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Analyzing the interactions between photovoltaic system and its ambient environment using CFD techniques: A review

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ABSTRACT

Since the utilization of renewable energy is crucial to achieve carbon neutrality, the global installation of photovoltaic (PV) devices has been growing exponentially in the past decade. As outdoor devices, PV will interact with the ambient environment, leading to impacts on power generation efficiency, system structure safety, and the surrounding microclimate. To investigate the various interactions between PV and its ambient environment, simulation with Computational Fluid Dynamics (CFD) is a frequently employed approach. Given the rapid increase of studies using CFD to investigate PV-environment interactions, this study provides a comprehensive review of the research reported in journal publications on this topic within the last decade, aiming to answer two questions: (1) Which interactions can be simulated using CFD? (2) How to simulate those interactions using CFD? A total of 69 studies were surveyed and they were categorized into six research subjects based on various interactions. According to the results, most studies applied CFD for simulations regarding PV thermal characteristics, PV cooling, and dust deposition & mitigation, whereas less were for investigating airflow & ventilation, wind loading, and microclimate. Practices of CFD setups were summarized for different steps of a simulation procedure. It was found that component scale, PV module geometry, three-dimensional modelling, Reynolds-averaged Navier-Stokes type, and SST k-ω turbulence model are generally favoured in simulations. Future research may focus on developing simplified models, boundary conditions, and parameterization methods for simulations in urban-scale and involving more complex physical phenomena.

1. Introduction

Climate change has been continuously affecting the entire world, leading to more frequent extreme weather events, sea level rising, ocean acidification, biodiversity loss, and more [1]. To mitigate global warming and address climate crisis, carbon neutrality, which aims to achieve net zero greenhouse gas emissions by the middle of 21st century, is a critical and essential action [2]. Utilizing renewable energy such as solar, wind, ocean etc., is crucial to achieve carbon neutrality as it creates much less greenhouse gas emissions when generating electricity if compared with burning fossil fuels [3]. To utilize the abundant and clean solar energy, Photovoltaics (PV) is one of the fastest growing renewable power generation technologies [4]. The rapid cost reduction of PV increases its economic attractiveness and can therefore lead to a continuously massive expansion of installations in the coming years, which is expected to deliver a significant contribution to the future global electricity generation [5]. According to the energy forecast by International Energy Agency (IEA), renewable power capacity will increase 1.2 terawatts over 2019-2024, where solar PV accounts for almost 60% of the total expansion [6].

To maximize the amount of solar energy that can be collected, PV systems are generally installed at positions outside a building structure or in an open area, leading to various installation types such as rooftop-mounted [7], wall-mounted [8], and ground-mounted [9]. For either installation type, PV will interact with its surroundings in terms as heat, mass, and momentum transfer and exchange, which involve heat transfer between PV and its vicinity, particle (e.g., dust, rain drop)

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deposition on PV surface, and wind impinging upon PV panels. These interactions can significantly impact the PV power generation efficiency, the PV system structure safety, and the ambient microclimate situation. For instance, as PV power generation is sensitive to both the incoming solar irradiance and the cell temperature, deposition and accumulation of dust on the panel surface will hinder both irradiance receiving and heat dissipation, causing a significant reduction in power output.

To investigate the interactions between PV and its ambient environment, methods involving laboratory experiment [10,11], on-site measurement [12,13], and computational fluid dynamics (CFD) simulation [14,15] have been extensively applied. Compared to the real-world experiment and measurement, the CFD numerical approach enables the investigations considering a variety of scenarios or design attempts in a virtual space. Fabrication of physical prototypes can thus be avoided and expenses and time for conducting research can be consequently reduced [16–19]. The words 'computational fluid dynamics' provide a clear and intuitive explanation of this technique: the analysis of systems involving fluid flow, heat transfer and associated phenomena by means of computer-based simulation [20]. CFD tackles fluid flow problems which are governed by conservation laws of mass, energy, and momentum using numerical algorithms, e.g., finite volume method [21] and finite element method [22]. Owing to the difficulty in directly solving the partial differential governing equations, CFD converts the governing equations into a system of algebraic equations and solves the equations by an iterative method to obtain an approximate numerical solution to the original problem.

With the continuous advancement in numerical algorithm and computational power, CFD has become a reliable and popular research method in various research fields including the PV system analysis. Published in 1997, the research conducted by Brinkworth et al. [23] was a pioneering study that employed CFD technique to investigate the interaction between PV and its surrounding air. Using a commercial CFD package, the authors explored the cooling effect of buoyant flow in a duct between the PV cladding and a backing wall. Since then, more research adopting CFD for PV-related study has been published, especially in the last decade, witnessing great success of the CFD approach and an increasingly important role that CFD played in the field. However, introducing CFD technique to the PV research domain brings not only opportunities but also challenges. For the PV community where CFD serves as a tool for problem solving, issues such as mismatching of tool and problem, unsuitable model selection, and inappropriate simulation setups could happen, especially for inexperienced CFD users. Meanwhile, since CFD results are obtained based on a simulation procedure that involves multiple steps, user-dependent results could be caused by possible errors in multiple decisions based on users' experience [24,25]. It is inferred that two possible reasons may contribute to the challenge. First, the complexity of CFD theory may hinder proper use of the tool though many CFD software are user-friendly. Users can have all setups successfully finished, but they may not completely understand why and how confident the setups are. Second, there is no existing reference or guideline that users can follow to learn, practice, and help solve their problems.

Given that many publications are on the topic of CFD investigations on PV-ambient interaction, it is necessary to conduct a systematic literature review and summarize the practices of CFD settings to serve as a reference or guideline for researchers, which can promote more appropriate and effective CFD analysis for future studies on this topic. To the best of the authors' knowledge, such review is absent in the existing literature, thus, the present study aims to fill this research gap. To do so, we aim to answer two key questions on CFD analysis of the interactions between PV and its ambient:

1. Which interactions between PV and the surrounding environment can be simulated using CFD, and have been investigated in previous studies?
2. How to simulate those interactions using CFD, i.e. the detailed CFD simulation setups, such as modelling scales, model parameters, turbulence models, etc.?

By answering the two critical questions, the capability and limitation of CFD and how to appropriately use CFD to model the interactions between PV and its ambient can be revealed. Researchers from both the CFD and the PV research communities will benefit from this literature survey. For CFD researchers, as capabilities and limitations of current models and treatments in CFD for specific interaction phenomena are of concern, the summary designates potential directions for CFD model improvements. For PV researchers, more attentions are paid to how to appropriately use the CFD tool to solve the related problems, and this study provides a reference of CFD practices for various scenarios.

The organization of this paper is shown in Fig. 1. Section 2 describes the methodology of literature search, and a bibliometric analysis of the reviewed articles is provided. Section 3 depicts CFD studies on PV-ambient environment interactions for different research subjects, which aims to answer the first question. Section 4 summarizes various practices of CFD setups reported in the reviewed studies for the purpose of answering the second question. Discussions on the review results are presented in Section 5, and finally we conclude the study and provide future research directions in Section 6.

2. Literature search and bibliometric analysis

The methodology of literature search, including keywords, searching strategy, and screening criteria is presented in this section. A literature summary is also provided.

2.1. Literature search methodology

In this work, we focused on the topic of CFD simulation of interactions between PV and its ambient environment. Literature search was conducted in June of 2022 using the academic search engine *Web of Science* with the following searching strategy,

Topic =['photovoltaic' OR 'photovoltaics' OR 'pv']
AND ['computational fluid dynamics' OR 'cfd'] (1)

Fig. 2 shows a detailed process of identifying and screening the literature. At the identification stage, to minimize the risk of missing papers that are within the topic of interests, we did not include more restrictive keywords such as 'interaction' and 'environment' in the preliminary search. As a result, we retrieved 458 papers from *Web of Science* published from 1997 to 2022, which include papers published in peer-reviewed journals and international conference proceedings.

We then down selected the papers by scanning their titles, abstracts, and main bodies to ensure that the articles surveyed were within the review scope and met the quality requirements. For example, given the scope of this review, studies concerning CFD simulations of interactions between PV and the cooling media/materials such as water [26,27], nanofluid [28,29], and phase change materials (PCMs) [30,31] were excluded because these media/materials are not considered as PV's ambient environment. Meanwhile, it was found that papers from conference proceedings usually provided extremely brief information on simulation and settings due to the article length limitation. Therefore, all conference papers were not included in this review. Besides, more attention was paid to the papers published within the last decade, i.e., from 2012 to 2022, and the earlier publications were skipped. This is because more than 90% of the papers retrieved were published in the past ten years, and the methods and applications reported in the earlier articles could be obsolete owing to the rapid development of CFD techniques and PV research in recent years. We also excluded the papers that the full text was not accessible. With the preliminary search and further screening, a total of 69 articles were included for survey

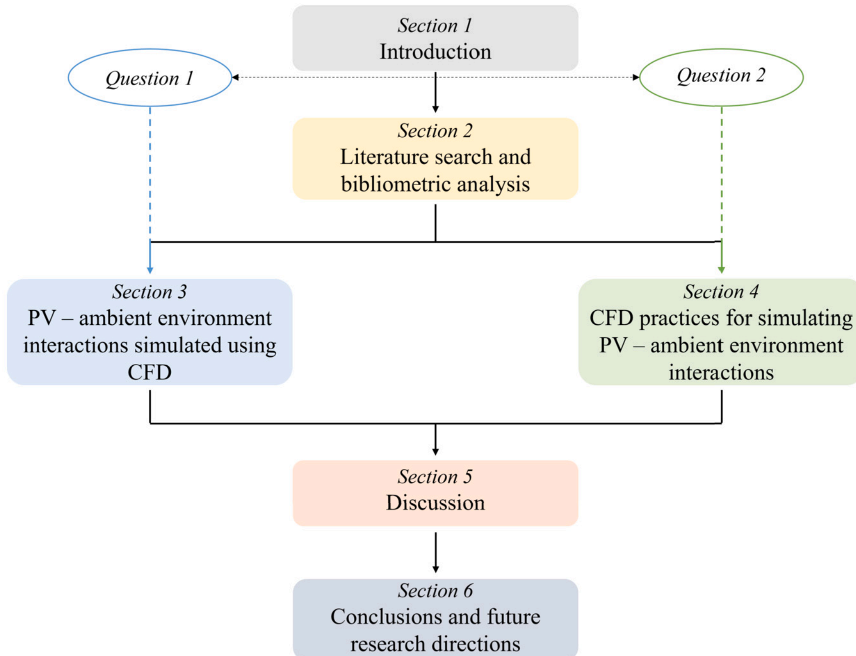


Fig. 1. Organization of the paper.

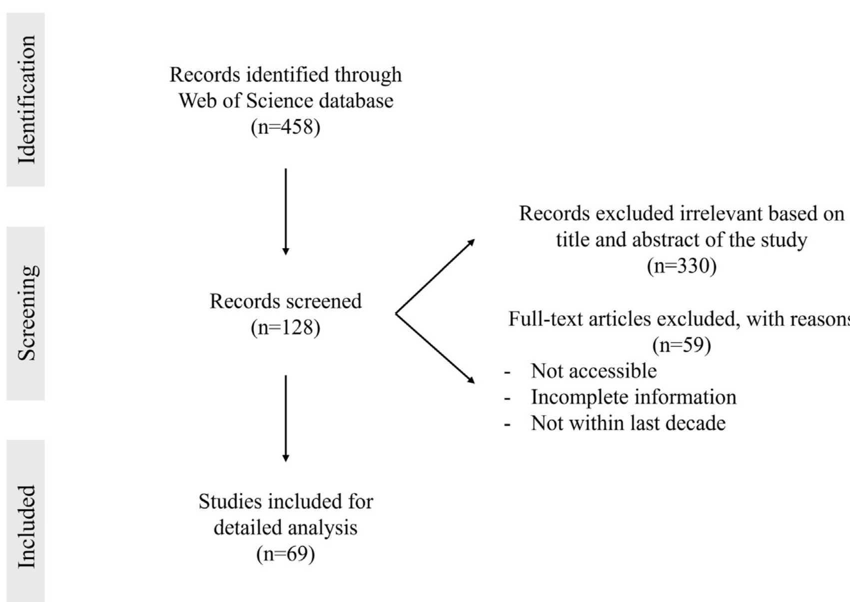


Fig. 2. The framework for literature search and screening.

and summary. Details of the 69 papers examined in this study are listed in Table A1. The papers are summarized with the following entries:

- Author(s) and publication year
- Research subject
  - Airflow & ventilation: air flow over the PV panel and ventilation of building-integrated PV system
  - PV thermal characteristics: thermal behaviour and response of PV and its mechanism
  - PV cooling: methods for PV thermal regulation and their effects
  - Microclimate: effect of PV utilization on its surrounding microclimate
  - Dust deposition & mitigation: dust deposition dynamics and sedimentation on PV panel surface and measures to mitigate the dust effect
  - Wind loading: wind impinging and its effect on PV panel surface or PV system structure
- Research objective
  - Performance evaluation (PEVA): evaluate PV performance regarding power generation, thermal responses, etc.
  - Impact assessment (IMPACT): evaluate the impact of ambient environment on PV or the impact of PV on ambient environment
  - Design / configuration optimization (DOPT): optimize the PV system / module design or configuration
  - Model development (MDEV): develop a new numerical model or mathematical correlation for PV simulation
- Modelling scale
  - Component scale: scale with order of magnitude ranging from 10^0 m to 10^1 m, which contains PV model(s) and building structure component(s)

- Building scale: scale with order of magnitude from 10^1 m to 10^2 m, which contains PV model(s) and building(s) or building-like block(s)
- Urban scale: scale with order of magnitude larger than several hundred meters, which contains PV model(s) and multiple buildings

• Geometry involved in the modelling
- PV panel (PP): a simplified plane with no thickness
- PV module (PM): a complicated structure that involves multi-layer materials, and detailed shape and configuration are represented
- Wind barrier (BA): a wall-like solid structure that is used to weaken the approaching wind
- Building component (BC): component of a building structure, such as a wall or a window
- Building (BU): building(s) or building-like block(s)

• Dimensionality
- Two-dimension (2D)
- Three-dimension (3D)

• Heat transfer
- Conduction (CD)
- Convection (CV)
- Radiation (RD)

• Simulation type
- Reynolds-averaged Navier-Stokes (RANS)
- Unsteady Reynolds-averaged Navier-Stokes (URANS)
- Large eddy simulation (LES)
- Not Given (NG)

• Turbulence model
- Standard $k-\varepsilon$
- Realizable $k-\varepsilon$
- Re-Normalization Group (RNG) $k-\varepsilon$
- Low Reynolds number (Low Re) $k-\varepsilon$
- Shear stress transport (SST) $k-\omega$
- Not Given (NG)

• Validation
- Validate with measurement data obtained from prototype experiment: represented by '○'
- Validate with data from literature: represented by '□'
- Without validation: represented by '×'

2.2. Bibliometric analysis

Fig. 3 demonstrates a summary of the reviewed articles based on their publication year, publication journals, number of citations, and geo-locations where the research was conducted. As illustrated in Fig. 3(a), the number of publications stayed stable from 2015 to 2018, and an obvious increase can be found in the last three years, contributing to approximately two thirds of the selected papers. Among the six research subjects, 'PV thermal characteristics' was continuously receiving research interests in the last decade, whereas topics on 'PV cooling' and 'Dust deposition & mitigation' gained increasingly attentions in the last three years.

In terms of publication journals, since PV is a technology for harvesting renewables, i.e., solar energy, most of the articles were published in energy-related journals, as shown in Fig. 3(b). Considering that the articles were published in a number of journals, we only listed journals that published at least three articles and grouped the remaining into a single category 'Others' for conciseness. The most favourable journals are Solar Energy, Renewable Energy, and Applied Energy, in where more than 30% of the total papers were published.

To estimate the quality and influence of an article, its number of citations is a commonly used index. We summarized the number of citations of the articles (until June 20, 2022) in each research subject, as demonstrated in Fig. 3(c). It can be observed that articles were generally cited less than 30 times, with papers for subjects 'PV thermal characteristics' and 'Microclimate' showing higher mean and median values of citations than those of other subjects. Table 1 lists the most highly cited articles in each research subject, which could guide the readers to the most popular research point for each subject. Among the six most cited papers, four were published more than five years and two were published within the last four years. The two most cited articles that were published recently focused on 'PV cooling' and 'Dust deposition & mitigation', respectively. This further indicate that these two research subjects were receiving increasing interests in the past few years, which is consistent with the trend in Fig. 3(a).

Regarding to the distribution of the geo-locations where the investigations were carried out, as shown in Fig. 3(d) the majority of the research were from regions located in Asia, Europe, and North America, e.g., 14 from China, 5 from UK, and 4 from Canada. In comparison, less research was found in regions near the equator where more abundant solar resource is available. It is conjectured that the possible reasons could be two-fold. First, regions where more research were conducted are generally more advanced in urbanization, leading to more interests in utilizing renewable to achieve sustainability. Second, compared to simulation, experiments or on-site measurements might be more preferred in regions near the equator because they are ideal and natural laboratories for PV research. Experiment or measurement-based studies on PV are out of the scope of the current study.

3. PV-ambient environment interactions simulated using CFD

To answer the first question "which interactions can be simulated using CFD?", the 69 articles were classified into 6 subjects regarding the PV-ambient environment interactions: 'Airflow & ventilation', 'PV thermal characteristics', 'PV cooling', 'Microclimate', 'Dust deposition & mitigation', and 'Wind loading'. Fig. 4 shows a concept map regarding the interactions simulated in each subjects, aiming to provide an intuitive illustration. Readers can refer to the corresponding sections for more detailed descriptions on the subjects. To figure out the difference among the studies within each subject, we summarized research objectives of the studies and made classifications accordingly. Table 2 lists the number of articles in each category.

3.1. Airflow & ventilation

In this subject, airflow over/around the PV panel, and in the air gap between the PV and building envelope are of concern. The integration of PV in buildings introduces irregularity, e.g., cavity, to building envelopes. The surrounding airflow and ventilation in the cavity could affect thermal conditions of PV and building envelopes, which consequently impacts PV generation efficiency and building energy performance, indicating an important topic in PV utilization. We identified that 5 out of the 69 studies (7.2%) were within the scope of this subject. Flow dynamics and heat transfer were generally involved in the simulations of interactions between PV and the ambient environment in these studies, and airflow and thermal distributions in/round the cavity were estimated (Fig. 5(a)). Despite similar interactions simulated in the studies, difference could also be found among them, which could be further classified into 2 categories based on their research objectives: impact assessment (3 studies) and performance evaluation (2 studies). For impact assessment, simulations were conducted with focuses on effects of varying installation and configuration of building-integrated PVs on PV and building thermal behaviours and flow characteristics [42]. For performance evaluation, on the other hand, PV system efficiency and building sustainability (e.g., load reduction, ventilation enhancement) were evaluated by performing simulations on ventilation in the cavity [43]. The comparable number of articles for impact assessment and performance evaluation indicates that both aspects are crucial to building-integrated PV applications, which determines whether and how to integrate the PV with buildings, respectively.

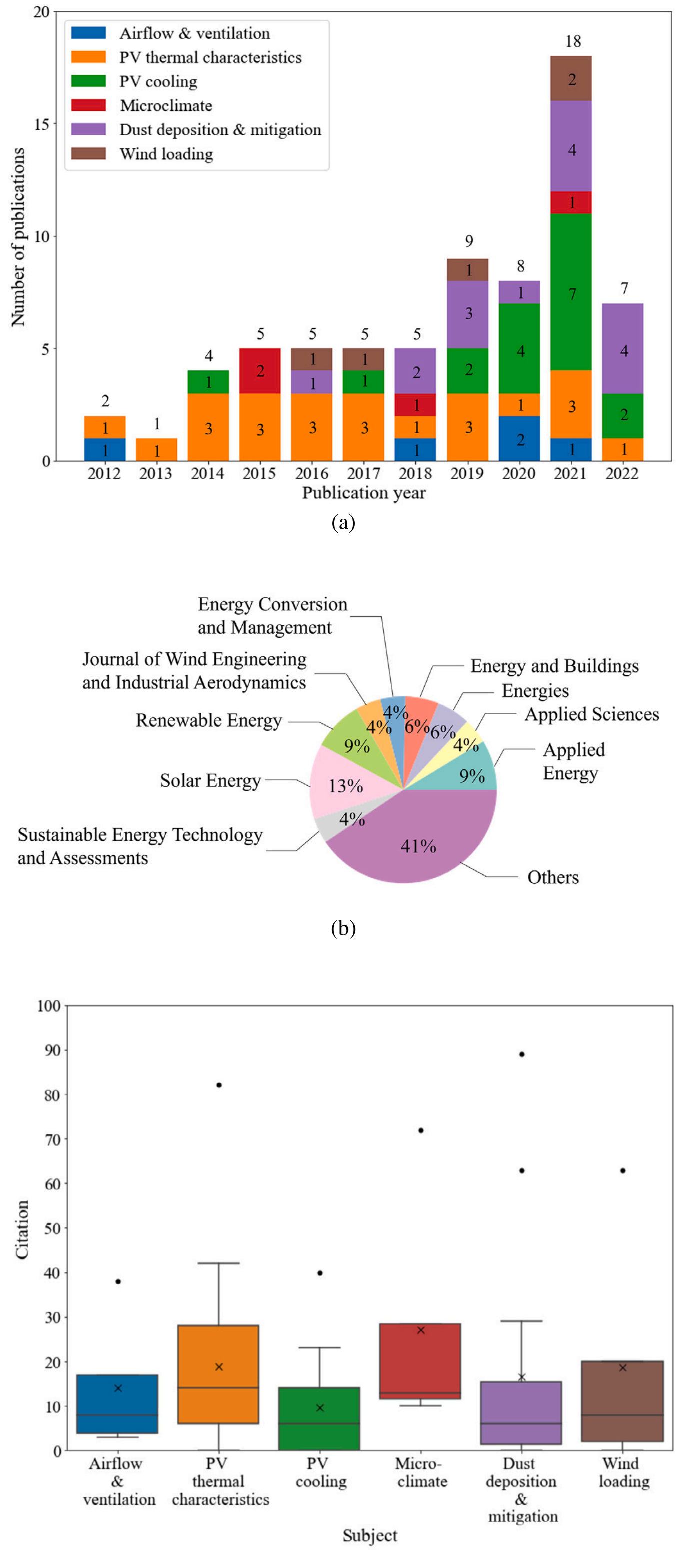
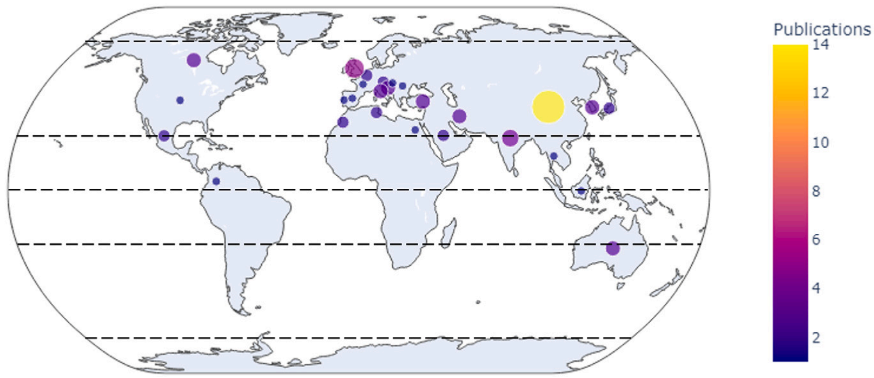


Fig. 3. Summary of articles reviewed: (a) number of articles published per year; (b) journals where the articles were published; (c) number of citations; (d) locations where the research was conducted. (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.)

3.2. PV thermal characteristics

This subject devotes to simulating the thermal behaviour and response of PV to the ambient environment and revealing the mechanism. The increasing in PV operating temperatures normally induces an unfavourable effect on the PV generation performance and lifetime. A reasonable procedure before the consideration and adoption of a specific cooling strategy is to understand PV thermal behaviour and response regarding its surroundings for various operating conditions. Among the 69 articles that were reviewed in this study, one third (23 studies) applied CFD to analyze PV thermal characteristics. The simulations were conducted with consideration of flow dynamics and



(d)

Fig. 3. (*continued*)

Table 1
Most cited papers for each research subject. The number of citations was retrieved until June 20, 2022.

Subject	Title	Published year	Journal	Number of citations
Airflow & ventilation	Modelling of natural convection in vertical and tilted photovoltaic applications [32]	2012	Energy and Buildings	38
PV thermal characteristics	Experimental and numerical investigation of a backside convective cooling mechanism on photovoltaic panels [33]	2016	Energy	82
PV cooling	A new passive PV heatsink design to reduce efficiency losses: A computational and experimental evaluation [34]	2020	Renewable Energy	40
Microclimate	A numerical simulation of the photovoltaic greenhouse microclimate [35]	2015	Solar Energy	72
Dust deposition & mitigation	Effects of particle sizes and tilt angles on dust deposition characteristics of a ground-mounted solar photovoltaic system [36]	2018	Applied Energy	89
Wind loading	A numerical approach to the investigation of wind loading on an array of ground mounted solar photovoltaic (PV) panels [37]	2016	Journal of Wind Engineering and Industrial Aerodynamics	63

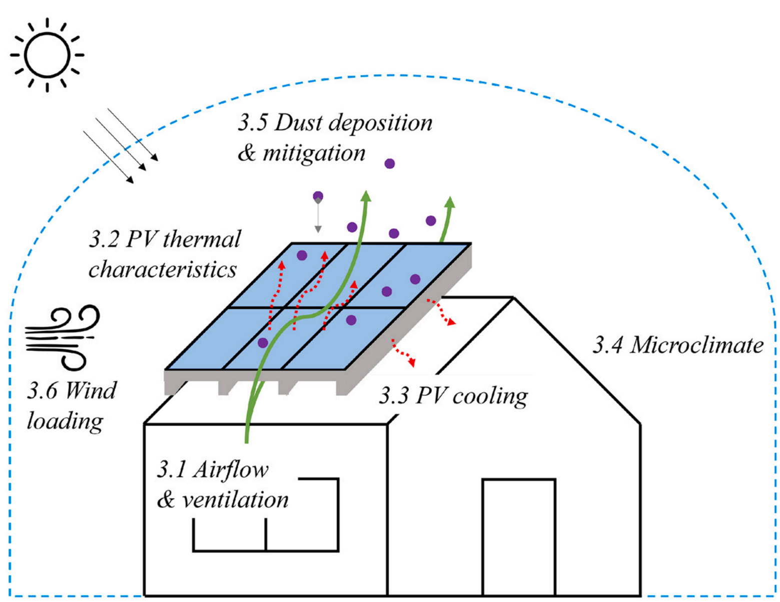


Fig. 4. Concept map of interactions simulated in each subject.

Table 2
Number of articles categorized by research subject and objective.

	Airflow & ventilation	PV thermal characteristics	PV cooling	Micro-climate	Dust deposition & mitigation	Wind loading
Performance evaluation	2	12	7	2	0	1
Impact assessment	3	5	1	2	12	4
Design/configuration optimization	0	3	9	0	3	0
Model development	0	3	0	0	0	0

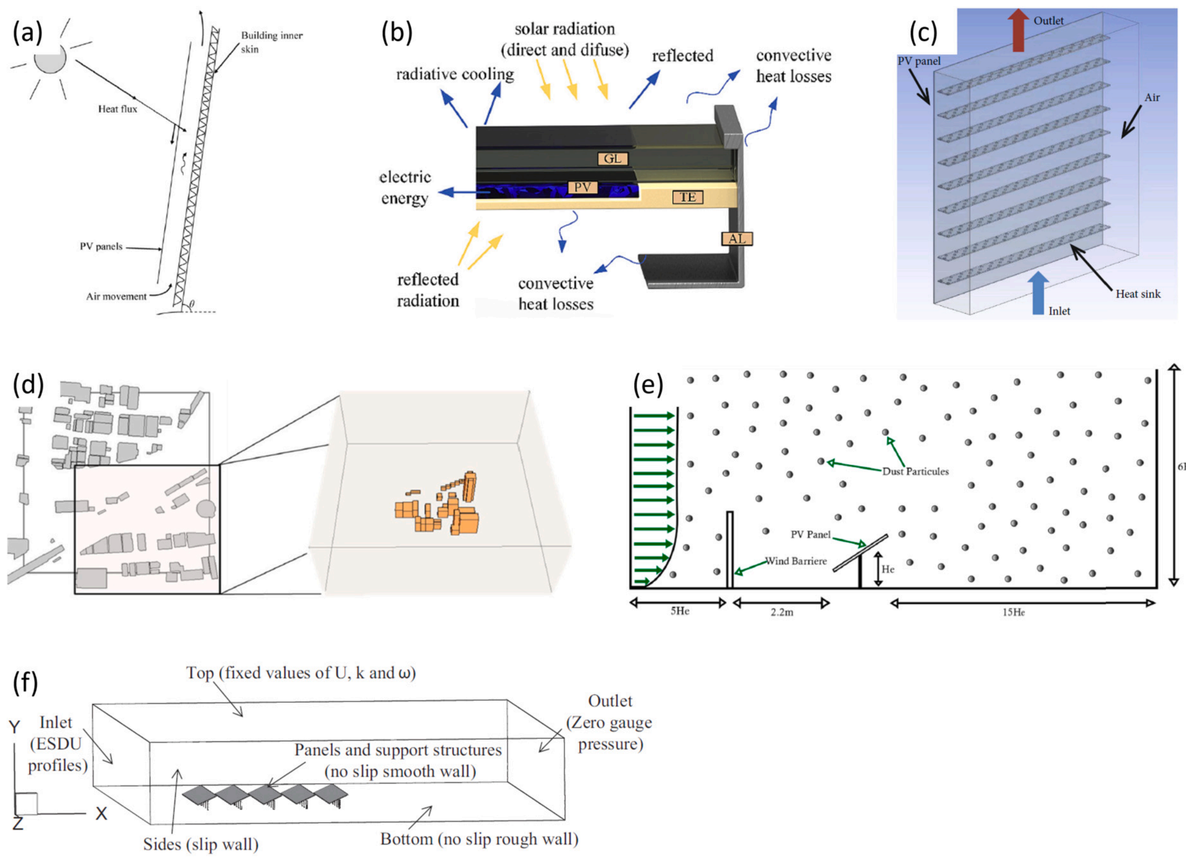


Fig. 5. Examples of interactions simulated in each subject: (a) Airflow & ventilation [32], (b) PV thermal characteristics [38], (c) PV cooling [39], (d) Microclimate [40], (e) Dust deposition & mitigation [41], (f) Wind loading [37].

heat transfer, which were basic processes involved in the PV-ambient environment interactions (Fig. 5(b)). The studies could be further categorized based on their research targets, where discrepancies among the studies could be observed. There are 12 papers for performance evaluation, 5 for impact assessment, 3 for design/configuration optimization, and 3 for model development. Evaluating the performance of PVs or PV-integrated systems gained most interests among the 4 research objectives. For instance, CFD simulations were performed to evaluate convective heat transfer from the inclined roof of a building with applications to PV-thermal system [44] and BIPV facade [45], respectively. For impact assessment, various environmental factors were considered, and their effects were simulated. For example, three-dimensional CFD model was adopted to investigate an effective heat transfer field and variations in the PV panel temperatures under windless, different windy and heat source conditions [38,46]. Design optimization was performed to improve the thermal efficiency of PV, which was achieved via simulations considering various design parameters [47,48] and installation technique [49]. Model development was conducted by establishing correlations between parameters of interest on the basis of CFD simulation results. For instance, a simplified numerical model was developed to analyze the heat transfer process and temperature distribution on each single layer of PV panels [50]. The diversity in research objectives indicates that PV thermal characteristics are a topic receiving extensive attentions from various aspects. It is reasonable to observe that a majority of studies aimed at performance evaluation, which is owing to the close correlation between PV performance and its thermal behaviour.

3.3. PV cooling

For the subject of PV cooling, CFD simulations were performed to investigate the measures for PV thermal regulation and the corresponding effects. Since the rise in PV cell operating temperature induces an almost linear reduction in power generation performance, therefore, continuous efforts are of necessity to regulate the cell temperature for improving the PV efficiency. There are 17 out of the 69 papers (24.6%) being within the subject of PV cooling. Similar to those in the subject of PV thermal characteristics, simulations for PV cooling refer to flow dynamics and heat transfer. However, more attentions were paid to cooling effect regarding heat dissipation and temperature reduction in cell temperature (Fig. 5(c)). Performance evaluation and design/configuration optimization are the two main research objectives identified in the studies. For instance, to test the performance of passive cooling under cross wind condition, a PV panel attached by an aluminium plate with perforated fins was modelled and flow and heat transfer simulations were conducted [39]. On the other hand, based on the analysis of thermal performance of PV panels under both windless and cross-wind conditions, several different attempts have been made on the optimization of PV design and configuration to improve the efficiency via lowering the operating temperature. Changing the shape [51], dimensions [34,52], and porosity [53] of the attached fins were attempted and the cooling effects were tested in the studies. The numbers of article for performance evaluation and design optimization are comparable, indicating that both objectives were of similar concern, which is because the two objectives essentially represent the two indispensable steps for enhancing PV cooling effectiveness.

3.4. Microclimate

Research on the subject of microclimate simulates interactions between PV and the ambient atmosphere, which put emphasis on the effect of PV utilization on the surrounding airflow and thermal environment. In view of a rapid increasing in PV adoption, the shading and thermal effects of PV could show visible influences on both outdoor (e.g., temperatures of building envelope and canopy air in urban area) and indoor (e.g., radiation distribution and thermal climate in greenhouse) environments, which could be relevant to urban heat island and greenhouse sustainability, respectively. A total of 4 papers (5.8%) were identified for the subject of microclimate, where both flow dynamics and heat transfer were simulated to clarify the flow and thermal distributions indoors and outdoors (Fig. 5(d)) considering the existence of PV. Meanwhile, two different research objectives could be found in the studies, where half is for performance evaluation and another half is for impact assessment. For performance evaluation, CFD was used to simulate the solar radiation distribution, thermal environment, water vapour outside and inside the greenhouse [35]. The simulation helped to evaluate the PV panel setup to improve the spatial distribution of sunlight received in the greenhouse. CFD simulation was conducted to catch the wind environment information, which was used to evaluate building design interventions for solar energy exploitation considering various design scenarios [54]. For impact assessment, CFD simulation coupled with weather research forecasting model was employed to assess building surface temperature, urban-canyon air temperature, and energy fluxes [40]. In [55], the effect of shading induced by south oriented PV panels on the greenhouse climate was quantified using a CFD tool. The climate behaviour during summer and winter days within a PV-integrated greenhouse was assessed, where solar radiation distribution, wind velocity, relative humidity, and air temperature were focused. Number of investigations performed for the purposes of performance evaluation and impact assessment were identical. The assessment on efficiency and sustainability discloses whether it is effective to deploy PV, while the clarification of the impact of utilization reveals whether it is feasible to install PV.

3.5. Dust deposition & mitigation

This subject simulates dust dynamics of deposition on PV panel surface and mitigation methods. Dust deposition and accumulation on PV surface can significantly reduce PV power generation due to the shading effect which blocks solar radiation from reaching the PV cells [56]. It is thus of necessity to understand the mechanism of dust deposition behaviours and explore mitigation measures to avoid severe PV performance degradation. There are 15 out of the 69 studies (21.7%) that employed CFD to investigate the mechanism and mitigation of dust deposition on the PV panel. Simulations in this subject generally involve flow dynamics over and around a PV panel and particle movements towards the panel (Fig. 5(e)). The dusts were treated as discrete particles that were carried by the airflow. Although within the same subject, the 15 studies can be further categorized into two groups regarding their research objectives: impact assessment and design/configuration optimization. The former aims to analyze the factors that influence the dust deposition and reveal the deposition mechanism, while the latter focuses on optimized strategies for dust mitigation. Among the 15 articles, most of the studies (12 of 15 studies) are for impact assessment while the remaining 3 studies are for optimizing the PV design or configuration. As for impact assessment, for example, influences of dust particle size, released quantity, force of gravity, roof inclination, surrounding building, and wind velocity on dust deposition behaviour were explored [57,58]. For the purpose of optimization, most studies were conducted to optimize wind barrier for soiling mitigation, e.g., the wind barrier height and its distance from the PV array for different panel tilt angles and dust particle sizes [59]. Compared to design/configuration optimization, impact assessment received more research interests. The possible reasons could be two-fold: (a) the complexity of dust motion and deposition requires more comprehensive investigations; (b) appropriate and effective mitigation measures are limited.

3.6. Wind loading

The subject of wind loading focuses on simulations of aerodynamic loads acting on the PV and its supporting structure. Since PV systems are always mounted outside and exposed to the open air to harvest solar energy, wind loading is thus crucial to PV wind resistance design, and safety and durability of PV applications, making it an important topic for PV research. CFD studies on wind loading were reported in 5 out of the 69 articles (7.2%) that were surveyed. Flow dynamics was comprehensively simulated in these studies to clarify the wind acting on the PV structure (Fig. 5(f)). Among the 5 studies for wind loading investigations, most of the articles (4 of 5 studies) aimed to assess the impact of wind load on PV that is either mounted on the ground [37,60] or on the building rooftop [61,62], whereas one study intended to conduct a performance evaluation [63]. To assess the effect of wind load, CFD simulations were carried out to acquire pressure distribution on the PV panel surface and/or the surrounding wind flow characteristics, which took into account of factors such as wind direction, PV array tilt angle, and clearance between PV array, etc. To evaluate the PV structural resilience performance of roof-mounted PV panels under wind conditions with typhoon strength, CFD was employed to simulate wind velocity and wind pressure distribution around the PV panels in consideration of various wind speeds, directions, and roof tilt angles [88]. The CFD results were then coupled with energy simulation to evaluate energy performance of PV generation. In this subject, it was observed that majority of the studies concentrated on the purpose of impact assessment. This is because a full understanding of wind effect on PV could determine how safe and durable the PV can be installed, which may not be relevant to PV efficiency though, but is a practical factor in PV utilization.

3.7. Closing remarks

Notably, there are discrepancies among article numbers of each subject, which indicates a bias in research interests among those research subjects. PV thermal characteristics received most attentions, with PV cooling and dust deposition & mitigation ranks second and third. In comparison, airflow & ventilation, wind loading, and microclimate attracted much less concentrations. The reason behind the phenomenon could be related to the long-existing issue in PV applications: how to improve the PV efficiency? Since solar irradiance and operating temperature are the two critical factors that affect the power generation performance of the PV system, investigations could thus be carried out

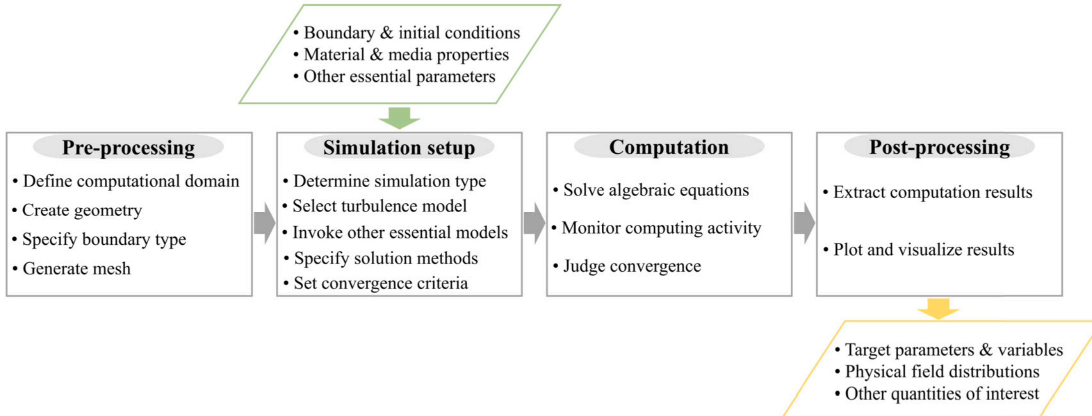


Fig. 6. Flowchart of a general process of conducting CFD simulation.

from the two aspects, leading to the three subjects with relation to shading of dust deposition and PV thermal behaviours. On the other side, the other three subjects are more related to additional effects of PV utilization and safety concerns, which are indeed important topics but seems not to be at the centre stage of CFD simulations on PV at present owing to simulation resource and capability. Besides, although simulations for the subjects 'Airflow & ventilation', 'PV thermal characteristics', 'PV cooling', and 'Microclimate' involve similar physical processes, i.e., flow dynamics and heat transfer, we treated the four subjects as independent categories. This is because the simulation method could differ from each other owing to different focuses in a specific subject. Detailed analysis on the simulation methods will be provided in the next section.

4. CFD practices for simulating PV-ambient environment interactions

The previous section answers the first question and this section aims to answer the second question: "how to simulate the interaction using CFD?", which summaries the practices of CFD usage and settings of the reviewed articles.

Before diving deep into the review results of CFD modelling methodologies, a general process for utilizing the CFD technique to conduct a simulation is shown in Fig. 6. Carrying out a CFD simulation comprises several steps which generally includes pre-processing, simulation setting, computation, and post-processing. In the pre-processing step, it is required to define a computational domain, within which solid geometries (e.g., a building block, a PV panel) should be created. Boundary types such as flow inlet, outlet, and solid wall for geometry and domain borders need to be specified. Then, discretization is performed, which approximates the continuous domain space with a large number of discrete control volumes (meshes / cells). Based on discretization, the governing equations can be converted to algebraic equations for numerical computation. After the pre-processing is finished, the next step is to set up simulation settings which involves simulation type, turbulence and other essential models, numerical algorithms, convergence criteria, etc. At this stage, boundary and/or initial conditions, material and media properties, and other parameters that are necessary for the simulation ought to be specified as input. With all the settings done, numerical computation can be executed, which solves the algebraic equations for the variables such as pressure, velocity, temperature, mass concentration, etc. The computation stops if the convergence criteria are satisfied. Then the simulation results can be extracted and visualized in the post-processing step. It is also feasible to export parameters or distributions of interests as output for further comparison and analysis.

The purpose of this section is to demonstrate how CFD tools can be applied to model the interaction between PV and its ambient environment, which summarizes application practices shown in the studies that were reviewed. Here, we focused on methodologies for domain and geometry, simulation type, turbulence model, and heat transfer models, despite that all procedures in the simulation process are critical to the computation in accuracy, stability and efficiency. The summary of mesh, solution strategy, convergence criteria, and computation algorithm were excluded because these practices are more related to the numerical algorithms for solving partial differential equations than modelling methodologies, which is beyond the scope of this study.

In the subsequent sections, following the general CFD simulation process, we will demonstrate the summary of practices for CFD in modelling the interaction between PV and the ambient environment. Section 4.1 describes domain and geometry related practices which includes modelling scale, geometries created, and their dimensionalities. Simulation type and turbulence model will be depicted in Section 4.2, followed by heat transfer modelling given in Section 4.3. Information about simulation target parameters will be shown in Section 4.4. In addition, summaries of how to validate the CFD model and which CFD software was used are presented in Sections 4.5 and 4.6, respectively.

4.1. Modelling scale, geometry, and dimensionality

Among the investigated 69 articles, their modelling scales can generally be classified into three categories: component, building, and urban scales, as demonstrated in Section 2.1. The classification is based on the size of the computational domain and the components involved. The component scale ranges from several meters to tens of meters, which contains a PV model and sometimes, a building structure component such as a wall. The building scale usually indicates a building or building-like block involved in the domain and its size could be extended to dozens of meters. The urban scale has the largest domain size that could reach several hundred meters and contain multiple buildings.

The review results show that the majority studies 71% (49 of 69 papers) were conducted in neighbouring scale, followed by 26% (18 of 69) studies considering building scale and only 3% (2 of 69) studies in urban scale. Fig. 7(a) illustrates the distribution of modelling scale for different research subjects, where a priority of modelling scale selected in each subject can be clearly found. For most subjects, modelling with the component scale occupies a major share (from 60% for airflow & ventilation and wind loading to 100% for PV cooling) among the three modelling scales. Especially for PV cooling studies, all the simulations were conducted in a component scale. However, urban scale modelling was not considered in these subjects. In comparison, for the microclimate subject, half of the simulations were performed in the building scale and another half was in the urban scale. It is anticipated that the selection of modelling scale could mainly depend on the research subject as it indicates the interaction that we concern and implies the affecting area of the interaction between PV and ambient environment. For instance, in PV cooling investigations, more attentions are paid to

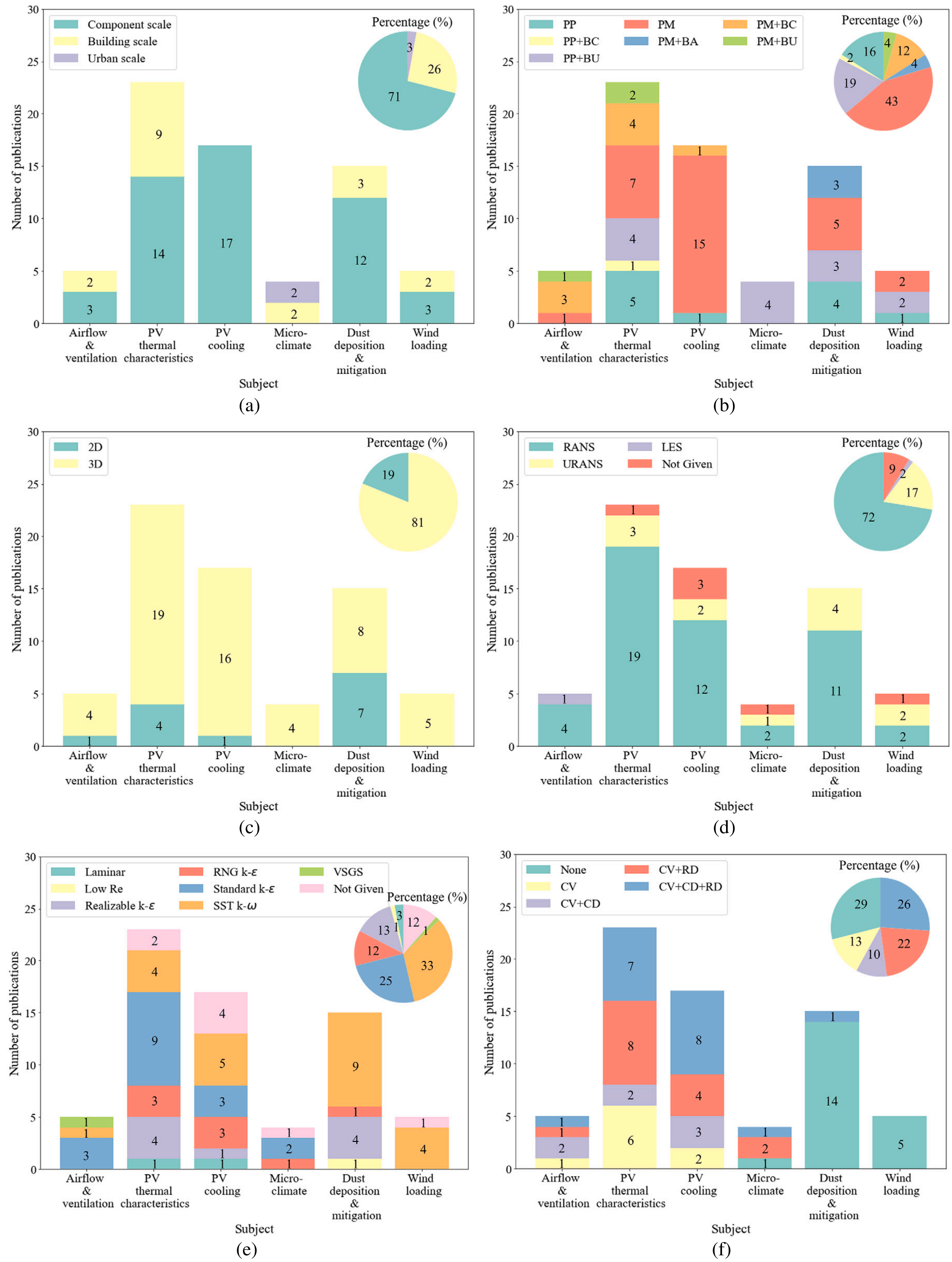


Fig. 7. Summary of the reviewed CFD simulations in terms of (a) modelling scales; (b) geometries; (c) modelling dimensionalities; (d) simulation types of the CFD simulations; (e) turbulence models; (f) heat transfer phenomena considered.

the heat transfer between the PV and its surrounding air, while interactions among the distant air and other objects are of no interest (e.g., [39,64]). Thus, it is sufficient to carry out the simulation in a component scale.

In terms of the geometries involved in the CFD simulations in the investigated 69 studies, they could be sorted by 7 different scenarios, including sole PV module (PM), PV module and wind barrier (PM+BA), PV module and building component (PM+BC), PV module and building (PM+BU), sole PV panel (PP), PV panel and building component (PP+BC), PV panel and building (PP+BU). Detailed explanations on the seven scenarios can be found in Section 2.1. Fig. 7(b) demonstrates the distribution of the involved components for different research subjects. The results show that 43% of the research (30 out of 69 papers) conducted simulation considering the sole PV module, followed by PV panel and building (13 papers), PV panels (11 papers) and PV module and building components (8 papers). PV modules were modelled in most studies that are related to heat transfer (i.e., Airflow & ventilation, PV thermal characteristics, and PV cooling) and heat conduction between layers of a PV module can thus be involved in the heat transfer process in the simulation. In comparison, PV panel model which treats the PV as a simplified plane without thickness is mainly applied in studies focusing on microclimate, dust deposition and wind loading. For studies with these subjects, fluid dynamics are of concern and most cases assume isothermal panels or detailed heat transfer process within the PV were not considered in the non-isothermal cases.

As to the dimensionality of the simulations, most papers established a three-dimensional (3D) numerical model (81%, 56 out of 69 papers), and the remaining are carried out using a two-dimensional (2D) model, as demonstrated in Fig. 7(c). The majority of papers based on a 2D model focus on the dust deposition & mitigation research. It is reasonable because only the flow field is considered, which is symmetric along the spanwise direction. However, a 2D model is not suitable for all research objectives, for example, the microclimate research involved complex geometry components so it is not possible to consider it as a symmetric boundary. More than half of the investigated papers with a 3D model study PV thermal characteristics (19 papers) and PV cooling (16 papers). Compared with those with a 2D model, it seems that employing a 3D model to investigate the PV thermal characteristics and PV cooling is preferred. This is mainly because the lateral effects have to be considered to ensure the accuracy in most cases as the flow and thermal distributions are asymmetric. Additionally, papers focusing on dust deposition and mitigation employed 2D or 3D model nearly equally.

4.2. Simulation type and turbulence model

As shown in Fig. 7(e), among the surveyed 69 studies, 6 (9%) of them did not specify the simulation type. For the remaining 63 studies, 62 applied Reynolds-Averaged Navier-Stokes (RANS) simulation, among which 12 were for unsteady state (URANS). Only one study was found using Large Eddy Simulation (LES) as approximation form of the governing equations. Even though it is widely demonstrated that LES is more accurate than RANS type simulation [65,66], the significantly higher computation cost of LES could be an important factor that prevents researchers from selecting this approach. Besides, in spite of ignoring the flow fluctuations and representing the flow field using the averaged form, RANS simulations can still provide sufficient accuracy in many scenarios. These two reasons are considered to contribute to a vast majority of studies being performed with RANS. Over 70% research were carried out with RANS for simulations regarding airflow & ventilation, PV thermal characteristics, PV cooling and dust deposition & mitigation. URANS is employed to record the transient development of the physical process to capture more details. The only paper employing LES focused on the subject of airflow & ventilation.

Fig. 7(e) shows the distribution of the utilization of turbulence models in the 69 studies. Among the papers, 8 did not specify the turbulence model, 2 simulated with laminar assumption and thus did not consider the turbulence effect, and 1 applied a subgrid-scale (SGS) model [67] in LES. For the remaining 58 studies using RANS approach with a two-equation eddy-viscosity model, the most commonly used turbulence model is SST $k-\omega$ model [68] (used in 23 studies, 33% in total). The model combines the $k-\omega$ formulation in the inner part of the fluid boundary layer and the SST formulation in the free-stream. Then it can handle the low Reynolds effect near the wall surface without any extra damping functions, and switch to a $k-\varepsilon$ behaviour far from the wall to avoid the sensitivity problem of a normal $k-\omega$ model. This merit may contribute to its popularity in PV simulations. The second most popular turbulence model is the standard $k-\varepsilon$ model [69] (used in 17 studies, 25% of total). The RNG $k-\varepsilon$ [70] (8 studies) and Realizable $k-\varepsilon$ [71] (9 studies) turbulence models appear to occupy similar share. Over the years, the standard $k-\varepsilon$ model has been one of the most popular turbulence models that is applied in many CFD studies. However, the well-known problems, i.e., the overestimate of production of kinetic energy near the obstacle frontal corner and the underestimate of turbulent kinetic energy in the wake region [72], caused a trend in using other turbulence models such as RNG and Realizable $k-\varepsilon$ models over the recent years. Among the reviewed studies, for research focusing on dust deposition and wind loading, since flow behaviour such as stagnation and separation is crucial to the simulation results, the standard $k-\varepsilon$ model was therefore not applied in these studies.

4.3. Heat transfer

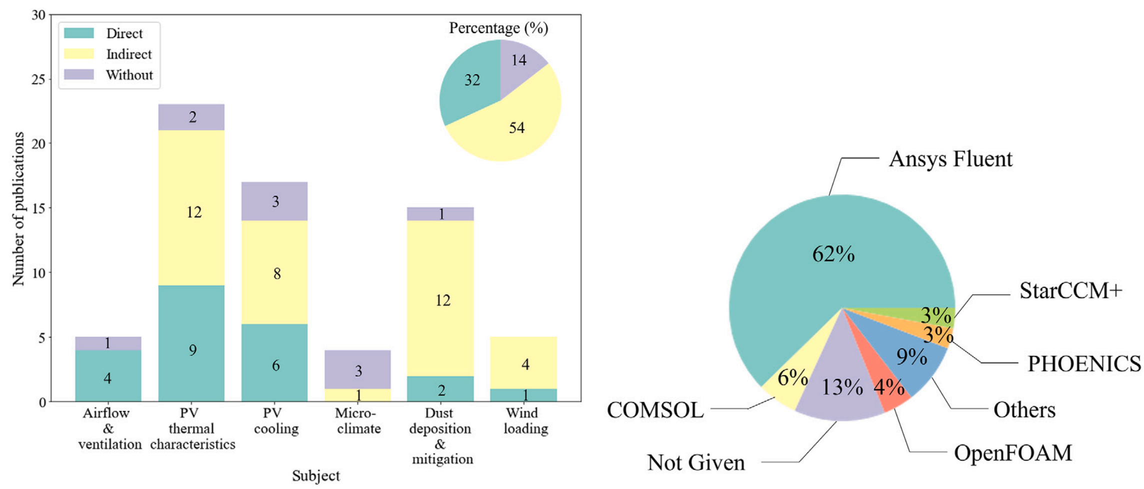
With respect to the heat transfer process, it includes three fundamental modes including conduction, convection and radiation. Fig. 7(f) shows the heat transfer phenomena that were simulated in the reviewed studies. It is found that 29% (20 of 69 studies) of the studies did not involve any heat transfer process in the simulation, demonstrating a majority of isothermal cases for the research concerning dust deposition and wind loading. For these two research subjects, wind force is considered as a dominant factor for both dust dynamics and wind load, and thus the thermal effects were generally neglected. For simulations involving heat transfer process, it can be categorized into four scenarios according to the combinations of the heat transfer modes: sole convection, convection and conduction, convection and radiation, and all three modes together. It is reasonable to find that heat convection was considered in all the non-isothermal studies because it is an essential way for the PV to dissipate heat into the ambient air. Multiple heat transfer processes were simultaneously taken into consideration for the studies concerning the other four subjects. Especially for the research concerning PV thermal characteristics and PV cooling, conductive and/or radiative heat transfer was/were combined with convection. As these two subjects focus on PV thermal behaviours, a detailed and complete heat transfer procedure which mainly involves receiving solar irradiance, heat conduction among solid layers of PV, and heat convection between PV and air, is thus necessary to be included in the simulation. To account for the heat conduction phenomena, PV model was represented by a complex structure involving multiple layers with different solid materials, and a simplified one-way conduction model was commonly applied. As for heat radiation from the sun, it was simulated by either a direct or indirect way. The direct way applied radiation models such as Discrete Ordinates (DO) model [73] (8 studies) and Surface-to-Surface (S2S) model [74] (5 studies) that were provided by the CFD software to compute the amount of heat transferred via radiation. Considering that the radiation simulation is generally computationally expensive, an alternative approach to take the solar radiation into account is to add an equivalent heat flux to the PV surface, which is regarded as an indirect method.

4.4. Target parameters

Considering that studies with different research subjects often have different concerning points which can be revealed by their target parameters in the simulation, we summarized those target parameters for each subject, as listed in Table 3. Here, the three most frequently-observed parameters for each category are listed as representative parameters for analysis and comparison. Air velocity is the most common target parameter, which appears in all the six categories. As air movement significantly affects thermal fields and dust behaviour, it is reasonable that air velocity has received the most interests in the studies. Air temperature and PV surface temperature are important parameters for research concerning thermal fields since these two parameters directly affect the amount of heat convection which is a primary heat transfer process in those studies. On the other hand, for the research regarding dust deposition & mitigation and wind loading, the temperature-related

Table 3
Top three target parameters that are of interests in the studies categorized by research subject.

Subject	Airflow & ventilation	PV thermal characteristics	PV cooling	Micro-climate	Dust deposition & mitigation	Wind loading
Parameter 1	Air velocity (4/5)	Air velocity (10/23)	Surface temperature (10/17)	Air velocity (4/4)	Deposition rate (12/15)	Wind pressure (4/5)
Parameter 2	Air temperature (4/5)	Surface temperature (8/23)	Air velocity (9/17)	Air temperature (3/4)	Air velocity (9/15)	Air velocity (3/5)
Parameter 3	Air flowrate (2/5)	Air temperature (7/23)	Cell temperature (6/17)	Surface temperature (2/4)	Turbulent kinetic energy (9/15)	Wind pressure coefficient (2/5)



(a) (b)

Fig. 8. Summary of (a) validation status of the CFD simulations; (b) software that were applied to conduct the CFD simulations.

parameters are not that important. Wind dynamics-related parameters such as turbulent kinetic energy and pressure coefficient are more important for dust behaviour and load characterization. It should be mentioned that all the target parameters can either be directly extracted from the CFD simulation results (e.g., air velocity, air temperature), or be computed based on other parameters (e.g., deposition rate). The readers can refer to CFD software documents to perform a similar post-processing for further analysis.

4.5. Validation

Validation is crucial to CFD modelling because it is “the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model” [75]. To perform a validation, CFD simulation results are required to compare with the measurement data. Ideally, measurement data should be gained from the physical prototype of the CFD model, which enables a direct comparison of the physical phenomena of interest between measurement and simulation. However, since it could be difficult to obtain measurement data for some specific cases, validation with sub-configuration using data from existing literature or other sources can be carried out for the model, which is defined as an indirect approach in this study (as compared to the direct way). The indirect approach could be very useful when conducting a simulation with complex physical phenomena involved because basic phenomena can be validated with measurement data in separate simple simulations.

According to the review result, 54% of the studies (37 of 69 studies) were conducted with an indirect validation, whereas 32% (22 studies) had a direct validation, and the remaining 14% (10 studies) were without validation, as demonstrated in Fig. 8(a). Both direct and indirect validations were performed in studies regarding PV thermal characteristics, PV cooling, dust deposition, and wind loading. Differently, indirect validation was not done in airflow & ventilation investigations, and PV research on microclimate were without direct validations. Most studies chose indirect validations indicated the difficulty in obtaining corresponding measurement data. Especially for dust deposition and wind loading studies, either conducting a laboratory experiment or performing an on-site measurement for dust quantification &loading and pressure monitoring could be challenging and costly. In comparison, measurements of airflow and temperature for PV thermal characteristics and cooling are easier and more practical, leading to more direct validations being conducted in those studies.

4.6. Software

The emergence of user-friendly and functional-rich CFD software significantly promotes the applications of CFD in various research areas. We summarized the CFD software that were used in modelling the interaction between PV and ambient environment, as shown in Fig. 8(b). Among the 69 studies, nine did not specify the CFD software that the authors used in their research. For the remaining articles, the majority of the studies (43 of 60 studies) selected the commercial program ANSYS Fluent [76] to conduct the simulation. Other software, such as COMSOL [77] and PHOENICS [78], accounts for much less share as compared to ANSYS Fluent. CFD code that was used in only one research was counted as the ‘Others’ category, which includes six programs such as Simcenter FLOEFD [79], SOLIDWORKS Flow [80], etc. Besides, except commercial programs, open-source software and in-house code were also found being used in some studies: with three applying OpenFOAM

[81] and one adopting customized LES code [32]. In general, the selection of the CFD software depends on its functionality, availability, and the user's preference. On the one hand, as most commercial software has version upgrade every year and thus equipped with more powerful functionalities, it could always be an appropriate choice for solving most simulation problems, as illustrated in Fig. 8(b). The user-friendly interface of commercial code makes it easy and convenient to conduct a simulation, which could also be an important reason for its popularity. On the other hand, the limitation in functionality customization and the relatively high price for purchasing a license motivated some users to adopt open-source codes or even write CFD codes by themselves.

5. Discussion

The previous two sections attempt to answer the two crucial questions regarding CFD simulation on the interactions between PV and its ambient environment. This is done by summarizing CFD application cases and setups that were reported in the reviewed studies.

For the cases simulated by CFD, it was found that most simulations (97%, 67 of 69 studies) were conducted in component or building scale while only 2 articles performed a simulation for an urban scale. The selection of simulation scale should rely on the physical phenomena of interest and its impact range. It is thus reasonable to simulate in a component or building scale for studies concerning PV thermal characteristics, PV cooling, dust deposition, wind and ventilation as the heat and mass transfer close to the PV is of concern. Nevertheless, in view of the trend and popularity of adopting PV in the urban area for renewable generation and utilization, the demand for studies on the interaction between PV and urban climate at a larger scale will increase in the coming years. For example, the impact of PV adoption on the urban heat island could be an interesting research topic since both positive and negative impacts were claimed in existing studies [82,83], which deserves a comprehensive investigation. The only one reviewed study that touched upon the related topic considered a computational domain with dimensions of $400 \times 400 \times 120\,\mathrm{m}^3$, where the configuration of building and PV were simplified and geometries were also limited [40]. Since the possible influence from surrounding buildings and PVs were neglected owing to the limited domain scale, the simulation results could be biased or inadequate to reveal the impact of PV. Therefore, it requires an urban scale simulation to investigate and quantify the interaction between PV and the urban climate.

Regarding the physical process simulated in the studies, research for dust deposition and wind loading tended to ignore heat transfer and only involved flow and/or dust dynamics between PV and ambient environment, while studies with other subjects always considered fluid flow and heat transfer but without dust behaviours. For a real-world scenario, the PV installed outside will experience multiple natural phenomena including but not limited to wind blowing, rain falling, dust deposition, dew formation and evaporation, and even vegetation transpiration, which indicates much more complicated interactions between PV and its ambient environment than those considered in the simulations. It is reasonable to exclude part of the interactions in some cases owing to their insignificant effect and the intention to simplify the simulation, as done in the reviewed studies. However, this treatment may not always be appropriate for cases concerning more realistic situations or more complicated PV types. For instance, as a novel configuration, PV-integrated green roof (PVIGR) [84] has received more attentions for its mutual benefits of PV and vegetation interactions. Due to the existence of vegetation under the PV panel, transpiration and its cooling effect on PV should also be taken into consideration in the modelling, resulting in a more complicated simulation. To the best of the author's knowledge, there has not been CFD simulation of complex physical phenomena that involves multiple process such as convection, radiation, evaporation, transpiration, dust deposition that occurred between PV and ambient environment yet. In view of expensive computational cost, performing a simulation either at an urban-scale or involving complicated physical process is impractical at the moment, which highlights the need for developing sophisticated CFD models, boundary conditions, and parameterization methods to enable such kind of study. Meanwhile, the corresponding experimental validation data is also required to verify the new model or treatment and the uncertainty assessment is necessary as well.

Given the review methodology and papers selected, this study has its limitations. The bibliometric information may be updated, as increasingly more studies within the topic are estimated to be published every few months according to the trend demonstrated in Fig. 1(a). Meanwhile, only one database was considered, which could lead to a limited review of more PV-environment interactions and CFD practices. In addition, only articles written in English were reviewed, and research published in other languages such as Chinese, Japanese, French were ignored.

6. Conclusions and future research directions

This paper presents a comprehensive review of CFD investigations on the interactions between PV and its ambient environment, aiming to answer the two research questions: (1) Which interactions can be simulated using CFD? (2) How to simulate those interactions using CFD? Articles published in peer-reviewed international journals within the last decade were retrieved from the database Web of Science, and a total of 69 papers were reviewed. We surveyed the studies based on the simulated PV-environment interactions and the corresponding setups in CFD. From this review study, the following conclusions can be made:

- Interactions between PV and its ambient environment that were simulated using CFD can be categorized into six subjects. Most studies employed CFD for simulations of PV thermal characteristics, PV cooling, and dust deposition & mitigation, whereas less were conducted for airflow & ventilation, wind loading, and microclimate.
- Diversities in setups of CFD in simulation scale, geometry, dimensionality, simulation type, turbulence model, and heat transfer were found. Component scale, PV module geometry, three-dimensional modelling, Reynolds-averaged Navier-Stokes type, and SST k-ω turbulence model are generally favoured in the simulations. Heat transfer was ignored in simulations for dust deposition & mitigation and wind loading, whereas convective heat transfer was considered in all the non-isothermal cases and simulations for PV thermal characteristics and PV cooling generally involved more complicated heat transfer phenomena.

Considering the increasing adoption of PV in urban areas and the more complicated PV integration configurations, research on interactions between PV and urban climate, and mechanism and impact of physical phenomena of the configuration is gaining more interests for environmental concerns and renewable generation efficiency. CFD simulation is anticipated to still play an important role in these studies, however, based on the review results, current treatments in the modelling may only be feasible for simulations at a small scale and with simplified physical phenomena, which may identify future research directions: developing practical treatments which are suitable for a simulation either at an urban scale or involving complex physical phenomena. These treatments could either be simplified models, boundary conditions, or parameterization methods in CFD. In addition, rigorous validation and uncertainty assessment of the treatments should be performed accordingly, which requires data from on-site measurements or laboratory experiments.

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.

Data availability

Data will be made available on request.

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Appendix A

Table A1
Summary of studies on CFD simulation of interactions between PV and ambient environment (listed in chronological order).

Ref.	Research objective	Research subject	Model scale	Geometry	Dimensionality	CD	CV	RD	Simulation type	Turbulence model	Validation
[44]	PEVA	PV thermal characteristics	building	PP+BU	3D	×	✓	×	RANS	Realizable $k-\varepsilon$/ SST $k-\omega$	□
[32]	IMPACT	airflow & ventilation	component	PM+BC	3D	✓	✓	×	LES	Vreman SGS	○
[85]	MDEV	PV thermal characteristics	building	PP	2D	×	✓	×	NG	NG	□
[86]	PEVA	PV thermal characteristics	component	PM+BC	3D	✓	✓	✓	RANS	RNG $k-\varepsilon$	○
[87]	PEVA	PV thermal characteristics	component	PM+BC	2D	✓	✓	✓	RANS	NG	□
[88]	PEVA	PV thermal characteristics	building	PP+BU	3D	×	✓	✓	RANS	Standard $k-\varepsilon$	×
[52]	DOPT	PV cooling	component	PM+BC	2D	×	✓	×	RANS	laminar	□
[89]	PEVA	PV thermal characteristics	component	PM	3D	×	✓	×	RANS	laminar	○
[35]	PEVA	microclimate	building	PP+BU	3D	×	✓	✓	NG	NG	×
[90]	PEVA	PV thermal characteristics	building	PM+BC	3D	×	✓	✓	RANS	Realizable $k-\varepsilon$	○
[49]	DOPT	PV thermal characteristics	component	PP	2D	×	✓	✓	RANS	RNG $k-\varepsilon$	○
[40]	IMPACT	microclimate	urban	PP+BU	3D	✓	✓	✓	URANS	Standard $k-\varepsilon$	×
[37]	IMPACT	wind load	component	PM	3D	×	×	×	URANS	SST $k-\omega$	□
[33]	IMPACT	PV thermal characteristics	component	PP	3D	×	✓	✓	RANS & URANS	SST $k-\omega$	○
[57]	IMPACT	Dust deposition & mitigation	building	PP+BU	2D	×	×	×	RANS	SST $k-\omega$	□
[50]	MDEV	PV thermal characteristics	component	PM	3D	✓	✓	✓	RANS	Standard $k-\varepsilon$	○
[48]	DOPT	PV thermal characteristics	building	PP+BC	3D	✓	✓	✓	RANS	Standard $k-\varepsilon$	□
[46]	PEVA	PV thermal characteristics	component	PM	3D	×	✓	✓	RANS & URANS	SST $k-\omega$	□
[60]	IMPACT	wind load	component	PM	3D	×	×	×	RANS	SST $k-\omega$	□
[91]	PEVA	PV cooling	component	PM	NG	×	×	✓	NG	NG	○
[92]	PEVA	PV thermal characteristics	component	PM+BC	3D	×	✓	×	URANS	Standard $k-\varepsilon$	○
[93]	MDEV	PV thermal characteristics	building	PP+BU	3D	×	✓	✓	RANS	Standard $k-\varepsilon$	□
[54]	PEVA	microclimate	urban	PP+BU	3D	×	×	×	RANS	RNG $k-\varepsilon$	×
[38]	PEVA	PV thermal characteristics	component	PM	3D	✓	✓	×	RANS	SST $k-\omega$	○
[36]	IMPACT	Dust deposition & mitigation	component	PP	2D	×	×	×	RANS	SST $k-\omega$	□
[94]	IMPACT	airflow & ventilation	component	PM+BC	3D	×	✓	×	RANS	Standard $k-\varepsilon$	○
[58]	IMPACT	Dust deposition & mitigation	building	PP+BU	2D	×	×	×	RANS	SST $k-\omega$	□
[95]	DOPT	PV cooling	component	PM	3D	×	✓	×	RANS	Standard $k-\varepsilon$	○
[96]	IMPACT	Dust deposition & mitigation	component	PM	2D	×	×	×	RANS	SST $k-\omega$	□
[97]	PEVA	PV thermal characteristics	building	PP+BU	3D	✓	✓	✓	RANS	Realizable $k-\varepsilon$	□
[98]	IMPACT	Dust deposition & mitigation	building	PP+BU	3D	×	×	×	RANS	RNG $k-\varepsilon$	□
[99]	IMPACT	Dust deposition & mitigation	component	PM	2D	×	×	×	URANS	SST $k-\omega$	□
[61]	IMPACT	wind load	building	PP+BU	3D	×	×	×	RANS	SST $k-\omega$	□
[100]	IMPACT	PV thermal characteristics	component	PM	3D	✓	✓	✓	RANS	Realizable $k-\varepsilon$	□
[101]	PEVA	PV cooling	component	PP	3D	✓	✓	✓	RANS	Standard $k-\varepsilon$	×
[102]	IMPACT	PV thermal characteristics	component	PP	3D	×	✓	✓	RANS	Standard $k-\varepsilon$	□
[34]	DOPT	PV cooling	component	PM	3D	✓	✓	✓	NG	NG	○
[42]	IMPACT	airflow & ventilation	building	PM+BC	3D	✓	✓	✓	RANS	SST $k-\omega$	×
[103]	DOPT	PV cooling	component	PM	3D	✓	✓	×	RANS	SST $k-\omega$	□
[104]	PEVA	PV thermal characteristics	component	PM	3D	✓	✓	×	RANS	Standard $k-\varepsilon$	×
[105]	PEVA	PV cooling	component	PM	3D	✓	✓	✓	RANS	NG	○
[39]	PEVA	PV cooling	component	PM	3D	✓	✓	×	RANS	RNG $k-\varepsilon$	×
[43]	PEVA	airflow & ventilation	component	PM	2D	✓	✓	×	RANS	Standard $k-\varepsilon$	○
[106]	IMPACT	Dust deposition & mitigation	component	PP	3D	×	×	×	RANS	Realizable $k-\varepsilon$	○
[107]	DOPT	PV cooling	component	PM	3D	×	✓	✓	RANS	SST $k-\omega$	□
[55]	IMPACT	microclimate	building	PP+BU	3D	×	✓	✓	RANS	Standard $k-\varepsilon$	□
[64]	PEVA	PV cooling	component	PM	3D	✓	✓	✓	RANS	Standard $k-\varepsilon$	×
[108]	PEVA	airflow & ventilation	building	PM+BU	3D	×	✓	✓	RANS	Standard $k-\varepsilon$	○
[51]	DOPT	PV cooling	component	PM	3D	✓	✓	×	NG	NG	□
[109]	PEVA	PV cooling	component	PM	3D	✓	✓	✓	RANS	Realizable $k-\varepsilon$	□
[110]	IMPACT	PV cooling	component	PM	3D	×	✓	✓	RANS	SST $k-\omega$	□
[111]	IMPACT	Dust deposition & mitigation	component	PP	3D	×	×	×	URANS	SST $k-\omega$	○
[53]	DOPT	PV cooling	component	PM	3D	✓	✓	✓	URANS	SST $k-\omega$	□
[59]	DOPT	Dust deposition & mitigation	component	PM+BA	2D	×	×	×	RANS	SST $k-\omega$	□
[45]	PEVA	PV thermal characteristics	building	PM+BU	3D	×	✓	×	RANS	Realizable $k-\varepsilon$	□
[112]	IMPACT	Dust deposition & mitigation	component	PM	3D	×	×	×	RANS	Realizable $k-\varepsilon$	□
[113]	IMPACT	Dust deposition & mitigation	component	PP	3D	×	×	×	URANS	Realizable $k-\varepsilon$	×
[114]	IMPACT	PV thermal characteristics	building	PM+BU	3D	✓	✓	✓	RANS	RNG $k-\varepsilon$	□
[63]	PEVA	wind load	building	PP+BU	3D	×	×	×	NG	NG	□
[115]	IMPACT	PV thermal characteristics	component	PP	2D	×	✓	✓	RANS	Standard $k-\varepsilon$	○
[116]	DOPT	PV cooling	component	PM	3D	×	✓	✓	RANS	RNG $k-\varepsilon$	○

Table A1 (*continued*)

Ref.	Research objective	Research subject	Model scale	Geometry	Dimensionality	CD	CV	RD	Simulation type	Turbulence model	Validation
[62]	IMPACT	wind load	component	PP	3D	×	×	×	URANS	SST $k-\omega$	○
[117]	DOPT	Dust deposition & mitigation	component	PM	3D	✓	✓	✓	URANS	Low Re	□
[41]	IMPACT	Dust deposition & mitigation	component	PM+BA	3D	×	×	×	RANS	SST $k-\omega$	□
[47]	DOPT	PV thermal characteristics	component	PM	3D	×	✓	×	URANS	Standard $k-\varepsilon$	□
[118]	DOPT	Dust deposition & mitigation	component	PM+BA	2D	×	×	×	RANS	SST $k-\omega$	□
[119]	PEVA	PV cooling	component	PM	3D	✓	✓	✓	URANS	SST $k-\omega$	○
[120]	DOPT	PV cooling	component	PM	3D	✓	✓	✓	RANS	RNG $k-\varepsilon$	□
[121]	IMPACT	Dust deposition & mitigation	component	PM	3D	×	×	×	RANS	Realizable $k-\varepsilon$	□

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