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Dust and soiling issues and impacts relating to solar energy systems: Literature review update for 2012–2015

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ABSTRACT

The purpose of this review survey is to provide a literature compilation, updating materials reported in several review papers on solar-device soiling and mitigation approaches published over the past 5 years. The focus is on the period 2013–2015, but an updated listing is also provided for the year 2012 for completeness. This literature review also provides the first update for a periodic, single collation report on such publications proposed in this journal two years ago. This review presents a listing of the publications, their publication source, and some brief tabulated information to help guide the reader into the focus of each of the works.

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1. Introduction and background

Soiling of solar collector surfaces ranks with climate conditions (temperature, humidity) and irradiance (spectrum, uniformity, intensity) as the major concerns for component and system reliability. Though R&D on soiling or dust accumulation has now spanned into its 8th decade, many mechanisms remain to be understood and problems to be solved. These needs are intensified by the growing markets in the solar-rich areas of the northern Africa, the Middle East, India, as well as the desert areas of China, Australia, and the United States. Coincidently, these areas are also characterized by high airborne-particle environments, intense dust storms, and water-availability concerns.

The interests and critical nature of these soiling issues are reflected by the publication history, represented in the histogram of Fig. 1. The initial period includes contributions from the solar pioneers (Hottel, Woertz, Tomlinson, Garg – are among the leaders) who envisioned that avoiding soiling would be important for the future adoption and use of collectors for their solar-thermal applications. The coming of the oil embargo in the early- to mid-1970s brought a focus on solar energy and expanded terrestrial applications—with the rise in publications during this period primarily on the effects on heliostats and mirrors used with

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concentrating solar-thermal power (CSP). Political changes at the start of the 1980s (and the diminishing of energy costs/crises) resulted in a loss of funding and related publications in solar and dust issues. The 1990s heralded some shifts. First, the rise of market experiments (e.g., "1000-, 10,000-, 100,000-, million-roof programs" worldwide), large central-station CSP, and then the successes of space exploration, and some limited renewed funding for solutions to soiling reliability issues. There was, for example, a major rise in investments coming from the PV-powered NASA Mars rover ("Sojourner")—which experienced extreme dust conditions with a remoteness that would not allow firsthand manual cleaning! This invigorated research into prevention approaches (coatings, vibration/ultrasonics, electrostatics, and especially electrodynamic screens) that would, in turn, reignite such high-tech remedies for earth-based systems as well.

The new century was marked by a growth in PV, both research and market expansions. This is attributed primarily *to incentive programs* such as the *feed-in tariffs* in Germany and Europe, and *system buy-down subsidies* in Japan and the U.S. Soiling research and product developments shifted as well toward PV because of the rise in applications and country programs. With the China dominance of manufacturing (and accompanying beneficial collapse in PV prices) starting in 2009/2010—as well as the rise in interest in new markets and investments in the desert locations (Saudi Arabia, Qatar, U.A.E. and other Gulf countries, Egypt, India, as well as the U.S., Australia, and China), the publications addressing dust and soiling issues rose to their highest annual levels; levels that can be expected to grow further because of the economic and energy benefits of dust mitigation for these solar-electric generators.

This survey follows on reference databases provided in several reviews that have been published on dust/soiling since 2010 (Table 1, discussed in the next section). It also builds on a commitment in a 2013 publication in this journal [see Tarver et al. 2013 in Table 1] to provide a periodic update to the publication reference base, as a "living document" to afford readers, researchers, developers, and system deployers with a literature base of research investments, product advancements, and latest research/advancements addressing of critical issues relating to this dust/soiling reliability area. This document covers the period 2013 through what has transpired through 2015. However, we have included a compilation, a more complete single listing for 2012—contained in the first section of the Literature Summary (References Section). The majority of these 2012-papers continue to cover the effect of soiling and dust accumulation on the performance of various solar technologies in various locations in the world. However, the focus of this literature review is on 2013–2015. In this period, we emphasize journal and conference publications that can be found through their "DOI" or web identifications—though some open-literature articles are also listed because of their content and interest.

2. Review papers (2010–2015)

Several key review papers covering PV, CPV, and CSP dust and soiling have been published over the past few years, and all have fairly high citation indices indicative of their coverage, interest, and significance. These papers are summarized in Table 1, which provides the source authors, the publication year, a summary of the review contribution and focus, and the solar technology covered. This also gives the reference base cited in each. Certainly prominent among these is that in 2010 by M. Mani and R. Pillai, which summarized performance investigations, recommendations

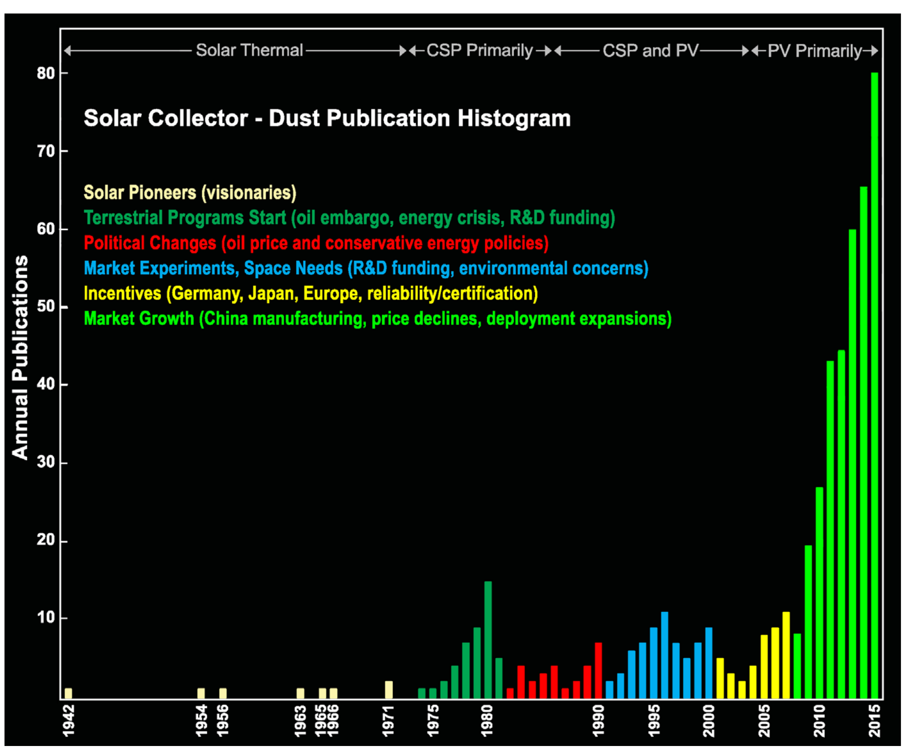

Fig. 1. Histogram of publications on dust and soiling showing general technology emphasis and driving forces (colored regions) underlying the positive or negative growth of the publication levels. Recent rise in publication volume responds to the significant lowering of PV costs and opening of markets in the solar-rich and dust-environment-rich areas of the world.

Table 1
Noteworthy recent review papers addressing soiling and dust issues.

Source	Contribution/Focus of review	Technology
Mani and Pillai (2010)	Evaluation of current research status on impact of dust on performance of PV systems. In-depth analysis of dust accumulation mechanisms and potential mitigation approaches. Climate zone definitions—and comprehensive evaluation of potential severity of soiling in various world climate regions/conditions. [23 References]	Flat-panel and concentrating PV
Bakirci (2012)	Review of methodologies to determine optimum tilt angles for solar collectors; irradiance with indications for soiling/dust. Case study for irradiance situation in Turkey. [57 References]	General solar collectors
Mekhilef, Rahman, and Kamalisarvestani (2012)	Review of the effects of dust accumulation, air velocity, and humidity on the performance of PV cells/systems—and the interrelationships among these three components. Indications of the effects of these on system design and deployment. Specific results for Malaysia region highlighted. [39 References]	Flat-panel PV
Ahmed Darwish, Kazem, and Sopian (2013)	Summary review of impact of dust and related environmental conditions on PV performance. Scope of the review encompasses: dust properties (physical size, morphology, electrostatic deposition behavior), particle biological and electrochemical properties, optimization and modeling studies, effects in various geographical/climatic zones (latitude) considering factor of tilt, altitude, and orientation, wind patterns and minimum dust accumulation for various PV module configurations, dust-particle geometry effects on its deposition behavior, electrostatic attraction on dust settlement, impact of progressive water (cement formation, staining, etc.) on performance. Review considers work in periods before and after 1990. Discussion of dust accumulation models. [22 References]	PV (flat plate) technologies
Bao, Zhang, Cai, Jiang, Xv, and Jia (2013)	Review of dust effects on PV performance (efficiency); dust deposition models/mechanisms, transmission losses and the effects of environmental/weather conditions on dust deposition. Commonly used PV module cleaning techniques (electrode screen dust mitigation and mechanical dust cleaning techniques) are discussed. Research directions evaluated. [14 References]	Flat-panel PV
Midtdal and Jelle (2013)	Comprehensive review of current-market, self-cleaning glazing products for soiling mitigation. Future research and technology directions—emphasis on solar applications. In-depth evaluation of optical property effects/aberrations. Hydrophobic, catalytic hydrophilic, etc. covered in detail. [48 References]	Solar applications (using glazing products)
Sharma and Chandal (2013)	Review and literature on performance and degradation of PV modules under outdoor operation for identifying research gaps for long term reliability of PV modules and improving the PV qualification standards for various geographical and climatic conditions. Reliability includes soiling issues. [84 References]	PV modules (outdoor exposure)
Tarver, Al-Qaraghuli, and Kazmerski (2013)	Comprehensive overview of soiling problems, primarily those associated with "dust" (e.g. dry sand) and combined dust–moisture conditions. Discussion of key contributions to the understanding, performance effects, and mitigation of these problems based on nature, pre-emption (e.g., siting), restoration (cleaning) and preventions (coatings, etc.). Compilation of compositional, chemical, and morphological analysis of dust from throughout the world. Discussion of research needs and directions. [256 References]	PV (flat-panel and concentration), flat-panel solar thermal, CSP (mirrors, heliostats, etc.)
Butuza (2014)	Focused literature search for the effects of soiling, dust and other surface deposits, on the performance of solar photovoltaic collectors. (Primarily provides a procedure for searching.) [16 References]	PV Panels
Ghazi, Sayigh, and Ip (2014)	Review of dust effects on performance PV and solar thermal collectors from 4 different climate zones. Separates review of studies from 3 historical time periods. Guidelines for mitigation and cleaning procedures pertinent to climate conditions presented. [92 References]	Flat-panel PV primarily, some flat plate solar thermal
Hernandez, Easterb, Murphy-Mariscal, Maestre, Tavassoli, Allen, Barrows, Belnap, Ochoa-Hueso, Ravi, and Allen (2014)	Review direct and indirect environmental impacts – both beneficial and adverse – of utility-scale solar energy (USSE) development, including impacts on biodiversity, land-use and land-cover change, soils, water resources, and human health. Environmental effects of panel washing (water). Soil erosion and effect on soil accumulation on panels; reducing effects by vegetation. Performance effects reviewed. [156 References]	Large-scale solar PV and CSP plants

Table 1 (*continued*)

Source	Contribution/Focus of review	Technology
Kazem, Chaichan, and Kazem (2014)	Review of effects of soiling and dust conditions on the PV performance in Iraq. Review of studies on the degradation rates and mechanisms. Effects of moisture and cleaning requirements. Climate zone issues presented and discussed in relationship to the soiling problems. Written to interest research, design, and installer groups. [130 References]	Flat-panel PV
Sayyah, Horrenstein, and Mazumder. (2014)	Comprehensive review of energy-yield losses due to soiling and dust accumulation with some focus on the semi-arid and desert locations. Effects of tilt angle, time exposures, various surfaces (materials), and locations (climate zones). Laboratory and outdoor experiments are included. Summary and evaluation of cleaning techniques (natural, traditional, and emerging). [120 References]	Flat-panel PV primarily *(various technologies included)*
Darwish, Kazem, Sopian, Al-Ghoul, and Alawadhi (2015)	Review of dust pollutant type on performance of PV panels. In-depth evaluation of various reports and various compositions of dust, the accumulation properties/mechanisms, and relationships to various PV parameters. [42 References]	Flat-panel PV
Maghami, Hizam, Gomes, Radzi, Resdad, Hajighorbani (2016)	Review of “key contributions” to the understanding, performance effects, and power loss due to soiling and dust on solar panels. Categorization of two shading types. Included are discussions of several cleaning techniques and dust adhesion prevention approaches. [55 References]	PV Panels

for mitigation of dust issues, and documented a useful and important categorization of climatic-zone influences for flat-panel and concentrating PV. This review paper ushered a series of other important contributions—each with a specific intent, area, and focus. These review papers provide a very useful basis for understanding the issues, what has been accomplished —from monitoring performance through mitigating the problems; from basic adhesion mechanisms to dust composition and morphology; from theory and modeling through experimental and measurement techniques; and from current comprehension to future research needs.

3. Discussion of publications 2013–2015

The number of publications during this period continue the trend beginning in 2009—with a growing volume reflecting both the investment in research funding in reliability and in the incredible expansion of installations worldwide. Most of these are concerned with the effect of dust or soiling at various locations in the world. This remains an important contribution to the knowledge base for several reasons. First, this provides inputs to a growing interest in establishing a global encyclopedia of actual dust and soiling trends. Second, these data provide important information for installers and system holders. The information benefits range from assisting in better site location to establishing reasonable cleaning schedules that can be an immense benefit to the operation and maintenance costs for the PV systems. And finally, these studies provide a basis for collaboration among research and developers (e.g., for PV power plants) to address the issues of soiling and mitigation.

The publications also indicate some trends toward these concerns with mitigation. This spans the spectrum from *restoration* (cleaning with brushes, pressurized air/gas, wiping, and use of water and various solvents and hybrid methods) to higher-technology approaches based on superhydrophobic/superhydrophilic coatings and electrodynamic and electrostatic screens. Though some of the publications address CSP (mirrors, heliostats) and CPV, the overwhelming number of these are directed toward PV flat-plate technologies (reflecting the price benefits of this solar approach and the large number of investments in installations). Finally, some “special reports of interest” are included at the end of the annual references. These are reports that include aspects of soiling or dust conditions, though the major focus of these pertain to other aspects of solar technology concerns.

Tables 2–4 provide summaries of the research and development publications for the years 2013, 2014, and 2015 respectively. The corresponding references (provided in Section 5. Literature Summary) have the “DOI” or internet access links wherever possible. The tables provide the geographical location and duration of the study (if appropriate), the technology addressed, the major results, and some related observations on the publication. Included at the end of the Literature Summary are several specialized reports and publications that include some higher level discussions of the importance of soiling issues to solar technology reliability. These range from “country programs” and professional organization reports/forecasts to specialized efforts at establishing solar device reliability/durability associated with specific climate or installation requirements.

Again, the primary purpose of this paper is to provide a “one-stop”, complete-as-possible reference listing of the publications for the period 2012 though 2015 (with 2015 having the highest number of annual publications to date) as an assistance to those involved with these soiling and dust issues for their own work.

4. Summary

This paper has provided an update of publications for the timeframe 2012–2015, guided by the proposal in the earlier review in this journal. This compilation builds on the reference basis provided in the review papers (Table 1) that have appeared in the past 5 years. It is acknowledged that the is a best-effort, knowing that with the extended literature and publication base in our multi-media world that some significant contributions are not included through this period to the end of 2015. Again, we ask the help of those working in this area to provide us with any publications that we have inadvertently missed. We do anticipate updating this compilation again for 2016, and annually thereafter.

Table 2
Summary of dust and soiling papers in 2013 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=ambient conditions/effects; *I=Instrumentation, *S=spectral effects, *TO=Tilt/Orientation.

Publication Source	Focus* *(see code below)*	Location [Duration]	Solar Device Type	Key Findings	Comments/Other Conditions
Adinoyi and Said (2013)	P, C	Saudi Arabia (Eastern Province) [6 months]	Crystalline Si Modules	50% power loss for uncleaned modules over this period. Power tracking improves output and decreases dust accumulation. Dust sample evaluated for composition/particle size	Temperature effects compared between single-crystal and multicrystalline technologies
Ahmed Darwish et al. (2013b)	P, CM, ME	Laboratory Studies	Crystalline Si Modules	Discusses and investigates the effect of some environmental variables with dust on the PV performance. Evaluates and compares result to other research on effect of dust properties, effect of PV system parameters and effects of environment parameters. Use of artificial soils for investigations.	Effects of wind speed and direction. Modeling of dust coverage effects. Module cleaning (effects).
Al-Ammri et al. (2013)	P, CM, MC	Laboratory Studies Urban lights Baghdad, Iraq [3-6 months]	Street Lights, Si Modules	Power losses by month, with $>60\%$ for 3-month period Feb-Apr; Comprehensive data provided. Morphology evaluations by microscope indicated particles with irregular shapes (roughly spherical) Particles have concentrations of carbon-based chemicals from local refineries (enhanced adhesion) Cleaning requirements discussed.	Indications of performance loss of the panels due to dust accumulation. Panels at 26 meters on streetlights. Temperature/irradiance measured. Bird dropping problems (including chemical interactions with modules)
Al-Sabounchi et al. (2013)	P, MC	Abu Dhabi, UAE [>6 months]	Si Modules-36KW system	Monthly monitoring of PV system loss. July timeframe worst with 27% loss due to dust. Monthly cleaning cycle proposed.	Complete system evaluation (temperature, irradiance, time of day parameters, inverters, etc.)
Appels et al. (2013)	P, CM, MC, TR	Central Europe (Belgium) [5 weeks]	Module cover glass; Si PV modules	3%-4% loss after 5 weeks exposure. Water cleaning with soft water required (transmission loss due to hard water shown). Studies of glass transmission loss with artificial dust.	SEM studies of accumulated particles (dust, pollen, etc.). Cleaning cycles discussed.
Awwad et al. (2013)	P	Amman, Jordan [3 month period]	240-W c-Si modules	Comparison in power output between cleaned and dust-accumulated modules; “Energy Gap” evaluated	Cleaning schedule indicated (daily)
Bai et al. (2013)	MS, CE	Modeling of Phoenix, Arizona systems [>9000 hours]	Si modules, 2-residential systems, 5KW and 6KW (glass surface)	Empirical modeling assuming annual 5% soiling loss Extensive and detailed cost, payback, tariff data. Financial modeling for PV systems	Study of assumed soiling rates to model costs and other consumer issues.
Bi et al. (2013)	CM, I	Urban Environments	General Technique for Sampling and Analysis	Novel method for collecting and evaluating dust samples collected from roadside locations Focus on evaluation of trace elements (e.g., Pb, anthropogenic contamination in urban areas)	Mainly a technique that can be applied to solar collector evaluations
Boyle et al. (2013)	TR	Outdoors, Commerce City, Colorado USA [1.5 years]	Module cover glasses	For dust accumulations <1.5 g/m^2, light transmission was reduced by 6% per g/m^2 of dust accumulation; Incidence angle does not impact the transmission reduction caused by dust deposition.	Periodic procedure to prevent volatilization of deposited dust Sampling of >100
Brooks et al. (2013)	P, MC	Tucson, Arizona USA	Flat-plate PV Modules	Comparison of 3 methodologies comparing cleaned and soiled modules: (1) Energy yields at MPP; (2) I-V characteristics of individual modules in field; (3) I-V characteristics of individual modules under simulator Method 3 reported most precise.	All modules indicate $\sim1\%$ gain in efficiency after cleaning
Canada (2013)	P, TO	Desert Southwest USA [Data - 20-year period]	Utility-Scale c-Si PV	Soiling evaluated considering: Tilt angle, human activity Annual power loss rates: 3%-6%	Washing procedures
Caron and Littmann (2013)	P, I	California USA [>1 month]	Thin-Film CdTe	Automated technique (monitoring station) to evaluate effects of dust accumulation on performance. Complex setup that eliminates sources of errors for precise evaluations. Soiling rates of 11.5%/month reported (agricultural areas);	Periodically cleaned module compared to uncleaned module. Small rainfalls (~0.5 mm rain) enough to restore performance of frameless module.
Charabi and Gastli (2013)	MS, P	Case Study for Oman	General PV Installations Modeled; CPV Focus	Effects of dust & temperature during the site assessment for large PV power plant in order to mitigate their vulnerability (performance losses) and optimize their operation efficiency. Case study use to eliminate areas from site consideration.	Different PV technologies are evaluated with CPV technology providing higher potential for implementing large solar plants. In fact, if all highly suitable land is exploited for CPV plants, supplying more than 750 times the current total power supply in Oman (estimated at 16.1 TWh in 2010).

Table 2 (*continued*)

Publication Source	Focus* *(see code below)*	Location [Duration]	Solar Device Type	Key Findings	Comments/Other Conditions
Dastoori et al. (2013)	P,A,TO	Laboratory Simulations/Tests (effects of dust charge)	Amorphous Si Modules (3)	Experiments to investigate the relation between the amount of charge on dust particles and their impact on the reduction of the PV modules output voltage. Complementary effects of tilt angle	Results: Significant effect on PV module voltage Epoxy powder used to simulate dust.
Della-Guistina et al. (2013)	P, I	Laboratory Studies	Reference Modules	Sinton Instruments FMT-350 to measure the effect of soiling and light induced degradation on PV modules.	Sinton Instruments FMT-350 module I-V flash tester using NREL primary calibration reference modules
Dunn et al. (2013)	P	Field testing of Soiling Monitoring Station	Thin-Film CdTe Modules	Soiling Ratio (SR) defined and determined. Soiling monitoring station designed and evaluated Uncertainty analysis provided (corrections for external parameters-T, irradiance, wind, etc.)	Detailed description and evaluation of two-module (one cleaned, one not) station with instrumentation
El-Din et al. (2013)	P, A	Alexandria, Egypt [2 months]	Thin-Film PV Module	As dust deposition density increased from 0 to 0.36 mg cm^{-2}, the corresponding reduction of efficiency and short circuit current I_{sc} are degraded by 17.71%. Reduction in V_{oc} was only to 97.86 of the clean module value. The average degradation of power and efficiency during the entire period of work (30 days) is 9.86%.	Effect of humidity since site was located near Mediterranean Sea. Dust effects more pronounced on cloudy days.
Ghazi et al (2013)	P, TO	Brighton, UK [1 month] and Laboratory experiments	Glass cover sheets; Examination of c-Si module installation	Transmission as function of soiling for various tilt angles (Brighton outdoor conditions) as function of average dust density Comparisons to indoor controlled tests.	Rainy conditions in UK tended to clean panels—so soiling was not a major issue. Other sources (birds) provided issues for PV modules (shading)
Gostein et al. (2013)	P, A	General outdoor measurement conditions/locations	Thin-Film CdTe and Cryst-Si Modules	Examines the difference between a soiling ratio (SR) metric calculated from measured temperature-corrected short-circuit current values (SR^{Isc}) (the fraction of irradiance reaching the soiled modules) versus a SR calculated from measured temperature-corrected PV module maximum power values (SR^{Pmax}) (the fraction of power produced by the soiled modules compared to clean modules). Clearly shows the need to determine power and Isc monitoring as representative.	Establishes differences and needs in monitoring power or short-circuit current.
Gottschaig et al. (2013)	P, S, A	Loughborough, UK [6 years]	Thin-Film a-Si, c-Si and CIGS modules	Focus primarily on operating conditions (temperature, irradiance, spectrum) Good analysis our outdoor exposure testing.	Minor focus on soiling/snow
Hirohata et al. (2013)	P	Japan [5 months]	PMMA Fresnel Lens (CPV)	Measurements with and without superhydrophobic (SH) coatings (anti-soiling) Without SH: 7.1% reduction after 5 months; With SH: 4.2% in same period.	Relationship between dust accumulation and wind conditions discussed.
John et al. (2013)	P	India	Super-hydrophobic antisoiling coatings	Development of TiO2-based SH coating for dust mitigation, coupled with water delivery system. System design presented.	Prototype system
Kalogirlou et al. (2013)	P, MC	Cyprus and Controlled Experiments [> 1 year]	Mono-, Multicrystalline and Amorphous Si Modules	Performance under prevailing Cyprus soiling conditions. Artificial dust & dust/moisture controlled experiments Power reductions comparisons among 3 technology types (as high as 43% loss in power) Dry dust affects a-Si module less than other two types	Interesting experiments with moisture. Cleaning experiences related (little required in summer; periodic cycles recommended during other times).
Kawamoto and Shibata (2013)	MC	Laboratory Testing	PV Panel Cleaning System	Electrodynamic system using electrostatic force to remove sand from module surface. Design uses parallel wire electrodes embedded in a cover glass plate of a solar pane (with single-phase voltage applied)—80% effective in dust removal	Power used is near zero.
Kazem et al. (2013)	P	Laboratory controlled study with outdoor tests	Multicrystalline Si module	Study of different dust/particle/pollutant types (ash, sand, red soil, calcium carbonate, silica gel) on the performance parameters of a commercial PV module.	Power output reported as function of time.
Klimm et al. (2013)	P, MC, CE	Laboratory Studies	10 MW PV plant as baseline	Anti-soiling coatings evaluated for effectiveness (dust mitigation and durability). Economic analysis of financial gain for 10MW PV plant with anti-soil investment.	Comparison of glass types

Kumar et al. (2013)	CM	Laboratory studies *(controlled conditions)*	Si panel (12 cm x 8 cm; glass surface)	Modeled showing both exponential and linear dependence of the efficiency on the gram-accumulation.	Dust: Bentonite-clay (aluminium phyllosilicate)
Levitan (2013)	P	Deserts	CSP and Other Solar Technologies	Popular discussion of what may limit the deployment of solar technologies in the desert regions (dust, water)	Scientific American “Clean Energy Wars”
Marion et al. (2013)	P, MS	Colorado, USA [2 winter periods (2010-2012)]	6 PV systems	Focus on *snow* Measured monthly PV losses of up to 90%, annual losses from 1% to 12%. Residential and non-residential systems	Good analogies for particulate soiling (models useful)
Massi Pavan et al. (2013)	MS	Italy (PV plant data) Laboratory modeling effort	Large-scale PV plants	Comparison between two different modeling techniques for the determination of the effect (power losses) of soiling on large-scale PV plants (neural network based). Comparisons to standard test condition results.	Modeling and results useful for determining cleaning cycles.
Mejia and Kleissl (2013)	P, TO	California, USA [year-long study]	Residential and Commercial PV Installations	Changes in efficiency of 186 residential and commercial PV sites were quantified during dry periods during 2010 Soiling losses averaged 0.051% per day overall and 26% of the sites had losses greater than 0.1% per day Module tilt angles investigated	Losses reported by geographical location in California Annual energy yield data
Midtdal and Jelle (2013)	P, MS	General	Mitigation Coatings for Solar Collectors	Extensive examination and evaluation of mitigation coatings for solar products. Currently, photocatalytic hydrophilic self-cleaning (dust) products appear superior to the hydrophobic. Perhaps it is that the the hydrophobic products are “easy-to-clean” rather than “self-cleaning”. Hydrophobic products have substantial benefits indoors, seeing that photocatalytic actions does not work without UV radiation, whereas photocatalytic hydrophilic products seem to have the greatest potential for further use with outdoor glazing products. Photocatalytic hydrophilic products require manual cleaning as well as the hydrophobic products.	Excellent presentation on mitigation coatings, their use, their limitations, and their benefits.
Moharram et al. (2013)	P, MC	Cairo, Egypt [∼45 days]	14-KW power plant-Crystalline Si Modules	Efficiency decreased 50% after 45 days of cleaning with non-pressurized water Using cleaning solution of anionic and cationic surfactants, efficiency remained constant (no degradation) “Cleaning the PV panels using the developed water system and a mixture of surfactants minimizes the amount of water needed for cleaning as well as the energy for spraying the water”	German University in Cairo Focus on minimizing water use in cleaning Detailed system description/design
Ndaiye et al. (2013)	P	Senegal [1-year study]	Commercial Multi- and Polycrystalline Si modules (2 locations)	Losses in module parameters (Voc, Isc, Pm, FF) as a function of dust accumulation over annual exposure. Power loss 18%-78% (mainly through Im) Losses in FF differing significantly for mc and pc modules (different manufacturers)	Power loss rates up to 17%/month observed. Consideration of shading effects.
Piliougine et al. (2013)	TR, P	Southern Spain [1-year]	6-Crystalline Si Modules	Evaluation of a new, commercial self-cleaning coating for photovoltaic applications Mean daily loss: 3.3%/day for uncoated; 2.5%/day for coated. Transmission losses: 12% uncoated, 10% coated.	3 coated/3 uncoated modules for comparison. Inhomogeneity of dust distribution caused additional power losses.
Qasem et al. (2013)	P, MS, CM, TO	Kuwait [Several years]	CdTe Modules	Spatially-resolved 3 dimensional model is developed using circuit analysis software PSPICE to investigate inhomogeneous, deposited dust on PV modules Effect of tilt angle on dust accumulation Extensive performance and reliability information	Temperature-performance for CdTe Module hot-spots due to dust shading
Rajput and Sudhakar (2013)	P	Outdoors; Bopal, India [undefined timeframe]	Two Si panels (Each 0.404 m^2) glass surface	Power and efficiency monitored as function of accumulation; Power reduction up to 92% and efficiency loss up to 89%)	Monitored solar radiation, temperature
Rao et al. (2013)	P, A	Tropical Locations India	PV Technologies	Focus PV in tropical locations. Effects of wind, temperature, dust and other environmental conditions are evaluated and discussed.	Experimental evaluations of panels in field. Similar to paper published in 2014
Sabah and Faraj (2013)	MC	Laboratory	Automated Robotic Cleaning System	Cleaning cycles determined using sensors Robotic, automated brushing system design is presented for PV panels	Though title indicated “self cleaning solar panels”, an automated robotic system with sensors is described.
		Mexico City, Mexico			Detailed information about overall system performance

Table 2 (*continued*)

Publication Source	Focus* *(see code below)*	Location [Duration]	Solar Device Type	Key Findings	Comments/Other Conditions
Santana-Rodriguez, et al. (2013)			PV System (Power Plant) 6.1 kW	Grid-connected system evaluation 4 solar PV technologies: mono-Si, poly-Si, a-Si:H, and CdS/CdTe Comparison for soiling and other environmental conditions Typical environmental pollution throughout the year in Mexico City causes the deposition of a fine dust layer onto the system "practically in a permanent way." An estimated loss of around 10% due to dust typical.	
Sayyah et al. (2013)	P, MC	General	CSP	Focus on the impact of dust accumulation on concentrated photovoltaic (CPV) and concentrated solar power (CSP) systems. Electrodynamic Screens (EDS) as mitigation methodology	Compare natural (rain) cleaning, manual cleaning, and EDS
Schaeffer et al. (2013)	MC	General	Dust Mitigation Coatings	Development of transparent superhydrophobic coatings for large surface areas—based on *functionalized silica nanoparticles* to coat optical elements and measured their transmission between 400 nm to 800 nm.	Application to instrument protection but also to dust mitigation. Interesting micro-level physical studies and spectral effects.
Smith et al. (2013)	P, MC	Portland, Oregon USA [> 4 months]	PV Arrays (Si)	Power losses up to 4% for uncleaned panels (17 days). Beneficial effects of rainfall and manual cleaning reported.	Temperature effects reported Cleaning procedures documented
Sueto et al. (2013)	MC	Laboratory experiments	PMMA Fresnel Lens (CPV)	Anti-soiling coating structure: WO_3/Graded Layer/Acrylic Urethane Capping Layer/PMMA Lens Coating effective in reducing particle adhesion and the surface electrostatic potential Relationship between these parameters investigated	Applied coatings to commercial Fresnel lens used in CPV (effective in reducing particle adhesion) Detailed information on coating application.
Touati et al. (2013a)	P	Qatar [100 days]	Monocrystalline Si and Amorphous Si Modules	10% decrease in efficiency due to dust accumulation during this period. Amorphous panel surfaces less affected by dust accumulation than the crystalline Si ones	Cleaning schedules indicated. Temperature effects on technology types reported.
Touati et al. (2013b)	P, CM	Qatar	Monocrystallin Si Modules	Mono-crystalline PV panels, caused the efficiency to decrease by 10%. This limitation makes solar PV an less reliability power source for unattended/remote locations Cleaning challenges discussed (regular cycles)	Some indications and evaluations of durability (e.g., undergoing cleaning)
Tylim (2013)	P, CE, MC	General	PV	Discussions of effects on annual energy delivery (case studies). Requirements for periodic cleaning	Cleaning schedule requirements Cost-benefits
Wang, et al. (2013)	CM,MC,	Laboratory studies; micro-scale force investigations	General studies of adhesion	AFM evaluations of force between particles and insulating surfaces. Result showed that charge is a factor in attracting particles, but not in the force holding them to the insulator	Use of AFM to measure force. Good fundamental study.
Yadav et al. (2013)	A,CM	Laboratory-wind tunnel experiments	Heliostats (CSP)	Understanding of deposition of dust on heliostats (planar); Air flow and deposition studied for single and multiple heliostat configurations; Velocity distribution and flow pattern critical to determining deposition	Soil composition of Jodpur studied and saltation in region; Ash used for experiment comparable to particles collected from PV panels in region.
Zhou et al. (2013)	MC	Laboratory Studies Western China	Electrodynamic Screens	Physical investigations of dust particle movements on surfaces for dust electrodynamic screens. Mathematical model of the dust removal efficiency and the optimization method for electric curtain design (multivariate function optimization methods). Theory basis for the development of self-cleaning techniques for large solar systems under climate conditions of western China	Detailed modeling and analysis.

*P=Performance, *MS=Modeling/Simulation; *CM=Composition/Morphology; *TR=Transmission/Reflection; *CE=Cost/Economics; *MC=Mitigation/Cleaning; *A=ambient conditions/effects; *I=Instrumentation; *S=Spectral Effects; TO=Tilt/Orientation

Table 3
Summary of dust and soiling papers in 2014 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=ambient conditions/effects; *I=Instrumentation, *S=spectral effects, *TO=Tilt/Orientation.

Publication Source	Focus* *(see code below)*	Location [Duration]	Solar Device Type	Key Findings	Comments/Other Conditions
Abrams et al. (2014)	P,TR, MC	12 field stations across the USA [1 year]	Si (module glass)	Report of robust dual-function anti-reflective and anti-soiling coating that is hydrophobic and self-cleaning	Installations by Sun Edison Procedures on preparation of glass included
Amarnadh et al. (2014)	P, TR, TO, A	Vellore, India (Southeast India) [1 month]	Monocrystalline and Poly-crystalline Si Modules; Glass Plates	Orientation (,) of module data. Efficiency vs. days of exposure; dust density vs. days of exposure Transmission of test plates reported vs. dust coverage; Function of tilt.	Temperature, humidity, and solar irradiance data provide.
Al-Jawah et al. (2014) (Dissertation)	MS, MC	Hypothetical 1-MW PV Plant in Saudi Arabia	PV	Development, testing, and evaluation of a framework to assist investors in photovoltaic (PV) power plants in dust-prone and arid regions make informed decisions regarding selection among PV panel cleaning alternatives. Multi-criteria decision method (MCDM) used to select among cleaning alternatives in light of competing criteria.	Questionnaire developed for experts to rate the degree of their agreement or disagreement on a Likert scale. Average results indicate agreement that the study can improve selection among PV panel cleaning alternatives.
Anshir Bashir et al. (2014)	P, A, TO	Taxila, Pakistan [Winter Months-January - March]	a-Si (single junction), single-crystal & multicrystalline Si modules	Some review of past performance reports associating performance with dust accumulation. Indications that soiling lowers the module operating temperature. Discussion of tilt, humidity, and wind effects.	Mono- and polycrystalline modules: Better performance in high-irradiance condition with lower power output at low irradiance. Amorphous Si: Good performance in low irradiance (better light absorption)
Boyle et al. (2014)	TR, A, CM	Colorado	Glass Cover Plates	Airborne concentrations of particles (smaller than 10 μm) are collected simultaneously dust accumulated on PV glass cover plates. Differences reported; effects of wind velocity.	Purpose for future modeling and dust accumulation interpretations.
Burton and King (2014a)	P, TR, CM	Laboratory Studies (standardized soil testing)	Multicrystalline Si Cells	Laboratory techniques to apply (simulated) soil to a specimen with quantification of results of the film on the transmission of incident light. Artificial soil is used and applied by aerosol spray device. Transmission performance loss due to deposited soil is predicted over a range of mass loadings. Demonstration that the composition (NIST traceable) of the blend, (termed “standard grime” by the authors) had a significant and reproducible influence on measured performance loss.	Aim at correlating laboratory studies with outdoor results and mitigation of soiling effects.
Burton and King (2014b)	P, CM, S	Laboratory Studies	PV glass coupons	Spectral loss due to the *color profile* (spectral effects) of the accumulated soiling material investigated. Use mixtures of previously reported “standard grime” with common mineral pigments (Fe_2O_3 and göthite). Results show: Soils rich in red pigments (Fe_2O_3) - greater integrated response than göthite containing soils rich in yellow pigment. The yellow soils caused a greater attenuation in 300-450 nm spectrum region and can have significant implications to specific devices (e.g., CdTe and mutlicrystalline Si technologies).	Focus on laboratory studies that can link with outdoor soiling results and effects of spectral content and relationships to “color” effects of soils.
Burton and King (2014c)	I, TR, MC	Laboratory Studies	Glass Cover Sheets	Expansion of earlier technique to measure the optical losses due to an artificially applied dust film. Sprayed artificial soil (described in paper). 1 gm/m^2 determined to be the limit of mass sensitivity to changing reflection characteristics (about same as a daily observed soil accumulation) Linear decreases observed between 1 gm/m^2 and 5 gm/m^2	Interesting observations and analysis about ensuring that the losses due to soil accumulation are outside the instrumental error. Also, importance to CPV of these particular studies are stressed.
Cano et al. (2014)	P, CM, A, TO, I	Mesa, Arizona USA [3-month Janurary through March period]	Crystalline Si Reference Cell Coupons	Investigations of the interrelationships among soiling loss, terrain of the installation, tilt angle, rain frequency/intensity. Design and development of inexpensive soiling station which evaluates soiling loss at different tilt angles (0°, 5°, 10°, 15°, 20°, 23°, 30°, 33°, 40°). Hot-dry climate results: the 0° tilt angle showed a 2.02% loss whereas 23° and 33° showed soiling loss close to 1% (during the first 3 months of 2011).	Detailed discussions, descriptions, and applications of developed test station. Computations of the solar irradiance performed.

Table 3 (*continued*)

Publication Source	Focus* *(see code below)*	Location [Duration]	Solar Device Type	Key Findings	Comments/Other Conditions
Chamaria et al. (2014)	MS	Laboratory Simulation and Modeling India	50 kW c-Si System	Loss modeled and calculated in terms of kWh. Low latitudes having medium dust density should also have daily cleaning due to lower tilt angle and higher dust deposition. Less of a problem in higher latitude regions.	Modeling and simulation of this 50kW system in India. Discussions of critical impact factors for dust loss for PV panels.
Cristaldi et al. (2014)	I, P, A, M	Milan, Italy and Laboratory Studies	Commercial Si module	Development of a (simple) method to evaluate dust on the performance of PV modules. Estimates reduction in PV performance. Accuracy/errors of measurements/technique evaluated. System includes pyramometer and PV module.	Good discussion of techniques and limitations Computations of the solar irradiance performed. Method differentiates between dust issues and other module ageing problems.
Fernández-Garcia et al. (2014)	MC, TR	Spain	CSP	Outdoor exposure of solar reflectors and applying different cleaning methods. Most effective cleaning method is using demineralized water and a brush, with an average efficiency of 98.8 % in rainy periods and 97.2 % in dry seasons. Innovative cleaning method based on a steam device with a soft tissue was inefficient (efficiency of 97.3 % in a rainy period).	Interesting investigation of a variety of cleaning processes for reflectors.
Ghosh and Ghosh (2015)	P,MS,MC	India	PV	Evaluation of the effects of dust adherence to module surface on efficiency. Modeling of the efficiency loss (Power, IV characteristics, irradiance) Evaluation of mitigation approaches (coatings, cleaning)	Description of cell and system operation.
Gostein et al. (2014)	P, MC	Desert Southwest USA, Arabian Peninsula, Western Australia [Annual Data]	Thin-Film CdTe Power Plants	Discussion on correct data collection methods. Soiling levels correlated with PV power plant performance. Discussions of measurement precision, non-uniformity soiling issues, & rainfall required for performance recovery.	Soiling Ration (SR) utilized. Identified soiling as "3rd most significant factor affecting PV power plant performance"—after irradiance and temperature.
Griffith et al. (2014)	P	South Africa [~1 year]	CSP Mirrors	Candidate CSP site cleanliness assessment using dust collection buckets and loss of reflectivity on mirror samples installed at the site. Instrumentation design presented.	Reflectivity loss (soiling) measured on a monthly cycle using a specially designed portable imaging-instrument. this purpose.
Herrmann et al. (2014b)	MS, A	Laboratory Studies	General GIS Analysis for Dust Risks at Geo Locations	Use of Geographic Information Systems (GIS) to model the soiling potentials in Middle East and North Africa (MENA) countries. Major result: Dust risk map of the MENA region, showing significant differentiation of soiling potentials.	Contribution to the development of appropriate indoor durability testing procedures and the identification of the most favorable solar locations.
Herrmann et al. (2014a)	MS, A	Focus on MENA region	PV	Discussions of parameters and events controlling soiling. Modeling of soiling (influences of climate conditions and collector characteristics). Global soiling rates estimated by GIS.	Preliminary but important modeling directions. Discussions of soiling conditions, controlling environments, etc. MENA information.
Hunter et al. (2014)	MC	Southwest U.S. Laboratory Studies	CSP mirrors and heliostats	Development and discussion of low cost, easy to apply anti-soiling coatings based on superhydrophobic (SH) functionalized nano-silica materials and polymer binders that mitigate dust adhesion problems and significantly reducing mirror cleaning costs/facility downtime	Coatings have excellent SH properties with water contact angles $>165°$ and rolling angles $<5°$.
Iberraken (2014)	P, A	Sahara Desert (Maghreb Countries, primarily Algeria)	Crystalline Si Modules	Effects of fine dust, dust wind, & sandstorms on the PV I-V characteristics reported.	Extensive report on reliability issues in these harsh, desert climates (e.g., EVA discoloration).
John et al. (2014b)	P, TO, MS	Arizona	Crystalline Si Modules from Field	Tilt evaluations (angle-of-incidence-AOI) and effects. PV modules retrieved from the field that had different dust densities have been measured for the dependence of the AOI curves on the dust gravimetric densities. Measured AOI curves were fitted and validated with the analytical/empirical models (literature reports).	Performed on specially developed tilt fixtures for precise evaluations.

John et al. (2014a)	P, TR, S, CM	Mesa, Arizona USA [1.5 years]	Crystalline Si Modules	Spectral reflectance and quantum efficiency changes at various wavelengths for dust accumulations. Heavily soiled solar cell (~74.6gm/m^2): very high reflectance loss and very low quantum efficiency at all wavelengths (measured vs cleaned panel). Examined 3-soiled solar cells cleaned using 3 different cleaning techniques - 60psi compressed air clean, brush assisted 30psi compressed air clean and water cleaned. Short circuit current, spectral reflectance's and quantum efficiency's dependence on wavelengths is reported before and after each cleaning steps	Various dust layer thickness studies for spectral changes/effect.
Kazem et al. (2014a)	P, TR	Iraq (outdoor) [1 year]	Crystalline Si Modules	Compares the energy performance of four identical PV-panels with 20 watt power; one cleaned daily, one weekly, and one uncleaned. by using Solmetric PV Analyzer for a period of Efficiency of panels determined: significant decrease in the relative conversion efficiency which was (7.9%, 20%, 27%) for the weekly cleaned, monthly cleaned and seasonally cleaned panels respectively relative to daily cleaned panel and the reduction in average performance factor was (5.7 , 12.6 ,17.2) for weekly cleaned, monthly cleaned and seasonally cleaned panels respectively.	Climatic and weather conditions included.
Kazmerski et al. (2014)	P, MC	MENA and India [> 1 year]	Crystalline Si primarily; Some CdTe thin film	Microanalysis of the chemistry and morphology of dust particles from these desert regions. Scanning of individual grains for composition. Effectiveness of dust mitigation coatings (from Saudi Arabia measurements) Overview of ongoing and past research.	Indications and evaluation of cementitious-layer formations due to moisture.
Ketjoy and Kony (2014) u	P,MS	Thailand [5-month perio]	Mono- and Multi-crystalline and Amorphous Si	Approach: 40 W of amorphous silicon, 75 W of monocrystalline silicon and 125 W of multicrystalline silicon; cleaned and exposed module from each group. Dust accumulation measured by dust-fall jar methods. The quantity of dust on PV module 55 mg/m^2.d, 260 mg/m^2.d and 425 mg/m^2 effect to decrease solar radiation of 3.71 %, 11.15 % and also effect to decrease electrical energy output from PV module of; 3.50 % of amorphous silicon when quantity of dust is equal to 260 mg and 7.28 % when quantity of dust is equal to 425 mg, 2.96 % of mono crystalline silicon when quantity of dust is equal to 260 mg and 5.79 % when quantity of dust is equal to 425 mg and 2.83 % of multi crystalline silicon when quantity of dust is equal to 260 mg and 6.03 % when quantity of dust is equal to 425 mg.	Modeling: relationship between the accumulative dust on photovoltaic module and electrical energy output of PV module
Khonkar et al. (2014)	P, MC, CE	Saudi Arabia Desert Conditions	CPV arrays (> 1000x concentration)	Differences between CPV (high conc.) and flat-plate PV. Dust 5-times greater effect on these CPV than flat-plate PV. I-V characteristics monitored to determine soiling effects. Current cleaning procedures discussed for these CPV	Study indicates need for further modeling. Questions on cost-effectiveness of cleaning in desert regions.
Kumar and Kaur (2014)	P	China [~1 year]	PV general	Impact: blocking transmission of sunlight, increasing of temperature of the and surface corrosion (due to chemical nature of the dust).	Discussions of general reliability issues and operation of PV cells/systems
Leloux et al. (2014)	P, M	High DNI Regions	CSV	Bankability issues relating to soiling, dust, climate, performance	DNI and environmental conditions
Lombardo et al. (2014)	P, MC	Various European Locations	Glass Materials in the Built Environment	Examination of rural, urban, and industrial environments for particulate matter deposited on glass. The formation of the deposit at the glass surface is a quite complex phenomenon controlled by the deposition of both gaseous and or particulate matter– complex reactions taking place before (in the atmosphere), during and after the deposition (at the glass surface)	Extensive chemical analysis. Indications for solar panel issues (including possible ageing)
Lorenz et al. (2014)	P, MS, CE	Laboratory Simulations	Module Cover Glass Sheets	Evaluation of hydrophobic and hydrophilic dust mitigation coatings. Gains of > 3% over uncoated surfaces (transmittance) Cost simulations and modeling based on lab simulations of dust coverage (with and without mitigation coatings)	Detailed modeling results for "dry years" and "wet years"
Lorenzo et al. (2014)	P	Southeast Spain	2-MW PV Plant	Non-uniform dust deposits lead to more than the short-circuit current reduction resulting from transmittance losses. When the affected PV modules are in a string together with other cleaned (or less dusty) ones, operation voltage losses arise-leading to power losses.	Non uniform temperature distributions result from the "shading" effects of the non-uniform dust distribution—'hot spots'

Table 3 (*continued*)

Publication Source	**Focus* *(see code below)***	**Location [Duration]**	**Solar Device Type**	**Key Findings**	**Comments/Other Conditions**
Maghami et al. (2014)	MC	Malaysia, Industrial Area	Si Modules	Identified industry-source dust on panel surface: siliceous, alumina and cement identified by EDX Impurity distributions on particle surfaces (maps of dust samples)	Also, highway (traffic) pollutants and bird droppings. Elemental identifications
Mallineni et al. (2014)	P, A, TO	Arizona	4-16 year-old PV Power Plants	Soiling losses in hot-dry climate zone. Soiling losses in 4-PV power plants with two different surroundings (urban and rural) and 3-different installation types (ground mount - fixed tilt, 1-axis tracking and rooftop - fixed tilt) Major Results: *Site 3 (Glendale, Arizona) - rural, 1-axis tracking*, 12 years, 6.9% soiling loss; *Site 4b (Mesa, Arizona) - urban, horizontal tilt (ground)*, 16 years, 11.1% soiling loss; *Site 4c (Mesa, Arizona*) - urban, 1-axis tracking, 4 years, 5.5% soiling loss; *Site 6 (Tempe, Arizona) - urban, 5o fixed tilt (rooftop)*, 8 years, 3.8% soiling loss.	Excellent basis from reliability observations on these installations.
Mazumder et al. (2014)	P, I, TR, CM	Laboratory Studies	Electrodynamic Screen Systems for PV (and CSP)	Report on transparent electrodynamic screens (EDS) and their applications for self-cleaning operation of solar mirrors - primary focus on the removal dust particles <30-μm diameter while maintaining specular reflection efficiency $<$ 90%. Focus: (1) loss of specular reflection efficiency as a function of particle size distribution of deposited dust, and (2) the effects of the electrode design and materials used for minimizing initial loss of specular reflectivity in producing EDS-integrated solar mirrors.	Very detailed description of technique, use, limitations, and effectiveness.
Mejia et al. (2014)	P, I	San Diego, CA USA [~3 months summer]	Large PV (86.4 KW) System	Large PV system: Soiling losses were found to be 0.21% per day, with an observed efficiency decrease from 7.2% to 5.6% during a 108 day dry period (summer). Following this observation, rain event restored most of the lost efficiency to 7.1%.	Correlated with weather station data located about 3.4 Km from site. Good irradiance correlations.
Ndiaye et al. (2014)	P	Dakar, Senegal	Multi- and Monocrystalline Si Modules	Pmax loss from 18 to 78% respectively for the polycrystalline module (pc-Si) and monocrystalline module (mc-si). Imax loss from 23 to 80% respectively pc-Si and mc-Si modules. Vmax and Voc are not affected by dust accumulation for both technologies.	Exposure times (dust accumulation) FF also monitored.
Naeem (2014)	P,MC	Metro Phoenix, Arizona USA	Si Modules	Two studies that focus on investigating the soiling effect on the performance of the PV modules: (1) investigate the optimum cleaning frequency for cleaning PV modules installed in Mesa, AZ (2) evaluating the soiling loss in different locations of Metro Phoenix area of Arizona, to validate the daily soiling rate obtained from the mock rooftop setup Soiling rates: (1) -0.061% for 20° tilt, and (2) -0.057 to -0.85% for 13-28° tilt.	5 cities in Phoenix area considered. Good description of experimental setup.
Pape et al. (2014)	P, ME, MC	Spain [Cleaning 3-26 day periods]	CSP systems (solar resource monitoring systems)	Effects of dust on irradiance affecting solar thermal plant performance and monitoring systems. Soiling characteristics of the rotating shadow band pyranometers compared to pyroheliometers. The pyroheliometer suffered of linearly growing errors of up to 30% after one month, the soiling impact on the rotating shadow band device generally stayed below 2%, without any visible trend of growing errors	Very useful discussions of solar resource monitoring equipment under various environmental conditions. Correction algorithms to improve the accuracy of the RSP sensors explained and presented. Instrument cleaning evaluated.
Polizos et al. (2014a)	MC	Coatings (Laboratory Studies)	CSP	Transparent superhydrophobic (SH) coatings based on multifunctional silica nanoparticles and polymeric binders developed and evaluated. Key findings: • The optical clarity of the coatings. The particles (average size smaller than 200 nm) were uniformly dispersed in organic binders and resulted in coatings with an average roughness value smaller than 30	Promising long-life coatings for CSP applications and PV as well

				nm. The nano-particles do not scatter light at wavelengths > 250 nm because of their small dimensions. • Enhanced particle binder interfaces with • multifunctional configuration significantly improves the abrasion resistance of the coatings without degrading their SH properties. • Accelerated weathering durability (UV exposure). Indications that the coatings are environmentally durable over several years of simulated UVA exposure.	
Polizos et al. (2014b)	MC	Laboratory Studies	Coating Development	• Method for fabricating scalable and cost-effective superhydrophobic coatings. • Chemical modification of diatomaceous earth nanostructured particles. • Abrasive resistance depends on the size and geometry of the diatomaceous earth (potential for long life).	Potential application for dust mitigation/protection for modules
Qasem et al. (2014)	P, TO, S, TR	Laboratory Studies (comparisons to Kuwait data)	Amorphous Si, CIGS, CdTe, and Crystalline Si Modules (and glass sheets)	PV performance and cover glass transmittance measurements. Experiments as functions of tilt angle. Demonstration of relationship between dust density and light transmittance (through glass) for dust below $\sim$19mg/cm^2. Higher-bandgap technologies (e.g., a-Si) more affected because of spectral response than lower bandgap (e.g., c-Si)	Extensive correlations among dust density, light transmission, and performance degradation. Chemical and physical data of dust used in these studies.
Rao et al. (2014)	P	Bangaluru, India (Laboratory and Outdoor Testing)	Si PV modules	Effect of outdoor exposure (dust) on I-V characteristics Indoor simulations Isc is sensitive to measuring dust-induced losses (from both indoor and outdoor measurements)	Extensive I-V measurements and comparisons between outdoor and laboratory (controlled conditions) measurements.
Sakhuja et al. (2014)	TR, MC, CM	Singapore [3 months]	Si Modules (glass surfaces)	Development, production, and testing of self-cleaning nanostructured glasses for mitigation. Results: Loss of 2% in efficiency for planar glass packaged solar module; and loss of 0.3% in efficiency for nanostructured glass packaged solar module.	Durability results promising for these nanostructured layers.
Sansom et al. (2014)	P, MC	Laboratory Studies	CSP (polymer and glass covers)	Comparisons of the optical properties and surface texture of glass and polymer film collectors for concentrating applications. Degradation of glass and polymer reflecting surfaces with sand and dust abrasion. Anti-soiling and self-cleaning coatings tested on glass and polymer film collector surfaces	Measurements: specular and hemispherical reflectance, surface roughness, and electron microscopy. Results interesting for CPV as well. Cleaning processes.
Said and Walwil (2014)	P, MC, TR, A	Dhahran, Saudi Arabia [45 days]	Module glass covers and PV panels	Effects of dust deposition of PV performance and cover glass transmission. ARC glass effects (indicated reduction in soiling) Higher particle size—higher adhesion forces Effects of moisture on enhanced adhesion 20% reduction in power output (5 gm^2 dust accumulation) after 45 days exposure	Interesting and novel AFM studies of adhesive forces (fundamental studies of adhesion). Extensive studies of composition.
Sayyah et al. (2014)	P	Laboratory Studies (Electrodynamic Screens)	PV modules	• Database reported for soiling losses in different parts of the world. • Environmental and design parameters of dust deposition discussed and evaluated. • Laboratory, outdoor, and predictive soiling studies. • Emerging method of electrodynamic screen for dust removal introduced and evaluated	Detailed overview of electrodynamic screen effectiveness and use.
Schaeffer et al. (2014b)	MC	Laboratory (superhydrophobic)	Solar anti-soiling coatings	Simple, durable spray-on SH coating based on functionalized SiO nanoparticles that can easily be applied to surfaces (e.g., optical sensors, photovoltaics, sights and lenses, textiles, construction materials, and electronic devices. Durability and mechanical properties reported.	See also paper Schaeffer et al. (2014a).
Schaeffer et al. (2014c)	MC, ME	Laboratory (superhydrophobic)	Solar anti-soiling coatings (large area)	Development of silica nanoparticle-based nano-coatings that can be applied to large surface areas (modules). Focus on transparency between 400 nm and 800 nm.	Contact angles, morphology, etc. reported. Modeling of coatings
Semaoui et al. (2014)	P	Algeria (Southern desert)	Si Modules	Dust accumulation over several months, with average loss of 4.38%/month	Ghardaia region, 600 km south of Algiers
Sharma et al. (2014)	P, A	Gurgaon, India [> 28 months]	HIT and multicrystalline Si Modules	Reliability and performance of HIT and multicrystalline Si modules under operating conditions, including soiling.	Wide-ranging investigations of the performance of two module technologies

Table 3 (*continued*)

Publication Source	Focus* *(see code below)*	Location [Duration]	Solar Device Type	Key Findings	Comments/Other Conditions
				All tested modules had observed soiling issues. Enhanced soiling effects at module edges (mounting points)	under operating conditions at the SERC (now NISE) test facility near New Delhi.
Sibai (2014)	P,MS	Saudi Arabia (hot dry desert)	Modeling of PV module performancee	Mathematical model for series-parallel photovoltaic modules, evaluate the model, and present the I-V and P-V characteristic plots for various temperatures, irradiance, and diode ideality factors – dust considerations.	Modeling for general hot climate conditions—with additional analysis for dust
Sinha et al. (2014)	P, A	Various	Si technologies	Atmospheric variables considered: temperature, humidity, aerosols, clouds, soiling, and snowfall, for arid versus temperate regions, with specific comparison of the U.S. Southwest and Saudi Arabia with the U. S. Southeast and Ontario, Canada. Specific dust/snow results: -3% for soiling with cleaning, and 0 to <;-5% for snowfall	Temperature and humidity effects received special attention.
Smith et al. (2014)	P	Laboratory and Outdoor Testing	Crystalline Si Modules	Flowing water system investigated to improve PV module performance, including the avoidance of soiling.	Focus on temperature and irradiance benefits for improvements in performance.
Stark et al. (2014)	P,TR	Laboratory Experiments, Modeling	CSP	Investigation of the application of electrodynamic screens for “efficient and cost-effective” dust removal from CSP mirrors Prototype mirrors constructed and evaluated Incorporation of transparent EDS causes an initial loss of 3% but would be able to maintain specular reflectivity more than 90% to meet the industrial requirement for CSP plants	Modeling, ray tracing Specular reflectivity measured inside weather chamber
Sulaiman et al. (2014)	P, I	Laboratory Testing (controlled conditions)	Crystalline Si	Focus: dust, water, sand and moss on the surface of solar photovoltaic panel: Primarily development of experimental system for controlled observations. Up to 86% loss in performance reported.	Cleaning requirements discussed.
Tan, et al. (2014)	MS, MC	Indoor issues with dust and surfaces	Indoor surfaces (general)	Air-conditioned environments (emphasis) for these indoor studies of dust adhesion to various surfaces. Interrelationships of dust adhesion with degree of surface roughness. Modeling using van de Waals forces.	Some focus on health issues, but studies of science interest to dust and soiling for PV
Toivola, et al. (2014)	P	Arizona, Florida, Ohio-USA [Multi-year outdoor testing]	CIGS Modules	Outdoor testing for reliability of Miasolé thin-film CIGS modules. Testing conditions and apparatus described; data shows soiling effects.	Product reliability investigation for thin film CIGS product.
Weber et al. (2014)	A, P, MC, I	Laboratory Studies	Si Modules	Development of soiling and abrasion tests for PV module surfaces. Beneficial effects of anti-soiling coatings demonstrated (anti abrasive and soil mitigation) Cleaning procedures discussed/demonstrated-including impact of cleaning on surface Abrasive tests and instrumentation designed and tested	Test procedure key to determining the service lifetime of module glass and coatings (dust mitigation, antireflection, etc.) under soiling conditions.
Wolfert-stetter et al. (2014)	I, P	General Locations	Metrology Stations	Effect of dust on MHP monitoring stations. Pyrheliometers extremely sensitive to dust (DNI). Reductions of measured DNI values exceeding 25% in only a few weeks are common. Methods to improve examined, the soiling level of each individual sensor can be determined by following a special sequence of sensor cleaning and brief breaks combined with a close examination of the sensor responses.	Dust observations on the effects on monitoring equipment.
Wu et al. (2014)	MD	Laboratory Studies	ITO Electrodes on Glass (Electro-dynamic)	ITO (transparent) electrons deposited in “forked” pattern on a glass substrate to electrodynamically mitigate dust issues. Report of 95% effective.	First of two studies (other in 2015 that improves on this approach)

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Publication Source	Focus Code*	Location [Duration]	Solar Device Type	Key Findings	Comments/Other Conditions
Alami Merrouni et al. (2015)	TR, MC	Morocco (Eastern) [3 months]	Solar Mirrors (CSP)	First reporting of the effect of dust on different solar mirror materials in Morocco. For glass and aluminum mirror materials, the" drop on cleanliness per time interval" was same for all the mirrors (over all the test periods). Highest average cleanliness drop per month for the horizontal mirrors was 45 % and 33 % for the glass and aluminum mirrors The +45° mirrors are less effective with a cleanliness drop of about 14 % for both reflectors. Mirrors installed on the 0° and -45° angles remained cleaner with a cleanliness average of about 97 % for both mirrors	Detailed analysis of the cleanliness of the mirror materials under the outdoor exposure conditions.
Ali et al. (2015)	P	Taxila, Pakistan [3-4 month]	Si PV Modules (single and poly)	Two modules of each type exposed for 3 months in winter timeframe. Monocrystalline and polycrystalline modules showed about 20% and 16% decrease of average output power respectively compared to the clean modules. Loss of output power and module efficiency in monocrystalline module was more compared to the polycrystalline module	Decrease of module efficiency (clean - dirty) in case of monocrystalline and polycrystalline module was 3.55% and 3.01%, respectively
Alnaser et al. (2015)	P, MC, CM	Bahrain [~6 months]	Crystalline Si 500-kWp Array	Density of accumulated dust ranged from 5-12 g/m^2 with an average PV power loss up to 40% of maximum available. Compositional analysis: Si (~15%) and Ca (~15%) in addition to Al (~6%), Mg (~5%), and Fe (~5%). Modeling with result of prediction (equation) of loss in transmission with dust accumulation.	Interesting study and discussions of the 8 of 2088 panels in array. Detailed explanation of performance of this large array with micro inverters (individual for each panel) Some discussion of cleaning. Energy management discussions.
Alqatari et al. (2015)	M, P, MC	Saudi Arabia	Modeling of dust mitigation in Saudi Arabia	Case study: modeling for dust mitigation in Saudi Arabia (large-scale PV) Spatiotemporal model analyzes atmospheric dust in the simulation of PV system performance in KSA. Modeling and analysis also considers dust mitigation, allowing for optimizing choice of self-cleaning technology at a particular time and location (aimed at recovering losses due to the soiling)	Modeling uses Saudi Arabia as a test case for validity.
Al Saluos (2015)	P,CM	Jordan, Laboratory Studies	Crystalline Si Modules	Module parameters (Voc, Jsc, Pm) as a function of dust depositions showing power losses of 90%. Investigation of dust characteristics	Reduction in system efficiency reported.
Bashker and Arya (2015)	P,	India	PV Panels (Si)	Accumulated dust on the surface of PV solar panel can decreases the PV system's overall efficiency up to 35% per month. Performance of PV panes is studied experimentally and used in calculating the effect of deposited dust on the energy efficiency of PV systems.	Specific for India. Discussions of maintenance.
Benatiallah et al. (2015)	P, A	Sahara Areas	Crystalline Si Modules	Interrelated dust and wind effects on the electrical performance of modules	Abstract of studies
Bhattacharya et al. (2015)	P, MC	Tripura, India [~6 months]	2-identical 37-W crystalline Si modules	Reduction of Voc, Isc, and efficiency reported (ranging from 9% to 13% loss in efficiency for 6 month duration. One module cleaned other left for exposure.	Data on Isc and Voc as function of irradiance level. Cleaning recommended.
Bohra et. Al (2015)	P	Bangalore, India Urban environments [1-month]	Rooftop PV	4 technologies: Poly-Si, Mono-Si, HIT, and CdTe thin film studied (for suitability in the urban environment). CdTe had highese soiling lossis (10.88%) after one-week and Poly-Si the least (4.21%).	Metropolitan areas considered for dust effects on PV performance Rooftop installations for these studies.

Table 4 (*continued*)

Publication Source	Focus Code*	Location [Duration]	Solar Device Type	Key Findings	Comments/Other Conditions
Boppana (2015)	P, M	Arizona USA	PV Power Plants (Si and CdTe)	Outdoor characterization of dust on two power plants located in cold, dry climate. Statistical risk analysis for power plant through failure mode, effect, and criticality analysis based on non-destructive field techniques and count data of the failure modes.	18 and 19-year old power plants analyzed. Frameless and framed modules compared
Bouaddi and Ihlal (2015)	P, TR	Southwest Morocco	CSP Mirrors	Evaluation of the rate of soiling of exposed solar mirrors by performing extensive reflectance measurements every 3-4 days Results: summer period (dry with predominant wind from Northeast) the cleanliness of the mirrors has dropped significantly: average monthly cleanliness is 69%, 68%, 76% for glass mirrors, and 76%, 74% , 72% for first type Al mirrors measured respectively in July, August, and September.	Agadir, Southwest Morocco (30°26'3.8"N 9°29'31.1" W), a site isolated from urban pollution and industrial activity. Weather data provided.
Bouchalkha (2015)	MS, MC	Modeling for Solar PV Panelsin Abu Dhabi	PV	Light scattering calculations from dust particles using the *T-matrix model* to estimate the effect of dust accumulation on the module surface Results: 10% reduction in module output after few days. Conclusion: Cleaning every 10-15 days (under normal Abu Dhabi ambient conditions)	Detailed layer-by-layer modeling to calculate dust effects on transmitted light.
Boyle et al. (2015)	P	Colorado USA (2-Front Range Locations) [1-5 weeks]	PV Glass Cover Plates	Mass accumulation rates between 1 and 50 mg/m2/day were observed (with variations over the year, location, and tilt angle). Total mass accumulations up to 2 g/m^2 for 1-5 week period, with transmissions losses to 11%. Transmission was a linear function of the mass of the dust accumulation (and not a function of the tilt or location)—with reduction of $\sim$4.1% for every g/m^2 accumulation.	Uncertainties in the measurements evaluated and discussed. Semi-arid area.
Brophy et al. (2015)	P, MC	Field and Laboratory Studies	PV modules	Field performance of anti-soiling coatings on PV modules Local conditions (climate zone) are critical to performance of the coatings. Tests on "robust dual-function antireflective and anti-soiling coating that is dense, homogeneous and intrinsically hydrophobic." Hydrophobic coatings have strongest anti dust adhesion properties	Hydrophobic, low surface energy coatings Dual purpose (also ARC) Two years date in field
Burton et al. (2015a)	TR, MC	Laboratory Studies	Module Glass Coupons	Objective: Low mass loadings of soil of PV module surfaces are common but difficult to quantify. Synthetic soil analog was sprayed onto glass coupons at with a high-volume, low-pressure pneumatic sprayer. A 0.1-g/m^2 soil loading determined to be the limit of mass measurement sensitivity (similar to some reports of daily soil accumulation).	Collected field-soil samples analyzed to develop a compositional analog for lab studies.
Burton et al. (2015b)	TR, MS, P	Laboratory Studies	High-Concentration PV Systems (CPV)	Modeling of the performance of 3-junction concentrator cell systems to various color pigments mixed in naturally occurring soils (spectral response changes). Wide changes in the responses (transmission) with different soils shown to be important for these CPV technologies. Major effect on altering the current balance between the top and middle cells in the 3-cell structure, especially with "yellow" pigmented soils.	Transmission changes evaluated on glass coupons. Modeling of effects of these different soils on the solar spectrum.
Cáceres et al (2015)	CE	Santiago, Chile	PV	Economic study of PV installations for residential PV in Santiago, Chile. Effects of dust on panel performance and on the LCOE for on-grid and off-grid.	PM-10 considerations

Cekirge and Elhassan (2015)	P	General	CSP (Towers and Parabolic Troughs)	Modeling of tower and trough systems for viability and operation *Small discussion of dust effects and potential impacts*	Good system comparisons
Chakraborty and Sadhu (2015)	P	Coal City, India	Mono-Si, HIT, Poly-Si, Micro-morph, a-Si:H, CIGS, CdTe Modules	"Technical mapping of PV" A-Si:H modules perform better under the typical temperature variant and dry environmental condition of the Coal City of India	Environmental conditions include soiling. Technology comparisons.
Choi et al. (2015)	MC	Development of dust prevention coatings (laboratory)	Dust mitigation coatings	Superhydrophobic coatings with high haze (micro-structured films) Studied gradient-index (n) material-based microstructures, *i.e.*, magnesium fluoride (MgF_2, $n \sim 1.37$) film-coated SU8 ultraviolet curable polymer ($n \sim 1.59$) microcones (MCs) with tapered architectures, on silicon (Si, $n \sim 3.9$) substrates Some report of antireflection properties of layers	Optoelectronic applications of these anti dust coating is the intent.
Doumane et al. (2015)	MS	Laboratory	Si PV	Module modeled by an equivalent electrical circuit (components have time-dependent characteristics determined under accelerated tests). Optical transmission loss leads to as much as a 11.5% over 25 years.	Extensive electrical engineering treatment of the module (circuit approach)
Ferrada et al. (2015)	P	Chile (coastal desert zone) [16 months]	mc-Si and crystalline Si modules	Difference of energy yield between the technologies larger for summer and smaller for winter. Performance ratio decreased due to the dust accumulation between -0.04%/day up to -0.13%/day (positive ambient temperature gradient), and between -0.13%/day up to -0.18%/day (negative ambient temperature gradient).	Studies include uncertainty analysis.
Fuentealba et al. (2015)	P	Atacama Desert, Chile [638 days]	a-Si/μc-Si tandem cell and Multi-crystalline Si Modules	*Thin-film module performance*: Decreased due to the dust accumulation at a rate from 4.2%-3.7%/month (decreasing temperature conditions) and from 4.8%-4.4%/month (increasing temperature). *Multicrystalline silicon module performance*: Degradation rates were 2.4%-1.8%/month (decreasing temperature), and 6.2%-3.7%/month (increasing temperature).	Coastal zone of Chile. Electricity rate costs reported for each technology—based on performance measurements. Cleaning thin-film modules had better return on electricity price than for cleaning the mc-Si technology.
Guo et al. (2015)	P, MS	Doha, Qatar [7 months]	Si Modules in Test Field	PV performance, ambient dust and weather conditions measured continuously from June 1 through December 31, 2014 Performance losses: 0.0042 +/-0.0080 per day for modules cleaned every sixth month, and 0.0045+/-0.0091 per day for modules cleaned every second month, in terms of a "cleanness index" based on the PV module's temperature. Modeling of dust performance.	Very good discussion of conditions and of measurement approaches.
Hacke et al.(2015)	P, MC	Laboratory	Reliability links with dust/soiling	Effects of module soiling on module glass surface resisting and resulting potential induced degradation (PID) Compared 3-soil types (Arizona road dust, soot, and sea salt) Variation in results for the soil type PID correlation with resistance.	"Sea salt yielded a 3.5 orders of magnitude decrease in resistance on the glass surface when the RH was increased over this RH range. Arizona road dust showed reduced sheet resistance at lower RH, but with less humidity sensitivity over the range tested. The soot sample did not show significant resistivity change compared to the unsoiled control."
Jasim et al. (2015)	P,MC,CE		Crystalline Si PV (cleaning systems)	Effects of dust on PV panel performance. Presents automated, closed-water cleaning system Techno-economic analysis is provided	
Jiang and Lu (2015)	P,A	Laboratory studies (Effect of module surface T on dust deposition)	Monocrystalline Si Modules (156 mm x 156 mm)	Effects of temperature on dust accumulation on Si modules. Measured deposition densities of dust particles were found to range from 0.50 mg/ m^2-0.84 mg/m^2. Higher surface temperature modules has a lower density due to the effect of thermophoresis force arising from the temperature gradient between its surface and the surrounding air; energy output ratios were found to increase from 0.947 to 0.971 with the increase of temperature gradient.	"Most obvious temperature gradient" for the thermophoresis force was found to be lower than 40 C.

Table 4 (*continued*)

Publication Source	Focus Code*	Location [Duration]	Solar Device Type	Key Findings	Comments/Other Conditions
Jin et al. (2015)	MS	Modeling and experimental studies (Laboratory)	Modeling of nanoscale roughness effects on particle collection	General studies of colloidal- and nano-scale particles on surfaces. Interesting look at surface roughness at the nanoscale and the effect of adhesion. Non-PV overall	This is a general paper on how particle are deposited on surface and how they interact with the surface. Mostly modeling—some experimental results.
John et al. (2015)	P,S	Laboratory Studies (India dust samples from various locations)	Si, CdTe, CIGS	Controlled artificial dust (from various climate-zone locations in India) deposition on module surfaces. Example: Soiling loss on a Si cell with Mumbai dust (17.1%) is about two times that of Jodhpur dust (9.8%) for the same soil gravimetric density of 3g/m^2. Spectral effects is highlighted by technology (Si, CIGS, CdTe)—corresponding to those bandgaps.	Excellent report on spectral effects (quantum efficiency measurements on cells). "The dust collected from Mumbai showed highest spectral loss, followed by Pondicherry, Agra, Hanle, Jodhpur and Gurgaon. The worst affected module technology was amorphous silicon (17.7%) followed by cadmium telluride (15.7%), crystalline silicon (15.4%) and CIGS (14.5%) for the same density (2.5g/m^2) of dust from Mumbai"
Karim et al. (2015)	A,S,TR	Morocco	CSP	Exposed mirrors in natural aging sites present low loss in reflectivity which doesn't exceed 0.4% after 240 days of outdoor exposure. The effect of sand properties on erosion phenomenon was found that the sand hardness affect the roughness parameters, while the sharp forms influence on the impacts properties(roughness parameters, impacts number, impacted area, impacts size diameter). Increasing the sand particle's size also increases the impacted area and the losses in relative specular reflectivity.	Ageing studies involving outdoor testing and laboratory experiments.
Kawamoto and Shibata (2015)	MC	Laboratory Studies	Si Modules	Cleaning using electrostatic force to remove sand from the surface of solar panels. Effectiveness: more than 90% of the adhering sand is repelled from the surface of the slightly inclined panel after the cleaning operation.	Power consumption $\sim$0. Parallel wires embedded in cover glass plate.
Kazmerski et al. (2015)	P, MC	Laboratory Studies of individual dust particles (from Middle East and from Brasil)	Module glass surfaces	Chemical/compositional measurements of dust samples from various geographical locations. Adhesion measurement by AFM of individual soiling grains on module glass surfaces indicating the relationship between particle surface chemistry and the adhesion. Comparative measurements on glass and glass coated with superhydrophobic and superhydrophilic films.	Studies of fundamental adhesion of single-dust particles to PV module glass surfaces. Cementation effects of moisture and from diesel fuel emissions indicated. Samples from Saudi Arabia and Brasil.
King (2015)	P, MS	Laboratory Simulations and Experimental Studies	PV module performance	Derating of PV module performance for many factors, including environmental ones such as soiling and dust. Advanced Soiling Study determining the influence of soil composition and morphology on light attenuation and scattering. Developed an improved modeling of angle-of-incidence accounting for diffuse utilization and soiling Validated a methodology to predict the string mismatch "derate factor" from available module characterization results (also relating to soiling)	The advanced soiling portions of this report are important and detailed. Very good gathering of the influences sources and factors for soiling.
Klimm et al. (2015)	A,MC,TR	Laboratory and Field Testing	PV Module Glass	Soiling and abrasion testing for harsh climates. Laboratory sand trickling test stand according to DIN 52 348. Results of the outdoor and indoor tested material show the strong influence of dust types and material properties on soiling and durability of the surfaces.	Laboratory apparatus description for testing

Klugmann-Radziemska (2015)	P, MC, CM	Gdansk, Poland (3 locations)	Si PV Modules	Linear relationship between the thickness of the soiling layer and the performance of the module (with reported observation of 25.5%/mm loss in power for naturally deposited dust). Maximum observed daily loss of 0.8%. Studies of morphology and chemistry of collected dust.	Module cleaning methods reported. Good background section providing foundation for these studies.
Lee et al. (2015)	MC	Taiwan	CIGS Modules	Development of a dust-monitoring platform system. CIGS modules monitored since 12/2012 Daily soiling loss (up to 30%/month) reported and impact on utility-scale plants and return-on-investment discussed	WIKI site that is providing fast access to PV monitoring results.
Leem et al. (2015)	MC	Laboratory	Si mini-modules	2-dimensional periodic conical micrograting structured (MGS) polymer films are studied for both "light harvesting"-ARC and self-cleaning for Si PV modules. Careful and detailed experimental studies.	Fabrication procedures provided for the nanostructured PET films.
Leem and Yu (2015)	MC	Laboratory [Month]	III-V solar cells	Self-cleaning surfaces for III-V solar cell applications. "Artificial inverted compound eye structured (ICESs)" (polydimethylsiloxane (PDMS) films with ARC and self-cleaning functions for the enhancement of solar power generation in encapsulated GaAs solar cells	Used GaAs cells with a cover glass
Li et al. (2015a)	MS, MC	Modeling and simulation	PV Modules	Modeling and simulation of a device for the removal of dust from module surfaces. PV module light electrical parameters analyzed for various directions of dust removal from the module.	Brush studies primarily
Li et al. (2015b)	MS, P	Modeling of Performance	PV Plant	Electricity quality and performance modeling based upon operating factors (including dust) Operating Statuses Identification (OSI)is utilized in the simulation formulation.	Modeling that includes effects of shading (e.g., from dust)
Lim et al. (2015)	MC, TR, P	Laboratory Studies	Dye-sensitized solar cells (DSSC)	Hydrophobic polymers evaluated for dust mitigation and for antireflection properties for PV modules. polydimethylsiloxane (PDMS) patterned with negatively tapered nanoholes (NHs) as a protective antireflection layer of the external glass surface.	Studies of the degree of hydrophobicity of the surfaces of these films. ARC-dust mitigation dual purpose.
Lopes de Jesus et al. (2015)	TR, MC, CM	Laboratory Studies	PV Module Glass	Hydrophilic, transparency, and adhesion studies of TiO_2 /SiO_2 composites containing different titanium content. Contact angles near 0° obtained. Abrasion and durability data provided.	Self-cleaning attributes of these films reported. Superhydrophilic coatings.
Martinez-Plaza et al. (2015)	P, MC	Qatar	PV (tracking, fixed)	Results of outdoor exposure of a specific model of multi-crystalline silicon (mc-Si) photovoltaic (PV) modules after their first complete year of operation at STF. Impact of module cleaning frequency, use of commercial anti-soiling coatings and module mounting on either fixed, one-axis-tracking or two-axis-tracking systems was studied.	Discussions of durability and cleaning requirements (detailed)
Martinez et al. (2015)	P, MC	Qatar	Various PV technology performance evaluation for dust situations	Descripton of the Qatar Foundation test facility (testing PV technologies most suited for the Qatar climate). Study examines several thin-film technologies for environmental conditions (including dust)	The Qatar Foundation group has extensive facilities and staffing for dust investigations. Possible indications of the better performance of high Eg thin films in heat/dust
Michels et al. (2015)	P,TO	Paraná, Brasil	Solarex MSX56 Si Modules	Dust levels reduced electricity production (power) levels by approximately 16%.	Mainly study of outdoor performance reliability
Mondal and Bansal (2015)	MC	General	PV Modules	Cleaning of PV panels with specially designed robotic arm (SPCRA) with 4-degrees of freedom. Arm has 2 prismatic and 2 revolute joints; system has unique end effector with water sprinkler, air blower and wiper.	Cost effectiveness and versatility of the system is discussed. System design and operation is provided. Nice summary of various cleaning systems
Negash and Tadiwose (2015)	P,TO	Ethiopia	Si PV Modules (site of 10kW PV plant)	Soiling losses for eight different tilt angle (0^0, 5^0,11.6^0,15^0,21.5^0,25^0,30^0 and 35^0) including the latitude of Bahir Dar City (11.6^0), Ethiopia	25^0 tilt angle had a least insolation loss and largest amount of energy absorbed
Nazar (2015)	P, MC	Discussions and Effects	General PV Modules	Improving the efficiency of panel by dust cleaning. Robots, self-cleaning surfaces (electrodynamic screens, robotic vacuum cleaners are discussed.	Includes discussion of solar trackers

Table 4 (*continued*)

Publication Source	Focus Code*	Location [Duration]	Solar Device Type	Key Findings	Comments/Other Conditions
Naeem and Talizhmani (2015)		Jeddah, Saudi Arabia		Correlations between climate zone (meteorological and other) conditions and the dust conditions. Requirements for local cleaning of PV module frequency and needs. Modeling of dust conditions on performance over time.	Conference paper presentation that summarized useful information for Jeddah, KSA and similar climate zones.
Pettersen et al. (2015)	P	Nordic Climates	Soiling/Snow on PV modules	SPICE modeling. Effects of panel orientation for snow and dust. Experiments for dust on mini-modules with and without anti-soiling coatings. Dry and wet cleaning of modules evaluated	Cleaning in all cases provided better results than coatings. Snow especially critical for non-uniformity (shading) issues.
Pettersen (2015) *Masters Thesis*	P, MS	Modeling and Experiment (Various Norway Conditions) [~1 year]	Si PV Module and Module Glass	Model to predict and quantify the effects of partial shading (e.g., by dust) on PV module output using *LTspiceIV*. Experimental validation under Norway climatic conditions: reduction in transmission of 0.92% for untreated module glass and 1.1% with anti-soiling coating (no effectiveness of coating)-over 1 week. Snow accumulations and effect on output also studied.	Results for snow depth reported. Extensive modeling results provided on shading effects.
Penetta et al. (2015)	P,TR	Queensland, Australia	CSP Reflectors	Dust accumulation effects on CSP performance. Correlations among humidity, temperature, and dust accumulation	Discussion of dust compromising mirror reflectivity.
Phinikarides et al. (2015)	P, MS	Cyprus [3-4 years]	PV System Performance PV (c-Si, CIGS, CdTe)	Seasonable variations, including those due to dust and soiling; estimated linear degradation rates Seasonal variations varied by technology. Differences in degradation rates reported by technology	Not significant focus on dust and soiling
Piotrowska-Woroniak et al. (2015)	P, MS	Poland (Great Lakes Region) [2012-2013]	PV 264 Si panels [50.16 kW]	Dust emissions modeled (kg/year) Analysis showed the installation resulted in reduction of dust emissions into the atmosphere—as well as greenhouse gases.	Indirect analysis of dust effects on performance
Rahman et al. (2015)	P	Laboratory Studied	Si PV Module (90W)	Observed module power reduced by 7.70 W due to dust falling on the surface of the solar module.	Studies primarily directed to temperature and climate effects.
Rajasekar (2015)		Laboratory Studies of Soiling; Field Studies for Power Plant	PV Panel Surfaces; Poly-Si minimodules and single mono-Si cells	Development of indoor experimental simulation techniques for soiling of PV surfaces. Failure and degradation modes of about 744 poly-Si glass/polymer frameless modules fielded for 18 years under the cold-dry climate of New York was evaluated. Thesis reports primarily results of indoor soiling studies.	Characterization tests: I-V, reflectance and quantum efficiency (QE) on both soiled, & cleaned coupons Controlled and well-reported laboratory experiments
Sansom et al. (2015)	P,MC	Egypt and Libya	CSP	Methodology to predicting the optical performance and physical topography of the glass collector surfaces of any given CSP plant in the presence of sand and dust storms, providing that local climate conditions are known & representative sand and dust particles samples are available	Characterization of dust particles CSP plant in Egypt, plus sand and dust samples from two desert locations in Libya
Scanlon (2015)	P	International	All PV Technologies	Summary of NREL R&D efforts in reliability, testing, standards development, and quality assurance—and coordinating such work internationally. Portion on importance of dust effects.	General report on reliability. Reference to NREL webcast.
Schaeffer et al. (2015)	MC	Laboratory (superhydrophobic coatings)	Solar Collectors	Functionalized silica nanoparticles to coat various optical elements with measured contact angles and optical transmission between 190 and 1100 nm on these elements. A described solution of the functionalized silica nanoparticles exhibited superhydrophobic behavior with a static contact angles $\geqslant 160°$.	Focus on windows and mirrors. Discussions of various hydrophobic properties.
Schill et al. (2015)	P	Gran Canary Island (Spain) [> 5 months]	Crystalline Si Modules	Soiling due primarily to building construction in area. 20% loss in efficiency (monitoring of I-V characteristics) in 5-month period.	Extensive instrumentation for monitoring of performance, climatic conditions, and irradiance.

				Non-uniformity in distribution (caused by rain effect) detected by shape of I-V characteristics. Heavy rain event reported to clean the modules—and completely restore the performance.	Detailed information on experimental setup and data acquisition.
Sengupta et al. (2015)	I, S	General (worldwide best-practices)	General best practices for solar measurements	Effect of dust and other airborne particles on the measured solar resource; Effect of these particles and other atmospheric components on the calibration of instrumentation. Very detailed information on maintenance and calibration of instrumentation.	Handbook links with major research and solar resource determinations in harsh climates such as Saudi Arabia (see KACARE portal:
Shi (2015)	P,CE	China	CSP	Viability of CSP technology in China power market. Consideration of dust as a obstacle to deployment and economics	M.S. Thesis Good discussions of issues in China relating to other parts of the world.
Shirakawa et al. (2015)	P, CM, A	São Paulo, Brazil [6-18 months]	Crystalline Si Modules	*Sub-aerial biofilm* (SAB) development on PV module surfaces (tropical conditions). Fungi were an important component of these biofilms; very few phototrophs were observed. Major microorganisms detected were melanised meristematic ascomycetes and pigmented bacterial genera *Arthrobacter* and *Tetracoccus*; Some diverse algae, cyanobacteria and bacteria were identified in biofilms. Photovoltaic modules: significant power reductions after 6, 12 (both 7%) and 18 (11%) months.	No differences between 6- and 12-month power observations in modules attributed to dual nature of soiling. Soiling effects removed by light rain.
Sleiman et al. (2015)	TR	General	Solar Roofs	Primarily a "cool roof" study, but this paper also examines solar reflectivity. Accelerated aging method for solar is both repeatable and reproducible within an acceptable range of standard deviations: the repeatability standard deviation s_r ranged from 0.008 to 0.015 (relative standard deviation of 1.2–2.1%) and the reproducibility standard deviation s_R ranged from 0.022 to 0.036 (relative standard deviation of 3.2–5.8%).	The 3rd in a series of 3 papers on "cool roof". The other two are cited in the notable others section.
Spataru et al. (2015)	MS	Denmark	Crystalline Si PV Test System and Laboratory Modeling	Shading and soiling considerations. Proposes a complete diagnostic method for detecting shading, increased series-resistance losses, and potential-induced degradation of the PV generator by analyzing changes its current-voltage characteristics.	Practical application: the diagnostic parameters and rules applied "as is" to a field test setup consisting of a crystalline silicon based PV string and a commercial string inverter capable of measuring the I-V curve of the PV string, yielding a similar high-detection rate.
Sulaiman et al. (2015)	P	Malaysia	Crystalline Si Modules	Effects of dust accumulation on the performance of PV panels. Experiment; dust particles on solar panels with a constant-power light source, to determine the resulting electrical power generated and efficiency. Results: the accumulated dust on the surface of photovoltaic solar panel can reduce the system's efficiency by up to 50%	Characterization of local Malaysia climate zone.
Tanesab et al. (2015)	P, MC, TR	Perth, Australia Temperate Climate Zones	PV Modules	Properties of dust: particles deposited on PV modules' surface were dominated by fine particles built of large amounts of quartz (SiO_2), followed by calcium oxide (CaO) and some minors of feldspars minerals ($KAlSi_3O_8$), which are primarily responsible for transmittance losses. Module degradation for this 18+ year installation was mostly due to non-dust issues, but dust can be attributed to some levels in the range of 16%-29%.	Modules were in field for 18 years with no cleaning schedule
Verma and Singhal (2015)	P	Gujrat, India Plant commissioned in 2012	Grid-Connected PV Plant (20 MW) a-Si:H modules	Major causes of cells/modules operating outside standard conditions: Voltage drop in the dc cables and protection diodes; Dirt and dust, Shade; Dispersion of parameters among the PV modules; Operation voltage out of the maximum power point (MPP); Spectrum and angle of incidence. Bird droppings major cause of "shading" Always returned to within 1% of rating after cleaning	Consideration of all loss mechanisms for this large thin-film PV plant; detailed review of power plant operation/reliability.

Table 4 (*continued*)

Publication Source	Focus Code*	Location [Duration]	Solar Device Type	Key Findings	Comments/Other Conditions
Weber et al. (2015)	P	Worldwide overview of issues	Soling and Cleaning of PV Modules; Potential effects on module abrasion	Importance of relationships among soiling, cleaning, and abrasion of module surfaces. Abrasion of coatings (e.g., ARCs) Climate zone informations requirements (wind speed/ direction, dust compositions, moisture, natural cleaning, water availability) Power reduction (more severe in desert countries than Germany)	Discussion of PVQAT activities with dust/interactions Very good overviews of cleaning, indoor simulations, testing, standard procedures, abrasion, etc.)
Wu at al. (2015)	MC	Laboratory Study	Electrodynamic Coatings	Transparent ITO "fork electrodes" were configured on glass substrates with different widths and separations. The effects of the electrode width, the electrode spacing, voltage, frequency, waveform, and the duty ratio on the dust removal efficiency were investigated for artificial dust removal.. Optimum conditions of dust removal: voltage - 1500 V, frequency - 15 Hz, square wave, 10% duty ratio, the electrode width - 0.5 mm, electrodes spacing -1.3 mm; dust removal with with 99% effiency.	Follow up on previous work in 2014
Xu et al. (2015)	TR	Laboratory and New York City	Glass Covers	Development and testing of high-performance polymeric coating on glass with a nano-scale surface roughness: both anti-reflective (ARC) as well as superhydrophobic properties.	Mechanical and chemical durability investigated and reported (suggests 30-year lifetime in NYC).
Yang et al. (2015)	ME	Acceptance procedures	Utility-Scale	Methodology for performance acceptance testing of solar boilers using Linear Fresnel Reflectors (LFR) with Direct Steam Generation (DSG). Proposed methodology is based on relevant ISO and American standards applying an adapted parameter identification technique. Discussions regarding soiling and measurement requirements and uncertainty analysis are also provided.	Methodology anticipated to improvement in the operation of next LFR power plants.
Yilbas et al. (2015)	P, TR, CM	Laboratory Measurements	PV Glass Surfaces (Chemical/ compositional properties of dust & adhesion to surfaces)	Effects of soiling and mud on the optical, chemical, and mechanical properties of PV module glass. The characteristics of the dust and the mud (cementitous layers) formed from this dust examined by analytical techniques (optical & scanning electron microscopy, AFM, XRD, energy spectroscopy, FTIR). Microtribometer used to measure adhesion, cohesion and frictional forces required for the removal of dry mud from the glass surfaces.	Extensive chemical and physical measurements of dust partical properties. Interesting and useful investigations of adhesive forces holding dust and "mud" to the module glass surfaces (macroscale determinations of force)
Zell et al. (2015)	P, A, S	Saudi Arabia	Solar Resource Assessment	In-depth and comprehensive discussion/analysis of solar resource assessment (results for Saudi Arabia) Stresses that accurate measurements of the solar Resource depend critically on environmental conditions such as ambient air temperature and dust levels that affect/ control project output, and are critical to project deployment. Affect of dust on solar spectra—and on the output from the PV system in these desert regions because of dust adhesion.	Excellent discussion and analysis of the solar resource in the desert regions-especially Saudi Arabia. Studies tied with the important KACARE program for solar deployment and research in KSA See website for detailed info on solar resources: https://rratlas.kacare.gov.sa/RRMMPublicPortal/)

*P=Performance, *MS=Modeling/Simulation; *CM=Composition/Morphology; *TR=Transmission/Reflection; *CE=Cost/Economics; *MC=Mitigation/Cleaning; *A=ambient conditions/effects; *I=Instrumentation; *S=Spectral Effects; TO=Tilt/Orientation

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