

Understanding non-localised impacts of bushfires on photovoltaic performance, reliability, and management strategies

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ARTICLE INFO

Handling Editor: Ranga Pitchumani

Keywords:

Extreme weather events
Bushfire modelling
Wildfires
PV yield modelling
Non-localised effects
Thermal degradation

ABSTRACT

Australia is among the world's most bushfire-prone regions, and the rapid expansion of photovoltaic (PV) systems has increased the vulnerability of energy generation to bushfires. This study provides a comprehensive assessment of how bushfire-driven atmospheric aerosols affect PV energy output, module temperature, and degradation. Using reanalysis and satellite observations, we analyse relationships between aerosol optical depth, radiative fire power, and module temperature across south-east Australia over a 20-year period (2003–2024). We then examine two major bushfire events: the 2019–2020 Black Summer bushfire and the 2009 Black Saturday bushfires to quantify their impacts on solar generation. During the Black Summer bushfire, energy generation declined up to 70 % near the bushfire hotspots and ~40 % in regions more than 150 km away from hotspots. We observe ~18 % reductions in energy generation near bushfire hotspots and 4–10 % for regions over 100 km from the hotspots during the Black Saturday bushfire. Results reveal modules operated up to 20 °C higher than the climatological threshold during the bushfire, contributing to ~0.15 % additional thermal degradation of the modules. This study highlights that accounting for bushfire-driven performance losses and temperature-induced degradation is critical to improving the operation and long-term reliability of large-scale solar farms.

1. Introduction

Australia is rapidly shifting its energy landscape by integrating a higher share of renewable energy to achieve the goals set by the large-scale renewable energy target [1]. As more large-scale, grid-connected photovoltaic (PV) systems are deployed, it becomes crucial to examine their resilience during extreme weather events like bushfires. Bushfires cause widespread socio-economic disruption by damaging infrastructure, impacting ecosystems, and endangering human health and livelihoods along with largely impacting the air quality [2]. Australia is one of the most bushfire-prone regions in the world and has experienced mega bushfires like Black Friday (affecting Victoria in 1939), Ash Wednesday (affecting Victoria and South Australia in 1983), Black Saturday (affecting Victoria in 2009), and the Black Summer (2019–2020). The Black Summer bushfire season (2019–2020) stands out as one of the most severe fire events in Australia's recent history. During this period, over 42 % of New South Wales state forests (equivalent to 0.91 million hectares) were affected, resulting in extensive damage to ecosystems and biodiversity [3,4]. Bushfire smoke consists of a complex mixture of aerosol species, with organic carbon and black carbon typically

comprising a substantial fraction of the particulate matter, along with inorganic aerosols, dust, and trace gases. The fine particulate matter known as PM_{2.5} (particles with a diameter of 2.5 µm or smaller), which is the dominant pollutant. These particles can travel long distances, often leading to hazardous concentrations of PM_{2.5} over large areas, reducing the air quality and imposing health risks [5,6]. The progression and intensity of a bushfire are predominantly influenced by fuel availability, low dry fuel moisture content due to elevated temperatures, high wind speeds, and reduced precipitation [3,7].

In addition to the environmental and health consequences, a major concern is the effect of bushfires on renewable energy infrastructure, particularly PV systems, which are highly vulnerable to changes in atmospheric conditions. Bushfires pose a threat to electricity transmission lines, along with reductions in energy generation due to an increase in the concentration of atmospheric aerosols. Surface-reaching solar radiation gets attenuated in the presence of aerosols due to scattering and absorption [8–10]. A previous experimental study on localised impacts of bushfires showed instantaneous reductions up to 73 % in PV generation during extreme conditions [11]. A similar study by Perry and Troccoli [12], demonstrated that controlled burns under clear-sky

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<https://doi.org/10.1016/j.solener.2026.115248>

Received 2 March 2026; Received in revised form 11 October 2026; Accepted 16 October 2026

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conditions can significantly reduce solar output by as much as 27 % due to the presence of smoke. The combination of reduced solar irradiance, caused by the scattering and absorption of sunlight by aerosols and soiling, led to measurable declines in PV performance. For instance, rooftop solar generation in New South Wales, Australia dropped by approximately 20 % during 2019–2020 bushfire season [13,14]. These studies also highlight the role of wind in dispersing aerosols beyond the fire-affected regions, which resulted in reduced rooftop PV generation. This indicates that the consequences of bushfire smoke on PV systems are not limited to areas near the source. Instead, wind-driven aerosol movement can extend the zone of impact, leading to widespread and non-localised reductions in solar power generation [5]. Therefore, even though understanding localized impacts is valuable, many aspects of grid planning, resource assessment, technology selection and site selection require broader-scale assessments and long-term estimates of potential effects. Corwin et al. [15] investigated the impacts of historical bushfires on irradiance and PV generation over the United States and reported reductions in global horizontal irradiance (GHI) up to 50 % in several regions during bushfire periods resulting in reductions > 10 % in PV generation. Similarly, Gilletly et al. [16] reported an average 8.3 % reduction in PV generation at sites near bushfire hot spots. Bushfire events in California have been associated with higher electricity prices due to an increase in energy demand and a reduction in solar generation capacity [17]. Consequently, dedicated forecasting studies have been developed to predict smoke transport and its impact on solar resources, enabling improved forecasting of PV generation and electricity demand management [16,18].

The aerosol particles released during the bushfires can settle on solar panels, called soiling, further reducing energy generation until the next cleaning event. The amount of particle deposition is dependent on the tilt angle of the modules and several other atmospheric conditions like relative humidity. The module's short-circuit current decreases due to the accumulation of aerosol particles on its surface, leading to increased transmission losses [19]. Aerosol particle accumulation can create localised hotspots on modules due to non-uniform illumination, resulting in elevated temperatures, accelerated degradation and reduced lifetime [20–22]. Different solar cell technologies exhibit varying sensitivity to smoke and aerosols. Previous studies have shown that a-Si modules are more susceptible to soiling in comparison to mono and multi-crystalline silicon [23]. Spectral analysis conducted during the Black Mountain fire in Canberra, Australia (March 2014), revealed that amorphous silicon (a-Si) thin-film cells experienced the most significant reduction in performance due to smoke, as they have the highest spectral response in the visible range where smoke particles primarily scatter and absorb light. In contrast, mono-crystalline silicon cells, along with thin-film technologies such as cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) were comparatively less impacted. This is particularly due to their enhanced response in the near-infrared and infrared spectral regions [12]. Temperature fluctuations, commonly observed during bushfires, also affect the bandgap of the semiconductor materials used in solar cells. As temperature increases, the bandgap of semiconductors tends to decrease, which in turn affects the spectrum of light that can be absorbed. Materials with narrower bandgaps like a-Si can capture lower-energy photons more effectively, but they may also experience greater energy losses due to heat [24]. Exposure to extreme temperatures can further impose thermal stress, potentially compromising the device's performance and long-term stability. Elevated module temperature can accelerate degradation mechanisms [25,26], and degradation modes like hotspots, light-induced degradation (LID), light and elevated temperature-induced degradation (LETID), junction box failure, etc. [27]. However, there is a lack of comprehensive studies dedicated towards understanding the implications of bushfires on module reliability and degradation.

Most of the existing literature has focused on the immediate, localized effects of bushfires on solar generation. A more comprehensive understanding of these broader spatial effects is essential for improving

resilience and forecasting in solar energy systems. Previous research has highlighted that the intensity, duration, and frequency of bushfires are projected to increase in the future [28], this poses a significant threat to the renewable energy industry infrastructure, generation, and reliability. In this study, we address these research gaps by understanding the past high-impact bushfires in Australia and quantifying the non-localised impacts of bushfires on energy generation and system reliability. To the best of our knowledge, this is one of the first papers to examine how elevated temperatures during bushfire periods affect module degradation. In this study, we examine module temperature, aerosol concentration, and fire radiative power over the past 20 years using hourly atmospheric variables from the global reanalysis dataset. We simulate module temperature, energy generation and degradation rates using hourly re-analysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis 5th generation, widely known as ERA5. We quantify the non-localised impacts of bushfire aerosol transport on generation by comparing polluted and non-polluted conditions. The findings from this study provide insights to enhance the reliability of large-scale solar farms by accounting for bushfire-induced performance losses and by demonstrating the role of elevated temperatures during bushfire periods in thermal degradation. This study contributes to the operation and management of solar assets by highlighting strategies for proactive maintenance and risk mitigation during and after bushfire events.

2. Data and methods

2.1. Data

In this study, we studied bushfire periods occurring between 2003 and 2024, using reanalysis data from the European Centre for Medium Range Weather Forecasts (ECMWF) Re-analysis (ERA5) [29] available at a ~28 km spatial resolution. We download the ERA5 data from ECMWF's Climate Data Store (CDS) (<https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=download>). To understand the impacts of bushfires on solar PV, we used hourly all-sky and clear-sky radiation, temperature, wind speed, direction, pressure, and relative humidity. We obtained 3-hourly aerosol optical depth (AOD) at 550 nm from the ECMWF Copernicus Atmosphere Monitoring Service (CAMS) [30] with spatial resolution of $0.75^\circ \times 0.75^\circ$. CAMS data is downloaded from the ECMWF's Atmospheric Data Store (ADS) (<https://ads.atmosphere.copernicus.eu/cdsapp#!/dataset/cams-global-reanalysis-eac4?tab=overview>). We use daily fire radiative power from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the NASA Aqua and Terra satellites downloaded from the Fire Information for Resource Management System (FIRMS) (<https://firms.modaps.eosdis.nasa.gov/download/>) [31]. MODIS Collection 6.1 provides hotspot locations corresponding to the centre of 1 km pixels identified by the detection algorithm as containing one or more active fires based on thermal anomalies. In this study, only hotspots with a fire detection confidence greater than 75 % were included.

2.2. Methods

Sudden cloud movements during the day can cause rapid drops in energy production, negatively affecting daily energy production and distribution rates. The main goal of this study is to understand aerosol-induced PV energy losses. Hence, we differentiated the daily weather conditions into clear-sky and cloudy and used cloud-free periods for this study. The cloudiness in the sky can be estimated using the daily clear-sky index (DCI). The DCI is calculated according to the following equation [32]:

$$DCI = \frac{\sum_{i=1}^n GHI_i}{\sum_{i=1}^n GHI_{CS_i}} \quad (1)$$

where GHI and GHI_{cs} are global horizontal irradiance under all-sky and clear-sky conditions, respectively. DCI is close to 1 under clear-sky conditions and is significantly lower on an overcast day. We calculate lulls to estimate consecutive hours of no-generation due to bushfire aerosols [33]. Lulls are defined as consecutive periods of little or no solar power generation during daylight hours due to insufficient solar irradiance [34]. In this study, a lull is identified when solar irradiance remains below 180 W m^{-2} for at least two consecutive hours [34]. To study lulls specifically due to aerosols, we used clear-sky periods in our analysis (where DCI was greater than 0.95).

We modeled PV generation for polluted and clean conditions using PVLIB [35] and varying aerosols concentrations. We used climatological aerosols to model clean generation, while time-varying aerosols during bushfire periods were used to model PV generation for polluted conditions. We used the isotropic model to obtain the plane-of-array irradiance. We estimated module temperature using the Sandia temperature model with ERA5 air temperature and wind speed, along with the plane-of-array irradiance. We use standard coefficients for open-rack glass-polymer PV modules [35]. It should be noted that the module temperature estimates are sensitive to the input meteorological variables and temperature coefficients. They should be chosen specifically for the system when performing solar farm assessments. We then obtain the power output using the PVWatts model [36] using the plane of array irradiance, module temperature and windspeed for clean and polluted conditions. We show the relative percentage change in generation due to the aerosols by comparing clean and polluted conditions. All the results are shown for single-axis tracker technology, which currently represent the dominant tracking technology in large-scale PV installations worldwide [37]. Note that the module temperature rise due to non-uniform soiling has not been modelled in this study.

The degradation rate due to cyclic thermal stress was:

$$k_{Tm} = A_{Tm}(\Delta T)^\theta C_N \exp\left(-\frac{E_{Tm}}{k_B \times T_U}\right) \quad (2)$$

where k_B is the Boltzmann constant ($8.62 \times 10^{-5} \text{ eV/K}$), ΔT represents difference in maximum and minimum module temperature (in Kelvin), T_U is the maximum temperature in Kelvin, C_N is the cycling rate and θ is a constant (taken as 2.24), A_{Tm} (taken as 2.04) is the pre-exponential constant, and E_{Tm} (0.43 eV) is the activation energy for thermal degradation of monocrystalline-silicon modules. These values were obtained from previous work by Kaaya et al [38].

The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model, developed by the U.S. National Oceanic and Atmospheric Administration (NOAA) [39] was used in this study to track air mass pathways and simulate the dispersion airborne pollutants from bushfire smoke. Forward air mass trajectories were generated for 10 m above ground level using meteorological data from the Global Data Assimilation System (GDAS; 1° resolution) to represent the near-surface transport of smoke aerosols relevant to solar irradiance attenuation and its impact on PV generation. These trajectories were initiated for the major bushfire hotspot location obtained from the centroid of major MODIS bushfire hotspot clusters and historical fire records from NSW National Parks and Wildlife Service [40] and Forest Fire Management Victoria [41] on the event dates and calculated for a month after the fire. The resulting trajectories were used to identify likely transport pathways of bushfire aerosols and assess their potential influence on regions experiencing elevated aerosol optical depth. To confirm the robustness of the forward trajectory analysis, we compared the forward trajectories from alternative datasets, including the NCEP Global Forecast System (0.25° resolution) and NCEP/NCAR Reanalysis (1° resolution). Similar transport pathways were obtained across datasets despite differences in spatial resolution.

3. Results

3.1. Bushfire season in Australia and module temp

Due to the spatial extent of Australia, the bushfire seasons vary regionally [28,42]. The bushfire season in south-eastern Australia extends from mid-October to mid-February, encompassing New South Wales (NSW) and Victoria. South-eastern Australia has the largest number of solar farms in the country and is also prone to frequent bushfires. Hence, in this paper, we will focus on this region to understand the impact of bushfires on the PV sector.

We show the mean climatological AOD (from 2003 to 2024) over Australia in Fig. 1a. The locations of the solar farms with an installed capacity greater than 1 MW are also shown in Fig. 1a. Regionally, AOD varies across Australia, with higher levels near the east coast and in Northern Australia (>0.09). Northern Australia has high AOD due to biomass burning from bushfires and the long-range transport of aerosols from the intercontinental region [43]. Carbonaceous aerosols can also originate from sources such as urban traffic, industrial activities, and other combustion-related emissions. Eastern coastal Australia has higher AOD due to long-range transport of sea-salt aerosols from the Pacific and increased biomass burning during bushfire seasons [44].

We show the scatter between monthly mean AOD and maximum module temperature for the study period (2003–2024) in Fig. 1b. Note that the scatter plot shows the mean values over the region marked with a black box in Fig. 1a. The FRP are aggregated for the time period for that region. The size of the scatter represents total monthly radiative fire power, where the PV modules tend to operate at higher temperatures during bushfire months when AOD levels are high (Fig. 1b). We observed the highest module temperature ($\sim 67^\circ\text{C}$) and fire radiative power for December 2019, corresponding to the Black Summer bushfire period, which records ~ 1.5 AOD for the region under study.

Previous studies have highlighted that extreme air temperatures and low fuel moisture content facilitate bushfire ignition and propagation [3,7]. Aerosols released during active bushfires can absorb heat, creating positive feedback between a warmer atmosphere and the number of bushfires [45]. Moreover, the additional heat generated by active fire events can further raise local air temperatures, contributing substantially to the increase in PV module temperatures as shown in Fig. 1b. Non-uniform soiling on the modules from bushfire smoke can cause localised temperature rise on module surfaces [20–22]. While non-uniform soiling may play an important role in influencing module temperatures during bushfire events, it was not explicitly considered in this study and should be investigated in future work.

3.2. Lessons from the past bushfires

In this section, we focus on understanding the non-localised impacts of two historical bushfires in Australia called the Black Summer bushfire (2019–2020) and the Black Saturday bushfire (2009). These bushfires caused severe destruction to infrastructure, widespread impacts, air quality and biodiversity [3,4,40,41,46,47]. The Black Summer bushfires resulted in severe air quality degradation, extensive smoke transport over large distances, and notable reductions in solar irradiance. The Black Saturday bushfire represents one of Australia's most intense fire events and provides an important case study of extreme fire activity and associated aerosol impacts. The use of case studies provides an opportunity for an in-depth understanding of bushfire smoke transport on generation, module temperature and thermal degradation of the modules.

3.2.1. Black Summer bushfire (2019–2020) – Impact on PV generation and module degradation

The Black Summer bushfire period was one of the massive catastrophic bushfires globally with severe fires in southeast Australia from November 2019 to January 2020. The bushfire hotspots and the AOD for

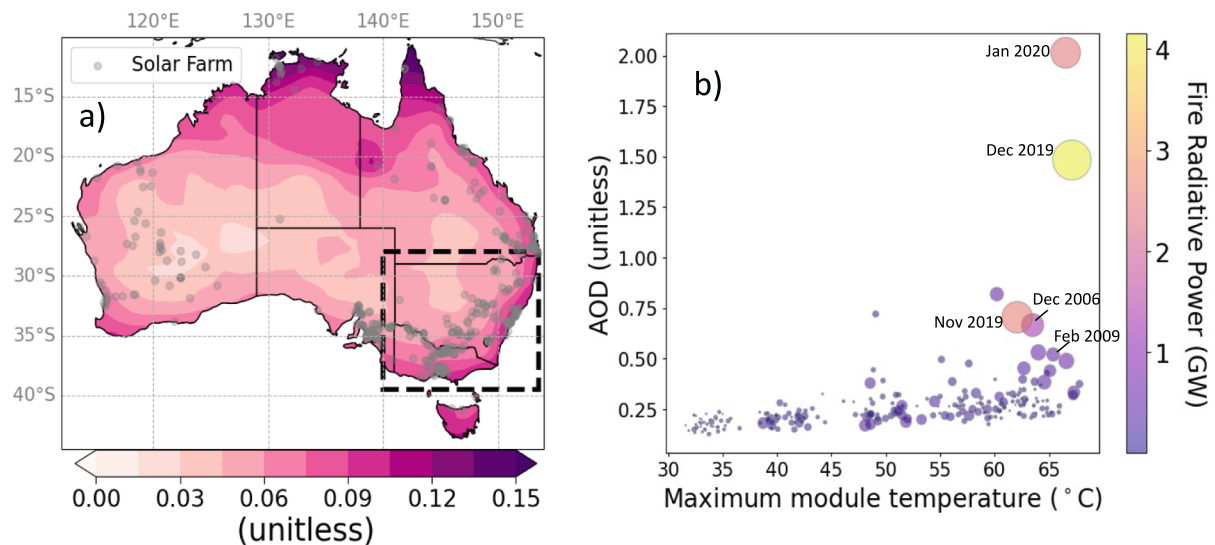


Fig. 1. A) aod climatology and location of large-scale solar farms. b) Scatter of monthly mean AOD and maximum module temperature for the 2003–2024 based on the region shown in the black box in Figure A. The size of the bubbles indicates the total fire radiative power for the month.

the 2019–2020 bushfire season are shown in Fig. 2a. Eastern coastal NSW and Victoria recorded the maximum number of bushfire hotspots, with AOD three to five times higher (Fig. 2a–d) than average (Fig. 1a) for these locations. The maximum AOD recorded during Black Summer exceeded > 1.7 near the hotspots.

Upon analysing the spatial variability of AOD for November–

December 2019 and January 2020, we notice that AOD increase not only for regions located in proximity to the hotspots but also in regional NSW, regional Victoria, and the south coast of Victoria (Fig. 2b–d). To analyse the impact of AOD on non-generation periods we estimate monthly mean lulls (Fig. 2 e–g) and monthly maximum lulls (Fig. 2 h–j) for the period. We estimate aerosol induced lulls by using clear-sky

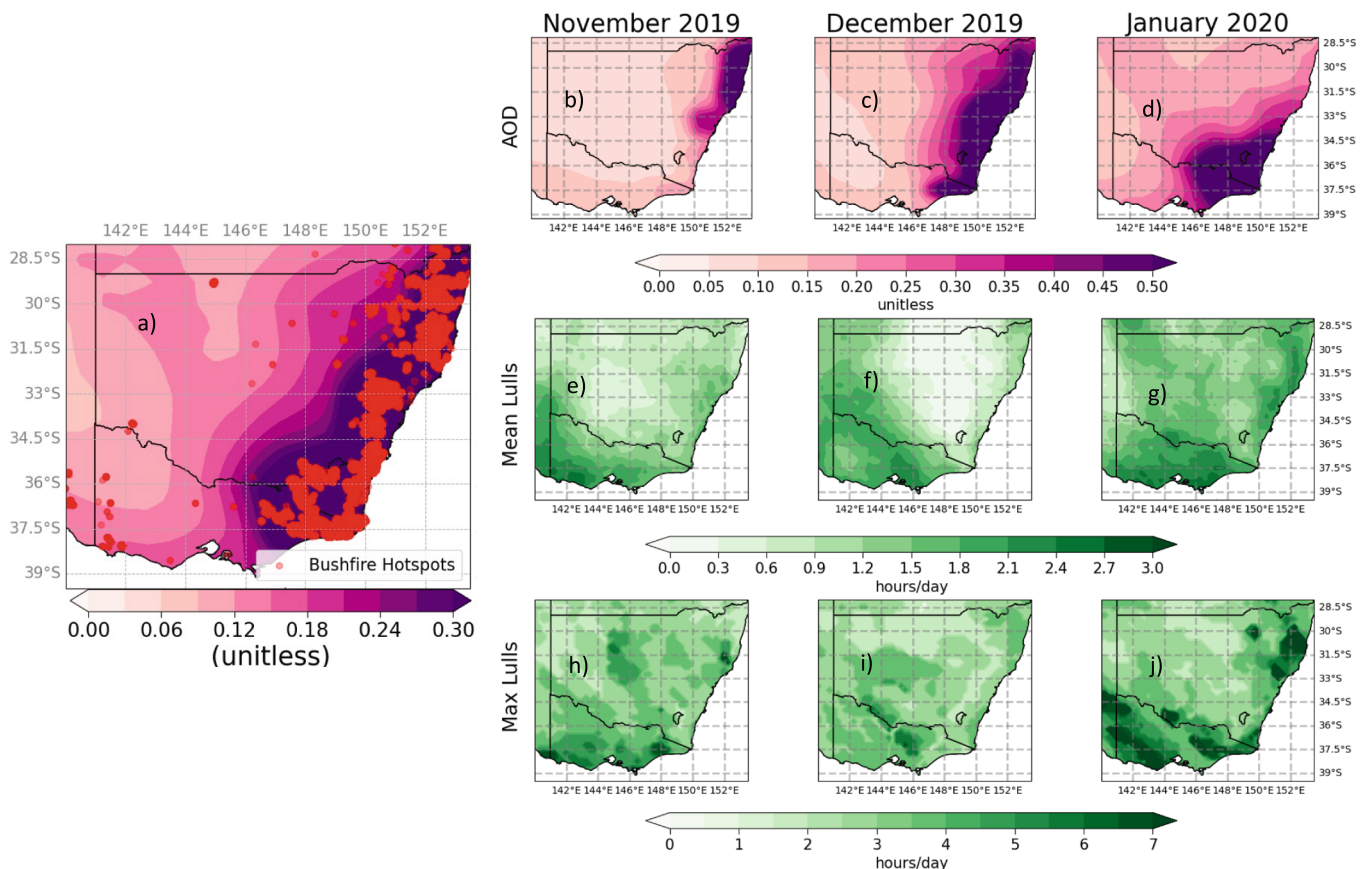


Fig. 2. A) mean aod during black summer bushfire period. the red dots show the bushfire hotspots. b–d) monthly mean aod for november 2019, december 2019 and january 2020 respectively. e–g) mean lulls for november 2019, december 2019 and january 2020, respectively. h–j) maximum lulls for november 2019, december 2019 and january 2020, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

periods. We observe mean lulls ranging from 15 min/day to 3 h/day in regions with high levels of AOD (>0.3). It should be noted that the lulls during December are the lowest due to aerosols only. Mean lulls are highest in January 2020, reaching up to 3 h/day near the coasts of NSW and southern Victoria. We also observe high mean lulls for regional NSW and Victoria during the bushfire period, emphasising the role of aerosol transport in low solar generation. Furthermore, our results show that bushfire hotspot regions near the NSW-Victoria border ($36\text{--}37^\circ\text{S}$, $146\text{--}150^\circ\text{E}$) experienced the longest lull periods of up to 8 h per day (Fig. 2j). Maximum lull analysis also shows that areas > 100 km away from bushfire hotspots recorded higher maximum lulls, highlighting the non-localised impact of bushfire on solar generation. The detailed trajectory analysis presented in Fig. 4a–b provides further evidence of the long-range transport of bushfire aerosols.

Our analysis reveals that regions located close to active bushfire zones experience the most severe decline in solar output, with generation falling by as much as 70 % (Fig. 33a–c). These substantial losses are consistent with the intense smoke plumes and aerosol loading produced by the fires, which significantly reduce incoming solar irradiance and thus limit PV output. However, the effects are not restricted to these immediate bushfire hotspot areas. Locations more than 150 km away also exhibit a sizeable reduction in generation, typically around 30–40 %. This pattern indicates that the influence of bushfires extends well beyond the bushfire hotspots itself. Smoke plumes can travel long distances under prevailing wind conditions, spreading atmospheric haze

across wide regions and reducing irradiance even in places that are physically remote from the fires. This is evident from the HYSPLIT trajectory simulations (Fig. 4b), which show that approximately 90 % of air parcel trajectories travelled up to ~ 200 km from the bushfire hotspots, corresponding to PV generation reductions of up to 80 %. In addition, around 30 % of trajectories travelled more than ~ 500 km inland from the Blue Mountains hotspot, where PV generation losses of up to 40 % were observed. The resulting drop in PV output therefore reflects the broader, non-localised nature of bushfire-driven air quality degradation.

During the Black Summer bushfire period, our results show that the modules operated $10\text{--}20^\circ\text{C}$ higher than the climatological module temperature (Fig. 3d), with this increase observed not only in regions near bushfire hotspots but also in more distant areas (>150 km from the hotspot). The higher temperatures can be attributed to both the anomalously hot year and the additional heat load from bushfire emissions. Similar findings were also reported by [13], who observed statistically significantly warmer temperatures under polluted conditions compared with clean conditions across most monitoring stations in NSW during the Black Summer bushfires. While increased AOD typically reduces surface-reaching solar radiation and tends to lower module operating temperatures, bushfire conditions are frequently associated with elevated ambient temperatures and smoke-induced heat retention, which can lead to higher module temperatures [28,48]. Furthermore, soiling due to bushfire smoke and particulate matter can cause localised hotspots on the modules, resulting in increased module temperature

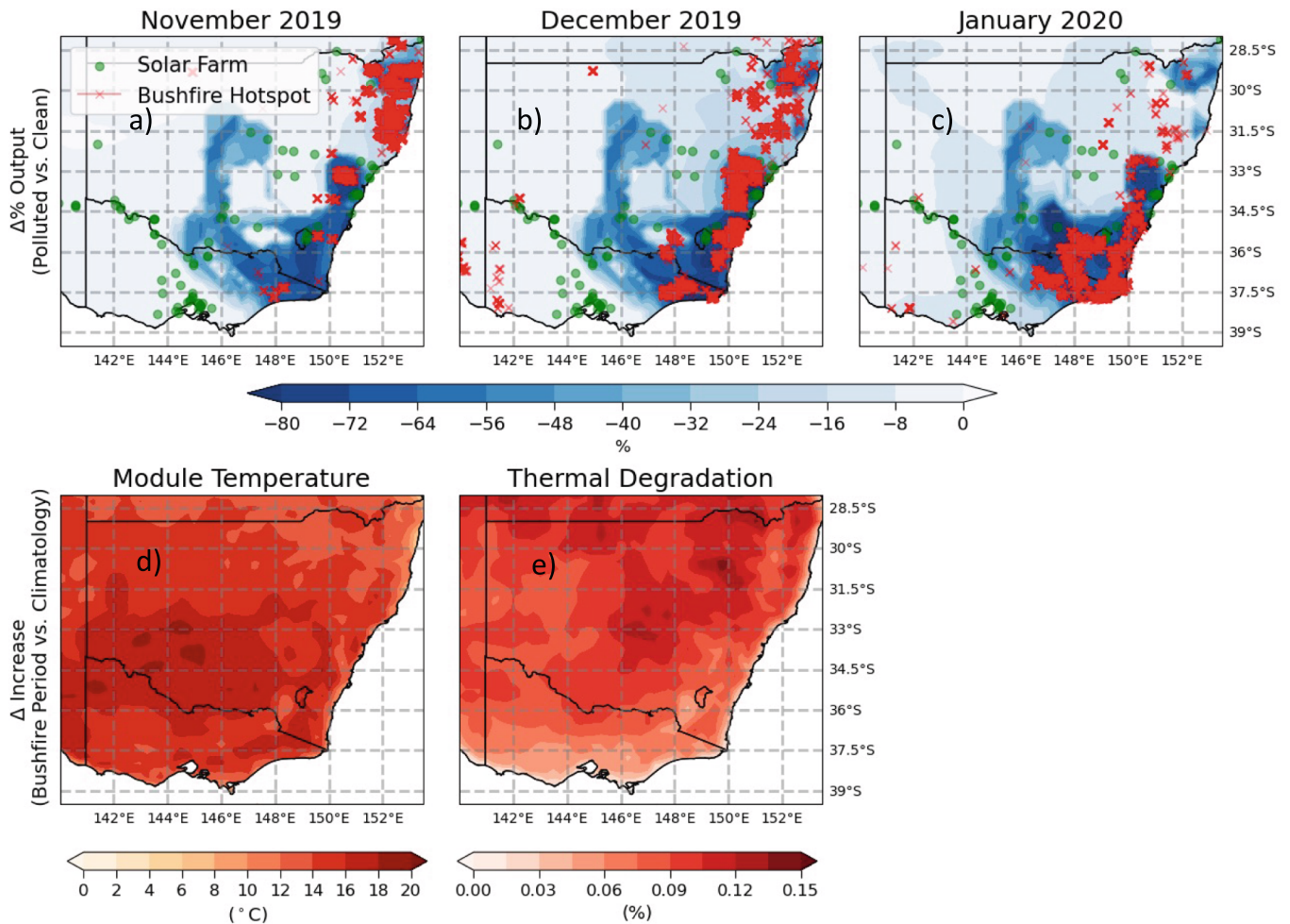


Fig. 3. A–c) generation loss due to polluted conditions during the black summer bushfire period shown for november 2019, december 2019 and january 2020 respectively. increase in module temperature and thermal degradation rates during black summer bushfire period relative to the climatology shown in d) and e) respectively.

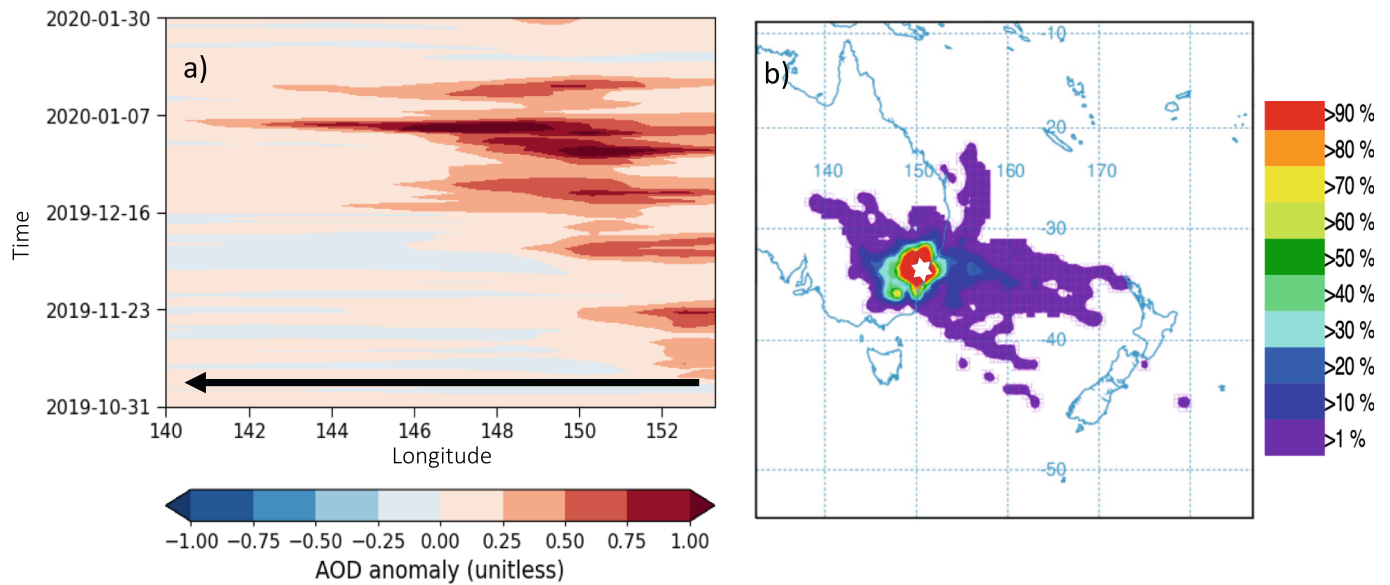


Fig. 4. A) Hovmoller plots of AOD anomaly showing inward regional transport of aerosols. The arrow indicates the direction in which the air parcel travels. b) Frequency of the end point of the trajectories at each grid point is shown using HYSPLIT simulation. HYSPLIT simulation is shown for 30-day period starting from 1st December 2019 for the bushfire hotspot at Blue Mountains, NSW, Australia (shown in white star). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

[20,22]. The observed changes in module temperature during the bushfire periods therefore are associated with the prevailing atmospheric conditions and should not be interpreted as a direct effect of increased AOD. In 2019, Australia experienced its highest maximum daytime temperatures on record, averaging $1.71\text{ }^{\circ}\text{C}$ above the long-term mean [49]. Our analysis indicates that the higher operating temperature of PV modules during this bushfire event contributed to $\sim 0.15\%$ additional thermal degradation of the modules (Fig. 3e). It should be noted that the estimated thermal degradation is attributed to the elevated module operating temperatures observed during the bushfire period and not directly to increased aerosol concentrations. Establishing a causal relationship between aerosols and module temperature would require dedicated sensitivity experiments using a regional climate model to isolate the effects of aerosol loading from other meteorological factors.

The regional transport of smoke from the hotspot regions, can be seen in the Hovmöller plot (Fig. 4a). Hovmoller plots are a useful visualization tool for studying aerosol transport as they show how aerosol distribution changes over time and along a specific dimension, typically longitude (or latitude) averaging the latitude (or longitude). In this case study, the time-longitude Hovmoller plot shows the AOD anomalies for the bushfire case study period. The positive values denote a higher concentration of AOD at that longitude. It should be noted that the spatial extent used in the HYSPLIT figures (Figs. 4b and 7b) are larger than that used in the AOD and meteorological analyses to capture the full transport pathways of bushfire smoke aerosols from the source regions.

We observe a high AOD near the coast ($\sim 152\text{--}153\text{ }^{\circ}\text{E}$ longitude) at the onset of the bushfire in November, which is transported inland by the beginning of January 2020 due to high winds. We obtain the trajectory frequency of the air parcels using the HYSPLIT model for December 2019 to January 2020 (Fig. 4b). Approximately 90 % of the trajectory endpoints remain concentrated near the fire origin (marked by the star in Fig. 4b), while atmospheric transport driven by strong winds re-distributes the remaining fraction. Trajectory frequency analysis using the HYSPLIT shows that approximately 40 % of the trajectories are advected inland towards regional NSW by early January 2020. A much smaller proportion ($\sim 1\%$) disperses further, spreading towards north-

western NSW and southern Queensland, with most of this minor fraction transported eastward across the Pacific Ocean towards New Zealand. The trajectory analysis represents the relative frequency of air parcel transport pathways and does not quantify aerosol mass or concentration. Future work could incorporate concentration-weighted trajectory analysis to better quantify the contribution of different transport pathways to observed aerosol loading. Similar backward trajectory analysis for PM concentrations from the 2019–2020 bushfires was carried out by Attiya et al. [5], and their study revealed that bushfire smoke was transported and dispersed from the Blue Mountains to greater Sydney. Further, they conducted analysis with CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation) and found high AOD over NSW and Queensland consistent to our findings.

3.2.2. Black Saturday bushfire (2009) – Impact on PV generation and module degradation

The most devastating bushfire event in Australia's recorded history, following a massive heatwave event occurred in Victoria, known as the Black Saturday bushfires (February 2009). The bushfires began on 7th February 2009, with major fires continuing until 10th February and some fires persisting until the end of February across several locations in Victoria. The Kinglake fire (8th February 2009) was among the most devastating fires in this series of events and was selected for simulating aerosol trajectories in this study. We show the bushfire hotspots (shown in red dots) and the mean AOD for the bushfire season (January – March 2009) in Fig. 5a. We find AOD near the bushfire hotspots is three times higher and clustered around Kinglake, Marysville (near $\sim 37\text{--}38\text{ }^{\circ}\text{S}$ and $144.5\text{--}155\text{ }^{\circ}\text{E}$) and West Gippsland ($38.5\text{ }^{\circ}\text{S}$, $155.5\text{ }^{\circ}\text{E}$). The monthly mean spatial variability of AOD after the Black Saturday bushfire (February 2009) indicates that AOD values in non-hotspot regions were approximately 1.2–1.8 times as high compared to pre-fire conditions (Fig. 5b–d). The impact of aerosol loading on lulls can be observed in both mean lulls (Fig. 5e–g) and maximum lulls plots (Fig. 5h–j), where high lulls are evident not only in regions located near bushfires but also in regions farther away from them. Our results show that mean lulls reach up to 2.5 h/day near the bushfire hotspots, with a maximum of 5 h/day.

We observe that regions situated close to active bushfire zones

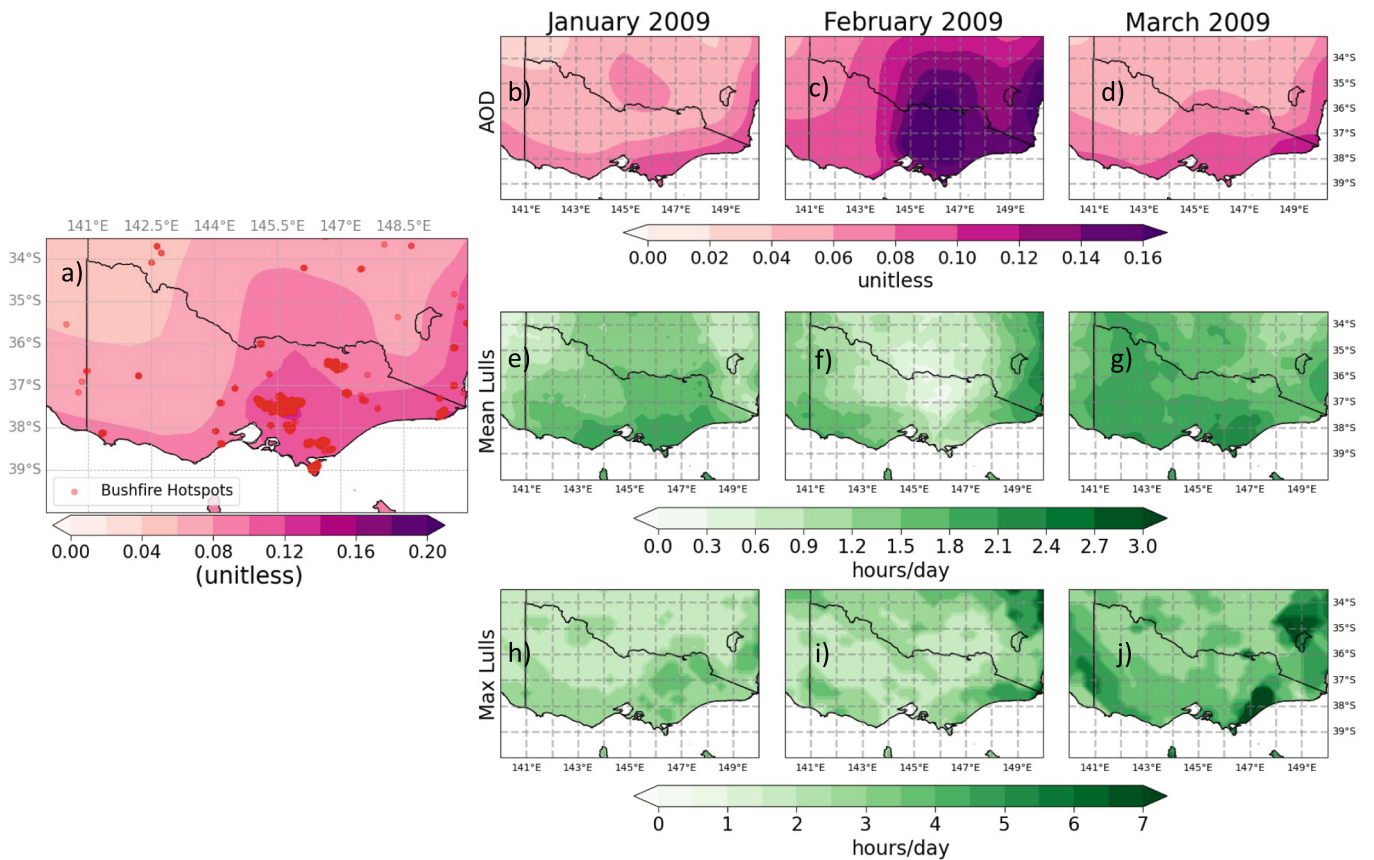


Fig. 5. A) mean aod during black saturday bushfire. the red dots show the bushfire hotspots. b-d) monthly mean aod for january, february, and march 2009 respectively. e-g) mean lulls january, february, and march 2009 respectively. h-j) maximum lulls for january, february, and march 2009 respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

experience notable declines in PV output, with generation falling by up to 18 % (Fig. 6a–c) due to the dense smoke and particulate matter released during the active fire. Importantly we also observe that the influence of the bushfires is not restricted to the immediate hotspot areas. Locations more than 100 km away also show generation losses of around 5–10 %, clearly demonstrating the non-localised impacts of bushfires. Modules experienced $\sim 18^\circ\text{C}$ higher temperature during the Black Saturday bushfire period (Fig. 6d), with modules operating ~ 13 – 15°C hotter near inland Victoria and regions closer to the NSW border from the hot summer with multiple heatwaves and the bushfires. This contributed to $\sim 0.12\%$ additional thermal degradation that year, as shown in Fig. 6e.

The regional transport of the aerosol particles is shown by the Hovmöller plot (Fig. 7a). The black dot indicates the massive fire date (8th February 2009), and the direction of transport is shown by the arrow. We observe that air parcels are transported from the origin towards the coastal regions of Victoria. This is further shown in the trajectory frequency plot in Fig. 7b for the bushfire day (9th February 2009), which shows that up to 30 % of the aerosol particles travel towards regional NSW and Victoria. We can observe up to 90 % of the aerosol concentration is confined near the fire origin (marked by the star in Fig. 7b), while atmospheric transport driven by strong winds redistributes the remaining fraction inland towards regional and coastal NSW and Victoria. A much smaller proportion ($\sim 1\%$) disperses further, spreading inland towards north-western Victoria and eastward towards New Zealand. Siddaway et al [47] investigated the bushfire smoke dispersion and impacts on the upper troposphere and stratosphere following the Black Saturday bushfire. Their study showed large quantities of smoke were injected into the lower stratosphere, where the plume was transported over long distances. They further showed that

AOD in the lower stratosphere increased by 35 % above the baseline after the massive fire, demonstrating the significant and prolonged atmospheric effects of this extreme bushfire event.

4. Discussion

Australia experiences a high bushfire risk with frequent bushfire periods. With climate change and increased global warming rates, the bushfire risks are expected to increase in the future. This can result in huge losses for solar farm asset owners, managers, distributors, and grid operators. Our results highlight non-localised impacts of bushfires on energy generation and reliability. However, bushfires are only one of several factors influencing solar resource variability and energy system reliability, and further studies that cover a broader range of extreme weather events are needed to better quantify these impacts. It is recommended to carefully select sites before making large-scale investments and to adopt precautionary measures for existing solar farms in risk-prone regions.

Bushfire mitigation strategies relevant to the development, operation and maintenance of solar farms are summarized in Table 1. Vegetation and surface management are central to reducing bushfire hazards in solar farms, as unmanaged grass and shrubs can act as fuel during extreme weather conditions. Routine practices such as mowing, slashing, or controlled grazing help reduce surface fuel loads and limit the risk of bushfire spread. Bushfire preparedness and infrastructure management provide a second layer of protection. Bushfire management plans typically define buffer zones, establish fire breaks, and allocate suppression resources to limit the extent of fire damage [50–52]. Electrical fault detection and protection systems can reduce the risk of onsite ignition events that may contribute to fire initiation under extreme

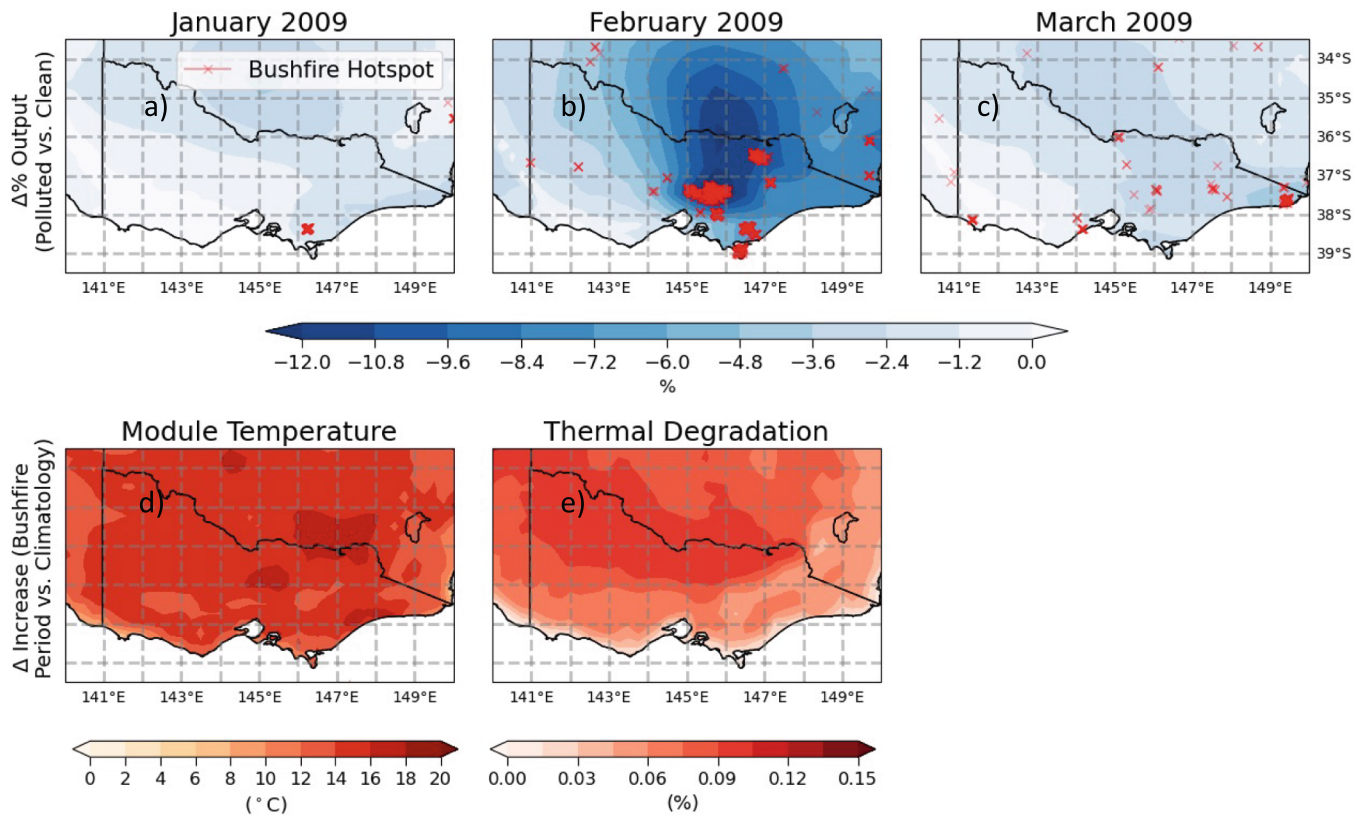


Fig. 6. A-c) generation loss during the black summer bushfire period shown for January, February and March 2009 respectively. Increase in module temperature and thermal degradation rates during black Saturday bushfire period relative to the climatology shown in d) and e) respectively.

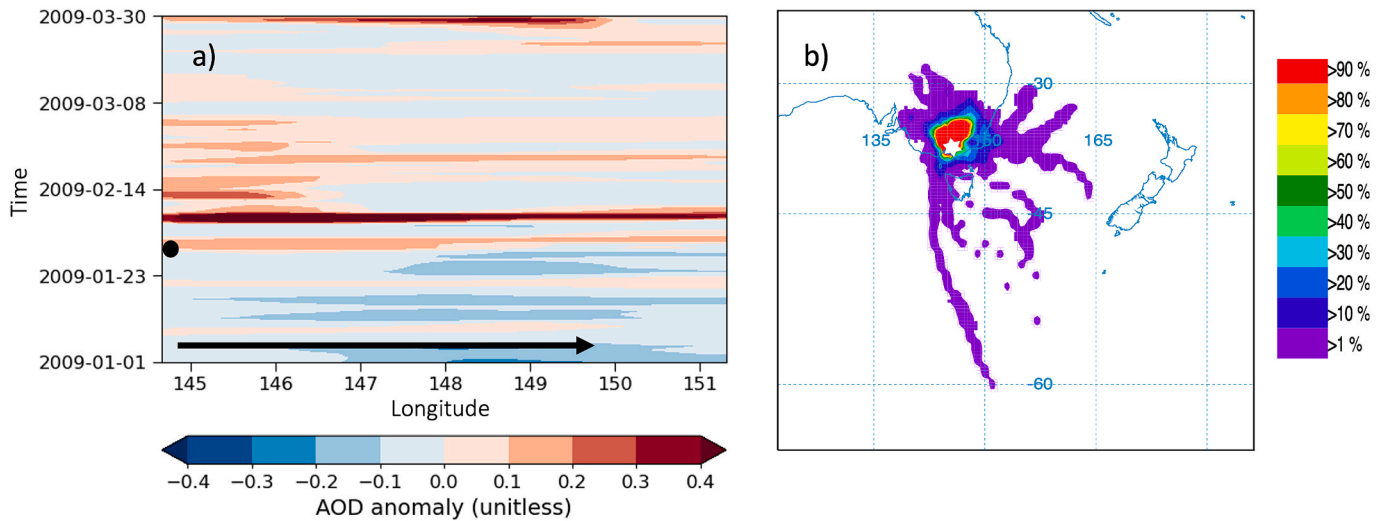


Fig. 7. A) Hovmöller plots of AOD anomaly showing inward regional transport of aerosols. The black dot shows the bushfire day, and the arrow indicates the direction of the air parcel trajectory. B) Frequency of the end point of the trajectories at each grid point is shown using HYSPLIT simulation. HYSPLIT simulation was shown for 30-day period starting from 8th February 2009 for the bushfire hotspot at Kinglake, Victoria, Australia (shown in white star).

bushfire conditions. Remote monitoring systems can also support early detection of electrical temperature anomalies and enable rapid system isolation of affected strings or inverters [53,54], thereby reducing ignition risk during bushfire periods. Further, using materials with high fire-resistance ratings, together with design adjustments such as optimal module tilt and enhanced airflow, can reduce both the likelihood of flame spread and the impact of elevated module temperatures on the module [55].

In parallel, regular cleaning of modules reduces the risk of soiling and defects, such as hotspots, thereby improving energy yield. Field studies have shown that soiling removal can recover between 2 and 6 % of annual generation [23,68–70], providing a cost-effective way to combine fire risk mitigation with operational efficiency. By combining vegetation control, module cleaning and inspection along with advanced monitoring into a predictive maintenance framework, and adapting resilient system design, solar farms can significantly lower

Table 1

Summarizes key bushfire mitigation strategies and associated operational responses that enhance the solar farm resilience during bushfire events.

Operational and Management Strategy	Primary Action	Cost Implication and Frequency	Energy Generation Benefit	Bushfire Risk Reduction	References
Enhancing bushfire forecasting, smoke trajectory modelling	Meteorological forecasting, smoke plume modelling, wind trajectory analysis, integration with grid and generation planning	Moderate, Recurring	Minimises unexpected generation losses and alternative generation dispatch during bushfire periods	Indirect risk reduction, reduces operational stress during regional fire events and supports safer system operation	[12,56]
Vegetation and Fuel Management	Mowing, grazing, slashing, maintaining assets	Moderate, Recurring	Reduces shading losses	Reduces ignition potential by limiting combustible fuel loads	[57,58]
Scheduled Module Cleaning	Regular cleaning of panels and site debris removal	Moderate, Periodic	+2–20 % yield improvement from dust removal	Indirect risk reduction, reduces operational stress during regional fire events and supports safer system operation	[13,14,59,60]
Thermal Monitoring and Inspections	Infrared/thermal imaging; inverter and connector checks	Higher upfront, low ongoing maintenance	Prevents downtime, improves reliability	Early fault detection prevents hotspots and electrical ignitions	[61]
Fire Management Plans	Fire breaks, suppression systems, emergency training	Low–moderate	reduces outage duration post-event	Enhances containment and recovery, minimises fire spread	[50,51]
Developing and investing in resilient system	Fire-resistant materials, ventilation, optimal tilt	Higher upfront, long-term savings	Preserves efficiency by lowering module temperature	Reduces both propagation risk and module overheating during extreme events	[58,62–64]
Predictive Maintenance Systems	Data-driven scheduling, remote monitoring, developing digital twins	Medium investment, high long-term savings	Maximises lifetime generation, reduces unplanned losses	Integrates vegetation, cleaning, and thermal risk data for holistic risk reduction	[65–67]

bushfire risks while safeguarding long-term performance and generation. Although the introduction of monitoring technologies and fire suppression systems requires additional expenditure, the reduction in asset losses, downtime, and generation represents a favourable cost-benefit outcome. While conventional bushfire mitigation strategies primarily address on-site ignition risk and asset protection, the impacts of bushfire smoke on the PV generation and dispatch are governed by regional fire behaviour and atmospheric transport processes beyond site control. Therefore, integrating bushfire forecasting along with smoke-plume trajectory modelling essential for maintaining generation reliability, enabling anticipatory operational responses, and enhancing overall power system resilience during extreme bushfire events.

5. Conclusion

In this study, we studied the impacts of bushfires on the generation and reliability of PV systems. We explored the relationship between simulated module temperature, fire radiative power and AOD and observed a positive correlation, indicating that high fire radiative power elevates the AOD levels and higher module temperatures during bushfire periods. These conditions collectively contribute to reduced photovoltaic power generation through enhanced atmospheric attenuation of incoming solar radiation and increased thermal losses at the module level. We demonstrated our approach for two extreme bushfire cases in Australia: the Black Summer bushfire (2019–2020) and the Black Saturday bushfire (2009). We evaluated the aerosol-induced impacts on generation by studying lulls under clear-sky periods. We observed that both the mean and maximum lulls are not only high for the bushfire hotspots, but also in regions far away from the hotspots, indicating a non-localised impact of bushfires due to the transport of aerosols. For both bushfire case studies, organic matter and black carbon were the predominant aerosol species in the study region, whereas dust, sulphate and sea-salt aerosols accounted for only a small proportion of the total AOD, indicating that the observed aerosol enhancement was primarily associated with bushfire smoke (Supplementary Fig. 1s). We further study the difference in generation under clean and polluted conditions. Generation under clean conditions is calculated by considering climatological aerosols, while real-time aerosols released during the bushfire period under investigation are used to simulate the polluted conditions. There is a notable reduction in energy generation at the bushfire hotspots due to the smoke and particulate matter, resulting in ~70 % reduction in energy generation during the Black Summer bushfire

and ~18 % during the Black Saturday bushfire. Our results showed a reduction of up to 40 % in generation during the Black Summer bushfire for non-bushfire hotspot regions, while we observed a reduction of up to 10 % for non-bushfire hotspot regions during the Black Saturday bushfire. It should be noted that the intensity of bushfire spread, duration of active burn, and prevalent winds during the Black Summer bushfires were higher than those of the Black Saturday bushfires, resulting in such extreme values for that period. The smoke dispersion during Black Summer bushfire was driven by persistent west-to-north-westerly winds and strong wind gusts in NSW (>100 km/h) directing smoke from Blue Mountain bushfire hotspots to Central Tablelands and Central-west region of NSW. In contrast, smoke dispersion during the Black Saturday bushfires was influenced by more variable wind conditions, with north-westerly winds promoting initial dispersion followed by a shift to south-westerly winds that altered transport pathways. Wind gusts up to 90 km/h were observed on the active burn days (Saturday, 7th – 9th February 2009). We also modelled and studied the elevated module temperature during the bushfire periods and their impact on accelerated thermal degradation for single axis tracker systems. We observe that the modules operated ~20 °C higher during the Black Summer bushfire period, contributing to about 0.15 % additional thermal degradation. Similarly, we observe a ~15–18 °C higher operating temperature of the modules during the Black Saturday bushfire period, which contributed to up to 0.12 % additional thermal degradation in the modules. We further discuss some operational and management strategies that solar farms can adapt to enhance energy generation and reduce bushfire-related risks during bushfire periods.

This framework can be combined to understand the frequent bushfire hotspots and air trajectory pathways as a pre-feasibility assessment for site selection of new solar farms. This is also beneficial for understanding optimal operational and management strategies for current operational solar farms that are in proximity to bushfire hotspots or can be affected due to aerosol dispersion and travel. Importantly, this approach is transferable to other bushfire prone regions globally, including California, southern Europe, and parts of South America, where recurring bushfire activity and atmospheric transport pose similar risks to solar energy generation and asset management. This bushfire trajectory analysis could be coupled with regional climate models to improve forecasting of solar power generation during bushfire events, provided that aerosol datasets are carefully selected and calibrated against ground-based observations to ensure accuracy under local conditions. Although reanalysis datasets provide valuable information, differences

in their underlying data assimilation methods can lead to discrepancies in aerosol estimates and, consequently, in predicted solar power generation. Future studies could incorporate LiDAR (Light Detection and Ranging) observations to investigate the vertical distribution and classification of bushfire aerosols complemented by aerosol Ångström parameters to characterize particle size distributions and improve discrimination between bushfire smoke and other aerosol types. Such analyses would provide a more comprehensive understanding of aerosol properties, transport dynamics, and their influence on solar irradiance, PV performance, and long-term module degradation during bushfire events. In this study, we do not explicitly account for the contribution of long-term climate change to changes in bushfire frequency, intensity, or aerosol emissions. Climate change may indirectly influence the occurrence and severity of bushfires and associated smoke events [48], which could affect the magnitude and frequency of future solar generation impacts. Future work should combine attribution methods and climate model simulations to distinguish the relative contributions of anthropogenic climate change, natural climate variability, and bushfire aerosols to solar resource variability and renewable energy system performance.

CRediT authorship contribution statement

Shukla Poddar: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bram Hoex:** Writing – review & editing, Project administration. **Merlinde Kay:** Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We sincerely thank the Australian National Computing Infrastructure (NCI) for providing computational resources for this work. This work was supported by the Australian Government through the Australian Renewable Energy Agency (ARENA) under Grant TRAC 2022/12 and the Australian Centre for Advanced Photovoltaics (ACAP).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.solener.2026.115248>.

Data availability

No new data was generated

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