Soiling Losses – Impact on the Performance of Photovoltaic Power Plants

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Executive Summary

On a global scale, the soiling of solar photovoltaic (PV) systems from dust and snow, and subsequent loss of energy yield, is the single most influential factor impacting system yield after irradiance. Especially in arid regions, soiling may affect large utility-scale PV plants to a significant extent – making it necessary to mitigate these effects by cleaning whole systems – and thus leading to a reduction of revenues, caused by higher operating and/or capital expenditures (e.g., for investments in anti-soiling coatings [ASC] or cleaning robots and their maintenance).

This report therefore summarizes aspects of soiling from different perspectives including particle types and global distributions (Chapter 1), mechanisms and contributing factors (Chapter 2), sensors and measurement techniques (Chapter 3), modelling approaches and results (Chapter 4), economic impacts (Chapter 5), mitigation strategies (Chapter 6), and special installation and operation considerations for snow shading as solar arrays increasingly proliferate into higher latitudes (Chapter 7). The report is intended to serve the communities of PV customers, PV industry, O&M companies, investors, asset managers, testing equipment developers, testing companies, standardization authorities and research institutions alike.

Chapter 1 provides an overview of particle sizes, types, and global distributions and impacts. Global surveys show the highest total suspended particle densities (100-200 µg/m^3) in equatorial regions around Africa and Asia, not including snow shading effects at high latitudes.

Chapter 2 characterizes the factors contributing to dust particle deposition and adhesion on glass and PV module. Silt size particles in the range of 2 µm to 63 µm are the predominant contributors to soiling in arid and semi-arid climates, as can be seen from analyses in the Atacama Desert, Chile, and Qatar. Gravitational forces contribute to shorter airborne times for medium to large particles (>10 µm), while smaller particles (<5 µm) remain airborne longer due to air turbulence, and very small particles (<1 µm) are easily removed from the atmosphere by rain and do not deposit. The basic soiling formation processes of cementation, capillary aging, and caking are described, all of which have specific effects on the severity, persistence, and resistance to removal. Dew formation also plays a role, often increasing particle deposition rates as illustrated with an example from the Atacama Desert, in conditions of ambient high humidity combined with radiative cooling of PV modules due to the high infrared emissivity of solar glass. A review of deposition and adhesion forces asserts that particles smaller than 10 µm are rarely removed by wind from PV modules.

Chapter 3 provides insight into how to measure soiling, with what kind of sensors, their metrics, and different principles of operation, which can be categorised into electrical (short-circuit current and power) and optical (image processing cameras, LEDs, and reflectance measurements). This information is critical for predictions of future soiling rates and cleaning decision timelines. Metrics generally comprise a soiling ratio and soiling rate. Soiling does not always occur homogenously over the whole module surface or plant and tends to accumulate in the lower parts of modules. If soiling is not distributed uniformly, the short circuit current measurements may underestimate the actual impact of soiling on PV power. As such, an underestimated cost factor is the integration of multiple soiling monitors into the overall monitoring infrastructure to account for this heterogeneity. IEC Standard 61724 "Photovoltaic system performance - Part 1: Monitoring" provides recommendations of when and where to measure soiling on site and how often to clean sensors to produce reliable results. On a general note, regarding soiling sensor measurement accuracy, more study is needed to quantify measurement uncertainty of different soiling sensing products.

Chapter 4 summarizes efforts to develop methods of modelling soiling based on different sets of parameters. These models can be categorised as micro-, regional- and macro models, and all have their strengths and weaknesses. The report differentiates between linear-regression, semi-physical, artificial neural network, and geospatial models, all of which have their specific fields of application, advantages, and disadvantages. Most of the models are calibrated against local phenomena. To date, globally applicable models tend to forecast the correct trends for higher soiling losses but correlate poorly with minor losses. Snow shedding models are also discussed and differentiated into the two categories of direct energy loss prediction and snow coverage prediction. Chapter 4 concludes with a Canadian case study that estimates energy losses predicted by two different snow models as predictors for soiling phenomenon in high latitudes. More work is still needed to understand the causes of discrepancy and to validate the models with more sites.

To provide a better overview of the global and economic dimensions of the problem, the report estimates the energy losses for PV plants on a global scale in Chapter 5. It is estimated that in 2018, soiling caused a loss of the annual PV energy production of at least 3-4%, which corresponded to an economic loss in the order of three to five billion euros. It is expected that these kinds of losses will translate to 4-5% in energy production, leading to subsequent financial losses in the range of four to seven billion euros by 2023. This is due to several factors. For example, more PV modules are installed in high-insolation regions, such as China or India, which are also more exposed to soiling. The reduced price of electricity in some regions will make cleaning “less convenient” because revenues for recovered energy will be lower. And, lastly, under identical soiling conditions, more efficient modules are subject to larger energy losses compared to less efficient PV modules. Various economic models have been proposed to identify the best fitting cleaning schedule under different constraints, to minimize revenue losses. Chapter 5 and Chapter 6 examine these kinds of models and the promises they make.

Two categories of possible mitigation strategies are summarized in Chapter 6. The first is preventive methods such as site assessment and planning, new module, and plant concepts, as well as anti-soiling coatings. The second is corrective mitigation methods such as different types of cleaning (by wet/dry brushes, cleaning robots, electrodynamic cleaning, etc.). Chapter 6 also provides an overview of generic “Best Time-to-Clean” models as decision support tools for triggering cleaning operations on site.

PV systems in high latitudes are proliferating due to the advent of bifacial modules, higher system efficiencies, and lower costs. Chapter 7 summarizes aspects of snow shading of PV systems, with an emphasis on performance factors like temperature, irradiance, albedo, and their global distribution. Focus areas for “snow research” are then highlighted, i.e., assessing snow losses, performance modelling, and performance optimization, as well as reliability aspects related to thermo-mechanical load stresses. These load stresses are exacerbated by extreme winter storms and freeze/thaw cycles that can crack solar cells, distort module frames, and damage coatings, resulting in under-performing and failed modules.

Chapter 7 then defines snow loss metrics and finally suggests design optimisations for snowy climates by demonstrating that climate-specific technological and design choices can lead to measurable efficiency gains. Choices fall into categories like module architecture (e.g., frame vs. frameless, cell stringing, etc.), module technology (cell size, cell design, bifacial vs. mono-facial) and finally system design (module orientation, height above ground, tilt angle, clip design and placement). To mitigate production losses, promising considerations for high latitude solar installations include frameless modules, steeper tilt angles, snow-shedding coatings, bifacial modules, and attention to array heights to minimize snow accumulation on the bottom edges of modules, among other factors.