PV soiling in dry climates: causes, impacts and solutions

O&M | In arid regions soiling can greatly impact the energy yield of PV systems and drive up their O&M costs. Benjamin Figgis, Amir Abdallah, Maulid Kivambe, Brahim Aissa, Kamran Ali, Cédric Broussillou and Veronica Bermudez of the Qatar Environment & Energy Research Institute, and Klemens Ilse of the Fraunhofer Center for Silicon Photovoltaics, review the main challenges associated with soiling of PV plants globally, and the most promising techniques for dust prevention and cleaning in dry climates, drawing on research results from six years of PV performance and soiling studies at QEERI's Outdoor Test Facility in Doha

In 2011, the government of Qatar recommended creating a solar-energy test station to assess the effect of local climate conditions on PV systems. This aimed to study whether the high temperature, humidity and dust could cause PV reliability risks, which had to be quantified and mitigated prior to large-scale development of PV plants. In 2012, the Outdoor Test Facility (OTF) was opened at Qatar Science & Technology Park [1].

Seven years later the OTF, now operated by Qatar Environment & Energy Research Institute (QEERI), has tested over 60 PV modules and found that Tier 1 modules themselves generally cope well with the harsh conditions (they show little electrical or mechanical degradation), but dust accumulation is a challenge. At the OTF, soiling causes the power of PV modules at 22° tilt to decrease by 10-20% per month. The soiling can, in extreme cases, form a homogenous whitish layer that appears visually opaque (Figure 1 left). This dust can however be quite effectively removed by rain, when the rainfall is heavy enough to dissolve the water-soluble components and wash away the particles (Figure 1 right). Actually, after 234 days without rain — the longest dry period experienced on the OTF — the power of never-cleaned modules decreased by 70% so the dust layer was, in effect, still 30% transparent.

Qatar's case is not the most extreme; soiling rates can reach 1 to 2% per day in some parts of India and China (Figure 2). ("Soiling rate" is typically defined as the decrease in PV performance ratio per day, due to accumulation of pollutants such as dust, pollen, or other organic matter.)

Figure 1. Examples of soiled modules (left) and modules naturally cleaned by heavy rain (right). These are the same test beds viewed from opposite side at the QEERI Outdoor Test Facility

A recent comprehensive review of the subject by Ilse et al [2] showed that in dry climates soiling rates are typically in the order of 0.1-1%/day for PV, with the most severe cases reported for concentrated solar power plants (CSP) due to sensitivity of the collector to the optical pathway. Many other locations, including parts of the US, southern Europe and Australia have lower but still problematic rates, in

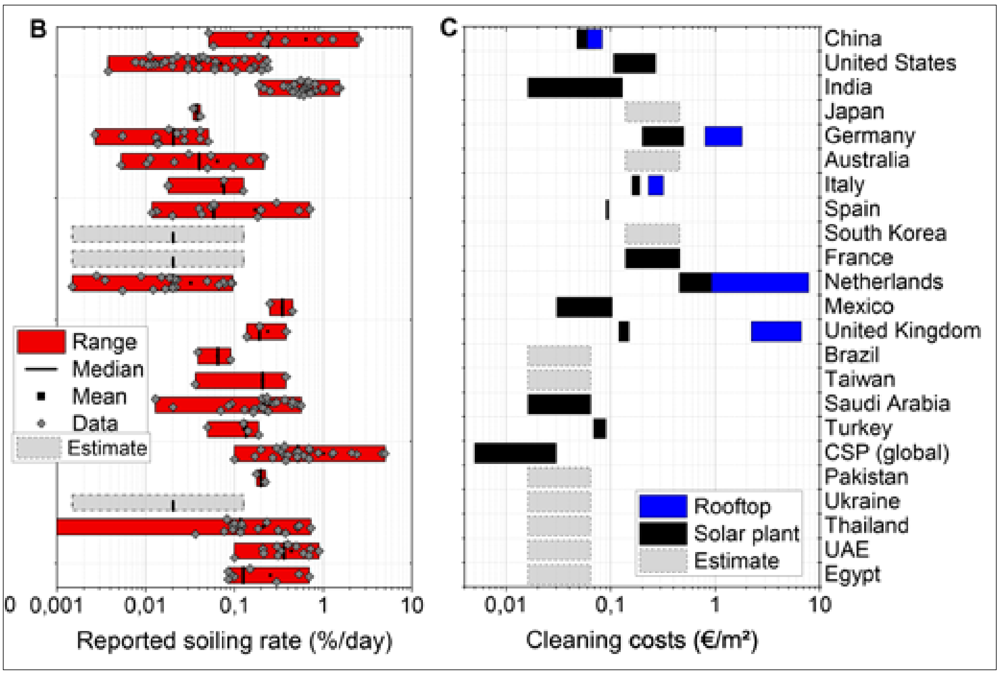
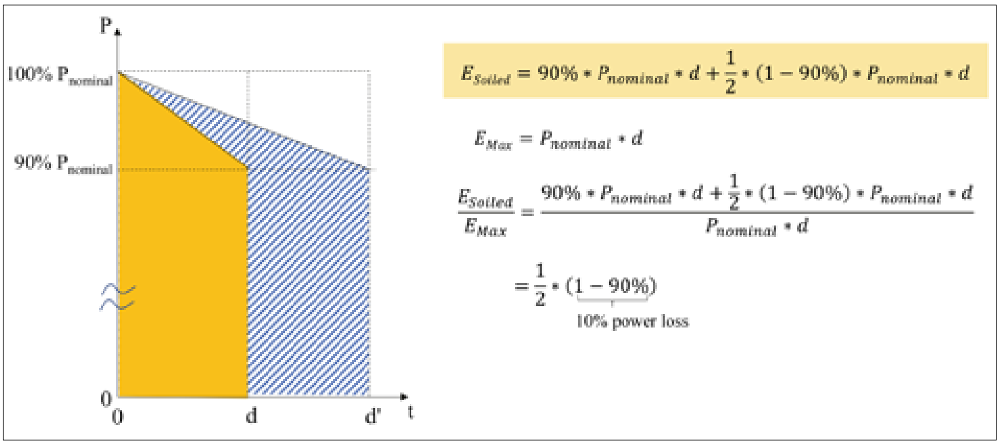


Figure 2. Examples of soiling rates and cleaning costs around the world [2]

the region of several percent per month. In other words, soiling is a concern for PV plants in much of the world. It is more severe in deserts due to high dust concentration and absence or rain. This results from almost permanent high atmospheric pressure that either prevents clouds forming or depletes them of water. Since few clouds form, they do not reflect sun light back to space, which increases both solar irradiance reaching the ground and moisture evaporation. At the same time, it severely limits the amount of rainfall. Thus, the ground is easily eroded, which generates inorganic dust particles prone to be suspended in air and re-deposited onto PV modules.



$$E_{Soiled} = 90\% * P_{nominal} * d + \frac{1}{2} * (1 - 90\%) * P_{nominal} * d$$

$$E_{Max} = P_{nominal} * d$$

$$\frac{E_{Soiled}}{E_{Max}} = \frac{90\% * P_{nominal} * d + \frac{1}{2} * (1 - 90\%) * P_{nominal} * d}{P_{nominal} * d}$$

$$= \frac{1}{2} * \underbrace{(1 - 90\%)}_{\text{10\% power loss}}$$

Figure 3. Typical power loss due to soiling as a function of time (yellow=high soiling; blue=moderate soiling) and calculation of energy loss which is half of power loss

Soiling increases the levelised cost of energy (LCOE) in two ways. First, the dust layer reduces the amount of light entering the module, thus lowering the electricity generation. Second, cleaning expenses increase the operation and maintenance (O&M) costs needed to achieve energy yield targets. It is estimated that soiling reduced solar energy production by around 3-4% globally in 2018, causing revenue losses of €3-5 billion(US$3.3-5.5 billion) [2]. Cleaning costs for ground-mounted PV plants vary greatly worldwide (Figure 2) but are typically in the range €0.01-0.1 per m^2 for the most-affected countries. These figures reflect the cost of manual cleaning, which is still the norm even in utility-scale plants (emerging technological solutions are discussed below). This cost range is for ground-mounted projects; rooftop cleaning costs considerably more. The economics of PV plants can, in principle, be improved by applying soiling knowledge: more accurate prediction of soiling losses (and thus energy production) at the planned site, and more efficient scheduling of cleaning.

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The decision on how often to clean is driven by project-specific parameters — e.g. soiling rate, electricity price, labour cost — so there is no "one size fits all" optimum frequency. According to Dr. Raed Bkayrat, formerly head of First Solar in the Middle East and now with cleaning-robot manufacturer NOMADD, utility PV plants in severe soiling locations such as the UAE are cleaned around 40-45 times per year in order to keep soiling energy loss below 3%, while in milder locations such as Jordan the frequency is around 25-30 times per year.

There are many methods for characterising PV soiling [3] hence terminology is important: if cleaning is done when the "power loss" of the PV plant (an instantaneous measure) reaches say 10% then the average "energy loss" since cleaned (a time-cumulative measure) will be half that (5%), assuming a constant daily soiling rate and the same irradiation each day. This simplified estimate does not depend on the constant soiling rate, as a lower rate will mean that the 90% power limit will take more days to be reached (d') but the overall energy loss will not change (in Figure 3 d or d' is the number of days needed to reach the power limit 90% *$P_{nominal}$).

It is worth asking the question — what if one never cleans at all? Even in deserts, it rains occasionally. In Qatar, we found that a "never cleaned" test array at the OTF produced 23.5% less energy over five years than a clean reference array. From these sample statistics (23.5% average energy loss without cleaning, and 70% power loss in the worst case – Figure 4), the idea of installing extra modules and relying only on rain cleaning does not appear realistic for typical desert PV projects. Indeed, even with low-cost modules available, the PV plant should ideally have a reliable (if not constant) total power in order to limit the costs of grid balancing. This situation could evolve in the future when new grid management systems or storage solutions become more cost-competitive but seems unlikely for deserts, especially during summer as it is when the power load curve matches best the PV production curve due to air conditioning demand. Thus, since cleaning in arid regions is unavoidable,

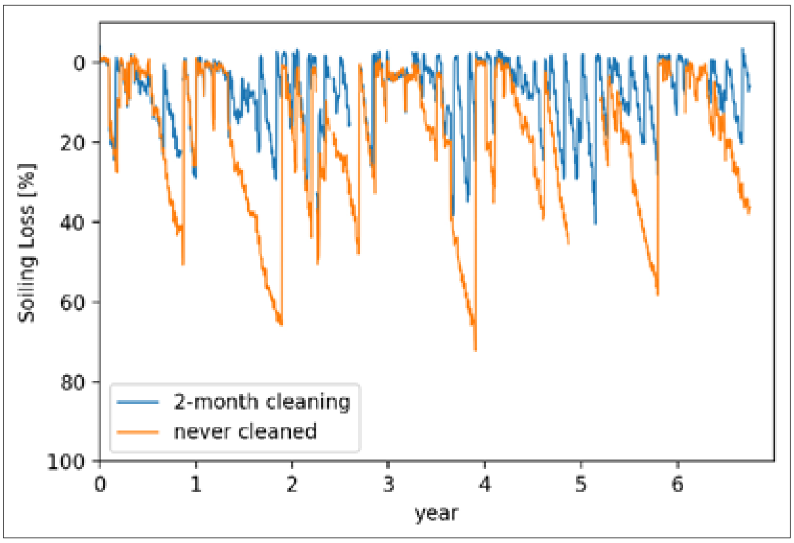

Figure 4. Soiling losses measured from 2013 (year 0) for arrays cleaned every two months (blue) and never (orange), in Doha

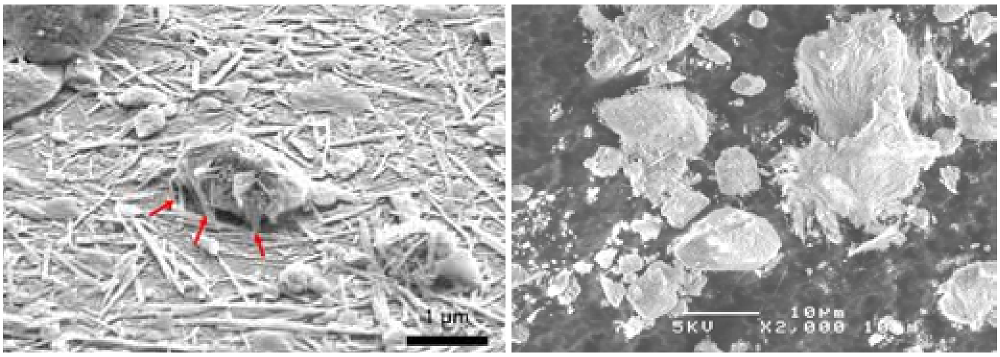

Figure 5. Scanning electron micrographs, at different scales, of dust particles cemented by palygorskite needles to glass substrates via natural outdoor exposure in Qatar (left [5], right [7])

the industry's goal is to bring down its cost and to optimise its frequency so that O&M cost is minimised and electricity production is maintained at high level.

Physics of soiling in deserts

What causes soiling? The answer appears simple: dust settling on PV module surfaces. But dust deposition is only half the story; more important is whether the dust sticks to modules after depositing (whether it can slide off or be removed by wind or rain). Here the physics is more complicated. What is the dust composed of? What is its size and shape? If wind can entrain dust particles from the ground, why doesn't it remove them from PV modules?

The "stickiest" soiling scenario is when dust is fine and contains soluble matter, and the climate is humid. Small particles (diameter less than several microns) are essentially immune to wind removal, because the aerodynamic drag force scales with the square of particle size, while the adhesion force scales with particle size itself. For this reason dust accumulating on PV modules tends to be finer than the surrounding airborne dust – large particles are blown off, but small particles remain [4]. Soluble environmental species, such as salts and nitrates, dissolve in the soiling layer under high humidity or dew at night. When the surface dries out again during the day, this matter "cements" dust particles to the module. Micrographs of cementation (Figure 5) vividly show that Qatar's dust chemistry and climate form palygorskite needles that are present on the glass surface and attach larger dust particles to the surface [5]. Even when the dust contains little soluble matter, capillary adhesion is seen at quite moderate humidity levels, which captures dust particles on the surface [6].

The physical link between humidity and dust adhesion is not just an academic curiosity; it translates to PV soiling rates observed in the field. At QEERI's OTF in Qatar, there is seasonal correlation between the soiling rate of PV modules and the proportion of days in which relative humidity exceeded 75% (Figure 6). To directly test the theory that eliminating condensation would reduce soiling, Ilse et al [8] performed an experiment with a heated glass coupon and an unheated reference one, and found that the heated coupon accumulated 65% less dust over four weeks. Further experimental evidence of the moisture/soiling connection came from an analysis by Fountoukis et al [9], which found high correlation (R^2 of 0.94) between the experimental performance ratio loss due to soiling and a mathematical parameter based on meteorological parameters PM10 and a sigmoid function of relative humidity (RH):

$$\text{Aerosol mass predicted to cause soiling} = \text{cumulative } PM_{10} \,/\, [1+\exp(-a(RH-b))]$$

where a and b are fitted constants.

We have seen that adhesion of dust to PV modules is governed by the dust properties and moisture. The rate at which dust settles on modules in the first place is influenced by many more factors. Some are features of the local environmental, but others can be controlled by engineers. A study [10] by Micheli of NREL found that — in the US at least — the best environmental predictor of variation in long-term PV soiling rate at different locations was PM2.5 (concentration of aerosol particulate matter up to 2.5µm). At the timescale of minutes, on the other hand, field microscopy at the OTF found that the accumulation rate was most dependent on wind speed [11]. These results are not contradictory but suggest that for site-selection purposes and O&M estimation, the local average PM concentration and wind speed are key factors for the PV soiling rate. The instantaneous physical motion of dust particles, on the other hand, is governed by particle size and wind speed.

Design of the PV plant can also influence the soiling rate. A major factor

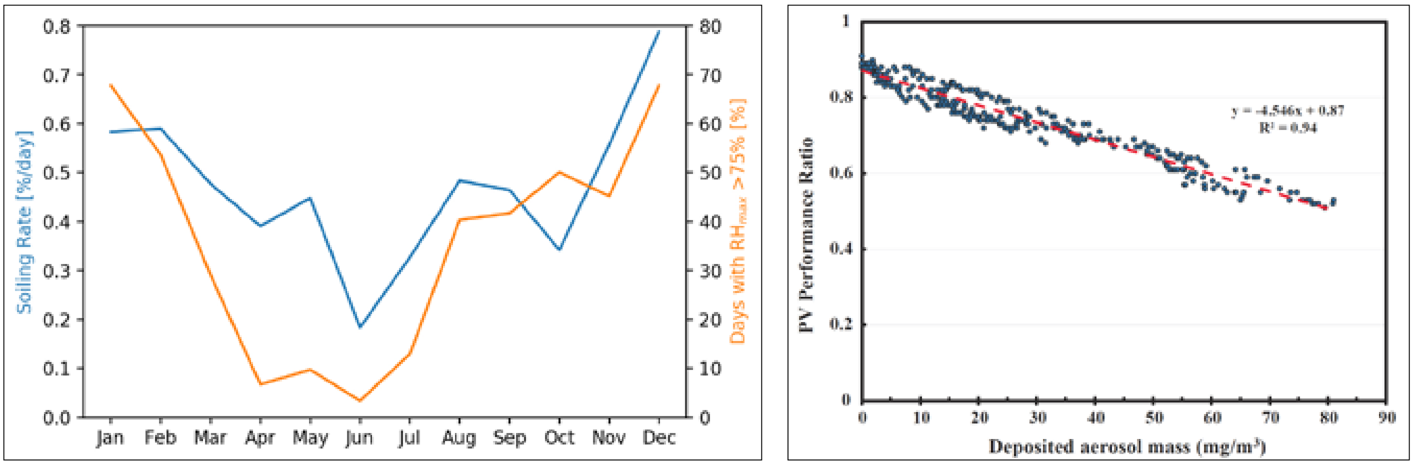

Figure 6. Left: seasonal correlation between humidity and PV soiling at the QEERI OTF. Blue line: daily soiling rate. Orange line: Percentage of days in the month in which the maximum relative humidity reached 75%. Right: PV performance ratio experimentally measured as a function of the aerosol mass (mg/m³) predicted to cause soiling based on cumulative PM10 measurements and a sigmoid function of relative humidity (meteorological data) from [9]

Figure 7. Test trackers with enhanced tilt ranges at the OTF in Qatar. Soiling was greatly reduced by vertical night stowing, but there was little gain from tilting to enhance dust resuspension during wind [13]

is tilt angle: the primary driver of outdoor dust deposition is gravity, and studies of PV soiling universally find the most severe loss at horizontal tilt and little loss when vertical [4]. We recently also determined [12] that soiling tends to be greater when the wind direction is from "behind" a tilted module (i.e. from the north, for a south-tilted module), all other conditions being the same. However, in practice the PV engineer can make little use of such information — the tilt of fixed modules is selected to maximise annual plane-of-array irradiation, and rows are spaced for shading and accessibility requirements.

As use of horizontal single-axis trackers (HSAT) grows, it raises the possibility of using their tilt to combat soiling. We conducted tests with full-size modules on HSAT at the QEERI OTF (Figure 7). The easy-to-implement approach of stowing the tracker at maximum tilt toward the night wind, rather than away from the wind, could simply (although slightly) reduce soiling [13]. Pushing this concept into less practical territory, stowing trackers vertically at night could reduce soiling by more than 40%. Also, HSAT can be "friendly" to PV cleaning by tilting to a steep angle during manual cleaning, or to horizontal when cleaning robots are used.

Anti-soiling technologies

Although manual cleaning of PV systems is still the most common method, it is desirable to minimise manual labor and a range of technological solutions are being developed. Those at the commercial stage are automated cleaning machines (robots) and anti-soiling coatings, while electrodynamic shields (EDS) are pre-commercial. Overviews of each follow.

Cleaning machines

PV cleaning machines have been available for many years. The first were truck-mounted, wet-brush systems, and these continue to be widely used where water is abundant. With the large deployment of PV in arid regions, models have been introduced that are waterless, fully autonomous, and run along the array (rather than using a truck), see Figure 8. A recent survey by Solarplaza [14] listed 16 commercial PV cleaning machines, with wet systems developed for Europe, USA and Japan, and dry systems for those markets and also arid ones. A common autonomous design is a long rotating brush that spans the width of the PV array and is guided by its edges. Robots also exist that are smaller than the width of the array and crawl along the modules themselves, but they are not widely used in commercial PV plants.

Advantages of robots include: they are effective at removing dust, can be run frequently, and are built from robust existing parts (motors, sensors and controllers). Because they have significant up-front cost but low operating cost, and manpower can be required to move them between PV rows, the economics of robots favor long, continuous PV rows and running them relatively often to maximize electricity generation. However frequent dry brushing raises the risk of abrasion of PV coatings, discussed below.

Specialised robots also exist for horizontal single-axis trackers and since robots are most efficiently deployed on long, continuous PV arrays, those trackers have been improved by manufacturers such as Soltec, Nextracker, PV Hardware, Soltigua and others to offer such long span continuous surface. These long-span trackers are currently being optimised to ensure wind load stability and to increase electricity production through the use of bifacial modules with reduced shading on the back side.

Credit: NOMADD Desert Solar Solutions

Figure 8. Dry-brush automatic cleaning machines are gradually being deployed at commercial PV projects in desert regions.

Coatings

Anti-reflective coatings have been widely used on PV modules for several years and in 2019 are present on more than 90% of all crystalline silicon modules [15], although their durability is still being improved to last up to 25 years. Efforts are also being made to develop anti-soiling coatings, which aim to reduce particle-to-coating adhesion forces in dry conditions or increase dust removal by water (rain or spraying). One approach has focused on TiO_2, used commercially in building glazing, which has a photocatalytic effect that breaks down organic matter. However, its light transmission is inferior to other coatings, and, in deserts, dust mostly comprises inorganic minerals. Another route has been to use hydrophobic materials, based on fluorine or methyl compounds, however such surfaces are prone to contamination and degradation. The main strategy being pursued at the moment is use of silica nanoparticles, whose properties are tuned by their morphology (roughness and voids) and binder.

In practice it has proven difficult to produce anti-soiling coatings that are effective, highly transparent and durable. To date only one large company (DSM) has fully commercialised and marketed an anti-soiling coating for PV modules, which uses silica nanoparticles, applied to solar glass in the factory. The product is designed to slow soiling so that the interval between cleanings is extended. Several smaller companies have developed coatings designed to be applied in the field, but to our knowledge they have not been widely adopted for refurbishment of existing PV plants.

EDS

Electrodynamic dust shields (EDS) aim to dispel dust particles from PV modules using local electric fields. The fields are generated by fine, interdigitated electrodes embedded in a transparent film on the front of the module. They are dynamic in that they are applied as periodic pulses, sometimes in traveling waves, so that particles are driven downward on a tilted surface. The concept first appeared in the 1970s for powder transport, was developed by NASA for PV panels on Mars and the moon, and over the past decade for PV. Although the technology has been well demonstrated in the laboratory, it has proved less effective in field tests mainly because of humidity. A recent field trial with full-size modules in Saudi Arabia reported an average cleaning efficiency of 32.1% [16], while a trial with mini-modules in Qatar [17] achieved in 16-33% removal. Based on current performance then, occasional cleaning using other methods is still required with EDS. Also, their sophisticated control electronics and installation of module electrodes raise cost and pose reliability challenges.

Abrasion

A key take-away from the above is that PV in dry climates will be cleaned with brushes for the foreseeable future: in the short term, cleaning machines will increasingly replace workers, and this will likely increase brushing frequency. In the long term, coatings and EDS might be deployed, which reduces brushing frequency but will not eliminate it. Since almost all PV modules now have anti-reflective coatings on their front glass [15], it is of great interest whether brush cleaning damages the coating (faster than normal exposure to the environment). Another question is how to test and compare coatings' abrasion resistance, given that existing test standards do not well simulate PV cleaning.

It is not straightforward to measure PV abrasion. One challenge is that the same coating material can have different properties when applied to a test coupon versus a full-size PV module. However, the most sensitive characterisation tools, such as photometers and profilometers, usually cannot accept full-size modules. Being tempered, the front glass of PV modules cannot be cut into smaller pieces for analyses. Anti-reflective coatings typically increase module power by around 4%, so even in the most extreme case (complete removal of the coating) the abrasion may be difficult to detect, especially from field monitoring. Another challenge is accelerated testing. This is needed because abrasion in normal field operation will not appear for months or years. One could simply conduct cleanings more frequently, say several times per day, but this would eliminate the dust layer that builds up between "normal" cleanings and may affect scratching. QEERI is starting an abrasion study with full-size modules combining realistic field exposure and cleaning with sensitive lab characterisation tools.

An abrasion study [18] using coupons, in which glass samples with various coatings and cleaning methods were tested in Dubai, confirmed that dry brushing was the most severe method and that coating abrasion resistance varied widely. But so far there have been no reports using commercial PV modules and cleaning practices in a desert environment that conclusively show whether (or how quickly) cleaning abrades the modules coatings. Meanwhile, the National Renewable Energy Laboratory is developing an international test standard for PV abrasion which should enable meaningful comparison of coatings' durability. ■

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Turn to p.22 for further exploration of how the solar industry is embracing new cleaning technologies.