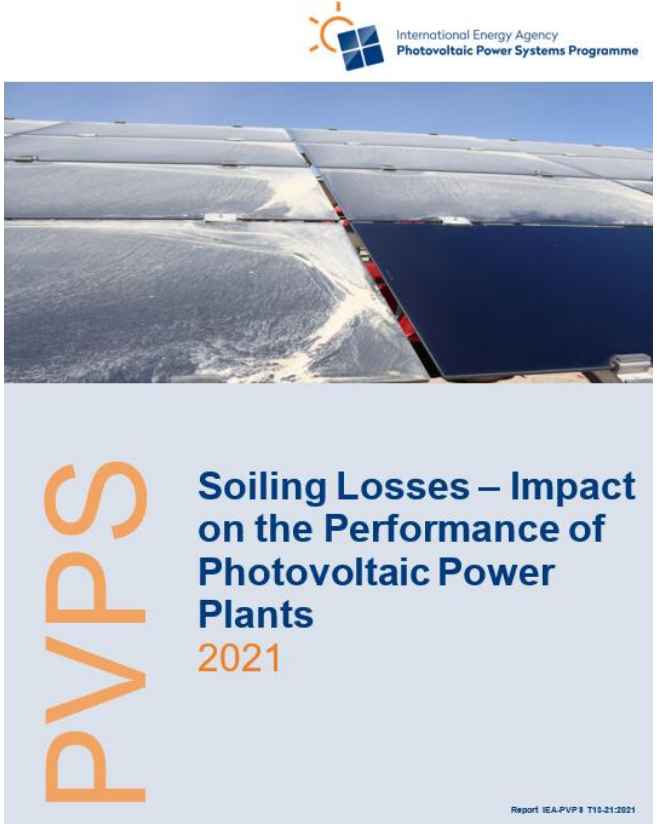
Soiling Issues for O&M of PV Plants

Christian Schill, Fraunhofer ISE

30 September 2021, Task 13 Focus Workshop on Operation & Maintenance

Credits for Task13 members



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Sources of Soiling

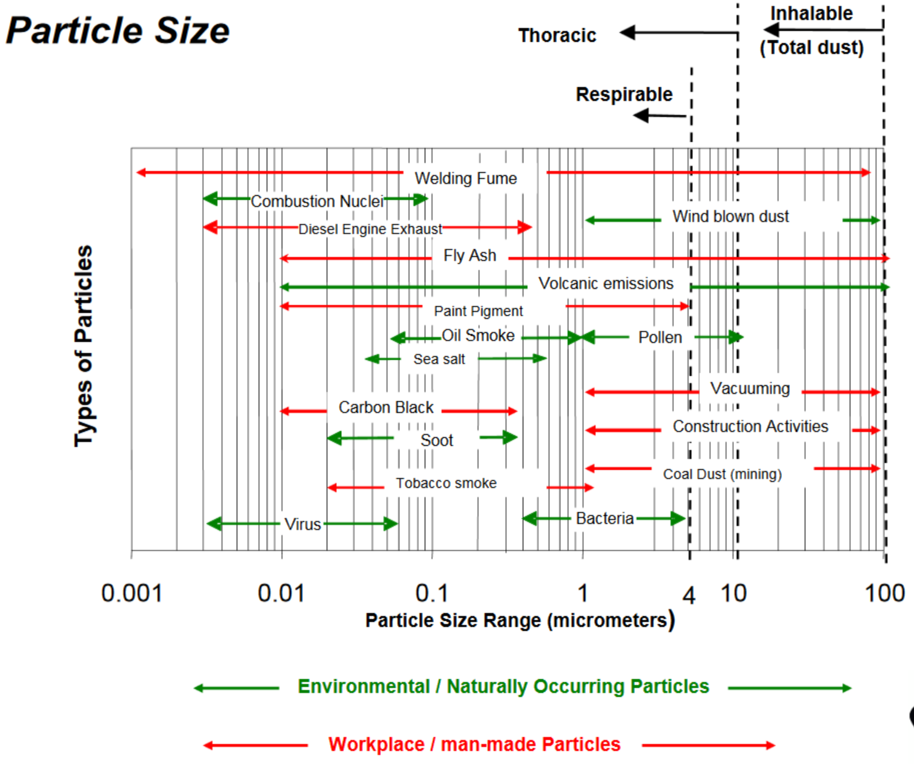
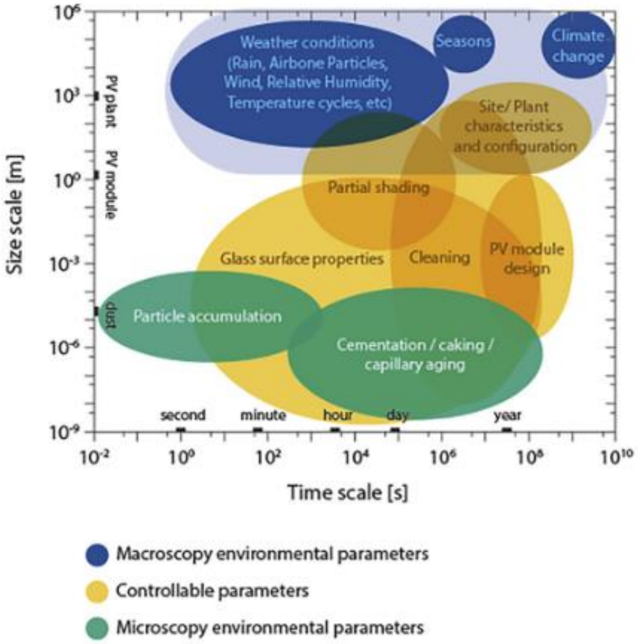
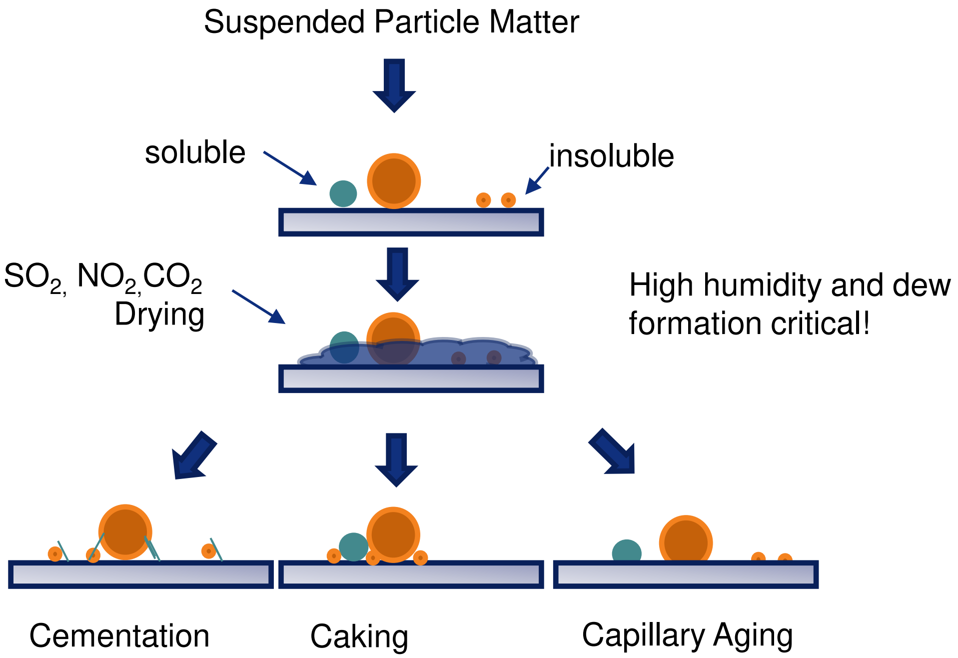


Image Courtesy TSI

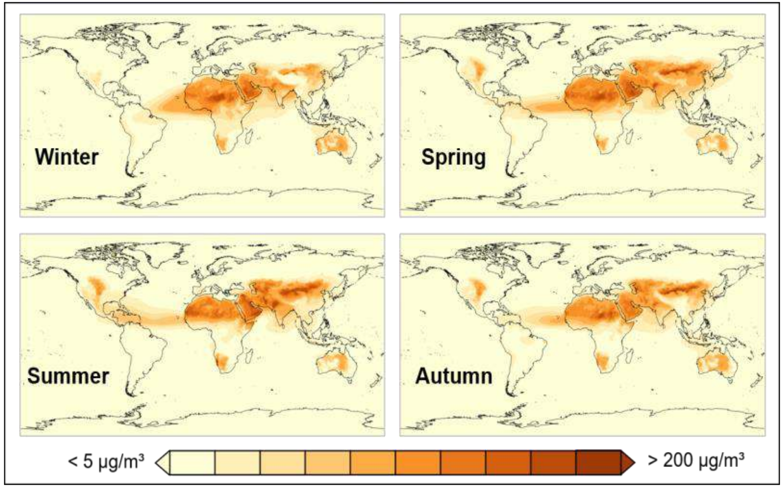
Basic physical Principles of Soiling



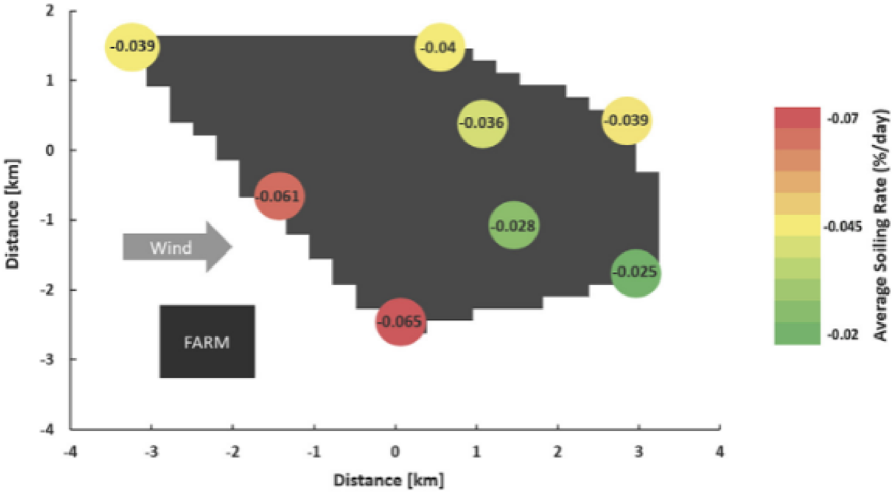


Left image: João Gabriel Bessa, Leonardo Micheli, Florencia Almonacid, Eduardo F. Fernández, Monitoring photovoltaic soiling: assessment, challenges, and perspectives of current and potential strategies, iScience,Volume 24, Issue 3, 2021, 102165, ISSN 2589-0042, (CC BY-NC-ND license); adapted from : K. Ilse, B. W. Figgis, V. Naumann, C. Hagendorf and J. Bagdahn, "Fundamentals of soiling processes on photovoltaic modules," *Renewable & Sustainable Energy Reviews,* vol. 98, p. 239–254, 2018
Right image: adapted from: K. Ilse, B. W. Figgis, V. Naumann, C. Hagendorf and J. Bagdahn, "Fundamentals of soiling processes on photovoltaic modules," *Renewable & Sustainable Energy Reviews,* vol. 98, p. 239–254, 2018

Spatial and temporal variation of soiling ratios



Source: kind permission by Jan Herrmann, University Freiburg



- Seasonal and intra-day variation

- Spatial variation within one plant
- Each plant is different

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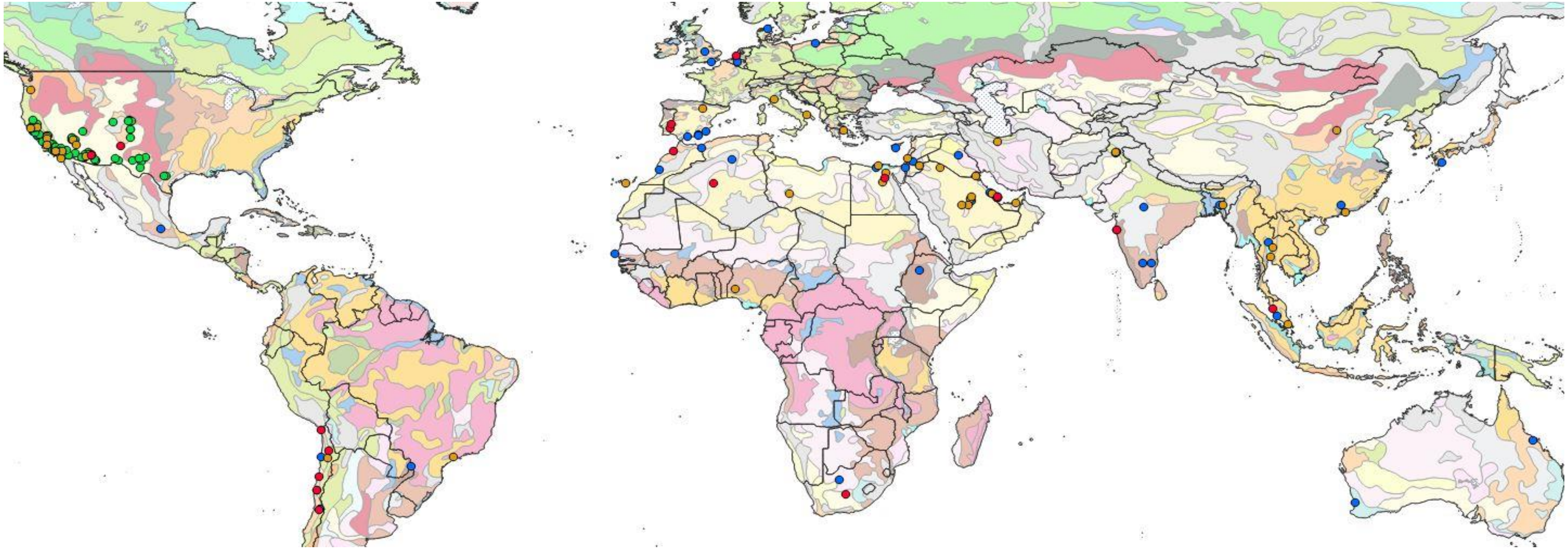
Right image: João Gabriel Bessa, Leonardo Micheli, Florencia Almonacid, Eduardo F. Fernández, Monitoring photovoltaic soiling: assessment, challenges, and perspectives of current and potential strategies, iScience,Volume 24, Issue 3, 2021, 102165, ISSN 2589-0042, (CC BY-NC-ND license); adapted from M. Gostein, J. R. Caron and B. Littmann, “Measuring soiling losses at utility-scale PV power plants,” IEEE, 2014, p. 0885–0890.

Global soiling publications



Harmonized World Soil Database

FAO/IIASA/ISRIC/ISS-CAS/JRC, 2008. Harmonized World Soil Database (version 1.0). FAO, Rome, Italy and IIASA, Laxenburg, Austria

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Inhomogeneous soiling and IR imaging

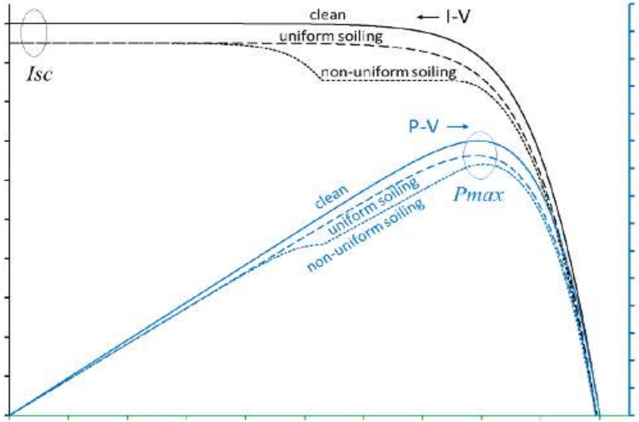
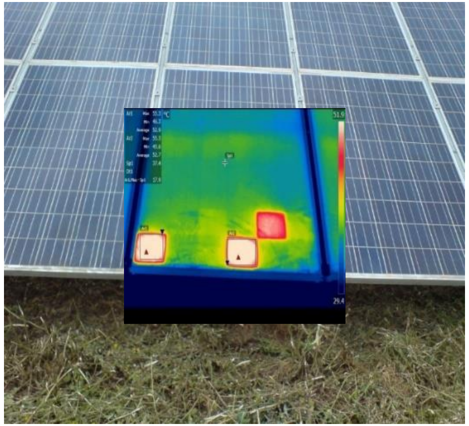


Figure 2-1: Illustration of soiled PV module and corresponding I-V & P-V curves



Most commonly used metric:

SRatio = Pmax_soiled / Pmax_clean

Image Sources: Atonometrics User Manual, with kind permission, D. Parlevliet, Task13; R. Zähringer, Fraunhofer ISE

IEC 61724-1:2021 Photovoltaic system performance

Part 1: Monitoring – Soiling

- Defines terms
- Measurement principles (MPP, Isc-based, clean vs. soiled)
- Sampling intervals per accuracy classes
- Number of sensors per plant size
    - (e.g. 6 sensors for 300 MW ≤ plant size ≤ 500 MW)
- Data analysis (“daily average, filter outliers” etc.)
- Recommends rain gauge, but states that having soiling measurements gives direct result
- states that snow loss may be detected by soiling sensor unless mounted atypically for array

Monitor Soiling: Overview of Sensors

Soiling Sensors					
Manufacturer	Atonometrics	Atonometrics	Campbell Scientific	Kipp and Zonen	NRG Sys- tems
Model name	Soiling Measurement System	Mars Soiling Sensor	CR-PVS1	Dust IQ	Soiling Measurement Kit
Method	Short-circuit current and power	Optical (im- age pro- cessing camera)	Short-circuit current	Optical (LED)	Short-circuit current
Module power range	Up to 450 W	Not applica- ble	Up to 300 W	Not appli- cable	3 panels of 15 W each
Power supply	10 to 30 VDC or 100 to 240 VAC	10 to 30 VDC	16 to 32 VDC	12 to 30 VDC	5 to 15 VDC
Output options	Ethernet	RS-485, Ethernet	RS-232	RS-485	Available upon request
Approximate Cost: Euro / USD	€ 6078 / $ 6900	€ 2600 / $2950	€ 2334 / $ 2649	€ 3807 / $ 4320	Available upon request

Compiled by Christopher Baldus-Jeurssen, Task13

Can Soiling be predicted? – Soiling models

Lead Author	Model Class	Year	Aim	Key Parameters	Main Findings	Reference
Kimber	Linear	2006	Extracting soiling loss from PV performance data.	PV Performance Ratio, Rainfall	The model generates a soiling loss profiles based on the rainfall pattern and on the soiling rate recorded during the longest dry spell. It requires the identification of a minimum cleaning treshold and of the length of dry period.	A. Kimber, L. Mitchell, S. Nogradi, and H. Wenger, 'The Effect of Soiling on Large Grid-Connected Photovoltaic Systems in California and the Southwest Region of the United States', in 2006 IEEE 4th World Conference on Photovoltaic Energy Conference, Waikoloa, HI, 2006, pp. 2391–2395, doi: 10.1109/WCPEC.2006.279690.
Qasem	Semi-Physical	2012	Modelling soiling loss profile using weather data	Ta, WS, WD, dust, tilt, rainfall	A model is developed to estimate the dust accumulation based on weather conditions and to convert this into an electrical loss based on the PV module characteristics and on the dust spectral transmittance	H. Qasem, T. R. Betts, and R. Gottschalg, Soiling Correction Model for Long Term Energy Prediction in Photovoltaic Modules. New York: Ieee, 2012.
Boyle	Linear	2015	Modelling a daily soiling profile measured at five U.S. Locations	TSP	A linear model is developed where the transmittance loss are a function of TSP and of the exposure time.	L. Boyle, 'don't soil your chances with solar energy:experiments of natural dust accumulation onsolar modules and the effect on lighttransmission'. .
Guo	Linear & Semi-Physical	2016	Modelling a daily soiling profile of a soiling measurement system in Qatar.	WS, PM10, RH	A multi-linear and a semi-physical models are developed and compared. Both models were found to return estimation with < 16% uncertainty when used to estimate the daily soiling loss profile.	Guo B, Javed W, Khan S, Figgis B, Mirza T. Models for Prediction of Soiling-Caused Photovoltaic Power Output Degradation Based on Environmental Variables in Doha, Qatar. ASME 2016 10th Int. Conf. Energy Sustain., 2016, p. 1–8. https://doi.org/10.1115/ES2016-59390.
Pulipaka	ANN & Linear	2016	Soiling loss is estimated from particle size composition	Particle size	Multi-linear regression and ANN are used to estimate the soiling losses based on particle size composition of the soil. ANN are found to perform better.	S. Pulipaka, F. Mani, and R. Kumar, 'Modeling of soiled PV module with neural networks and regression using particle size composition', Sol. Energy, vol. 123, pp. 116–126, Jan. 2016, doi: 10.1016/j.solener.2015.11.012.
Javed	ANN & Linear	2017	Modelling a daily soiling profile of a soiling measurement system in Qatar.	Same-day PM10, WS, WD, Ta, RH, Previous-day PM10, WS, RH, Wind Gust frequency and exposure time	A 10-input ANN model was able to significantly model the soiling loss trends, returning better results than a multilinear approach based on the same inputs. PM10, WS and RH were found to be parameters better correlated with soiling.	W. Javed, B. Guo, and B. Figgis, 'Modeling of photovoltaic soiling loss as a function of environmental variables', Solar Energy, vol. 157, pp. 397–407, Nov. 2017, doi: 10.1016/j.solener.2017.08.046.
Bergin	Semi-Physical	2017	Modelling the profile of a soiling measurement in India	PM components concentrations	The soiling profiles is modelled based on the concentration of each PM10 and PM2.5 components, taking into account each specific component's absorption and scattering efficiency.	Bergin MH, Greenwald R, Xu J, Berta Y, Chameides WL. Influence of aerosol dry deposition on photosynthetically active radiation available to plants: A case study in the Yangtze delta region of China. Geophys Res Lett 2001;28:3605–8. https://doi.org/10.1029/2001GL013461 .
Micheli	Linear	2017	Ranking the average soiling losses of 20 soiling station in the USA.	PM10, PM2.5, Rainfall	PM10, PM2.5 and rainfall are found to be the best soiling predictors, out of 100+ potential variables, when the average losses of different sites are compared.	Micheli L, Muller M. An investigation of the key parameters for predicting PV soiling losses. Prog Photovoltaics Res Appl 2017;25:291–307. https://doi.org/10.1002/pip.2860.
Figgis	Linear	2018	Modelling soiling deposition and resuspension	WS, PM10	Multilinear relations are proposed to estimate soiling accumulation, deposition, resuspension and rebound rates	Figgis B, Guo B, Javed W, Ahzi S, Rémond Y. Dominant environmental parameters for dust deposition and resuspension in desert climates. Aerosol Sci Technol 2018;52:788–98. https://doi.org/10.1080/02786826.2018.1462473.
Cordero	Linear	2018	Modelling soiling rates in Chile	AOD	A linear correaltion is found in between AOD and soiling rates. Ground-measurements outperformed satellite-derived data.	Cordero RR, Damiani A, Laroze D, MacDonell S, Jorquera J, Sepúlveda E, et al. Effects of soiling on photovoltaic (PV) modules in the Atacama Desert. Sci Rep 2018;8:1–14. https://doi.org/10.1038/s41598-018-32291-8.
You	Semi-Physical	2018	Modelling the soiling loss profile for seven cities worldwide	PM50-20, Vd	The soiling accumulation is calculated based on the deposition velocity, calculate from the local conditions.	You S, Lim YJ, Dai Y, Wang CH. On the temporal modelling of solar photovoltaic soiling: Energy and economic impacts in seven cities. Appl Energy 2018;228:1136–46. https://doi.org/10.1016/j.apenergy.2018.07.020.
Zhou	Semi-Physical	2019	Modelling soiling loss based on particle deposition estimation	PM, Rainfall	The soiling losses are estimated using a Community Multiscale Air Quality (CMAQ) model. The estimated PV panel transmittance are lower compared to on-site measurements.	L. Zhou et al., 'The impact of air pollutant deposition on solar energy system efficiency: An approach to estimate PV soiling effects with the Community Multiscale Air Quality (CMAQ) model', Sci. Total Environ., vol. 651, pp. 456–465, Feb. 2019, doi: 10.1016/j.scitotenv.2018.09.194.
Micheli	Linear	2019	Rank the severity of the average soiling losses of 41 soiling stations in the USA using environmental parameters.	PM10, PM2.5, Rainfall	The work confirms that PM10 and PM2.5 are the best soiling predictors, followed by parameters describing the average and maximum length of the dry periods. Although, Despite that, it found that the results could be significantly affected by the environmental parameters sourcing and processing methodology.	Micheli, M. G. Deceglie, and M. Muller, 'Predicting photovoltaic soiling losses using environmental parameters: An update', Progress in Photovoltaics: Research and Applications, vol. 27, no. 3, pp. 210–219, Mar. 2019, doi: 10.1002/pip.3079.
Shapsough	Linear & ANN	2019	Modelling the soiling loss profile of a PV installation in the UAE	Irradiance, Rainfall, Exposure time	A multi-linear and an ANN models were used to estimate the performance of a soiled PV module, with no significant difference between their results.	S. Shapsough, R. Dhaouadi, and I. Zualkernan, 'Using Linear Regression and Back Propagation Neural Networks to Predict Performance of Soiled PV Modules', Procedia Computer Science, vol. 155, pp. 463–470, 2019, doi: 10.1016/j.procs.2019.08.065.
Micheli	Geo-spatial	2019	Estimating average soiling loss from nearby data	Nearby soiling data, site's characteristics	The average soiling loss of a site can be estimate using soiling data from nearby sites, by using spatial interpolation.	Micheli L, Deceglie MG, Muller M. Mapping Photovoltaic Soiling Using Spatial Interpolation Techniques. IEEE J Photovoltaics 2019;9:272–7. https://doi.org/10.1109/JPHOTOV.2018.2872548.
Laarabi	ANN	2019	Modelling the soiling rate of a site in Morocco	Irradiance, Ws, Wd, Ta, RH, Rainfall	A 6-35-1 ANN model is implemented and validated. A sensitivity analysis shows that relative humidity, first, and, second, wind	Laarabi B, May Tzuc O, Dahlioui D, Bassam A, Flota-Bañuelos M, Barhdadi A. Artificial neural network modeling and sensitivity analysis for soiling effects on photovoltaic panels in Morocco. Superlattices Microstruct

Different types of models (n>15):

1. **Linear Regression Models**
2. **Semi-Physical models**
3. **ANN**
4. **Geospatial models**

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Mitigation: preventive and corrective measures

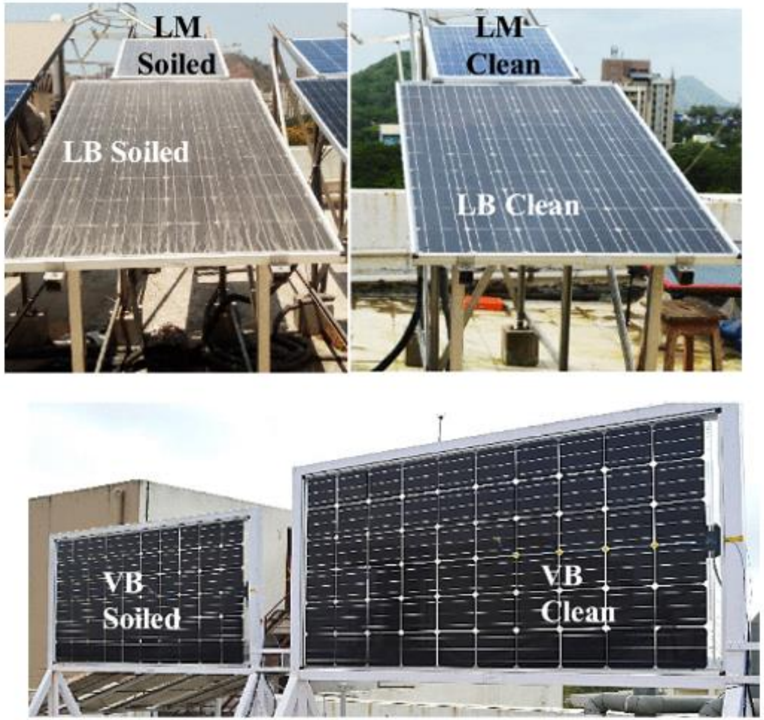
Preventive measures fall rather into the responsibility of EPCs:

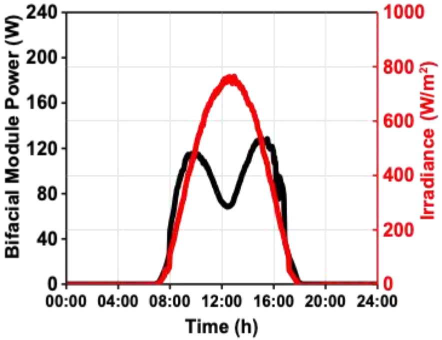
- site- and module selection,
- anti-soiling coating applications,
- site adaption

whereas corrective measures fall into the competence of O&M:

- choosing the right cleaning technology and schedule

Mitigation System Design: Vertical Bifacial E/W

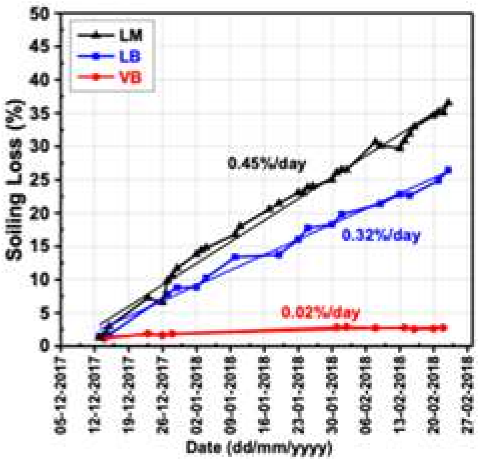


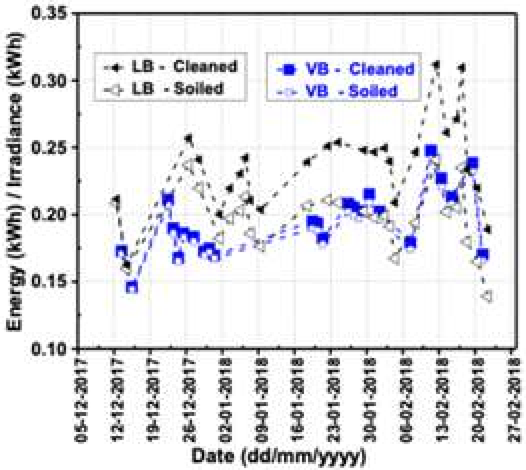


VB: Vertical Bifacial
LB: Latitude tilt Bifacial
LM: Latitude tilt Monofacial

A Study by
Anil Kottantharayil and colleagues, India

Mitigation System Design: Vertical Bifacial E/W





Latitude tilt Bifacial cleaned: always higher
Latitude tilt Bifacial soiled: initially higher, after ~7 weeks lower than Vertical Bifacial (VB)

Mitigation: Cleaning Methods

Manually, semi-automatic, fully-automatic

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Image Source: Khadka, Nasib & Bista, Aayush & Adhikari, Binamra & Shrestha, Ashish & Bista, Diwakar & Adhikary, Brijesh. (2020). Current Practices of Solar Photovoltaic Panel Cleaning System and Future Prospects of Machine Learning Implementation. IEEE Access. PP. 1-1. 10.1109/ACCESS.2020.3011553.

Mitigation: Cleaning Methods

- Manual devices, dust brooms, water brushes, nozzles (see module datasheet for max pressure!)
- Truck-mounted devices
- Semi-automatic systems use portable robots which can be manually moved from row to row. (battery-powered or wired, rail-mounted, frame-mounted or freely movable)
- Fully automatic systems: regularly clean one row of modules. These systems are often solar-powered, and they can be rail-mounted, frame-mounted or freely movable.

Mitigation: Cleaning per Weather condition

Weather/Area	Cleaning technique applied
Desert	Vibration of surface and aerodynamic streamlining
Dry	Electrostatic biasing, autonomous robotic cleaning, sprinkler
Rainy, humid	Special techniques are not required, but can be combined with anti-reflective coating
Cold, moist	Autonomous/robotic cleaning, sprinkler, and anti-reflective coating
Snow	Stowing/inverting, anti-reflective coating
Hot, arid, sunny	Electrostatic biasing, autonomous/robotic cleaning, sprinkler
Cloudy, shaded	Autonomous/robotic cleaning, sprinkler, aerodynamic streamlining

Adapted from S. Mondal, A. K. Mondal, A. Sharma, V. Devalla, S. Rana, S. Kumar and J. K. Pandey, "An overview of cleaning and prevention processes for enhancing efficiency of solar photovoltaic panels," *CURRENT SCIENCE,* vol. 115, no. 6, p. 13, 2018

Generic « Best Time to Clean »

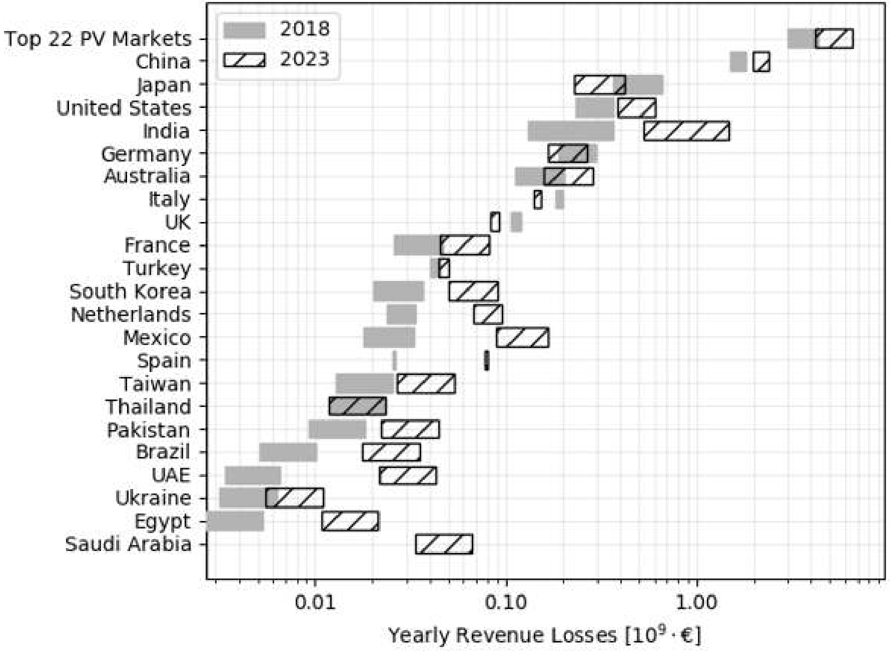
→ balancing the total cost of cleaning against the cost of energy lost to soiling.

Jones (2016)

- Cost of cleaning operation at the start of the interval (C_c)
- The value of the energy lost due to soiling over the interval between cleans (V_L)
- The value of energy sold over the interval (V_S)
- The power loss due to soiling ($L_s(t)$)
- The power generated by the plant without soiling ($P(t)$)
- Electricity Tariffs ($R(t)$)

R. K. Jones, A. Baras, A. A. Saeeri, A. Al Qahtani, A. O. Al Amoudi, Y. Al Shaya, M. Alodan and S. A. Al-Hsaien, “Optimized Cleaning Cost and Schedule Based on Observed Soiling Conditions for Photovoltaic Plants in Central Saudi Arabia,” *IEEE Journal of Photovoltaics,* vol. 6, no. 3, p. 730–738, 2016.

Global economic Impact of Soiling



Estimate:
2018:
- loss ~ 3% to 4% of annual PV energy
- Economic loss ~ 3 - 5 billion €

2023:
- increase up to 4% to 5% and 4 to 7 billion €

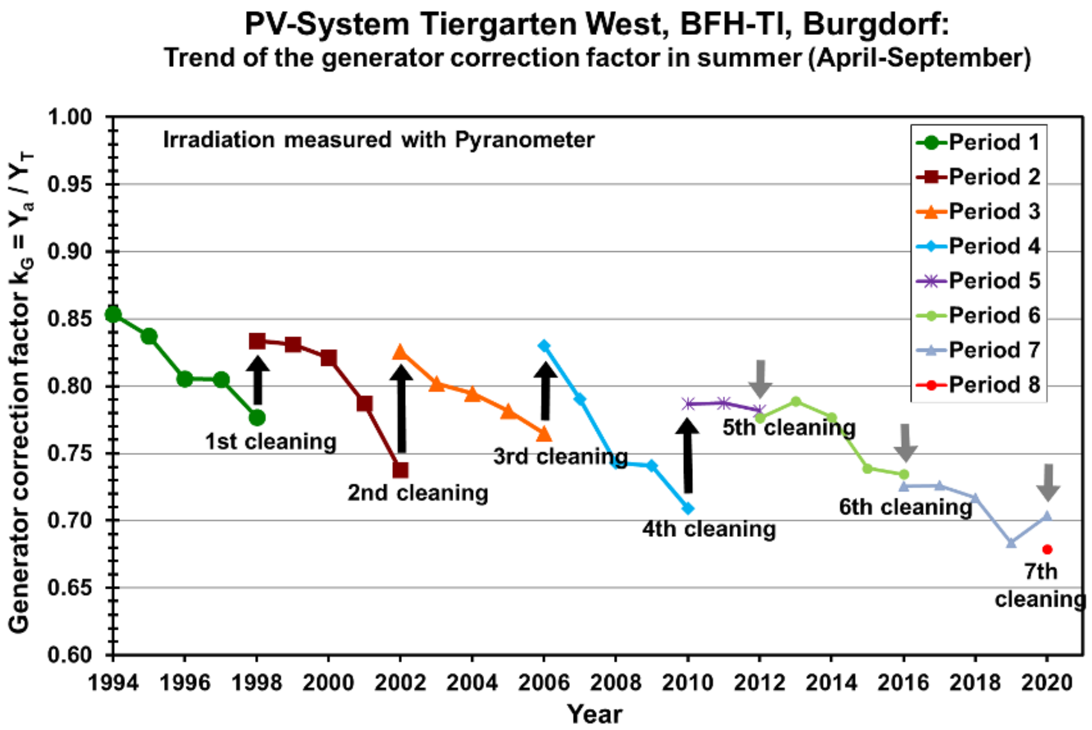
Factors:
- Installation in high-insolation regions → Soiling
- reduced price of electricity: less revenue
- Same soiling, more efficient modules: larger energy losses

Based on optimal cleaning schedule scenario
In a real world: even higher losses

Adapted from K. Ilse, L. Micheli, B. W. Figgis, K. Lange, D. Daßler, H. Hanifi, F. Wolfertstetter, V. Naumann, C. Hagendorf, R. Gottschalg and J. Bagdahn, "Techno-Economic Assessment of Soiling Losses and Mitigation Strategies for Solar Power Generation," *Joule,* vol. 3, no. 10, p. 2303–2321, 2019.

Use case Soiling in temperate climates

- Thomas Schott, Rosmarie Neukomm, CH
- Main pollution is a railway line (Bern-Zürich) at a distance of less than 100 m of the PV system.
- natural rainfall > 1'000 l/m²a
- Nat. cleaning considered to be sufficient BEFORE installation of the plant.



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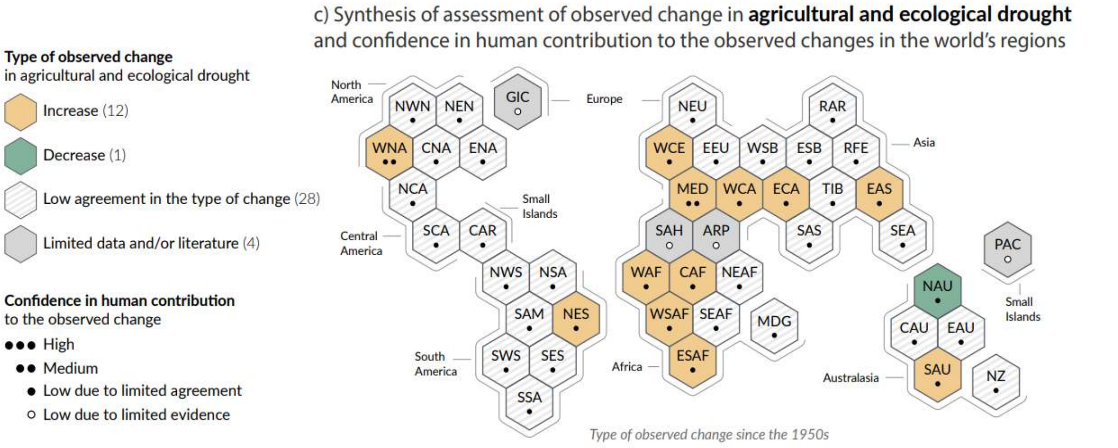
An outlook: IPCC projections



Each hexagon corresponds to one of the IPCC AR6 WGI reference regions

NWN *North-Western North America*

IPCC AR6 WGI reference regions: **North America: NWN** *(North-Western North America,* **NEN** *(North-Eastern North America),* **WNA** *(Western North America),* **CNA** *(Central North America),* **ENA** *(Eastern North America),* **Central America: NCA** *(Northern Central America),* **SCA** *(Southern Central America),* **CAR** *(Caribbean),* **South America: NWS** *(North-Western South America),* **NSA** *(Northern South America),* **NES** *(North-Eastern South America),* **SAM** *(South American Monsoon),* **SWS** *(South-Western South America),* **SES** *(South-Eastern South America),* **SSA** *(Southern South America),* **Europe: GIC** *(Greenland/Iceland),* **NEU** *(Northern Europe),* **WCE** *(Western and Central Europe),* **EEU** *(Eastern Europe),* **MED** *(Mediterranean),* **Africa: MED** *(Mediterranean),* **SAH** *(Sahara),* **WAF** *(Western Africa),* **CAF** *(Central Africa),* **NEAF** *(North Eastern Africa),* **SEAF** *(South Eastern Africa),* **WSAF** *(West Southern Africa),* **ESAF** *(East Southern Africa),* **MDG** *(Madagascar),* **Asia: RAR** *(Russian Arctic),* **WSB** *(West Siberia),* **ESB** *(East Siberia),* **RFE** *(Russian Far East),* **WCA** *(West Central Asia),* **ECA** *(East Central Asia),* **TIB** *(Tibetan Plateau),* **EAS** *(East Asia),* **ARP** *(Arabian Peninsula),* **SAS** *(South Asia),* **SEA** *(South East Asia),* **Australasia: NAU** *(Northern Australia),* **CAU** *(Central Australia),* **EAU** *(Eastern Australia),* **SAU** *(Southern Australia),* **NZ** *(New Zealand),* **Small Islands: CAR** *(Caribbean),* **PAC** *(Pacific Small Islands)*

Observed changes in global droughts and human contribution, IPCC report 2021: the problem will become worse in sunbelt regions

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Source: Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Water-field, O. Yelekçi, R. Yu and B. Zhou, Ed., Climate Change 2021 - The Physical Science Basis, Vols. IPCC, 2021: Summary for Policymakers., Cambridge University Press, p. 42.

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Matching Soil type against soiling publications

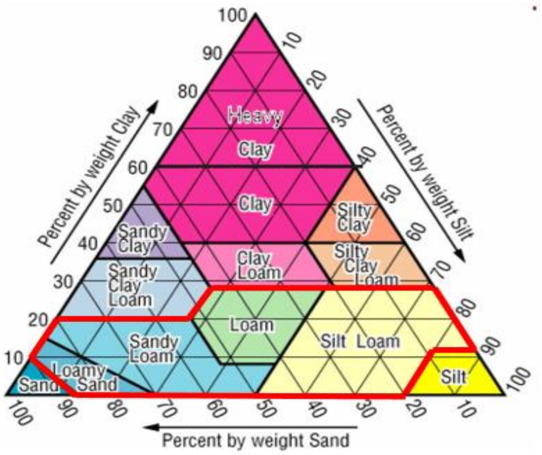
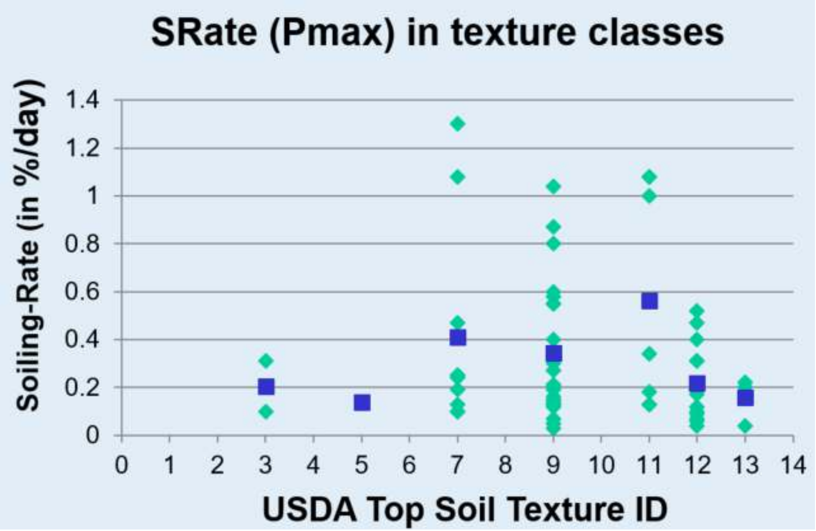


Image source U.S Department of Agriculture, Public domain



1	clay(heavy)
2	silty clay
3	clay (light)
4	silty clay loam
5	clay loam
6	silt
7	silt loam
8	sandy clay
9	loam
10	sandy clay loam
11	sandy loam
12	loamy sand
13	sand

Image Source: ISE

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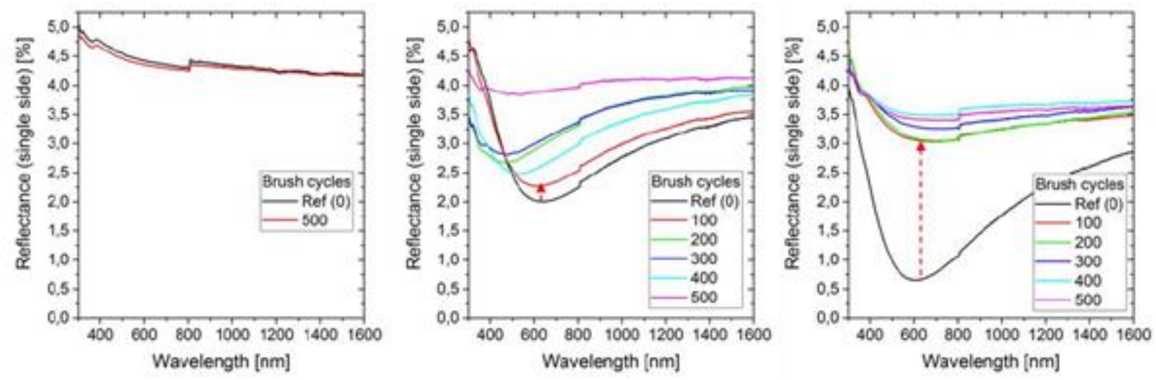
Data with kind permission by
Jim J John, Characterization of Soiling Loss on Photovoltaic Modules, and Development of a Novel Cleaning System, 2016, http://www.ee.iitb.ac.in/~anilkg/Jim-thesis.pdf.

PV Module cleaning tests



Spectral reflectance of 3 glass types:

a) float glass without ARC,
b) float glass with ARC
c) structured glass with ARC - after up to 500 linear abrasion test cycles with a brush according to ASTM D2486

Laboratory car wash for testing the scratch resistance of coatings in accordance to ISO 20566

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Amtec Kistler GmbH, *Laboratory car wash for testing the scratch resistance of coatings, www.amteckistler.de, download 2020.*, 2020.