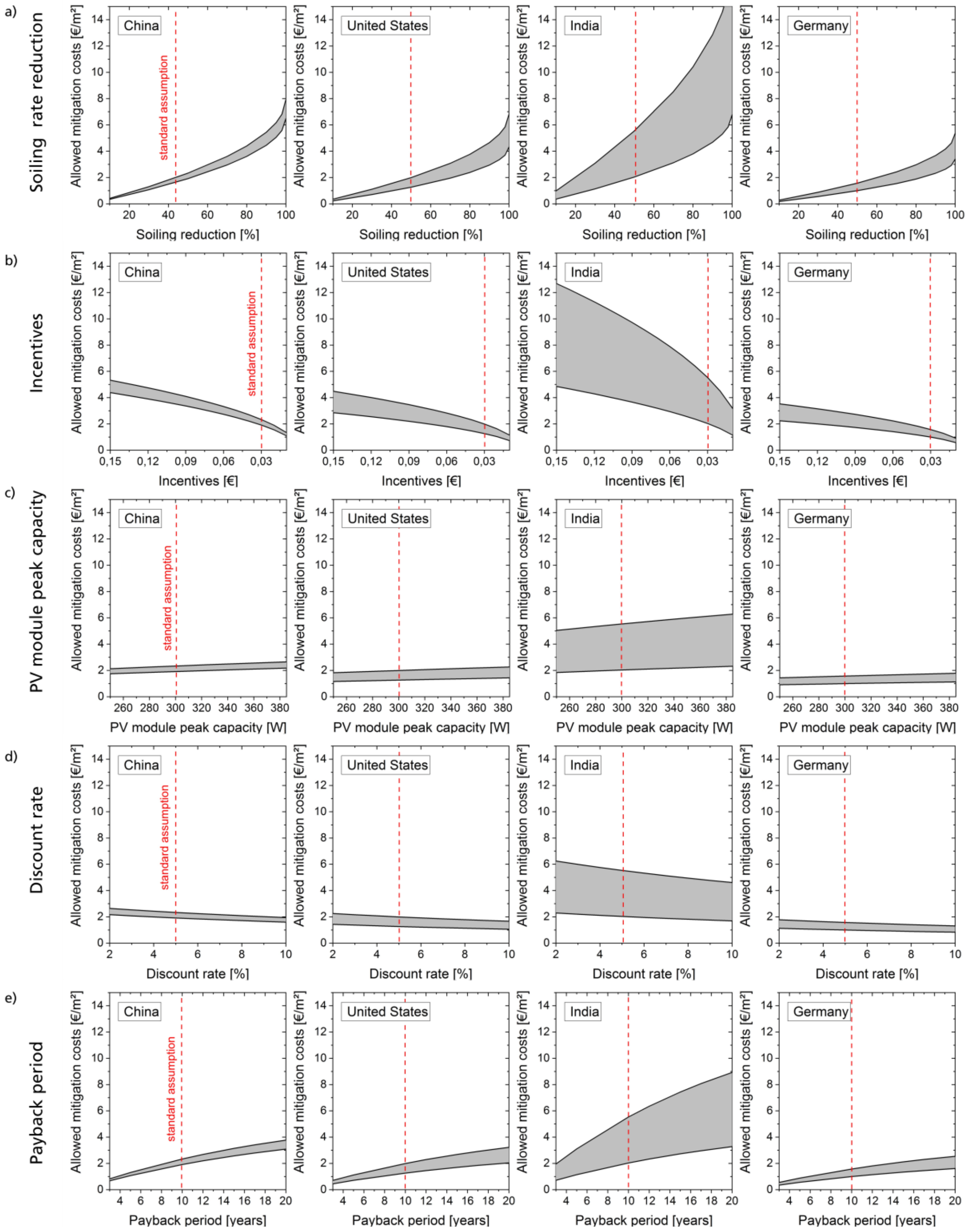
Some authors have suggested that the impact of soiling on the performance of PV systems, and on their predictability, could be addressed by oversizing the capacity of PV systems, or by limiting the size of the inverter. The convenience of this approach relies on a number of factors, including but not limited to the cost of the PV modules. According to the "PV Snapshot of Photovoltaics – February 2018"[79], the lowest system price for a commercial system was 0.61€/W_p. Assuming the same PV module configuration of 300 W_p and 1.64 m², that would correspond to about 112€/m² to build 100% PV production. Accordingly, an increase of the power output of a system by 1% equals 1.12 €/m².

In Germany, assuming 0.30 €/m² per cleaning and an optimum number of cleaning cycles of 0.6 cleanings per year, the overall cleaning costs for 20 years would be 3.60 €/m² costs. The corresponding output power loss for the condition of "no cleaning" can be estimated to be 3% increased on average. Accordingly, a 1% increase of power output due to cleaning would equal 1.20 €/m². This would make an investment into new installations more favourable compared to cleaning, even though cleaning would be profitable for the given conditions.

If now a scenario in China is considered, with cleaning costs of about 0.06 €/m² per cleaning, an optimum of 7 cleanings per year, the overall cleaning costs for 20 years would be 8.40€/m². In the case that this system is not maintained with respect to soiling and only cleaned by natural cleaning, an increase in output loss of 10% might be assumed, which considered peak losses of 20% between natural cleaning events such as rain. Accordingly, an increase of 1% power output would equal 0.84 €/m². Comparing the costs for 1% increase of output power for the two approaches, cleaning is about 25% cheaper than a new installation and with that the more reasonable investment.

Therefore, the convenience of oversizing a PV system instead of mitigating soiling is not a universally valid assumption. In addition, regulatory framework conditions, a more reliable yield forecast (favourable for investors), and a shortage of available land might favour the operation of cleanings, even if ideally not economically convenient.

Figure S3: Sensitivity analysis for the calculation of allowed costs for soiling mitigation for selected countries China, United States, India and Germany, including the parameters of a) soiling rate reduction, b) incentives for power supply to the grid (feed-in tariffs), c) PV module peak capacity (assuming standard size of 1.64 m²), d) discount rate and e) payback time



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