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Solar energy dust and soiling R & D progress: Literature review update for 2016

Suellen C.S. Costa[a], Antonia Sonia A.C. Diniz[a], Lawrence L. Kazmerski[a,b,*]

[a] Pontifícia Universidade Católica de Minas Gerais (PUC Minas), Belo Horizonte, Brazil
[b] Renewable and Sustainable Energy Institute (RASEI), a partnership between the University of Colorado Boulder (CU-Boulder) & the National Renewable Energy Laboratory (NREL), Golden, CO, United States

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ABSTRACT

The objective of this literature review and survey is to provide a compilation and assessment of recent published reports for solar-electric device soiling R & D, to extend and update the compendium covering 2012–2015 we published last year. This review provides a comprehensive listing of the publications with references for 2016—with some preliminary 2017 publications that have appeared at the time of this writing. Photovoltaics (PV) and concentrating solar (thermal) power (CSP) technologies are covered. To guide the reader, tabulated information on the investigative focus of the studies, the location, the duration (if pertinent), the solar-device type, key findings and other useful information within the report is presented.

1. Introduction and background

Solar-energy technologies are now accepted and growing in our world electricity markets—and continue to mature technically and commercially. This does not obviate the continued and critical need for research and development, whether to pursue new technologies to ensure that clean energy meets the needs of future generations of consumers. Or more of immediate importance—to make certain that current technologies are reliable, durable, and dependable. Among such current R & D issues, solar-device soiling or dust/particle obstruction of the incoming solar resource has come to the forefront of critical concerns for technology viability. Solar programs in the sun-abundant areas of the Middle East, North Africa, China, United States, and India have established hundreds-of-gigawatt targets over the next decade—and most of these geographical areas are also characterized by high airborne and settled particulate environments, dust storms, high pollution or other harsh-climate conditions—and many times, a water-resource scarcity that limits some approaches to cleaning and restoration.

This paper represents the continuation of our effort to provide periodic update to the publication reference base (a "living resource") for researchers, developers, manufacturers, and system installers [see Ref. 29]. Historically, interest in the "dust-solar device" performance relationship goes back nearly 8-decades. But serious (but inconsistent) investments in terrestrial solar energy also brought attention to this external limiting factor for operating solar thermal and solar electric systems. We reported the increased research publications in dust and soiling, linking the research publication output with funding levels, political obstruction, technology achievements, market experiments and incentives, and the recent mercurial market growth (many times attributed to the "China syndrome" responsible for driving down prices). Over these decades, the investments in soiling/dust mitigation research and understanding have shifted, reflecting the market realities, from solar thermal (heat), to concentrating solar (thermal) power (CSP), to the current dominance of photovoltaics. Fig. 1 is the histogram for "dust" publications covering this "market growth" period starting in about 2008 (building on the previous report [36]). This shows the focus on PV (with about 85% of the publications this past year on this technology) and reflecting the incredible growth of research and financial resource investment. Beyond the significant science and technology involved in the work, the interest in mitigating this problem has also become part of the financial investment community and bankability.

This present survey builds on our report last year that covered the period 2012 through 2015. That literature review also provided overviews of 15 noteworthy review papers that were published over the period 2010–2015 and formed a major portion of the base of last year's literature review. We continue to emphasize journal and conference publications that can be accessed through their "DOI" or web identification. We have also endeavored to include accessible academic thesis or dissertations—sources that can provide more depth and content to the issues of soiling. Because of the timing, we also provide a listing of 2017 publications that have already appeared in the literature in the attempt to make this database more current.

* Corresponding author at: University of Colorado Boulder, Colorado, USA.

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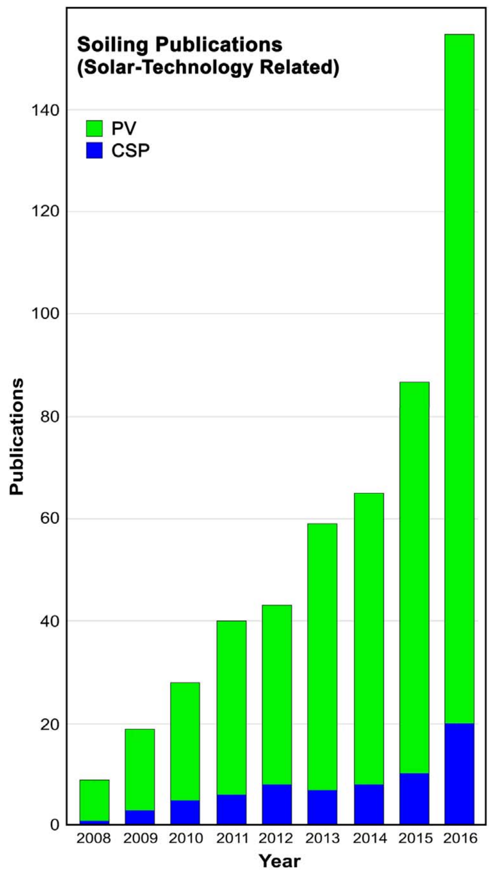

Fig. 1. Histogram of publications for the recent period of solar-electricity market growth (2008–2016), spurred by significant decrease in PV pricing. Relative PV and CSP publication volumes are indicated.

2. Literature review (2016)

The year 2016 continues the growth trend in publications, reflecting again the investments in R & D in reliability and in the number of systems deployed (from kW-scale residential and commercial rooftops to 100-MW solar fields). The 2016 annual PV shipments, for example, exceeded 70 GW and the cumulative worldwide installations are exceeded 300 GW. This year 2016 was also the record single-year for soiling-related R & D papers, with about a 80% growth in these literature reports over 2015 (Fig. 1).[1]

Those dealing with PV dominated the literature survey. Following our protocol from last year, we have tracked all publications into the major interest categories, adding three new ones (number 12–14 on the following list), because they are receiving added attention in the last couple years. The categorization covers: (1) Performance (coded “P”) – the effects on modules or system output, (2) Modeling and simulation (MS) areas that have grown to include information on gathered data and predictive modeling, (3) Composition and morphology of the dust (CM), which includes chemical properties and distributions, size, and shape. (4) Transmission and reflection characteristics (TR), the effects of the dust on the transmitted light (e.g., impinging on the solar cells in the module) or reflected light (important for mirrors and heliostats). (5) Cost and economic factors (CE), especially those relating to operation and maintenance. (6) Mitigation techniques and cleaning (MC), the approaches from preempting soiling situations, restoring the soiled device surface by various cleaning approaches, and prevention (the incorporation of passive and/or active coatings for minimizing dust adhesion). (7) Ambient conditions (A) relating to the effects of the local environment especially climate zones. (8) Instrumentation (I) (detectors for monitoring, dust measurement capabilities, etc.). (10) Spectral effects of the deposited dust (S), having important relations for the technology used. (11) The orientation or tilt of the device (TO) which can be effective for maximizing output while minimizing dust issues. (12) The electronic nature of the dust, especially its charge (C), a fundamental parameter important of the interaction with the surface of the device and the charge state of the surface itself. (13) Dust simulators (DS), which are growing in importance for controlled laboratory experimentation. And, (14) standards (S), contributions from the world community to either measurement techniques or the certification of product for operating in real conditions.

To gauge the technical interests, we have assigned each of the publications with the major investigation area from the categories above, excluding “performance.” Almost every soiling paper deals in some way with “performance,”, whether the IV or output of a PV module or system, or some parameter of a mirror or heliostat, as the major foundation for evaluation. This assignment is a best-effort estimation to gain some insight into the evolving research interests and investments. Fig. 2 provide summarize these results of the evaluation of the 2016 publications for PV and CSP, respectively.

With the maturing of this area of research, the research has become more focused and more science-based. For example, six-years prior, 80% of the publications just monitored and reported the decrease in performance (e.g., “the short-circuit current deceased 14% over the one-month exposure”) of a PV module or array as a function of dust accumulation. In the case of CSP, 90% monitored the reflection vs. dust exposure. This had the intended benefit to establish performance ratios, mainly for establishing the severity of the problem or, in some cases, determining cleaning requirements. With the expansion and evolution of the research community dealing with this issue, the research has become more sophistocated and more directed toward understanding and solving the soiling problem that steals significant percentages of an installation’s output. And this translates into the bankability issues.

Fig. 2 indicate that the major research categories are concerned with *mitigation* of the dust problem and cleaning methods, and *climate-zone* documentation on the severity of the soiling situation in a particular-geographical area. In many cases, these issues are inter-related—and publications do correlate, for example, the required period-for-cleaning with the particular-climate condition.

A significant addition to the soiling research has been the investment and development of *modeling and simulation*. These approaches have become quite sophisticated and complex, with two major ones found in the literature: (1) Modeling of collected data from monitoring stations or from installed arrays. This is, in turn, used to understand seasonal variations, investigate meteorological influences (wind, rain, snow, . . .), evaluate unusual occurrences such as dust or wind storms, and to establish cleaning cycles or monitor their effectiveness. This modeling is usually associated with an existing installation. The second is (2) predictive modeling. This is more recent, and these simulations can be even more complex. They try to utilize every available dataset for a target area, whether an existing weather station, a solar resource monitoring unit, aerosol particle counters (P10, P20, etc.), satellite data, etc. to feed into the analysis to predict the extent of the dust problem for a given location. This modeling is useful for either validating a location for a planned installation—or finding an optimum location for a solar plant. One concept behind this approach is that it does not call for the investment in multiple dust monitoring systems—and could present a significant cost savings.

The remaining categories show a trend toward fundamental investigations that are primarily laboratory based. The determinations of the *dust physical and chemical properties* are aimed many times at determining the adhesion mechanisms holding the dust particles to the

[1] With the first, pioneering publication on the issue of soiling by Hoyt Hottel and B.B. Woertz (*The performance of flat plate solar heat collectors. Trans. ASME, 1942:64:91–104*) in 1942, the importance of that visionary work is highlighted by the nearly 160 times more literature references in 2016.

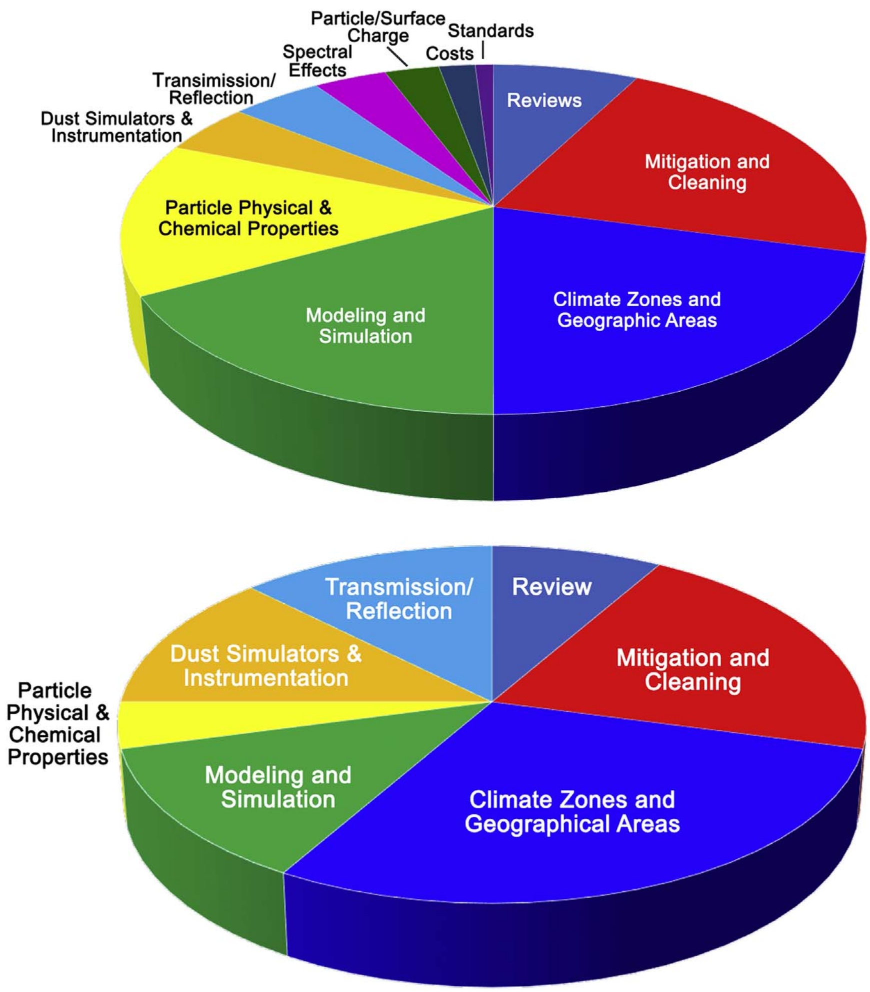

Fig. 2. Distribution of PV and CSP soiling papers in 2016, assigned to key categories of technical focus.

substrate surface. Part of this is also the understanding on how the particles connect to each other and to that module or reflector surface—the "cementation" or solidification process that plagues areas that have levels of moisture (e.g., heavy morning dews) that interact with the soiling particles and become "bonded" to the surface and each other under high temperature and ultraviolet light conditions. Removing the resulting layer tends to be difficult in many cases using conventional cleaning techniques. For PV, the nature of the charge of the particles and the surfaces has begun to be explored in detail. This relates to both the interest in the process of dust attaching to the module surface—as well as the increased interest in static and dynamic screen to "repel" the dust. Controlled experiments are crucial—leading to the development of *dust simulators* that can provide rapid, laboratory investigative systems. Likewise, the use of solar simulators and reflectometers/spectrometers have accelerated the understanding of *spectral effects* and *transmission/reflection properties* of the layers.

Finally, primarily for PV, the *costs* of cleaning, costs of mitigation approaches, the cost of electricity lost/gained under the environmental conditions, the related costs of system sizing, etc. are being investigation and reported. And, because this is an issue that related to reliability, the development and evaluation of standards are being addressed—especially standards relating to harsh climates where the dust issues can dominate. (Table 1)

2.1. Review papers (2016)

Table 1 provides information for the major review papers that were published—along with a summary of the review contribution and focus and the primary solar technology covered. Likely due to the increasing interest in this research area, the number of reviews have nearly equaled the total for the previous three years (2013–2015). Review paper provide a good introduction to the progress of work in this area and for understanding the issues. Reviews cover entire areas and technologies—and have also started to become more focused (e.g., mitigation/antireflection coatings, abrasion characteristics, etc.).

2.2. Research/technology papers and information (2016)

Certainly, 2016 experienced a substantial increase in the volume of research reported on this important research area—with about 2/3 more publications over the previous year. Tables 2 and 3 summarize these R & D reports, separated for PV and CSP, respectively. As already noted, these publications have a major focus on mitigating the soiling problem—and bringing more sophisticated approaches to understanding and addressing soiling in the real world. The primary purpose of this literature examination is to provide an accessible, "one-stop" and complete-as-possible resource to assist those involved with these soiling and dust issues for their own research or development efforts.

Major and growing focus of research evaluations relates to climate zones, the physics and chemistry of the dust particles collected on the modules/reflectors and that of the aerosols, and mitigation issues relating to the indigenous geography. But there is a growing recognition that *"all dust is not local."* For some time, it has been recognized that Saharan sand is carried long distances into Europe and especially the Eastern Mediterranean (depending on the meteorological conditions and time of the year) *[See, for example, Athanasopoulou, E., Protonotariou, A., Papangelis, G., Tombrou, M., Mihalopoulos, N., and Gerasopoulos, E.: Long-range transport of Saharan dust and chemical*

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Table 1
Noteworthy *review papers and reports* addressing soiling and related issues published in 2016 (presented in alphabetical order of first-author name).

Source and Author Country [Reference Number]	Contributions/Focus of Review	Technology
Costa, Diniz, Kazmerski (Brazil/USA) [36]	Literature compilation, updating publications reported by previous soiling/dust reviews. The materials cover the timeframe 2012–2015. The purpose is to provide a periodic, single-collection point for such publications and literature for the dust and soiling areas relating to solar technologies. [253 References]	PV, CSP, Solar Thermal
Hanaei, Assadi, Saidur (Malaysia/Saudi Arabia) [67]	Discussion of the basic/desired properties of antireflection and anti-soiling coatings. Processing methodologies for films on silicon and silica substrates. Potential and benefits of incorporating carbon nanotubes (CNTs) into anti-soiling coatings and ARCs. Information on the processing, utility, and recent development of CNT-based coating (primarily for PV applications) [126 References]	Dust Mitigating and Antireflection Coatings for Solar Cell Applications
Khojasteh, Kazerooni, Salarian, Kamali (Iran) [99]	Comprehensive survey and study of the dynamics and kinematics (spreading, retraction, bouncing, etc.) of surface interactions of the impingement of liquid droplets–examining superhydrophobic surfaces. Applications and mechanics involved with self-cleaning, ice resisting, corrosion protection, and other uses are covered and reviewed. Latest scientific findings and reports. [221 References]	Dynamics of the impact of droplets impinging on superhydrophobic surfaces and coatings (General)
Maghami, Hizam, Comes, Radzi, Resdad, Hajighorbani (Malaysia) [125]	Review of 'key contributions' to the understanding, performance, and power loss due to soiling and dust on solar panels (tabulated summary). Country and geographical region assignment of dust intensity in 4 zones, with the Middle East and Africa worst (Zone 4) and the greater parts of the U.S., Australia, Europe far less sever (Zone 2). Categorization of two (soft and hard) shading types with effects on the electrical properties of the panels. Most discussion on c-Si technologies. Included are discussion of several cleaning techniques and dust adhesion prevention approaches. [55 References]	PV Modules
Mehmood, Al-Sulaiman, Yilbas, Salhi, Ahmed, Hossain (Saudi Arabia) [120]	Recent advances in antireflective (AR), transparent, and superhydrophobic surfaces, focusing for use on glass and polymer materials, are summarized. Four areas are reviewed: (i) basic concepts and principles of antireflection and self-cleaning coatings; (ii) detailed fabrication methods and mechanisms; (iii) Practical applications and issues; and, (iv) Future research/expectations. A comprehensive overview and evaluation of superhydrophobic coatings for solar technologies. [209 References]	Dust Mitigating and Antireflection Coatings for Solar Applications
Miller, Muller, and Simpson (USA) [124]	Detailed review of abrasion characterization and testing methods for PV module technologies. Durability of the front module surface is associated with impingement of energetic particles and contamination by soiling. Anti-soiling and anti-refection films are considered in this review. Literature for falling and forced sand tests and standards is reviewed and surveyed. Various abrasion testers and systems are evaluated. [60 References]	Abrasion Testing/Evaluation of PV Module Surfaces; Test Standards
Mokri, Ali, Emziani (UAE) [127]	Literature review and analysis of the potential of solar energy in the UAE. Review includes discussions and examples of the critical effects of local environmental/climate conditions on the performance of solar technologies. Review also considers solar resource evaluation (including dust effects), financing strategies, and benefits of solar for electricity generation, water (desalination), and transportation. Discussion of cleaning and costs. Examples and descriptions from *Masdar Institute*. [116 References]	CSP and PV Dust effects on solar resource and accumulation effects on PV panel performance
Tripathi, Kumar, Murthy, Aruna (India) [171]	Review of environmental factors on the performances of solar energy systems. Major parameters include dust, temperature, humidity, wind. Detailed discussions and analysis of the effects of mining and site factors (especially local). Summary of prevention (clean environment) and cooling aspects for reducing environmental impacts on solar system operation. [19 References]	PV Panels and Systems
Zaihidee, Mekhilef, Seyedmahmoudian, Horan (Malaysia/Australia) [182]	Review and analysis of the deteriorative effects of dust on the performance of PV modules. Two such factors are emphasized: (1) Effects on disturbing and limiting the available solar resource; and (2) Adverse effects on panel temperature, shading, abrasion. Both can be responsible for reversible and non-reversible degradation in module performance. Details on effects of dust (layer) deposition on specific electrical parameters of panels are examined. [65 References]	PV Modules

transformations over the Eastern Mediterranean. Atmospheric Environment, 2016;140:592–604]. Wind conditions carry dust from Thar Desert in India (sometimes termed the 'dustiest place on earth") across India, Pakistan, and the Arabian sea [*See, for example, A.S. Goudie and N.J. Middleton, Desert Dust in the Global System, Springer, New York;2006. ISBN-10 3–540-32354-6*]. Recently the soiling particles on some modules in Brazil were found to have traces of phosphorous. This was at first attributed possible to fertilizers used in adjacent agricultural field. However, NASA has reported what is an incredible journey—one that carries phosphorus from a small region in the Sarhara, the Bodelé Depression in Chad [See, *Yu, H., M. Chin, T. L. Yuan, et al.. The fertilizing role of African dust in the Amazon rainforest: A first multiyear assessment based on data from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations. Geophysical Research Letters, 2015;42 (6):1984–1991.* http://dx.doi.org/10.1002/2015GL063040]. This was originally a lake bed, and over centuries it disappeared leaving dead microorganisms

Table 2
Photovoltaic Technology Applications: Summary of dust and soiling papers published in 2016 indicating primary focus, device/materials investigate, conditions and findings. The *Focus Code* (for primary contributions) is: *P = Performance, *MS = Modeling/Simulation; *CM = Composition/Morphology; *TR = Transmission/Reflection; *CE = Cost/Economics; *MC = Mitigation/Cleaning; *A = Climate conditions/effects; *I = Instrumentation, *S = spectral effects, *TO = Tilt/Orientation, *EC = electrical charge of particles, *DS = Dust Simulator, *ST = Standards.

Publication Source [Reference Number]	**Focus** ***(see code)****	**Location [Duration]**	**Solar Device Type**	**Key Findings**	**Comments/Other Conditions**
Abbdallah et al. [1]	A, P	Qatar [~1 year]	Si Heterojuncton and mono-C Si Modules	Study and comparison of 2 PV technologies (Si Heterojunction, sometimes still called HIT cell, and monocrystalline Si) under the harsh climate conditions (temperature and dust) in Qatar. Results: Higher-efficiency Si Heterojunction array: higher energy yield than for monocrystalline Si array. Dust: Energy yield and performance ratio decreased by about 15% due to dust accumulation over 1-month. Cleaning schedules discussed; cleaning restored arrays to “close to its initial value”.	Excellent presentations of IV data and operating parameters. Monthly energy yield and performance ratios presented graphically for arrays. Useful presentation of PV operation in harsh climate.
Abhilash and Panchal [3]	MC, TO	India	Si PV module (with tracking)	Focus: brief description of the design and construction of microcontroller-based cleaning and tracking system; Algorithms presented Results: ● tracking system without cleaning the panel, the efficiency is less than of the panel which is fixed and cleaned. ● the efficiency of the panel is decreased by 50%, even though it is tracking without cleaning.	Descriptive report of mechanical cleaning system on a tracking PV module.
Aïssa et al. [5]	CM, P	Qatar (Doha) [weeks]	Si Modules	Detailed chemical, physical, and morphology characteristics of dust particles collected from module surfaces operating in the *Science and Technology Park* (Doha, Qatar) are reported. ● Dust particles have average diameter size of about 2-µm, with addition to the presence of larger non-uniform particles of few-tens µm-size. ● Primarily calcite (58% atomic content) ● Particles with magnetic properties detected ● Transmission drop up to 26% measured optically ● Effect on particle accumulation on the I-V characteristics presented and analyzed (indications of non-uniform dust accumulation from I-V).	Techniques: optical and scanning electron microscopy, X-ray diffraction, atomic force microscopy, Raman, FTIR, UV-Vis and VSM were used to characterize the collected dust particles. Interesting investigations using vibrating-sample magnetometry *(method to map patterns of magnetism in soil)* to investigate the magnetic properties of the dust particles. Interesting photos of dust conditions.
Al-Shabaan et al. [8]	CM, P	Laboratory Testing (Jordan)	Mono-crystalline Si Modules	Effect of particle size and mass deposition density (g/m^2) on the maximum output power point (P_m) shows that “fine” and “medium” size have more effect in decreasing the transmitted light because of “ability to spread” on surface. Effect to decrease power output is more. Test particle mass deposition densities were 5 g/m^2, 2.5 g/m^2, 1 g/m^2, with an equal distribution (1/3) from different grain size.	Data used to locate PV power station at Al-Hussein Bin Talal University in Jordan to mitigate issues with dust/soiling. P_m reductions between 37.6%-46.4% for $5g/m^2$ and 5.6% to 20.0% for $1g/m^2$ mass densities under experiment.
Al Shehri et al. [6]	MC, TR, CE	Saudi Arabia (Thuwal) Laboratory Experiments	Low-Iron Glass Samples (76 mm x 26 mm x 1 mm)	Effects of *dry cleaning* for the removal of field settled dust particles settled down on glass module surfaces and the impact of brushing on the transmission of the glass. Studies demonstrate the need for careful assessment and optimization of brush properties (bristle type, softness, length, etc.). Positive observation: After washing, all brushed module surfaces were restored to original specifications. (The cleaning efficiency using coarse black nylon brush is not as effective as cleaning using water and delicate wipers.)	Extensive, well documented, and current investigation of dry cleaning of PV glass module surfaces Well-documented and described experimental conditions and equipment. In the analysis of transmittance reduction, the wavelengths of 500 to 700 nm were considered, since in this range that the maximum power generation occurs for most photovoltaic technologies.

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Table 2 (*continued*)

Publication Source [Reference Number]	**Focus *(see code)****	**Location [Duration]**	**Solar Device Type**	**Key Findings**	**Comments/Other Conditions**
Al-Showany [9]	A, P	Iraq (Kirkuk City) [~3 months]	Crystalline Si Modules (2-identical 75 W)	Evaluation of local weather conditions and pollution/soiling on the Si module performance. Efficiency vs. dust density Voltage loss for soiled panel ("fine dust" and pollution) for period of three months was about 3.8% compared with clean pane, and 13.8% if it has been compared with voltage production by panel when cooled by water.	Report: Effects of T on module electrical parameters. Circulated water used to cool and control the temperature of the modules. Very nice presentation of data.
Al-Waeli et al. [10]	CE, A	Oman (Desert Conditions)	PV Water Pumping System	Evaluation of the environmental conditions (temperature, dust, wind, etc.) to design an optimal water irrigation/pumping PV system in desert. Economic analysis: HOMER and REPS.OM	Detailed examination of system economics relating to environmental issues.
Aly et al. [11]	A, P, MS	Qatar	Small Si PV System	Summary of effect on reduction of PV module efficiency (temperature, dust, etc.) Technique proposed to overcoming heating; techniques tested on small array with positive results	Shading discussed Modeling: 3D finite element modeling for validation
Aouad et al. [13]	MS	Modeling	Surface physics	Specialized particle image velicometry (PIV) is used to study the flow patterns created by coherent horizontal liquid jets (on vertical wall). Thin, fast moving film with radial flow is confirmed. Provides explanation for differences between measured and modeled fluid flows.	Potential importance for optimizing the cleaning of PV module surfaces (Studies here on polypropylene and polymethylmethacrylate
Ashhab and Akash [14]	TO, P	MENA Region, UAE	Silicon Modules	Performance of PV modules as function of dust accumulation and tilt angles. Tilt angle effects evaluated for various MENA locations and conditions.	Identification of possible optimum tilt angle to mitigate dust effects (by location)
Bahattab et al. [15]	MC	Laboratory Experiments and Saudi Arabia Field Tests	Glass PV Cover Glass	Antireflective and anti-soiling films (deposited on glass substrates by sol-gel processing; nanotech); Porous SiO_2 films are ARC and mitigating. Laboratory experiments use artificial dust; then compared with outdoor exposure experiments. Surface coverage of specimen correlates to their optical performance. Film coating are observed to significantly improve transmittance for dust exposed compared to non-coated samples.	Good descriptions of film deposition and preparation conditions and effectiveness of the coatings.
Bai et al. [16]	MC	Laboratory Experiments (China)	Glass substrates	Preparation and evaluation of self-recovering superhydrophobic coatings. Method: spraying the mixture of polymethylmethacrylate/zinc stearate/stearic acid. Contact angles to 158°; Good UV-durability	Claim long-term stability in environmental conditions. Paper is more general for the applications of these coatings.
Barth et al. [17]	A, MS	Qatar	Wind Effects on PV Arrays	Field wind conditions are evaluated and defined (Qatar). Modeling: Computational Fluid Dynamics Effect on PV parameters and dust	Comparisons between model and collected data.
Batra et al. [18]	P, CM	Laboratory (India)	PV Modules	Evaluation of effects of 2-India dust samples, fly ash, and rice husk dust on the performance of PV panels. Experiments under simulated light indicate that the rice husk has the highest impact on reducing module performance.	Particle properties established with scanning electron microscopy "Bardarpur dust" of two types are used (from historic region in South Delhi District)
Belluardo et al. [19]	A, P	Italy (Northeast) Airport Bolzano Dolomiti [~2 months]	Multi-technology PV Module	Performance evaluations of Si modules exposed in Airport runway construction area during dry period (no rainfall for 2-month period) Comparisons of different glass surfaces (smooth vs. textured) One monocrystalline module and one Cadmium Telluride module of the system in study presented daily losses of the -0.02% and -0.08%, respectively.	Evaluated effects of module orientation (i.e., "portrait" vs. "landscape"); Also, framed and frameless modules. Data found from the calculation of the performance ratio.

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Table 2 (*continued*)

Publication Source [Reference Number]	**Focus *(see code)****	**Location [Duration]**	**Solar Device Type**	**Key Findings**	**Comments/Other Conditions**
Bernard [21] ***Ph.D. Thesis***	A, P, MS	Ghana [4 months]	Si Module (50 W)	Monitored: Dust concentration, irradiance, wind velocity, module electrical characteristics. Performance: power output decreased by 28.7% and panel efficiency reduced by 5.6%. for 4-month period. Model developed for Dust settling during the Harmattan Season in Ghana and effects.	Harmattan Season: November to March affecting latitudes north of the latitudinal position of the Inter-Tropical Convergence Zone (ITCZ), separating the Saharan dust-laden northeast winds from the southwest monsoon winds.
Boyle et al. [26]	CM	Colorado, USA [> 1 year]	Special soiling stations (glass)	Field measurements of mass accumulation and airborne PM_{10} (> one year, 2 sites, Front Range of Colorado). Objective: Develop soiling prediction models. Dry dust only; both sites deposition velocities 2 cm/s. Coarse particles dominate. Modeling to estimate average soiling rates investigated and evaluated.	PM_{10} is used to describe particles of 10 micrometers or less.
Bunyan et al. [27]	MC, A, P	Kuwait [1 year]	Si Modules	Effects of dust density on annual PV panel output. Establishment of required cleaning cycles based on experimental data for proper scheduling by comparing cleaned and soiled (impurity accumulation") panels (power output). Results: frequent *weekly* water washing is a necessity to maintain the power efficiency loss of 15.07%(April), 13.74% (May), 10.685% (October) and 8.742% (November) respectively, and frequent *monthly* water washing for the remaining months of the year.	Period: Sarayat season in April and May, winter and summer Shamal for one year. Details of experimental set-ups and methodologies.
Cabrera et al. [29]	A, P TR, TO	Chile (Atacama Desert) and Germany (Frauhofer) Laboratory and Field Tests [~8 months	PV Modules (Monofacial and Bifacial)	Investigation: influence of abrasion and soiling on solar modules using different combinations of solar module materials and solar cells under simulated test conditions. Field Measurement: Modules cleaned every 60 days. *Outdoor Results:* ● ARC glass exhibits higher I_{sc} losses than standard uncoated glasses due to soiling. ● In dirty condition, higher PR was observed on "montofacial" half-size than on full-size cell modules (the rear side covered: 97% compared to 94%). ● Under bifacial operation much higher but similar PRs for half- and full-size modules (both 107%) were reached. ● No abrasion over test times Laboratory Results*:* ● IEC and MIL-STD standards used. ● Abrasion indoor test, the ARC layer on the glass was removed by all dust types after one minute of exposure and for 200-μm to 500-μm dust grain size. Increasing the exposure time, higher transmissivity (T), reflectivity (R) and I_{sc} losses were observed. ● Tilt angle effects: from 90° to 30° and reducing the grain size to 63-μm to 112-μm, lower losses were observed. ● Model for indoor: predicts T and R losses for geographic region, glass type, and sand density on the glass surface.	Observation: Glass or transparent backsheets help to compensate for the soiling losses due to increased internal reflection of light coming from the rear side of the module. Model: Predicts 3.5% higher T losses and 2.4% R losses for ARC compared to STD glasses with dust of less than 63μm grain size (location independent). Extensive and very complete investigations, providing expert comparisons of laboratory and field testing.

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Table 2 (*continued*)

Publication Source [Reference Number]	**Focus** ***(see code)****	**Location [Duration]**	**Solar Device Type**	**Key Findings**	**Comments/Other Conditions**
Capdevila et al. [30]	MS, P	Egypt (Nubian Desert) [~1 year]	PV Modules, Modeling	Prediction and verification based on a combination of sub-yearly soiling rates from relevant reference locations, aerosol optical depth (AOD) values and 6-months on-site measurements. Result: Forecast monthly soiling losses for a complete year. Parameters: – Solar resource (global horizontal irradiance) – Temperature (average daily ambient) – Wind speed – Humidity – Precipitation – Aerosol Optical Depth (AOD) – Average particle size – - Dust deposition rate and surface distribution PV site located in a region of the Nubian Dessert (Egypt). Methodology: Time-dependent soiling determination developed.	Correlation between forecast soiling profiles underway. Soiling losses have strong seasonal behavior with monthly averages between 1.5% (low AOD) and 15% (high AOD).
Chaouki et al. [31]	CM, A	Morocco (Rabat)	Collection from PV Module Field	Chemical and physical analyses of soiling particles collected from PV modules at the RDI Solar Platform in Rabat. Characterization: XRD, XRF, thermal analysis, and IR spectroscopy. Results of Phys/Chem: Silica, alumina, iron oxide, calcium oxide, magnesium oxide and potassium oxide (most prevalent)	Optical measurements: Transmission of Petri glass correlated with the dust chemical/physical properties and thickness. Uniformity of dust on glass evaluated.
Chen, J. et al. [32]	MC	Laboratory (China, USA)	Glass Substrates	Experimental fabrication and evaluation of “antifogging, antifeflective, and self-cleaning transparent silica” films Results: Multifunctional silica nanoparticles thin (SNT) coating Roughness and morphology related function of deposition time. Nanostructures account for superhydrophic characteristics without having any other chemical additions. Films displayed both good antireflection and self-cleaning properties.	The antifogging property of the SNT coating was investigated. Detailed preparation conditions provided.
Chen, S.A. et al. [33]	MS, A, P	Australia (Northern) [12 months]	PV Rooftop System (53 kWp) Simulations and Modeling	Data-driven framework to systematically characterize the relationships between performance of photovoltaic (PV) system and various environmental factors. Predictive for residential and commercial PV building installations Comparison of the energy performance of a PV system in relation to the different climatic variables of the site.	Datasets developed, explained, and evaluated. Solar radiation – proportional to the energy yield, but it can be affected if there is presence of clouds. Relative humidity - Higher energy yield in the months with lower relative humidity, but this relation may be non-linear. Ambient temperature - Influences the reduction of electrical parameters of output the system. Rainfall - contributes significantly to cleaning modules.
Chesnutt et al. [35]	MC	Laboratory (USA)	Power Consumption Required for Mitigation	Objective: Determine performance and power consumption of electrodynamic dust shield (EDS) to clean solar panels as a function of dust particle size. Average power required to lift a particle off the surface was smallest with the smallest particle; And, power requirement decreased with diameter with a constant loading of particles on the EDS. Calculated from our simulation data, power consumption per unit area of an experimental EDS agreed with previous experimental studies.	Investigation of an important portion of the viability of EDS operation and power consumption to mitigate dust on solar surfaces.

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Publication Source [Reference Number]	**Focus** ***(see code)****	**Location [Duration]**	**Solar Device Type**	**Key Findings**	**Comments/Other Conditions**
Chesnutt et al. [34]	MC, MS	Desert Conditions	EDS Screens	Objective: Determine the optimal EDS parameters for effective PV module cleaning. Simulation of charges particles transported, colliding and adhering to the module surface. Results: Determination of mechanisms for which individual dust particles were repelled and attracted by EDS electrodes under different conditions that produced different transport patterns (used in turn to improve the performance/effectiveness of dust mitigation for PV panels.	Fundamental modeling of particle interactions and control under various EDS operational conditions.
Crowell et al. [37]	P, EC	Laboratory (USA)	PV Modules or Solar Mirrors	Electrodynamic Screens (EDS): Evaluation of the charging of particles on surfaces using EDS. Mechanisms of electrostatic charging investigated/identified (occur simultaneously): ● contact charging, ● tribocharging (contact electrification process that enables buildup of static electricity), ● corona charging and ● micro-filamentary discharge (MFD) process causing injection of positive charge carriers to the EDS surface from the positive electrodes. Experimental: the charge-to-mass ratio (Q/M) measured for dust particles over a wide diameter range (4 µm-100 µm) on EDS operation and find the particles are charged with a net positive charge at a high Q/M level and are swept off unidirectional on the EDS film surface under the action of the applied electric field.	Extensive examination on operation of the EDS screens from the mechanisms of surface charging and discharging.
Dadas et al. [38]	P, TR, A	Laboratory Experiments (India)	Poly-C Si Solar Cells/ Panel	Objectives: Study losses caused by the accumulation of dust on the surface of photovoltaic modules and effect of dust layers on the transmissivity of PV module glass. Dust: Playground soil	Indoor controlled experiments are conducted, explained, and illustrated, evaluating dust effects on PV panel/cell performance.
Daiuma et al. [39]	P, A	Niamey (Niger) and Abidjan (Côte d'Ivoire)	Polycrystalline Si modules	Objectives: (1) To evaluate the sensitivity of monocrystalline PV module performance to local meteorological conditions (temperature, humidity, solar radiation) in two contrasted cities over West Africa (compared to manufacturers' specifications), (2) To compare to literature reports; (3) To provide an in-depth evaluation of weather and irradiance effects (comparing Niamey (Niger) and Abidjan (Côte d'Ivoire))	Very nice and useful descriptions of the two areas under evaluation.
Darwish et al. [41]	P, MS	Laboratory Experiments; Malaysia	Si PV Panels	Objective: experimental investigation of the effects of the natural dust and corresponding environmental parameters on PV performance. Dust compositions: [SiO_2 (45.53%), CaO (24.62%), Al_2O_3 (10.83%), Fe_2O_3 (10.46%), MgO (6.33%), K_2O (0.87%), TiO_2 (0.45%), SO_3 (0.24%), MnO_2 (0.21), Cr_2O_3 (0.23%), SrO (0.13%) and NiO (0.09%)]	Modeling of the electrical parameters to predict performance under specific weather conditions.
Dastoori et al. [42]	EC, P, TO	Laboratory Experiments (Scotland)	Amorphous Si Modules (different sizes)	Analyzes the effects of the charge of accumulated dust particles on PV module performance. Dust particles: Epoxy powder Charging Method: Corona and tribo-electric methods and varying the charge levels of the accumulated dust particles. Results: Charge level of accumulated dust particles have significant impact on PV on module power output and associated dust particle accumulations are not a function of the panel tilt angle	Regression analysis (R2) show relationships between the charge level and PV module output voltage. Higher charge levels of the dust particles increase the reduction in the PV modules' output. Very complete descriptions of the experimental methodologies.

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Publication Source [Reference Number]	**Focus** ***(see code)****	**Location [Duration]**	**Solar Device Type**	**Key Findings**	**Comments/Other Conditions**
Deceglie et al. [43]	MS	Generalized Methodology (USA) (Data from 2 unidentified sites)	General PV Module Performance	Method: Analyzes time-series production data from photovoltaic systems to extract the rate at which energy yield is affected by the accumulation of dust, dirt, and other forms of soiling. Methodology: First quantifies daily soiling rates from PV production data: then demonstrates utility for two different sites. Data determined using *Theil-Sen method* (slope of performance-time characteristics). Statistical method provides straightforward way to compare data with acceptable confidence levels.	Excellent statistics-based methodology for analyzing data sets; base for building risk factors, cleaning cycles, and comparisons for soiling issues; possible standard for researchers. Thiel-Sen vs. least squares comparison.
Ennaoui et al. [46]	P	Qatar [Test results since 2013]	~20 PV Technologies	Focus: PV technology performance in harsh climates. Examples Under Test: crystalline Si, thin film, concentrating (thermal Linear Fresnel collector) and battery storage. Correlation with simulated yearly module generation, module temperature, solar irradiation (GHI, DNI,) and soiling conditions	Overview of test facility with extensive technology investments in harsh climate zone.
Fathi et al. [48]	MC	MENA Region	Si Modules (Glass)	Evaluation of nanotechnology coating for dust mitigation in heavy-dust and low-water regions. Hydrophobic coating provides for cooler operation of PV module, mitigation of dust issue, and reduces water requirements. "Nanotol" coating: Composition not provides (patent underway). Contact angles report (90°) and: "total price of about 0.72Euros/m^2/2 years, where the treatment is valid for two years at least".	Thermoelectric (thermal imaging) analysis of coating. Some interesting details on CeNano GmBH, June 2016: http://www.cenano.co.uk/nanotechnology-products/information-center/press/press-news/news-details/beneficial-effects-of-nano-hydrophobic-coatings-for-solar-photovoltaic-modules-in-dusty-environment/
Fang et al. [47]	MC	China (Mu Us Sandyland)	Solar Module Plant Configuration	Engineering used to design layout of PV plant in windy area. • Project: solar panels made the wind speed in the height of 20 cm and 200 cm decreased by 44.06% and 63.68%, respectively. Wind speed is positive to height in the project area periphery and middle of the solar panels, and the wind speed below 60 cm between the solar panels increased much more obviously, which is not conducive to sand (soiling) stabilization. • In the project area periphery, straw checkerboard barriers, gravel capping and soil covering measures play an important role in sand-fixing, in which gravel capping measures is the optimum. • In addition to straw, between the solar panels, gravel in undercutting area plus red mud in accumulating area is the best combination to reduce soiling.	•Solar panels make the spatial distribution of wind speed flow field changed significantly, wind speed near the surface at the wind outlet of solar panels increased while the wind speed far away the ground at wind inlet of solar panels reduced, and undercutting area and stacking area between the solar panels occurred. Information: *Mu Us Sandy Land* is a desert in Central China. It is crossed by the Great Wall of China at the southeastern end of the desert.
Ferretti et al. [51]	MC	Germany (Berlin)	PV Module Surfaces	Primary objective: impact of cleaning on the surface of the modules (e.g. ARC) and possible damage (abrasion). Resistance to abrasion of various coatings evaluated. Results are correlated with reflection measurements and the effect of sand/dust exposure.	A comparison of the reflection data (after accelerated aging test) with different particle sizes on different types of ARC.

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Publication Source [Reference Number]	**Focus** ***(see code)****	**Location [Duration]**	**Solar Device Type**	**Key Findings**	**Comments/Other Conditions**
Figgis et al. [53]	CM, A	Qatar (Doha) [10 days]	Borosilicate glass (5cm x5 cmx 0.16cm)	Development of the outdoor soiling microscope with objective the measure the deposit and removal of individual dust particles larger than 10 µm^2, and it used for detecting the onset and disappearance of condensation. Relation between the rate of soiling in PV modules and environmental parameters such as aerosol concentration, humidity and wind speed. The dust deposition is dependent of the wind speed, but it presents low correlation with PM10 aerosol concentration.	The deposition is mainly influenced by wind speed, while removal is dependent of the wind speed and the relative humidity.
Figgis et al. [54]	I, TO	Measurement Technique Review	PV module surfaces	Review of common techniques used in soiling measurements and characterization. Annual variations reported.	Angle of incidence of sun is reported to have a large impact on the apparent soiling loss of PV array with a "heavy" dust accumulation.
Fountoukis et al. [55]	MC	Arabian Peninsula	Evaluation of major dust simulation and forecasting models	Evaluation of the two primary dust emission models based on weather forecasting modeling for Middle East. Significant differences are reported in spatial distribution of dust emissions as well as sizes. AFWA simulation predicts 30% higher dust emission fluxes than S11 simulation, for example; And S11 predicts 50% lower PM10 concentrations.	Useful evaluation of the modeling approaches—key for predictive modeling of dust situations in various climate zones. AFWA, WRF-Chem, and S11 discussed.
George et al. [57]	MC	Laboratory	Coating of various substrates	Fabrication of polymer surfaces that exhibit superhydrophobic (and underwater superaerophobic) behavior by replicating femtosecond laser fabricated patterns via soft lithography.	"Nature-inspired" engineering of micro- and nanoscale roughness to enable hydrophobic behavior. General uses. Description of processing to realize these coatings.
Ghiotto et al. [58]	P, MS	Australia (Geraldton) [36 months]	PV Power Plant 10 MW (CdTe Modules)	Comparison of predicted results obtained using the Typical Meteorological Year (TMY), expected results obtained of the simulation using measurement data of site and actual results for a photovoltaic plant. In the months of low rainfall, greater soil deposition was observed and, consequently, a greater reduction in the output of the module. It is important to consider the variation of the solar spectrum in the performance simulations.	It was identified a reduction from to 2% in the output electrical parameters of the modules due to deposition dust. The actual energy presented a difference between 0.24% and 1.98% higher than predicted.
Giolando [59]	TR, MC	Laboratory	Soda lime glass substrates (10 cm x 10 cm x 3 mm) General Use	Development a self-cleaning coating on soda-lime glass obtained from a dispersion of titanium dioxide nanocrystals in an ethanolic solution of *cis*-di (ethyl formate) tetrachloride tin and ammonium bifluoride, denominated fluorine-doped tin oxide (FTO)/ titanium dioxide coating.	FTO/titanium dioxide coating has high transmittance of visible light; increased abrasion resistance; stable to tempering temperatures and self-cleaning properties in ambient sunlight, and in addition it is also electrically conducting and it can be used to provide anti-static properties to the coated device.
Gostein et al. [60]	MC, P	USA	Si PV Modules	Deployment of soiling monitoring stations with custom PV modules having coatings with both hydrophilic and hydrophobic properties (evaluating soiling properties). Soiling of samples is evaluated by comparison to an automatically washed reference cell (part of station). Details of the effectiveness of the coatings—and the monitoring process.	Very good and detailed descriptions of the experimental stations and the procedures.
Guo et al. [63]	CM, A	Qatar (Doha)	Adhesion Studies to Module Glass	<u>Investigation</u>: the effects of environmental factors on dust particle adhesion of common materials used at Doha as glass windows and solar panels, among others: Mechanisms for dust particles attaching to the surfaces of different morphology. <u>Dust Adhesion to Glass</u>: Particle area density level and optimization of surface roughness could lead to better control of dust adhesion.	Surface roughness and morphology of glass substrates is evaluated by atomic force microscopy (AFM). Morphological evaluation of dust particles is carried out using microscopic techniques (optical microscope, scanning electron microscope). The particle analysis of optical images is conducted by using image-processing software proving information of shape, diameter, and size distribution of dust particles.

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Publication Source [Reference Number]	**Focus *(see code)****	**Location [Duration]**	**Solar Device Type**	**Key Findings**	**Comments/Other Conditions**
Guo et al. [65]	MS	Qatar (Doha)	Modeling with comparisons to collected data	Model: A larger data set used to fit the previously developed linear model for daily CI change and daily average values of PM10, WS, and RH. And, a semi-physical model was developed to consider the non-linear mechanics of turbulent deposition, resuspension of deposited dust, and the effect of relative humidity on resuspension. This semi-physical model predicts the daily ΔCI slight more accurately than the linear model. Paper provides a potentially significant contribution to developing models that can be used for economic analysis of PV solar projects and plant maintenance.	Improvement of their previous model at the *Qatar Foundation Solar Test Facility*. The parameters obtained for the semi-physical model are in general agreement with literature values and are consistent with the physical meanings of these quantities. Detailed descriptions of the models and their development.
Hashim et al. [68]	TO, P, A	Iraq (Baghdad) [~12 months]	Si PV Modules	Effect of orientation/tilt: Evaluation of dust accumulation on fixed PV modules with different inclined angles (15°, 33°, 45°, and 60°). Ambient: PV modules performance and dust issues under different weather conditions (rain, wind, and humidity).	Observations: • The power losses of fixed solar panel at tilt angle 60° are less than that of solar panel at tilt angle 15°. • Weather conditions affect significantly on the accumulation of dust on solar panels and their performance (e.g., cleaning by rain in October). The high wind speed leads to natural cleaning, reducing the accumulated dust on the solar panels surface (summer months). The accumulated dust on the solar panels surface in summer months is more than that in winter months.
Hassabou et al. [69]	MC, A	Qatar and Germany	PV Modules (Thermal Management)	Focus: Effect of module temperature on mitigating the build-up of water that can combine with dust to form mud (then solid) coatings on PV modules. Condensation of water on the cell surface during night can be prevented by maintaining the temperature of solar PV panels above the dew point during night. (Cementation or solidification)	Study of PCM for passive thermal management of solar systems. Passive cooling can be realized by integration of PCM layers with the back side of PV panels. Benefits: increase both instantaneous conversion efficiency by 3-5%, while it can considerably increase the life span of PV modules and reduces maintenance and cleaning costs.
Ilse et al. [73]	CM, A, P, MC	Qatar and Germany	PV Modules (cementation)	Fundamental (and pioneering) studies of the soiling behavior and cementation or cement-like process for dust adhesion on PV module surfaces. Excellent TEM and EDX analysis of the interaction of Qatar dust particles with the module glass surface, showing extraordinary images with small fibrous structures between the surface and particle. New explanation of the cementation process involving the growth of fibrous clay materials	1-month exposures in Qatar desert provided these results. Very careful study-that provides alternative to previous “Na” based explanations of the cementation process.
Jamil et al. [74]	A, P	Malaysia [1 day]	Polycrystalline Si Module	Experimental-approach investigating the effect of soiling on PV module performance in a tropical climate (hot/humid Malaysia). Result: A worst case observed with ~20% reduction in power output.	Power, efficiency monitoring of test module.
Janko et al. [75]	MS	Arizona (Phoenix)	PV Modules for Simulations	Focus: Transient environmental factors such as clouds, rain, and dust storms presenting performance “uncertainties and challenges” for residential PV roofs. Model: Simulating residential loads, rooftop solar PV output, and dust storm effects on solar PV output to examine transients in the net system load. Phoenix, Arizona metropolitan area is used as a case study (dust storms several times per year).	Various solar PV penetration rates are also simulated to allow insight into resulting net loads as PV penetration increases in coming years.

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Publication Source [Reference Number]	**Focus** ***(see code)****	**Location [Duration]**	**Solar Device Type**	**Key Findings**	**Comments/Other Conditions**
Javed et al. [78]	A, P, CM	Qatar [Annual]	PV Modules	Objective: Determine the daily power output losses associated with the accumulation of dust on PV modules; relationship to environmental (weather, humidity, etc.) conditions Analysis of the composition of the collected dust. Results: Annually, ~0.52%/day loss for modules cleaned every second month. The mean and median particle size (by volume) was approximately 18 µm (mean) and 14 µm (median). Chemistry: Ca, Si, Fe, Mg, and Al. Minerals: Calcite, dolomite, and quartz.	Discussions of special harsh climate issues in MENA region. Stress impact of local climate on the performance (and sizing) of systems.
Jiahuan et al. [79]	MS, TO, A	China (Northern)	Modeling and simulation for PV operation	Modeling: Annual power output of PV plants of 36 cities (annual precipitation < 800mm) in Northern China, where the dust accumulation is > than southern China. Results: ● The mean annual power output of the 36 cities is 209.62 ± 30.15 kWh·5/m^2, with the maximal and minimal power outputs in Lhasa and Xi'an; ● The dust accumulation minimal effect on the optimal tilt angles; ● The maximal power output losses by dust (5.32%) is obtained in regions with annual precipitation is 100-200 mm, and the minimal power output losses by dust (2.09%), obtained in regions with the annual precipitation is 600-800 mm.	Extensive modeling of PV in multiple cities.
Jiang and Lu [80]	P, A	China (Hong Kong)	Si Modules	Experimental investigation: Dust particle deposition process on solar photovoltaic (PV) modules with different surface temperatures by a heating plate to illustrate the effect of the temperature difference (thermophoresis) between the module surface and the surrounding air on the dust accumulation process under different operating temperatures.	Careful and well-explained experimental investigations.
John et al. [82]	P, A, S, CM	India Laboratory Studies	Si, CdTe, CIGS Dust Collected from 6-Climate Zones in India	Controlled laboratory dust experiments using soiling samples collected from 6 locations (different climate zones) in India. Example of Results: Soiling loss on c-Si with Mumbai dust (17.1%) is about 2x that of Jodhpur dust (9.8%) for the same soil gravimetric density (3g/m^2). Dust from other areas (Pondicherry, Agra, Jodhpur, Hanle, and Gurgaon) are also reported. Cell type and spectral effects is major contribution of this study.	Excellent report on spectral effects (quantum efficiency measurements on cells). Comprehensive report.
John [81] ***Ph.D. Thesis***	A, P, MC, S, TR, CM, TO, I	India	All PV Module Technologies Deployed in all India Climate Zones	"One stop shop" for soiling information relating to (1) PV technologies, (2) spectral effects, (3) composition and morphology, (4) climate zone relationships, (5) cleaning, (6) module performance.	Extensive investigations and evaluations of dust issues relating to India's climate and growing PV investments. Several key publications have resulted from this dissertation.
Jones et al. [84]	MC, A, MS, CE	Saudi Arabia	PV modules	Determination and modeling of optimum cleaning schedules based upon real soiling conditions in Saudi Arabia (*K.A.CARE* studies). Cost considerations and calculations.	Very detailed, useful, and well-presented formulation of this important issue. Straightforward evaluation relating to severe soiling conditions (verifications)
Júnior et al. [86]	TO, P	Brazil	Si PV Modules	Detailed examination of the sensitivity of PV module performance as a function of ambient conditions (soiling, temperature). Evaluation of the effect of soiling on the tilt and azimuth of the PV module (total consideration of the orientation).	In Portuguese.

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Publication Source [Reference Number]	**Focus** ***(see code)****	**Location [Duration]**	**Solar Device Type**	**Key Findings**	**Comments/Other Conditions**
Kadhum et al. [87]	P, A	Iraq (Baghdad) [9 months]	Silicon Module	Evaluation of the effect of dust deposition in relation to the output parameters of the photovoltaic module. The dust has effect limited about the output current of the module, so the current decreases, but after a certain amount of deposited dust, the current tends to stabilize. In case of the output voltage, this is reduced proportionally to the amount of dust.	The rain is the most important factor that prevents the power degrading because of cleaning of the dust buildup; second factor is location that is related to the extent of dust accumulation.
Kazem and Chaichan [92]	S, P	Oman Laboratory Tests	Si Module	Investigation of the spectral effects on PV module performance using seven-selected colored filters and combinations. The study provides information that can be related to dust accumulation on PV panels and related spectral effects.	Elementary study that has interesting implications for laboratory-level dust investigations.
Kazem and Chaichan [91]	A	Oman (Desert Conditions)	Si Systems	Objective: Design and evaluation of best PV electrical power for Oman desert region. Parameters: Solar radiation, temperature, orientation, environment, and cost.	Broader evaluation of PV system performance in desert region. Consideration of Oman load demands.
Kazem and Chaichan [90]	P, A	Oman	Si Modules	Investigation: Environmental effects on PV module performance (temperature, humidity, wind, dust). Wind-dust interrelationships: Report that the wind significantly reduces dust accumulations. Local climate conditions (e.g., rain) can contribute to dust mitigation.	Mainly studies on temperature and humidity.
Kazem and Chaichan [89]	CM, P	Oman (Northern) [Up to 6 months]	Si Modules	Investigation: Energy losses caused by dust deposition on PV modules in Northern Oman. Study: Six dust samples collected over three months from six locations in Northern Oman evaluating physical properties. Results: ● 64% of particles had diameters 2μm-63μm ● Deposition rates depended on area ● Average daily loss in PV performance: 0.05% ● 3-4-month data show 30-40% power loss	Some indications of cleaning times No limitations for PV deployments.
Kazmerski et al. [93]	CM	MENA, Brazil (Laboratory)	Collected Dust Particles from Location on Module Glass	Fundamental studies of the adhesion of single dust particles to the module glass surface relating adhering force to surface composition of dust and glass. Special AFM technique used to evaluate levels of lateral force for various chemistries, dust particle sizes, etc. Measurement on cement-like situations (soluble salts, hydrocarbon bonding of particles)	Evaluation of relationships between chemistry and strength of adhering force. Evaluation of superhydrophobic and superhydrophilic surfaces as well.
Kazmerski et al. [95]	MC, P	Worldwide Locations	General PV Technologies	Examination and evaluation of the preemption (land preparation, orientation), restoration (cleaning), and prevention (coatings, screens) approaches to dust mitigation.	Discussion, estimation, viability, and comparison of costs for approaches.
Kazmerski et al. [94]	CM	MENA, Brazil (Laboratory)	Collected Dust Particles from Location on Module Glass	Refinement of procedure from [52] to estimate the force/unit area of contact between the particle and the glass. 3-D visualization technique used for estimating particle contact with substrate. Experimental data indicate that there is a normalization.	First measurement of inter-particle bonding strength.
Khademi et al. [96]	A, MS	Iran	3.2 kW Si Power Plant	Relationships between PV plant performance and climate zones. Modeling and prediction of the power output from 3.2 kW PV power plant using the MLP-ABC (multilayer perceptron-artificial bee colony) algorithm. “Dust” effects on resource is integral part of modeling.	A detailed economic analysis is also presented for sunny and cloudy weather conditions using COMFAR III software.

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Publication Source [Reference Number]	**Focus *(see code)****	**Location [Duration]**	**Solar Device Type**	**Key Findings**	**Comments/Other Conditions**
Khanum et al. [98]	P, S, A	General (Data mainly from India conditions near Bangaluru)	Si Modules	Examines the relationships between light scattering, absorption and reflection at surface of glass before the light impinges on the solar cell in the module. Proposes that the IR absorbed by the dust can allow the cells to operate at lower temperatures. (Absorption vs. wavelength data presented)Considers wind, installation geometry, and dust sources as controlling parameters.	Dust has to be the right chemistry and physical dimensions to provide this temperature benefit. Paper has many experimental details (chemistry of dust, etc.).
Khanum et al. [97]	P, CM, S	India [12 months]	Silicon Module	Priority: Analysis of the temperature increase due to the deposition of dust in silicon modules. The tests performed in this study proved that dusty PV have higher temperature than clean PV. Results: Identified the temperature increase in places surface of module with dust and surrounding surface, justified by the absorption of infrared radiation (IR).	Analysis of the physical-chemical composition of dust indicating C and Si as the major elements.
Kim et al. [100]	MC	Korea (Laboratory)	Thin-Film Solar Cells (development of coatings)	Objective: Investigation of simple methods to provide superhydrophobic coatings on solar cells for dual as ARC and anti-mitigation coatings. Approach: Al-doped ZnO nanorods are grown onto a Ga-doped ZnO film using a hydrothermal method. Results: (i) electrical contact from Schottky to ohmic; (ii) tapered shape reduce the surface total reflectance and increase cell performance; (iii) nanorods show the self-cleanable performance	Use of approach intended for ZnO layers on thin-film cells.
Kiran and Padaki [101]	MC	Laboratory Proposal	All PV Module Technologies	Proposal for method for self-cleaning of PV modules: System: DC motor, gear system or conveyor belt system, software system, battery, solar panel, rolling brush.	Essentially an automated brush system.
Koehl and Hoffmann [102]	MC, P, A	Germany [~60 day]	Si modules	Evaluation of the interrelationships of rain (moisture) and dust to causing potential-induced degradation (PID) in PV modules. Module temperatures and leakage currents used to study the rain-induced and soiling-induced increase in module surface conductivity—leading to possible PID. Conclusion: Rain and soiling are most hazardous conditions leading to PID	Module reliability link to soiling. Excellent descriptions of experimental investigations and conditions.
Kumar and Nagarajan [104]	CE, P	India (Tamil, Nadu) [6 months]	Rooftop Si PV Power Plant 320 mc-Si modules	High-level and detailed examination of the economics and operation of rooftop PV in hot/humid India zone. ● PV panel's continuous operation normally covered with a fine layer of dust and dirt, decreasing the amount of light fall on each PV cell ● The soiling losses were calculated 5% - 6% during the winter and 7% - 8% during the summer period in the year, resulting in annual losses at 6.5% in 2015.	Use of transformer-less string inverters.
Labelle et al. [106]	MC	United States (California)	Concentrating Photovoltaics	Evaluation: Coating solutions for concentrated photovoltaic (CPV): designed to be effective for anti-soiling and compatible with the optical concentration architecture.	The coating solutions tested had different properties, as state (solution or solid), deposition method, among others, but of high transmittance (above 97% for 400-1700 nm).
Landgraf et al. [107]	P, MS	Germany and Sahara Desert	Si PV Systems	Portion of the *"PerduS"* project of the *German Weather Service (DWD)*, the Karlsruhe Institute of Technology (KIT) and *Meteocontrol* currently examine how dust, as haze in the atmosphere and deposited on solar panels, impacts the performance of PV systems. Saharan dust: decrease resource by 10-20% in atmosphere Mix of Saharan dust with rain = "blood rain"	Comparisons in Sahara Desert and in Germany

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Publication Source [Reference Number]	**Focus *(see code)****	**Location [Duration]**	**Solar Device Type**	**Key Findings**	**Comments/Other Conditions**
Larson et al. [108]	P, MS	United States (San Diego) [4 years]	Si Module System	Development of the forecasting method for power output from PV power plants using least-squares optimization of Numerical Weather Prediction (NWP) and forecasting of the global horizontal irradiance (GHI). Soiling effects evaluated for system performance.	The forecast skill ranged from 13% to 23% over a persistence model. Location: Canyon Crest Academy and La Costa Canyon High School,
La Russa et al. [105]	MC	Italy	Films on ceramic-type surfaces	'Nano-sized titanium dioxide' possesses photocatalytic features providing self-cleaning properties to the materials with simple and non-expensive procedures. surface properties of TiO_2 coatings have been correlated with their soiling prevention.	Emphasis for use in historical sites. Application to other anti-soiling situations—PV.
Löbmann [109]	MC	Germany (Laboratory)	Anti-soiling and ARCs	Chapter: On the strategies of solutions based on sol-gel processing techniques in the production of anti-soiling coatings and ARCs. Porous SiO_2 films combine ARC and anti-soiling properties.	Chapter covers preparation, effectiveness of these bi-use films, and applications.
Lopez-Garcia et al. [110]	P, MC	European Solar Test Installation, Italy (Ispra) [30 years]	Crystalline Silicon PV Modules	Test used 28 modules produced by a single manufacturer, with different structural characteristics (modules with simple glass surface and modules with textured glass surface), exposed to open air for more than 30 years without cleaning. Manual cleaning increased the performance of the module, while high pressure water spraying showed only minor improvements in PV with textured glass. The results of improvement performance PV after the cleaning were in average value of 9.8% in P_{max}.	The results showed uniform soiling behavior for the flat-glass modules, while the modules with textured glass exhibited a greater variation in soiling.
Lu et al. [111]	P, CM, MS	China (Hong Kong)	Mono-c-Si Modules	Effect of dust and soiling on roof-mounted PV systems. Rate of dust deposition: Initially increased rate then decreased with larger dust particle size. Gravity effects on dust deposition (size of particles) investigated. Model for estimation of efficiency loss.	CFD simulations used. Follows previous publication: http://dx.doi.org/10.1016/j.apenergy.2016.07.030
Mani et al. [113]	MS	India (Shekhawati Region)	Si Modules	Model: Quantifies the relationship between PV power output, incident irradiance, and soil particle size and composition. Soil samples collected from Shekhawati Region (semi-arid area in northeast part of Rajasthan) and used in artificial soiling experiments. Result: Non-linear relationships between irradiance and power (regression analysis) and composition Tilt angle effects to maximize power.	Deviations: Soil present on the panel (with diameter 75 μm and below), the deviation from the tilt angle of a clean panel is 4°. if the soil Soil with particles (150 μm and 300 μm) the deviation is 8°.
Mani et al. [114]	P, A	India	BIPV Applications 5.25 kWp rooftop system	The current study is an experimental investigation into a 5.25 kWp roof integrated BIPV lab at Indian Institute of Science, Bangalore (India). Environmental conditions analyzed for performance.	PV performance characterized by higher operating temperature that detrimental to its efficiency and power output. Well-thought-out arguments for BIPV approaches for PV.
Mantha [160] ***PhD. Thesis***	DS, I, P	USA (Arizona)	Development of Dust Simulators (evaluated on Crystalline Si Coupons)	Detailed and careful development of three types of indoor artificial soiling deposition techniques replicating the outside environmental conditions to achieve required soil density, uniformity and other required properties. Systems: (i) Gravity deposition method, (ii) Dew deposition method, and (iii) Humid deposition method.	Excellent source for developing laboratory dust simulators. Validation on polycrystalline Si submodules. Soil evaluated included "Arizona" reference dust and dust sample collected from PV installations in Arizona.
Mariano et al. [85]	P, A, MC	Brazil (Curitiba) [3 years]	Grid-connected PV systems	Interest: Performance parameters - Final yield, performance ratio and capacity factor. Study included evaluation of dust deposition on PV panels and effect on performance in locations in Curitiba. Module cleaning and cleaning cycles investigated.	Examined temperature effects; relative humidity; wind speed/direction; frequency of dust occurrence; precipitation, tilting.

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Table 2 (*continued*)

Publication Source [Reference Number]	**Focus *(see code)****	**Location [Duration]**	**Solar Device Type**	**Key Findings**	**Comments/Other Conditions**
Mathiak et al. [115]	ST, TR, MC	Germany and Hot/ Arid Climates	Evaluation of Standards	Qualification and test procedures for PV modules in hot and dry climates evaluated. Important: Sand abrasion and dry cleaning resistivity test for PV modules. Two sand abrasion test methods (MIL STD 810G: Blowing sand, DIN 52348: Sand trickling) are compared concerning effects on transmittance and reflectance of PV glasses and PV modules.	Address issues for PV power plants for dust storms, cleaning concepts, and anti-sand storm measures.
Mayhoub [116]	MC, P	Egypt (Survey and Laboratory)	Windows for Daylighting	Surveys and analyzes the cleaning methods currently used for solar devices and conventional ***daylighting systems***. Introduces technologies that can currently be used to produce an "innovative daylighting systems (IDS)" cleaning system. Very fine coverage of six cleaning mechanisms and 12 cleaning systems that suit different types of IDS in various operating circumstances. These include air-blowing, water jetting, dragging-contact, rotary-contact and certain aid treatments. Air-cleaning and washing with water can both be used to restore functionality. Wiping and scrubbing are effective for increasing efficiency. (Further improvement is noted by drying solar collectors after washing.)	Interesting and useful link to PV issues. The systems discussed are all essentially available commercially.
Mazumder et al. [119]	MC, I	USA (Laboratory and Field Experience)	Electro Dynamic Screens (EDS)	Progress of the electrodynamic screen (EDS) technology for frequent water-free cleaning with low-energy requirements (alternative coating approach). Principles, modeling, construction, and lamination of the EDS films on modules and mirrors & experimental data showing power output restoration are examined Production and manufacturing options proposed. Uses in CSP reflectors indicated. Thorough and useful evaluation of this technology.	Though many applications have been investigation for CSP, this paper has a focus on PV. The results show the potential of EDS applications in largescale solar plants for frequent removal dust and achieving a high-performance ratio of the plant by maintaining high optical efficiency on the average compared to the water cleaning process.
Mazumder et al. [117]	MC	USA (Laboratory and Field Experience)	EDS (novel approach)	Novel approach using Corning Willow^{TM} glass (flexible, thin glass sheets). Potential high impact application for PV modules. Experimental data and analysis showing initial utility of this novel approach.	Co-benefit possible for PID. Very nice presentation of experimen- tal results and experiments. Important use of new thin-glass type that is of interest to many applications.
Micheli, Muller and Kurtz [123]	MS, P, CM, A	United States [24 months]	Mono-crystalline Si	Detailed predictive modeling. PM10 seems to better explain the trend of the soiling losses than other air-quality indexes. The frequency of rainfalls is more important than the amount of rain. It is important to consider the characteristics of climatic zones, including the frequency of rainfall, particulate matter, other factors.	Comparison between the different types of particles deposited on PV cells (TSP, PM10 and PM2.5). Important approach for PV installation considerations.
Mohsin et al. [126]	MC	Jordan	2 C-Si Modules	Prototype, smart automatic cleaning (and module cooling) system evaluated. System optimization with automatic data acquisition. Procedure: 2 modules – one cleaned, one not. "*8.7% was obtained as a result of minimizing the operational disturbances of dust accumulation and high surface temperature of the photovoltaic panel* " System: Pressurized water (through nozzles).	Water consumption reported to be "reasonable" Benefit to cooling of module (cooling provided important control parameter) Panel surfaces maintained < 30°C

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Table 2 (*continued*)

Publication Source [Reference Number]	**Focus *(see code)****	**Location [Duration]**	**Solar Device Type**	**Key Findings**	**Comments/Other Conditions**
Naeem and Tamizhmani [128]	A, P, TO	USA (Arizona) [3 months]	~20 c-Si (tilted) Modules	Mock rooftop configuration and monitored during dry and wet periods. Results: Heavy rain is an adequate cleaning “agent” Light rain can be cleaning or a “soiling agent” Dust storms in this climate zone are not severe issues because they are typically followed by rain.	Correlation of dust effect are correlated with weather and dust events. In-depth and interesting data for desert region in the USA.
Nobre et al. [130]	A, P	India (Delhi)	c-Si Modules/Sytems	Evaluation of rooftop systems within 100 km of Delhi. Two loss mechanisms: (i) soiling due to dust, and (ii) air pollution (decreasing the solar insolation). Results: ● soiling leads to losses between 0.3% and 0.6%/day. ● Air pollution could represent yield losses of ~6% on an annual basis for the sun's radiation.	Critical analysis bringing some caution for developers in this area of India.
Oh et al. [131]	MC	Korea Laboratory Processing and Testing	Module Glass	Focus: silica-based anti-soiling and anti-reflection coatings Coating is room-temperature processed (applied) Results: ● 2.56% improvement on average because of the anti-reflection function. ● Soiling loss is mitigated by > 3.85% according to the laboratory-based tests.	Descriptions of the processing of the coatings and the testing.
Ota et al. [132]	MC, P	Japan [7 months]	ARC/Anti-soiling coating on CIGS Module (and array)	Study: Silica-based layer with ARC and anti-soiling properties, coated onto the glass surface of a CIGS module Output of CIGS array: 3.2% better for coated modules than uncoated for the 7-month period.	Additional benefit noted: coating reduced the reflection of the light entering from a high incident angle.
Patil and Mallaradhya [134]	MC, P	India Energy Park, BEC Bagalkot	Si Modules (Automated Wiper System)	Design: Automated PV panel cleaning system. Detector (IR LED & photodiode detect dust accumulation on panel) System: automatic wiper dust cleaning mechanism for solar panel Results: 1.6%-2.2% increase in output by regular cleaning	Minimal description of the wiper system. Good discussion of results.
Parajuli et al. [133]	MS	MENA Region	Examination of Airborne Dust in MENA region (simulation)	Minerals in dust (dust storms): Technical analysis Analysis and Simulation: Dust emissions with both prognostic CESM winds and with CESM winds that are implemented with ERA-interim reanalysis values compare the simulated results with MODIS satellite data, MACC reanalysis data, AERONET station data, and CALIPSO 3-d aerosol profile data.	Result: “Anthropogenic dust sources that are not directly repre-sented by existing erodibility maps, shows improved performance in terms of the simulated dust optical depth (DOD) and aerosol optical depth (AOD) com-pared to existing erodibility maps although the performance of dif dferent erodibility maps varies by region.”
Paudyal and Shakya [135]	P, CM, A	Nepal (Kathmandu) [5 months]	Polycrystalline Si Modules	Decrease of 29.76% in the efficiency of modules not cleaned during the 5 months of analyses. The density of dust deposited in the modules ranged from 0.1047 g/m^2 to 9.6711 g/m^2. Dust concentration in the bottom of the modules.	Model calculates the global solar irradiation incident on the PV. Equation developed to calculate efficiency decrease of the module according with deposition dust.
Pedersen et al. [136]	P, MC	Norway	Glass and PV Modules	Study: ● Evaluation of losses due to soiling of modules in an inland climate in Norway. ● Assessment of the cleaning effect of rain in this environment. ● Demonstrate the effect of soiling can be accurately determined by a combination of optical measurements and high precision balance measurements (dust density is assessed by measuring the weight-changes of cloths used to clean glass samples).	Correlation with transmission losses from dust Interesting results and implications for a very Northern climate zone.

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Publication Source [Reference Number]	Focus *(see code)**	Location [Duration]	Solar Device Type	Key Findings	Comments/Other Conditions
Pitschel [140] ***Honors Thesis***	CE	USA (Michigan)	5-kW PV Array at Western Michigan Univ.	Focus: Optimizing net energy savings of PV system by using least cost approaches to tilt schedules and panel cleaning. Cleaning test used to evaluate viability and cost of panel cleaning with respect to pollen, dust, and soiling accumulation. Result: 35 degree tilt best	Detailed costing for known expense parameters (e.g., costs of labor to change tilt, cost of panel cleaning).
Pulipaka and Kumar [141]	MS, P, TO, CM	India Laboratory	Si Modules	Simulation: Irradiance loss factor quantifying the relation among irradiance, tilt angle, & PV power output. Results: Artificial soiling experiment and Sieve analysis are performed to obtain data for developing contours, & contour analysis used to determine the difference in power of a soiled panel from clean panel. A correction factor (soil particle size) is used to calculate power of the soiled module.	(i) Angular loss on a panel with soil sample containing 150 µm particle size in abundance was observed to be 22%. (ii) With 75-µm particles, the loss is 24%. (iii) With 300-µm particles, loss is 23.7% loss, (iv) With 75-µm particles, 52% angular loss.
Pulipaka and Kumar [143]	MS, TO, P, CM	India Laboratory	Si Modules	Calculations: a hybrid clustering algorithm used to "preprocess the data" that is used for neural network training and uses data division technique to predict the power output of a soiled solar panel. Soil Characterization: XRD, FTIR (size/composition) Neural network model predicts the power output (accuracy analyzed)	Artificial soiling experiments are conducted to obtain the data for developing the model.
Pulipaka, Mani, and Kumar [142]	MS, P, CM	India Laboratory	Si Modules	Model: Regression and neural network analysis. Experimental Support: Composition and particle size of dust ("quantifying parameters") Results: Dust particles size relation to power losses in PV modules.	Results: Paper provides similar studies, some complementary, to those reported by authors other two papers.
Qasem et al. [144]	I, MS	UAE (Dubai)	Arrays in Dubai	New approach for optimizing operation of a PV plant considering dust assessment & management Key data input: Image analysis of array using drones ("aerial robotics") having high resolution cameras. Novel MATLAB-based algorithm is used for dust detection and the method used for assessing the level of dust on a given surface	Algorithm is validated using actual electrical measurement of the array. Provides optimization of O & M
Rabanal-Arabach et al. [145]	P, TO, A	Egypt (El Gourna)	Vertically mounted Bi-Facial Si Modules (60 Modules)	Evaluation and arguments for choosing a proper mounting structure for vertically mounted bifacial modules facing east-west in desert climate conditions. Reduces shading, dust accumulation. The soiling test demonstrates that VMBM are practically unaffected by dust accumulation for this specific desert location.	mounting frame shading effect can easily turn on the bypass diode, diminish the power output up to ~10%. The ARC glass improves the mean energy yield for the VMBM by > 4.2%.
Rai et al. [146]	TO, P	India (Delhi)	CdTe and c-Si Modules	The soiling test demonstrates that vertically mounted bifacial modules are practically unaffected by dust accumulation for this specific desert location. spectral mismatch factor increases with the concentration of dust.	The mismatch factor gain increase in CdTe as compared to mono-crystalline module tha enhance the absorbance better, but the lower tilt is mostly effected due to higher-accumulation of dust and decrease in transmittance.

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Publication Source [Reference Number]	**Focus** ***(see code)****	**Location [Duration]**	**Solar Device Type**	**Key Findings**	**Comments/Other Conditions**
Ramli et al. [147]	P, A	Indonesia (Surabaya)	c-Si Modules	Effect of weather and dust on PV module performance. Results: ● Effects of dust accumulation and weather conditions on PV panel power output analyzed after 1-4 weeks of exposure. ● Two weeks of dust accumulation caused a PV power output reduction of 10.8% in an average relative humidity of 52.24%. ● Under rain conditions - decrease in PV output power of more than 40% in average relative humidity of 76.32%, and a decrease in output power during cloudy conditions of more than 45% in an average relative humidity of 60.45% was observed.	Climate: local environmental conditions including dust, rain, and cloud cover significantly reduce PV power output.
Rifai et al. [148]	MC, CM, MS	Saudi Arabia (Dhahran) Laboratory Experiments	Module Cover Glass	Study: environmental dust removal from the rotating disk effectiveness in surface cleaning of a photovoltaic panel cover plate. Dust Particle Characterization: scanning electron and atomic force microscopes, energy dispersive spectroscopy, and X-ray diffraction.	Adhesion measurements using AFM: Adhesive forces to disk greater than model used for calculations (which only considered Van der Waals Forces).
Saidan et al. [151]	P, A, CM	Iraq (Baghdad) [1 month]	Monocrystalline Si modules	The experimental results showed that dust can reduce the maximum current from 6.9% to 16.4% depending on the time-period of exposure of the PV modules to dust (i.e. from one day to one month)	Experimental results compared with analytical model results (estimation of decrease in short-circuit current, reduction in maximum current, and efficiency of soiled module compared to cleaned module; analysis of decrease efficiency due to dust).
Sabbaghpur Arani et al. [150]	MS	Iran (Kashan)	Simulations	Fault analysis of PV arrays to increase reliability. Common faults analyzed: shading condition (including dust), open-circuit fault, degradation fault, line-to-line fault, bypass diode fault, and bridging fault	Dust effects included in modeling.
Salvaggio et al. [152]	MC	Italy Laboratory Processing	ARC and Soiling-resistant films for PV	Self-cleaning coatings and ARC. Process: Photoactive TiO_2-only transparent coatings prepared by forming first a nanosol through controlled hydrolysis of tetraisopropyl orthotitanate (TIPT), followed by deposition of this nanosol on glass substrates by dip-coating with a final calcination step to form the surface nano-textured thin film.	Good optical properties (< 1% loss in transmission).
Samadhitya et al. [4]	A, P	India (Jabalpur) 3 months	2-Identical Poly-c Si Modules	Experimental investigation on two identical Si modules (tilted 10°). Evaluation of effects of ambient temperature, irradiance, wind speed (on mass density buildup of dust).	Fairly-thorough investigation of the meteorological effects on dust accumulation for this region. Examination of IV characteristics.
Sayyah et al. [158]	P, MC	Laboratory Evaluations of EDS	Electro-dynamic screens (EDS)	Relationships between EDS designs and electric-field distributions reported. Relationships to adhesion and repulsion of dust particles examined. Detrimental effects of humidity and moisture on EDS performance reported	Developed closed-form mathematical expressions for forces. Detailed examinations of the fundamental nature of the EDS processes.
Schweiger et al. [159]	P	Germany (Cologne) [~1 year]	General Performance of PV Modules	Indoor and outdoor testing of PV modules. Performance comparisons between indoor and outdoor operation (environmental effects)	Spectral conditions analyzed. Primarily a study of general performance, but some environmental effects are noted. Presentation of test configuration.
Sharma and Jain [161]	P, MC	India (Mumbai)	Two rooftop sites: (1) 40.5 kW (Powai); (2) 95 kW (IIT)	Rooftop PV array analysis for dust performance. Evaluation of the effect of soiling and the extent of soiling for two rooftop system in Maharashthra. Propose cleaning and mitigation schemes. Observations: Use of anti-soiling coatings can be effective; Cleaning cycles can be optimized to ensure output; Permanent hotspot from bird droppings if not cleaned; and Automated cleaning advantages.	Examination of discoloration, cracks, hotspots, bird droppings, and shading.

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Publication Source [Reference Number]	**Focus** ***(see code)****	**Location [Duration]**	**Solar Device Type**	**Key Findings**	**Comments/Other Conditions**
Spataru [162] ***Ph.D. Thesis***	P	Denmark	Many citations and illustrations of degradation	Diagnostic methods for characterizing and detecting degradation modes in c-Si PV modules/arrays: ● Failure analysis, accelerated testing, and degradation studies; ● Inverter and monitoring Diagnostic techniques for shading and soiling. Performance effects of soiling.	Comprehensive exposition on many failure mechanisms, causes, and detection. Illustration of observed degradation sources (including soiling).
Sun and Liu [163]	MS	China (desert, mountain areas)	Dust modeling (aerosols)	Regional climate model coupled with a dust module used to simulate dust aerosol distribution and its effects on the atmospheric heat source over the TP, East Asian summer monsoon onset, and precipitation in East Asia modulated by the uplift of the northern TP. Results: dust greatly increases in the Taklamakan Desert accompanied with the uplift of the northern TP, and the increase exceeds 150 μg/kg in Spring.	Highly detailed modeling and simulation of aerosol dust.
TamizhMani et al. [164]	I, A, P, TO	USA (Arizona, Florida, Colorado, New Mexico, Vermont) [1 year]	Dust monitoring	Five stations installed in USA for purpose of collecting data on soiling loss. Developed stations to monitor that include 10-tilt angles. Results: Arizona had highest annual soiling loss with high dependence on tilt angle; other sites almost no loss with not large dependence on tilt angle.	Excellent development of highly versatile research monitoring station.
Thangaraj and Velury [167]	P, A	India (Bangalore)	Rooftop PV Systems	4-different types of rooftop PV systems (poly-Si, mc-Si, HIT, and TF CdTe) installed on Infosys building for one-month). Comparison of cleaned and uncleaned modules. As much as 22% change in 1-month period.	Soiling losses measured. Very good descriptions of the rooftop installations. Infosys has major PV investments in India.
Touati et al. [169]	I, MC	Qatar (Doha)	Polycrystalline Si Modules	Instrumentation Development: System with buck-boost converter enhanced with a maximum power-point tracker (MPPT) serving as a PV load, sensors- system that collects climatic parameters including dust, wireless radio, and a LabVIEW-based monitoring and recording station. Results: Max power output from a poly-crystalline panel decreases by around 30% for a dust exposure of five months (cleaning required with specific frequency for this region).	Complete system design and description provided.
Urrejola et al. [172]	P, A	Chile (Santiago) [~2 years]	Poly-, mc Si and Thin Film PV modules	Performance degradation for PV systems (2014-2015). Results: degradation between 0.13% and 0.56%/day under soiling in highly polluted Santiago. Yearly degradation of the arrays system was found to be in the order of 1.29% for the polycrystalline array, 1.74% for the monocrystalline array, and 2.77% for the thin film system array. Cleaning Rates: optimal strategies of cleaning for different energy prices; a critical cleaning period of 45 days for a real case, independent on cleaning cost and energy prices was determined.	Discussions of reasons for different degradation for PV technologies tested. Data is weather corrected. Thin-film modules are a-Si:H.
Vasisht et al. [174]	P, A	India (IIsc Bangalore)	20 kW c-Si System	Evaluation of the Performance Ratio of the system. Although not dealing with dust directly, the information covers the seasonal and environmental occurrences to evaluate PV system performance.	Good foundation science and technology of critical parameters for PV system performance
Vengatesh, et al. [175]	P, TO, A	India (Tamil Nadu)	c-Si Modules	Performance of PV module under uniform and non-uniform conditions such as change in irradiation (passing clouds), change in temperature, accumulation of dust, and change in wind speed using MATLAB-Simulink environment.	Parallel configuration of PV module is observed to have better characteristics for non-uniform conditions and minimizing shadowing effects.

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Publication Source [Reference Number]	**Focus *(see code)****	**Location [Duration]**	**Solar Device Type**	**Key Findings**	**Comments/Other Conditions**
Wild [178]	MS, P	Australia (Simulation/ Modeling)	PV Array	The SAM model is used to model and simulate PV output for 3 PV systems installed at Gatton (Australia). Content: Use of 3 different module soiling levels (low, medium, high). Result: Medium and high rates reduce PV output 1.1% to 1.4% and 3.1% to 3.8% depending on the PV technology.	Some discussions of importance to the systems costs.
Yadav [180]	P, I	India (Uttar Pradesh) Laboratory (controlled conditions)	Crystalline Si Module	Special "self-designed" PV module having a series-parallel configuration was used for partial shading and dust accumulation studies. Results: The results show that diagonal partial shading pattern and ash dust sample have more effect on the PV module performance among all the considered shading patterns and dust samples.	Special measurement technique: uses 2-moving shading patterns (horizontal and diagonal) and four dust samples of different particle properties at three-irradiance levels.
Yoon and Kim [181]	P, A	Korea	Inverter	Effects of dust in desert regions on the inverter in a PV system. Inverters installed outdoors are especially sensitive to temperature fluctuations and fine dust in the air. Examination of approaches and techniques to overcome these issues for desert regions.	Detailed information on the electrical tests and performances of the inverters.
Zarei and Abdolzadeh [183]	MS, TO	Iran	Si Modules	Optical and thermal modeling of PV module performance as a function of tilt. Comparisons to actual data show good correlations. Results: Example - maximum output power of a 30° tilted (dust surface) PV module with 0.224 mg/cm^2 dust deposition density on its surface is 13.5% lower than the clean tilted PV module.	Model and study is useful for PV designers to predict PV performance under thermal and dusty conditions.
Zorn [184]	A, CM	Iceland Laboratory	Si Modules	Effect of volcano eruptions (volcanic ash) on the performance of PV modules. Investigation: influence of volcanic tephra deposition on PV modules performance. Systematic set of experiments conducted under controlled conditions using an artificial light source, measuring the electrical power generated from the PV-modules (determining the dependency of the volume of tephra covering a module and its subsequent loss in power produced & influence of the tephra grain size).	Dust: Fine ash has a trachybasaltic (volcanic rock with composition between trachyte and basalt) composition (typically less than 60-µm diameters) Interesting discussion and presentation of very disruptive dust event for PV and other solar applications.

rich in phosphorus. Satellite measurements have tracked the trans-Atlantic movement from this small region to deposit the material on South America—and especially the Amazon region, where the phosphorous is the source of critical nutrients for the rainforest (about 24,250 tons a year). And the source for accumulated dust on some PV installations.

It should also be noted that there are several *outreach activities* to share research results, inform about ongoing efforts, and discuss approaches to these soiling issues. These include:

- Professional Society and regional major annual conferences on PV and CSP that are incorporating the science and technology of soiling in their reliability programs:

(1) *SolarPACES* (www.solarpaces.org), dealing with solar thermal, CSP, and CPV primarily.
(2) *IEEE Photovoltaic Specialists Conference* (IEEE PVSC) (www.ieee-pvsc.org) - The oldest of the dedicated PV conferences dealing with science and technology (U.S. based)
(3) *International Photovoltaic Science and Engineering Conference* (PVSEC) (http://pvsec-27.com) – The annual Asia-Pacific based PV international meeting, representing the largest producers and users of this solar-electric technology.
(4) *European Photovoltaic Solar Energy Conference* (EU PVSEC) (www.photovoltaic-conference.com) - European PV meeting, which has been the largest of these conferences dealing with PV research, technologies, industry, and applications.
(5) Recent new and directed workshops: (1) *Soiling on PV Modules* (co-sponsored by NREL and the Dubai Electricity and Water Authority – DEWA. First workshop held in Dubai, April 2016; Next scheduled for Dubai, October 2017. (2) Texas A & M at Qatar has been hosting an annual *Workshop on Anti-Dust Technologies*, organized by the Qatar Environment & Energy Research Institute. (3) The *Solar Energy Research Institute for India and the United States* (SERIIUS) (www.SERIIUS.org) has ongoing programs and projects that link with other world activities concerned with solar device reliability and soiling. They hold periodic workshops and meeting focusing on these areas in India and the U.S.

- Web-based activities and information:

(1) International PV Quality Assurance Task Force (PVQAT) established its Task Group 12 focused on understanding, quantifying, and mitigating losses of electricity generation for PV systems caused

Table 3
Concentrating Solar (Thermal) Power (CSP) Technology Applications: Summary of dust and soiling papers published in 2016 indicating primary focus, device/materials investigate, conditions and findings. The *Focus Code* (for primary contributions) is: *P = Performance, *MS = Modeling/Simulation; *CM = Composition/Morphology; *TR = Transmission/Reflection; *CE = Cost/Economics; *MC = Mitigation/Cleaning; *A = Climate conditions/effects; *I = Instrumentation, *S = spectral effects, *TO = Tilt/Orientation, *EC = electrical charge of particles, *DS = Dust Simulator, *ST = Standards.

Publication Source [Reference Number]	**Focus** ***(see code)****	**Location [Duration]**	**Solar Device Type**	**Key Findings**	**Comments/Other Conditions**
Anglani et al. [12]	MC, MS	Laboratory/Modeling Studies	CSP Systems	Evaluation and numerical study of the use of high-pressure water spray systems to clean CSP reflectors (mirrors, heliostats, etc.) Fluid dynamics simulations used with ANSYS CFX software to evaluate the shear forces ("critical phenomena" to the soil/dust removal process): provide the basis for optimizing the dust removal. Report on tests varying key parameters of inter-axial nozzle distance, standoff distance, jet pressure, and jet impingement-angle.	Results: Forces generated over "flat" target surface are proportional to both the inlet pressure and the water velocity over the surface. The shear stresses decrease with increase in the stand-off distance.
Bouaddi and Ihlal [25]	P, TR, A	Morocco (Southwestern) [~6 months]	CSP Aluminum Mirrors	Object: measured reflectance data are modeled using locally weighted regression to capture the changes in reflectance over time. Reflectance from Al mirror determined over 6-month monitoring period.	Effect on potential plant outputs.
Bouaddi et al. [23]	P, MS, A, CM	Morocco	CSP Aluminum and Glass Mirrors	Two Morocco sites: Agadir and Tantan, Results: ● Monthly soiling study revealed that glass mirrors are more susceptible to soiling ● Aluminum I, II, and III mirror performed differently in reflectance recovery after rain. ● Cumulative long-term soiling: exposed mirrors were found to lose up to 73% of their initial cleanliness during the first 12-weeks of exposure. DFA modeling of the long-term soiling time series found, based on the Akaike Information Criterion (AIC - measure of the relative quality of statistical models for a given set of data), that the best model has two shared trend patterns.	Aluminum mirror proposed to be better in these environments. Soils: Tantan region is characterized by Gray-brown and Calcareous soils, with sandy Silt topsoil, which is intermediate between silica sand and the hamadias silt (*silt*-loam soil with varying hygroscopic moisture). Agadir region has mainly calcimorphic soils, with topsoil characterized by loam or sandy loam texture, & isohumic (soils with characteristics determined by climate and local vegetation) sub-tropical soils (brown/chestnut soils) with loam or sandy loam topsoil & clay loam in deeper soils.
Bouaddi and Ihlal [24]	P, A, CM	Morocco (Southwestern) [1 month]	CSP glass and Al reflectors	The monthly soiling of second-surface silvered-glass and aluminum type mirrors exposed in southwest Morocco is evaluated. Results: ● glass mirrors present a lower reflectance values than the aluminum type. ● rain has stronger cleaning effect on the glass than on the aluminum type mirror. Comparisons of mirror material performance.	Cleanliness factors reported over monthly period for mirror types, with degradations for each.
Burgess-Gallop [28] ***Honors Thesis***	I, A	Australia	Remote sensing of heliostat performance	Development, examination, and evaluation of the technical feasibility of applying and automating remote sensing techniques to estimate the solar-weighted specular-reflectance of heliostats within concentrating solar thermal (CST) plants. Experiment: primary remote sensing technique investigated uses a visible-range imaging sensor to estimate the reduction in specular reflectance of a soiled heliostat.	Look at optimizing the cleaning cycle for heliostats.
Ennaceri et al. [45]	P, A	Morocco	CSP mirrors	Objective: Identify ageing tests suitable for the nature of different mirror samples and the specifics of different potential sites in Morocco where the CSP reflectors can be potentially deployed. Harsh weather conditions, including dust storms and temperature, are discussed.	Considers several types of highly reflective CSP mirrors.
Fernández-Garcia et al. [50]	MC	Spain and General	CSP Systems	Discussions of various anti-dust mitigation coatings for CSP mirrors (Section 2.1).	Complete discussion and explanation of the hardware, components, and operation of CSP solar plants.
García-Segura et al. [56]	MC, A	Spain	CSP Systems	Minor discussions of the need to enhance the anti-soiling properties of CPS reflectors. Some soiling and cleaning operations.	Mainly a paper on CSP durability in harsh climates.
Guan et al. [62]	I, CM, TR	Australia [1 year]	Mirrors	System to monitor the effects of dust on the reflector surfaces: (1) Dust monitor collecting data and weather conditions; (2) Metallic test bench with different solar mirrors to correlate the surface dust deposition and the reflectance.	System provides for real-time monitoring.

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Table 3 (*continued*)

Publication Source [Reference Number]	**Focus** ***(see code)****	**Location [Duration]**	**Solar Device Type**	**Key Findings**	**Comments/Other Conditions**
				Results: Average dust diameter < 20 µm and dust concentration ~30 µg/m^3 (over one year). Reflectance decreased to about 20% from 92% after 1-month exposure.	
Heimsath et al. [70]	TR, MS	Israel (Negev Desert) and Germany	Outdoor and Laboratory Measurements of Reflectors	Understanding of the effect of dust on specular reflectance in solar mirror. Results: ● noticeable decrease of specular reflectance when the angle of incidence is increased (shading and blocking mechanisms caused by dirt particles). ● Main physical cause: near-angle scattering leads to a further decrease of specular reflectance for smaller angles of acceptance. Study considered mirror samples tested both outdoor exposed and indoor artificially soiled.	Model proposed and evaluated.
Houssame et al. [71]	DS, I, ST	Morocco	CSP Systems (Dust Simulator System)	System: Accelerated sand abrasion aging chamber designed for improving the reliability and repeatability of existing systems. Based on the open circuit sand blower design (Mil Spec with existing sand abrasion standards). Dimensions: 185 cm x 56 cm x 44 cm.	Major focus: Abrasion of reflector surfaces from sand impingement.
Musango [83] ***Masters Thesis***	I, MS	South Africa	CSP Reflectors	A reflector optical degradation assessment device ("real-time cleanliness monitoring sensor" (RCMS)) was designed, developed and tested for its ability to measure soiling optical degradation for mirrors. Neural network model developed to simultaneously relate various weather factor to optical loss by soiling. Error analysis carried out on results.	Model demonstrated that a combination of weather factors could be used to estimate the optical degradation caused by soiling on CSP reflectors. High coefficient of determination was observed from the neural network model results, as compared to the correlations that considered the relationship between cleanliness and a single weather factor, done in the experimental analysis.
Pennetta et al. [138]	P, A	Australia	CSP reflectors (factors such as wind effects on dust accumulation)	Object: To provide in-depth insight to interaction between the main parameters and airborne dust concentration, providing quantitative information for the development of future mirror dust models. Outcomes: (i) Critical role of wind responsible of dust concentration in conjunction with occurrence of higher wind (direction) in the range 60-120°. (ii) Monotonic increase of ambient dust accumulation has been observed with high correspondence to wind direction. (iii) very low effect of the ambient temperature and contribution of the barometric pressure.	Observations: Dust is the main cause of reflectivity loss and cleaning of mirrors is critical to restore economical and adequate level of reflectivity. Buy, the high cost of cleaning requires additional assessments and identification of a balanced plan for dust removal or prevention.
Pennetta et al. [137]	P, A	Australia	CSP reflectors	Insights to the interaction between the most relevant weather parameters affecting soil accumulation. Results: (i) Significant dependency of dust concentration versus humidity and ambient temperature, (ii) Relationships between wind speed and ambient temperature. Observation: As the temperature decreases, an increase of humidity and dust concentration occurs (overnight phenomena).	Indications that more effective cleaning can be accomplished in the early mornings.

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Table 3 (*continued*)

Publication Source [Reference Number]	**Focus *(see code)****	**Location [Duration]**	**Solar Device Type**	**Key Findings**	**Comments/Other Conditions**
Ruiz-Arias et al. [149]		Spain and USA Analysis of Resource	CSP	CSP requires adequate direct-normal insolation (DNI). Current methods of using aerosol optical depth (AOD) lead to "systematic underestimation of predicted long-term DNI"—and this can be up to 10% (not helpful for CSP). Recommendations: Use of daily or monthly AOD data are provided on a geographical basis.	A very good presentation of the methods, current-status/usages, limitations, and possible sources of error in evaluating solar resource (especially for concentrating technologies). Discussions directed for CSP—but useful for PV community as well.
Samson et al. [154]	MC	Spain (Plataforma Solar de Almería) and UK (Cranfield)	CSP	Cleaning of polymer coatings on CSP reflectors (mirrors). Relationships to accelerated ageing by contact cleaning procedures. Effects on optical parameters and visual characteristics of the polymer coatings with cleaning using brushes and water. Cleaning with soft brushes and (small amount) water using both linear and rotational motion provide best solution.	Careful and detailed study and evaluation of these cleaning processes used by CSP installations.
Samson et al. [155]	MC	Iran, Libya, and Algeria	CSP	Objectives: Investigations of the airborne particle size, shape, and composition of dust in three arid locations (suitable for CSP plants) in Iran, Libya, and Algeria. Results: Sand/dust collected at heights between 0.5 to 2.0 m, but have different particle size than collected from mirror (smaller on collected mirror surface). One explanation is that the large grain size particles rebound from surface.	Mirror cleaning is discussed in terms of the particle sizes.
Sansom and Fernández-García [153]	P, TR	Spain and U.K. Laboratory	Polymer Reflectors (CSP)	Study: Accelerated ageing of commercially available silvered-polymer film by contact cleaning using *brushes and water*. The effects of a range of cleaning brushes are discussed, with and without the presence of water, in the presence of sand and dust particles from selected representative locations. Reflectance measurements and visual inspection show that a soft cleaning brush with a small amount of water, used in a cleaning head with both linear and rotational motion, can clean polymer film reflecting surfaces without inflicting surface damage or reducing specular reflectance.	Detailed physical investigations of the effect of cleaning and resulting damage (loss of reflectivity) for polymer reflectors for CSP systems.

Table 4

Photovoltaic Technology Applications: *PRELIMINARY* summary of dust and soiling papers published in 2017 indicating primary focus, device/materials investigate, conditions and findings. This is a *partial listing* for year 2017 (up the time of submission). The *Focus Code* (for primary contributions) is: *P = Performance, *MS = Modeling/Simulation; *CM = Composition/Morphology; *TR = Transmission/Reflection; *CE = Cost/Economics; *MC = Mitigation/Cleaning; *A = Climate Conditions/Effects; *I = Instrumentation, *S = Spectral Effects, *TO = Tilt/Orientation, *EC = Electronic Charge of Particles/Surface, *DS = Dust Simulator, *ST = Standards [76,165].

Publication Source [Reference Number]	**Focus** ***(see code)****	**Location [Duration]**	**Solar Device Type**	**Key Findings**	**Comments/Other Conditions**
Abderrezek and Fathi [2]	P, CM, TR	Algeria (Outdoor and Laboratory)	Si Panels	Effect of dust on electrical and thermal behavior. Evaluation of different dust types on transmission of light to the panel. Particles evaluated for composition and size. Module IV characteristic monitored for accumulation and uniformity.	Energy2D computer simulation code used to validate the thermal behavior applied to the glazing and PV module (glass, EVA, cell, frame and Tedlar).
Al-Salem [7]	MS	Saudi Arabia (Simulation)	Simulation of 2-row PV panel configuration	Prediction of dust accumulation due to "dynamic shading" in 2-rows of PV modules. A" LaGrangian solver" was used to track the movement of dust particles. The 2 rows of panels with different heights above ground H and separation L are modeled to determine dead spots, where air would decelerate causing the dust particles to settle on the surface of the panels	Conclusions (detailed modeling): • For reduction of dust accumulation tropical areas with angle of tilt ~24°, the panels are better installed at a height to distance ratio between 0.5 and 0.7.• Installing the panels on the ground with no clearance is "worst case" since it positions the 2nd panel in the wake of the first panel.• Increasing the height of the PV installation does not necessarily reduce dust deposition, because the wake widens.
Bergin et al. [20]	P, A, MS	India, China, and the Arabian Peninsula		Study: Combine PV field measurements and global modeling to estimate the influence of dust and PM related to anthropogenic sources (e.g., fossil and biomass fuel combustion) on module/plant power output. Results: (1) Energy reduction by ~17–25% across India, China, Arabian Penninsula, with roughly equal contributions from ambient PM and PM deposited on photovoltaic surfaces; (2) Northern India: Dust and anthropogenic PM are comparable; Eastern China: anthropogenic PM dominates.	PM is responsible for solar power reduction of ~1 GW in India and ~11 GW in China China (of current generation capacity)
Bouaddi et al. [22]	A, MS	Morocco(Arid Climate Zones(> > 12 weeks)	CSP Mirrors	Continued documentation on the soiling issues in the two areas in Morocco: Agadir and Tantan (southwestern Morocco). Soiling patterns on mirrors established; effects of environmental parameter (wind, rain, etc.) Glass vs. various aluminum mirrors. Dry period: Al superior to glass.	DFA modeling of long-term soiling. Continuation of several previous papers in 2016.
Daniento et al. [40] [REVIEW]	P, I, MS	Italy and U.K.	Review	Review of recent advance on monitoring, diagnosis, and power forecasting for photovoltaic systems is presented in this paper. Previous works are classified into 5 categories: Electrical methods, Data analysis based on artificial intelligence, power forecasting, thermal analysis, and power converter reliability.	Covers mainly last 5 years of publications. Reliability Review. [129 References]
Du Plessis [44] ***MEng Thesis***	P, MC, A	South Africa (Semi-Arid)	C-Si PV Power Plants and 16 mc-Si Modules	Performance: Understanding of soiling and extent of problem in semi-arid areas (for investors, researchers). Mitigation Techniques: (i) Hydrophobic anti-soiling coating, (ii) Biweekly and long term (six months) cleaning routines, consisting of water based (wet) and dry clean methods. Results of these mitigation methods are compared to that of modules exposed indefinitely. Results: clearness ratio (CR) is further quantifies dust soiling for the stationary modules, which compares the PR of modules to that of two reference modules, cleaned biweekly. For the 6-month stationary module analysis, results conclude a maximum recorded reduction in CR of 2.7 %. A maximum ideal PR difference of ~1:9 % is recorded for both the coated and uncoated sets of long term exposed modules, compared to the short term cleaned modules. Single-axis tracking system also evaluated; coated modules show 5.5% CR.	Extensive evaluation of the soiling in these semi-arid regions of South Africa. Excellent treatment of data acquisition and monitoring.
Fathi et al. [49]	P, MC, A	Algeria and Germany	PV (Si Modules)	Issues relating to hot climates with high dust density and low water availability. Application of nanotechnology coatings (hydrophobic) f or dust mitigation. Thermoelectric analysis used to investigate effect of nano-coating on photovoltaic (PV) (showing they are cooler in operation). This behavior is due to hot spot caused by shading effects of dust compared to uncoated PV panels.	Aimed at MENA region.

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Table 4 (*continued*)

Publication Source [Reference Number]	**Focus** *(see code)**	**Location [Duration]**	**Solar Device Type**	**Key Findings**	**Comments/Other Conditions**
Figgis et al. [52] [REVIEW]	MC, A	Qatar	Review of Adhesion Mechanisms for Dust on PV Modules	Review of adhesion mechanics of soiling particle to the PV module surface. Focus on desert climate zones. Presents "original data" from Qatar environmental conditions. Discussion of mitigation approaches.	Interesting introduction to adhesions issues; look at the complexities—including cementation. Review of soiling issues in arid regions.
Guan et al. [61]	P, TR, A	China (Chang'an District, Xi'an) [Months]	Si PV Modules in Solar Park	Study: Effect of dust deposition on the module temperature, the transmittance, and the output power of the PV modules. Interest in the effects of on the dust deposition density on module temperature. Result: Dust accumulation reduced the transmission but also the module temperature.	Transmittance of a PV module decline ~20% within 8 days due to natural dust deposition.
Guo at al. [64]	P, MC	Qatar	EDS Screens (Tested on PV Modules in Field)	EDS fabricated on PV modules and test in field (Qatar). Field Test: Electrodes were damage, and no mitigation effects could be observed. Result: Need for redesign of EDS device based upon this design and electrical requirements.	EDS Structure: Polyethylene terephthalate (PET) substrate w/ screen-printed silver electrodes, and PET cover sheet that is bonded to the substrate using a synthetic rubber adhesive.
Gupta [66] [REVIEW]	P, A	India (Rajasthan, Thar Desert)	Review of past research on dust	Appraisal of the status of current research studying dust effects on PV modules (performance). Gap analysis of current research and needs. Tabulated data on historical publications.	[101 References]
Hudedmani et al. [72]	CM, P	India	Cleaning of Si PV Modules	Comparative study of various cleaning methods of solar panels, with emphasis on an innovative approach using the separation of dust by electrostatic precipitator (ESP).	Because ESP only apply energy to the particles, technique is efficient.
Jamil et al. [176] [REVIEW]	P, MC	Malaysia	Review of dust mitigation approaches for PV modules	Types of soiling are defined. Mitigation techniques are reviewed and evaluated (advantages and disadvantages on the mitigation techniques). Two tables provided that summarize the methods and provide a "guide for selection of the appropriate approach."	Extensive discussion of the cleaning processes.
Javed et al. [77]	CM, A, P	Qatar (Doha) [10 months]	Si modules in Doha Test Facility	Characterization of dust collected from modules in Doha test facility (accumulation rate determined gravimetrically). Dust characterized: Particle size analysis, X-ray fluorescence (XRF), X-ray diffraction (XRD), and scanning electron microscopy (SEM). Cleanness index change rate (CICR) reported. Composition/chemistry: Calcium most abundant element in the accumulated dust, followed by silicon, iron, magnesium and aluminum. Calcite, dolomite, and quartz were the dominant minerals.	Data reported useful for quantitatively determining the degree of soiling and its effect on PV performance in similar regions to this desert location.
Kamouch and El Hor [88]	A, P, TO, CE	Saudi Arabia (Jarzan Region) [16 weeks]	PV Modules	Effects of dust accumulation on photovoltaic solar panels in Jazan region (KSA). Effects are evaluated in outdoor measurements and it was found that regular dust accumulation reduces the solar cells efficiency by about 10% for an exposure time of 16 weeks. Tilted panel (angle of 30°) accumulates more dust than the panel tilted by 50°.	Jazan (or Jazin) Region is the second smallest region of Saudi Arabia. It stretches 300 km along the southern Red Sea coast, just north of Yemen.
Kosmopoulos et al. [103]	MS, P, A	Greece (Eastern Mediterranean)	Eastern Mediterranean	Impact of dust on surface solar radiation examining extreme dust events. Radiative transfer model (RTM) and chemical transport model (CTM) simulations were used to quantify the extent of dust impact on surface irradiances. Results: Reduction in solar energy exploitation capacity of PV and CSP installations, under this high aerosol load.	Region: anomalously high aerosol loads were recorded between the 30 January and 3 February 2015
Madhi et al. [112]	P, A	Iraq	Small c-Si PV System	Effect of Iraqi climate conditions (temperature, solar radiation, wind velocity) on the performance of PV system. Effect of dust and pollution accumulation on performance and the mitigating effects of rain and wind were shown to be critical.	Significant report on local climate conditions affecting PV performance and the interplay among these various climate parameters. Comments on occupation-time effects.

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Table 4 (*continued*)

Publication Source [Reference Number]	**Focus** *(see code)**	**Location [Duration]**	**Solar Device Type**	**Key Findings**	**Comments/Other Conditions**
Mazunder et al. [118]	MC, P	Overview of EDS technology	EDS for PV and CSP	Overview of EDS operation and status of technology development. Principles of the device operation, fabrication and lamination into PV modules and CSP reflectors. Challenges and benefits of this technology.	Excellent overview of the EDS technology and experiences in operation and development.
Menoufi [121]	P, ST	Worldwide	Recommend standard	Introduction of the PV Soiling Index (PVSI), indicating the performance of PV modules under dust exposure/accumulating at standard operating conditions (STC) (independent of location)	A recommendation that IEC 6089 be used with STC conditions: Based upon Literature Review
Micheli and Muller [122]	MS, P	US	Predictive modeling evaluations	Comparison of data from 102 meteorological and environmental stations with reports from 20 soiling stations in the US to evaluated "predictive modeling". Best to have monitoring stations near PV installations (R^2 as high as 0.82). Precipitation patterns; long dry periods are best correlation with the soiling ratio.	Outstanding study toward predictive modeling approaches. More correlations with station or system data recommended and required. Importance of PC2.5 and PC10 data.
Nipu et al. [129]	P, MS	Bangladesh	Si modules	Effect of dust on the PV module performance. The increase in temperature due to dust accumulation determined with thermal camera and the reduction in power has been analyzed through *PSpice simulation* and experimental data for the different amount of accumulated dust.	Monitored I_{sc}.
Piedra and Moosmüller [139]	MS	Computational Simulations	Optical losses and particle size effects	Focus: PV power loss due to aerosol deposition on PV devices degrading their efficiency as function of particle size and imaginary part of the particle refractive index that is as function of intrinsic optical characteristics of the deposited particles. Approach: Scattering calculations simulating the interaction of light with particles on substrates that analyzed franction of the power lost as function of particle size and particle complex refractive index. Results: *Smaller particles and a relatively large imaginary part of their refractive index*–absorption losses dominate; *Larger particles and a relatively small imaginary part of the refractive index*–backscattering losses dominate.	Important study showing the importance of the amount of dust on module that should be correlated with the optical parameters. Excellent graphical description of "absorption loss domination" and Hemispherical backward scattering domination" as fuctions of particle size parameter and imaginary index of reflraction. Good discussion of previous optical modeling for particles.
Sayyah et al. [157]	MC, A	Laboratory Studies	EDS Configurations	Objective: Determine the acquired electrical charge by dust particles (charge to mass measurements) on two different laboratory sets of EDS prototypes. Results: Electric field intensity is critical in charging dust particle. Higher humidity – lower charge/mass. Various EDS device parameters investigated on charging. The charge-to-mass ratio measurements identifiec four key parameters: electrode width *w*, inter-electrode spacing *g*, applied voltage, and relative humidity.	
Sayyah et al. [156]	P, MC	Laboratory Studies	Electro-dynamic screens (EDS)	Objective: To evaluate the performance of different electrodynamic-screen (EDS) prototypes, operated under different conditions, in removing fine dust particles in the laboratory environment. Several configurations of electrode spacing, tilt angles, and RH investigated (using fine dust)	Experimental investigations exploring the limits and effectiveness of EDS approaches. Very detailed experiments with positive results for approaches.
Tanesab et al. [166]	P, A	Perth, Western Australia and Nusa Tenggara Timur, Indonesia	Comparison of Si module performance in two different climate zones	Objective: Seasonal variations of dust accumulation on the degradation of PV modules: two different climate areas, Perth, Western Australia *(temperate climate region)* and Nusa Tenggara Timur, Indonesia *(a tropical climate region)*. Observations: Temperate Zone: Max performance at beginning of summer, decrease at end of season, increase again in Autumn. Tropical Zone: Max at beginning of "wet season", dropped slightly at end of this period, then decreased in dry season.	Both dust related and other factors affected the performance (degradation) of the PV modules. Dust "d-rating" discussed.
Ticos et al. [168]	MC, I	Extraterrestrial - Mars	Plasma jet technique to remove dust at low pressures	Concept: An efficient and robust technique for removing dust and sand from surfaces immersed in CO_2 at low pressure (e.g., Mars). Technique uses a pulsed-plasma jet produced between two biased coaxial electrodes. Advantage: Can effectively operate at about 5 Torr—Mars environment.	Interesting video that demonstrates the technique (using Mars dust).
Tripathi et al. [170]	P, A	India (Controlled Testing)	Crystalline Si Modules	Evaluations of the relationships between dust accumulation on a PV panel, shading effects, and panel temperature. Examination of cell and string effects.	Reports increases in temperature above the temperature at the Pmax, causing power losses.

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Table 4 (*continued*)

Publication Source [Reference Number]	**Focus** (*see code*)*	**Location [Duration]**	**Solar Device Type**	**Key Findings**	**Comments/Other Conditions**
Vakili et al. [173]	MS	Tehran, Iran (test case)	Partculate level prediction	Modeling: empirical methods and models (forecasting the amount of solar radiation and conditions) based on novel methods of Artificial Neural Network (ANN) modeling for accurate predictions.	Interesting investigation of ANN to predict particulate distributions in environment.
Wang et al. [177]	MS, P, TO, TR	China	Module simulation Studies	Reports the relationship between the dust deposition and the sunlight transmittance of the solar PV module, improved models considering the effect of incident angle and tilt angle are developed based on the overlay model. Simulation provides analyze the characteristics of each model.	Experiments underway to validate the model.
Wirth [179]	P, A	Germany	General PV Performance	Comments on the relative performance and dust issues in Germany.	Annual updated Laboratory report on host of PV performance parameters.

by soiling. A major outreach by this organization is the monthly webinar program. Information on access and schedules: http://www.pvqat.org/project-status/task-group-12.html

(2) Web materials: In general, industry, manufacturers, and research laboratories provide up-to-date, valuable information on cleaning techniques, new advancements, and seminars/workshops/meetings of interest to this area.

2.3. Preliminary listing of 2017 literature

Because this literature survey for 2016 in being submitted several months into the new year (to ensure coverage of that annual publication base), we have decided to provide a listing of “coming attractions” for 2017. It is cautioned that even for this first quarter of 2017 that the listing is not complete because some references are not made available on-line or through search engines. However, we consider it important to provide this summary of those ongoing contributions and activities to make this survey report a bit more useful. Table 4 presents this summary (a preface for next-years planned compilation), with the references listed separately following the 2016 compilation at the end of this paper.

3. Summary

This literature review has provided an update of publications for the year 2016 (with a brief listing of available articles for the first part of 2017). This is a continuation of the planned, periodic compilation of the references for solar device soiling research and development. Again, this builds on our last-year publication, which was based on materials reported in several published journal reviews over the period 2010 through 2015. In continuing this effort, we again as for the help of those working in this area to provide us with any publication that we have inadvertently missed. We also would like to have suggestions and guidance for improving this presentation. As we stated in last year’s paper, we anticipate continuing this compilation annually in support of this area of research.

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