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Review article

Cutting-edge developments in active and passive photovoltaic cooling for reduced temperature operation

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ABSTRACT

Considering the substantial increase in deployment, photovoltaics are hovering to emerge as the predominant worldwide energy producer in the foreseeable future. Nevertheless, the operating efficiency and endurance of photovoltaic (PV) systems are significantly stalled by the heightened operating temperatures encountered by solar radiation. This article comprehensively analyzes novel active and passive PV cooling techniques, encompassing their operational mechanisms, cooling efficiency, and eventual implementations in solar devices. Extensive scholarly research has examined various PV cooling methods and techniques to optimize system cooling and efficiency. The primary goal of this effort is to compile a reference for future researchers and specialists by reviewing and comparing the results of current investigations. The study also comprised a bibliometric analysis that provides valuable insights into the influence of research on incorporating cooling systems into solar systems. These insights play a decisive role in recognizing new trends and progressing the field towards more efficient systems, hence advancing upcoming development. Furthermore, an extensive classification and assessment of every conceivable cooling technology was furnished to facilitate a comparison among diverse cooling methodologies. The research was structured in a tabular manner, containing the following details for each cooling technique: solar panel type, cooling method, cooling fluid or substance used, research category, average temperature reduction resulting from cooling, and enhanced electrical efficiency. The study indicates that cooling methods significantly enhance electrical efficiency, with potential increases varying from 0.28 % to 97.6 %. Additionally, this application is assessed to decrease the solar panel's operative temperature, ranging from 0.8 °C to 39.9 °C.

Abbreviations:

PV	Photovoltaic
PVCE	Photovoltaic conversion efficiency
Sim.	Numerical simulation
Exp.	Experimental work
Th.	Theoretical work
SC	Spray cooling
DC	Duty cycle (on/off time ratio)

Nomenclature:

CO_2	Carbon dioxide
Al	Aluminum
Al_2O_3	Aluminum dioxide
Cu	Copper
TiO_2	Titanium oxide
CuO	Copper oxide
Fe_2O_3	Iron oxide
MWCNT	Multi-walled carbon nanotube
EG	Ethylene glycol
TEG	Thermoelectric generator
CNT	Carbon nanotube
PCM	Phase change material
TE	Thermoelectric
PDMS	Polydimethylsiloxane
PET	Polyethylene terephthalate
RT55	Rubitherm® PCM RT55
RT27	Rubitherm® PCM RT27
OM29	savENRG™ PCM-OM29
MgO	Magnesium oxide
GaSb	Gallium antimonide
$T_{s,t}$	Top surface temperature
$T_{s,b}$	Bottom surface temperature
$\dot{q}$	Internal heating

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CLPHP	Closed-loop pulsing heat pipe	P_{rad}	Heat radiated from the surface
PHP	Pulsating heat pipe	P_{atm}	Heat absorbed from the atmosphere
FPVS	Floating Photovoltaic System	P_{sol}	Heat generated from the sun
		$q_{c,t}$	PV cell upper surface convective heat flux
		$q_{b,t}$	PV cell lower surface convective heat flux

1. Introduction

Energy is a crucial prerequisite for the expansion of the global economy and is currently in great demand. Nevertheless, fossil fuels provide 75 % of the total energy production, so contributing to the escalation of CO_2 emissions and the phenomenon of global warming. To mitigate this issue and reduce dependence on fossil fuels, there is an international initiative to transition to renewable energy sources [1–3]. Globally, numerous CO_2 emission reduction strategies have been implemented. Solar energy is an indisputable option for reducing CO_2 emissions due to its widespread availability and inexpensive cost [4]. Photovoltaic (PV) cells, which are composed of semiconducting materials, are employed to convert the energy from solar radiation into electricity [5]. PVs are favored for electricity generation because they lack moving elements, generate no noise or pollution, have a lengthy lifespan, and convert solar radiation directly. PV panels comprise various components and systems, each serving a significant function and possessing distinct properties. A visual of the constituent elements of a solar panel and a PV system is illustrated in Fig. 1.

While photovoltaic technology offers various advantages, it also faces several fundamental challenges. These include susceptibility to damage from hail, accumulation of dust on the front, and an increased operational temperature, significantly diminishing the system's performance. High temperatures can negatively impact electric generation efficiency in current PV technology, resulting in decreased energy production. To resolve this issue, novel solutions that integrate passive, active, and combined cooling systems have been devised [7,8]. These systems aim to demote the operating temperature of solar panels, thus augmenting energy production. The active cooling approaches in the research involved forced convection cooling, which applied air [9], water [10], and nanofluid [11] as cooling fluids. Active cooling configurations achieve precise temperature control [12] and optimize operational efficiency by employing fans and pumps to circulate cooling fluid. Alternatively, passive cooling systems utilize natural convection without requiring additional energy input. They are generally more straightforward to set up and can sometimes be a more cost-effective option [8].

1.1. Motivation for the present review

The main focus of this study is to examine the impact of different cooling methods on the efficiency of solar panels. To the best of our knowledge, there are no review papers in the existing literature that are comparable to this investigation, particularly within the scope of this study. Existing literature has extensively covered research and reviews on photovoltaic cooling. However, as far as the authors are aware, no review articles comprehensively address simultaneously bibliometric literature review, active, passive, and hybrid solar panel cooling technologies, and current developments in photovoltaic cooling methods, specifically focusing on research undertaken in the last ten years. Furthermore, while the literature contains review papers on the subject in a broad sense, this study specifically focuses on studies that investigate the cooling of solar panels using different methodologies.

This article provides a comprehensive discussion of several techniques used to cool photovoltaic panels. This study accomplishes a bibliometric analysis utilizing Scopus data from 2014 to 2023. Diverse statistical approaches are used to examine the data, which are graphically shown using bar charts and keyword mapping. This review study thoroughly examines various cooling approaches associated with PV cooling and separately analyzes their impact on reducing operational temperature and increasing electrical efficiency. Based on the evaluation of several techniques and their impact on the performance of PV panels, major challenges in photovoltaic cooling are identified and recommendations are provided to further improve their efficiency and lower their working temperature.

2. Bibliometric analysis

Bibliometric analysis is a widely used and rigorous approach for investigating and examining enormous quantities of scientific information. This facilitates the analysis of the complex evolutionary characteristics of a certain subject, while also shedding light on the emerging areas within that discipline [13,14]. Bibliometric analysis evaluates research impact, productivity, trends, and gaps, providing valuable information for financing organizations, educational establishments, investigators, and potential areas for future investigations. It utilizes mathematical and statistical methods to assess scientific publications by focusing on their exterior properties [15,16]. This technique utilizes citation mapping to quantitatively synthesize a study topic and offer valuable insights into the primary research streams [17,18]. This study explores the current status of PV panel cooling methods using bibliometric analysis, which involves the use of visual inspection along with mathematical and statistical tools. The objective is to explore the distribution of literature on the subject, analyze quantitative linkages, examine the research structure, investigate financial factors, and assess author contributions.

2.1. Acquiring, filtering, and presenting data for bibliometric analysis

This study utilized the Scopus database due to its extensive coverage of engineering papers, which outweighs that of the Web of Science database [19,20]. A comprehensive search strategy was implemented for the bibliometric study, encompassing numerous keywords pertinent

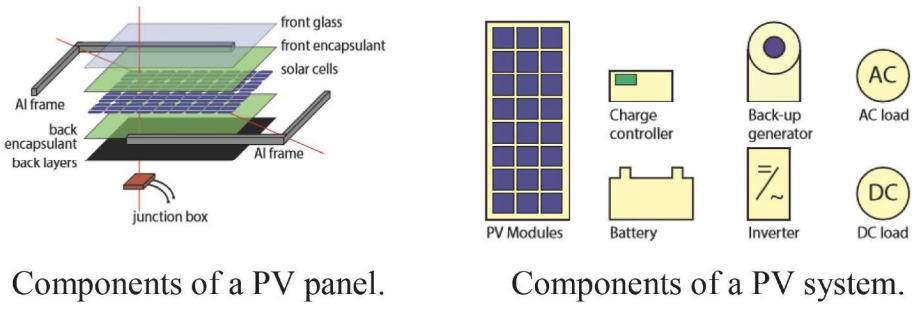

Fig. 1. A visual depiction of parts of a solar panel and a solar power system [6].