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Photovoltaics in the built environment: A critical review

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ABSTRACT

In this manuscript we review research on the feedback mechanisms between photovoltaic energy production and the urban environment, with an emphasis on synthesizing what is known, while drawing attention to limitations, and indeed errors in, the literature on this topic.

We include in our analysis studies on photovoltaic (PV) systems in urban settings – on buildings, as shade structures, or as stand-alone arrays within an urban environment. We further limit the review to studies that investigate how the urban setting affects the performance of PV systems or how PV systems affect their surrounding urban environment. Our review is based on a systematic search of the literature, which revealed 116 unique articles that addressed the underlying questions in a meaningful way. While there are conflicting results reported across this body of literature, our review and synthesis reveal two key findings: (1) PV can significantly warm the city during the day, provide some cooling at night, and potentially increase energy use for air conditioning of buildings in some climates and building types; and (2) placing PV in an urban setting can adversely affect PV efficiency, reducing overall power production up to 20% in comparison to PV applications in rural settings. It is recommended that future developments of PV technologies focus both on increased efficiency and the need to increase reflection of wavelengths of energy not converted to electricity by the PV cells. Furthermore, designs for urban PV systems should explicitly consider the effects of elevated urban temperatures, pollution, and shading on system performance.

1. Background

Photovoltaic electricity generation has grown at an exponentially increasing rate in recent years, rising from 12 terawatt-hours (TWh) in 2008 to 554 TWh in 2018 [1], representing an average increase of 47% per year. Currently, over 3.0% (2019) of global electricity demand is met with this distributed energy generation source that produces no carbon dioxide emissions during its operation [2,3]. Because of its ability to convert the plentiful energy resource of sunlight into electricity, without contributing to greenhouse gas emissions, and to generate and deliver that energy locally thereby enhancing energy security, the photovoltaics (PV) industry is likely to continue to grow.

Given this growth, it is probable that the portion of global electricity supply provided by photovoltaics will increase by an order of magnitude in the foreseeable future, with much of that growth occurring within the physical boundaries of cities. At these levels, the effects of PV deployment on urban environments, and the inverse effects of densely populated areas on PV efficiency, become increasingly urgent to understand and predict.

The photovoltaic effect was first reported by Becquerel in 1839 [4], and is closely related to the photoelectric effect described by Hertz [5], Planck [6], and Einstein [7]. Silicon p-n junction solar cells were first demonstrated in 1954 [8], and advanced versions of silicon solar cells represent 95% of the power of PV modules produced globally in 2019 [9]. From approximately 2016 to 2019, PV modules have been produced increasingly with single-crystal silicon wafers, as opposed to lower-cost multicrystalline Si. Advances in cell efficiency and manufacturing technology have led to a dramatic PV electricity cost reduction from 2.1 to 0.28 $/W from 2009 to 2019 for PV modules, the basic laminated and weather-resistant component that is assembled into a full PV system. Lower cost per watt translates to a lower levelized cost of energy (LCOE) of the full PV system, measured in $/kWh of solar electricity produced. LCOE reached a global average value of 0.068 $/kWh in 2019 for utility-scale PV [10], and continues to become even less expensive.

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Photovoltaic systems have many forms depending on the system size, the environment in which the PV system is located, and the people or organizations that the PV system is designed to serve. Utility-scale PV is typically the largest type of PV system, with generation capacity ranging from roughly 100 kW to 2 GW. These are typically ground-mounted systems, often in rows of fixed-tilt arrays, but increasingly in one-axis tracking systems that follow the sun from east to west, reducing cosine losses due to sun angle, increasing the energy yield (kWh of electricity produced in one year/kW rated capacity of system) and extending the power-producing hours farther into the late afternoon hours of high electricity demand. There is increasing interest in integrating these electricity-producing PV fields with the functionality of agriculture for grazing or raising crops, in what are known as agrivoltaic systems. When utility-scale PV systems are located near urban centers, increased solar absorption of PV fields compared to surrounding terrain can warm the ambient air, increasing ambient temperatures in the nearby cities, and in peri-urban and suburban areas [11].

In cities and surrounding inhabited areas, the interaction of PV systems with people's lives and experiences becomes an increasingly important part of PV design and implementation. Building-applied photovoltaics (BAPV), in which modules are affixed to rooftops or facades of existing buildings are an important and presently dominant form of PV systems for both commercially owned and residential systems. This type of system has the advantage of being able to be retrofitted onto present structures. However, since the PV system was not part of the initial design of the building, structural, economic, and aesthetic compromises may need to be made. As an example, Fig. 1 shows an aerial view of the Arizona State University campus, a semi-urban setting with BAPV systems on the roofs of multiple buildings, parking structures, and sports arenas.

In building-integrated photovoltaics (BIPV), the PV system is typically folded into the initial building architectural and aesthetic design (Figs. 2 and 3), and may perform multiple functions: in addition to providing electricity, BIPV systems may comprise part or all of roof or wall surfaces, protecting the inhabitants from the elements and replacing conventional building-skin materials; they may comprise windows, skylights, and semi-transparent facades; or they may provide partial or total shade to inhabited spaces below. Earlier studies suggest that many cities could potentially supply their own electricity needs with PV integrated into urban settings, if PV technologies demonstrated at the laboratory scale can be manufactured cost-effectively [12]. However, both BAPV and BIPV systems are highly absorptive of solar radiation and can heat up to temperatures well above those of surrounding structures. The modules then become radiative heat sources for inhabitants and structures beneath them, and convective heat sources which can significantly raise the temperature of the ambient air in cities, contributing to the urban heat island effect [13,14].

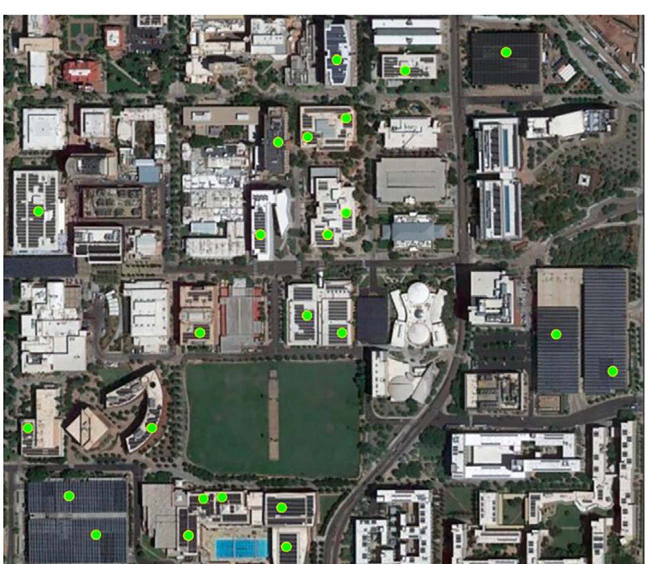

Fig. 1. Photovoltaic systems applied to existing rooftops and parking structures on the campus of Arizona State University, Tempe, Arizona, exemplifying building-applied photovoltaic (BAPV) systems. PV systems are denoted with a green dot. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The combined advantages of local solar electricity generation at costs that are frequently lower than alternative forms of added capacity, avoidance of climate-warming carbon emissions, energy resilience enabled by a distributed generation network, and fuel-free energy production without the sociopolitical ramifications of securing international fossil fuel deposits or the refining and disposal of nuclear materials, seem poised to create a rapid increase in PV deployment to provide global electricity needs. In urban spaces, an estimated influx of 2.5 billion people to cities by 2050 [15] will dramatically increase both the energy demands of cities and the number of new urban structures for living, work, and recreation into which PV can be functionally and aesthetically integrated.

The recent and anticipated future growth of urban PV is exciting from the perspective of the renewable energy generation, but also introduces pressing questions. Photovoltaic panels both alter, and are affected by their local environments, in terms of ambient temperature, wavelength-dependent radiant flux, shading of panels by nearby structures and shade provided by panels to inhabitants beneath.

In the urban context we pose the two related research questions that are at the foundation of this review.

1. When PV systems are implemented in urban areas, how do aspects of the urban environment affect PV performance?
2. What are the impacts of PV (beneficial and adverse) on the urban environment?

We address these questions through a systematic and critical review of published research addressing the topic of urban PV.

2. Bibliographic search process methods

There are seven classes of PV-urban climate interactions that we investigate in this review. These interactions fall into two broad categories. The first category involves the impact of the urban environment on performance and efficiency of PV systems. This includes the role of each of the following: (a) urban air temperature; (b) urban air pollution; (c) partial shading of PV; and (d) deposition of particulate matter and soiling in an urban setting.

The second category of studies focuses on the impact of urban PV on the local environment. This takes on three elements of PV impacts: (e) on urban air temperatures; (f) on building heating and cooling loads; and (g) on provision of outdoor shade.

We developed suitably broad individual searches for each of these seven topic areas. Each search used multiple variants for key terms. For example, to identify manuscripts focused on photovoltaics, we included search synonyms such as "PV", "solar power", and "solar panel". Most of the search criteria were applied to article titles, keywords, and abstracts. However, to limit the search results to the most relevant articles, some of the search criteria focused

Fig. 2. A rooftop building-integrated photovoltaic (BIPV) system on the Aula Pierluigi Nervi, Vatican. Although the modules are on metal supports that are separate from the building structure itself, the array of modules has been aesthetically integrated into the architectural form.

Fig. 3. Building-integrated PV providing solar electricity and shade for inhabited spaces at the Ludesch Community Center, Ludesch, Austria. Photo: Bruno Klomfar.

only on article titles. A full summary of the search strings is shown in Table S1.

The search criteria were implemented in two of the most-widely used abstract and citation databases, Scopus and Web of Science. Scopus, from Elsevier, has more than 69 million records covering more than 34,000 peer-reviewed journals across the life sciences, social sciences, health sciences, and physical sciences. The Web of Science from Clarivate, first launched in 1997 and contains more than 90 million records, indexing more than 21,000 journals, books, and conference proceedings. While these two citation databases have substantial overlap, each typically yields some unique records for any given search. By combining searches in both databases, we are able to ensure that this review covers the vast majority of relevant published literature, with a few important caveats. First, and foremost, this search is limited to English-language articles. There are, no doubt, relevant contributions in other languages. Additionally, this review ignores the soft literature (that which is not archived in citation databases). This includes information presented in websites, some conference proceedings, and industry/government reports. However, given the large number of manuscripts considered in this review, we are confident that key topics, approaches, and findings are adequately represented.

This review covers a broad topic, with many publications in each of the subtopic areas. As summarized in Table 1, our initial screening revealed a total of 256 unique articles, as of Aug. 30, 2020. We subjectively screened this list for relevance, removing from consideration 140 articles that were peripheral to the core concerns of each subtopic. This left a total of 116 articles for review. In some cases, high-quality, but very focused review articles exist within the subtopics. In those cases, we focus our analysis on summarizing key elements of those reviews, emphasizing

Table 1
Summary of search results across the seven subtopics.

Subtopic area	Search Results				Subtopic Review Articles
	Scopus	Web of Science	Unique Articles	Total Relevant Articles*	
air T impact on PV	36	14	37	[11,06]	3
air pollution impact on PV	9	4	9	[05,06]	0
Partial shading impact on PV	69	3	69	[30, 00]	2
soiling impact on PV	56	28	63	[30,03]	2
PV impact on air T	14	7	14	[08,01]	0
PV impact on buildings	52	10	54	[11,11]	1
PV impact on shade	25	16	26	[04,01]	1
Total Unique Articles**	**245**	**65**	**256**	**116**	**8**

* [a, b] – Here, a is the number of relevant articles found using the subtopic search terms, and b is the number of relevant articles in this topic area resulting from search terms in other subtopic searches.
** Total unique article after removing duplicates.

the most impactful manuscripts within that subtopic, and supplementing that content with our own analysis of papers published since the publication of the available review articles.

3. Synthesis results

3.1. How does the urban environment affect PV performance?

Electrical output from PV panels depends on solar irradiance reaching the PV surface and PV cell temperatures. However, while PV panels are rated under clear sky conditions and at standard test conditions (STC) of 25 °C, urban areas are known for their elevated air temperatures, air pollution, partial shading, and soiling. As illustrated in Fig. 4, each of these factors significantly impact PV efficiency and power output in urban settings [16,17,18,19]. The following sections highlight these relationships and summarize past studies that have sought to quantify the effects.

3.1.1. Air temperature

The temperature sensitivity of PV panels depends on the panel design and materials. Open-circuit voltage (V_{oc}) and fill factor (FF) decrease with increasing temperature, while short-circuit current density (J_{sc}) goes up, with open-circuit voltage generally having the largest change, resulting in a net decrease in solar module efficiency η as temperature increases. It can be shown that the open-circuit voltage decreases by approximately 2 mV per °C independent of the solar cell bandgap. So the relative change in V_{oc} will be smaller for PV materials with larger bandgap and larger V_{oc}. For the temperature excursions encountered in normal outdoor operation, these main solar cell parameters of Voc, FF, Jsc, and efficiency are generally assumed to vary linearly with ambient air temperature. Equation (1) shows this relationship between the working efficiency, η, and cell temperature, T_c [20]. The rated electrical efficiency, η_{T_ref}, of the module is calibrated at a reference temperature, T_{ref}, and solar radiation of 1000 W/m^2.

$$\eta = \eta_{T\_ref}\left[1 - \beta_{ref}\left(T_c - T_{ref}\right)\right] \quad (1)$$

The temperature coefficient of efficiency, β_{ref}, for silicon PV modules is usually around 0.2–0.5 relative %/°C [21,22]. Here, relative % change indicates the change in the ratio $(\eta - \eta_{T_{ref}})/\eta_{T\_ref}$. As a result of this temperature sensitivity, the maximum power output decreases and cost of energy production from PV increases with operating cell temperatures [23]. Fig. 5 shows the qualitative sensitivity of PV module maximum power output to cell temperature for different module technologies (Cadmium telluride (CdTe) with $\beta = 0.32\%$ /°C [24], Copper indium gallium selenide (CIGS) with $\beta = 0.33\%$ /°C [25], crystalline silicon – full cell (c-Si 1) with $\beta = 0.39\%$ /°C [26], crystalline silicon – half cell (c-Si 2) with $\beta = 0.35\%$ /°C [27], and crystalline silicon – back contact (c-Si 3) with $\beta = 0.29\%$ /°C [28], silicon heterojunction (SHJ) with $\beta = 0.23\%$ /°C [29]).

With solar reflectance less than 10% and efficiencies less than 20% [30], most current PV panels absorb as much as 70% of the incident solar energy. In contrast to many of the surfaces that PV

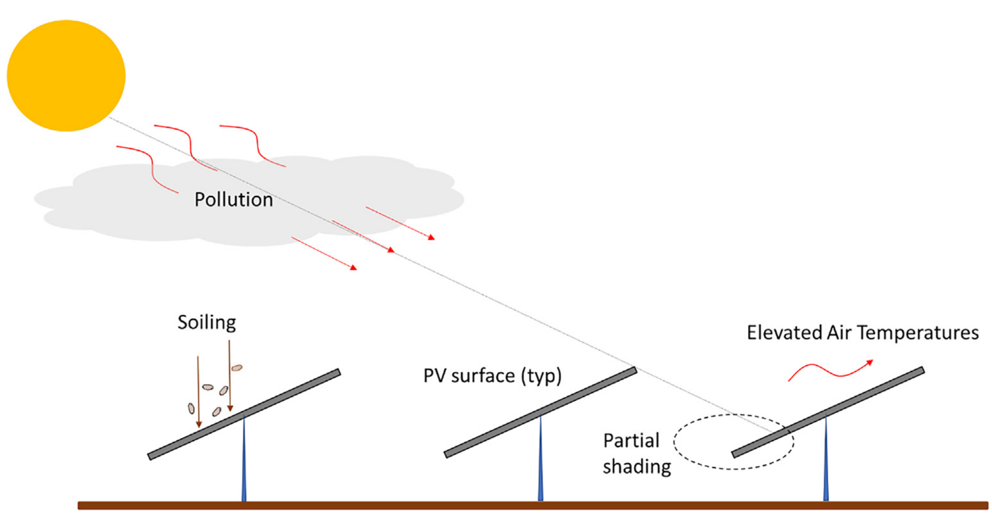

Fig. 4. Schematic representation of the aspects of the urban environment that influence PV performance. These include attenuation effects of air pollution, deposition of particulates (soiling), partial shading from trees, buildings, and other urban structures, and the role of air temperature in reducing panel efficiencies.

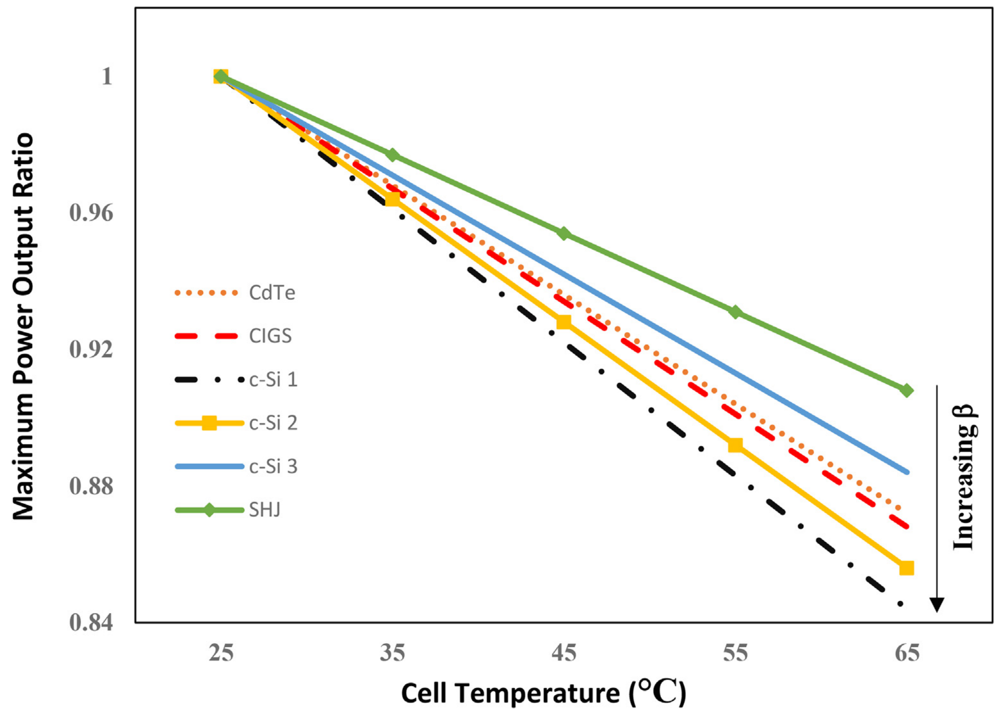

Fig. 5. Photovoltaic module maximum power output ratio (working maximum power relative to maximum power under standard operating conditions) as a function of temperature for several PV module technologies. The values are normalized to standard test conditions (STC) to show the temperature dependence of different PV technologies more clearly.

arrays shade, the PV panels themselves have very low thermal mass. So, while a paved or dirt surface may absorb a similar fraction of incident solar radiation, they are thermally massive surfaces that will store some of the absorbed energy, radiating and convecting it back into the urban environment over the diurnal cycle. However, because PV panels have low thermal mass, they heat up at a faster rate than other urban surfaces, radiating and convecting much of the absorbed solar energy into the urban environment with virtually no time delay. Convective heat exchange between panels and the surrounding air is proportional to the temperature difference between the panel surface and the air, and can thus increase or decrease power output depending upon the local convection coefficients and sign and magnitude of this temperature difference [31–33]. An experimental study conducted in Thailand found that monthly power output from PV peaks during the months with an average ambient temperature lower than 35 °C [34]. The pattern of improved performance during colder months (winter), has been observed in other cities as well [35]. This effect is particularly evident for regions near the equator where winter months receive a significant amount of solar irradiance, but are still characterized by cooler ambient conditions [21]. In hot locations such as Arizona in the summer, the cell temperature of PV panels can be as high as 90 °C, resulting in reduced power generation by as much as 30% [36]. An experimental study from Libya measured PV cell temperatures as high as 125 °C [37]. It should be noted, however, that peak cell temperatures depend on multiple environmental factors beyond air temperature (*i.e.,* cloud cover, soiling and air pollution). In Australia, elevated air temperature has been identified as the most significant factor affecting PV performance in urban settings [38].

As urban areas are often warmer than the unbuilt surroundings—a phenomenon referred to as the urban heat island (UHI) effect [39–42] — it is to be expected that locating PV in urban environments may have an additional detrimental effect on PV efficiency and total power output. The magnitude of the UHI is typically largest in the overnight hours, but can still be as large as 4 °C or more during the day [43], contributing to elevated PV panel surface temperatures. Due to lack of space in urban regions, PV panels are usually installed on building roofs, walkways, or parking lots. One drawback of this practice is that urban airsheds are warmer than their rural surroundings, leading to poorer performance for PV in built areas than those installed in nearby rural settings [44]. Moreover, the hotter ambient air temperature can further reduce the power generation by affecting electrical resistance in cables and power management infrastructure.

Multiple approaches have been used to try to reduce PV cell temperatures. One such approach is to circulate a coolant on the underside surface of the PV panel to remove excess heat. Such approaches can be designed to operate only when the net benefit of increased PV power output more than offsets the energy cost to operate the cooling system [45]. However, the cooling system adds significant capital cost to the system, as well as increased module construction costs, maintenance costs, and reliability concerns. Another approach to cooling PV panels is through use of phase change materials [46,47]. Phase change materials (PCM) work by using excess thermal energy to melt an encapsulated material, without increasing its temperature. This process can be reversed in the cooler nighttime hours, so that the modulating effects on surface temperature can be repeated day after day. A recent study shows that the use of PCM can reduce the peak cell operating temperature by nearly 7 °C [48]. However, the drawback of this strategy is that PCMs are costly with the payback period for this application of current technologies as high as 10–20 years [49]. The coupling of rooftop PV systems with a vegetated green roof is another strategy to improve performance by reducing operating temperatures. In integrated PV/green roof systems the vegetation reduces the surrounding air temperature and reduces the thermal radiation radiated from the roof surface to the panels. However, the potential savings from this strategy is estimated to be relatively low [50]. The backside of PV panels can potentially be used as a heat source for low-temperature thermal processes, such as heat pumps, desalination, or dehydration [51,52]. However, the value of using PV modules as a heat source must be balanced against lower PV electrical output at the higher temperatures used for process heat. Currently, methods to reduce PV cell operating temperature are among the most promising approaches for improving PV performance in urban applications [53]. A recent study shows that use of module materials with greater thermal conductivity (Tedlar/polyester/Tedlar) can reduce daily average module operating temperature as much as 3 °C, which results in a 1.5% relative efficiency increase [54]. Encouraging developments using silicon heterojunction technology may also enable PV cells to achieve efficiencies above 20%, while also maintaining a relatively low-temperature coefficient (~0.2%/°C), enabling them to perform better in high temperature environments, see Fig. 5, [55].

Even though most currently installed and available PV technologies have a rated electrical efficiency from 15% to 20%, the working efficiency may be considerably lower than rated values, particularly during summer in hot climate regions. Previous studies reported that these reductions in PV power output could be as high as 30%. In addition to these losses, increase in air temperature due to the UHI effect can potentially further reduce PV efficiency. Additional studies are required to evaluate these impacts, as the link between air and surface temperatures is complex, and the UHI effect varies seasonally and diurnally. Nevertheless, PV performance in urban settings is likely impacted by elevated temperatures associated with the urban heat island effect, as well as other urban factors as discussed below.

3.1.2. Air pollution

The presence of atmospheric pollutants in the urban airshed contributes to a reduction in available solar energy at the urban surface. Similar to the UHI effect, the urban pollution island—higher air pollutant concentrations in the urban atmosphere than in nearby surroundings—is also a major challenge to PV power generation in urban settings [56]. Urban metabolism and the thermochemical perturbation that occurs when urban built features replace natural features, results in a higher rate of air pollutant generation, including fine and ultra-fine particles and gaseous emissions from combustion processes, building construction processes, and other urban activities. Some of these emissions act as precursors in the formation of photochemical smog. These processes affect PV performance through the deposition of pollutants on PV surfaces and as a result of increased scattering of solar radiation. Particle deposition on PV panels results in absorption and backscattering of insolation, reducing the transmittance of the panel surface. The process by which airborne particles deposit and accumulate on PV panels is known as soft shading (more details are provided in the soiling section) [57].

A five-year-long study (2014–2018) was conducted in several Chinese cities to assess the impact of aerosol pollution on PV power generation at the city level [58]. This study found that cities with higher pollutant levels have an average annual PV power output reduction by 0.15–0.31 kWh $(m^2{\cdot}day)^{-1}$ relative to clean air conditions—a roughly 4.8–9.0% reduction in PV power generation. A similar study conducted in Shanghai, China, observed a power generation reduction of up to 5.5% due to atmospheric pollutants [59]. Similar, albeit lower power production penalties have been observed in less polluted cities. For example, PV installed in dusty urban areas of Athens, Greece were found to suffer a 0.4% reduction in absolute efficiency associated with air pollution in summer months [60]. Several studies have explored the roles of deposition of different natural pollutants, such as red soil, limestone, and carbonaceous fly-ash particles, common near urban construction and industrial sites [61–63]. The results from these studies show that the greatest reduction in power output is caused by the deposition of red soil particles, followed by limestone and then carbon-based ash. A case study in Santiago de Chile found that the aggregate effects of atmospheric pollutants reduced global horizontal irradiance by 3.5%, and direct normal irradiance by 14.1%. The study also found that a PV panel exposed to a hypothetical atmosphere free of aerosols would have 8.7% higher annual output than under actual polluted conditions [64]. The adverse effect of pollutants on PV performance depends on particle size distribution (mean diameter and standard deviation). Fine particles such as cement and carbon particles have a greater effect in reducing PV performance than coarser particles [65]. An indoor test study, based on artificial dust, by [66] found that, for a constant dust deposition density of 10 gm^{-2}, particle sizes of 0–38μm could reduce power output by 16%, while coarser particles (110–150μm) reduce power output by only 5.4%. Another observational study conducted in Warsaw, Poland found a 2.1% reduction in PV efficiency due to deposition of dust and other pollutants over the period of a single week [67]. So urban air pollution can be detrimental to PV performance, reducing power output by 5% to 15%. These effects are strongest in large, polluted urban centers with significant local industry, but may also occur at regional scales (in urban and rural settings) due to mid- to long-range transport of pollution downwind of cities [68].

3.1.3. Partial shading

The scarcity of open space in urban regions compels installation of PV on rooftops, building façades, walkways, and parking lots. As a result, photovoltaic panels are often placed in locations that receive partial shading at various times of the day or year [69,70]. This shading comes from neighboring buildings, trees, and urban-influenced cloud cover. Several studies have investigated the effect of partial shading on PV performance, showing lower power output from urban PV than the calculated/expected values [71–78]. These studies find that there is typically a power output reduction of 50% to 80% for shaded cells when compared with unshaded cells in the same module. A study conducted in Mexico City to compare the performance of PV installed in urban areas with rural installations found that, due to reduced solar irradiance in the urban environment, PV in rural areas generates 20% greater power output [17]. This is mainly due to the higher view factor (minimal partial shading) of PV in rural areas.

However, it should be noted that view factors are determined by PV orientation, obstacle heights, and obstacle proximity to PV panels. Thus, the proper orientation of PV cells, based on local conditions, plays an important role in addressing the challenge of partial shading in urban settings [79–81]. Therefore, in order to incorporate urban shadow effects for specific regions, several modeling studies used geographic information system (GIS) mapping for determining the actual shadow coverage on PV panels [82–85]. Three-dimensional regional modeling can be implemented in GIS-based analysis, thereby including effects of complex geometries of rooftops, vertical building surfaces, and other urban geographical features [86–89]. A GIS study based on Cambridge, MA, USA compared simulated results for annual electricity yield with two PV installations, observing errors ranging from 3.6% to 5.6% [90]. In addition to GIS-based efforts, several other studies also considered 3D profiles by including urban morphology parameters such as height and width of buildings, site coverage, orientation of both PV and buildings, and spacing between buildings [91,92]. Additionally, the adverse shading effects of obstacles in the urban environment can be partially offset if these obstacles are used to reflect solar energy onto the PV panels at certain times of day. Specifically, a recent study by [93] found that the use of aluminum reflectors can increase the total daily intensity of incident solar energy by over 5%.

Separate from power output, the voltage and current characteristics of PV arrays are non-linearly impacted by partial shading, resulting in a complex power-voltage curve with multiple local maxima [94–96]. Another drawback of partial shading is that the shaded PV cells act as a sink and drain the power from the highest irradiated modules, leading to hotspots. The remedy for this problem is use of bypass diodes, which lead to a non-ideal situation of multiple peaks in the power-voltage characteristic curves [97]. This multipeak phenomenon can lead to failure of conventional maximum power point tracking control systems. Recent studies address the interconnection topology for PV installations to minimize the impact of partial shading and hotspots during PV power generation [98–102].

Studies show that PV array connections and configurations (*e.g.*, series, parallel, series–parallel, total-cross-tied, bridged-linked, and honey-comb) respond differently to the effects of partial shading [78,103]. Among these configuration types, total-cross-tied systems show better performance than other configurations for all the partial shadow cases [104–106]. The worst performance under partial shading is from systems with series connections [107]. Total-cross-tied PV configurations can be further enhanced by optimal SuDoKu-style rearrangement for the array, without altering the electrical connections [108,109]. In this technique, the PV array is arranged based on the SuDoKu puzzle pattern to distribute the shading effect over the entire array, this will reduce the effect of shading of modules in any row thereby enhancing the generated PV power output. Other technologies such as DC-DC optimizers are also used to minimize the impact of partial shading on PV efficiencies [110]. So, while partial shading of PV in urban settings presents significant challenges and can reduce array power output by more than 20%, PV design and installation topology can help address the penalty of partial shading. However, ongoing urban development and construction projects can further impact power output after initial project design and installation. Partial shading in complex urban settings presents one of the most significant challenges affecting power production from PV in urban settings. The design and siting of urban installations must therefore take into account current and potential future obstacles to solar access.

3.1.4. Soiling

The loss of PV power output due to the accumulation of dirt, dust, sand, snow, and other contaminants on the PV surface is termed as soiling. In general, soiling can be divided into two categories: soft shading and hard shading. Soft shading occurs when fine particles settle on PV surfaces, reducing the transmissivity of the panel surface. Hard shading, on other hand, occurs when deposited particles completely block insolation from reaching PV cells over a portion of the PV module surface [57]. This section focuses on hard shading, as soft shading was discussed in the section on air pollution. Hard shading has more impact on PV performance than soft shading. Like partial shading, soiling (hard shading) of a small section of the PV array will lead not only to reduced power output, but also leads to a complex power-voltage curve for the array with multiple local maxima, making maximum-power-point tracking more difficult.

Unlike other effects on PV power production, soiling is more dependent on factors such as dust distribution and its intensity, than on specific urban–rural differences. The effect of soiling on PV performance is greater in dry regions than in humid regions. For example, arid regions in North Africa and the Middle East (Asia) have the worst soiling impact on PV performance in the world [111]. Another study comparing soiling impacts in seven cities (Taichung, Tokyo, Hami, Malibu, Sanlucar la Mayor, Doha, and Walkaway) found that Doha experienced the greatest impact from soiling, with a power loss of 80% over a 140 days of exposure without cleaning [112]. However, a separate study focused on Doha, found that weekly cleaning of the PV surface can improve power output by up to 6% [113]. Another study that looked at the effect of dust deposition on PV in Athens, Greece, found that PV performance drops by 6.5% within 8 weeks [114]. This is mainly due to the reduction in light transmittance. For dusty regions, several studies suggest installing PV modules vertically to avoid cleaning and maintenances issues [115,116]. However, this practice will clearly result in substantial power output reduction due to non-optimal orientation between the panel surfaces and the sun, making it inappropriate in many applications. Other studies have developed and evaluated models to estimate the impact of soiling on PV, with an emphasis on understanding the economic implications [38,117–121]. The mathematical models developed in these studies can forecast PV system power output with reasonable accuracy under a variety of soiling conditions.

As noted above, urban processes such as construction, and other commercial and industrial activities affect the soiling rate in the urban environment. For instance, Santiago, Chile, experiences roughly a 7% reduction in annual energy generation due to soiling, despite frequent rainfall events [122]. Even in desert-free regions such as Poland, researchers found a 13.4% reduction in PV energy efficiency on a sunny day due to dust deposition on PV panels [123]. One of the main reasons for this reduction of PV efficiency is due to the presence of particulate matter (PM2.5) in the urban airshed. Industrial processes such as combustion of solid and liquid fuels are the primary source of PM2.5 generation in urban regions. A study from Shanghai, China, found that the amount of solar radiation available for a PV array falls off exponentially with PM2.5 concentration in the atmosphere [59]. Apart from industrial processes, increase in construction activity can also cause soiling. For example, in Grand Canary Island, Spain, researchers monitored the soiling impact on PV associated with the construction of a nearby building. They observed a 20% reduction in efficiency within 5 months [124,125]. This construction-related soiling effect likely depends on the characteristics of the construction project (*e.g.*, concrete vs. wood construction).

In arid cities, lack of soil moisture and fine grain size of soils contributes to atmospheric transport of small particles, subsequent deposition on panels, and reduction in panel power output. For example, in Sharjah, UAE, researchers found that soiling of panels can result in a power loss up to 40% over a period of only a few months [126]. Conversely, in humid cities, atmospheric and soil moisture may diminish the role of PV module soiling relative to other urban effects. In Perak, Malaysia, a study observed a soiling-related performance decrease of 4.5% over a month [127]. Thus, for more humid locations, the adverse effects of soiling may not be as significant as other urban effects. Nevertheless, to overcome the soiling effect on PV, it is wise to maintain appropriate cleaning intervals, especially in an urban environment where natural cleaning (rain) might not be sufficient [128–132].

3.2. How does PV affect the urban environment?

In addition to the influence of urban conditions on PV power output, the presence of PV power systems in cities can in turn affect the urban environment as a direct result of their influence on the urban energy balance (see Fig. 6). PV in urban settings results in three distinct effects on urban systems—perturbations to urban air temperatures; impacts on building energy demand for heating and cooling; and alteration of thermal comfort for individuals in spaces shaded by PV. These effects are driven by a combination of PV panel radiative properties, PV conversion efficiency, and mounting style which affect convection of heat from the panel to the air and radiative exchange of thermal energy between panels and the surrounding environment.

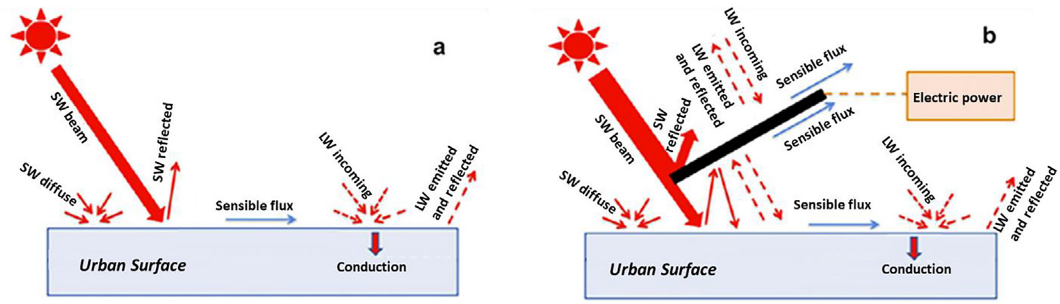

Fig. 6. The energy balance of (a) an arbitrary dry urban surface and (b) that surface shaded by a photovoltaic panel. In this example, the urban surface can be bare ground, pavement, or a building rooftop (after Scherba *et al.*, 2011).

3.2.1. Air temperature

Photovoltaic panels impact the urban energy balance and can therefore affect urban air temperatures. During the day, PV panels often absorb a higher fraction of solar energy than the surfaces they shade. This is particularly true for applications on commercial rooftops. As noted above, crystalline silicon solar cells represent 95% of existing PV modules, and these modules have a solar reflectance (albedo) that is typically less than 0.10 for the entire solar spectrum with conversion efficiencies less than 20% [30]. So, typical PV panels convert 70% of the incident solar energy into thermal gain. While some urban surfaces absorb a higher fraction of incident solar energy (*e.g.*, asphalt has a solar absorptance ranging from 80 to 90%, depending on age and weathering), many urban PV systems are installed above much higher reflectance surfaces such as light-colored roof membranes or shingles which may only absorb 15–35% of incident solar energy. So first, and foremost, evaluation of the impact of PV on urban air temperatures must consider the solar reflectance of the surfaces shaded by the PV panels.

The thermal characteristics and installation of PV panels are also key determinants of their impact on urban air temperatures. Specifically, urban PV panels are mounted above rooftops, on vertical walls, or shading large areas such as pedestrian walkways or parking lots. In the vast majority of cases, there is an air gap between the panel and the surface beneath it. This is highly desirable from a PV efficiency standpoint, as flush-mounted panels tend to operate at higher temperatures, diminishing their efficiency. At the same time, this results in convective heat transfer from both surfaces of the PV panel to the air. Furthermore, given the relatively low thermal mass of PV panels, they have less thermal inertia, heating up and cooling down more rapidly than other surfaces in the urban environment. This is especially true at night, when the high sky view factor, combined with the low thermal mass, enables PV panels to cool off rapidly to below ambient air temperatures.

One subset of research focused on the impact of PV on air temperatures uses the problematic concept of "effective albedo". In this approach, the albedo of the roof or ground surfaces is simply substituted with this effective albedo A_{eff}, equated to the sum of the PV panel solar reflectance ρ and PV panel solar energy conversion efficiency η, as in Eq. (2).

$$A_{eff} = \rho + \eta \tag{2}$$

While this seems reasonable on the surface and has some utility, it is crucial to recognize that the PV panel energy balance is more complicated. Specifically, the vast majority of urban PV modules are either elevated above roof surfaces (by 0.2–1 m) or further elevated (3–10 m) above other surfaces such as parking lots or pedestrian pavilions [133,134]. As a result, heat is convected away from the PV panel on both the top and bottom surfaces. Local wind speeds and hence convection coefficients may be slightly higher on the top surface. Nevertheless, as noted by [14], ignoring convective flux from the bottom surface results in an error in estimated convective heat flux to the environment by roughly a factor of 2. Hence, approaches which ignore this effect can lead to erroneous calculated results, and conclusions from such studies must be viewed skeptically.

Such studies which treat PV panels simply as a roofing or ground cover material with an effective albedo also employ two other assumptions that must be checked for validity. First, they make assumptions regarding the solar reflectance of the underlying surfaces that the PV panels cover, often assuming these surfaces to be dark. These studies also make assumptions about panel efficiency. While currently deployed, and widely available technology has conversion efficiencies ranging from 0.15 to 0.20, these studies often use unrealistically high conversion efficiencies. And, as noted above, actual operating efficiencies are oftentimes lower due to cell operating temperatures that can be significantly elevated above STC.

Studies using the "effective albedo" approach have helped to increase discussion of the interplay between PV modules and urban air temperature, but since this approach is a simplification, it can lead to erroneous predictions. Thus, these findings require detailed reevaluation, particularly regarding conclusions affecting research strategy and policy. In an early study using the "effective albedo" approach a mesoscale atmospheric model (an urbanized version of MM5 – [135]) was used to predict that widespread use of PV across the Los Angeles basin in California, USA would result in a 0.2 °C decrease in air temperatures during the summer daytime [136]. That study assumed panel efficiencies of 30% and also assumed that the panels were replacing roof surfaces that were otherwise dark in color (solar reflectance of ~0.15). However, buildings in hotter climates often utilize higher reflectance roof coatings, with solar reflectivity greater than 0.6. Even in moderate climates, buildings typically have rooftop solar reflectivity greater than 0.2 [137]. Thus, setting albedo for all building rooftops to 0.15 is unrealistic. A subsequent study by Ma et al. (2017) for Sydney, Australia, suggested that widespread use of urban photovoltaics could decrease peak summer daytime temperatures by 1 °C [138]. This study also used a mesoscale atmospheric model (WRF [139]) and implemented the same method of increasing rooftop albedo to represent PV panels, but neglected convective heat transfer occurring on the lower surfaces of the PV panels. As a result, it significantly underestimated daytime convective warming due to the PV panels. A microscale atmospheric modeling study in Ontario, Canada found that large-scale adoption of PV instead of cool (white) roofs would result in an outdoor warming penalty. Specifically, [140] found that rooftop PV could result in up to 0.5 °C urban warming. However, the study also used the effective albedo approach to represent PV panels and assumed the panels were flush against the roofs. Therefore, the magnitude of urban warming found in this study is likely an underestimate. Masson *et al.* (2014) introduced a sophisticated model for the PV energy balance to compute the air temperature effects of PV using the Town Energy Balance scheme [141,142]. In their model they assumed that the PV lower surface temperature is the same as the ambient air temperature. However, since PV panels have very low thermal storage capacity, the surface temperature difference between the lower and upper surface of PV modules is typically small or negligible, and PV panel surface temperatures routinely exceed 70 °C, especially for very hot locations such as Phoenix, AZ [36,48]. Thus, the assumption used in the Masson study is inappropriate, leading to significant errors in estimation of convective heat from PV panels to the surrounding air. Pham et al. (2019) report other inconsistencies with the model used in the Masson study, indicating that the calculations require reevaluation before any conclusions can be drawn [14]. Salamanca et al. (2016) used the same erroneous assumption for PV lower surface temperature for a mesoscale atmospheric numerical modeling using WRF v3.4.1, thereby also reporting misleading cooling benefits of PV installations [143]. Another study coupled a computational fluid dynamics (CFD) model with the WRF model and a 1-D heat conduction model to simulate the air temperature effects of PV [144]. This study found a cooling benefit of 0.1 °C during daytime and 0.4 °C at night. The study used the WRF results, along with Monin–Obukhov Similarity Theory [145], to determine the boundary conditions for the CFD model. The CFD model was then coupled with a one-dimensional heat conduction model to evaluate the surface temperature of the roof, walls, and solar PV modules. However, the system modeled assumed that all exterior surfaces of the building are covered with PV panels, and that building surfaces are separated from the PV panels by a completely enclosed 0.6-m air gap that does not mix with surrounding air, ignoring the significant convective heating of ambient air by the lower PV surfaces in most PV systems. The model also includes several inconsistent assumptions for boundary conditions and the governing equation for the 1-D heat conduction model. Hence, the conclusions from this study are also suspect.

Other studies with more detailed and accurate representations of the PV energy balance, suggest that urban photovoltaics actually result in daytime warming of the urban airshed. For example, Scherba *et al.* (2011) conducted a simulation study, informed and validated by field measurements to explore the effects of PV installed above three specific roof types. These were a dark roof with solar reflectance of 0.06, a white roof with solar reflectance of 0.7, and a vegetated green roof with substrate thickness of 0.15 m and a leaf area index of 1.0. They found that roof-mounted PV on a very dark roof resulted in less total warming of the urban airshed than the unshaded very dark roof alone (with solar reflectance of 0.06). However, they also found that, when PV panels were added above a lighter colored roof (with solar reflectance of 0.7), the net effect was a significant warming of the urban airshed [146]. Another experimental study, conducted in southern Arizona, found that a large scale array of PV modules resulted in an air temperature warming of 1.5 °C during the day, and 3–4 °C during the night [147]. The study suggests that trapping of longwave radiation between the shaded ground and PV panels warmed the ground surface, resulting in higher ambient air temperature. However, due to low thermal storage and high thermal emissivity, the PV panels should remain cooler than the ambient air during most of the night, as shown by Pham el., 2019 [14]. While warming of the ambient air in the daytime is expected, warming at night is somewhat surprising and worthy of further investigation. This could be an artifact of where and how the ambient air temperatures were measured, but insufficient data are presented to support this hypothesis. Another observational study, also conducted in southern Arizona, found daily average air temperature near PV arrays was 1.3 °C warmer than a nearby reference site without PV [11]. These values (air temperature penalties) are dependent on the efficiency of PV panels. Thus, the use of low-efficiency, low-cost, and readily-available PV panels, may reduce the overall solar reflectance, thereby increasing the risks of urban heating by PV, particularly during the day [148,149].

A recent experimental study compared the effects of unshaded parking lot surfaces with surfaces shaded either by PV panels or by shade surfaces coated with a highly reflective coating. Shade structures using PV panels above an asphalt surface (solar reflectance of 0.19) resulted in an 80% increase in total convective flux to the urban airshed. However, when the PV shade was replaced with a white shade surface, the net convective flux to the urban airshed was actually 50% lower than that from the unshaded ground surface [14]. While this study had several limitations, including that it used a small-scale test system, and that it indirectly estimated convective fluxes, it does highlight the urban warming downside of PV, suggesting that highly reflective artificial shade structures would be much preferable from an urban cooling perspective. A follow-on study with the same apparatus found that the addition of a PV array above a light-colored roof resulted in an increase in daytime summer convective flux to the surrounding air by a factor of 10—from a daytime average of 25 W/m^2 to 250 W/m^2 [13].

So, while there is some discrepancy in the literature, the prevailing experimental evidence and recent, detailed modeling, incorporating longwave exchange between PV and urban surfaces, convective heat transfer from both sides of PV panels, and other improvements, suggest that current implementations of PV in urban settings will have a warming effect on air temperatures during the day, with a likely cooling effect at night. While the local power production potential of urban PV is desirable, highly reflective roofs and shade structures provide more cooling benefit.

3.2.2. Building energy use

Separate from the impacts on the ambient environment, PV mounted on building walls and roofs affects the building energy balance, potentially influencing air conditioning and heating loads for the building. BAPV shades the building from direct solar radiation, but also blocks longwave radiative exchange with the sky, potentially reducing the rate at which the building façade surface is able to cool at night. These competing radiative effects can have a range of implications for the thermal comfort of unconditioned buildings and the energy consumption of conditioned buildings. Furthermore, the implications depend upon building type/occupancy, local climate, time of day, and time of year. For example, buildings in moderate climate regions during summer require cooling energy primarily during daytime hours, while those in hotter climates may require cooling into the evening and overnight hours. Thus, the presence of PV may reduce cooling demand during the daytime, but, in hotter climates, it may also increase cooling load at night [150,151]. In certain situations, PV's role in increasing cooling load during the night might be more significant than the cooling benefits in the daytime, especially for residential buildings [13]. In addition to these factors, insulation level also plays an important role in building cooling loads. For instance, if the building is well insulated, the presence of PV will have less of an impact on cooling demand, both in daytime and nighttime. The drawback of most studies that evaluate the role of BAPV in building energy use is that they tend to ignore these factors, generalizing results for all building types.

Furthermore, limitations in simulation software, particularly with respect to an inability to track the impact of PV on thermal (long-wavelength, or longwave) radiative exchange, leads to uncertain and misleading results. For instance, Dang et al (2020) conducted a whole building energy model simulation using EnergyPlus to investigate the potential benefits of PV panels to reduce the cooling energy for buildings in Ho Chi Minh City, Vietnam

[152]. Their results show a potential reduction in cooling energy demand resulting from installation of rooftop PV panels. EnergyPlus is a well-respected and widely used whole building simulation software which can handle most aspects of building physics [153]. However, despite being able to track the direct effect of PV panel shadows on the rooftop surface energy balance, EnergyPlus is not capable of computing the PV impact on longwave radiation exchange. In actuality, the PV panels reduce the ability of the roof surface to radiatively cool through longwave radiative exchange with the sky, particularly at night; they also radiate longwave energy to the roof surface, particularly during the day. These effects are not captured by EnergyPlus, as it does not track the full radiative energy balance between building surfaces and PV panels. As a result, simulations of rooftop PV with EnergyPlus may overestimate air conditioning energy savings. Another study used the same model to investigate the reduction in heat gain due to rooftop PV panels on apartments and villas in Saudi Arabia. The study found a 2% reduction in total cooling load [154]. However, considering that EnergyPlus ignores the nighttime radiative penalty, it is possible, or even likely in a city in a locale such as Saudi Arabia with significant cooling demand at night, that PV may introduce a net penalty in terms of air conditioning energy use. Several other studies followed the same erroneous method, without considering longwave radiative heat transfer interaction between the panel and rooftop surface, finding similar modest air conditioning benefits resulting from rooftop PV [155–160]. As a result, the conclusions from this large body of literature remain in doubt, particularly for hot climate cities.

For moderate climate regions, where the cooling load is dominated by solar radiation, the use of PV may still reduce the overall cooling load, if the daytime benefit prevails over the nighttime penalty. However, the only way to confirm this is by using an approach that suitably accounts for both the longwave and shortwave rooftop energy balance effects of PV. A numerical study conducted using measured roof surface and air temperature data in Western Greece observed a 17.8% reduction in cooling load during summer and a 6.7% increase in seasonal (winter) heating load associated with rooftop PV [161]. Results from an experimental study in China found that the presence of PV on rooftops reduced cooling loads by 27.2–37.4% during daytime hours, but only reduced total daily air conditioning energy use by 18.8–27.5% [162]. Other studies from moderate climate regions also showed a similar pattern [163,164]. However, for extremely hot places, rooftop PV panels may have a net penalty on building cooling loads. For example, in a combined measurement and modeling study in Phoenix Arizona, [13] found a net air conditioning penalty that was equivalent to roughly 10% of the electrical energy produced by the PV panels. A recent numerical study, based on Hefei, China, shows that the integration of radiative cooling into the PV panel glazing could reduce the nighttime penalty, however, this will lead to a slight penalty in electrical efficiency [165].

It should also be noted that air conditioning energy penalties or savings also depend on building type (*e.g.* residential vs. commercial) and characteristics (particularly roof insulation level). Also, while most studies of building PV have focused on rooftop applications, several studies have recently explored the use of PV panels as window blinds or semi-transparent solar cell windows for indoor thermal comfort and cooling benefits. However, these studies have not compared PV blind/window performance with that of conventional highly reflective blinds [166–169].

In summary, BAPV has the potential to reduce cooling energy demand in buildings in moderate climate cities, but may actually result in an increased air conditioning load in very hot climates. This uncertainty points to an important need in the modeling of BAPV—new models must be introduced that adequately track both shortwave and longwave radiative interactions between PV and building surfaces.

3.2.3. Provision of shade and thermal comfort

PV-panel-based shade structures are increasingly competing with alternatives such as tree shade and other artificial shade structures as a mechanism for improving outdoor thermal comfort in cities. Implementation of PV shade for pedestrian walkways and parking lots is growing particularly fast in hot desert environments such as Phoenix, AZ (Fig. 7). By shading pedestrians (and their parked cars) from direct solar radiation, PV panels reduce direct exposure to the sun, providing a more thermally comfortable environment during daytime. However, as noted previously, PV panels can become quite hot during the day, radiating high levels of thermal energy to the environments and individuals they shade. As a result, environments shaded by PV will likely be less comfortable than those shaded by cooler surfaces with a higher solar reflectance [140]. Thermal environments under PV shade structures may also remain warmer at night than unshaded environments due to trapping of thermal radiation, especially under clear sky conditions. As an example of this, a study conducted in Phoenix, AZ, showed that although unshaded pavement absorbs more energy during the day, its surface remains cooler at night than pavement shaded by PV. [14]. This result suggests that pedestrians shaded by PV panels feel warmer during the night, than they would in an unshaded environment. However, results from this study also show that, during the night, PV panels remain cooler than the ambient air due to their high thermal emissivity and low thermal storage. The net effect of PV on outdoor thermal comfort at night is therefore a balance between the beneficial convective cooling and the adverse effects of blocking longwave radiation heat transfer to the sky. Other studies have compared shading from PV structures to that provided by a tree canopy, finding that solar panels used for shading streets result in lower pavement surface temperatures [170–172]. This is generally attributed to the more fulsome shade coverage provided by opaque panels in comparison with the incomplete shade provided by moderately dense tree canopies. However, it should also be noted that these studies do not consider the adverse effects of the hot PV surfaces on convective warming of the surrounding airshed. Therefore, future studies are required to consider these factors and account for the net effect of PV on outdoor thermal comfort.

4. Discussion & conclusions

The findings from the analyzed literature show that urban influenced parameters such as air temperature, pollution, soiling, and shading play a non-trivial role in affecting PV power generation. While it is difficult to quantify the impact of elevated urban air temperatures (the urban heat island effect) on PV panel surface temperatures, and hence power production, the UHI likely results in a reduction in power production that varies seasonally and diurnally.

Air pollution can further reduce power production of PV installations by 5 to 15%. Studies show that the deposition of fine particles may reduce PV power output more than coarse particles. While this effect is most notable in highly polluted urban environs, it can also manifest itself in rural installations downwind of urban and industrial pollution sources.

Soiling, particularly in arid regions with drier soils and higher levels of airborne particulates, has been shown in several studies to have the potential to reduce power output of PV installations by more than 40%. Urban areas often have a higher fraction of impervious surfaces such as roads, parking lots, and buildings. Thus, they may be less apt to have high atmospheric loading of particulates from soils. Nevertheless, other sources of soiling in urban environments, including soot from vehicles and industry and dust from construction activities may significantly contribute to soiling

Fig. 7. Rows of PV shade structures provide shaded parking for hundreds of parking spaces on the Arizona State University west campus in Glendale, AZ. Photo: David Sailor.

of PV. However, research suggests that periodic cleaning of PV surfaces, either from precipitation or from routine maintenance can maintain the generation penalty of soiling at less than 10%.

Shading remains one of the most significant challenges to maintaining performance of PV systems in dense urban areas. Even partial shading from trees or other buildings can significantly impact power production. The average effects of this penalty can be on the order of 20%. However, careful design of urban installations, accounting for current, and potential future shading, can greatly reduce this issue.

While the urban environment can adversely impact power production from PV installations, the presence of PV systems can also impact several key aspects of the urban environment. Specifically, PV systems affect urban air temperatures, building energy consumption, and the provision of shade. Studies of the impact of urban PV systems on urban air temperatures show conflicting results. Our analysis suggests this is due to errors and inappropriate assumptions in some studies—most notably treating PV panels as one-sided thermally massive surfaces with an effective albedo. Multiple observational studies have shown that large-scale PV installations can warm the air during the day by several degrees C, while potentially cooling the air at night. This is largely due to the fact that PV panels have very little thermal mass, therefore converting much of the excess absorbed solar energy into convective warming of the surrounding air. We conclude that further controlled empirical studies and validated modeling efforts are needed, particularly because the conflicting studies differ not simply in magnitude of their projections, but in terms of the sign of the anticipated impact of PV on air temperatures. Ultimately, in evaluating the impact of PV on urban air temperatures, it is crucial to use realistic values for PV efficiency, PV installation characteristics, and the solar reflectance of urban surfaces the installed PV would shade.

The literature is also somewhat divided on the question of how roof-mounted PV affects the energy performance of the building. While it is reasonable to expect that the shading of the building from solar radiation would reduce air conditioning demand, the magnitude of this savings depends significantly on the assumption of the albedo of the roof surface being shaded, the level of building insulation, and other building construction and operation characteristics. Also, it is worth noting that roof-mounted PV will inhibit longwave cooling of the roof surface at night, providing a mechanism for increasing air conditioning loads, particularly in urban climates where air conditioning demand remains high at night. Ultimately, the impact of PV on building air conditioning demand in summer, and heating demand in winter depends on many factors and it is therefore difficult to generalize the impact.

As a general rule, any form of shading in hot urban environments is beneficial. This can be accomplished through tree cover, shade of buildings, or dedicated shade structures. When shade structures integrate PV, they serve the dual purpose of generating electricity while shading pedestrians and parked cars from solar gains. At the same time, research has shown that PV shade structure surfaces are much hotter than those of shade structures with high solar reflectance on their top surfaces. As a result, purely from the perspective of pedestrian thermal comfort, highly reflective shade structures are preferable as they will produce lower mean radiant temperatures for pedestrians.

As our synthesis suggests, photovoltaics in urban settings offer many benefits, but also are fraught with challenges—both in terms of how the urban environment affects their performance, and how they can adversely affect the urban environment and energy consumption for air conditioning. These complexities are often difficult to convey to the general public or to local/regional decision-makers who are typically seeking simplified summaries regarding the evaluation of technologies. The scientific community must be careful in conveying the adverse effects of any sustainability solutions, as they are sometimes taken out of context and can dramatically slow the penetration of technologies that, despite their limitations, remain an overall benefit to society; urban PV is no different.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2021.111479.

References

[1] IEA. International Energy Agency, Data and statistics.
[2] G.M. Wilson et al., The 2020 photovoltaic technologies roadmap, J. Phys. D Appl. Phys. 53 (49) (2020), https://doi.org/10.1088/1361-6463/ab9c6a 493001.

[3] D. Feldman, R. Margolis, Q4 2019/Q1 2020 Solar Industry Update, NREL/PR-6A20-77010, National Renewable Energy Lab. (NREL), Golden, CO (United States), 2020.
[4] A.E. Becquerel, Recherche sur les effets de la radiation chimique de la lumière solaire, au moyen des courants électriques, Comptes rendus hebdomadaires des séances de l'Académie des sciences 9 (1839) 145–149.
[5] H. Hertz, Ueber einen Einfluss des ultravioletten Lichtes auf die electrische Entladung, Annalen der Physik 267(8) 983-1000, 1887, Art no. 1887AnP...267..983H, 10.1002/andp.18872670827.
[6] M. Planck, Ueber das Gesetz der Energieverteilung im Normalspectrum (On the Law of Distribution of Energy in the Normal Spectrum), Annalen der Physik 4(3), 1901, Art no. 1901AnP...309. 553P, 10.1002/andp.19013090310.
[7] A. Einstein, Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt (On a Heuristic Viewpoint Concerning the Production and Transformation of Light), Annalen der Physik, 322(6), 132-148, 1905, Art no. 1905AnP...322..132E, 10.1002/andp.19053220607.
[8] D.M. Chapin, C.S. Fuller, G.L. Pearson, A new silicon p-n junction photocell for converting solar radiation into electrical power, J. Appl. Phys. 25 (5) (1954) 676–677, https://doi.org/10.1063/1.1721711.
[9] Photovoltaics-Report, Photovoltaics Report, Fraunhofer Institute for Solar Energy Systems, ISE, vol. https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf, 2020.
[10] M. Taylor. Renewable Power Generation Costs in 2019: Latest Trends and Drivers. International Renewable Energy Agency (IRENA). (Accessed Oct. 11, 2020.
[11] A.M. Broadbent, E.S. Krayenhoff, M. Georgescu, D.J. Sailor, The observed effects of utility-scale photovoltaics on near-surface air temperature and energy balance, *J. Appl. Meteorol. Climatol.* 58 (5) (2019) 989–1006, https://doi.org/10.1175/JAMC-D-18-0271.1.
[12] D.M. Kammen, D.A. Sunter, City-integrated renewable energy for urban sustainability, Science 352 (6288) (2016) 922–928, https://doi.org/10.1126/science.aad9302.
[13] K.E. Brown, A. Baniassadi, J.V. Pham, D.J. Sailor, P.E. Phelan, Effects of rooftop photovoltaics on building cooling demand and sensible heat flux into the environment for an installation on a white roof, ASME J. Eng. Sustain. Build. Cities 1 (2020) 2.
[14] J.V. Pham, A. Baniassadi, K.E. Brown, J. Heusinger, D.J. Sailor, Comparing photovoltaic and reflective shade surfaces in the urban environment: Effects on surface sensible heat flux and pedestrian thermal comfort, Urban Clim., 29, 2019, Art no. 100500, 10.1016/j.uclim.2019.100500.
[15] U. N. UN, Department of Economic and Social Affairs, Population Division (2019), World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420), vol. New York, United Nations, 2019.
[16] A.J. Hamad, Performance evaluation of polycrystalline photovoltaic module based on varying temperature for baghdad city climate, J. Adv. Res. Fluid Mech. Therm. Sci., 68(2), 2020, 164-176, 10.37934/ARFMTS.68.2.164176.
[17] W. Tian, Y. Wang, J. Ren, L. Zhu, Effect of urban climate on building integrated photovoltaics performance, Energy Convers. Manage. 48 (1) (2007) 1–8, https://doi.org/10.1016/j.enconman.2006.05.015.
[18] M.M. Fouad, L.A. Shihata, E.I. Morgan, An integrated review of factors influencing the perfomance of photovoltaic panels, Renew. Sustain. Energy Rev. 80 (2017) 1499–1511, https://doi.org/10.1016/j.rser.2017.05.141.
[19] D. Thevenard, Review and recommendations for improving the modelling of building integrated photovoltaic systems, in IBPSA 2005 - International Building Performance Simulation Association 2005, 2005, pp. 1221-1228. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84869746228&partnerID=40&md5=277c6201fbce11ffa8da9cc754a7871e. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84869746228&partnerID=40&md5=277c6201fbce11ffa8da9cc754a7871e.
[20] D.L. Evans, Simplified method for predicting photovoltaic array output, Sol. Energy 27 (6) (1981) 555–560, https://doi.org/10.1016/0038-092X(81)90051-7.
[21] S. Dubey, J. N. Sarvaiya, B. Seshadri, Temperature dependent photovoltaic (PV) efficiency and its effect on PV production in the world - A review C3 - Energy Procedia, (2013) 33, 311-321, 10.1016/j.egypro.2013.05.072. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84897547514&doi=10.1016%2fj.egypro.2013.05.072&partnerID=40&md5=d9c468543d4d5f32c8ab06285d4cae48.
[22] J.K. Kaldellis, M. Kapsali, K.A. Kavadias, Temperature and wind speed impact on the efficiency of PV installations. Experience obtained from outdoor measurements in Greece, Renewable Energy 66 (2014) 612–624, https://doi.org/10.1016/j.renene.2013.12.041.
[23] A.M. Ali, S.S. Mustafa, A.H. Mutlag, Design optimization of solar power system with respect to temperature and sun tracking C3 - Al-Sadiq International Conference on Multidisciplinary in IT and Communication Techniques Science and Applications, AIC-MITCSA 2016, (2016), pp. 317-321, 10.1109/AIC-MITCSA.2016.7759956. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85006984308&doi=10.1109%2fAIC-MITCSA.2016.7759956&partnerID=40&md5=6876a2e62f84b98c2c90b9810f41cda2.
[24] FirstSolar. Series-6 of First Solar. https://www.firstsolar.com/Modules/Series-6 (accessed March 16, 2021, 2021).
[25] SolarFrontier. SFK185-S of Solar Frontier. https://www.solar-frontier.com/eng/solutions/products/pdf/SAB12-0745_01_Product_Data_Sheet_SFK185-S.PDF (accessed March 16, 2021.
[26] TrinaSolar. Tallmax of Trina Solar. https://static.trinasolar.com/sites/default/files/Datasheet_Tallmax_1500V%20M%20Plus_2019_May.pdf (accessed March 16, 2021.
[27] JASolar. JAM66S30 of JA Solar. https://www.eeusolar.com/Solar-Panel/JAM66S30-480-505-MR-1000V.html (accessed March 16, 2021).
[28] SunPower. X-Series: X21-470-COM of SunPower. https://us.sunpower.com/sites/default/files/sunpower-x-series-commercial-solar-panels-x21-470-com-datasheet-524935-revb_1.pdf (accessed March 16th, 2021.
[29] T. Mishima, M. Taguchi, H. Sakata, E. Maruyama, Development status of high-efficiency HIT solar cells, Sol. Energy Mater. Sol. Cells 95 (1) (2011) 18–21, https://doi.org/10.1016/j.solmat.2010.04.030.
[30] J. P. Silva, G. Nofuentes, J. V. Muñoz, Spectral reflectance patterns of photovoltaic modules and their thermal effects, J. Solar Energy Eng., 132(4), 2010, 10.1115/1.4002246.
[31] F.H. Gandoman, S.H.E. Abdel Aleem, N. Omar, A. Ahmadi, F.Q. Alenezi, Short-term solar power forecasting considering cloud coverage and ambient temperature variation effects, Renewable Energy 123 (2018) 793–805, https://doi.org/10.1016/j.renene.2018.02.102.
[32] A. Tuomiranta, P. Marpu, S. Munawwar, H. Ghedira, Validation of thermal models for photovoltaic cells under hot desert climates C3 [Online]. Available: Energy Procedia 57 (2014) 136–143. https://www.scopus.com/inward/record.uri?eid=2-s2.0-84922276440&doi=10.1016%2fj.egypro.2014.10.017&partnerID=40&md5=e1d9af5a3a998f8b8d171beb73bb05b4, https://doi.org/10.1016/j.egypro.2014.10.017.
[33] Y.B. Assoa et al., Thermal analysis of a BIPV system by various modelling approaches, Sol. Energy 155 (2017) 1289–1299, https://doi.org/10.1016/j.solener.2017.07.066.
[34] K. Chumpolrat et al., Effect of ambient temperature on performance of grid-connected inverter installed in Thailand, Int. J. Photoenergy 2014 (2014), https://doi.org/10.1155/2014/502628.
[35] K.E. Amori, H.M. Taqi Al-Najjar, Analysis of thermal and electrical performance of a hybrid (PV/T) air based solar collector for Iraq, Appl. Energy 98 (2012) 384–395, https://doi.org/10.1016/j.apenergy.2012.03.061.
[36] J. Oh, G. TamizhMani, E. Palomino, Temperatures of building applied photovoltaic (BAPV) modules: Air gap effects C3 - Proceedings of SPIE - The International Society for Optical Engineering, 2010, vol. 7773, 10.1117/12.861069. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-77957826468&doi=10.1117%2f12.861069&partnerID=40&md5=ee8cef8017ae1f171516eb262a31eb8f.
[37] Y.F. Nassar, A.A. Salem, The reliability of the photovoltaic utilization in southern cities of Libya, Desalination, 209 (1-3) SPEC. ISS, 86-90, 2007, 10.1016/j.desal.2007.04.013.
[38] J. Principe, W. Takeuchi, Assessment of solar PV power potential over Asia Pacific region with remote sensing considering meteorological factors, J. Renewable Sustain. Energy, 11(1), 2019, 10.1063/1.5059335.
[39] T.R. Oke, The Energetic Basis of the Urban Heat Island, 108(455), 1-24, 1982.
[40] T.R. Oke, Boundary Layer Climates, Routledge, London, 1987.
[41] W.G.V. Balchin, N. Pye, A micro-climatological investigation of bath and the surrounding district, Q. J. R. Meteorolog. Soc. 73 (317–318) (1947) 297–323, https://doi.org/10.1002/qj.49707331706.
[42] L. Howard, The Climate of London, vol. I - III, ed. London, 1833.
[43] K.A. Hibbard, F.M. Hoffman, D. Huntzinger, T.O. West, Changes in land cover and terrestrial biogeochemistry, vol. I, ed: In Climate Science Special Report: Fourth National Climate Assessment, U.S. Global Change Research Program, Washington, DC, 2017, pp. 277–302.
[44] Y. Wang et al., Interactions between Building Integrated Photovoltaics and microclimate in urban environments C3 - International Solar Energy Conference, 2005, pp. 499-504, 10.1115/ISEC2005-76219. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-33748215078&doi=10.1115%2fISEC2005-76219&partnerID=40&md5=54757eec3b79c7fd79530185488d0c1c.
[45] M.K. Smith et al., Water cooling method to improve the performance of field-mounted, insulated, and concentrating photovoltaic modules, J. Solar Energy Eng., 136(3), 2014, 10.1115/1.4026466.
[46] K. Kant, A. Anand, A. Shukla, A. Sharma, Heat transfer study of building integrated photovoltaic (BIPV) with nano-enhanced phase change materials, J. Storage Mater. 30 (2020), https://doi.org/10.1016/j.est.2020.101563.
[47] M.A. Kibria, R. Saidur, F.A. Al-Sulaiman, M.M.A. Aziz, Development of a thermal model for a hybrid photovoltaic module and phase change materials storage integrated in buildings, Sol. Energy 124 (2016) 114–123, https://doi.org/10.1016/j.solener.2015.11.027.
[48] A. Hasan, H. Alnoman, Y. Rashid, Impact of integrated photovoltaic-phase change material system on building energy efficiency in hot climate, Energy Build. 130 (2016) 495–505, https://doi.org/10.1016/j.enbuild.2016.08.059.
[49] J.H.C. Hendricks, W.G.J.H.M. Van Sark, Annual performance enhancement of building integrated photovoltaic modules by applying phase change materials, Prog. Photovoltaics Res. Appl. 21 (4) (2013) 620–630, https://doi.org/10.1002/pip.1240.
[50] A. Nagengast, C. Hendrickson, H. Scott Matthews, Variations in photovoltaic performance due to climate and low-slope roof choice, Energy Build. 64 (2013) 493–502, https://doi.org/10.1016/j.enbuild.2013.05.009.
[51] H.D. Fu, G. Pei, J. Ji, H. Long, T. Zhang, T.T. Chow, Experimental study of a photovoltaic solar-assisted heat-pump/heat-pipe system, Appl. Therm. Eng. 40 (2012) 343–350, https://doi.org/10.1016/j.applthermaleng.2012.02.036.

[52] A. Kasaeian et al., Solar humidification-dehumidification desalination systems: A critical review, Energy Convers. Manage. 201 (2019), https://doi.org/10.1016/j.enconman.2019.112129 112129.
[53] A.A.A. Al-Khazzar, Behavior of four solar PV modules with temperature variation, Int. J. Renewable Energy Res., 6(3), 1091-1099, 2016. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84995632221&partnerID=40&md5=0c00c64eff081f9c7c3bea7b48cc47f7.
[54] J. Oh et al., Reduction of PV module temperature using thermally conductive backsheets, IEEE J. Photovoltaics 8 (5) (2018) 1160–1167, https://doi.org/10.1109/JPHOTOV.2018.2841511.
[55] A. Descoeudres et al., Silicon heterojunction solar cells: towards low-cost high-efficiency industrial devices and application to low-concentration PV, Energy Procedia 77 (2015) 508–514, https://doi.org/10.1016/j.egypro.2015.07.072.
[56] H. Li et al., Interaction between urban heat island and urban pollution island during summer in Berlin, Sci. Total Environ. 636 (2018) 818–828, https://doi.org/10.1016/j.scitotenv.2018.04.254.
[57] M.R. Maghami, H. Hizam, C. Gomes, M.A. Radzi, M.I. Rezadad, S. Hajighorbani, Power loss due to soiling on solar panel: A review, Renew. Sustain. Energy Rev. 59 (2016) 1307–1316, https://doi.org/10.1016/j.rser.2016.01.044.
[58] L. Zhang, X. Yi, M. Zhao, Z. Gu, Reduction in solar photovoltaic generation due to aerosol pollution in megacities in western China, Indoor Built Environ. (2020), https://doi.org/10.1177/1420326X20939310.
[59] H. Wang, X. Meng, J. Chen, Effect of air quality and dust deposition on power generation performance of photovoltaic module on building roof, Build. Serv. Eng. Res. Technol. 41 (1) (2020) 73–85, https://doi.org/10.1177/0143624419868806.
[60] J.K. Kaldellis, A. Kokala, M. Kapsali, Natural air pollution deposition impact on the efficiency of PV panels in urban environment, Fresenius Environ. Bull., 19 (12), 2864-2872, 2010. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-78650344240&partnerID=40&md5=b573c1cbc6e8cb93f55fddf913d58271.
[61] J.K. Kaldellis, P. Fragos, M. Kapsali, Systematic experimental study of the pollution deposition impact on the energy yield of photovoltaic installations, Renewable Energy 36 (10) (2011) 2717–2724, https://doi.org/10.1016/j.renene.2011.03.004.
[62] J.K. Kaldellis, M. Kapsali, Simulating the dust effect on the energy performance of photovoltaic generators based on experimental measurements, Energy 36 (8) (2011) 5154–5161, https://doi.org/10.1016/j.energy.2011.06.018.
[63] P. Krzysztof, H. Wiktor, N. Henryk, K. Wojciech, Energy performance of photovoltaic panels due to phenomena of urban air pollution disposal C3 - Proceedings of the 2016 17th International Carpathian Control Conference, ICCC 2016, 2016, pp. 407-412, 10.1109/CarpathianCC.2016.7501132. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84979581732&doi=10.1109%2fCarpathianCC.2016.7501132&partnerID=40&md5=fdaca29790edef7f0cd5a0d152c17ddf.
[64] M. Del Hoyo, R. Rondanelli, R. Escobar, Significant decrease of photovoltaic power production by aerosols. The case of Santiago de Chile, Renewable Energy 148 (2020) 1137–1149, https://doi.org/10.1016/j.renene.2019.10.005.
[65] M.S. El-Shobokshy, F.M. Hussein, Effect of dust with different physical properties on the performance of photovoltaic cells, Sol. Energy 51 (6) (1993) 505–511, https://doi.org/10.1016/0038-092X(93)90135-B.
[66] Y. Yang, D. Zhu, D. Li, M. Ge, N. Chen, Influence of dust accumulation and light intensity on output power of photovoltaic modules, Nongye Gongcheng Xuebao/Trans. Chin. Soc. Agric. Eng.ineering, 35(5), 203-211, 2019, 10.11975/j.issn.1002-6819.2019.05.025.
[67] M. Jaszczur et al., The field experiments and model of the natural dust deposition effects on photovoltaic module efficiency, Environ. Sci. Pollut. Res. 26 (9) (2019) 8402–8417, https://doi.org/10.1007/s11356-018-1970-x.
[68] X. S. Luo, C. C. M. Ip, W. Li, S. Tao, X. D. Li, Spatial–temporal variations, sources, and transport of airborne inhalable metals (PM 10) in urban and rural areas of northern China, Atmos. Chem. Phys. Discuss., 14(9), 2014.
[69] D. Masa-Bote, E. Caamaño-Martín, Methodology for estimating building integrated photovoltaics electricity production under shadowing conditions and case study, Renew. Sustain. Energy Rev. 31 (2014) 492–500, https://doi.org/10.1016/j.rser.2013.12.019.
[70] X. Song, E. Miller, D. Garmire, Experimental study of solar spectrum impact on solar cells C3 - Nanotechnology 2010: Bio Sensors, Instruments, Medical, Environment and Energy - Technical Proceedings of the 2010 NSTI Nanotechnology Conference and Expo, NSTI-Nanotech 2010, 2010, vol. 3, pp. 761-764. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-78049439961&partnerID=40&md5=4bd638b9d17f090787504b859087fc7e. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-78049439961&partnerID=40&md5=4bd638b9d17f090787504b859087fc7e.
[71] H. Patel, V. Agarwal, MATLAB-based modeling to study the effects of partial shading on PV array characteristics, IEEE Trans. Energy Convers. 23 (1) (2008) 302–310, https://doi.org/10.1109/TEC.2007.914308.
[72] N. Rakesh, T.V. Madhavaram, K. Ajith, G.R. Naik, P.N. Reddy, A new technique to enhance output power from solar PV array under different partial shaded conditions C3, in: Proceedings of the 2015 IEEE International Conference on Electron Devices and Solid-State Circuits, 2015, pp. 345–348, https://doi.org/10.1109/EDSSC.2015.7285121.
[73] A.S. Joshi, G.N. Tiwari, Evaluation of solar radiation and its application for photovoltaic/thermal air collector for Indian composite climate, Int. J. Energy Res. 31 (8) (2007) 811–828, https://doi.org/10.1002/er.1265.
[74] A. Fezzani, I. Hadj Mahammed, S. Bazi, A mathematical model to determine the shading effects in the I-V characteristic of a photovoltaic module, Lect. Notes Electr. Eng. 411(2017), 181-190.
[75] L. Alcantara, M. Campos, Analysis of seasonal aspects of nebulosity on the project of fixed photovoltaic installations at the City of Belém, Brazil, IEEE Lat. Am. Trans. 17 (4) (2019) 625–632, https://doi.org/10.1109/TLA.2019.8891887.
[76] A. Fezzani, I.H. Mahammed, S. Said, MATLAB-based modeling of shading effects in photovoltaic arrays C3 - STA 2014 - 15th International Conference on Sciences and Techniques of Automatic Control and Computer Engineering, 2014, pp. 781-787, 10.1109/STA.2014.7086686. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84949925401&doi=10.1109%2fSTA.2014.7086686&partnerID=40&md5=60a888d6f50efbe72b85bf773f6f2450.
[77] M. Amin, A.H. El Hakea, Component rating optimization methodology for the protection of photovoltaic solar power system components from shading effect C3 - Proceedings of the International Conference on Industrial Engineering and Operations Management, 2016, vol. 8-10 March 2016, p. 2451. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85018376122&partnerID=40&md5=4a4d8fb22f7ac4e7882d52e51f8cc39e. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85018376122&partnerID=40&md5=4a4d8fb22f7ac4e7882d52e51f8cc39e.
[78] M. Jazayeri, S. Uysal, K. Jazayeri, A comparative study on different photovoltaic array topologies under partial shading conditions C3 - Proceedings of the IEEE Power Engineering Society Transmission and Distribution Conference, 2014. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84908409093&partnerID=40&md5=bac18367ee944d233743206a215fd5fc. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84908409093&partnerID=40&md5=bac18367ee944d233743206a215fd5fc.
[79] N. Somboonwit, A. Boontore, Partial shading effects of surrounding obstacle parameters on building integrated photovoltaic (BIPV) system efficiency in Thailand C3 - PLEA 2018 - Smart and Healthy within the Two-Degree Limit: Proceedings of the 34th International Conference on Passive and Low Energy Architecture, 2018, vol. 2, pp. 613-619. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85086595924&partnerID=40&md5=40f843aff777c28d1b611e1d46a6e7f4. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85086595924&partnerID=40&md5=40f843aff777c28d1b611e1d46a6e7f4.
[80] M. Dorman, E. Erell, A. Vulkan, I. Kloog, Shadow: R package for geometric shadow calculations in an urban environment, R J., 11(1), 2019, 10.32614/rj-2019-024.
[81] H.T. Nguyen, J.M. Pearce, Estimating potential photovoltaic yield with r.sun and the open source Geographical Resources Analysis Support System, Sol. Energy 84 (5) (2010) 831–843, https://doi.org/10.1016/j.solener.2010.02.009.
[82] S. Freitas, C. Catita, P. Redweik, M.C. Brito, Modelling solar potential in the urban environment: State-of-the-art review, Renew. Sustain. Energy Rev. 41 (2015) 915–931, https://doi.org/10.1016/j.rser.2014.08.060.
[83] M. Šúri, J. Hofierka, A new GIS-based solar radiation model and its application to photovoltaic assessments, Trans. GIS, 10.1111/j.1467-9671.2004.00174.x 8 (2), 175-190, 2004/04/01 2004, 10.1111/j.1467-9671.2004.00174.x.
[84] J. Hofierka, J. Kaňuk, Assessment of photovoltaic potential in urban areas using open-source solar radiation tools, Renewable Energy 34 (10) (2009) 2206–2214, https://doi.org/10.1016/j.renene.2009.02.021.
[85] H.T. Nguyen, J.M. Pearce, Incorporating shading losses in solar photovoltaic potential assessment at the municipal scale, Sol. Energy 86 (5) (2012) 1245–1260, https://doi.org/10.1016/j.solener.2012.01.017.
[86] J. Hofierka, M. Zlocha, A new 3-D solar radiation model for 3-D city models, Trans. GIS, 10.1111/j.1467-9671.2012.01337.x 16(50, 681-690, 2012/10/01 2012, 10.1111/j.1467-9671.2012.01337.x.
[87] A. Verso, A. Martin, J. Amador, J. Dominguez, GIS-based method to evaluate the photovoltaic potential in the urban environments: The particular case of Miraflores de la Sierra, Sol. Energy 117 (2015) 236–245, https://doi.org/10.1016/j.solener.2015.04.018.
[88] A. Vulkan, I. Kloog, M. Dorman, E. Erell, Modeling the potential for PV installation in residential buildings in dense urban areas, Energy Build. 169 (2018) 97–109, https://doi.org/10.1016/j.enbuild.2018.03.052.
[89] P. Redweik, C. Catita, M. Brito, Solar energy potential on roofs and facades in an urban landscape, Sol. Energy 97 (2013) 332–341, https://doi.org/10.1016/j.solener.2013.08.036.
[90] J.A. Jakubiec, C.F. Reinhart, A method for predicting city-wide electricity gains from photovoltaic panels based on LiDAR and GIS data combined with hourly Daysim simulations, Sol. Energy 93 (2013) 127–143, https://doi.org/10.1016/j.solener.2013.03.022.
[91] K.S. Lee, J.W. Lee, J.S. Lee, Feasibility study on the relation between housing density and solar accessibility and potential uses, Renewable Energy 85 (2016) 749–758, https://doi.org/10.1016/j.renene.2015.06.070.
[92] D. Li, G. Liu, S. Liao, Solar potential in urban residential buildings, Sol. Energy 111 (2015) 225–235, https://doi.org/10.1016/j.solener.2014.10.045.
[93] M.S. Rao, M. Agrawal, Performance Analysis of Partial Shading on Solar Photovoltaic System under Aluminium Reflectors C3 - 2020 IEEE International Students' Conference on Electrical, Electronics and Computer

Science, SCEECS 2020, 2020, 10.1109/SCEECS48394.2020.74. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85086314617&doi=10.1109%2fSCEECS48394.2020.74&partnerID=40&md5=64f34450b0704b2b4a95a32ae42aeec8.
[94] I. Iskender, M.Z. Abdulazeez, N. Genc, Impact of environmental factors on photovoltaic systems, Adv. Energy Res.: Energy Power Eng. (2012) 237–262.
[95] Y.H. Ji, J.G. Kim, S.H. Park, J.H. Kim, C.Y. Won, C-language based PV array simulation technique considering effects of partial shading C3 - Proceedings of the IEEE International Conference on Industrial Technology, 2009, 10.1109/ICIT.2009.4939687. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-67650320614&doi=10.1109%2fICIT.2009.4939687&partnerID=40&md5=997c716a1c4f9c837aaeba9a6c783c14.
[96] R. Alik, A. Jusoh, and T. Sutikno, A study of shading effect on photovoltaic modules with proposed P & O checking algorithm, Int. J. Electr. Comput. Eng., 7(1), 29-40, 2017, 10.11591/ijece.v7i1.pp29-40.
[97] S. Kumar, Apoorva, P. K. Sadhu, MATLAB-Based Simulation to analyze the aftermath of Partial Shading on Solar Cell C3 - 2018 International Conference on Power Energy, Environment and Intelligent Control, PEEIC 2018, 2019, pp. 437-441, 10.1109/PEEIC.2018.8665486. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85064106933&doi=10.1109%2fPEEIC.2018.8665486&partnerID=40&md5=228924f137e5b02a491abd564b25bf62.
[98] W. Yin, Q. Tong, Y. Xu, Y. Zhang, Y. Zhou, Partial Shading Impact on PV Array System and the Hard-Shading Location with BP Algorithm C3 - 7th International Conference on Smart Grid, icSmartGrid 2019, 2019, pp. 21-26, 10.1109/icSmartGrid48354.2019.8990864. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85081056039&doi=10.1109%2ficSmartGrid48354.2019.8990864&partnerID=40&md5=200cd8b35eaf798152bb28f81ccbc518.
[99] P.R. Satpathy, A. Sarangi, S. Jena, B. Jena, R. Sharma, Topology alteration for output power maximization in PV arrays under partial shading C3 - International Conference on Technologies for Smart City Energy Security and Power: Smart Solutions for Smart Cities, ICSESP 2018 - Proceedings," 2018, vol. 2018-January, pp. 1-6, 10.1109/ICSESP.2018.8376699. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85049876151&doi=10.1109%2fICSESP.2018.8376699&partnerID=40&md5=ed04ee3e5214aae8dcbad5dc2fe68869.
[100] K. Saravanan, C. Sharmeela, An intelligent reconfiguration technique for enhancing the power from photovoltaic module in partially shaded environments, Int. J. Power Energy Convers. 7 (2) (2016) 178–190, https://doi.org/10.1504/IJPEC.2016.076526.
[101] V.K. Kolakaluri, C. Vyjayanthi, S. Mikkili, PV-battery hybrid system with less AH capacity for standalone DC loads, Int. J. Emerg. Electr. Power Syst., 20(4), 2019, 10.1515/ijeeps-2019-0011.
[102] A.M.I. Aldaoudeyeh, Photovoltaic-battery scheme to enhance PV array characteristics in partial shading conditions, IET Renew. Power Gener. 10 (1) (2016) 108–115, https://doi.org/10.1049/iet-rpg.2015.0177.
[103] V. Bala Raju, C. Chengaiah, Modeling and relative research of solar photovoltaic array topologies under partial shading conditions, Int. J. Innov. Technol. Explor. Eng., 8(6) Special Issue 4, pp. 340-346, 2019, 10.35940/ijitee.F1069.0486S419.
[104] O. Bingöl, B. Özkaya, Analysis and comparison of different PV array configurations under partial shading conditions, Sol. Energy 160 (2018) 336–343, https://doi.org/10.1016/j.solener.2017.12.004.
[105] R. Darussalam, R.I. Pramana, A. Rajani, Experimental investigation of serial parallel and total-cross-tied configuration photovoltaic under partial shading conditions C3 - Proceeding - ICSEEA 2017 International Conference on Sustainable Energy Engineering and Application: "Continuous Improvement of Sustainable Energy for Eco-Mobility, 2017, vol. 2018-January, pp. 140-144, 10.1109/ICSEEA.2017.8267699. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85050759923&doi=10.1109%2fICSEEA.2017.8267699&partnerID=40&md5=d465fd5860c493f6df99400468be6c45.
[106] V.B. Raju, C. Chengaiah, Power Enhancement of Solar PV Arrays under Partial Shading Conditions with Reconfiguration Methods C3 - 2019 Innovations in Power and Advanced Computing Technologies, i-PACT 2019, 2019, 10.1109/i-PACT44901.2019.8960012. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85078973877&doi=10.1109%2fi-PACT44901.2019.8960012&partnerID=40&md5=d1fe96899c2a41171a782481d01acc15.
[107] P. dos Santos Vicente, E.M. Vicente, M.G. Simoes, and E. R. Ribeiro, Shading position effects on photovoltaic panel output power, Int. Trans. Electr. Energy Syst., 30(1), 2020, 10.1002/2050-7038.12163.
[108] G. Sai Krishna, T. Moger, Improved SuDoKu reconfiguration technique for total-cross-tied PV array to enhance maximum power under partial shading conditions, Renew. Sustain. Energy Rev. 109 (2019) 333–348, https://doi.org/10.1016/j.rser.2019.04.037.
[109] D. Manimegalai, M. Karthikeyan, S.C. Vijayakumar, Maximizing power output of partially shaded photovoltaic arrays using SuDoKu configuration [Online]. Available: ARPN J. Eng. Appl. Sci. 13 (1) (2018) 124–133. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85040631617&partnerID=40&md5=4e14fc99bf2dd566e1f5c493ca949bce.
[110] L. Hernández-Callejo, S. Gallardo-Saavedra, A. Diez-Cercadillo, V. Alonso-Gómez, Study of the influence of DC-DC optimizers on PV-energy generation, in Smart Cities, Cham, S. Nesmachnow and L. Hernández Callejo, Eds., 2019// 2019: Springer International Publishing, pp. 1-17.
[111] S. Ghazi, A. Sayigh, K. Ip, Dust effect on flat surfaces – A review paper, Renew. Sustain. Energy Rev. 33 (2014) 742–751, https://doi.org/10.1016/j.rser.2014.02.016.
[112] S. You, Y.J. Lim, Y. Dai, C.H. Wang, On the temporal modelling of solar photovoltaic soiling: Energy and economic impacts in seven cities, Appl. Energy 228 (2018) 1136–1146, https://doi.org/10.1016/j.apenergy.2018.07.020.
[113] M. Al-Housani, Y. Bicer, M. Koç, Assessment of various dry photovoltaic cleaning techniques and frequencies on the power output of CdTe-type modules in dusty environments, Sustainability (Switzerland), vol. 11, no. 10, 2019, 10.3390/su11102850.
[114] J.K. Kaldellis, A. Kokala, Quantifying the decrease of the photovoltaic panels' energy yield due to phenomena of natural air pollution disposal, *Energy* 35 (12) (2010) 4862–4869, https://doi.org/10.1016/j.energy.2010.09.002.
[115] A. Elnosh et al., Field study of factors influencing performance of PV modules in buildings (BIPV/BAPV) installed in UAE C3 - 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion, WCPEC 2018 - A Joint Conference of 45th IEEE PVSC, 28th PVSEC and 34th EU PVSEC," 2018, pp. 565-568, 10.1109/PVSC.2018.8547298. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85059890462&doi=10.1109%2fPVSC.2018.8547298&partnerID=40&md5=bf8ed42b3e23ca48c7600c9594f99b7e.
[116] M. Nassereddine, M. Nagrial, J. Rizk, A. Hellany, Advanced PV system for sustainable housing; maximum output power with low maintenance for sandy area C3 - 2019 International Conference on Electrical Engineering Research and Practice, iCEERP 2019," 2019, 10.1109/ICEERP49088.2019.8956973. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85078932797&doi=10.1109%2fICEERP49088.2019.8956973&partnerID=40&md5=33c2cb7e230bf864993709f1ed48fe53.
[117] H. Salimi, H. Ahmadi Danesh Ashtiani, A. Mirabdolah Lavasani, R. Fazaeli, Experimental analysis and modeling of weather condition effects on photovoltaic systems' performance: Tehran case study, Energy Sources, Part A: Recov. Util. Environ Effects, 2020, 10.1080/15567036.2020.1765902.
[118] B. Guo, W. Javed, S. Khan, B. Figgis, T. Mirza, Models for prediction of soiling-caused photovoltaic power output degradation based on environmental variables in Doha, Qatar C3 - ASME 2016 10th International Conference on Energy Sustainability, ES 2016, collocated with the ASME 2016 Power Conference and the ASME 2016 14th International Conference on Fuel Cell Science, Engineering and Technology, 2016, vol. 1, 10.1115/ES2016-59390. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85002158001&doi=10.1115%2fES2016-59390&partnerID=40&md5=b9887c50c6df306348c8639c85dcbd08.
[119] H. Lu, L. Lu, Y. Wang, Numerical investigation of dust pollution on a solar photovoltaic (PV) system mounted on an isolated building, Appl. Energy 180 (2016) 27–36, https://doi.org/10.1016/j.apenergy.2016.07.030.
[120] L. Zhou et al., The impact of air pollutant deposition on solar energy system efficiency: An approach to estimate PV soiling effects with the Community Multiscale Air Quality (CMAQ) model, Sci. Total Environ. 651 (2019) 456–465, https://doi.org/10.1016/j.scitotenv.2018.09.194.
[121] I.M. Peters, S. Karthik, H. Liu, T. Buonassisi, A. Nobre, Urban haze and photovoltaics, Energy Environ. Sci. 11 (10) (2018) 3043–3054, https://doi.org/10.1039/c8ee01100a.
[122] R. R. Cordero et al., Effects of soiling on photovoltaic (PV) modules in the Atacama Desert, Sci. Rep., 8(1), 2018, 10.1038/s41598-018-32291-8.
[123] M. Jaszczur, Q. Hassan, J. Teneta, K. Styszko, W. Nawrot, R. Hanus, Study of dust deposition and temperature impact on solar photovoltaic module C3 [Online]. Available: MATEC Web Conf. 240 (2018). https://www.scopus.com/inward/record.uri?eid=2-s2.0-85058243445&doi=10.1051%2fmatecconf%2f201824004005&partnerID=40&md5=ea72a18b55e15e595f5e288d88397554, https://doi.org/10.1051/matecconf/201824004005.
[124] C. Schill, S. Brachmann, M. Koehl, Impact of soiling on IV-curves and efficiency of PV-modules, Sol. Energy 112 (2015) 259–262, https://doi.org/10.1016/j.solener.2014.12.003.
[125] C. Schill, S. Brachmann, M. Heck, K.A. Weiss, M. Koehl, Impact of heavy soiling on the power output of PV-modules C3 - Proceedings of SPIE - The International Society for Optical Engineering, vol. 8112, 2011, 10.1117/12.893721.
[126] S. Shapsough, M. Takrouri, R. Dhaouadi, I. Zualkernan, An IoT-based remote IV tracing system for analysis of city-wide solar power facilities, Sustain. Cities Soc. 57 (2020), https://doi.org/10.1016/j.scs.2020.102041.
[127] S.A. Sulaiman, M.R.M. Razif, T.D. Han, S.M. Atnaw, S.N.A. Tamili, Impact of soiling rate on solar photovoltaic panel in Malaysia C3 - MATEC Web of Conferences," 2018, vol. 225, 10.1051/matecconf/201822504008. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85056798953&doi=10.1051%2fmatecconf%2f201822504008&partnerID=40&md5=1169c88d24bd639fadb91726e2f8415e.
[128] S. Toth, M. Hannigan, M. Vance, M. Deceglie, Enhanced photovoltaic soiling in an urban environment C3 - Conference Record of the IEEE Photovoltaic Specialists Conference, 2019, pp. 2904-2907, 10.1109/PVSC40753.2019.8980735. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85081617995&doi=10.1109%2fPVSC40753.2019.8980735&partnerID=40&md5=eae604bcd46b5ba74eff6a56fc5b6583.
[129] E. Urrejola et al., Effect of soiling and sunlight exposure on the performance ratio of photovoltaic technologies in Santiago, Chile, Energy Convers. Manage. 114 (2016) 338–347, https://doi.org/10.1016/j.enconman.2016.02.016.

[130] A.S. Alghamdi, A.S. Bahaj, L.S. Blunden, Y. Wu, Dust removal from solar PV modules by automated cleaning systems, Energies, 12, 2019.
[131] E. Tarigan, The effect of dust on solar PV system energy output under urban climate of Surabaya, Indonesia C3 – J. Phys.: Conf. Series, (2019) 1373, 1 ed., 10.1088/1742-6596/1373/1/012025. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85077083834&doi=10.1088%2f1742-6596%2f1373%2f1%2f012025&partnerID=40&md5=1d1e6ac721823e97160a8cdeee77000a.
[132] S. Belihi, D. Dahlioui, B. Laarabi, A. Barhdadi, On the use of dew for cleaning PV panels in morocco: literature survey and experimental results C3 - Proceedings of 2019 7th International Renewable and Sustainable Energy Conference, IRSEC 2019, 2019, 10.1109/IRSEC48032.2019.9078178. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85084671707&doi=10.1109%2fIRSEC48032.2019.9078178&partnerID=40&md5=a37c78baba62b0edbc44c296051c852a.
[133] V. Beutner, R. Singh, C. Stark, Temperature and power study of adhered and racked double glass photovoltaic modules, in 2017 IEEE 44th Photovoltaic Specialist Conference (PVSC), 25-30 June 2017 2017, pp. 1855-1857, 10.1109/PVSC.2017.8366390.
[134] G. Osma-Pinto, G. Ordóñez-Plata, Measuring factors influencing performance of rooftop PV panels in warm tropical climates, Sol. Energy 185 (2019) 112–123, https://doi.org/10.1016/j.solener.2019.04.053.
[135] H. Taha, Meso-urban meteorological and photochemical modeling of heat island mitigation, Atmos. Environ. 42 (38) (2008) 8795–8809, https://doi.org/10.1016/j.atmosenv.2008.06.036.
[136] H. Taha, The potential for air-temperature impact from large-scale deployment of solar photovoltaic arrays in urban areas, *Sol. Energy* 91 (2013) 358–367, https://doi.org/10.1016/j.solener.2012.09.014.
[137] J.A. Reagan, D.M. Acklam, Solar reflectivity of common building materials and its influence on the roof heat gain of typical southwestern U.S.A. residences, *Energy Build.* 2 (3) (1979) 237–248, https://doi.org/10.1016/0378-7788(79)90009-4.
[138] S. Ma, M. Goldstein, A.J. Pitman, N. Haghdadi, I. MacGill, Pricing the urban cooling benefits of solar panel deployment in Sydney, Australia, Sci. Rep. 7 (2017), https://doi.org/10.1038/srep43938.
[139] F. Chen et al., The integrated WRF/urban modelling system: Development, evaluation, and applications to urban environmental problems, *Int. J. Climatol.* 31 (2) (2011) 273–288, https://doi.org/10.1002/joc.2158.
[140] U. Berardi, J. Graham, Investigation of the impacts of microclimate on PV energy efficiency and outdoor thermal comfort, Sustain, Cities Soc. 62 (2020), https://doi.org/10.1016/j.scs.2020.102402.
[141] V. Masson, M. Bonhomme, J. L. Salagnac, X. Briottet, A. Lemonsu, Solar panels reduce both global warming and urban heat island, Front. Environ. Sci., 2 (JUN), 2014, Art no. 14, 10.3389/fenvs.2014.00014.
[142] V. Masson, A physically-based scheme for the urban energy budget in atmospheric models, Bound.-Layer Meteorol. 94 (3) (2000) 357–397, https://doi.org/10.1023/A:1002463829265.
[143] F. Salamanca, M. Georgescu, A. Mahalov, M. Moustaoui, A. Martilli, Citywide impacts of cool roof and rooftop solar photovoltaic deployment on near-surface air temperature and cooling energy demand, *Bound.-Layer Meteorol.* 161 (1) (2016) 203–221, https://doi.org/10.1007/s10546-016-0160-y.
[144] A. Cortes, Y. Murashita, T. Matsuo, A. Kondo, H. Shimadera, Y. Inoue, Numerical evaluation of the effect of photovoltaic cell installation on urban thermal environment, Sustain. Cities Soc. 19 (2015) 250–258, https://doi.org/10.1016/j.scs.2015.07.012.
[145] T. Foken, 50 years of the Monin-Obukhov similarity theory, Bound.-Layer Meteorol. 119 (3) (2006) 431–447, https://doi.org/10.1007/s10546-006-9048-6.
[146] A. Scherba, D.J. Sailor, T.N. Rosenstiel, C.C. Wamser, Modeling impacts of roof reflectivity, integrated photovoltaic panels and green roof systems on sensible heat flux into the urban environment, Build. Environ. 46 (12) (2011) 2542–2551, https://doi.org/10.1016/j.buildenv.2011.06.012.
[147] G.A. Barron-Gafford, R.L. Minor, N.A. Allen, A.D. Cronin, A.E. Brooks, M.A. Pavao-Zuckerman, The photovoltaic heat island effect: Larger solar power plants increase local temperatures, Sci. Rep., 6, 2016, Art no. 35070, 10.1038/srep35070.
[148] B.R. Burg, P. Ruch, S. Paredes, B. Michel, Effects of radiative forcing of building integrated photovoltaic systems in different urban climates, Sol. Energy 147 (2017) 399–405, https://doi.org/10.1016/j.solener.2017.03.004.
[149] B.R. Burg et al., Ecological and economical advantages of efficient solar systems, AIP Conf. Proc. 1616 (1) (2020/09/11 2014,) 317–320, https://doi.org/10.1063/1.4897086.
[150] S. Nagpal, S. Shah, Effect of photovoltaic cover on urban surface energy balance C3 - Proceedings of the Solar World Congress 2005: Bringing Water to the World, Including Proceedings of 34th ASES Annual Conference and Proceedings of 30th National Passive Solar Conference, 2005, vol. 2, pp. 1108-1113. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84870527673&partnerID=40&md5=015c289c35d8225bc82fd1a940869679. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84870527673&partnerID=40&md5=015c289c35d8225bc82fd1a940869679.
[151] S. Nagpal, Integration of photovoltaics in building envelope: Effect on whole building energy performance C3 - American Solar Energy Society - Solar 2006: 35th ASES Annual Conf., 31st ASES National Passive Solar Conf., 1st ASES Policy and Marketing Conf., ASME Solar Energy Division Int. Solar Energy Conference, 2006, vol. 1, pp. 458-462. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84867943655&partnerID=40&md5=95c5c3922edf59b5d406b22349f0280b. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84867943655&partnerID=40&md5=95c5c3922edf59b5d406b22349f0280b.
[152] H.A. Dang, T.K. Nguyen, Impacts of roof-top solar photovoltaic modules on building energy performance: case study of a residence in HCM City, Vietnam C3 - IOP Conference Series: Earth and Environmental Science," 2020, vol. 505, 1 ed., 10.1088/1755-1315/505/1/012014. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85089033230&doi=10.1088%2f1755-1315%2f505%2f1%2f012014&partnerID=40&md5=51b4793462d17372428902fd17e012dd.
[153] D.B. Crawley et al., EnergyPlus: creating a new-generation building energy simulation program, Energy Build. 33 (4) (2001) 319–331, https://doi.org/10.1016/S0378-7788(00)00114-6.
[154] A.H.A. Dehwah, M. Asif, Assessment of net energy contribution to buildings by rooftop photovoltaic systems in hot-humid climates, Renewable Energy 131 (2019) 1288–1299, https://doi.org/10.1016/j.renene.2018.08.031.
[155] A. M. Ekoe A Akata, D. Njomo, B. Agrawal, Assessment of Building Integrated Photovoltaic (BIPV) for sustainable energy performance in tropical regions of Cameroon, Renew. Sustain. Energy Rev., 80, 1138-1152, 2017, 10.1016/j.rser.2017.05.155.
[156] R. Elghamry, H. Hassan, M. Ahmed, S. Ookawara, Effect of the PV position and orientation on energy consumption in a facility C3 - 5th International Conference on Renewable Energy: Generation and Application, ICREGA 2018, " 2018, vol. 2018-January, pp. 158-163, 10.1109/ICREGA.2018.8337597. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85050469040&doi=10.1109%2fICREGA.2018.8337597&partnerID=40&md5=bc53ea8e35018462748bfff05b5cdaf4.
[157] L.G. Popa, M. Brumaru, Optimizing buildings energy performance through photovoltaic panel integration within a mobile shading system C3 [Online]. Available: Procedia Manuf. 22 (2018) 765–772. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85049234191&doi=10.1016%2fj.promfg.2018.03.109&partnerID=40&md5=8042fb04300a35b06d2825ec06319610, https://doi.org/10.1016/j.promfg.2018.03.109.
[158] M. Zubair, A.B. Awan, R.P. Praveen, Analysis of photovoltaic arrays efficiency for reduction of building cooling load in hot climates, Build. Serv. Eng. Res. Technol. 39 (6) (2018) 733–748, https://doi.org/10.1177/0143624418780633.
[159] Y. Kotak, E.J. Gago, P. Mohanty, T. Muneer, Installation of roof-top solar PV modules and their impact on building cooling load, Build. Serv. Eng. Res. Technol. 35 (6) (2014) 613–633, https://doi.org/10.1177/0143624414527098.
[160] S.B. Sadineni, F. Atallah, R.F. Boehm, Impact of roof integrated PV orientation on the residential electricity peak demand, Appl. Energy 92 (2012) 204–210, https://doi.org/10.1016/j.apenergy.2011.10.026.
[161] V. Kapsalis, D. Karamanis, On the effect of roof added photovoltaics on building's energy demand, Energy Build. 108 (2015) 195–204, https://doi.org/10.1016/j.enbuild.2015.09.016.
[162] S. Liu, Y. Yan, Z. Zhang, J. Bai, Effect of distributed photovoltaic power station on cooling load induced by roof for sunny day in summer, Therm. Sci. Eng. Progr. 10 (2019) 36–41, https://doi.org/10.1016/j.tsep.2018.12.009.
[163] E. Vardoulakis, D. Karamanis, The effect of shading of building integrated photovoltaics on roof surface temperature and heat transfer in buildings C3 - Proceedings of the 25th International Conference on Efficiency, Cost, Optimization and Simulation of Energy Conversion Systems and Processes, ECOS 2012, 2012, vol. 7, pp. 273-280. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84896526901&partnerID=40&md5=b4eeccb98e0edd9adb5e51892b569aeb. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84896526901&partnerID=40&md5=b4eeccb98e0edd9adb5e51892b569aeb.
[164] D. Wang, T. Qi, Y. Liu, Y. Wang, J. Fan, H. Du, A method for evaluating both shading and power generation effects of rooftop solar PV panels for different climate zones of China, Sol. Energy 205 (2020) 432–445, https://doi.org/10.1016/j.solener.2020.05.009.
[165] B. Zhao, M. Hu, X. Ao, G. Pei, Conceptual development of a building-integrated photovoltaic–radiative cooling system and preliminary performance analysis in Eastern China, Appl. Energy 205 (2017) 626–634, https://doi.org/10.1016/j.apenergy.2017.08.011.
[166] A.L.S. Chan, Evaluating the impact of photovoltaic systems on the thermal performance of buildings and its implication to building energy code. A case study in subtropical Hong Kong, Energy Policy 119 (2018) 674–688, https://doi.org/10.1016/j.enpol.2018.04.041.
[167] S. Hong, A. Choi, M. Sung, Impact of bi-directional PV blind control method on lighting, heating and cooling energy consumption in mock-up rooms, Energy Build. 176 (2018) 1–16, https://doi.org/10.1016/j.enbuild.2018.07.022.
[168] S. Tak, S. Woo, J. Park, S. Park, Effect of the changeable organic semi-transparent solar cell window on building energy efficiency and user comfort, Sustainability, 9(6), 2017, 10.3390/su9060950.
[169] Y.T. Chae, J. Kim, H. Park, B. Shin, Building energy performance evaluation of building integrated photovoltaic (BIPV) window with semi-transparent solar cells, Appl. Energy 129 (2014) 217–227, https://doi.org/10.1016/j.apenergy.2014.04.106.
[170] J.S. Golden, J. Carlson, K.E. Kaloush, P. Phelan, A comparative study of the thermal and radiative impacts of photovoltaic canopies on pavement surface temperatures, Sol. Energy 81 (7) (2007) 872–883, https://doi.org/10.1016/j.solener.2006.11.007.

[171] J. Golden, S. Nagpal, S. Shah, Role of photovoltaics in urban heat island mitigation C3 - Electric Utilities Environmental Conference, EUEC 2005: 8th Annual Joint EPA, DOE, EEI, EPRI Conference on Air Quality, Global Climate Change and Renewable Energy, 2006, vol. 2006. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-33846256661&partnerID=40&md5=925018d86a3a514df3ad2ba890d66565. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-33846256661&partnerID=40&md5=925018d86a3a514df3ad2ba890d66565.

[172] J.S. Golden, Photovoltaic canopies: Thermodynamics to achieve a sustainable systems approach to mitigate the urban heat island hysteresis lag effect, Int. J. Sustain. Energy 25 (1) (2006) 1–21, https://doi.org/10.1080/14786450600593139.