Dust in the Wind:
An Historical Timeline of Soiling R&D for Solar Technologies

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Abstract

The current multi-GW annual solar markets have brought a heightened focus on system reliability and sustained performance. Many of these growing markets are situated in world climate zones that are most solar-rich, but ironically co-located in geographies that are most soiling-prone. This paper documents the more than 7 decade-history of the research invested into the science and solutions of soiling of solar components—highlighting the motivation and milestones; the researchers and personalities, the R&D and commercial priorities, and the associated progress. The presentation follows a historical timeline that begins starting with the 1940-1970s, examines the changing emphases from solar thermal to solar electric, highlights the interesting contributions from the requirements for space and in particular the first Mars-rover (Sojourner), and documents key contributions through the recent growth in soiling R&D coincident with the PV market expansions attributed to China and its manufacturing with associated precipitous (and fortunate) technology-price declines. This paper also highlights key current and future research directions, speculates on short-term approaches preventing solar showstoppers, and envisions some "holy-grail" schemes that might lead to the final solution(s).

Keywords: Soiling, dust, photovoltaics, concentrating solar power, solar thermal, history

1. Introduction

The growth in photovoltaic (PV) manufacturing and markets has been monumental over the past decade, reaching about 0.5-terawatt of cumulative installed-PV capacity through 2018 (Fig. 1) (Mints 2019). In turn, this has increased demands for reliable and sustained performance from this clean-energy source. Many of these growing, multi-GW markets are situated in world climate-zones that are most solar-rich, but ironically co-located in geographies that are most soiling-prone (e.g., northern Africa, the Middle East, India, as well as the desert areas of China, Australia, the United States, and Chile). Unless addressed, these solar installations can lose 20%-50% of their generation capability in monthly timeframes—along with the associated loss of monetary income. This paper documents the more than seven-decades history of the research invested into the science and solutions of soiling of solar components—highlighting the motivation and milestones; the researchers and personalities, the R&D and commercial priorities, and the associated progress.

The overview follows an historical timeline that begins in the 1940-1970s, during which the early solar pioneers and visionaries (all associated with ISES) first recognized the potential detrimental effects of soiling, primarily working on solar-thermal collectors. With the Middle East oil embargo and resulting energy crisis in the 1973 timeframe, the emphasis expanded to terrestrial electricity production. And the R&D investment in soiling grew primarily for concentrating solar (thermal) power (CSP). During the 1980s, the collapse of oil prices and conservative political influences severely limited government budgets with buildup of fossil-fuel energy sources. The 1990s presented a shift, with solar-market experiments for CSP and PV driven by manufacturing interests and environmental concerns. Coincidently, space-ventures turned toward Mars—and the "dust" issues with PV and the first Mars-rover (Sojourner) provided investments in dust-mitigation research from NASA. Terrestrial soiling research extended into the early 2000s with incentive programs (Germany, Japan, Europe). This soiling research focus was shared by CSP and PV. Then over this past decade, the incredible PV market expansion because of China and its manufacturing with associated precipitous (and fortunate) price declines, mandated serious attention to these soiling problems. Accompanying this about 75-year

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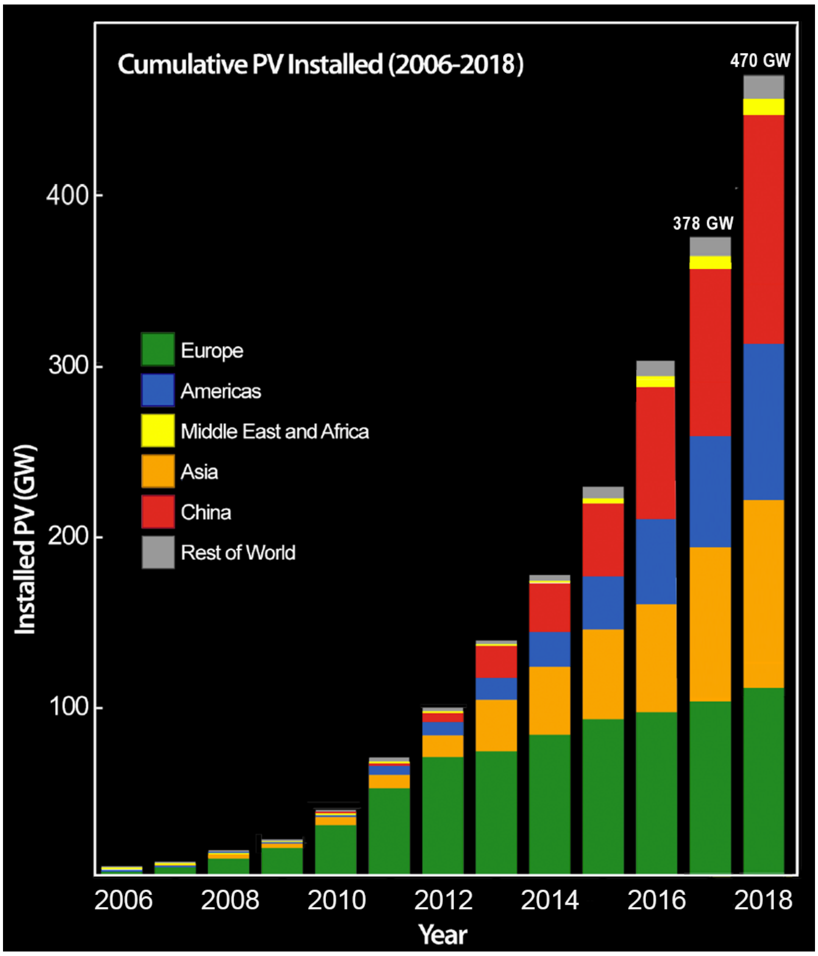

Fig. 1: Cumulative PV installations as function of year for various geographical areas

progression, the markets, technologies, R&D investments, and politics is mirrored by the volume of soiling journal and conference publications—which have progressed from a handful in the first 2-decades to more than 300 in 2018 alone.

This paper examines this history and the key science and technology contributions associated with these periods. Much of the material is covered in several reviews of soiling that have been published in the last decade (Mani and Pillai, 2010; Bakirci, 2012; Mekhilef et al., 2013; Bao et al., 2013; Midtdal and Jelle, 2013; Sharma and Chandal, 2013; Tarver et al., 2013,; Butuza, 2014; Ghazi et al., 2014; Hernandez et al., 2014; Kazem et al., 2014; Sayyah et al., 2014; Darwish et al. 2015; Maghami et al., 2016; Costa et al, 2016, 2018; Sainthiya and Beniwal, 2017; Pringle et al., 2017; Omara et al., 2017; Jamil et al., 2017; Guerin, 2017; Fouad et al., 2017; Figgis et al., 2017; Zurita et al., 2018; Sun et al., 2018; Sowden et al., 2018; Shaju and Chacko, 2018; Saravan and Darvekar, 2018; Said et al., 2018; Rao et al., 2018; Picotti et al., 2018; Mussard and Amara, 2018; Mellit et al., 2018; Ilse et al., 2018; Hammad et al., 2018; Hadwan and Alkholidi, 2018; Deb and Brahmbhatt, 2018; Comerio et al., 2018; Bouaddi et al., 2018; Babatunde et al., 2018; Al-Thani et al., 2018; Santhakumari and Sagar, 2019; Gulfam and Zhang, 2019; Dewi et al., 2019, Comerio et al., 2019; Al-Douri et al., 2019). In addition, key current and future research directions are highlighted. We speculate on short-term approaches preventing solar showstoppers and envision some "holy-grail" schemes that might lead to the ultimate solution(s).

2. Historical Analysis of the Evolution of Soiling R&D

The interests, investments, and level of critical interest in soiling issues are reflected by the publication history, represented in the histogram of Fig. 2. Traditionally, the research output and funding levels are traditionally manifested through the literature publications reporting on a technology's needs, relevance, and improvements. In this section, we identify particular periods, motivations, technologies, and external driving forces that have been responsible for R&D progress..

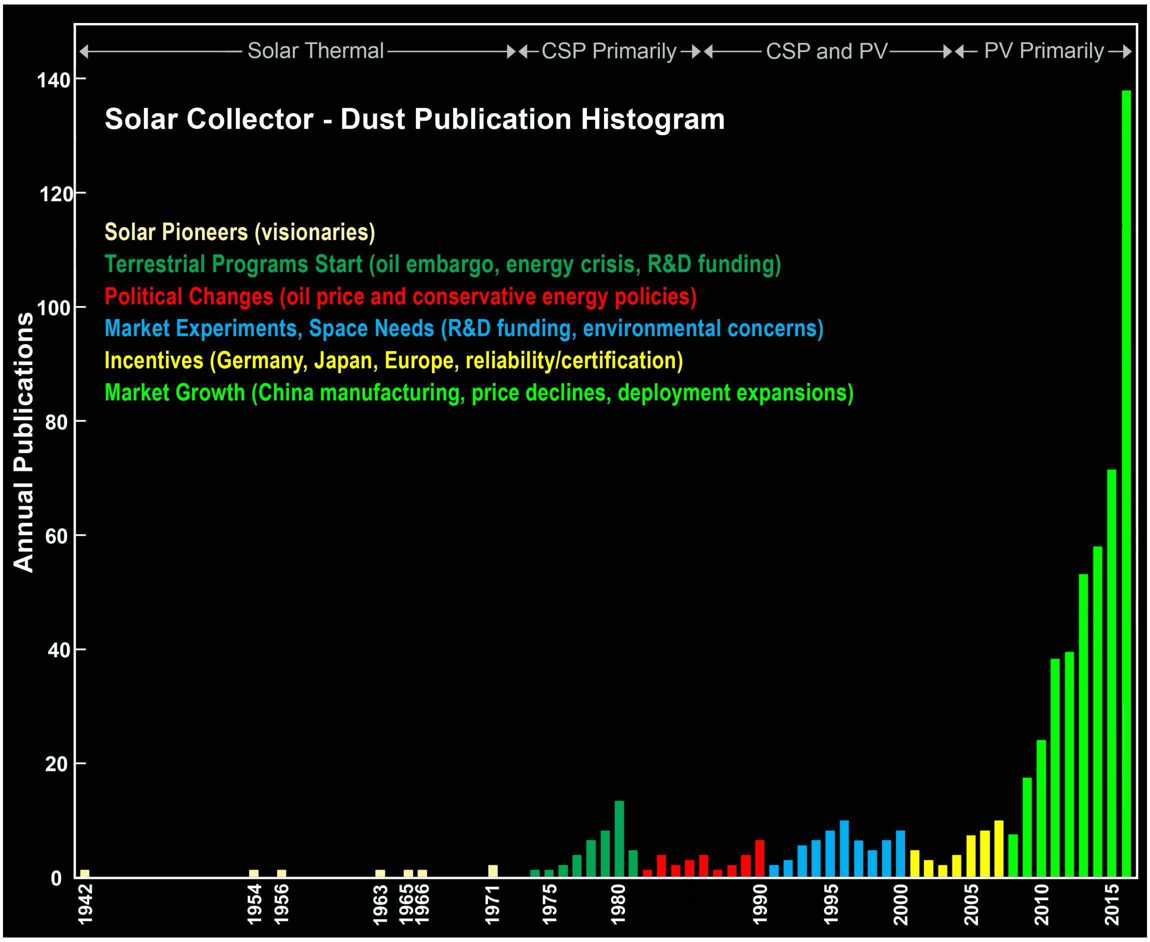

Fig. 2: Histogram showing soiling publications annually over the period 1942 through 2016

2.1 The early years (1940-1979): Solar pioneers

The initial serious attention to the effects of soiling on solar-component performances can be attributed to early solar pioneers and visionaries. The contributions of Hottel, Woertz, Tomlinson, Sayigh, and Garg not only recognized the debilitating effects that "dust" could have on the future adoption and use of solar collectors, but also established some need for investigation the science underlying the soiling processes. This nascent work was centered on **solar thermal applications** (solar water heaters, stills, concentrators, furnaces) which dominated the early technologies. We provide some added details of this early work of those pioneers who were also ISES leaders.

The seminal 1942-publication by Hottel and Woertz (1942) is one that is attributed as initiating this research-interest in soiling and solar energy. This paper first reported progress of the performance of solar-heat collectors, primarily the collection of heat in a fluid and the utilization of that heat. In the conduct of this experiment for the collectors on the first-solar house at Massachusetts Institute of Technology (MIT), the researchers evaluated of the effects of dirt on the collector operation. Figure 3 shows Dr. Hoyt Hottel (1903-1998) and Dr. Maria Telkes (1900-1995), two ISES pioneers, along with the MIT house that they had developed and served as the basis for these first dust experiments. Dr. Byron B. Woertz is the figure on the room, working on the "heat traps." The "instrumentation" for quantifying the effects was that of visual inspection—in which the researcher estimated the degree of "dirtiness" on 5-point grading scale (see except from paper in Fig. 4).

The critical nature of soiling was recognized by more focused research reports in the over the next two decades, still concerned with solar thermal. Pioneering studies included reports by Dietz (1963), Bagnold (1965), Matsuda and Aoyoma (1971), Hamberg and Tomlinson (1971), and Gilligan and Brzuskiewicz (1976). Special note are those research investigations by ISES leaders: (1) H.P. Garg (1974) evaluated the changes in transmission of glass solar-thermal cover sheets as a function of exposure time in India. This study noted the differences in vertical and horizontal mounted samples; and (2) A.A.S. Sayigh (1978) used flat-plate collector glass cover sheets to evaluate the changes in collector performance in the more-harsh climates in Kuwait (comparing clean and soiled surfaces). It is probably the first investigation of the effects of angle-of-inclination on the soil accumulation and the initial investigation of early generation PV panels under these desert conditions.

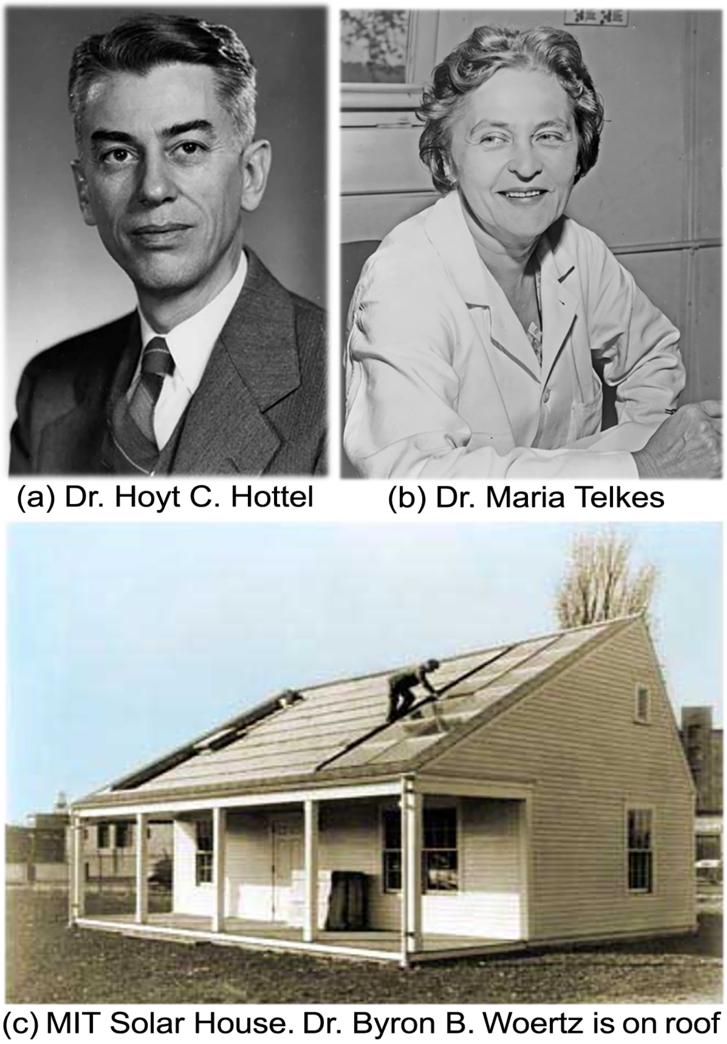

Fig. 3: Early pioneers: (a) Dr. Hoyt C. Hottel (1903-1993); (b) Dr. Maria Telkes (1900-1995), co-designer of MIT house; (c) MIT 1st Solar House (1939)-first "soiling laboratory," with Dr. B.B. Woertz working on heat collector on the roof.

Historically, this period also heralded the major tipping point for PV technology, with the Bell Telephone Laboratories "solar battery" discovery in 1954. This Si solar cell was the first to reach efficiencies beyond 6%, making them interesting for real electricity generation applications. This also led in this period to the first solar-powered satellite, Vanguard I, in 1958, providing the first markets to test and use this new technology. These events were key to the developments in the next periods of soiling research. This study also pioneered the methodology used in many current soiling monitoring stations. Following Fig. 4, the effect of dirt on the collector performances were obtained by comparing the mean of the west and center units (uncleaned collectors) with the clean east collector. From these data, they obtained a measure (D) of the effect of soiling—essentially the reduction in transmission through the glass cover sheet

2.2 Terrestrial energy programs (1973-1980): The first stages of soiling research

The 1973 oil-embargo and associated "energy crisis" sparked the heightened attention and serious consideration of solar energy to replace these diminished fossil fuel sources. Government investments around the world swelled in the early-to-late 1970s to accelerate the development and use of these "alternative energy" technologies. Major laboratories (notably, the Solar Energy Research Institute–SERI, and the Florida Solar Energy Center-FSEC in the U.S. and Fraunhofer ISE in Germany) were established with focused missions on solar energy research, development, and deployment. The scientific community grew, as did the volume of conferences, workshops, and meetings.

(*g*) Attic and laboratory temperature, necessary for making thermometer-stem corrections.
(*h*) A qualitative estimation of dirtiness of uncleaned collector units. The top panes of glass of the east unit were maintained clean at all times. The west and center units were never cleaned except by rain or snow. Visual observations of dirtiness were recorded day by day in the form of a grading 1 to 5, grade 1 being clean and grade 5 being very dirty; all grading was done by the same individual.

Fig. 4: Excerpt from seminal paper by H.C. Hottel and B.B. Woertz ("The performance of flat plate solar heat collectors," ASME Transactions 64, 91-104 (1942) describing measurement of soiling.

The soiling related work in this initial period" mainly focused on effects on heliostats and mirrors used with **concentrating solar thermal power (CSP)**. These were considered the most advanced and least expensive in the pathway to commercialization. These systems were deployed early for testing in areas having necessary high AM-direct solar irradiance component—mainly in desert regions. This brought the bothersome environmental condition of "dust" that collected on the reflective surfaces—and the search for understanding the soiling process and effects on performance. The annual publication volume (Figure 2) reflected the research funding growth.

The quality of the papers in this period were primarily aimed at establishing the effects of dust accumulation reflection (for mirrors) and transmission (for lenses) of the concentrating components. The cleaning of these surfaces started to receive attention, primarily using water for restoration. The major research was led by Sandia National Laboratories and Jet Propulsion Laboratories in the U.S. Perhaps the seminal publication during this period was that of Ed Cuddihy, which provided the earliest roadmap to the design and choice of coatings or surfaces that resist soiling. The "Cuddihy rules" designed surfaces that are:

1. Hard (less susceptible to embedding particles or being damaged by them)
2. Smooth (less likely to trap particles)
3. Hydrophobic (less attractive to ionic species, adsorption of solids, and retention of water)
4. Low-surface energy (lower chemical reactions)
5. Chemically clean (especially of materials classified as potentially ''sticky'')
6. Chemically clean of water soluble salts (which are likely to link with other soiling agents)

Cuddihy investigated two primary techniques to achieve his desirable chemical characteristics—hydrophobicity and low-surface energy—of low-soiling surfaces. The first technique for glass involves chemical coupling of fluorinated compounds to the glass surface. The second technique involved chemical replacement on the surface of all Group I ions (which are hydrophilic) with hydrophobic Group II and preferably Group III ions.

2.3 Political change (1981-1990): Uncertainty

Political change and the rapid increase of oil availability and decrease in fuel costs redirected energy priorities. Conservative governments label solar advocates as "tree huggers"—and the budgets were cut severely. Although this would have been the best time to invest in clean energy approaches, many research groups and beginning commercial ventures had to cut back or abandon efforts. In the U.S., budgets were slashed by >75%. Remaining investments turned toward fundamental research—and the more applied R&D in soiling mitigation was left to linger. Figure 2 shows an accompanying and expected drop in the publications. But, though the CSP focus continued, a subtle change occurred with an initiation of interest in soiling issues with PV.

2.4 Market experiments (1990-2000): Roofs, space interests, R&D increases

The 1990s heralded some shifts in interest and rekindling of solar energy potential. First, the rise of market experiments. The "1000-, 10,0000-, 100,000, and million roof programs" were born in Germany (1991), spread to Japan (1994), bolstered by Germany (1999) and then fashioned in the U.S. (2001). Large central-station CSP experiments were initiated. And, the successes of space exploration and the issues that arose from the PV-powered NASA Mars Rover (*Soujouner*) with extreme dust conditions and remoteness on that planet—invigorated research into prevention approaches. These included coatings, vibrations/ultra-sonics, electrostatics, and electrodynamic screens. This reignited application and development of such high-tech remedies for earth-bound systems as well.

2.5 Incentives (2001-2007): Germany, Japan, Europe, reliability/certification

The new century was marked by a significant growth in PV, both research and sizeable market expansions. This was driven by incentive programs such as the feed-in tariffs in Germany and European system buy-down subsidies in Japan and the U.S. The research community started to become interested in soiling research because of the rise in applications and country programs—and some realization by the developers that dirty modules were *money losers* in their power systems.

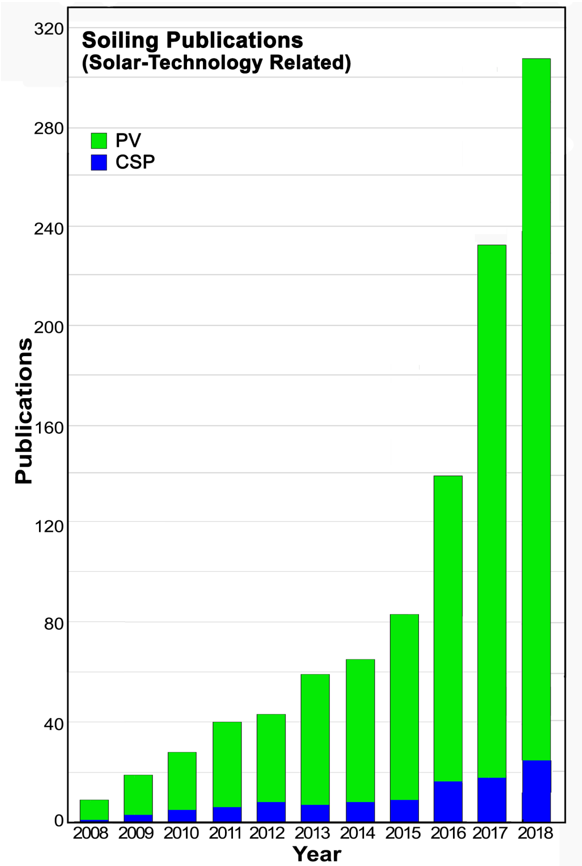

Fig. 5: Expansion of data from Fig. 2 to inclde 2017 and 2018 publication data. Emphasis of the reporting continues to be dominated by PV, but there is some increased interest in CSP due to added funding for this technology..

2.6 *Beyond-the-tipping-point* market growth (2008-present): China leads; solar is real

With the China dominance in manufacturing of PV (*they showed the world how*) starting in 2009/2010, a beneficial collapse in PV prices took place. Following, a rise in new markets and investments in desert locations (Saudi Arabia, Qatar, U.A.E. and other Gulf countries) and the U.S. Europe and Australia—as well as major deployment programs in India and China, the publications addressing dust and soiling issues rose to the highest annual levels. And these levels can be expected to continue to be significant in the literature because of the economic and energy benefits of dust mitigation for these solar electric generators. During this period, PV has been the primary attention of this massive publication rise. One of the disruptive consequences of the rapid and order-of-magnitude drop in PV prices has been that deployments of other solar electric approaches (e.g., CSP) have slowed.

3. Current Soiling R&D Effort and Future Directions

The past two years continue to reflect the research interest and priority for mitigating the soiling issues (though the annual PV shipments in these two year were about constant). The publications continue to center on PV—though there is some uptake in those concerned with CSP, as represented in Fig. 5). This is due to some increase in funding (e.g., in the U.S. DOE solar programs) and in southern Europe and northern Africa installations.

Soiling technical interests have shown some trends over the past decade. In the period 2010-2015, about 80% of the publications mainly monitored and reported on the decrease in performances of components and systems. This work was important in establishing the performance ratios and soiling rates in a particular location, with a variety of purposes including determining the suitability for a potential installation and/or estimation of cleaning periods. More recently with the expansion of the soiling-related research efforts, the research has become more sophisticated, more directed toward understanding, and increasingly focuses on solving the soiling problem that steals significant percentages of an installation's output. There has been a rise and a refinement of laboratory based soiling studies and the development of "dust simulators" to allow for evaluations under very controlled conditions (including soiling rates, angles, humidity, temperature, and irradiance conditions). Associated with this has been the used of "dust standards," although there is some discussion on whether these materials standards are generally translatable to real dust conditions encountered in various geographical conditions. This translates into bankability issues, important for financial investments, insurance, and consumer acceptance.

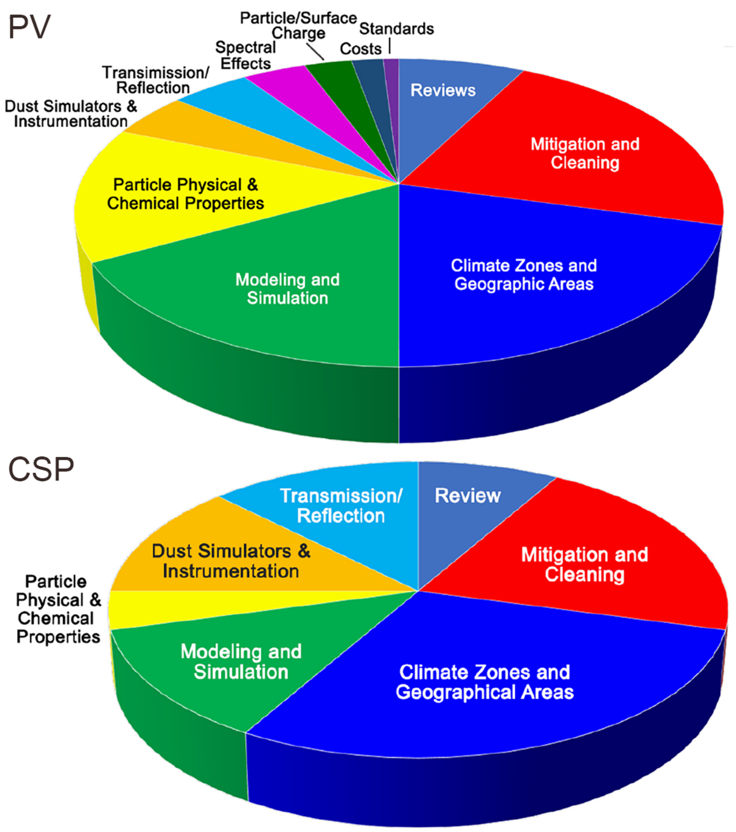

Fig. 6: Research topic areas for publications over the period 2017 and 2018.

Figure 6 presents the compilation of research reports from the years 2017 and 2018. The major focuses are on ***cleaning methods and mitigation*** of the soiling problem, as well as the interrelated interpreting the severity of the soiling in a particular geographical area or climate zone. A significant elevation to 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 (systems). 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 (PM2.5, PM10), 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. A recent "revived" evaluation has been the use of wind tunnel experiments for evaluation of soiling, especially for orientations and determination of wind effects. One concept behind this overall modeling 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 substrate surface. Part of this is also the understanding on how the particles connect to each other and to that module or reflector surface— the "cementation" or solidification process that plagues areas that have levels of moisture (e.g., heavy morning dews) that interact with the soiling particles and become "bonded" to the surface and each other under high temperature and ultraviolet light conditions. Removing the resulting layer tends to be difficult in many cases using conventional cleaning techniques. For PV, the nature of the charge of the particles and the surfaces has begun to be explored in detail. This relates to both the interest in the process of dust attaching to the module surface—as well as the increased interest in static and dynamic screen to "repel" the dust. Controlled experiments are crucial—leading to the development of dust simulators that can provide rapid, laboratory investigative systems. Likewise, the use of solar simulators and reflectometers/spectrometers have accelerated the understanding of spectral effects and transmission/reflection properties of the layers. Finally, primarily for PV, the costs of cleaning, costs of mitigation approaches, the cost of electricity lost/gained under the environmental conditions, the related costs of system sizing, etc. are being investigation and reported. And, because this is an issue that related to reliability, the development and evaluation of standards are being addressed—especially standards relating to harsh climates where the dust issues can dominate.

The future needs more research in this important area. This includes the development of standards that focus on harsh climates, those that have higher temperatures and high degrees of soiling, in particular. Comprehensive, user friendly (web based) design modeling tools will become available soon for determination of soiling rate/ratios for all geographic areas for use by developers and installers for system sizing and O&M (cleaning cycles) requirements affecting the maintenance costs. But the major question is, will the quest for the "holy grail" be completed? Will we produce a cost-effective, durable, dual-purpose anti-soiling and anti-reflection coating for module technologies and for CSP reflectors that have 10-20 year lifetime? This would certainly revolutionize these aspects of solar technology.

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