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# Fundamentals of soiling processes on photovoltaic modules

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ABSTRACT

The topic of soiling of photovoltaic module (PV) and concentrated solar power (CSP) collectors has recently gained increasing attention due to its impact on solar power production, especially in arid and semi-arid areas with high concentrations of airborne dust. Soiling describes the deposition of dust and other contaminants on surfaces, reducing solar irradiation by absorbing or reflecting the sunlight, causing energy yield losses which can exceed 1% per day. The amount of soiling is influenced by complex interactions of many factors which can vary significantly from site to site.

In this study we provide a detailed overview of macroscopic and microscopic factors influencing soiling. This includes a global analysis of key parameters including airborne dust concentrations, dust characteristics (mineral composition, size distribution), and particle deposition rates. A theoretical model for relevant particle adhesion and removal forces is presented to achieve a microscopic understanding of wind cleaning effects. Further, it was found that dew occurs frequently on PV modules in many soiling affected areas and that this can significantly increase particle adhesion. Therefore, a detailed analysis and model of the dew-driven soiling mechanisms of cementation, particle caking, and capillary aging are given on the basis of microstructural material and dust characterization of outdoor exposed glass samples. Furthermore, we study the complex interplay and dynamics of different environmental parameters (relative humidity, ambient and module temperature, airborne dust concentration, wind speed) and their correlation to dust accumulation, and provide explanations with the help of the developed models. Overall the study aims to provide a useful, in-depth but also global overview and fundamental understanding of soiling processes on PV modules down to the microscale, which could be used to develop appropriate soiling mitigation strategies.

## 1. Introduction

Regarding the problem of climate change, great efforts are needed to reach the 2015 Paris goals for 2100, i.e. a maximum increase of 1.5–2.0 °C in global temperature compared to pre-industrialisation by significantly reducing $CO_2$ emissions. Renewable energies and especially photovoltaics (PV) are regarded as an important contribution for decarbonisation of our energy system. Furthermore, with commercial offers to supply PV-generated electricity decreasing below 2 ct/kWh, it appears that solar power will become the cheapest form of electricity in many regions of the world. However, areas with high irradiation levels (the global sun-belt) often suffer from high airborne dust loads. Deposition of dust and dirt on PV modules or mirror surfaces leads to power losses since it reduces solar energy received by the collector by absorbing or scattering the sunlight. A striking example for soiled PV modules compared to a cleaned one can be seen in Fig. 1. For PV, the maximum energy yield loss per day can exceed 1% [1], which accumulates over time if the surface is not cleaned (see also Fig. 3). Therefore, soiling is one of the major concerns of component and system reliability in areas with high concentrations of airborne particulates. In contrast to the past, when PV was mainly installed in moderate climates, the majority of future markets in coming years will be in areas in which high soiling losses are reported in literature, foremost China and India [2].

Typically, power losses due to soiling can be reduced by frequent cleaning of the PV modules. Unlike other power degradation

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**Nomenclature**

| | |
|---|---|
| $A$ | Hamaker constant |
| $a$ | Contact radius of separation |
| $d$ | Particle diameter |
| $\varepsilon_0$ | Vacuum permittivity |
| $E_{1/2}$ | Young modulus |
| $F_C$ | Capillary force |
| $F_D$ | Drag force |
| $F_G$ | Gravity |
| $F_L$ | Lift force |
| $F_{VdW}$ | Van der Waals force |
| $F_{adh}$ | Sum of adhesion forces |
| $F_{el}$ | Electrostatic force |
| $g$ | Gravitational acceleration |
| $\gamma_w$ | Surface tension |
| $\lambda_{1/2}$ | Characteristic length of roughness feature |
| $M_D$ | Drag moment |
| $\mu$ | Dynamic viscosity of air |
| $\nu$ | Kinematic viscosity |
| $PM_{2.5/10}$ | Particulate matter with an aerodynamic diameter smaller than 2.5 µm or 10 µm |
| $q$ | Electric charge |
| $\bar{q}_{BE}$ | Mean particle charge at Boltzmann equilibrium |
| $rms_{1/2}$ | Root mean square of surface roughness |
| $\varrho$ | Density |
| $s$ | Distance of separation |
| $\sigma_{BE}$ | Surface charge density at Boltzmann equilibrium |
| $\sigma_{max}$ | Maximum surface charge density |
| $\theta_{1/2}$ | Water contact angle |
| $u_*$ | Friction/shear velocity |
| $v$ | Wind speed/free stream velocity |
| $v_{Stokes}$ | Stokes settling velocity |
| $W_a$ | Surface energy /work of adhesion |
| $\upsilon_{1/2}$ | Poisson ratio |

mechanisms of PV modules, such as potential induced and light induced degradation (PID and LID), the power output degradation due to soiling can usually be reversed and the light transmission restored to 100%. On the other hand, frequent cleaning will result in high operation and maintenance (O&M) costs, increasing the levelized cost of electricity (LCOE), especially for regions where water and labour are scarce or expensive. Hence, there are great efforts to optimize cleaning strategies, including different approaches such as wet or dry cleaning, automated or manual cleaning methods, different brush or cloth types or chemical additives. Besides cleaning, another mitigation strategy is to reduce the dust accumulation rate using the natural cleaning mechanisms of wind and rain. To increase their cleaning effect, much work is being undertaken to develop anti-soiling coatings [3–9].

In regions with low rainfall and high soiling rates, such as arid and semi-arid climates, dust removal by wind can be utilized as a natural cleaning mechanism. The effective soiling rate and anti-soiling functionality of surfaces will be the result of particle deposition versus particle removal/resuspension, which are determined by particle adhesion forces and removal forces. The complex interplay of relevant forces and their multiple influencing factors is discussed in chapter 3.

Detailed evaluation of the soiling processes is a truly complex problem because of the many influencing factors such as environmental parameters (e.g. airborne dust concentration, relative humidity, wind speed and direction, ambient temperature), PV module properties (e.g. surface roughness and chemistry, module frame, temperature), site and installation characteristics (e.g. tilt angle, orientation) and others. Furthermore, dynamic factors such as changes in these parameters over different time scales (e.g. nanoseconds of particle impact or seasonal changes of environmental factors or climate change over years) play a role, as well as dynamics and history of particle adhesion (e.g. initial state, aging, cementation). In addition, one has to consider a combination of processes and influencing factors at the macro, system scale (e.g. wind turbulences in a PV field, partial shading by inhomogeneous soiling) and processes which take place at the micro- and nanoscales (e.g. particle size, surface adhesion mechanisms). Fig. 2 summarizes some of these influencing factors in terms of relevant size and time scales. Bringing together all the influencing factors, size scales and time frames is ambitious, since this also requires a large variety of characterization methods. Accordingly, most of the scientific studies can only address some part of the whole picture.

In this paper we provide a comprehensive study of the link between macroscopic/system scale environmental parameters and the microscale properties of dust particles, particle adhesion and removal. These factors are examined theoretically and by experimental approaches. First of all, we provide a short overview of soiling field studies from the literature, which cover further details of the important influencing factors (Section 2). This is followed by an in-depth analysis of the key-

**Fig. 1.** Soiled and cleaned PV modules after one month of soiling at the QEERI Solar Test Facility in Doha, Qatar.

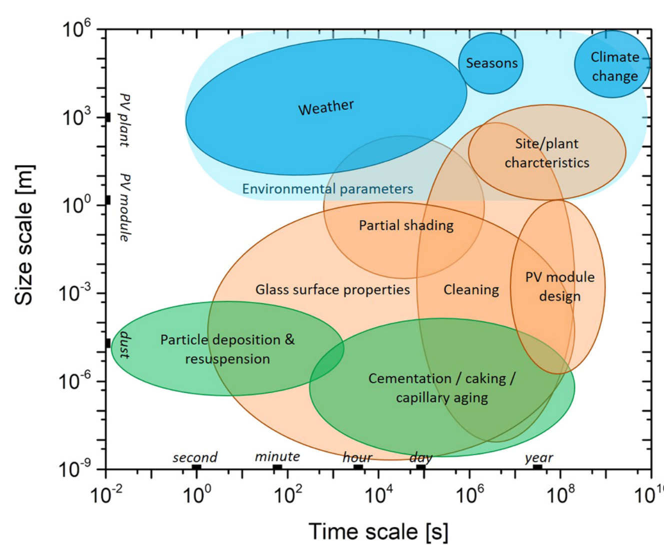


**Fig. 2.** Complexity of the soiling problem due to many influencing factors with huge variations in size and time scales. The macroscopic environmental parameters are coloured in blue whereas the microscopic soiling processes are shown in green. Controllable influencing factors such as the module or plant design as well as operation and maintenance strategies are marked in orange.