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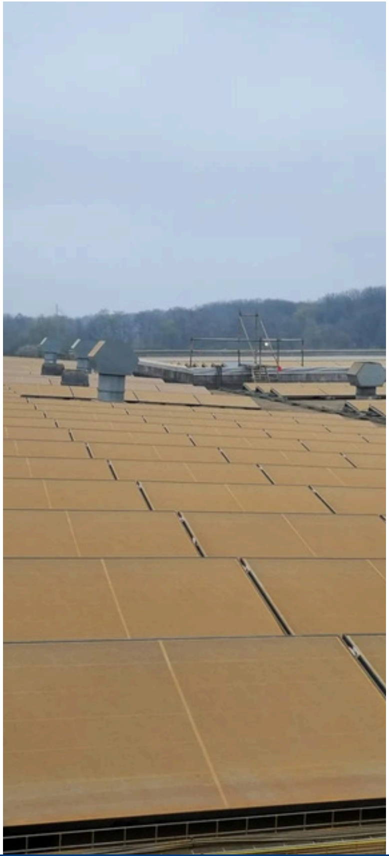
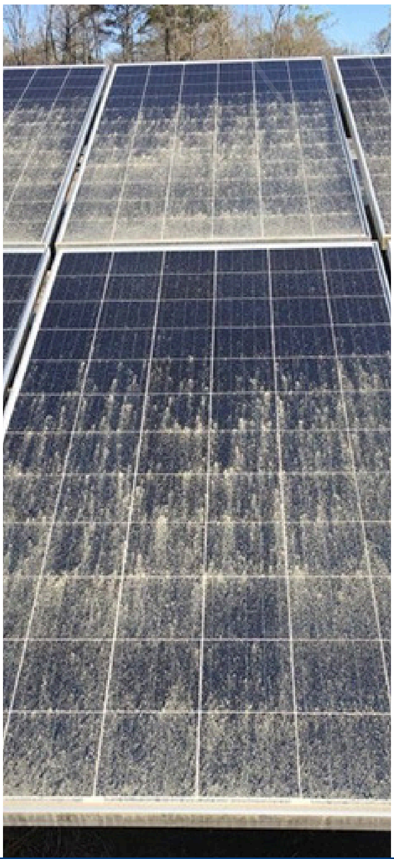


Task 13 Reliability and Performance of Photovoltaic Systems
Task 16 Solar Resource for High Penetration and Large Scale Applications

PVPS

FACT SHEET

Understanding, Measuring, and Mitigating Soiling Losses in PV Power Systems

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Soiling of PV Power Systems

Soiling – caused by dust, pollution, and biological debris – is a **leading cause of PV underperformance**. This fact sheet provides key facts, data, and recommendations for understanding, measuring, forecasting, and mitigating soiling impacts, with insights for developers, operators, and planners.

Types of Soiling *:

Aerosol deposits, such as:

- Natural: mineral dust, sea salt, pollen
- Anthropogenic: industrial emissions, vehicle exhaust, agricultural particles

Macroscopic deposits and growths, such as:

- Bird droppings
- Leaves and organic debris
- Lichen, moss, and other biological growths

Impact of Soiling on PV Systems Performance

Soiling reduces the energy yield, raises O&M costs, accelerates degradation, and increases the uncertainty in PV production forecasts.

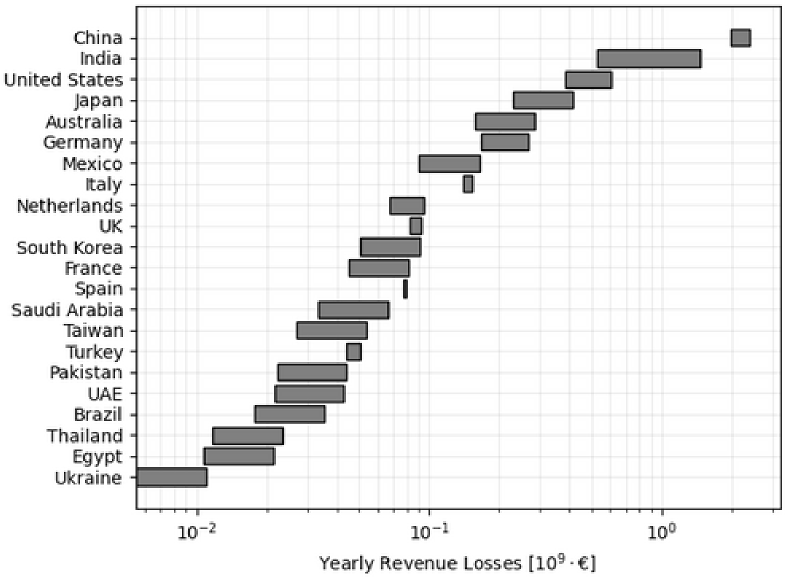


Figure 1: Estimated 2023 yearly revenue loss from soiling per country, based on Ilse et al. (2019).

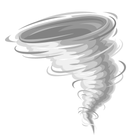
Soiling is considered responsible for an average, growing, 4% to 7% global energy loss and causes a multi-billion-euro loss every year worldwide.

Scenarios

As climate change will impact PV system operation, soiling might become a more severe challenge.

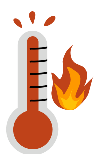
Droughts

- More airborne particles
- Less rainfall



Dust Storms

Sudden and severe soiling accumulation events



Climate Change

Amplifies both phenomena

* Snow is sometimes also included as a type of soiling, but we do not use this nomenclature in the fact sheet.

Soiling Data for Yield Assessment and Project Planning

- **Soiling data should be included in the yield assessment** and allow to select adequate mitigation measures.
- **Soiling losses depend particularly on aerosols** (particulate matter, PM) and precipitation, and can therefore vary significantly with the season and from year to year.
- **Soiling measurements are often not available** for the project's site of interest and, if they are, mostly short-term data sets are available.
- **Soiling modelling based on available meteorological data** is possible.
- **The accuracy of the models is site dependent and influenced strongly by its input data sets**. The model assumptions related to the cleaning effect of rain are also a major source of uncertainty. A calibration of the models with site specific soiling measurements can help to enhance accuracy.
- When using modelled soiling data, the **uncertainty involved must be considered** and further research is required.

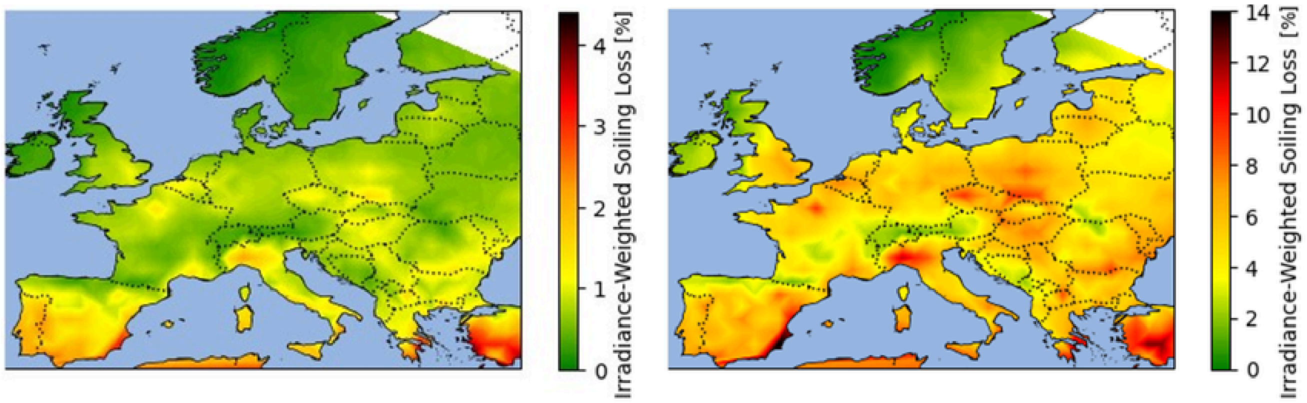


Figure 2: Average soiling loss maps assuming two different cleaning effects of rain. Cleaning is only assumed for more than 5 mm of rain per day in both cases. Left: Full cleaning if this threshold is surpassed. Right: Only 10% of the soiling particles are removed when the threshold is exceeded, indicating a pronounced case of persistent soiling (image from Fernandez Solas et al., 2024).

Soiling Monitoring and Forecasting

Soiling measurements are also of interest during the acceptance and operation phases of a PV plant. They are required for Class A monitoring systems according to IEC 61724-1.*

Soiling forecasts can help to improve PV production forecasts and to optimize the cleaning scheduling (e.g. avoid cleaning just before strong rainfall or dust event).

* Photovoltaic System Performance–Part 1: Monitoring, IEC Standard IEC 61724-1:2021, IEC, Geneva, Switzerland, 2021. [Online]. Available: https://webstore.iec.ch/publication/65561

Soiling Monitoring

Soiling measurements can be obtained with several methods and commercially available sensors, e.g.:

- **Comparison** of power or short-circuit current **of a pair of PV devices** (one cleaned, one soiled)
- **Scattering-based non-imaging methods** (measured back- or forward scattered light increases with soiling loss)
- **Microscope-based methods** (detection of individual particles in images and conversion to soiling loss)
- **Lamp-based methods** (comparison of PV cell signal caused by light from a lamp at current soiling level to signal after cleaning)
- **PV module image-based method** (determination of soiling loss from images of PV modules obtained e.g. with drones)

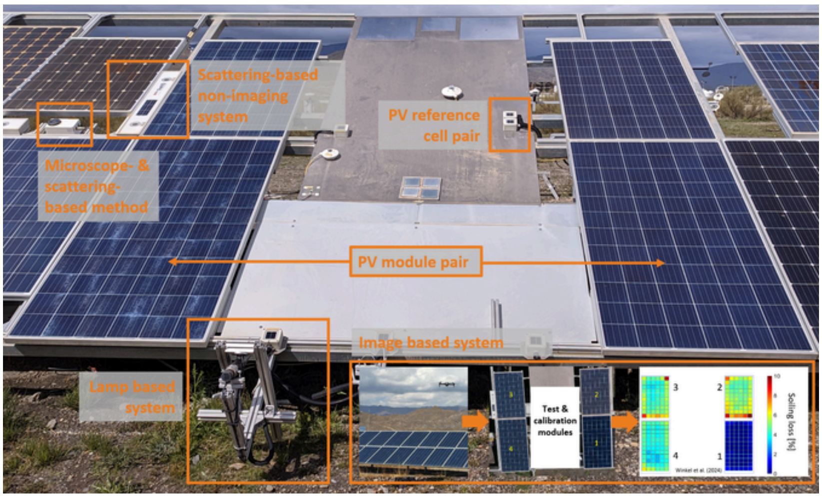


Figure 3: Various PV module and reference cell pairs and soiling sensors for soiling monitoring at CIEMAT's Plataforma Solar de Almería (photo: DLR, Germany).

Measurement, data acquisition, and processing methods should be selected in accordance with best practices to ensure the expected level of accuracy.

Soiling Forecasting

Soiling forecasts can be created based on models and measurements, using, e.g.:

- **Climatologies** or **multi-year re-analysis data**
- **Persistence forecasts** based on the most recent measurements of the soiling rate or loss
- **Statistical methods or machine learning approaches** with soiling measurements and or meteorological data as input parameters
- **Forecasts of meteorological data** as input for soiling models

>>> Using recent soiling measurements as a starting point is essential for high accuracy.

>>> The uncertainty of soiling forecasts is higher than that of historical soiling models.

>>> Further research is needed, but soiling forecasts are already valuable if their uncertainty is treated correctly for applications such as cleaning optimization.

Mitigation

There is no “one-size-fits-all” solution:
Mitigation strategies must be tailored to local conditions and system/site characteristics.

Cleaning is the most common solution, but soiling mitigation starts before operation:
Effective strategies can also be applied during the site assessment, component selection, and system design phases. These include adoption of soiling prevention measures (Figure 4) and designs that facilitate cleaning operations.

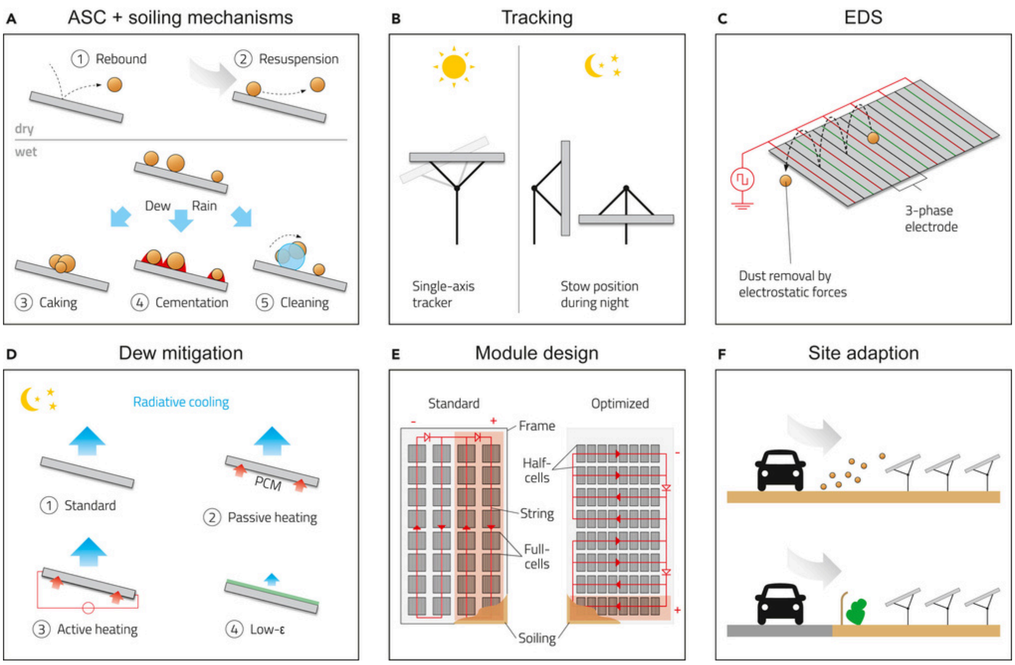


Figure 4: Soiling mitigation approaches apart from cleaning. ASC refers to Anti-Soiling-Coating and EDS to Electrodynamic Shield. Available in Task 13 Report on Soiling Losses impacts (2022).

Cleaning technologies should be selected based on site-specific factors such as water availability, system layout, and budget. Business models also vary: plant operators may either purchase and manage a cleaning system or outsource the service.

Cleaning too often
Wasted OPEX

Cleaning too late
Energy & revenue loss

Cleaning schedules must be optimized to balance the revenues from the recovered energy and the operational costs

Cleaning System Selection

Assess Soiling Conditions
Quantify site-specific soiling through in-situ measurements and historical data.

→

Evaluate Cleaning Technologies
Compare available solutions by efficiency, cost, and investment needs.

→

Analyse Cost-Effectiveness
Balance cleaning costs with expected energy gains.

→

Consider Constraints
Ensure cleaning system fits plant layout and avoids production limits like clipping or curtailment.

Perspectives

As market conditions change, PV system designs and operational strategies evolve, and extreme weather intensifies, soiling losses and mitigation approaches become more complex and important.

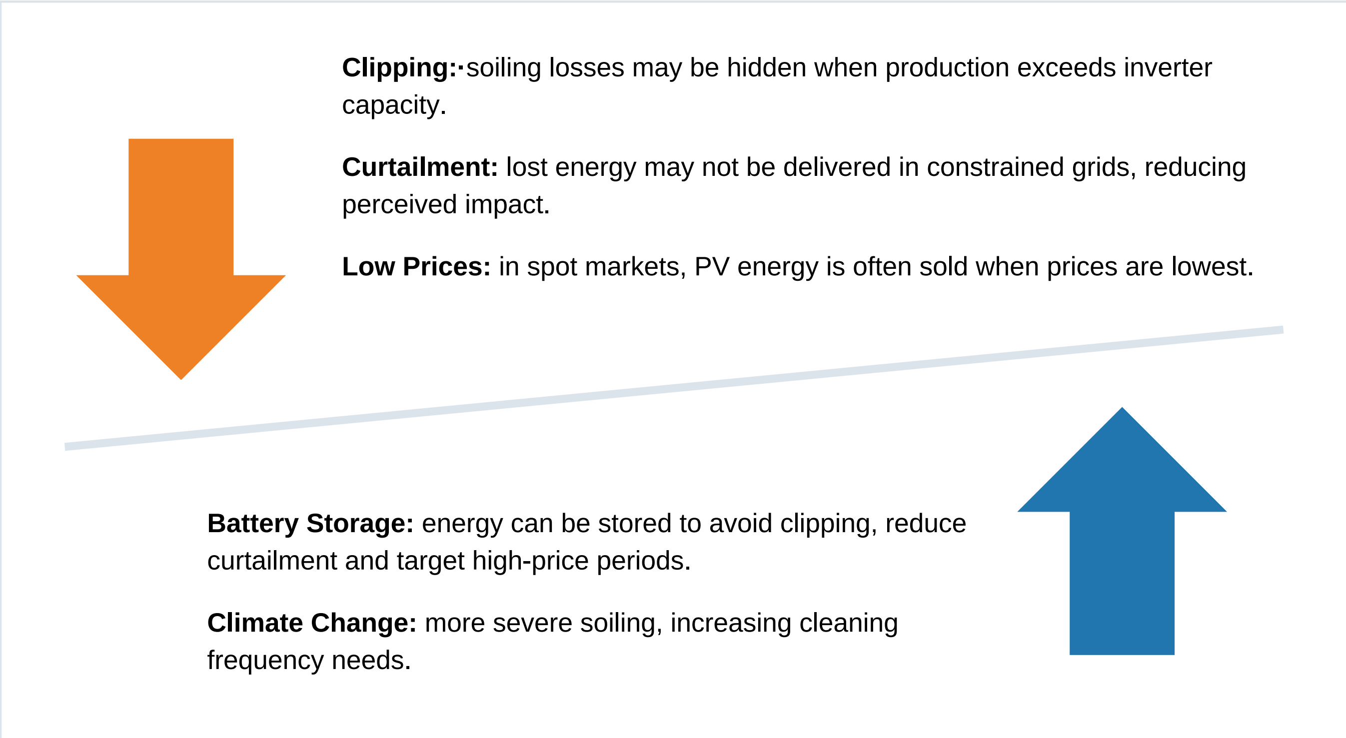


Figure 5: Drivers and barriers to effective soiling management

PVPS Activities on Soiling

Soiling is addressed in PVPS Tasks 13 (Reliability and Performance of Photovoltaic Systems) and 16 (Solar Resource for High Penetration and Large Scale Applications). Activities include

- assessing the current magnitude of soiling losses and predicting future trends worldwide, for specific regions and sites;
- analysing the influence of technological advancements (e.g., bifacial modules) on soiling losses;
- evaluating the effect of shifting environmental conditions on soiling;
- reviewing and enhancing state-of-the-art soiling monitoring and modelling options (incl. uncertainties, intercomparison studies or round-robin tests)
- assessing current and perspective mitigation strategies considering the impact of factors external to PV production, such as inverter size and grid constraints.

If you are interested in more insights and detailed data, explore our reports on the topic "Soiling Losses - Impact on the Performance of Photovoltaic Power Plants 2022", chapter 5 in "Best Practices Handbook for the Collection and Use of Solar Resource Data for Solar Energy Applications" and chapter 5 in "Optimisation of PV Systems for Different Climates"

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Task 13 aims to enhance the quality, performance, and reliability of PV modules and systems by summarizing technical aspects, gathering global data, and disseminating results through reports, workshops, webinars, and web content. Task 13's expertise ensures relevant analysis for stakeholders, contributing to technology advancement, risk mitigation, and standardization in PV research and industry.

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Task 16 provides access to comprehensive international studies and experiences with solar resources and forecasts. It supports different stakeholders from research, instrument manufacturers as well as private data providers and utilities.

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