

The Indexing Development for Assessing Impact of Wildfire Smoke on Photovoltaic System Performance

Amjad Jebriil Ali , *Student Member, IEEE*, Long Zhao , *Member, IEEE*,
 Mohammad Heidari Kapourchali , *Member, IEEE*, and Wei-Jen Lee , *Life Fellow, IEEE*

Abstract—Comprehending the impact of wildfire smoke on photovoltaic (PV) systems is of utmost importance in ensuring the dependability and consistency of power systems, particularly due to the growing prevalence of PV installations and the occurrence of wildfires. Nevertheless, this issue has not received extensive investigation within the current literature. A major obstacle in studying this phenomenon lies in accurately quantifying the impact of smoke. Conventional techniques such as aerosol optical depth (AOD) and PM 2.5 are inadequate for accurately assessing the influence of wildfire smoke on PV systems due to the complex interplay of smoke elevation, dynamics, and nonlinear effects on the solar spectral irradiance. To address this challenge, a new methodology is developed in this research that employs the optical properties of wildfire smoke. This approach utilizes the spectral response (SR) of PV devices to estimate the theoretical reduction in PV power output. The findings of this study enable precise measurement of the power output reduction caused by wildfire smoke for different types of PV cells. This newly devised method can be adopted for power system operation and planning to ensure the stability and reliability of power grids. Additionally, this study highlights the need to consider different PV cell technologies in regions at high risk of wildfires to minimize the power reduction caused by wildfire smoke.

Index Terms—Air quality, DERs, haze, light-spectrum, modeling, PM 2.5, PV systems, solar radiation, spectral response, wildfire smoke.

I. INTRODUCTION

OVER the past three decades, there has been a significant global increase of approximately 170% in Carbon Dioxide (CO₂) emissions. In order to combat the effects of climate

change, the adoption of renewable energy is imperative [1], [2], [3]. Remarkable advancements have been made in renewable energy technologies in recent years [2]. Despite the challenges posed by the COVID-19 pandemic, more than 260 GW of renewable energy capacity was added worldwide in 2020 [4], resulting in renewable electricity generation accounting for approximately 30% of global electricity production [5]. The enhanced efficiency and reduced costs of Photovoltaic (PV) systems have played a crucial role in accelerating the integration of solar power across various levels of the power grid [6]. By the end of 2020, global PV installations had reached 760 GWDC, and the integration of PV systems has been extensively explored in existing literature [7], [8], [9], [10], [11]. In order to achieve the objective of 100% carbon-free electricity by 2035, numerous policies have been implemented to facilitate the widespread implementation of PV systems [12]. In 2020, the U.S. Federal Energy Regulatory Commission (FERC) approved Order 2222, which enables Distributed Energy Resources (DERs) to participate in wholesale electricity markets through aggregation [13]. This FERC Order is expected to further increase the capacity of PV systems at the distribution level. Additionally, the U.S. Solar Energy Technology Office of the Department of Energy has set a target of generating utility-scale electricity at a cost of 3 cents/kWh by 2030 [6].

Additionally, wildfires have become increasingly prevalent worldwide. In 2021, many countries reported record-breaking wildfires, primarily triggered by exceptionally high temperatures and associated drought conditions. These wildfires emitted a staggering 1.76 billion tons of carbon globally [14]. As of October 18, 2021, the European Forest Fire Information System (EFFIS) estimated that between 1.2 million and 1.6 million acres had burned within European Union countries [15]. Australia experienced the burning of 7.04 million hectares due to wildfires during the 2019-2020 period [16]. The Canadian Interagency Forest Fire Centre (CIFFC) reported 6317 wildfires that burned 10.34 million acres as of September 15, 2021 [17]. According to the US National Interagency Fire Center (NIFC), the acreage burned by wildfires increased from 7.4 million acres in 2000 to 10.12 million acres in 2020, with 40% of these fires occurring in California [18], [19]. In September 2020, solar generation in California was 13.4% lower than the previous year due to the impact of wildfires, despite a 5.3% increase in installed solar capacity [20]. A 2015 report from the U.S. Department of Agriculture (USDA) projected that catastrophic wildfires will burn twice as many acres by 2050 [21].

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Amjad Jebriil Ali and Long Zhao are with the Department of Electrical Engineering and Computer Science, South Dakota School of Mines and Technology, Rapid City, SD 57701 USA (e-mail: amjed.jebriil@gmail.com; long.zhao@sdsmt.edu).

Mohammad Heidari Kapourchali is with the Department of Electrical Engineering, University of Alaska Anchorage, Anchorage, AK 99508 USA (e-mail: mhkapourchali@alaska.edu).

Wei-Jen Lee is with the Electrical Engineering Department, University of Texas at Arlington, Arlington, TX 76019 USA (e-mail: wlee@uta.edu).

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For power systems with high penetration of PV systems, the presence of wildfire smoke can substantially reduce PV system generation [22]. As wildfire smoke can travel over long distances and significantly diminish solar irradiance, it poses a significant risk to the reliability and stability of power grids that heavily rely on PV systems. Therefore, accurately quantifying the impact of wildfire smoke on PV generation is crucial, as it can inform power system operation and planning strategies.

Multiple studies have been conducted to explore the impact of wildfire smoke on solar irradiance. In one study [23], the authors investigated the influence of smoke clouds from wildfires in Yellowstone National Park on incident broadband and spectral solar irradiance in Golden, Colorado. The findings revealed a significant impact of smoke clouds on both Direct Nominal Irradiance (DNI) and Diffused Horizontal Irradiance (DHI), while the effect on Global Horizontal Irradiance (GHI) was comparatively less pronounced. Another study [24] demonstrated that Global Solar Radiation (GSR) follows a sinusoidal pattern similar to clear skies but with a reduced amplitude of 20% to 40% due to smoke scattering. However, there are limited numerical solutions available in the literature to accurately quantify the impact of wildfire smoke on the power generation of PV systems.

Existing literature primarily relies on the use of air quality indices such as PM 2.5 (particulate matter with diameters of 2.5 micrometers or less) or aerosol optical depth (AOD) to assess the influence of wildfire smoke on PV power generation. Research has investigated the effect of air pollution on PV output at different times of the day, revealing a decrease in PV power output with increasing pollution levels [24]. In China, a study conducted from 2003 to 2014 found that air pollution led to an average annual energy reduction of 20% to 25% in PV generation [25]. Furthermore, it was observed that two-axis tracking PV systems experienced greater energy reduction compared to fixed arrays due to their response to Global Horizontal Irradiance (GHI) instead of DNI [25].

While PM 2.5 and AOD are commonly used, they have limitations that affect the accuracy of quantifying the impact of wildfire smoke on PV power generation. PM 2.5 measurements are influenced by location and altitude, and this paper's Section II investigates the reliability of using PM 2.5 for smoke quantification, revealing its unreliability. Similarly, relying solely on AOD at specific wavelengths without considering the diverse optical properties of smoke is insufficient for accurately quantifying the impact of wildfire smoke on PV power generation. Wildfire smoke exhibits nonlinear effects on solar spectra at different wavelengths, causing variations in the intensity of solar irradiance. Consequently, relying on AOD at a single wavelength, such as 500 nm, is not a reliable approach. Additionally, wildfire smoke is a complex mixture of trace gases and aerosols, many of which are short-lived and chemically reactive, leading to the formation of photochemical smog. This smog absorbs visible light and a significant amount of Ultraviolet-A (UV-A) radiation, complicating the quantification of wildfire smoke due to its intricate composition and dynamic nature [26], [27], [28], [29], [30], [31], [32], [33], [34]. Furthermore, the optical properties of smoke can vary substantially across different climate zones and with the age of the smoke [35], [36].



Morning sunlight on a wildfire-smoky day.



Afternoon sunlight on a wildfire-smoky day.

Fig. 1. Sunlight of a wildfire smoky day.

In summary, accurately quantifying the impact of wildfire smoke on PV power generation poses significant challenges due to factors such as smoke elevation, dynamics, composition, and the nonlinear effects it has on solar spectra. The limitations of using PM 2.5 and AOD for quantification further complicate the task. It is essential to consider the complex nature of smoke and its interactions with solar radiation to achieve a comprehensive understanding of its impact on PV systems.

This study focuses on investigating the impact of wildfire smoke on PV systems by analyzing the spectral characteristics of solar cells and sunlight. During wildfire events, the sunlight undergoes a noticeable color change, appearing red or amber, as depicted in Fig. 1. This alteration in color is a result of elevated smoke plumes in the atmosphere, which significantly reduce Ultraviolet (UV) and visible light while exerting less influence on the infrared portion of the light spectrum [22], [27], [37]. The reddish sky caused by wildfire smoke exhibits similarities to the visual effects produced by urban haze and dust, leading to soiling and reduced irradiance conditions [38], [39], [40], [41], [42]. These findings are crucial as the efficiency of solar cells varies with the wavelength of sunlight. The SR (A/W) denotes the ratio of the current generated by the solar cell to the incident power on the cell [43], [44], [45], [46].

In [47], the authors explored the variations in PV cell output energy across different wavelength ranges of the solar light spectrum. The results indicated that crystalline silicon modules exhibit non-uniform responses to sunlight, being more sensitive to the red spectrum while less sensitive to the green spectrum. Another study [48] developed an approach to estimate PV power output based on SR. Seasonal and diurnal variations for various silicon-based PV panel types were investigated in [49] and [50],

while [51] focused on minimizing the mismatch between PV cell SR and available solar radiation to enhance PV performance. The authors in [52] examined the deviation of PV output from rated power by considering spectral, temperature, and irradiance effects. These studies collectively highlight the significant impact of light spectrum on different types of solar cells. However, none of these studies have provided a numerical solution to accurately quantify the influence of wildfire smoke on PV power output.

In this study, a novel indexing concept called the Absorption Radiation Index (*ARI*) is proposed and introduced. The impact of wildfire smoke on PV generation can be quantified by considering both the SR and the *ARI*. The main contributions of this paper are shown as follows:

- *Assessment of PM 2.5 Accuracy:* The study critically evaluates the reliability and accuracy of using PM 2.5 as a measure to quantify the impact of wildfire smoke on PV systems. By investigating the limitations and dependencies of PM 2.5 measurements on location and altitude, the study provides insights into the suitability of this air quality index for accurately assessing the effects of smoke on PV systems.
- *Feasibility of Artificial Woodburning Smoke:* The paper explores the feasibility of using artificial woodburning smoke to study the impact of smoke on solar systems. By employing controlled experimental setups, the study investigates the effects of simulated smoke on PV systems, shedding light on the potential implications of real wildfire smoke.
- *Development of the Absorption Radiation Index (ARI):* This study introduces a novel indexing concept, the *ARI*, which is based on the solar spectrum. The *ARI* is specifically designed to quantify the impact of wildfire smoke on the power output of PV systems. By considering the characteristics of the solar spectrum affected by smoke, this index provides a more comprehensive and accurate measure of the smoke-induced reduction in PV power output.
- *Approximation of PV Power Output Reduction:* The study develops an approach to approximate the reduction in PV power output based on the analysis of the light spectrum. By considering the nonlinear effects of smoke on solar spectra at different wavelengths, the approach enables a more precise estimation of the impact of wildfire smoke on PV systems.
- *Comparison of Solar Cell Generation Efficiency:* This study compares the efficiency of different types of solar cell generation, considering the specific impact of wildfire smoke. By analyzing and comparing the performance of various PV technologies in the presence of smoke, the study provides insights into the varying responses and sensitivities of different PV cell types to the effects of smoke.

Accurate quantification of how wildfire smoke affects photovoltaic system efficiency is crucial for decision-makers and grid operators. This knowledge enables them to implement effective mitigation strategies. These strategies include deploying mobile resilience resources [53], controlling dynamic thermal ratings

TABLE I
PM 2.5 COMPARISON OF DIFFERENT SMOKY DAYS

	PM 2.5 ($\mu\text{g}/\text{m}^3$)	AQI	POA (W/m^2)	I_{sc} (A)	V_{oc} (V)	PV power (W)
Non-Smoky	4.3	Good	1017	0.612	20.77	10.078
Smoky	6	Good	622	0.329	21.29	5.5503

[54], [55], [56], [57], [58], and boosting operating reserves to safeguard against grid frequency deviations [59], [60].

The rest of the paper is structured as follows: Section II presents the assessment of using PM 2.5 for smoke quantification and in-lab wildfire smoke simulation experiment; Section III discusses the development of the *ARI*; Section IV shows a case study using actual wildfire spectrum data; The conclusion is presented in Section V.

II. PM 2.5 AND IN-LAB EXPERIMENTS ASSESSMENTS

A. Assessment of PM 2.5 Accuracy

Numerous studies have utilized PM 2.5 as an indicator to assess the impact of wildfire smoke on PV systems [19], [61], [62]. In order to evaluate the accuracy of PM 2.5 for quantifying wildfire smoke and its effects, an experiment was conducted as part of this research. Measurements were taken at the South Dakota Mines campus during noon in September 2021, where PM 2.5 levels were measured at ground level. Simultaneously, measurements were taken for Direct Nominal Irradiance (DNI) on the plane of array (POA) and the power output of a 10 W mono-crystalline PV panel with a Fill Factor (FF) of 0.7929. To differentiate the impact of wildfire smoke on PV systems, measurements were recorded on two consecutive days: a clear, cloudless, and smoke-free day (September 8, 2021), and a clear, cloudless, but smoky day (September 9, 2021). The result is shown in Table I.

Interestingly, despite the PM 2.5 levels being relatively low and indicative of good air quality on the smoky day, the power output of the PV panel experienced a significant reduction of 45% compared to the smoke-free day. It is important to note that the locations and elevations of measurement points can significantly influence the results of PM 2.5 measurements. However, when the measurements are taken in proximity to the wildfire location, air quality measurements can be considered as a critical indicator for quantifying the impact of wildfire smoke.

Consequently, relying solely on PM 2.5 as an accurate index for quantifying the impact of wildfire smoke on PV systems is inadequate. The findings of this study emphasize the limitations of using PM 2.5 as a standalone measure and highlight the need for additional factors and indices to comprehensively assess the effects of wildfire smoke on PV systems.

B. In-Lab Experiment and Artificial Smoke

To simulate the presence of wildfire smoke, an in-lab experiment was conducted due to the limited duration of the actual wildfire season [63], [64], [65]. The experiment took place on October 28, 2021, and October 29, 2021, both of which were non-smoky and cloudless days. The South Dakota Mines campus



Fig. 2. Artificial smoke experiment using a greenhouse.

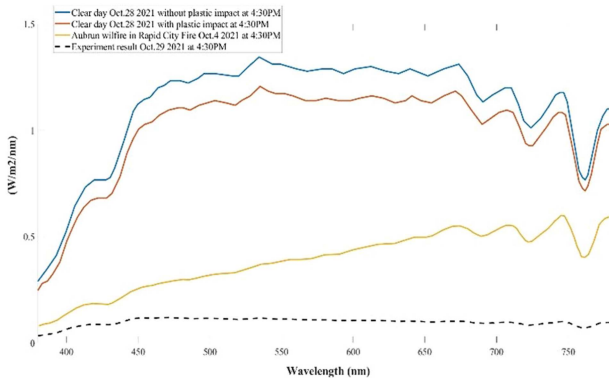


Fig. 3. Sunlight spectral irradiance comparison.

served as the location for the experiment. A commercial greenhouse covered with polyethylene plastic was utilized to contain the smoke generated by wood smoking chunks, as depicted in Fig. 2. To ensure that the plastic cover did not impact the solar spectral irradiance, measurements of Direct Nominal Irradiance (DNI) solar spectral irradiance were taken simultaneously both inside and outside the greenhouse.

On October 28, 2021, hourly measurements of the sunlight spectrum were recorded and will serve as the spectral reference for a non-smoky day. On October 29, 2021, smoke was generated inside the greenhouse to simulate the conditions of wildfire smoke, and the DNI solar spectral irradiance was measured within the greenhouse environment. In order to illustrate the difference in spectral irradiance between the simulated wildfire smoke and real wildfire smoke, Fig. 3 showcases the measured DNI solar spectral irradiance at 4:30 PM. The real wildfire event used in this research occurred on October 4, 2021, in Rapid City, SD, and will be discussed in detail in Section IV of the paper.

Fig. 3. clearly demonstrates the distinguishable differences between the sunlight spectral irradiance of artificial woodburning smoke and real wildfire smoke. Consequently, the intended outcomes of the in-lab generated smoke experiment could not be achieved due to the absence of chemical smog reactions that occur in real wildfire situations. When wood is burned under a plastic cover to generate smoke, essential elements such as

oxygen are depleted, hindering the formation of photochemical smog. Additionally, the presence of the plastic cover prevents the absorption of short wavelengths in the solar spectra, as the polyethylene material has low transmittance in the UV range [66]. Similar, limitations are expected in a glass greenhouse due to the low transmittance of glass in the UV wavelength range [67].

These findings highlight the intricate nature of wildfire smoke, making it inappropriate to simulate accurately within an in-lab environment. Therefore, it is imperative to investigate the impacts of wildfire smoke on PV systems based on real wildfire events to obtain meaningful and reliable results.

III. INDEXING DEVELOPMENT

A. Spectral Response

As previously discussed, different PV cells exhibit distinct spectral response (SR) characteristics. The SR of a PV cell is primarily influenced by the bandgap of the materials utilized in its fabrication. The bandgap establishes the upper limit of the wavelength range to which the SR responds [44], [45], [46].

$$SR(\lambda) = J_L(\lambda)/G(\lambda) \quad (1)$$

where $J_L(\lambda)$ is the light-generated current density for a specific wavelength “ λ ” and $G(\lambda)$ is the spectral irradiance of the incident light measured in $W/m^2/nm$. According to [44], the short-circuit current density $J_{s.c}$ is approximately equal to the light-generated current density J_L for PV modules. Thus, (1) can be rewritten as follows:

$$SR(\lambda) = J_{s.c}(\lambda)/G(\lambda) \quad (2)$$

The short circuit current density $J_{s.c}$ can be determined by integrating (2) over the wavelength range as shown in (3):

$$J_{s.c} = \int_{\lambda_1}^{\lambda_2} G_m(\lambda) \cdot SR(\lambda) \cdot d\lambda \quad (3)$$

where $J_{s.c}$ is the total short circuit current density which represents the short circuit current generated in A per unit area in m^2 of the PV cell from λ_1 to λ_2 . $G_m(\lambda)$ is the solar spectral irradiance in $W/m^2/nm$ at wavelength λ . The λ_1 and λ_2 represent the starting and the ending point of the solar spectral irradiance. Accordingly, (4) can be derived to determine the reduction in $J_{s.c}$ due to wildfire smoke:

$$J_{s.cr}\% = \frac{J_{s.cc} - J_{s.cs}}{J_{s.cc}} \times 100\% \quad (4)$$

where $J_{s.cr}\%$ represents the reduction percentage of the generated short circuit current density due to the smoke, and $J_{s.cc}$ (A/m^2) is the short circuit current density generated for measured solar spectral irradiance on a clear cloudless day. $J_{s.cs}$ (A/m^2) is the short circuit current density generated for measured solar spectral irradiance on a cloudless, smoky day. For PV panels, the short circuit current $I_{s.c}$ depends on the type of solar cells. Unlike the open circuit voltage $V_{o.c}$, the short circuit current $I_{s.c}$ can be affected by solar radiation substantially [68]. At a constant cell temperature, the $I_{s.c}$ increases linearly with the growing solar irradiance [68], [69], [70], [71], and PV power

output mainly depends on $I_{s,c}$ [71]. So, determining the percentage reduction on $I_{s,c}$ will enable quantifying the theoretical percentage PV power output reduction. Therefore, PV power generation reduction caused by wildfire smoke can be derived from (4) and shown as follows:

$$P_{pv,r}\% \approx J_{s,cr}\% = \frac{J_{s,cc} - J_{s,cs}}{J_{s,cc}} \times 100\% \quad (5)$$

where $P_{pv,r}\%$ represents the percentage of the PV power output reduction.

B. Absorption Radiation Index

Considering the distinct SR characteristics of various solar cell technologies, this study introduces and develops a new index parameter known as the Absorption Radiation Index (ARI) to quantitatively measure the impact of wildfire smoke on PV power output. The ARI is defined as the extent to which solar radiation is affected (absorbed or reflected) by the suspended particles present in the atmosphere. In addition to quantifying the impact of wildfire smoke, the ARI can also be applied to assess the effects of other atmospheric phenomena such as volcanic ash, dust storms, or haze on the power output of PV systems.

By conceptualizing the ARI based on the solar spectrum, this index parameter considers the optical properties of suspended particles in the atmosphere and their influence on different wavelengths of the solar spectra. Therefore, the ARI can be considered a reliable and accurate index parameter for assessing the impact of suspended particles on PV power output.

The ARI can be determined in (6):

$$ARI = \frac{CSS - PSS}{CSS} \quad (6)$$

where CSS (W/m^2) is the solar radiation of a clear sky, and PSS (W/m^2) is the solar radiation of a polluted atmosphere. The range of ARI is from 0 to 1, 0 represents a clear sky without any polluted particles, and 1 indicates an atmosphere is completely covered by suspended particles (No sunlight can be reached the surface). CSS and PSS are calculated in (7) and (8):

$$CSS = \int_{\lambda_1}^{\lambda_2} G_{CS}(\lambda).d\lambda \quad (7)$$

$$PSS = \int_{\lambda_1}^{\lambda_2} G_{PS}(\lambda).d\lambda \quad (8)$$

where G_{CS} is the measured solar spectral irradiance or intensity of a Clear Sky on a cloudless day, and G_{PS} is the measured solar spectral irradiance or intensity of a Polluted Sky on a cloudless day. Therefore, the ARI can be utilized to quantify the wildfire smoke impact based on the SR of solar cell materials for power generation of PV systems.

IV. ARI VALIDATION AND CASE STUDY

The ARI, being a spectrum-based index parameter, can be calculated using either the intensity of the sunlight spectrum or solar irradiance to accurately quantify the impact of wildfire smoke on solar power generation. This flexibility allows power system operators and researchers to employ various spectrum

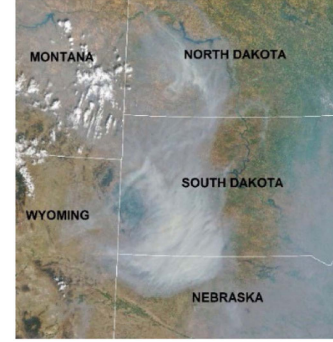


Fig. 4. NASA's satellite image on September 7, 2022 [72].



Fig. 5. Spectral measurement setup on the PV panels.

measurement devices according to their specific needs and applications.

A. ARI Validation

To validate the ARI for wildfire smoke impact on PV performance assessment, a wildfire event in summer 2022 was utilized in this section. Based on data from the National Interagency Fire Center (NIFC), a total of 96 significant fires ravaged approximately 690000 acres (equivalent to 2800 square kilometers) across eight states on September 9, 2022 [72]. The majority of these fires were concentrated in the Northern Rockies, the Great Basin, and the Pacific Northwest regions. Specifically, Idaho experienced 37 fires, Montana had 22 fires, while Oregon and Washington each had 12 fires. Fig. 4, captured by NASA's Terra satellite on September 7, 2022 [72], displays an image illustrating the smoke from these western fires descending over the Black Hills and northern plains.

By utilizing light spectral intensity and solar irradiance, the ARI was calculated to quantify the impact of wildfire smoke on PV system power generation. Through this approach, the ARI provides a reliable and comprehensive means of assessing the influence of wildfire smoke on the generation of solar power systems. This study conducted measurements and collected sunlight spectral data during periods affected by smoky wildfires. A 3-kW grid-tied solar system installed on the South Dakota Mines campus served as the testing platform. The PV system is oriented with an azimuth of 215° and has a tilt angle of 16° . The solar spectrum was measured continuously throughout the day at the Plane of Array (POA) of the PV panels, as depicted in Fig. 5. For this purpose, a preconfigured spectrometer with

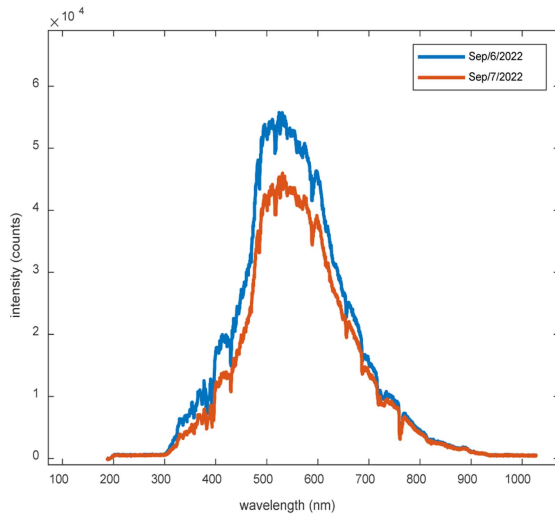


Fig. 6. Measured solar spectral intensity at 12:00 PM.

TABLE II
PV OUTPUT REDUCTION AND THE ARI

Day	Time	ARI	PV Power reduction (%)
Sep. 07, 2022	9:00 AM	0.4911	41.30
	12:00 PM	0.1894	12.56
	3:00 PM	0.2241	15.09
	6:00 PM	0.061	6.102

a cosine corrector was utilized, offering a spectral range from 187 nm to 1028 nm [73]. The data collected using this device provided the necessary information for analyzing and validating the *ARI* in relation to the impact of smoky wildfires on the solar spectrum.

To demonstrate the impact of wildfire smoke on the solar spectrum, a comparison of the solar spectra at noon on two consecutive days was presented in Fig. 6. The severity of the wildfire smoke on September 7, 2022, was notably higher than that on September 6, 2022. This figure clearly illustrates the nonlinear influence of wildfire smoke on the spectral intensity across different wavelengths.

To quantify the impact of wildfire smoke on PV power output, the *ARI* was calculated based on the definition provided in equation (6). Additionally, the reduction in PV power output percentage was measured at different times during the smoky day. The *ARI* values and corresponding PV power output reduction percentages were tabulated in Table II. It is worth noting that, for this particular case study, the outdoor temperatures on September 6 and September 7 were similar, allowing us to neglect the temperature-related effects on PV efficiency. Fig. 7 illustrates that the PV power output reduction resulting from wildfire smoke can be reasonably estimated using *ARI* in a linear way. This result highlights that the *ARI*, obtained through the measurement of solar spectrum intensity, can serve as a prominent indexing parameter for accurately quantifying the reduction in solar generation caused by wildfire smoke.

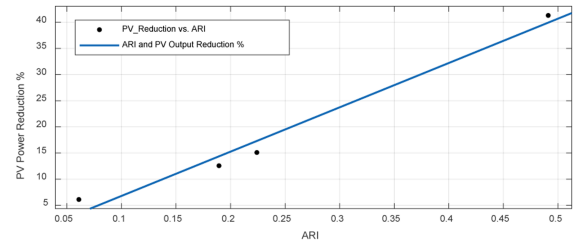


Fig. 7. *ARI* and PV power output reduction percentage.



Fig. 8. Auburn wildfire smoke dynamics around 4:30 PM.

B. *ARI* for Different Solar Cells

A wildfire that occurred north of Rapid City, South Dakota on October 4th, 2021 was utilized to evaluate the smoke impact on different solar cell technologies. The fire burned approximately 964 acres over a span of two days before it was brought under control [74]. In order to evaluate the impact of the smoke plume on Direct Normal Irradiance (DNI) and solar spectral irradiance, measurements were taken around 4:30 PM local time. The DNI fluctuated as the smoke density changed due to wind movements, as depicted in Fig. 8. The measurements revealed that the highest reduction in solar radiation reached more than 85% when compared to the same time on the previous day.

In order to examine the impact of wildfire smoke on solar irradiance across various solar cell technologies, measurements of sunlight irradiance were conducted using a spectrometer with a wavelength range of 380 nm to 780 nm [75]. The measured spectrum curves demonstrate a significant decline in power, ranging from 34.56% to 84.38%. This reduction primarily occurs in the ultraviolet (UV) and visible range of the solar spectrum, specifically wavelengths below 700 nm. By considering the *ARI* and *SR* characteristics of different solar cell technologies, an estimation of the potential power output reductions for four major PV cell technologies is calculated using the Auburn wildfire spectral irradiance and presented in Table III. Notably, different PV panels exhibit varying percentages of power reduction under the same smoke conditions. PV panels with larger bandgaps, such as a-Si (amorphous silicon), and concentrated SR in the low wavelength range (visible range), experience more significant power reduction compared to panels with smaller bandgaps, such as m-Si (monocrystalline silicon).

The plot in Fig. 9 illustrates the percentage reduction in PV power output for various types of PV cells based on the *ARI*. Preliminary models for each PV cell type, namely a-Si (amorphous silicon), CdTe (cadmium telluride), CIGS (copper indium gallium selenide), and m-Si (monocrystalline silicon), were developed using curve fitting techniques as shown in

TABLE III
ARI AND POWER REDUCTION OF 4 DIFFERENT SOLAR CELL TECHNOLOGIES

ARI	Theoretical Power output reduction (%)			
	a-Si	m-Si	CdTe	CIGS
0.346	37.10	31.8	30.80	32.93
0.565	59.56	53.95	52.99	55.01
0.642	67.42	61.91	61.03	62.89
0.789	80.88	78.07	77.76	78.44
0.795	81.28	78.97	78.78	79.23
0.665	69.60	64.46	63.67	65.35
0.843	84.93	84.76	84.93	84.61
0.816	83.12	81.28	81.18	81.43
0.840	84.69	84.21	84.33	84.11
0.431	45.67	40.58	38.97	41.61
0.808	82.30	80.4	80.07	80.58
0.795	84.43	83.63	83.51	83.59

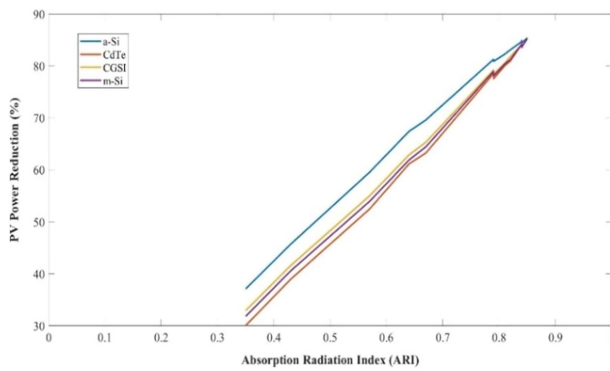


Fig. 9. Estimation of theoretical PV generation reduction based on the ARI.

TABLE IV
PRELIMINARY ARI-BASED MODELS FOR FOUR TYPES OF SOLAR CELLS

Types	Models
a-Si	$y = 52.62 - 41.46 \cos(2.309x) + 18.36 \sin(2.309x)$
CdTe	$y = -295.5x^4 + 788.4x^3 - 736.9x^2 + 393.5x - 46.72$
CIGS	$y = -412.6x^4 + 1027x^3 - 920.7x^2 + 453.8x - 3.8688$
m-Si	$y = 112.7 \sin(x - 3.14) - 10.55(x - 10)^2 + 1053$

TABLE V
GOODNESS OF THE PRELIMINARY MODEL

Types	R ²	SSE	RMSE
a-Si	0.9997	0.9956	0.315
CdTe	0.9993	2.919	0.5695
CIGS	0.9996	1.389	0.3929
m-Si	0.9994	2.249	0.4522

Table IV. In the developed models, y represents the percentage reduction in power output of PV systems, while x represents the ARI. The accuracy of the models was evaluated using various goodness-of-fit parameters, namely Square Error (R^2), Sum Square Error (SSE), and Root Mean Square Error (RMSE), which were applied to the fitted data and presented in Table V. The R^2 parameter, ranging between 0 and 1, represents the goodness of fit, with 1 indicating a perfect fit of the model to the data. The SSE quantifies the total squared differences between the predicted values and the actual values in the dataset, where a lower SSE indicates superior model performance. Similarly,

RMSE measures the average deviation between the predicted values and the actual values, and a lower RMSE also indicates improved model performance.

The analysis result indicates that PV panels composed of a-Si are most severely affected by wildfire smoke, resulting in the most significant reduction in power generation for a given ARI value. Conversely, PV panels made of CdTe exhibit a relatively minor decrease in power output. Therefore, considering these findings, PV panels constructed with CdTe are recommended for regions prone to high wildfire risks.

V. CONCLUSION

This paper presents a novel indexing parameter, Aerosol Reduction Index (ARI), specifically designed to accurately quantify the effect of wildfire smoke on PV system performance. The ARI leverages the sunlight spectrum, providing an insightful alternative to existing methods such as AOD and PM 2.5, which possess considerable limitations in precisely measuring the impact of wildfire smoke on PV system outputs. By utilizing two wildfire events, this paper has demonstrated the efficacy of the ARI in accurately indicating reductions in PV power output due to wildfire smoke. The methodology of utilizing either spectrum intensity or solar irradiance to obtain the ARI is not only effective but also provides versatile options for implementation.

Furthermore, this paper employed the ARI to evaluate the effects of wildfire smoke on different solar cell materials, resulting in a preliminary model of power output reduction. This model has illuminated the relative resilience of CdTe solar cells to wildfire smoke, suggesting its appropriateness for PV systems in areas with a high wildfire risk.

In essence, the ARI proposed herein stands to significantly improve the understanding and measurement of wildfire smoke's impact on solar PV performance. The broader implications of this work could inform better strategies for PV system installation, particularly in high wildfire risk areas, by guiding the selection of the most resilient PV cell technology. As the pressing issue of wildfires persists due to climate change, this research provides an important contribution to the sustainable operation of PV systems. Future research could explore developing strategies to reconfigure solar arrays in response to shading from wildfires.

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