SOLAR TECHNOLOGY SOILING R&D: HISTORY, PROGRESS, STATUS, AND TRENDS

Summary

Throughout the current world nearing TW annual installations, soiling is a fundamental issue limiting solar technology performance and related financial losses. This paper documents & reviews the some 8-decade history of the research invested into the science and solutions of soiling of solar components, highlighting the motivation and milestones and the associated progress. This includes the technological & political influences driving the investments. Reflecting this 80-year progression, the markets, technologies, R&D investments, and politics are mirrored by the volume of journal and conference publications. The trends from observation of the effects on performance to mitigation; from submicron determinations of particle chemistry and adhesion to the losses on multi-MW systems; and the progress from 'Edisonian' trial-and-error approaches to the use of AI and ML for monitoring & designing potential solutions. This paper highlights key current/future directions and envisions some *"Holy Grail"* schemes that might lead to the ultimate solutions.

Keywords: PV, CSP, solar, soiling, performance, review

1. Introduction

The 2025 global-installed-PV will exceed 2-TW, and the growing multi-GW annual solar markets have brought a heightened focus on system reliability and sustained, optimal performance (Mints, 2025). 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 reviews, documents, and analyzes the >8-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, the associated progress, and the future based on revolutionary science approaches.

The presentation follows a historical timeline shown in Fig. 1 that begins with the 1940-1970s, during which the early solar pioneers and visionaries first recognized the potential detrimental effects of soiling, primarily working on solar thermal collectors. Hottel and Woertz provided the earliest foundational alert that soiling losses are significant for solar collector performance (Hottel and Woertz, 1942). With the Middle East oil embargo and resulting energy crisis, the emphasis expanded from space 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 (Landis, 1994(. Terrestrial soiling research extended into the early 2000s with incentive programs (Germany, Japan, Europe). This soiling-timeframe 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 price declines, mandated serious attention to these soiling problems. Accompanying this 80-year 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 annual hundreds of publications for PV and CSP over the last half-decade. Currently political threats have re-emerged with the imposition of global tariffs on materials and products in the clean energy sector (Mints, 2025)–and some movement toward last century's energy investments and technologies. In this paper, the trends from soley observing the effects on performance toward needed mitigation; from sub-micron determinations of particle chemistry and adhesion to the losses on multi-MW systems; and the progress from 'Edisonian' trial-and-error approaches to the use of AI and ML for potential solutions. This paper reviews the historical PV and CSP literature and 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 ultimate solution(s).

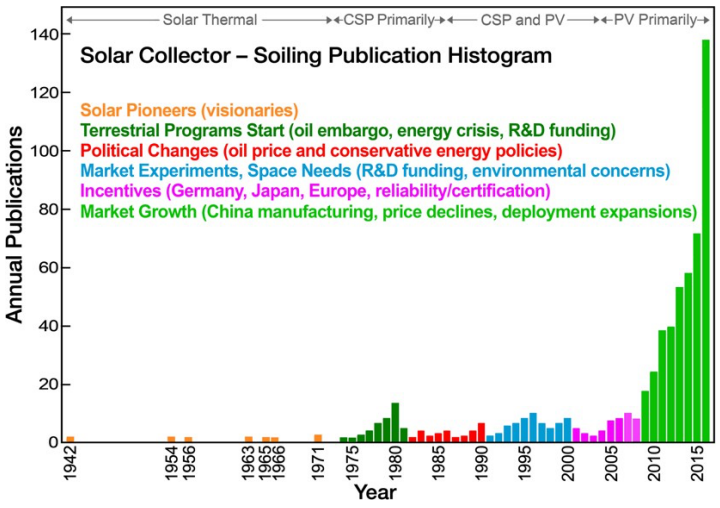

Fig. 1. Histogram of solar soiling publications over period 1942 to 2016, indicating defined era and technology emphases.

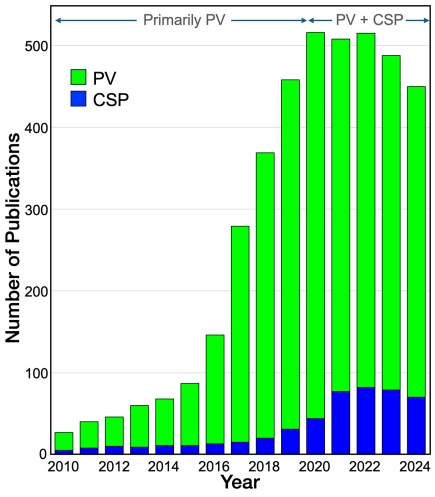

Fig. 2. Literature in PV market growth period (2010-2024) indicating dominance of PV and recent re-emergence in CSP soiling research.

2. Trends and Expanding R&D Priorities

The literature population levels, of course, follow the market levels and needs and the related R&D investments by government and private sectors. Certainly, this is reflected in the growth in publications over the past decade or so with the falling solar prices leading to massive worldwide solar electricity expansions. This is highlighted in Fig. 2, with publications exceeding 400/year since 2019. (The 2024 levels are likely about 10%-20% low on this chart due to delays in reporting by journals and conferences.) This growth period had been dominated by PV-related activities—although in the last few years, new considerations of CSP have increased investigation into soiling issues for this technology in which particulate accumulations are even more critical to performance degradations.

Over the 8-decade course of this research, the research focus has shifted. The trends and priorities are illustrated in the pie charts in Fig. 3, each summarizing the literature reports in 11 defined categories over 2-year (biennial) periods. Trends from 2017-2024: (1) The **routine observations and reports of PV (CSP) performance** under various soiling and climate conditions have declined substantially; (2) **Modeling and simulation** have increased to provide guidance and insight needed for understanding and mitigation, fairly constant in contributions over 2017-2024; (3) With the substantial deployment levels and the realization of the critical loss in performance, the trend has critically focused on solving the problem through inventing, developing, testing, and validating **mitigation techniques** from about 10% in 2017-2018 to 34% in 2023-2024. And (4) following technical and scientific developments, state-of-the-art computational methods, characterization, and nanotechnology have become prominent in soiling R&D. This includes the application of **artificial intelligence (AI) and machine learning (ML)** methodologies to the understanding & the identification of solution pathways.

The advancement of R&D in this area is also reflected in the increasing number of ***reviews*** that have been published, with more than 50 over the past two years. The paper will highlight these specifically including their contributions to the understanding and documentation of the state-of-the-art.

3. Mitigation and Developing Use of AI/ML

The mitigation of soiling to maintain or restore adequate performance level in PV (or CSP) systems has emerged as the primary focus for research and commercial deployed products. The issues of minimizing the effects of soiling to optimize solar power plant operation include: (1) Preemption (maximizing the initial conditions) through ensuring best-possible module (or reflector) surface properties, site integrity (location, terrain preparation, cultivation), and module exposure control (tilt, tracking, stowing); (2) Restoration (cleaning) by washing (water, cleaning agents), mechanical removal (brushing, wiping, forced air, vibration), Hybrids (combining several techniques), robots, automation; and, (3) Prevention (surface modifications) using high high-tech coatings (nanotechnology, superhydrophobic, super hydrophilic). Certainly, research in this final category has grown—to be the bit more than half the publications in the 2023-2024 mitigation category (Fig.

3). These represent the *Holy Grail* solution but are still primarily in the stage of development and optimization. Lifetime and durability are the primary issues with these (as it is with antireflection coatings).

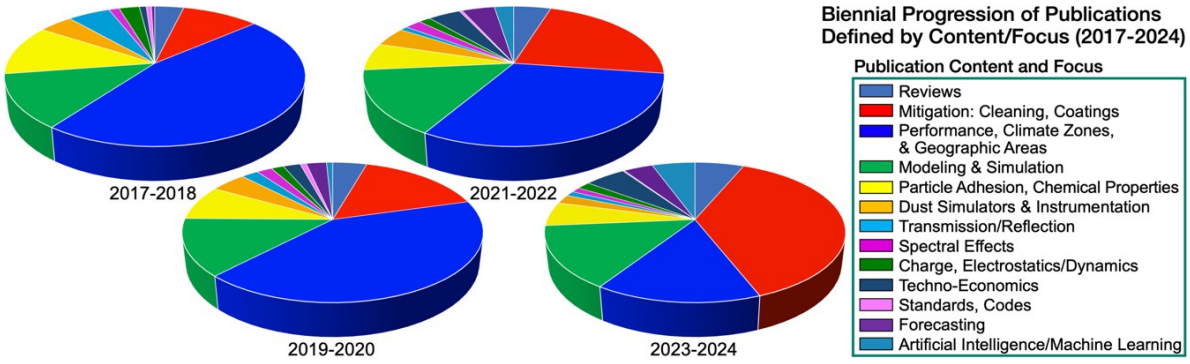

Fig. 3. Trends in literature R&D content, indicating clear increased interests in mitigation (cleaning, coatings) and AI/ML applications. The charts are presented over biennial periods.

Artificial intelligence (AI) and machine learning (ML) have already become immersed in in the PV value chain, from materials development through system operation. And the use of these methodologies has become a growing science-based assistance to soiling R&D (Fig. 3). This includes specific materials design of anti-soiling coatings, to the operation of cleaning robots, to the rapid on-site alerts and implementation of cleaning cycles or identification of soiling related issues (e.g., non-uniform heating, hot spots).

This paper discusses the status of the mitigation techniques, current limitations, costs, and future expectations. Additionally, the functionality of AI/ML in this R&D area is summarized—including the huge future expectations and their timelines. Specific needs for advancement of these methodologies for future soiling R&D will be envisioned.

4. Summary and Expectations

This paper is designed to provide a critical review and analysis of where soiling R&D has been and where it is going. It is meant to complement the contributions to this IEEE PVSC in this research area. (This paper provides more in-depth analysis and complementary addition to previous review publications.) Charts will be included mapping global soiling research distributions (with a focus on literature contributions). Tables will include important reviews and well as published dissertations/theses over these periods. The presentation will include media representations—as well as an internet-available site for the large, indicated literature base. The presentation will identify specific important contributions to the understanding of the soiling process, mechanisms, physics, and chemistry—and specifically the advancement of mitigation approaches and technologies.

4. References

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