Preliminary insights into the impact between photovoltaic installations and climate change

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Solar photovoltaic (PV) installations are growing exponentially globally, with a rising fraction of solar PVs in the renewable energy mix. Climate change is also expected to influence PV installations worldwide. Understanding the climate change impact on PV installations has been the scope of many recent studies. This article reviews recent studies on climate change impacts on PV installations based on the present scenario, and examines the effect of rising temperatures on the performance and service life of PV installations. On the contrary, PV installations may also cause an increase in the local ambient temperature. The impact of PV installations on the local and global climate is yet to be established. Comprehensive studies need to be undertaken to examine the impact between climate change and the performance of PV installations.

Keywords: Ambient temperature, climate change, failure probability, performance and service life, solar photovoltaics.

SOLAR photovoltaic (PV) installations are a promising future energy resource to combat climate change. During the operational phase, emissions from PV panels are significantly less than fossil fuel-based energy sources[1]. Solar PVs convert a specific fraction of the solar radiation spectrum (say up to 1100 nm for a typical 1.1 eV band-gap material) into electricity, while the remaining may heat the panel.

The magnitude and nature of change in the performance due to changes in the ambient conditions are complex to determine. Here, an effort has been made to understand them through a literature review.

To date, most of the studies have focused on the impact of climate change on PV potential. They provide information on the changes in weather and environmental conditions to which the PV modules are exposed and not how they aggravate/alleviate the degradation of these modules.

Understanding the impact of climate change on the performance of PV panels (a reliability metric representing the fraction of the time these panels are functional as intended) is challenging. The rate at which a PV panel degrades affects its economic viability, performance and service life. The service life of a PV panel is directly linked to the number of end-of-life (EoL) panels[2,3]. As the number of PV installations per year worldwide is rising, it is paramount to plan for PV installations in the future, anticipating climate change scenarios.

The local climate greatly influences the performance of a PV system and degradation, but the PV system can also impact local and global climate. For example, a sizeable utility-scale PV installation can cause a change in land albedo (radiation reflected by a surface), affecting the net radiation balance during daytime[4,5]. To understand these phenomena, researchers have attempted both experimental and modelling approaches. Figure 1 summarizes the possible interactions between climate change, global/local climate and a PV system.

Climate change impact on PV performance

A study considered the PV performance model as a function of irradiance and temperature[6]. The authors estimated a relative reduction of 3.8–22.8% of electricity output for 2071–2100 due to climate change in Nordic countries[6]. A simulation study indicated an increase in PV output from 2010 to 2080 in Europe and China, a reduction in the western USA and Saudi Arabia, and a change in Algeria and Australia[7]. This study concluded that there exists a strong regional difference in the impact of climate change on PV potential. Another study dealt with the sensitivity of aerosols on photovoltaic energy (PVE) using climate models[8]. The study reported a reduction of PVE up to 7% between 2000 and 2030 in Eastern Europe and northern Africa and an increase of up to 10% in Western Europe and the East Mediterranean[8]. In Greece, a 4% increase in energy output was expected[8]. The increase in total radiation compensated for the loss due to increase in temperature. Another study estimated PV power production in Europe to change from 2% to –14% (ref. 9). Based on 39 climate models, a study concluded that most parts of the world experience a decrease in PV yield, except large parts of Europe, the southeast of North America and Southeast China[10]. A regional study in West Africa reported that all regions, except Liberia and Sierra Leone, showed a negative PV output trend[11]. The total radiation at the surface depended significantly on cloud cover. The influence of changes in cloud cover on PV potential was studied through simulation[12]. During winter, a reduction in cloud cover caused a general increase in the PV potential

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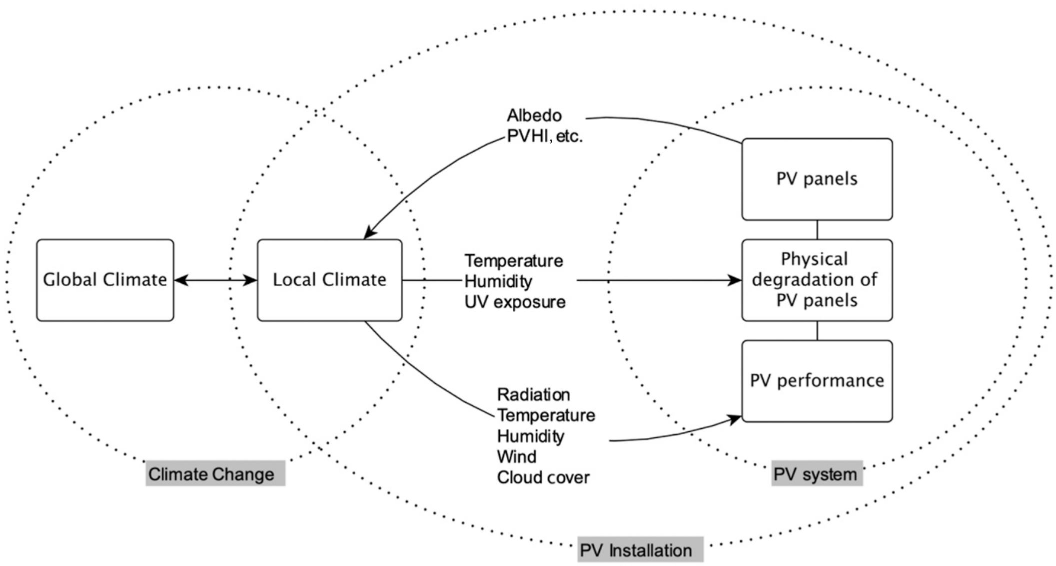

Figure 1. Interactions between climate change, global/local climate and the photovoltaic (PV) system.

and lower operating temperature, and a decrease in PV potential was observed due to temperature rise through simulation[12]. In China, due to solar dimming, which occurs when aerosols absorb radiation, a loss of 12–13% of PV electricity generation has been estimated[13]. Global PV power output was calculated based on the first-order approximation of temperature effect on PV power output and the IPCC projections of temperature change by the end of this century. A median of 15 kWh/kWp and a maximum loss of 50 kWh/kWp was also reported[14]. A positive trend in PV output has been observed consistently in Western Europe and Southeast China[7,10]. Concentrated solar power seems to be affected more than solar PVs because of the higher impact of climate change on direct beam solar radiation. More locations are affected, and a maximum of around 20% increase in concentrated solar power may be expected[7]. It is to be noted that the literature does not consider the influence of climate change on the manufacturing, degradation and other market conditions of PV panels but focuses only on these changes in performance due to changes in the operating conditions of the PV installations. Table 1 summarizes the changes in the PV performance parameters of PV systems estimated by various studies. The range of change in performance parameters represents the values corresponding to simulated scenarios. Table 2 provides a qualitative description of the vulnerability of various factors to climate change and the PV installation. These factors are associated with solar PVs and the environment. The corresponding interventions and considerations have also been suggested for these factors. Figure 2 *a* shows the general methodology followed by the studies discussed here. Various climate models and an ensemble of models with different emissions scenarios were used. Appendices 1 and 2 provide details of the PV performance models and climate models respectively.

Weather variables impacting PV under climate change

Radiation and temperature are generally considered to be the influencing parameters for PV performance in the literature. Only a few studies consider wind speed, angle of incidence, tilt angle and ground reflection (Table 3). Simple analytical models used in studies have estimated the individual effects of temperature, radiation and wind speed on the changes in the PV potential in future climate. However, wind direction is also an important factor which affects the surface temperature of the PV panels, conversion efficiency and dust settlement. This factor is not explicitly examined in the studies reviewed here. The sensitivity of the PV power output to radiation and temperature has been determined to be location-dependent, and neither of the weather variables was found to consistently dominate[7]. The effect of other variables has not been considered in the study[7]. Typically, for a crystalline silicon-based PV cell, the efficiency decreases with an increase in temperature and increases with an increase in radiation. For an increase of 1 K temperature, the efficiency decreases by an order of magnitude higher than when the radiation decreases by 1 W/m^2. Typical temperature and radiation coefficients are around -4×10^{-3} per K and $+0.06 \times 10^{-3}$ per W/m^2 respectively. Model estimations have shown that change in surface temperature due to climate change is location-dependent[7]; it is around –1 to 9 K (change in efficiency is 4×10^{-3} to -36×10^{-3}). Also, the change in total surface radiation is around –35 to 40 W/m^2 (change in efficiency is -2.1×10^{-3} to 4×10^{-3}). The temperature change (as a result of climate change) is a dominant environmental factor influencing PV performance. In certain locations, the combined effect of decrease and increase in efficiency due

Table 1. Collation of the impact of performance results of photovoltaic (PV) systems due to climate change from various studies

Location of the study	Year of projection	Base year	PV parameter affected	Change in the PV parameter (%)	Weather parameter affecting the change
Algeria (north)[7]	2080	2010	PV energy output	–1.24 to ~2.02	Rad and *T*
Eastern Europe and Northern Africa[8]	2030	2000	PV energy output	–7	Rad and *T*
Algeria[10]	2050	2006–15	PV output per year	–0.05 to ~0.05	Rad and *T*
South Africa[10]	2050	2006–15	PV output per year	–0.054 to ~0.028	Rad and *T*
ECOWAS[11]	2045	2006	PV output per year	–0.032 to ~0.013	Rad and *T*
Canary Islands[12]	2045–54 and 2090–99	1995–2004	PV potential	–5 to ~5	Rad, *T* and ws
Saudi Arabia[7]	2080	2010	PV energy output	–1.36 to ~ –5.29	Rad and *T*
China (south)[7]	2080	2010	PV energy output	2.69 to ~4.3	Rad and *T*
China[10]	2050	2006–2015	PV output per year	–0.12 to ~0.0068	Rad and *T*
India[10]	2050	2006–2015	PV output per year	–0.12 to ~0.0045	Rad and *T*
Australia (south)[7]	2080	2010	PV energy output	–0.603 to ~0.82	Rad and *T*
Australia[10]	2050	2006–2015	PV output per year	–0.06 to ~0.086	Rad and *T*
Spain[7]	2080	2010	PV energy output	3.48 to ~5.04	Rad and *T*
Germany (south)[7]	2080	2010	PV energy output	3.75 to ~4.44	Rad and *T*
Copenhagen[6]	2071–2100	1961–1990	PV energy output	–4.3 to ~ –3.8	Rad, *T* and grs
Oslo[6]	2071–2100	1961–1990	PV energy output	–7.5 to ~ –5.9	Rad, *T* and grs
Trondheim[6]	2071–2100	1961–1990	PV energy output	–15.6 to ~ –10.8	Rad, *T* and grs
Tromso[6]	2071–2100	1961–1990	PV energy output	–15.2 to ~ –12.7	Rad, *T* and grs
Helsinki[6]	2071–2100	1961–1990	PV energy output	–22.8 to ~ –13.6	Rad, *T* and grs
Western Europe and Eastern Mediterranean[8]	2030	2000	PV energy output	–10	Rad and *T*
Greece[30]	2011–50	1950–2000 (*T*) and 1985–2005 (Rad)	PV output	–1 to ~2	Rad and *T*
Greece[30]	2061–2100	1950–2000 (*T*) and 1985–2005 (Rad)	PV output	2 to ~3	Rad and *T*
Germany[10]	2050	2006–2015	PV output per year	–0.14 to ~0.26	Rad and *T*
Spain[10]	2050	2006–2015	PV output per year	0.024 to ~0.09	Rad and *T*
Europe[9]	2070–99	1970–1999	PV power output	–14 to ~2	Rad, *T* and ws
Northwest metropolitan Germany[31]	2036–65	1971–2000	Solar capacity factor	0.2	Rad
Northwest metropolitan Germany[31]	2071–2100	1971–2000	Solar capacity factor	0.4	Rad
California[7]	2080	2010	PV energy output	–2.61 to ~0.831	Rad and *T*
Nevada[7]	2080	2010	PV energy output	–2.44 to ~ –3.95	Rad and *T*
California[10]	2050	2006–15	PV output per year	–0.086 to ~0.034	Rad and *T*
Texas[32]	2041–50	1995–2005	PV potential	–1 to ~1	Rad, *T* and ws

'Rad' refers to the surface solar radiation, *T* the air temperature, 'ws' the wind speed and 'grs' refers to the ground reflection by snow.

to temperature and radiation may be compensated to have no net effect.

Climate change impact on the service life of PV panels

The number of years that PV panels generate electricity, which is of economic benefit, is known as its service life. The failure probability of PV panels is generally modelled using the Weibull distribution[15]. This fares well in representing real-life PV reliability data[15,16]. Hence, based on a few studies which have shown the suitability of the Weibull distribution to the service life estimation of PV panels[15–17], we have estimated the failure probability of these panels[18].

The dependence of temperature on the service life of a PV panel is modelled through the Arrhenius expression[19]. The Arrhenius model generally represents the lifetime of a product/component (including PV panels[20]), which depends on temperature.

In the Weibull model, the scale parameter (here, $e^{(\gamma_0 + (\gamma_1/T))}$) represents the service life of the PV panels, and the shape parameter (here, β) represents the failure rate of the panels. The Arrhenius model relates lifetime with temperature and involves two constants. Combining the Weibull distribution and Arrhenius model, estimations on the probability of failure are made as follows

$$F(t,T) = 1 - e^{-\left(\frac{t}{e^{\left(\gamma_0 + \frac{\gamma_1}{T}\right)}}\right)^{\beta}}. \tag{1}$$

Here, to demonstrate the effect of temperature on the probability of failure, the PV panels are assumed to be at the nominal operating cell temperature (NOCT) of 47°C, and the Arrhenius parameters γ_0 and γ_1 in $e^{(\gamma_0 + (\gamma_1/T))}$ are derived for a PV service life of 30 years and F is the probability of failure. Using these constants as the equivalent Arrhenius model, the scale parameter is calculated for different temperatures. There can be multiple equivalent models (multiple

Table 2. Vulnerability of various factors associated with PV power generation to climate change and PV installations

Factors	Vulnerability due to climate change	Vulnerability due to PV installations	Possible interventions/considerations
Ambient temperature	Annual global mean temperature is expected to rise[33], causing PV efficiency (production) to fall.	Temperature rise in a specific zone around PV installations has been observed. However, more evidences are needed. Albedo modification due to large-scale installations influences and can lead to rise in ambient temperature.	• PV cell technological improvements in temperature coefficients. • Installation guidelines might provide enough ventilation to avoid heat storage in the PV panel arrays.
Temperature extremes	It is likely that heat waves are more intense, longer and frequent[33] causing higher chances of degradation and reduction in efficiency.		• Choice of PV panel technology while implementing in climate zones prone to high temperatures. • PV manufacturers to consider climate zone-specific modifications to PV panels.
Surface-reaching solar radiation	Changes in cloud cover and aerosols are likely to cause a change in surface-reaching solar radiation.	Albedo modification of land due to large-scale PV installations changes the earth–atmosphere radiative balance.	• PV manufacturers to consider modification for PV assembly to improve conversion efficiency, such that less heat is stored below PV.
Cloud cover	Likely reduction in cloud cover expected in most of the tropic and subtropic zones[33], which may result in increase in PV output.		
Rainfall, relative humidity, mean water vapour	Global averaged mean water vapour, evaporation and precipitation are projected to increase[33]. This is likely to increase the risk of degradation (especially due to corrosion).		• Cleaning schedules to be optimized to utilize natural cleaning by rainfall. It is recommended to implement rainwater harvesting around PV arrays for cleaning the panels.
Precipitation extremes and droughts, tropical cyclones	Intensity of precipitation events is projected to increase. Likely increase in the peak wind intensities of cyclones[33]. This may cause physical damage to PV installations.		• Climate zone-specific design consideration in the PV array frame, foundation and drainage system for rainwater is suggested.
PV panel physical/ electrical degradation	Indirectly affected by the environmental factors vulnerability of climate change.		• Choice of PV panel technology while implementing in climate zones prone to extreme weather events.
PV conversion efficiency	Rise in mean temperature is likely to cause low PV conversion efficiency.		• PV cell technological improvements in temperature coefficients. • Choice of PV panel technology while implementing in climate zones prone to high temperatures.
PV panel cleaning	Cleaning cycles may reduce as PV panels are likely to be cleaned naturally with an increase in precipitation frequency.		• Cleaning schedules to be optimized to utilize natural cleaning by rainfall. It is recommended to implement rainwater harvesting around PV arrays for the cleaning panels.
Building integrated photovoltaic (BiPV) installations	Higher temperatures cause a rise in the indoor ambient temperature and may increase the cooling load of the building. Also, PV efficiency would be low. This has a negative impact on the thermal comfort of the occupants.		• Provision of thermal insulation below the PV panel arrays to reduce thermal transmittance.
Rooftop/BAPV installations	Rise in PV installations as a climate change mitigation strategy.	Albedo modifications due to PV installation work contrary to 'cool roof', which is meant to avoid urban heat island effect.	• Policies regarding rooftop installations may be reassessed to account for the urban heating induced by albedo modifications due to PV installations. • PV manufacturers may consider modifications to PV assembly to improve conversion efficiency resulting in lower energy (heat) transmission through PV panels

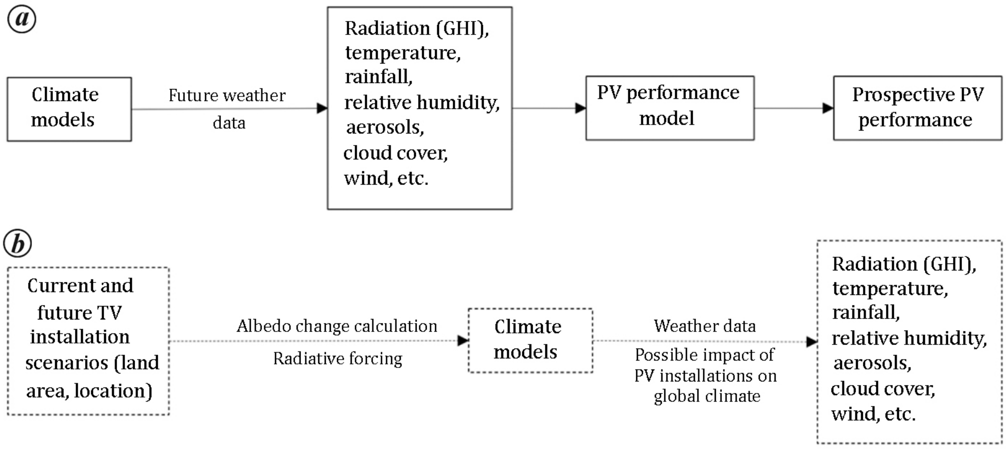

Figure 2. ***a***, General methodology used in recent studies to estimate the change in PV energy output due to climate change. ***b***, Proposed methodology to estimate the possible impact of PV installations (current and prospective scenario) on global climate.

Table 3. PV performance models used in recent studies

Parameters considered in PV performance	Reference
Radiation and temperature	7, 10, 29, 30, 34
Radiation, temperature and ground reflection (snow)	6
Radiation and tilt angle	31
Tilt angle/angle of incidence, radiation and temperature	8
Radiation, temperature and wind speed	9, 11, 32, 35

sets of γ_0 and γ_1) in this case, and we have presented the mean of probability calculated based on various models (Figure 3).

Generally, large PV systems are spread over a few square kilometres. Hence, climate change projections at the city level are more appropriate for understanding the vulnerability of these systems to climate change. A study in which the climate projections of 520 cities worldwide were discussed was chosen as an appropriate source for the temperature projection data[21]. Among all the cities, the maximum change in the warmest month's temperature was +8°C, and the maximum change in the coldest month's temperature was –2.5°C. These two temperatures have been considered to demonstrate the impact of temperature on the probability of failure of PV systems. The Weibull shape parameters considered here are based on the literature[2,15,17,20,22]. The change in probability of failure due to temperature is shown for two shape parameters, classified as early-loss scenario and regular-loss scenario[2]. The early-loss scenario (shape factor of 2.4928) considers transportation or installation damage failure and other serious damages leading to panel removal, while the regular-loss scenario (shape factor of 5.3759) does not consider any of these infant, midlife or wear-out failures[2].

Figure 3 shows a plot of the probability of failure of the panels with age. To demonstrate the possible changes in the probability of failure with temperature, 328 K was considered the maximum warmest month's temperature by 2050, and 317.5 K as the minimum coldest month's temperature by 2050. It can be seen from Figure 3 that a rise in temperature causes an increase in the probability of failure of the PV panels. This implies an early decommissioning of the panels and an increase in the number of EoL panels. If the PV panels are exposed to higher temperatures in the future climate, their service life can be expected to be less than the present, given that the other conditions are the same. Other weather variables like humidity, temperature variations and ultraviolet radiation also influence degradation. Climate change may also alter these variables, and incorporating its influence on service life can be the scope of further studies.

Impact of PV installations on climate

PV panels are designed to absorb much of the spectrum in solar radiation and reflect less. The panels are spread out on large areas on the ground facing the sun. This alters the ground albedo (reflectance) when the panels are installed in large numbers, thus changing the Earth's atmospheric energy balance[4]. A study theoretically calculated that the negative impact caused by the PV albedo effect is far outweighed by the positive effects caused by replacing PV installations with fossil fuels[4]. PV plant installations involve the cutting of trees and change in land use. The soil characteristics are also affected during the installation of PV plants. These effects have been elaborated and reviewed[23], revealing that the PV system fares better in environmental impact relative to the traditional power sources. The shading effect caused by a PV plant (installed on the roof) is expected to lower a building's cooling load. A numerical simulation estimated significant cooling load reduction for a case study in Tokyo, Japan[24]. According to this simulation, a

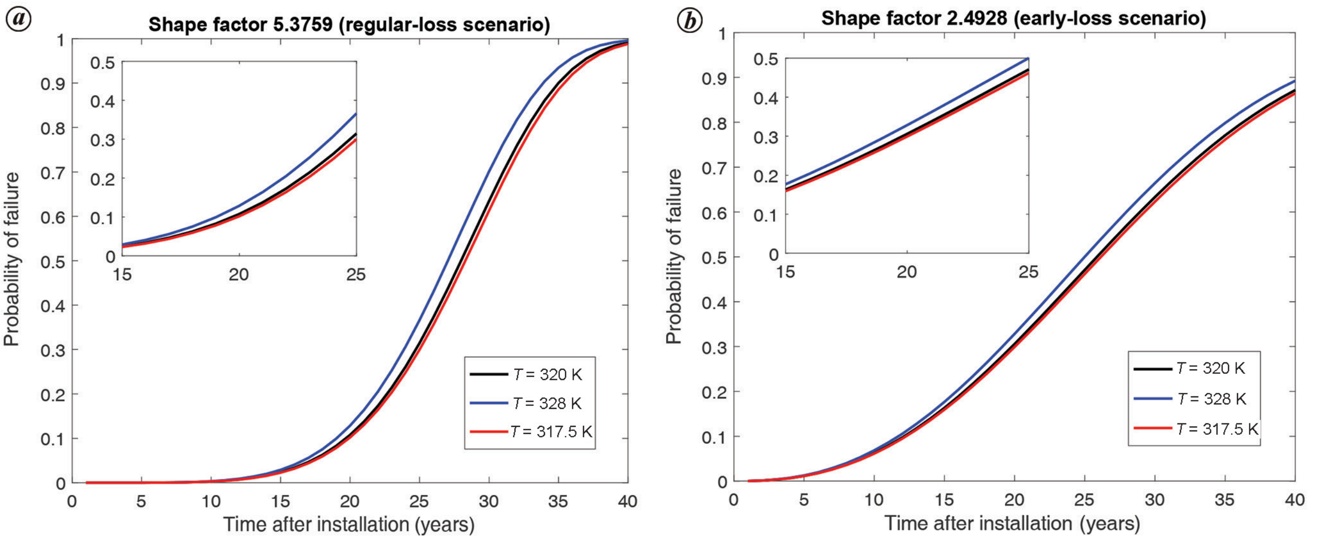

Figure 3. Probability of failure with time after PV installation. *T* = 320 K refers to nominal operating cell temperature (NOCT). *T* = 328 K would be the maximum warmest month's temperature and *T* = 317.5 K would be the minimum coldest month's temperature by 2050 of all 520 cities studied[21]. (***a***) Regular-loss and (***b***) early-loss scenarios[2].

Table 4. Description of studies related to the understanding of the impact of PV panels on global/local climate

Reference/ year	Category of work	Details of the study	Experiment/ observation duration	Results
24 (2003)	Theoretical and/or simulation work (AWS data used)	Development of PV heat transfer model to estimate the impact of PV on urban heat island (UHI). Numerical simulation for a clear summer day. PV panel efficiency is 8% and PV panel albedo is 0.2.	One day	Increase in the average sensible heat flux of 40–80 W/m^2. Hence, the influence of the PV panel on UHI is negligible.
4 (2009)	Theoretical and/or simulation work	Estimation of radiative forcing due to the PV–albedo effect.		
26 (2013)	Theoretical and/or simulation work (AWS data used)	Computational fluid dynamics analysis of 1 MW PV farm to estimate the potential of photovoltaic heat island (PVHI).	18 months	The centre of the PV farm is 1.9°C higher than ambient, and matches the ambient at 5–18 m height and 300 m away horizontally. The PV panels are cooled at night, and the heat island effect is unlikely to occur.
36 (2014)	Theoretical and/or simulation work	The TEB model is used to simulate the influence of PV panels on UHI in the Paris metropolitan area, France.	One year	Reduction in air temperature by 0.05 and 0.2 K during January and August respectively.
29 (2016)	Theoretical and/or simulation work	Global climate models used, with large-scale PV panels installed to simulate the effect on global climate		Reduction in surface temperature in most of the locations.
5 (2016)	Experiment with measurements/ observations	Ambient air temperature over the PV plant, a parking lot and a vacant land (control) compared to verify PVHI in arid climate	One year	Temperatures over a PV plant are generally 3°–4°C warmer than wildlands at night.
27 (2017)	Experiment with measurements/ observations	Net radiation and temperature (ambient air and soil) over the PV farm and a vacant land (control) compared to verify PVHI.	One year	During non-winter, the daytime air temperature in the PV farm is higher than that in a region without PV.

minor change in the sensible heat flux was observed. Meteorological models were used to evaluate the potential impact on air temperature for a region around Los Angeles, USA[25]. Simulations showed no significant change in the ambient air temperature due to the presence of PV panels. An increase in air temperature around PV panel installations

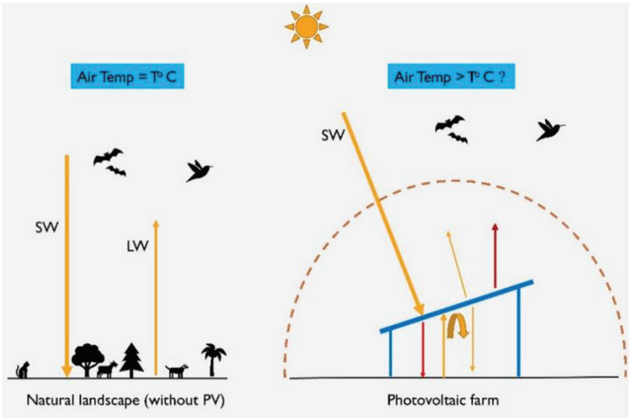

Figure 4. Radiation heat exchange with and without PV installation, and its influence on air temperature (drawing not to scale). SW, Shortwave radiation; LW, Longwave radiation.

was reported using computational fluid dynamics and *in situ* measurements[26]. These measurements were made on a large farm (spread non-uniformly around 4 km^2) in North America. It was found that annual average air temperatures at the centre of the farm and 2.5 m off the ground were higher than ambient air by 1.9°C. At 5–18 m height, this difference had declined. It was found to gradually decline at around 300 m away from the solar farm, and the air temperature was close to ambient temperature. The surface temperature of the PV modules was higher than ambient air temperature during the day, and on a sunny day, it could reach 20°C more than ambient air temperature. Such high differences between PV module temperature and ambient air temperature allow heat transfer towards ambient air and cause the ambient air temperature to increase in such farms. Hence, a zone of 300 m from the perimeter, with a height of 5–18 m, accommodates the effect of any temperature changes due to the PV panels.

To understand the PV panel-induced heat island effect, a year-long measurement of air temperature around a PV farm was made[5]. The authors defined the PV heat island effect as the difference in ambient air temperature between a PV plant and a desert landscape. A consistent increase in air temperature was observed above PV installations compared to the surrounding natural environment. The heat flux measurements provided further insights into the energy balance of the system. The shortwave and longwave radiation in the upward and downward directions and soil temperature at different depths were measured[27]. The net radiation, being the difference between incoming and outgoing radiation, was higher in the PV farm over the entire year, indicating radiation collection at the PV farm. The air temperature above the PV panels was higher than at other sites during summer, and there was no change during winter. Numerical simulations for two cities, Phoenix and Tucson, in the US, have been performed to understand the effect of cool roofs and PV roofs on the urban heat island effect. The PV roof was found to alleviate the urban heat island effect[28].

Table 4 summarises studies related to understanding the impact of PV panels on global/local climate. The factors influencing energy balance between the panels, ground (roof of a building), and atmosphere are weather parameters, ambient air properties, wind speed, humidity, age of the panels type, conversion efficiency and its optical and thermal properties, PV panel frame characteristics, ground (roof) properties, the geometry of installation, radiation (magnitude and spectra), surrounding anthropogenic activities and landscape. Many studies have reported a rise in temperature near the panels. There is considerable scope to understand the dimensions of the zone/boundary of influence of the PV panels (Figure 4). A much larger scope lies in a comprehensive understanding of the changes in ambient air due to PV installations in different climate zones and latitudes.

Climate models have been tested with and without solar PV systems. It shows that the local climate is influenced by solar PV panels more than the global climate. The effect includes changes in the surface temperature and rainfall. A study has examined the effects of PV installations on global climate using the community climate system model (CCSM4)[29]. In the simulations, solar panels have been installed in the northern Sahara Desert and the desert areas of Asia, North America and Australia. The simulations indicate changes in surface temperature and precipitation at a regional scale but a weak impact globally. To understand the impact of PV installations on global climate, we have proposed a generic methodology (Figure 2 *b*).

Conclusion

The literature on the impact of climate change on PV panels has been reviewed here. The studies reviewed have reported the potential of PV panels, energy output and other performance factors for the future climate. The changes in the degradation of PV panels due to climate change are not accounted for in the literature. The performance of these

Appendix 1. Details of PV performance models used to evaluate the impact of climate change on them

Reference	Parameters considered	Model details
	PV performance models	
7	Radiation and temperature	$\frac{\eta_{cell}}{\eta_{ref}} = 1 - \beta(T_{cell} - T_{ref}) + \gamma \log_{10} G_{tot}$, where η_{ref} is the reference efficiency, β and γ are the temperature and irradiance coefficients respectively. T_{cell} and T_{ref} are the cell and reference temperatures respectively. T_{cell} is a function of ambient temperature and T_{cell} is determined through an empirical equation. $P_{PV} = G_{tot}\ \eta_{cell}$, where P_{PV} is the power output of the PV panel.
34	Radiation and temperature	Efficiency is inversely proportional to ambient temperature.
6	Radiation, temperature and ground reflection (snow)	• The annual energy production of a PV panel is calculated using a one-diode PV model built in-house. • A modified version of the PV simulator part of the HYDROGen Energy ModelS (HYDROGEMS).
8	Tilt angle/angle of incidence, radiation and temperature	• The effect of shallow-angle reflectance dealt with in this model and other losses remain constant. • The dust and snow cover effect is not considered. • The key assumption is that the percentage of diffuse irradiation, R remains constant under different climatic conditions
30	Radiation and temperature	$\frac{\Delta P_{PV}}{\eta_{ref}} = -\Delta T G_{tot}\beta c_2 + \Delta G_{tot}(1 - \beta c_2 + \beta T_{ref} - 2\beta c_3 - T\beta c_2) - \Delta G_{tot}^2\beta c_3 + \Delta G_{tot}\Delta T\beta c_2 + \Delta G_{tot}\gamma\log_{10}(G_{tot} + \Delta G_{tot}) + G_{tot}\gamma\log_{10}\left(\frac{G_{tot} + \Delta G_{tot}}{G_{tot}}\right)$. $\frac{P_{PV}}{\eta_{ref}} = G_{tot}(1 - \beta(c_1 + c_2 T + c_3 G_{tot} - T_{ref}) + \gamma\log_{10} G_{tot})$, where ΔP_{PV} is the change in photovoltaic power output, η_{ref} the reference photovoltaic efficiency, ΔT and ΔG are the change in temperature and irradiance between the baseline and scenario period respectively, T the daytime temperature for the baseline period, T_{ref} the reference temperature, β and γ the temperature and irradiance coefficient set by the cell material and structure respectively and c_1, c_2, c_3 are the coefficients which depend on details of the module and mounting that affect heat transfer from the cell.
10	Radiation and temperature	$\frac{\eta_{cell}}{\eta_{ref}} = 1 - \beta(T_{cell} - T_{ref}) + \gamma\log_{10} G_{tot}$,
9	Radiation, temperature and wind speed	$PV_{pot(t)} = P_R(t)\frac{RSDS(t)}{RSDS_{STC}}$ $RSDC_{STC} = 1000\ Wm^{-2}$, where P_R is the performance ratio. $P_R(t) = 1 + \gamma(T_{cell}(t) - T_{STC})$, where T_{cell} is the PV cell temperature, $T_{STC} = 25°C$ and $\gamma = -0.005°C^{-1}$. $T_{cell}(t) = c_1 + c_2 TAS(t) + c_3 RSDS(t) + c_4 VWS(t)$, where TAS is the air temperature, RSDS the radiation and VWS is the wind speed.
11	Radiation and temperature	$\frac{\eta_{cell}}{\eta_{ref}} = 1 - \beta(T_{cell} - T_{ref}) + \gamma\log_{10} G_{tot}$, $\Delta P_{PV} = G_{tot}\eta_{cell}$, where P_{PV} is the power output of PV panel. $\frac{\Delta P_{PV}}{\eta_{ref}} = -\Delta T G_{tot}\beta c_2 + \Delta G_{tot}(1 - \beta c_2 + \beta T_{ref} - 2\beta c_3 - T\beta c_2) - \Delta G_{tot}^2\beta c_3 + \Delta G_{tot}\Delta T\beta c_2 + \Delta G_{tot}\gamma\log_{10}(G_{tot} + \Delta G_{tot}) + G_{tot}\gamma\log_{10}\left(\frac{G_{tot} + \Delta G_{tot}}{G_{tot}}\right)$. $\frac{P_{PV}}{\eta_{ref}} = G_{tot}(1 - \beta(c_1 + c_2 T + c_3 G_{tot} - T_{ref}) + \gamma\log_{10} G_{tot})$,
37	Radiation, temperature and wind speed	System advisor model (SAM)
38	Radiation, temperature	$PV_{pot} = G(c_1 + c_2 u_{wind} + c_3 G + c_4 T_a)$, $c_1 = \frac{(1+\gamma(d - T_{STC})}{G_{STC}};\ c_2 = \frac{\gamma c}{G_{STC}};\ c_3 = \frac{\gamma b}{G_{STC}};\ c_4 = \frac{\gamma a}{G_{STC}}$. $\Delta PV_{Pot} = \Delta G(c_1 + c_2 u_{wind} + c_3\Delta G + 2c_3 G + c_4 T_a) + c_2 G\Delta u_{wind} + c_4 G\Delta T_a + c_2\Delta G\Delta u_{wind} + c_4\Delta G\Delta T_a$, where PV_{Pot} is the PV potential, G the radiation, u_{wind} the wind speed, T_a the air temperature, γ the maximum power thermal coefficient, a, b, c, d are constants and T_{STC} and G_{STC} are the temperature and radiation at standard testing conditions respectively.

Appendix 2. Climate models and emission scenarios used in the recent studies

Reference	Climate models	Emission scenarios	Forecasting horizon	Base time-period
7	HadGEM1, HadCM3	IPCC A1B	2010–80	1980–1999
34	ECHAM5-MPIOM, dynamically downscaled by the regional climate model RegCM	IPCC A2	2011–40 and 2041–70	1961–1990
6	HIRHAM (Norwegian Meteorological Institute)	IPCC A2, B2	2071–2100	1961–90
8	ECHAM5-HAM aerosol-climate model	IPCC B2	2030	2000
30	ENSEMBLES data, RCMs-C4IRCA3, ETHZ-CLM, MPI-M_REMO, SMHIRCA, CNRM-RM5.1 and their driving GCMs (HadCM3Q16, HadCM3Q0, ECHAM5-r3, BCM, APREGE RM5.1)	IPCC A1B	2011–50 and 2061–2100	Control period: 1950–2000 for temperature and 1985–2005 for irradiance
39	UKCP09 (probabilistic climate change projections)	Low, medium and high	2040–69 and 2070–99	1961–1990
10	CMIP5 data	RCP 8.5	Mid 21st century	2006–15
9	EURO-CORDEX (RCMs – HIRHAM 5, CCLM 4.8.17, WRF 3.3.1, RACMO 2.2, REMO 2009, RCA 4)	RCP 4.5, RCP 8.5	2070–99	1970–99
11	GFDL–ESM2M, NorESM1–M, MPI- ESM–LR, MIROC5, IPSL–CM5A–MR, EC–EARTH, CNRM–CM5, CanESM2	RCP 8.5	2006–45	2006–15
31	REMO, CLM	IPCC A1B	2036–65 and 2071–2100	1971–2000
32	ACCESS, CCSM4, GFDL, IPSL and MPI with regional climate model RegCM4	RCP 8.5	2040–50	1995–2005
12	CMIP5 data	RCP 4.5, RCP 8.5	2045–54 and 2090–99	1995–2004

panels is considered a vital function of radiation and temperature in most of the studies. A more realistic estimation can be obtained by considering more factors affecting the performance of the PV panels and their interaction. In this article, we have used the Weibull distribution and Arrhenius model to show that with an increase in temperature, the probability of failure (which is a direct indicator of the service life of PV panels) also increases. The state-of-the-art developments regarding the impact of a PV installation on global/local climate are reviewed. There are more studies on local climate impact than on global climate. Multiple studies have observed that the PV installations do not significantly alter the magnitude of ambient air parameters. A much larger scope lies in a comprehensive understanding of the changes in ambient air due to PV installations in different climate zones and latitudes. It is reflected in many studies that any direct impact of a PV installation is limited to local climate/urban heating but not on a global scale. The simulations indicate a regional impact but a weak impact on a global scale. The impact on global climate due to the albedo modification of the land by virtue of PV arrays is inconclusive, and we see a potential scope to understand this impact in detail. Thus, a more accurate estimation of the cross-impact between climate change and a PV system is needed, and technological advancements to alleviate the negative impacts are suggested here.

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