Development of A Quantification Method for The Impact of Wildfire Smoke on Photovoltaic Systems

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***Abstract*— Understanding the impact of wildfire smoke on photovoltaic (PV) systems is critical for the reliability and stability of power systems with the increasing PV penetration and wildfire events. However, this problem has not been widely discussed and studied in the existing literature. One of the significant challenges for this study is the quantification of the smoke. Because of the wildfire smoke elevation, dynamics, and nonlinear effects on solar spectral irradiance, traditional methods such as aerosol optical depth (AOD) and PM 2.5 cannot be utilized to quantify the impact of wildfire smoke on PV systems accurately. In this study, a novel method is developed using the optical properties of wildfire smoke, and an approach based on PV devices' spectral response (*SR*) is presented to estimate the theoretical PV power output reduction. The outcome of this study can precisely measure the power output reduction caused by wildfire smoke for different types of PV cells. This developed method can be adopted for power systems operation and planning to ensure the stability and reliability of the power grids. Besides, this paper also shows that different PV cell technologies need to be considered for high wildfire-risk areas to minimize the power reduction caused by wildfire smoke.**

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

I. Introduction

In the last 30 years, Carbon Dioxide (CO_2) emissions have increased by about 170% globally. To fight climate change, renewable energy is a crucial solution [1, 2]. Renewable energy technologies have been remarkably developed in the past few decades [1]. Despite the COVID-19 pandemic, more than 260 GW of renewable energy capacity was added globally in 2020 [3], and the global share of renewable electricity generation reached around 30% [4]. Improved efficiency of Photovoltaic (PV) systems and decreased costs are major factors in boosting the adoption of solar generation across all levels of power systems [5]. At the end of 2020, global PV installations reached 760 GW_{DC}, and PV systems integration has been widely discussed in existing literature [6-10]. To achieve 100 percent carbon-free electricity by 2035, different policies have been released to facilitate the implementation of PV systems [11]. In 2020, the U.S. Federal Energy Regulatory Commission (FERC) Order 2222 was approved, allowing DERs to participate in wholesale electricity markets in aggregation [12]. This FERC Order will further boost the capacity of PV systems at the distribution level. Furthermore, the U.S. Solar Energy Technology Office of the Department of Energy targets 3 cents/kWh for electricity generated by utility systems by 2030 [5]. In the meantime, wildfires have been increasing notably all over the globe. In 2021, several countries reported new wildfire records, mainly caused by the record-high temperature and associated drought. In 2021, wildfires emitted 1.76 billion tons of carbon globally [13]. As of October 18, 2021, the European Forest Fire Information System (EFFIS) estimates that between 1.2 million acres and 1.6 million acres had burned within European Union countries, [14]. In Australia, 7.04 million hectares were burned by wildfire over the 2019-2020 period [15]. As of September 15, 2021, the Canadian Interagency Forest Fire Centre (CIFFC) reported 6,317 wildfires that had burned 10.34 million acres [16]. According to the US National Interagency Fire Center (NIFC), acres burned by wildfires have increased from 7.4 million acres in 2000 to 10.12 million acres in 2020, and 40% of these wildfires happened in California [17, 18]. In September 2020, California solar generation was 13.4% lower than the previous year due to the wildfires, despite a 5.3% increase in installed solar generating capacity [19]. Fig.1 demonstrates wildland fires and acres burned nationwide in the U.S. Based on a report in 2015 from the U.S. Department of Agriculture (USDA), catastrophic blazes are projected to burn twice as many acres by 2050 [20].

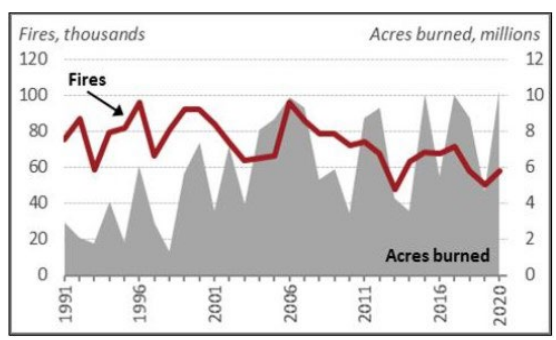

Fig. 1. Annual wildfires and acres burned, 1991-2020 [18].

For power systems with high penetration of PV systems, wildfire smoke can reduce the generation of the PV system substantially [22]. Because wildfire smoke travels hundreds of miles and reduces solar irradiance noticeably, the reliability and stability of power grids with high penetration of PV systems could be jeopardized. Thus, it is critical to quantify wildfire

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smoke impact on PV generation, which can be applied to power system operation and planning.

Multiple studies investigated the impact of wildfire smoke on solar irradiance. The authors in [21] studied the influence of the Yellowstone National Park wildfire smoke clouds on incident broadband and spectral solar irradiance in Golden, Colorado. The result shows that smoke clouds impact both Direct Nominal Irradiance (DNI) and Diffused Horizontal Irradiance (DHI) significantly, but less so on (Global Horizontal Irradiance) GHI. Paper [22] shows that the Global Solar Radiation (GSR) follows approximately a sine curve as in clear skies, with a 20% to 40% reduction in amplitude due to smoke scattering. However, very limited studies have provided numerical solutions to quantify the impact of wildfire smoke on the power generation of PV systems. Existing literature mainly uses air quality index PM 2.5 or aerosol optical depth (AOD) to study the wildfire smoke impact on PV power generation. PM 2.5 is particulate matter (PM) with diameters of 2.5 micrometers or less in the air. PM 2.5 has been widely used to index air quality for haze. California Independent System Operator (CAISO) revealed an article from Energy Information Administration (EIA) showing that PV power generation decreases when PM 2.5 increases due to wildfire smoke [22]. Similarly, a study examined the effect of air pollution on PV output at various periods of the day [23]. The results revealed that as the pollution increases, PV power output decreases. Paper [25] investigated the average reduction of PV generation energy due to air pollution from 2003 to 2014 in China. The study showed that the annual average energy reduction reached 20% to 25%. Moreover, the authors also found that two-axis tracking PV systems have more energy reduction than fixed arrays because fixed PV systems respond to GHI instead of DNI [24]. According to the National Oceanic and Atmospheric Administration (NOAA), aerosol optical depth is a dimensionless number representing the measure of the extinction of the solar beam by dust and haze. These pollution particles block sunlight by absorbing or scattering light [25]. In [26], authors from Australia studied the impact of wildfire smoke on PV generation by setting up a fire and measuring aerosol and spectral response (*SR*). The power output reduction ranged from 7% to 27%. The authors in [27] quantified the wildfire smoke by relying on retrieving satellite archived data for aerosol optical depth (AOD) at specific wavelengths 500-550 nm.

Nevertheless, PM 2.5 and AOD have their limitations which could affect the quantification accuracy for wildfire smoke impact on PV power generation. PM 2.5 is heavily location and altitude-dependent, and Section II of this paper investigates the accuracy of using PM 2.5 to quantify wildfire smoke impact on the PV system. It shows that using PM 2.5 is unreliable for smoke quantification. Also, using AOD at specific wavelengths without considering the different optical properties of smoke is insufficient for quantification of wildfire smoke impact on PV power generation. Since wildfire smoke has a nonlinear effect on solar spectra at different wavelengths, the intensity of solar irradiance at specific wavelengths will differ more than at other wavelengths, which makes using AOD only at a particular wavelength (e.g., 500nm) not a reliable approach. Wildfire smoke is a complicated mixture of trace gases and aerosols, many of which are short-lived and chemically reactive, and this mixture affects atmospheric composition in complex ways that are not entirely understood [28-30]. As a result of these reactions, photochemical smog is formed. Photochemical smog involves the rapid oxidation of short-lived reactive trace gases and the production of ozone and secondary organic aerosols under solar irradiation, particularly ultraviolet light irradiation. The process of formation of photochemical smog absorbs visible light and a profound amount of Ultraviolet-A UV-A [31, 32]. Paper [33] examines the effect of wildfire smoke on ozone (O_3) production at an urban site in Bakersfield, CA. Researchers observed that daytime median concentrations of O_3, particulate matter with diameters less than 2.5 μm (PM2.5), carbon monoxide (CO), and volatile organic compounds were higher on smoky weekdays. Furthermore, the optical properties of smoke may differ substantially among different climate zones and smoke ages [34]. Therefore, quantifying wildfire smoke is highly challenging considering the smoke elevation, dynamism, and composition [35].

To investigate the wildfire smoke impact on PV systems, this work focuses on the spectral characteristics of solar cells and sunlight spectra. During the periods of wildfires, the visible sunlight turns red or amber, as shown in Fig. 2. This is because the elevated smoke plumes in the sky cause severe Ultraviolet (UV) and visible light reduction, and wildfire smoke has less impact on the infrared on the wavelength range of the light spectrum [21, 26, 36]. The red color of the sky induced by the wildfire smoke is similar to the effect of the soiling and low irradiance conditions caused by haze from urban sources and dust [37-41]. These findings are critical since solar cell efficiency varies with the wavelength of sunlight. Based on the types of PV used, the *SR* of the cell will differ shown in Fig. 3 [42]. The *SR* (A/W) is defined as the ratio of the current generated by the solar cell to the power incident on the solar cell [43-45]. In [46], the authors studied how the output energy of PV cells varies according to the wavelength ranges of the solar light spectrum. The result shows that crystalline silicon modules do not respond uniformly to sunlight and are more sensitive to the red spectrum and less sensitive to the green spectrum. Paper [47] developed an approach to estimate PV power output based on *SR*. The authors in [48] and [49] studied the seasonal and diurnal variations for different types of PV panels made from silicon, and in [50] authors eliminated the mismatch between the *SR* of PV cells and the available solar radiation to enhance the PV performance. In [51], the authors studied the deviation of PV output from the rated power, linking spectral, temperature, and irradiance effects. All the studies have shown that the light spectrum has significant impacts on different solar cells. However, none of the studies provides a numerical solution to quantify the impact of wildfire smoke on PV power output. In this study, a new indexing concept, Absorption Radiation Index (*ARI*), is proposed and introduced. Wildfire smoke impact on PV generation can be quantified based on the *SR* and the *ARI*. The main contributions of this paper are shown as follows:

- This study assesses the accuracy of using PM 2.5 for wildfire smoke impact on PV systems.
- This paper evaluates the feasibility of using artificial woodburning smoke to study the impact on solar systems.

- This paper develops a new indexing concept, the *ARI,* based on the solar spectrum to quantify wildfire smoke impact on the power output of PV systems.
- This study developed an approach to approximate the PV power output reduction based on the light spectrum.
- This study compared different types of PV generation efficiency considering the impact of wildfire smoke.

Morning sunlight on a wildfire-smoky day.

Afternoon sunlight on a wildfire-smoky day.

Fig. 2. Sunlight of a wildfire smoky day

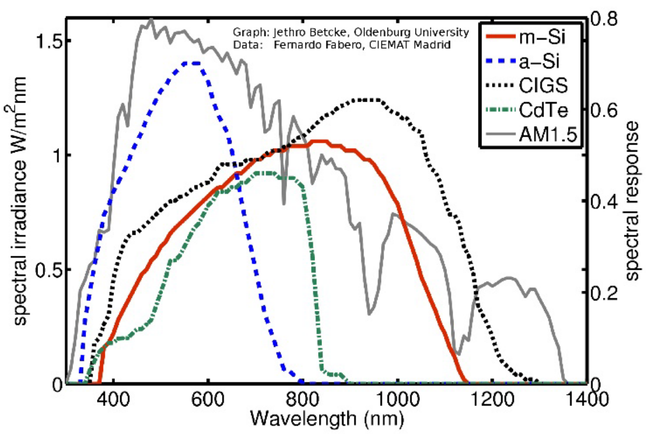

Fig. 3. *SR* characteristics of different solar module technologies [52].

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. Assessment of PM 2.5 and Artificial Smoke for Wildfire Smoke Impact on PV Systems

A. Accuracy of PM 2.5

Different studies have used PM 2.5 as an indicator of wildfire smoke impact on PV systems [19, 53, 54]. To assess the accuracy of PM 2.5 on wildfire smoke quantification, an experiment was conducted in this research. Measurements were taken on the South Dakota Mines campus at noon in September 2021, and PM 2.5 was measured at the ground level. Meanwhile, the DNI on the plane of array (POA) and the output power of a 10 W mono-crystalline PV panel with 0.7929 Fill Factor (FF) were measured simultaneously. To distinguish the wildfire smoke impact on PV systems, measurements were taken on two consecutive days: a clear cloudless smoke-free day (September 8, 2021) and a clear cloudless smoky day (September 9, 2021). Though the PM 2.5 level was low and considered good air quality during the smoky day, the power output of the PV panel was reduced by 45% compared to the smoke-free day. As shown in Fig. 4, wildfire smoke plumes elevate from where the wildfire occurs. Locations and elevations can change the PM 2.5 measurement results significantly. However, air quality measurement can be considered a critical index for wildfire smoke quantification when the measurement is taken close to the fire location as shown in Fig.5. Therefore, solely using PM 2.5 cannot be considered an accurate index to quantify the impact of the wildfire smoke on the PV systems.

TABLE I: TWO DAYS OF MEASURED RESULTS

	PM 2.5 (μg/m^3)	AQI	POA (W/m^2)	$I_{s.c}$ (A)	$V_{o.c}$ (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

Fig. 4. Wildfire smoke elevation dynamics [55].

Fig. 5. Air quality and the wildfire [56].

B. *Artificial Smoke and Real Wildfire Smoke*

Due to the short duration of the wildfire season [57], an in-lab wildfire smoke experiment was conducted on October 28, 2021, and October 29, 2021, to simulate wildfire smoke. Both days were non-smoky and cloudless. The experiment was conducted on the South Dakota Mines campus. A commercial greenhouse covered by a polyethylene plastic is used to contain the smoke generated by the wood smoking chunks illustrated in Fig. 6. To eliminate the impact of the plastic cover on solar spectral irradiance, the DNI solar spectral irradiance was measured inside and outside the greenhouse simultaneously. On October 28, 2021, the sunlight spectrum was measured hourly and will be used as a non-smoky day spectral reference. On October 29, 2021, the smoke was generated inside the greenhouse to simulate wildfire smoke, and the DNI solar spectral irradiance was measured inside the greenhouse. To show the difference in spectral irradiance between simulated wildfire smoke and real wildfire smoke, Fig.7 presents the measured DNI solar spectral irradiance at 4:30 PM. The real wildfire utilized in this research happened on October 4, 2021, in Rapid City, SD, which will be discussed in section V.

Fig. 6. The artificial woodboring smoke experiment with a greenhouse.

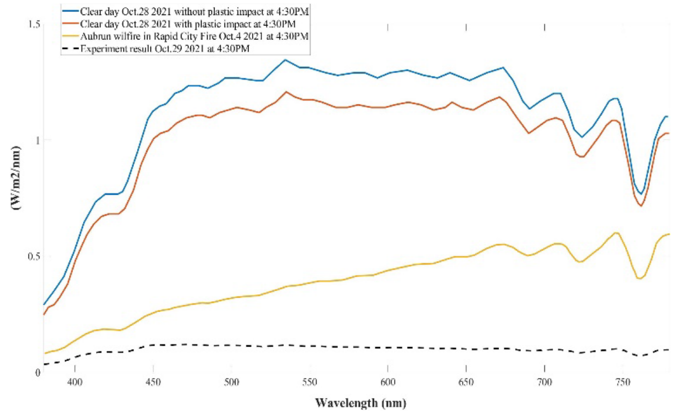

Fig. 7. Expected and obtained results of a wildfire simulation experiment.

As shown in Fig. 7, the sunlight spectral irradiance of artificial woodburning smoke is clearly distinguished from the sunlight spectral irradiance of real wildfire smoke. Therefore, the anticipated outcome could not be attained using the in-lab generated smoke, mainly because of the missing chemical smog reactions in real wildfires. Since wood was burned under the plastic cover to generate smoke, oxygen, as an essential element for photochemical smog reactions, is exhausted. Also, the plastic cover prevented photochemical smog formation, which absorbs the short wavelengths of solar spectra (low transmittance of the polyethylene in the UV range) [58]. Similar findings are expected for a glass greenhouse for the same reason (low transmittance of the glass in the UV wavelength range) [58]. This experiment shows that wildfire smoke is highly complex, and it is improper using the in-lab environment to simulate. Therefore, wildfire smoke impacts on PV systems must be investigated based on real wildfires.

III. Spectrum-Based Indexing Method

A. *Spectral Response (SR) of PV Cells*

As mentioned before, different PV cells have various *SR* characteristics shown in Fig. 3. The *SR* is primarily determined by the bandgap of the materials used in fabrication, which sets the upper wavelength limit of the *SR* [43-45]. The *SR* is defined in [43] as follows:

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

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 [43], 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):

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

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:

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

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 [59]. At a constant cell temperature, the $I_{s.c}$ increases linearly with the growing solar irradiance [59-61]. Fig. 8 demonstrates that PV power output mainly depends on $I_{s.c}$ [61]. 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:

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

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

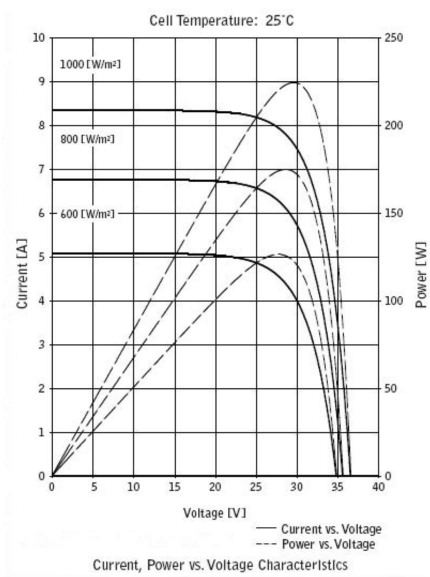

Fig. 8. Current, power vs. voltage characteristics [62].

B. Absorption Radiation Index (ARI)

Considering the *SR* characteristics of different solar cell technologies, the *ARI* is introduced and developed as a new index parameter to quantify wildfire smoke impact on PV power output. The *ARI* is defined as the amount of solar radiation affected (absorbed/reflected) by the suspended particles in the sky. Besides the wildfire smoke, the *ARI* can also be utilized for volcanic ash, dust storms, or haze to quantify their impacts on the power output of PV systems. Since the concept of the *ARI* is developed based on the solar spectrum, it can be considered an accurate index parameter based on the optical properties of suspended particles in the atmosphere and the impact on different wavelengths of the solar spectra. The *ARI* can be determined in (6):

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

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 coved by suspended particles (No sunlight can be reached the surface). *CSS* and *PSS* are calculated in (7) and (8):

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

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

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. Case Studies

Since the *ARI* is a spectrum-based index parameter, it can be determined by using either sunlight spectrum intensity or solar irradiance to quantify wildfire smoke impact on solar power generation. This will enable power system operators and researchers to use different spectrum measurement devices for their own purposes and applications. To validate the *ARI*, two wildfire events around the Black Hills National Forest were utilized as different case studies in this section. The *ARI* is obtained using light spectral intensity and solar irradiance to quantify wildfire smoke impact on PV system power generation.

A. Wildfire Case Study 1 Using Spectral Intensity

According to the National Interagency Fire Center (NIFC), on September 9, 2022, at least 96 large fires burned 690,000 acres (2800 square kilometers) in eight states [63]. Many fires were clustered in the Northern Rockies, the Great Basin, and the Pacific Northwest, with 37 burned in Idaho, 22 in Montana, 12 apiece in Oregon and Washington, and 10 in California. Fig. 9 is an image from NASA's Terra satellite showing smoke from the western fires settling over the Black Hills and northern plains on September 7, 2022 [63].

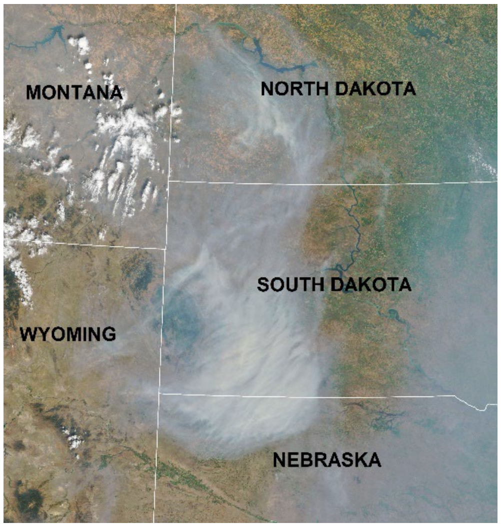

Fig. 9. NASA's Terra satellite image on September 7, 2022 [63].

To validate the proposed *ARI*, this study measured and collected the sunlight spectral data during the smoky wildfire periods. A 3-kW grid-tied solar system installed on the South Dakota Mines campus was utilized. The PV system has an orientation of 215° as an Azimuth, and the tilt angle is 16°. The solar spectrum is measured all day long on the Plane of Array (POA) of the PV panels shown in Fig. 10. The solar spectrum was measured and collected using a preconfigured spectrometer with a cosine corrector. The device has a spectral range from 187nm to1028nm [64].

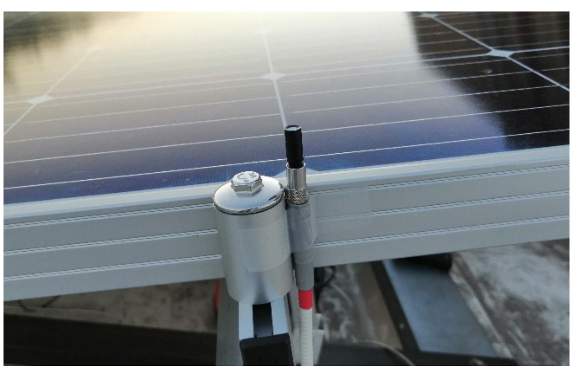

Fig. 10. Solar spectral irradiance measurement setup on the PV panels.

To show the wildfire smoke impact on the solar spectrum, as an example, the solar spectrum at noon of two consecutive days was plotted in Fig. 11. The wildfire smoke of September 7, 2022, was much more severe than September 6, 2022. This figure shows that wildfire smoke nonlinearly impacts the spectral intensity at different wavelengths. Based on the definition of *ARI* in (6), the *ARI* and PV power output reduction percentage at different times of the smoky day were calculated and measured, respectively, as shown in Table II. Considering September 6 and September 7 have similar outdoor temperatures, the temperature impacts on PV efficiency can be neglected in this case study.

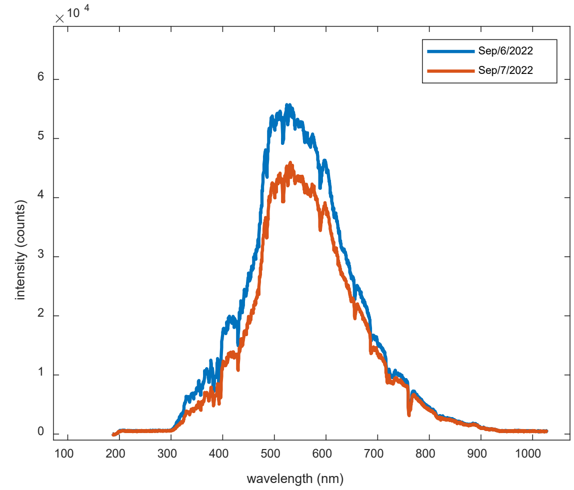

Fig. 11. Measured solar spectral intensity at 12:00 PM.

TABLE II. THE *ARI* AND THE PV SYSTEM POWER REDUCTION

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

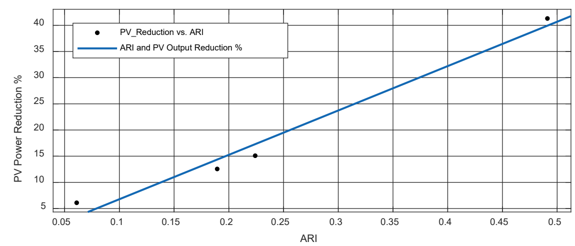

Fig. 12. *ARI* and PV power output reduction percentage

Fig. 12 shows that by applying the *ARI*, the PV power output reduction caused by the wildfire smoke can be approximately represented and quantified using a simple linear function shown below:

$$\text{PV Power Output Reduction } \% \approx (0.85 \times ARI) \times 100\ \% \qquad (9)$$

The accuracy of the function can be improved with different curve-fitting algorithms. This case study shows that the proposed *ARI* can be obtained using solar spectrum intensity and considered as a dominant indexing parameter to quantify the wildfire smoke impact on solar generation reduction.

B. *Wildfire Case Study 2 Using Solar Irradiance*

On October 4, 2021, a wildfire broke out north of Rapid City, South Dakota, as displayed in Fig. 13. The Fire burned around 964 acres over two days before it was contained [65]. To assess the impact of the smoke plume on the DNI and solar spectral irradiance, measurements were taken around 4:30 PM local time. The DNI varies as the density of the smoke changes due to wind blowing, as demonstrated in Fig. 14. The measurements show that the highest percentage of solar radiation reduction reached more than 85 % compared to the same time on the previous day.

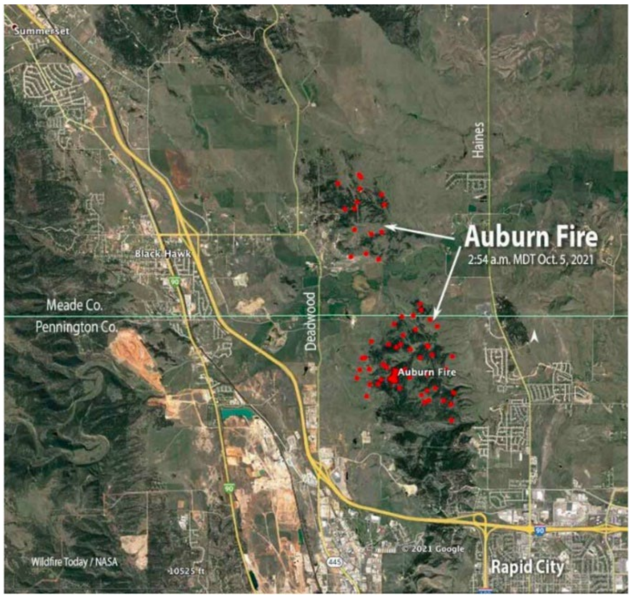

Fig. 13. Auburn fire satellite image [65].

Fig. 14. Auburn wildfire smoke dynamics around 4:30 PM.

To investigate the impact of wildfire smoke on solar irradiance for different PV cell technologies, sunlight irradiance was measured using a spectrometer with a wavelength range of 380nm to 780nm [66]. Fig. 15 shows a non-smoky and cloudless solar spectral irradiance at 4:30 PM local time on October 3, 2021. Meanwhile, Fig. 17 shows a series of solar spectral irradiance measurements under the Auburn wildfire smoke. A significant drooping in power is represented by the depicted spectrum curves in Fig. 17, ranging from 34.56% to 84.38%. The considerable reduction is in the UV and visible range of the solar spectrum (wavelength range below 700nm). Based on *ARI* and *SR* characteristics shown in Fig. 3, an estimation of theoretical power output reductions for four major PV cell technologies is calculated using Auburn wildfire spectral irradiance and shown in Table III. It can be noticed that different PV panels have different percentages of power reduction under the same smoke. For the same *ARI*, the PV panels that have a large bandgap (e.g., a-Si) and their *SR* concentrated at a low wavelength range (visible range) have more power reduction compared to smaller bandgap PV panels (e.g., m-Si).

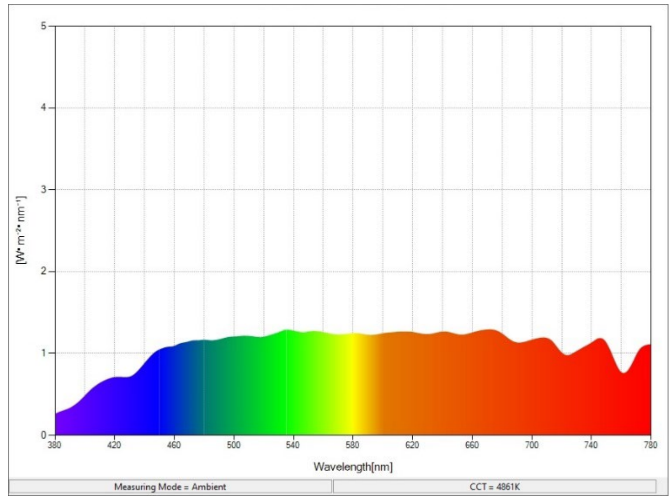

Fig. 15. Non-smoky and cloud-free solar irradiance at 4:30 PM.

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

Sub-fig No. in Fig. 17	***ARI***	**Theoretical Power output reduction (%)**			
		a-Si	m-Si	CdTe	CIGS
1	0.346	37.10	31.8	30.80	32.93
2	0.565	59.56	53.95	52.99	55.01
3	0.642	67.42	61.91	61.03	62.89
4	0.789	80.88	78.07	77.76	78.44
5	0.795	81.28	78.97	78.78	79.23
6	0.665	69.60	64.46	63.67	65.35
7	0.843	84.93	84.76	84.93	84.61
8	0.816	83.12	81.28	81.18	81.43
9	0.840	84.69	84.21	84.33	84.11
10	0.431	45.67	40.58	38.97	41.61
11	0.808	82.30	80.4	80.07	80.58
12	0.795	84.43	83.63	83.51	83.59

Fig.16 shows the plot of PV power output reduction percentage for different types of PV cells using *ARI*. The preliminary models are developed based on the curve fitting technique for each type of PV cell shown in (10), (11), (12), and (13) for a-Si, CdTe, CIGS, and m-Si, respectively. The accuracy of the built models is tested using parameters of the goodness of the fitted data, namely, Square Error (R^2), Sum Square Error (SSE), and Root Mean Square Error (RMSE).

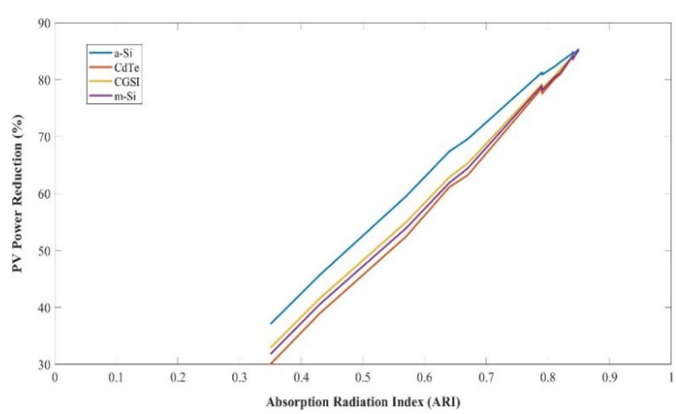

Fig. 16. Estimation of theoretical PV generation reduction based on the *ARI* of Auburn Wildfire.

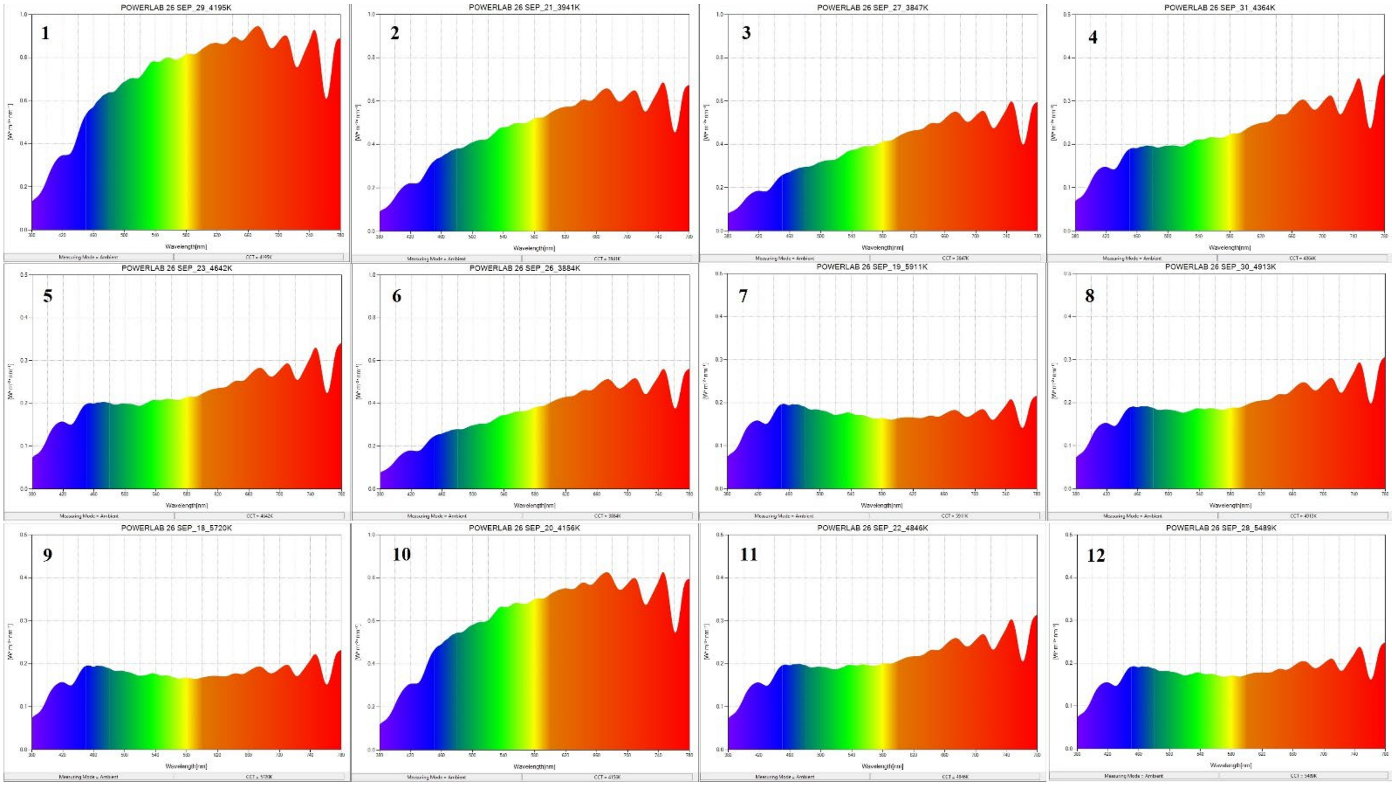

Fig. 17. Auburn wildfire measured solar spectral irradiance.

$$y = 52.62 - 41.46 \cos(2.309x) + 18.36 \sin(2.309x) \quad R^2 = 0.9997,\ SSE=0.9956,\ RMSE=0.315 \tag{10}$$

$$y = -295.5x^4 + 788.4x^3 - 736.9x^2 + 393.5x - 46.72 \quad R^2 = 0.9993,\ SSE=2.919,\ RMSE=0.5695 \tag{11}$$

$$y = -412.6x^4 + 1027x^3 - 920.7x^2 + 453.8x - 3.8688 \quad R^2 = 0.9996,\ SSE=1.389,\ RMSE=0.3929 \tag{12}$$

$$y = 112.7 \sin(x - 3.14) - 10.55(x - 10)^2 + 1053 \quad R^2 = 0.9994,\ SSE=2.249,\ RMSE=0.4522 \tag{13}$$

where y is the power output reduction of PV systems in percentage, and x is the *ARI*. Based on the developed models and Fig. 16, PV panels made by a-Si will be impacted by the wildfire smoke the most, and the PV system has the most significant power generation reduction with the same *ARI* values. Meanwhile, PV panels made by CdTe have a minor power output reduction. Based on this result, PV panels made by CdTe are recommended for areas with high wildfire risks.

V. Conclusion

In this paper, a new indexing parameter *ARI* is proposed and developed based on the sunlight spectrum to quantify the impact of wildfire smoke on PV power generation. The *ARI* can be obtained using either spectrum intensity or solar irradiance. Meanwhile, the existing methods for wildfire smoke impact on PV systems, such as AOD and PM 2.5, are also discussed and investigated. The results show that both AOD and PM 2.5 have different limitations, which are unable to provide accurate quantification for wildfire smoke impact on PV power output. To validate and verify the proposed *ARI*, two case studies are conducted and presented in this paper using two different types of spectral data collected under actual wildfire events. Both case studies show that the *ARI* can be utilized to quantify and indicate the power generation reduction of PV systems caused by wildfire smoke. Besides, the impact of wildfire smoke on different solar cell materials is evaluated and studied based on the *ARI* and *SRs*. The preliminary model of power output reduction for each solar cell technology was developed based on the *ARI* using curve fitting techniques. The model shows that wildfire smoke has the least impact on PV panels made by CdTe. Thus, future PV systems installation in high-risk wildfire areas needs to select proper PV cell technologies to ensure the minimal impact from wildfire smoke.

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