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

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

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

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ABSTRACT

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

1. Introduction and background

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

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

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

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

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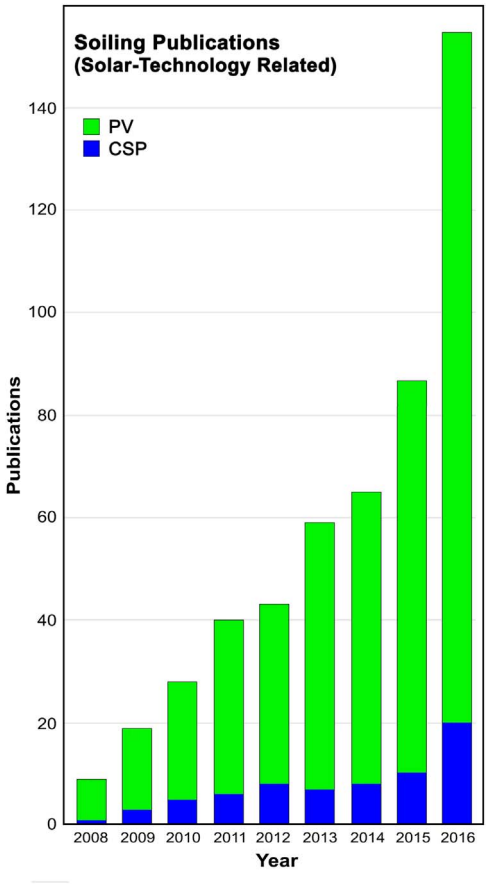

Fig. 1. Histogram of publications for the recent period of solar-electricity market growth (2008–2016), spurred by significant decrease in PV pricing. Relative PV and CSP publication volumes are indicated.

2. Literature review (2016)

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

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

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

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

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

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

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

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