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A Comprehensive Review and Comparison of Cooling Techniques for Photovoltaic Panels: An Emphasis on Experimental Setup and Energy Efficiency Ratios

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Abstract

This study delves into exploring and comparing various cooling technologies for PV panels, with a special focus on revealing the harmful effect of excessive heat absorption on solar energy efficiency. Effective temperature management and dissipation of excess heat are essential to protect the integrity of PV panels and improve power generation. With a strong emphasis on the importance of experimental setups, this comprehensive research examines the methodologies and cooling methods used across a wide range of experimental studies, illustrating the complexities of data collection and analysis. Supported by schematic illustrations depicting various experimental setups, this study demystifies the complexities inherent in distinct PV cooling methods. Furthermore, the research extends beyond experimentation to include a comprehensive examination of the energy and economic aspects associated with various cooling technologies, including the calculation and presentation of energy efficiency ratios. It is worth noting that the results confirm the superiority of passive cooling techniques, including heat sinks (43%), PCM (25), evaporation techniques (36%), and spray cooling systems (54%), in contrast to active cooling methods, as indicated by their net energy efficiency ratios. Passive cooling is advantageous for its low maintenance and cost-effectiveness, whereas active cooling, though effective in hot climates and enhancing PV efficiency, incurs higher initial costs and maintenance requirements. The novelty of this research lies in its detailed classification of cooling techniques and the specific materials used for each method, coupled with a thorough examination of the measuring tools employed. Furthermore, this study includes a comprehensive comparative analysis based on energy and economic aspects, alongside the advantages and disadvantages of each cooling technique. These invaluable insights hold the potential to revolutionize the development of efficient and dependable cooling strategies for PV systems, thereby elevating the feasibility and sustainability of solar energy as a pivotal cornerstone in our future energy landscape.

Keywords: Heat absorption, PV panels cooling, Experimental setups, Energy efficiency, Feasibility, Passive cooling, Active cooling.

1. Introduction

As global energy demand continues to rise and the environmental impact of fossil fuels becomes more apparent, the pursuit of sustainable and renewable energy sources has become critical

[1,2,3,4]. Among these sources, photovoltaic technology has emerged as a promising solution for harnessing the abundant and clean energy from the sun. Photovoltaic systems made up of solar panels that convert sunlight into electricity through semiconductor materials, provide a renewable, environmentally friendly path to meeting our growing energy needs.

However, despite its enormous potential, PV technology faces significant challenges that hinder its efficiency and reliability. PV panels often suffer from low conversion efficiency due to various factors, including dust [5], reflection [6], shading [6], and temperature [7-8]. Among these factors, temperature plays a crucial role, as photovoltaic cells convert only the visible part of the light into electrical energy, while the rest, especially infrared light, is converted into thermal energy. This excess heat can be harmful to PV panels, reducing their performance and lifespan. Excessive heat can not only reduce the efficiency of these panels but also shorten their service life, resulting in reduced power output and possible permanent damage. Therefore, finding efficient and reliable cooling methods for PV systems has become essential [9-10].

In response to this challenge, scientists and researchers around the world have embarked on a mission to develop innovative cooling technologies to enhance the efficiency and longevity of photovoltaic panels. This endeavor has given rise to a variety of cooling methods, ranging from natural and passive cooling methods to more advanced and active solutions that use liquid cooling and forced convection. As a result, a large number of research studies have been conducted in the field of photovoltaic cooling.

Several research papers have concentrated on specific aspects of cooling techniques. For example, Bhaker, S.S. [11] delved into water-based cooling methods, while Yahya Sheikh et al.[12] enhanced the efficiency of solar panels by integrating a passive multi-layered PCM cooling system. Salehi, R. et al. [13] investigated the performance of solar cells cooled using a heatsink and nanofluid augmented with aluminum nanoparticles, and Charbel Habchi, et al. [14], Studied the performance of PV panels with parallel water pipe integration. Furthermore, Siah Chehreh Ghadikolaei, S. [15], provided a comprehensive review of cooling methods, although thermal and evaporative cooling methods were not extensively covered. Yuanlong et al. [16] conducted a thorough assessment of PV/T systems using phase change materials, taking into account external, energy, economic, and environmental factors. Ali Salari et al. [17] carried out an up-to-date review of the performance analysis of thermo-PV systems employing nanofluids, with a focus on energy, electricity, economic, and environmental (4E) considerations. Hussain Madhi et al. [18] reviewed photovoltaic/thermal systems employing mono nanofluids and hybrid nanofluids for cooling purposes.

This comprehensive study is dedicated to the thorough examination and comparison of various cooling technologies for PV panels, with a primary focus on experimental setups. It delves deeply into the methodologies and cooling materials employed in a wide range of experimental papers. What sets this research apart is its detailed exploration of the specific classification of cooling techniques and the materials used for each method, accompanied by a thorough examination of the measuring tools employed. The study also provides detailed insights into the measurement tools, shedding light on the intricacies of data collection and analysis. Furthermore, this research extends beyond experimentation to encompass an in-depth exploration of the energy and economic aspects associated with different cooling techniques. Energy efficiency ratios are meticulously calculated and presented, allowing for meaningful comparisons among these methods in terms of both cost-effectiveness and net electrical energy improvements. With a dedication to offering clear and accessible insights, this paper includes numerous schematic illustrations depicting various experimental setups, this study aims to illuminate the complexities of various PV cooling methods. The valuable insights gained from this research hold the potential to revolutionize the development of efficient and reliable cooling strategies for PV systems, thus advancing the feasibility and sustainability of solar energy as a crucial component of our future energy landscape.

2. Summary of PV Cooling Techniques

In the field of solar panel cooling technologies, various methods utilizing different materials are employed to optimize thermal management. The flow chart below (Fig. 1) illustrates the classification of cooling techniques based on the main materials used for such applications.

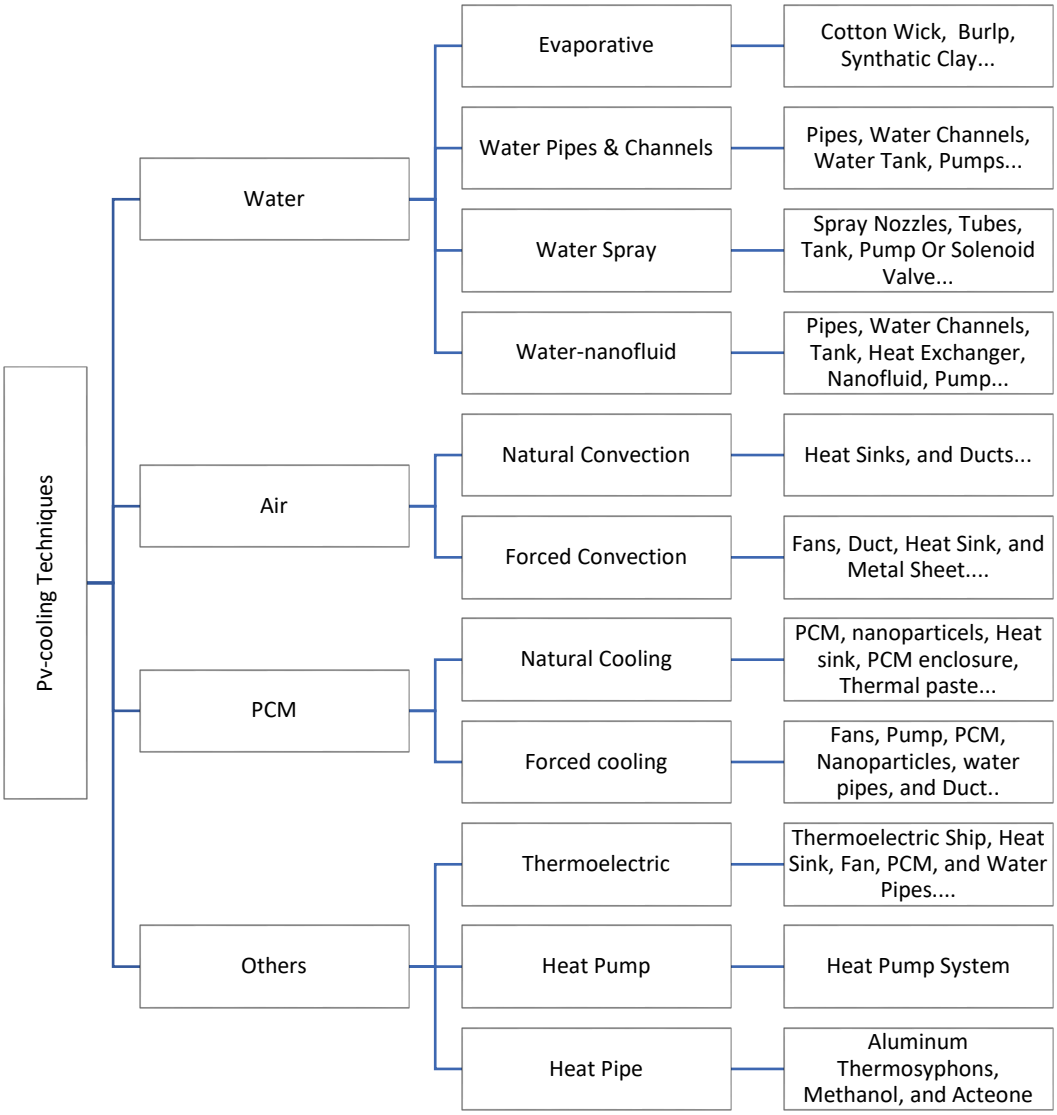

Fig. 1: Classification of PV-cooling techniques based on the main materials used for such cooling techniques.

This chart categorizes cooling techniques based on the primary materials utilized for cooling applications. It illustrates various methods such as Phase Change Materials (PCMs), heat sinks, water pipes, and other systems employed for managing thermal energy in PV systems. Each category represents different approaches to optimizing energy usage and enhancing the efficiency of solar panel cooling.

3. Experimental Setup for Various Cooling Methods

3.1. Water cooling Methods

Water cooling methods have emerged as pivotal solutions in enhancing the efficiency and longevity of photovoltaic systems, offering an effective means to counteract the adverse effects of elevated operating temperatures on PV panels. Water-based cooling techniques, including evaporation, water cooling tubes, water cooling channels, and water nanofluid cooling technologies, have garnered significant attention due to their potential to maintain optimal operating conditions for PV arrays. This article delves into the realm of water cooling methods in the context of photovoltaics, exploring the diverse technologies, materials, experimental setups, and outcomes associated with these cooling approaches. By comprehensively examining these cooling methods, we aim to provide valuable insights into how water-based cooling strategies can significantly enhance the performance and reliability of PV systems in diverse environmental conditions.

3.1.1. Evaporative techniques

Utilizing evaporative cooling techniques offers an effective solution for mitigating the adverse effects of elevated temperatures on photovoltaic systems. These methods maintain lower operating temperatures for PV panels by employing heat exchange through water evaporation. In this process, water is applied to a porous material attached to the backside of the PV panels. As the water evaporates, it absorbs heat from the panels, thereby lowering their temperature. Researchers have explored various materials, techniques, and experimental setups to enhance the performance and efficiency of PV systems through evaporative cooling. A typical experimental setup (as shown in Fig. 2) includes essential components such as a water tank, cotton wick, and an array of measurement instruments like flow meters, K-type thermocouples, pyranometers, data loggers, multimeters, humidity sensors, and weather stations. This comprehensive suite of tools and materials ensures precise data collection and assessment of the effectiveness of evaporative cooling in PV applications.

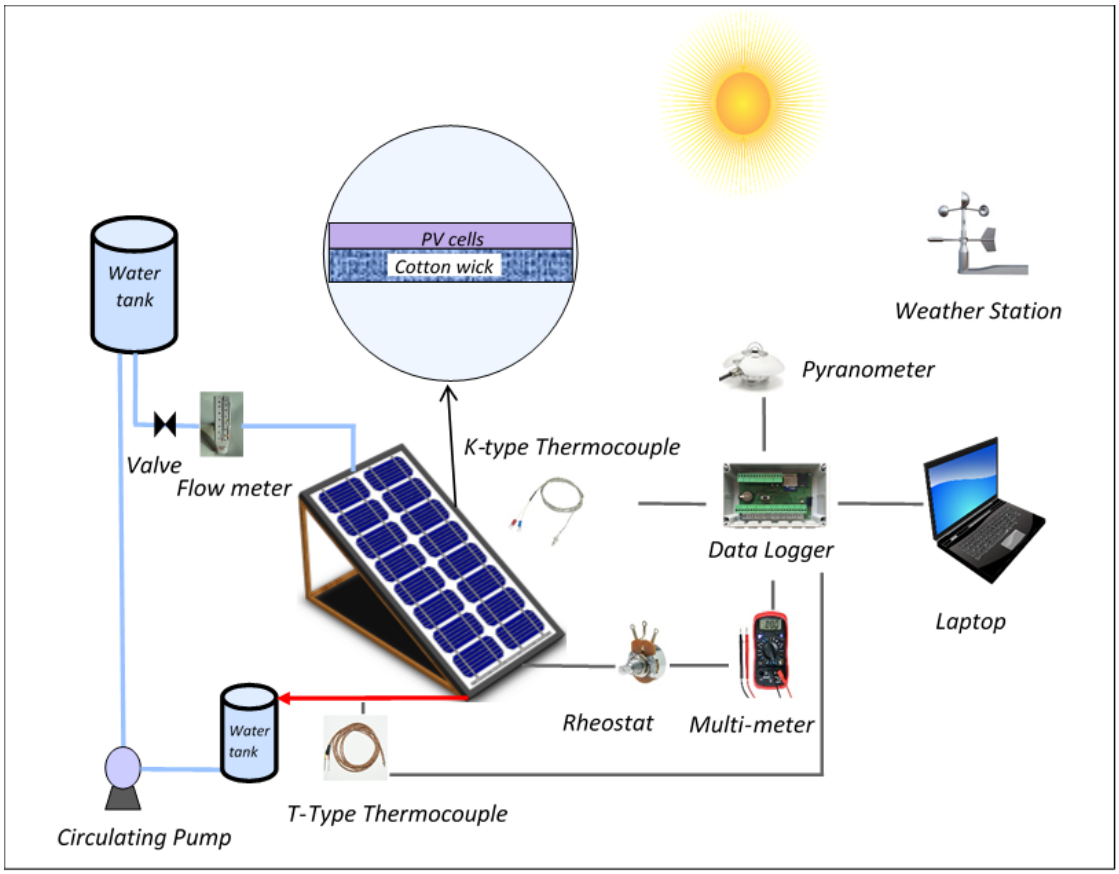

Fig. 2: Schematic representation of an experimental setup for cooling photovoltaics using the evaporation technique.

Below is a summary table presenting an overview of various evaporative cooling methods applied to photovoltaic technologies, including the cooling materials used, the measurement tools employed, and the key results obtained from each study.

Table 1: Evaporative Cooling Methods in Photovoltaic Systems: Materials, Measurements, and Outcomes.

Authors	Cooling Methodology	PV Technology	Cooling Materials	Measurement Tools	Key Findings
Mustapha Dida et al. [19]	Burlap attached to PV back surface	Polycrystalline silicon PV modules (80 W)	Burlap cloth, water tank, elastic pipe	Variable resistor (PHYWE SE6), Digital multimeters (METEX ME-31), K-type thermocouples, data logger (Keithley 2750), pyranometer (LP02), hot wire anemometer (Testo 425)	Temperature decreased by 20°C, η_el increased by 14.75%.
M. Chandrasekar et al. [20]	Cotton wicks attached to PV back	Single crystalline silicon cells (50 Wp)	Cotton wick, water, Al2O3/water nanofluid, CuO/water nanofluid, water tank	K-type thermocouples with a resolution of 0.1°C, channel temperature indicator, Multi-meter for measuring module power output, 1000 Ohm resistor	Cotton wick increased electrical efficiency by 1.4%, nanofluids decreased efficiency.
M. Chandrasekar et al. [21]	Heat spreader with cotton wick attached to PV back	Single crystalline silicon cells (25 Wp)	Aluminum heat spreaders, PVC pipes	Digital multi-meter, K-type thermocouples with channel temperature indicator, rheostat (100 Ohm and 1.25 A), solar	Temperature decreased by 12%, electrical yield increased by 14%.

				pyranometer, PVC pipes (100 mm diameter)	
Abdul Hai Alami [22]	Synthetic clay and aluminum support	Monocrystalline and bus bar cells	Synthetic clay, Thermal grease, electrical tape, aluminum layer	Xenon Arc Lamps, K-type thermocouples (for cell T), T-type thermocouples (for room T), digital hygrometer (Hygroset) for humidity, VSP-300 potentiostat, Apoogee SP-230 Class-I Pyranometer	Temperature lowered from over 28°C to about 10°C, and energy production increased by 34.6%.
M. Lucas et al. [23]	Photovoltaic evaporative chimney	Poly-crystalline silicon PV modules (255 Wp)	Tank, PVC pipes, pump, flat spray nozzles, Vlaves, Filter, electrical heater (1.5 KW)	Grid-tied micro-inverter (APsystems YC500A), electrical resistance of 750 W, Arduino microcontroller, first class pyranometer, K-type thermocouples, data acquisition unit Agilent 34972, other data from a meteorological station	Electrical efficiency increased by an average of 4.9%, up to a maximum of 7.6%.
Zeyad A. Haidar et al. [24]	Cloth attached to PV with water flow	Crystalline silicon modules (75 Wp)	Cloth, rubber pipes, water tank, valve to control water flow, aluminum bars to support pipes, wooden frame to hold PV	K-type thermocouples (TME brand), Pico data logger, first-class SR11-05 pyranometer	Temperature lowered by over 20°C, electrical efficiency increased by about 14%.
Ephraim Bonah Agyekum et al. [25]	Cotton wick mesh attached to PV back	Crystalline silicon modules (30 Wp)	Cotton wick mesh, silicone gel, water tank, PVC pipe tube, universal sealant moment silicone gel (white), aluminum metal sheet	K-type thermocouples with a resolution of 0.1°C, SD logger 88598, GM 1362-EN-01 thermometer for measuring ambient temperature, Tenmars TM-207 pyranometer, clamp meter to measure current and voltage, Testo 875 camera to record infra-red thermal images	Temperature lowered by 23.55°C, power output increased by 30.3%, electrical efficiency improved by 1.53%.
A. Almuwailhi et al. [26]	Wet fabric in a cooling duct	Polycrystalline silicon PV (320 Wp)	Fabric, cooling channel, fans, axial flow fans, submerged water pump, water tank, and nozzles to spread water on the fabric	T-type Thermocouples, data logger (Agilent 34972A), Pacer DA400 anemometer, microinverter (Enphase IQ7) for generating loads, Maximum power point tracking (MPPT), thermal camera (FLIR-T440)	Electrical efficiency increased by 1.2% to 4% under various cooling conditions.

Table 1 presents a diverse range of experimental methodologies employed to enhance the efficiency of photovoltaic systems through innovative cooling techniques. These studies primarily focus on PV panels of varying sizes (25Wp-320Wp) and technologies and aim to reduce their operating temperatures to improve energy production. Several cooling materials and tools are utilized in these experiments, including cotton wicks, synthetic clay, burlap cloth, and fabric, each with unique applications and outcomes. The instruments employed for measurements encompass a variety of temperature sensors, data loggers, and pyranometers, ensuring precise data collection. Notably, these cooling methods yield promising results, with temperature reductions ranging from 10°C to over 23°C, leading to considerable enhancements in electrical efficiency, up to 14 %. Evaporative cooling, facilitated by water flow through fabrics or wicks, emerges as a particularly effective approach, with studies reporting significant improvements in PV performance under

both natural and forced convection conditions, highlighting its potential for practical application in PV installations.

3.1.2. Water pipes and cooling channel

Water pipes and cooling channels constitute specialized techniques within the realm of water cooling methods for photovoltaic systems. In these techniques, water is circulated through pipes or channels that are in contact with the PV panels, effectively cooling them by absorbing their heat. The heated water is then collected and can be reused for domestic purposes or other applications, thus enhancing the overall efficiency and sustainability of the system. In this section, we delve into the unique attributes, materials employed, and experimental setups designed to evaluate the effectiveness of water pipes and cooling channels in maintaining ideal operating temperatures for PV modules. Fig. 3 provides a schematic representation of an experimental setup designed for photovoltaic water cooling using copper pipes and cooling channels. This setup is crucial for assessing the effectiveness of water-based cooling methods in maintaining optimal operating temperatures for photovoltaic panels.

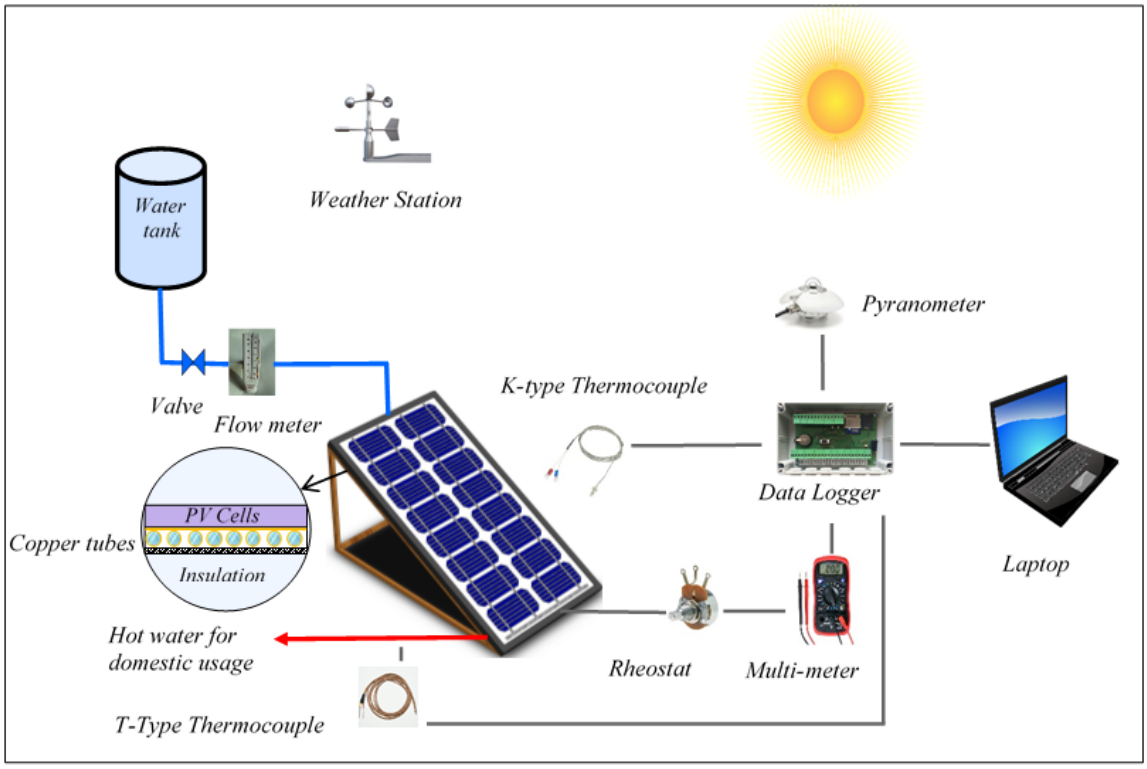

Fig.3: Schematic Representation of an Experimental Setup for Cooling Photovoltaic Panels Using Pipes and Cooling Channels.

In the following table, we provide an overview of various cooling techniques employed to enhance the efficiency of photovoltaic systems, with a specific emphasis on the materials, measurement tools, and the main results.

Table 2: Water Pipes and Cooling Channels in Photovoltaic Systems: Materials, Measurements, and Outcomes.

Authors	Cooling Methodology	PV Technology	Cooling Materials	Measurement Tools	Key Findings
Bhaidara et al. [27]	They utilized a cooling panel with inlet and outlet water flow, connected to the	Mono-crystalline type with a 230W rated power.	Cooling panel, insulated tank, PVC (Polyvinyl Chloride) pipes, water pump (0.5	K-type thermocouples, flow-meter (Max 3.6 L/min), two batteries (12V, 80A), MPPT (Sunsaver), DC bulbs (24	Lowering the temperature to about 20% resulted in an increase in the

	backside of a PV module		hp), bypass system that regulates the pressure.	V 70 W) as a load, Pyranometer, Hydro-thermo-anemometer, Thermocouple thermometer.	electrical efficiency by 9%.
M.M. Rahman et al. [28]	They attached a finned tube heat exchanger to the back of a Monocrystalline solar module.	Monocrystalline solar module model SY-90M with a maximum power of 90 W.	90 OSRAM halogen bulbs forming a solar emulator, Heat exchanger consists of seven circular parallel copper tubes, Centrifugal pump of model Pentax CP45 (5–35 L/min), and Cooling radiator.	Digital dataTaker (model DT80), MPPT was used to measure the outputs of the PV module, Flow meter (model LZB-10B, capacity 16–160 L/h), Two PTFE exposed welded-tip K-type thermocouples, Pyranometer LI-COR PY82186, Humidity sensor HU1030NA.	Lowering the temperature from 56°C to 22.4°C increases the electrical efficiency by 15.72 %.
A. E. Kabeel et al. [29]	They cooled the PV panel with a sun reflector by using an air-cooling duct installed on the top side and a water-cooling system attached to the bottom side of the PV panel.	Polycrystalline silicon type with a maximum power of 130 W.	Rectangular wooden box with 30 mm thickness, Clear float glass cover 3 mm thickness, Cooling water distribution system, Cylindrical pipe of 90 mm diameter to control air cooling, Two flat reflectors, DC 5W water pump, DC 10W air blower at a rate of 61 m3/h.	K-type thermocouples, Solarimeter, Calibrated container, Vane anemometer.	Using the reflector alone, reflector and air-cooled, reflector and water-cooled, and reflector with both air and water-cooled, power output improved by 16.81%, 21.62%, 35.13%, and 39.69%, respectively.
Ahmed N. Shmroukh [30]	Copper tubes were attached to the rear of the PV module in various configurations: (a) open-loop, (b) closed-loop natural convection, and (c) closed-loop forced convection.	Thin-film type with 38 Wp (SCHOTT Solar Panel).	Thick wooden frame, 3/8-in-diameter copper pipes, 1-inch-thick glass wool insulation, Insulated DC pump (12-V, 4.3 W, 1.5 l/min), Galvanized steel water tank, Fin-and-tube heat exchanger, Axial flow cooling fan (12-V, 2.1-W).	Pressure gauge (0–15 bar), K-Type thermocouples (-50 °C to 150 °C), Avometer A2F1, Pyrometer CM4, Infrared camera IC120LV (384×288 Pixel), Water volume flow rate laboratory-graded glass bottle, Anemometer UT363 (0–30 m/s), Humidity probe HTC.PT.2H (1%–99% RH).	The use of an open-loop water cooling system resulted in an increase in electrical efficiency by 5.1%.
Kamal Singh et al. [31]	The cooling system installed at the back side of the photovoltaic module consists of copper tubes mounted on an absorbent copper plate.	Polycrystalline silicon with a peak power of 10 Wp.	Copper absorber plate (32×19mm), Copper pipes, water tank of 15L, polystyrene as insulation, 240 V AC water pump.	Flow meter, Digital thermocouple, multi-volt meter.	Lowering the temperature by 15.23% resulted in an increase in electrical efficiency by 6.08%.
Linus Idoko et al. [32]	The water-cooling system consists of (a) an aluminum heat sink at the back side of the PV module, and (b) manually spray ice water on the front side of the PV module.	Two Suntech 250 watts solar PV module.	Watering can, Ice blocks, Aluminium heat sink, Thermal grease, Set of Spanners, Measuring tape, Long nose & combination plier, PV module stand, Flexible cable.	Infrared thermometer, Al 300 data logger (6 channels), Four multimeters, Meteon Irradiance meter with Pyranometer, Two rheostats (variable resistors).	Reducing the surface temperature to 20°C resulted in an increase in output power by 20.96W and improved electrical efficiency by at least 3%.
Ahmer A.B.	They used a convergent cooling channel installed at	Monocrystalline silicon type	Converging channel with an angle of 2°, Heat exchanger,	Maximum power point tracker (SOL-1), Eight Type K calibrated	Lowering the temperature significantly from

Baloch et al. [33]	the back side of the PV.	(Sun Power C60).	Glasswool insulation, Water flow rate of 1.8 Lpm., 12 V battery, Load.	thermocouples, Data Acquisition (DAQ) system, Pyranometer (CMP 22), Anemometer (05103L Wind Monitor), Radiation shield (41382LC2), Flow meter (FTB-1300 Series), Current Transducer.	71.2°C to 45.1°C resulted in a maximum percentage increase in conversion efficiency of 36.1%.
Diego Vittorini et al. [34]	They fixed a serpentine tube to the rear side of the module through a conductive layer.	Photovoltaic module with a maximum power of 170 Wp.	The cooling circuit consists of 1/8 in bent coiled copper pipe, Pump, Pipes, Thermal grease, and a conductive layer.	Thermocouple K-type, Maximum Power tracker, Flow meter, Resistive Load, Pressure sensor, Infrared camera, Meteo Station, and Data Acquisition system.	Thermal recovery for cogeneration purposes was found to be ineffective, but it was possible to achieve an electrical efficiency of 20% with a 33% improvement.
Ashish Saxena et al. [35]	They attached a copper tube with a length equal to the width of the PV panel, featuring 8 holes of 1 mm each, to the top of the panel.	Photovoltaic module with a maximum power of 40 Wp.	Water tank of 50 liters capacity, Copper tube, Pipe, Control valve.	A thermocouple, Constant resistance of 115.5 Ω, Data logger, Convertor equipped with maximum power point tracking (MPPT) device, 6 halogen bulbs (of rated capacity of 150 W each), Pyranometer.	The total energy output increased by approximately 29% when compared to an uncooled photovoltaic system.
Qi Shi et al. [36]	They cooled the PV from the rear side by an insulated cooling duct consisting of aluminum sheets, copper tubes, and thermally conductive silicone.	Monocrystalline silicon module with peak power of 100 Wp.	Water tank, Water pipes, Valves and electricity output system, Copper tubes, Insulation layer, Aluminum sheet, Thermal conductive silicone.	Solar simulator, Data logger GL800, Pyranometer MS-802 (0-4000W/m2), Thermal resistance Pt100 (-200-400°C), Glass rotameter/Flow meter LZB-15 (40-400L/h), Curve tracer MP-170, I-V checker MP170 (1000V/20A).	The collector achieved an annual efficiency of 44.2%, while the annual electrical efficiency was 10.2%.
Afroza Nahar et al. [37]	They used a photovoltaic module with a cooling channel.	LB250QM-60 polycrystalline silicon (p-Si) PV panel 250 Wp.	Overhead reservoir tank, Water pipes, Cooling channel.	LI-COR PY82186 model silicon pyranometer, I-V tracer is used for measuring module output, Flow meter LZB-10B, PTFE exposed welded-tip K-type thermocouples, Data Taker DT80 model data logger.	The maximum overall efficiency of the PV/T system was found to be 84.4% using numerical analysis, while empirical values gave a slightly lower efficiency of 80%.
Guilherme Zanlorenzi et al. [38]	They used a serpentine copper cooling tube attached to the back side of the PV.	Polycrystalline (M Prime 3 R Plus da Martifer Solar) with 250 Wp.	Water pump, "L" fastening brackets, Styrofoam filling, Aluminum Foil serpentine coating, 3/8" Copper pipe serpentine.	Temperature sensor LM35, Solar Inverter, Utility Grid, Battery Bank, Data Acquisition Device, Controller Device.	The average operating temperature was reduced by 8.83 °C, representing an 11.42% reduction. This resulted in an 8.22% improvement in output power and an average efficiency improvement of 33.28%.

This table offers an overview of diverse cooling techniques employed to boost photovoltaic system efficiency. It encompasses various PV sizes (10Wp-250Wp) and technologies, materials, measurement tools, and their corresponding outcomes. These studies demonstrate the adaptability of cooling techniques across PV technologies like mono-crystalline, thin-film, and polycrystalline

systems. Researchers employ a spectrum of materials, from copper tubes to wooden frames, emphasizing flexibility in material selection. An array of measurement tools, including thermocouples, flow meters, and pyranometers, ensures precise data collection. The results show significant improvements in electrical efficiency due to temperature reductions ranging from 3% to 34.1%, affirming the potential of cooling methods to enhance PV system performance across diverse setups.

3.1.3. Water spray cooling techniques

Water spray cooling techniques are useful in improving the performance and efficiency of PV systems, especially in hot, arid, and dusty environments. These methods not only cool the PV modules effectively but also serve the dual purpose of keeping them clean. Fig. 4 shows an experimental setup designed to cool PV systems using spray nozzles, which include a water tank, spray nozzles, a solenoid valve, and a filter. Basic measuring instruments such as K-type thermocouples for PV temperature monitoring, T-type thermocouples for water temperature, flow meter, Arduino data logger, rheostat, pyranometer, and weather station are integrated into the system. This comprehensive setup allows the cooling process to be precisely monitored and controlled, ensuring efficient temperature reduction and improved energy conversion, even under challenging environmental conditions.

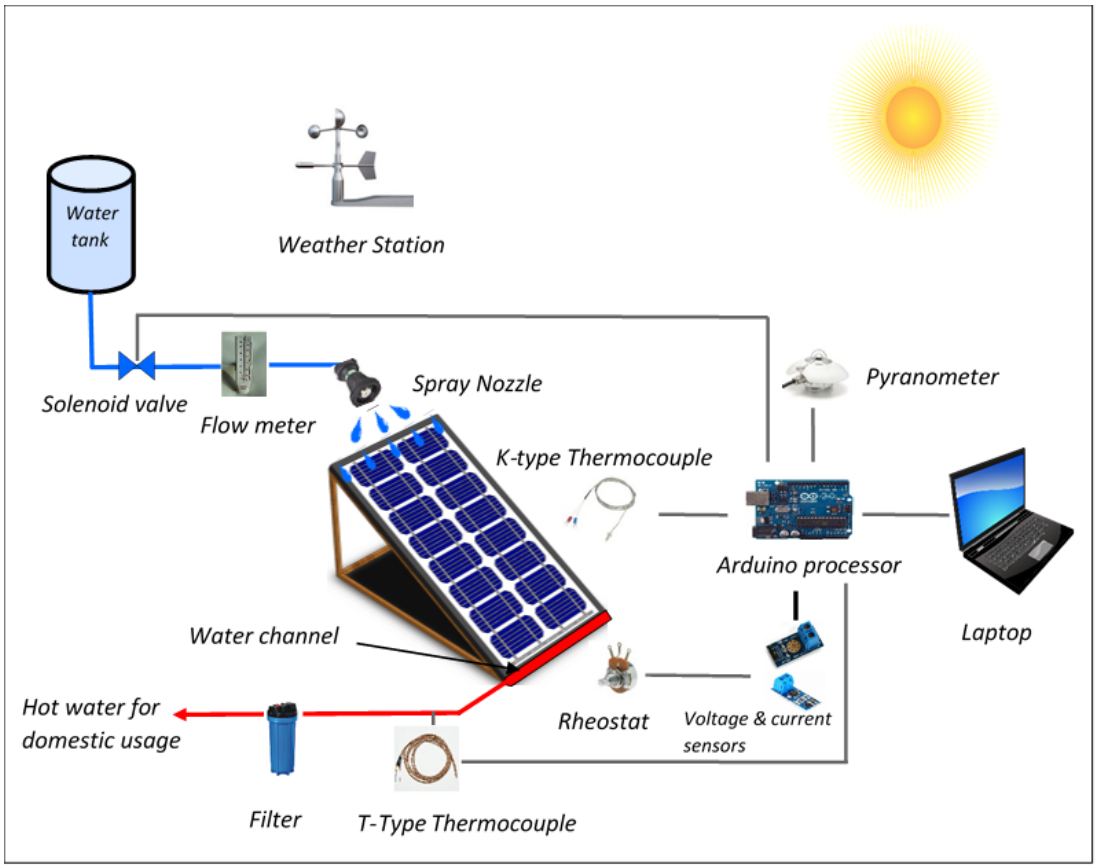

Fig. 4: Schematic Representation of an Experimental Setup for Cooling Photovoltaic Panels Using Spray Nozzles.

In the table below, we delve into the specifics of spray cooling as a vital technique in photovoltaic systems. This summary encapsulates the methodologies applied, the types of PV technologies involved, the materials used for cooling, the tools employed for precise measurements, and the noteworthy outcomes.

Table 3: Sprayer in Photovoltaic Systems: Materials, Measurements, and Outcomes.

Authors	Cooling Methodology	PV Technology	Cooling Materials	Measurement Tools	Key Findings
Azadeh Kordzadeh [39]	Tube with tiny holes attached at the front side of the PV	Crystalline type with 36 cells	Water tank, Pump PS150 Boost Lorentz 1000 L/h, Permanent magnet DC motor, Filter, Tube with tiny regular holes	Thermometer model PT100, Controller model PS150, MPPT, Pyranometer model Kip & Zonen, Digital flow meter	The array's power output experiences a significant increase.
K.A. Moharram et al. [40]	Water spray nozzles were used to cool the PV module from the front side.	Monocrystalline silicon with 185 Wp	Aluminum water tank (0.3m3), Centrifugal pump (1 hp), 120 water nozzles, Drain pipe, Filter	Pyranometer, Thermocouples, Data acquisition system	The highest output power is achieved when the cooling temperature reaches the Maximum Allowable Temperature (MAT) of 45°C.
Hiren D. Raval et al. [41]	Water flowing over the panel	Solar PV panel 70 Wp (M/s Kotak Urja Limited)	Frame structure, Water tank, Perforated pipe 2mm in diameter, Drain pipe	Rheostat, K-type thermocouples, Pyranometer (Kipp & Zonen CM4 pyranometer).	The energy efficiency was improved from approximately 6% to 40%.
Y.M. Irwan et al. [42]	Water flowing over the panel	Monocrystalline PV panel with 50Wp	Water tank, DC water pump, Pipes with tiny holes	Halogen lamps bulbs as a solar simulator, Digital solar power meter (TES), Thermocouples	A decrease in temperature of about 5 to 23°C increased power from 9 to 22%.
Ahmed Elnozahy et al. [43]	Automatic water spray system for cooling and cleaning.	SF80-A thin film PV module with 80 Wp	Source of water, Electric solenoid valve, Copper pipe with nozzles, Water tank with water level float valve	Control circuit (relay, Data logger, control device (OM320), Control program), Pyranometer, K-type thermocouple, OM320 data logger, Variable resistor, Ammeter, Voltmeter, Flow meter	The cooled and cleaned surface module demonstrated an efficiency of 11.7%, whereas the module without cooling and cleaning showed 9% efficiency.
Jen-Cheng Wang et al. [44]	Automatic water spray-cooling system.	Multi-crystalline silicone cells	Water tank, Aqua pump, Sprinkler, Several wireless nodes	Thermometer, Anemometer, Pyranometer, Weather station	The energy conversion increased by approximately 17.75%.
Chia-Yi Mah et al. [45]	A thin film of water flowing over the panel	260 W silicon crystalline solar panels (model MYS 60 CF-260)	Drilled PVC pipe, Water pump 135 W, Water recycling system, Mounting rack	Temperature sensor (DS18B20), I-V curve tracer (PVPM1040X), Thermography camera (FLIR i5), Solar irradiance meter (S0Z-03), Micro-Inverter (Hoymiles MI-500), Power meter, Water flow meter, Weather station, Arduino Mega	The output power is enhanced by 15%.
German Osma-Pinto et al. [46]	Irrigation system to cool the photovoltaic module	255 W, 1.6 m2 polycrystalline PV panels CS6P-255 (Canadian Solar)	PV panel Frame, 40 L cava (tank) of expanded polystyrene, Submergible pump, Supply PVC pipeline, Water provider, Collecting PVC	Pyranometer (Kipp&Zonen SMP-11), Air velocity sensors (EE576, EE671, and DC-12), Thermocouples K-type, Data loggers (OMEGA OM-CP-OCTTEMP2000, PACE XR5-SE-20 mV, and CAMPBELL CR800X), Pyranometer (Pi), DC energy meters (AcuDC243, Class 0.5	The daily power generation can be increased by up to 10% using the irrigation system.

			pipeline, Relay, Controller	in power), AC energy meter (Acuvim IIR, Class 0.2 in power)	
Piero Bevilacqua et al. [47]	Different types of cooling systems, consisting of (a) spray nozzles, (b) spray nozzles and a thin metal plate, and (c) a mechanical fan with a thin metal cover	Polycrystalline silicon modules with 245 Wp	Aluminum frame to install PV, Thin metallic cover, Small mechanical fan, Wide cone water spray nozzles, Water piping, Thin metallic panel	Micro-inverter with MPPT, Pyranometer, Temperature sensor (Pt 100), Humidity sensor (capacitive), Wind speed sensor, Wind direction sensor, Weather station	This system achieved a higher efficiency performance of 14.3% compared to 12.7% for the reference module.
Amirhosein Hadipour et al. [48]	Pulsed spray water cooling system	Monocrystalline silicon solar cells with 85 Wp	Five-micron nozzles (simple orifice type), Solenoid valve	Infrared camera, Type K thermocouple, Digital multimeter with data storage capability, Pyranometer with data storage capability, Rheostat	Power output increased by 27.7% using 1/9 of the water normally required for continuous cooling.
Opeyeolu Timothy Laseinde et al. [49]	Automatic water spray cooling system	Type is undefined	Water tank, Pump, Small pots pipes for spraying water, Arduino board, Microcontroller-based water spraying cooling system	Thermometers, Four watts 300/400 mm red polycarbonate traffic light Emitting Diode to measure the efficiency of the solar panel	The electrical efficiency of the solar panel array increased by 16.65%.

Table 3 provides a comparative analysis of cooling techniques applied to photovoltaic systems, encompassing a wide spectrum of outcomes and PV technology types, primarily within the range of 50Wp to 255Wp. These experiments employ a variety of measuring tools, including pyranometers, thermocouples, data acquisition systems, weather stations, infrared cameras, multimeters, and flow meters. The materials used for cooling in these experiments range from water tanks, pumps, and specialized nozzles to copper pipes, frames, and perforated pipes. Notably, the outcomes exhibit significant variability, with improvements in energy efficiency ranging from approximately 6% to 40%. This diversity in measuring tools and cooling materials underscores the importance of tailoring cooling strategies to specific PV technology types and sizes to achieve optimal performance enhancements.

3.1.4. Water nanofluid cooling techniques

Water nanofluid cooling technologies are at the forefront of innovative thermal management for photovoltaic panels. By suspending nanometer-sized solid particles in water, these technologies improve heat transfer properties, offering the potential to dramatically improve small-scale thermal management of PV panels, revolutionizing the energy efficiency and performance of this renewable energy technology. Fig. 5 shows a comprehensive experimental setup designed for efficient cooling of photovoltaic panels using water nanofluids as the cooling medium. The main components include a tank, valve, circulating pump, copper pipes, and heat extraction heat exchanger. Temperature measurements are conducted by K-type thermocouples for PV temperature and T-type thermocouples for water temperature, ensuring accurate monitoring. Additional instruments such as a flow meter, rheostat, multimeter, data logger, pyranometer, and weather station allow detailed data collection and analysis. This setup represents a well-organized approach to enhancing the cooling efficiency of PV panels.

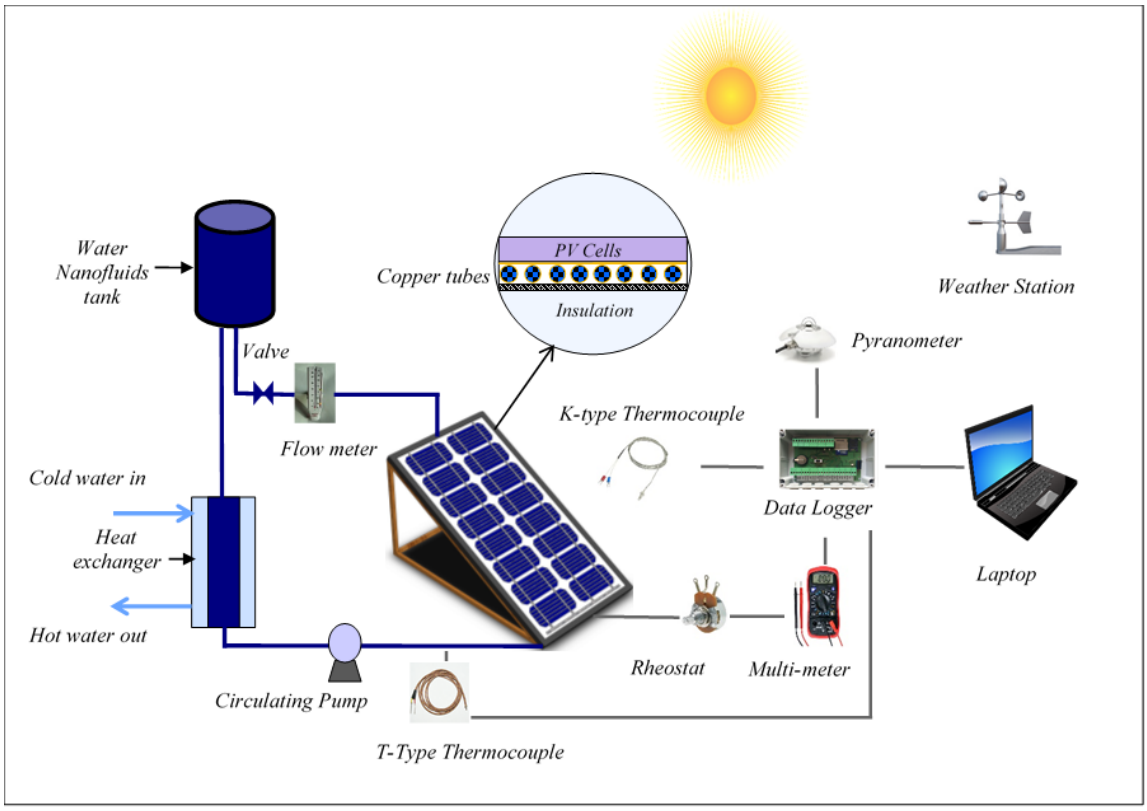

Fig. 5: Schematic Representation of an Experimental Setup for Cooling Photovoltaic Panels Using Water Nanofluid.

The following table offers a concise overview of experiments involving water nanofluids in photovoltaic systems, including cooling techniques, PV technologies, materials, measurement tools, and efficiency improvements.

Table 4: Water Nanofluids in Photovoltaic Systems: Materials, Measurements, and Outcomes.

Authors	Cooling Methodology	PV Technology	Cooling Materials	Measurement Tools	Key Findings
Mohammad Sardarabadi et al. [50]	Water nanofluids flow through the tube collector at the bottom of the photovoltaic module.	40W mono-crystalline silicon, photovoltaic module (Suntech Co., China).	Sheet-and-tube collector, aluminum-oxide/water nanofluids, titanium-oxide/ water nanofluids, zinc-oxide/water nanofluids, ultra-sonic vibrator.	K-type sensors, data logger (Testo-177-T4, UK), solar power meter (TES-1333, Taiwan), and rotary flow meter (20–60 l/ h).	ZnO/water and TiO2/water exhibit superior electrical efficiency performance.
Nooshin Karami et al. [51]	Straight and helical cooling channels are designed for nanofluid flow to cool the PV module.	SS-5WP Polycrystalline PV module.	Straight and helical channels, Boehmite particles (AlOOH-xH2O), nanofluid storage tank, cooling water storage tank, cooling water pump, nanofluid pump, cooling water coil (heat exchanger), needle valves.	Solar simulator (3 metal halide lamps), pyranometer (Tes1333R), thermometer (BTM-4208SD), ampere/voltmeter, pressure gauge (Nataly, Italy).	The electrical efficiency improved by 37.67% with a helical configuration and by 20.57% with a straight channel.

Jee Joe Michael et al. [52]	Cooling channel designed for nanofluid flow to cool PV module.	37W PV module.	Metal thermal absorber, thermal conductive adhesive, copper sheet, glass layer, single water aluminum channel/tray, copper oxide (CuO) nanoparticles, glass wool thermal insulation, thermal storage tank, ladder-type heat exchange, pump.	Pyranometer (LP02, Hukseflux), data acquisition (Agilent) system, rotameter, thermometer, ampere/voltmeter.	The thermal efficiency has been significantly improved, and there is potential for an improvement in electrical efficiency.
Saber R. Abballah et al. [53]	Nanofluid flows through a serpentine copper pipe.	SS-10WP mono-crystalline PV modules.	Al2O3 nanofluid, copper pipe, 5 liters tank, circulating pump, control valve.	Thermocouples (Type K), digital environmental meter and multimeters, data acquisition system (NI-USB-6210), variable resistance 1.5 KΩ, solar power meter (TM-206), digital environmental meter.	The average and maximum electrical efficiency were enhanced by 13.58% and 16.4%, respectively.
Ali H. A. Al-Waeli et al. [54]	Water- Carbide silicon (SiC) as a coolant solution.	STF–120P6 PV module 120Wp.	Water reservoirs, nanofluid storage container, water pump (Stream PM45), carbide silicon (SiC) nanoparticles, ultrasonic shaker, heat exchanger.	Apogee pyrometer, flow meter (Coriolis), anemometer, data acquisition modules, DC electric load, data-logger, thermocouples (Type K), interface module sensor unit (Adam 4019+), liquid density tester DII-300L, viscometer (model: LVDV-III).	Incorporating 3 wt% SiC nanofluid resulted in a maximum electrical efficiency improvement of 24.1% when compared to the reference PV.
Munzer.S.Y. Ebaid et al. [55]	PV with (TiO2) and (Al2O3) nanofluids.	Mono-crystalline silicon PV modules.	Aluminum rectangular channel, heat sink, two circulating centrifugal pumps, two 15L insulated tanks, air-cooled heat exchanger, PVC pipes, Al2O3 and TiO2 nanoparticles, ultrasonic processor (UP400S).	K-type thermocouples, flow meter, solar power meter, digital multimeter, and data logger.	Both types of nanofluids caused a greater reduction in the average temperature of the PV cell. Furthermore, the Al2O3 nanofluid exhibited superior performance compared to the TiO2 nanofluid.
Saber Abdo et al. [56]	Hydrogel beads with alumina nanofluids.	Multi-crystalline PV panels 200W.	Aluminum Plates (as PV panel), blue paint coating, two attached fins, perforated acrylic rectangular container, alumina nanomaterial, nano-saturated hydrogels.	Solar simulator (6 halogen lamps), thermocouples Type K-Type, analytical balance Range 0–120 g, data Acquisition system Pico Technology TC- 08, digital environmental meter (EXTECH 45,170), solar power meter (Extech SP505).	The electrical efficiency of the panels can be enhanced by about 10.1% by utilizing the optimal concentration of the nanofluid.
Jinxin Feng et al. [57]	Nanoemulsions PCM as nanofluid coolant.	Monocrystalline silicon solar cell (100 W).	Nanoemulsions PCM, aluminum heatsinks, serpentine pipe, low constant thermal bath, thermal silica, silicone hose.	Solar simulator, solar radiometer (YGC-TBQ), K-type thermocouple, data logger (Agilent34970A, USA), rotameter.	Compared to water cooling, the temperature was reduced by 5.3%, and only 50% of the pumping power was required to achieve the same performance.

Amin Shahsavar et al. [58]	Water magnetite nanofluid through a finned and un-finned thermal collector.	Mono-crystalline silicon 10 W.	Sheet-and-tube collectors (copper), water/magnetite nanofluid, stone wool insulation, thermal grease, DC pump, heat exchanger, reservoir, constant water bath.	Solar simulator, thermometer K-type, temperature sensor (TES-1327 K), lux meter (TROTEC-BF06), multimeter (LUTURON-DW6060), rotary flow meter (Malema-M10000), pressure transmitter (Rosemount 3051CD).	There was an improvement in efficiency of 12.06%, 10.87%, and 8.40% for PVT systems with 8 fins and serpentine tubes, 4 fins and serpentine tubes, and serpentine tube systems, respectively.

In this table summarizing experiments on water nanofluids in photovoltaic systems, various types of PV technologies are explored, including monocrystalline, and polycrystalline silicon modules. The experiments cover a range of PV sizes, from 10W to 200W, and investigate different nanofluids such as zinc oxide (ZnO), titanium oxide (TiO2), copper oxide (CuO), alumina (Al2O3), silicon carbide (SiC), and nanoemulsions phase change materials (PCMs) as cooling solutions. Cooling materials utilized consist of sheet-and-tube collectors, straight and helical channels, metal thermal absorbers, serpentine copper pipes, ultra-sonic vibrators, and more. Measurement tools, including pyranometers, thermocouples, data loggers, and flow meters, are employed to evaluate the efficiency improvements achieved through these experiments, which range from approximately 8.4% to 37.67%. This comprehensive range of PV types, sizes, nanofluids, and cooling materials underscores the versatility of water nanofluids in enhancing the performance of various PV systems.

3.2. Air Cooling Methods

Air cooling, whether through natural convection or forced convection (fan-driven cooling), plays a significant role in the temperature management of photovoltaic systems. These cooling techniques are essential for maintaining optimal operating conditions, contributing significantly to the reduction of the operating temperature of PV modules and thereby increasing their efficiency and overall energy output. In this context, diverse technologies, materials, experimental setups, and outcomes associated with these cooling approaches, shed light on their role in enhancing the performance of PV systems.

3.2.1. Natural convection

Natural convection relies on the natural movement of air to dissipate heat from the PV panels, making it a cost-effective and environmentally friendly solution. Furthermore, this technique can be enhanced by increasing the heat transfer area through the use of fins and extended surface designs. Fig. 6 illustrates a schematic representation of an experimental setup designed for cooling photovoltaic panels using a finned heat sink. In this setup, various measuring tools are employed, including a K-type thermocouple to monitor the PV temperature, a hot wire anemometer to measure air velocity, a data logger, a multimeter, a pyranometer for solar radiation measurements, and a weather station to record environmental conditions. This setup allows for precise monitoring and assessment of the cooling efficiency and its impact on photovoltaic system performance.

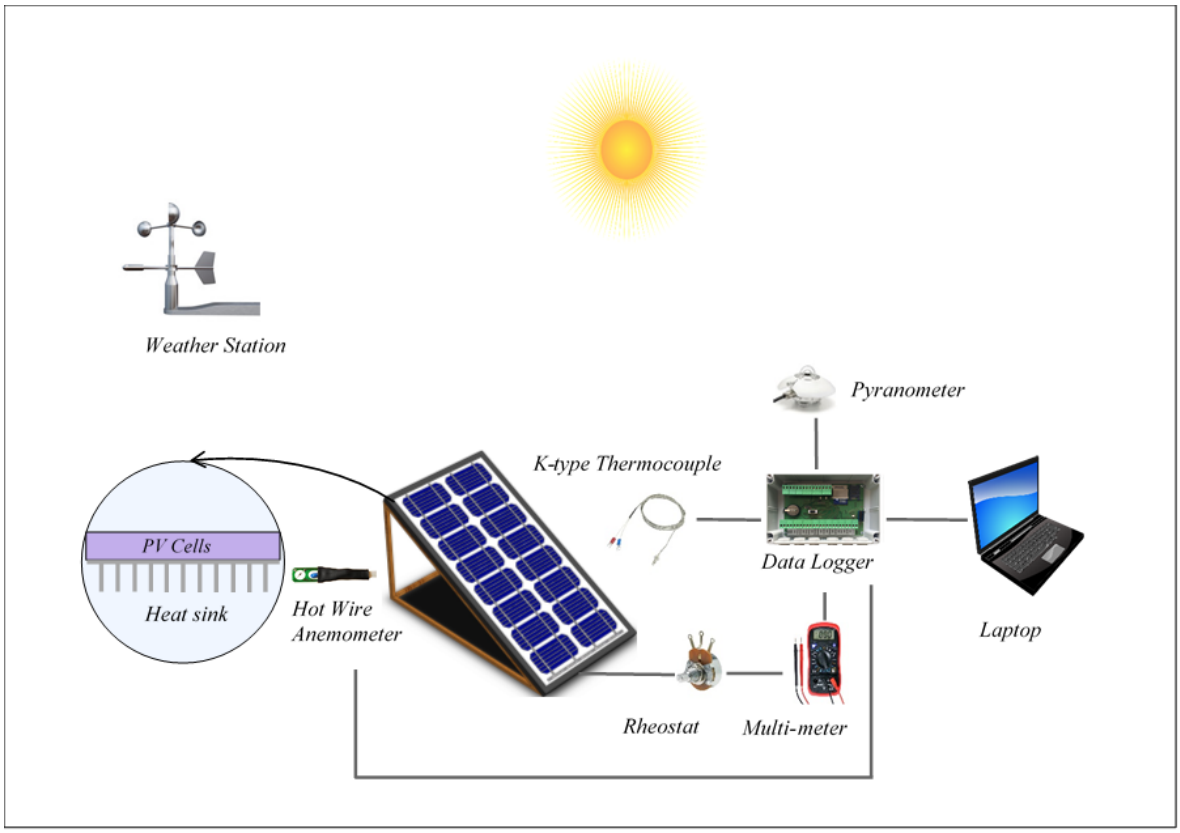

Fig. 6: Schematic Representation of an Experimental Setup for Cooling Photovoltaic Panels Using Finned Heat Sink.

The table below summarizes key aspects of natural air cooling techniques for photovoltaic systems, including methods, PV types, materials, measurement tools, and outcomes.

Table 5: Natural convection cooling in Photovoltaic Systems: Materials, Measurements, and Outcomes.

Authors	Cooling Methodology	PV Technology	Cooling Materials	Measurement Tools	Key Findings
Laura Maturi et al. [59]	The heat sink on the backside of the PV module	Glass–glass PV modules based on copper–indium–gallium–selenide CIGS technology	Heat sink made of aluminum fins, thermally conductive adhesive, frame, thermal insulation, transparent panel to control air flux, tempered glass	Sun simulator, maximum power point (ppt) tracking, four DC loads to dissipate the produced energy, two AGM batteries 12 V–26 A h, I–V-curve tracer (PVPM 1000C), thermocouples (type T), pyranometer, hot-wire anemometer FV A935-TH5K2	The output power increased by 2.3% as a result of a 5.2°C decrease in temperature.
Ahmad El Mays et al. [60]	Aluminum finned heat sink attached to the backside of the PV	Polycrystalline PV module with 30 Wp	Frame to hold the PV, finned plate of aluminum, thermal grease	IR thermometer, thermocouple k-type, solar meter to measure irradiation, multi-meters, rheostat	The temperature decreased by 6°C, leading to an increase in output power by 1.86 W and an increase in electrical efficiency by 1.75%.

Filip Grubisic-Cabo et al. [61]	Aluminum fins attached to the back side of the PV panels	Si-poly PV panel with a nominal power output of 50W	Aluminum fins, thermal conductive glue	Arduino Uno R3 motherboard (A1R3), SD card along with real-time clock timestamps (DLS), LCD-TFT screen with a joystick (TFTS), HAENNI Solar 130 pyranometer (PYR), MOSFET resistance (Variable resistance), voltmeter & amperemeter, PICO TC-08 data logger	Compared to the reference PV, the randomly placed finned PV performed better with an increase in electrical efficiency of about 2%.
Usman Jamil Rajput et al. [62]	Aluminum cylindrical fins attached to the backside surface of the PV panel	Commercial Pc-Si (model number KS20).	Pin fins heatsink with an aluminum base, polyurethane foam, ARTIC SILVER adhesive	Infrared thermometer MTP 1328 IR (20 -170°), K-type thermocouples (5°C - 150°C), J-type thermocouples (10 - 650°C), ambient thermometer NI-cDAQ-9211, TES pyranometer 1333R, DAQ USB 628 xM, halogen light source, resistors, Fluke millimeters (Model 87-5)	A cylindrical heat sink reduced the temperature by 25°C, while a single-channel PV/T collector reduced it by 36.5°C.
Ayman Abdel-Raheim Amr et al. [63]	The fin heat sink attached to the backside of the PV panel	Monocrystalline SUNTECH Module STP 250-20/wd with 250 Wp	Fin heat sink	Digital Clamp (SEW 3900 cl), digital multimeter (UT58DEC), thermometer (HANNA-HI 935009) -50.0 to199.9°C, anemometer (Testo 425) 0 to + 20 $m\ s$, solar power meter (TENMARS-TM-206) 0 to 1999 $W\ m2$, Type –K thermocouple 200 to 1350 °C	The use of fins leads to a decrease of about 4-5°C in cell temperature.
Fatih Bayrak et al. [64]	Investigation of different fin sizes, lengths, and arrangements on the performance of a photovoltaic panel	A polycrystalline photovoltaic panel, which is 75W	Aluminum fins, thermal paste	Pyranometer model CMP3 (A KIPP & ZONEN brand), T-type thermocouple (OMEGA), 40-channel data compiler (KEITHLEY 2701), regulatable resistance of 150 W, multimeters, anemometer (DT-619)	The maximum energy and exergy efficiency values were determined to be 11.55% and 10.91%, respectively.
A.M. Elbreki et al. [65]	Lapping fins attached to the backside of the PV panel	Pc-Si Solartif, 40W PV module	Lapping fins	Thermometer, multimeter, pyranometer	The use of 18 lapping fins resulted in a temperature reduction of 24.57°C and an associated improvement in electrical efficiency of 1.39%.
J.G. Hernandez-Perez et al. [66]	Different designs of heat sinks to cool PV panels from the back side	15 W Dokio DSP-15P polycrystalline silicon solar panels	PV frame, segmented heat sink, conventional heat sink, epoxy resin with metal powder (Devcon R2-42)	K-type thermocouples, ADAM data acquisition module model 6018, weather station	The most effective dissipator led to a temperature decrease of up to 10°C and an associated improvement in electrical efficiency of up to 4%.

J.G. Hernandez-Perez et al. [67]	Discontinuous fin heat sink attached to the rear side of the PV panel	15 W power DSP-15P polycrystalline silicon cells	DC fan, discontinuous finned heat sink	4 halogen lamps of 500 W are used as a solar simulator, pyranometer, digital anemometer, Fluke Ti-S40 thermographic camera	The temperature decreased by a maximum of 5.5°C.

In this table, various types of photovoltaic panels ranging from 30Wp to 250Wp are subjected to natural convection cooling techniques. These panels include glass-glass PV modules with CIGS technology, monocrystalline PV modules, and polycrystalline photovoltaic panels. The cooling methods primarily rely on natural convection with the addition of materials such as aluminum fins, thermal paste, and thermal grease. The measuring tools utilized encompass infrared thermometers, thermocouples (K-type, J-type, and T-type), solar power meters, data loggers, anemometers, and more. Temperature reductions range from approximately 2.3°C to 36.5°C, resulting in improvements in electrical efficiency and energy output.

3.2.2. Forced convection

Forced air cooling uses fans or blowers to enhance heat dissipation, proving especially valuable in areas with limited natural airflow; However, it entails significant fan power consumption. Fig. 7 shows a schematic representation of an experimental setup specifically designed to cool PV panels through a cooling duct and DC fans. This setup seeks to enhance the effectiveness and productivity of PV systems by efficiently regulating their operating temperatures. To measure and evaluate the cooling process, a basic set of instruments was incorporated, including a hot-wire anemometer for air velocity measurements, a K-type thermocouple for monitoring the temperature of the PV panel, a data logger for recording accurate data, a rheostat, and an electrical multimeter. In addition, a pyrometer is used to evaluate solar radiation, while a weather station captures environmental conditions. This comprehensive set of measurement tools ensures accurate data and comprehensive analysis of the effect of cooling on PV system performance.

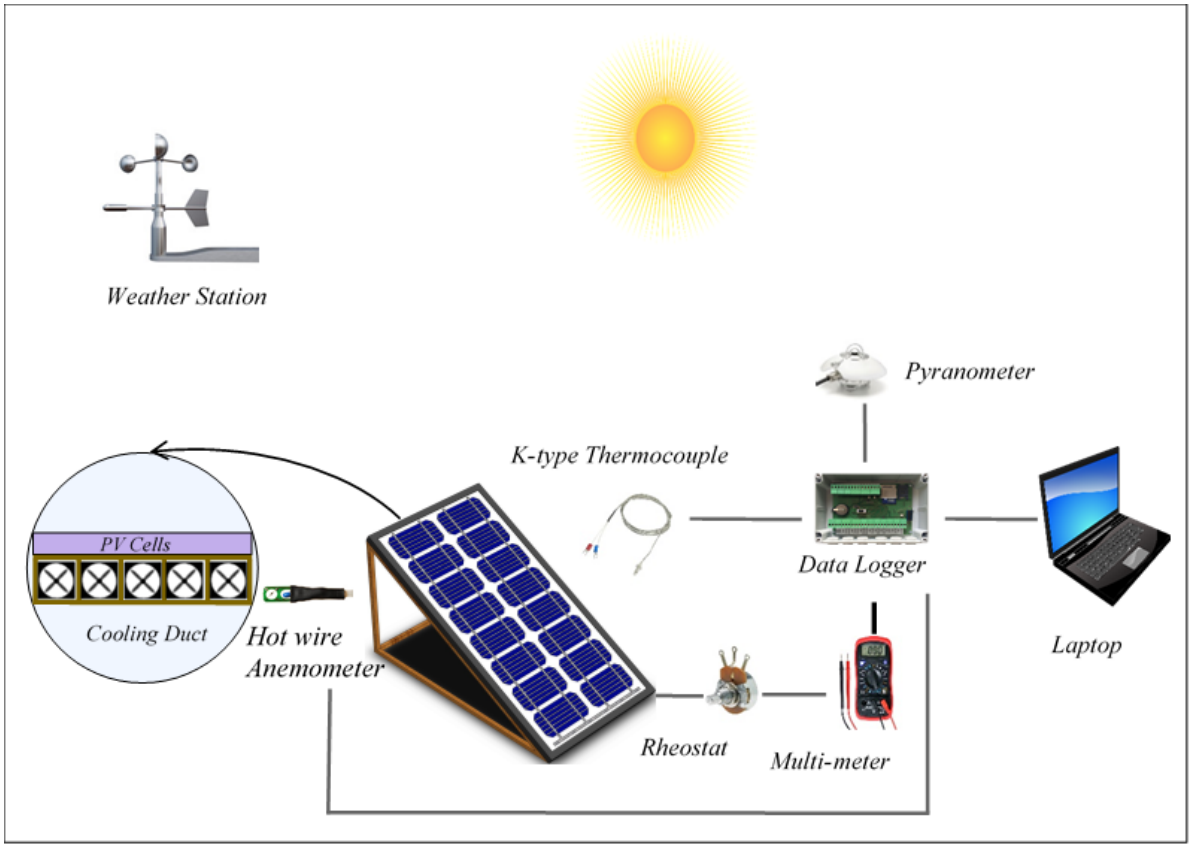

Fig. 7: Schematic Representation of an Experimental Setup for Cooling Photovoltaic Panels Using Cooling Ducts and DC Fans.

The table below provides a brief overview of research conducted on forced convection cooling techniques applied to PV systems. These studies explore different cooling methods aimed at improving the performance of PV systems. The table includes details on methodologies, types of PV, cooling material, measurement tools, and key results.

Table 6: Forced convection cooling in Photovoltaic Systems: Materials, Measurements, and Outcomes.

Authors	Cooling Methodology	PV Technology	Cooling Materials	Measurement Tools	Key Findings
Juwel Chandra Mojumder et al. [68]	Single-pass PV/T collector system with rectangular fins and PV modules	Polycrystalline Silicon (poly-Si) cell type PV module with rated output power of 40W	Rectangular aluminum fins with different fin parameters, thin flat metallic sheet (TFMS), DC fans, cylindrical tube, insulation	Solar controller device (CMP24, 12V-20A), Lead (Pb) acid batteries, variable wire-wound resistor, metal vane thermo-Anemometer (0.2-50 m/s), K-type thermocouple sensors, 4-channel temperature meter data logger, pyranometer, halogen lamps	Achieved the highest thermal efficiency of around 56.19% and maximum electrical efficiency of approximately 13.75%.
H.G. Teo et al. [69]	Parallel set of ducts attached to the back of polycrystalline solar modules	55-watt polycrystalline solar modules	Air ducts, duct fins, DC blower, AC blower	Deep cycle gel batteries, maximum power point tracker (MPPT), pyranometer, T-type thermocouples, anemometer, multimeter	Increased electrical efficiency from a range of 8-9% to a range of 12-14%.
Shahsavar et al. [70]	PV/T system with different types of air-cooling channels and PV panels	Two polycrystalline type PV panels (45 ×2 W)	Thin metal (Aluminum) sheet (TMS), air channel casing built from Medium Density Fiberboard (MDF) wood, fiberglass insulation, black paint, DC fans of 6.6 W, 5 mm-thick glass plate	BM 6 Kipp and Zonen pyranometer, digital Testo 405-V1 thermometer, Type PT 100 thermocouples, NRG-40 anemometer, DT-9205 type multimeter, two spots of 35 W used as a resistive load	The study identified an optimal number of fans for achieving maximum electrical efficiency.
F. Hussain et al. [71]	PV/T system with honeycomb heat exchanger installed at the back side of a photovoltaic module	Mono-crystalline (SW 85) photovoltaic module	A hexagonal honeycomb heat exchanger, a piece of acrylic, a blower, a galvanized duct, a voltage regulator to control the air speed of the blower, an aluminum sheet, polyethylene as thermal insulation	Solar simulator, Type T thermocouples, Agilent 34401A Digital Multimeter, LICOR pyranometer	The use of a honeycomb structure increased the system's thermal efficiency from 27% to 87%, and the PV module's electrical efficiency improved by 0.1%.
A.S. Kaiser et al. [72]	PV/T with air cooling duct at the rear side of the PV module	Photovoltaic module (270 W, ET Solar, ET P672270)	Cooling duct, DC fan	Pt100 sensors, hot film anemometer (Elektronik), ultrasonic anemometer (Gill Instruments Ltd.), pyranometer (EPPLET Lab. Inc.), variable load (own making), data logger 34980A (Agilent)	19% increase in power output achieved at a duct velocity of 6 m/s.
M. Gholampour et al. [73]	Photovoltaic panel associated with Unglazed Transpired	Polycrystal-Si PV with 45 Wp	Unglazed Transpired Collector (PV/UTC), DC source, DC fans	8-channel thermometer, amperemeter, voltmeter, pyranometer, resistance 5Ω	Installing PV panels on the UTC can lead to

	Collector (PV/UTC)				photovoltaic cooling.
Alibakhsh Kasaeian et al. [74]	Photovoltaic module with cooling duct installed at the rear side with different depths and different mass flow rates	Monocrystalline PV module	Steel plate as a thermal absorber, aluminum oxide paste, air channel made of Plexiglas, DATECH 1238-12HBIA fans	Hukseflux type-SR12 pyranometer, hotwire anemometer YK-2004AH, AM-4220 anemometer, thermocouple's type-K, thermometer type TM-946, temperature sensors SMT160, data logger, multimeters, variable resistance of 50 (Ω)	Electrical efficiency ranged between 12%-12.4%.
Hasan Saygin et al. [75]	PV with modified air collector	Poly-crystalline PV with 80 Wp	Glass cover, wooden frame for the duct collector, black paint, a single-inlet centrifugal fan (FBSY-1), a motor speed controller (22F-A8P0N103), Styrofoam insulation, frame to hold the PV module	Thermocouples, data loggers (TESTO 176 T4), pyranometer, SD card, multi-meter (FLUKE 115 TRUE RMS), an inclined tube manometer (angle of 15˚)	The PV/T system achieves the highest electrical efficiency with a gap distance of 5 cm and a mass flow rate of 0.021 kg/s.

The table presents research on forced convection cooling techniques applied to PV systems, revealing a variety of results, from maximizing thermal efficiency of approximately 87% to enhancing electrical efficiency of 8-14%. Several PV technologies have been studied, with the predominant PV size being 45Wp. It is worth noting that these experiments used a range of measuring instruments, including pyranometers, thermocouples (type K and type T), anemometers, and multimeters, supported by data loggers, ensuring comprehensive data collection and analysis. This research confirms the potential of using forced convection cooling methods to enhance the performance of PV systems across different configurations and sizes.

3.3. Phase Change Material Cooling Methods

PCM cooling for PV systems is a transformative technology that optimizes solar panel performance by regulating temperature. This technology uses Phase Change Materials that can efficiently absorb, store, and release thermal energy, ensuring PV modules operate within their ideal temperature range. By preventing overheating, PCM cooling improves the efficiency and reliability of solar panels, contributing to the advancement of sustainable solar energy solutions. The energy stored by PCMs is released to the ambient environment, but due to their low thermal conductivity, researchers have enhanced heat transfer by incorporating nanoparticles into the PCM or using different types of heat sinks. Additionally, some methods utilize the extracted heat by integrating PCMs with water pipes, cooling channels, or other systems. This approach further optimizes energy usage and efficiency, allowing for the effective management and utilization of thermal energy captured by the PCMs. Fig. 8 depicts a schematic representation of an experimental setup designed for cooling photovoltaic systems using a Phase Change Material enclosure. This innovative cooling technique involves attaching the PCM enclosure to the PV module to manage excess heat generation. The setup includes critical measurement tools such as K-type thermocouples for PV and T-type thermocouples for PCM, a pyranometer for solar radiation assessment, a rheostat for electrical control, a multimeter for electrical measurements, a data logger for continuous data recording, and a weather station to monitor environmental conditions. This configuration allows researchers to investigate the impact of PCM cooling on PV system performance while gathering essential data on temperature, radiation, and electrical characteristics.

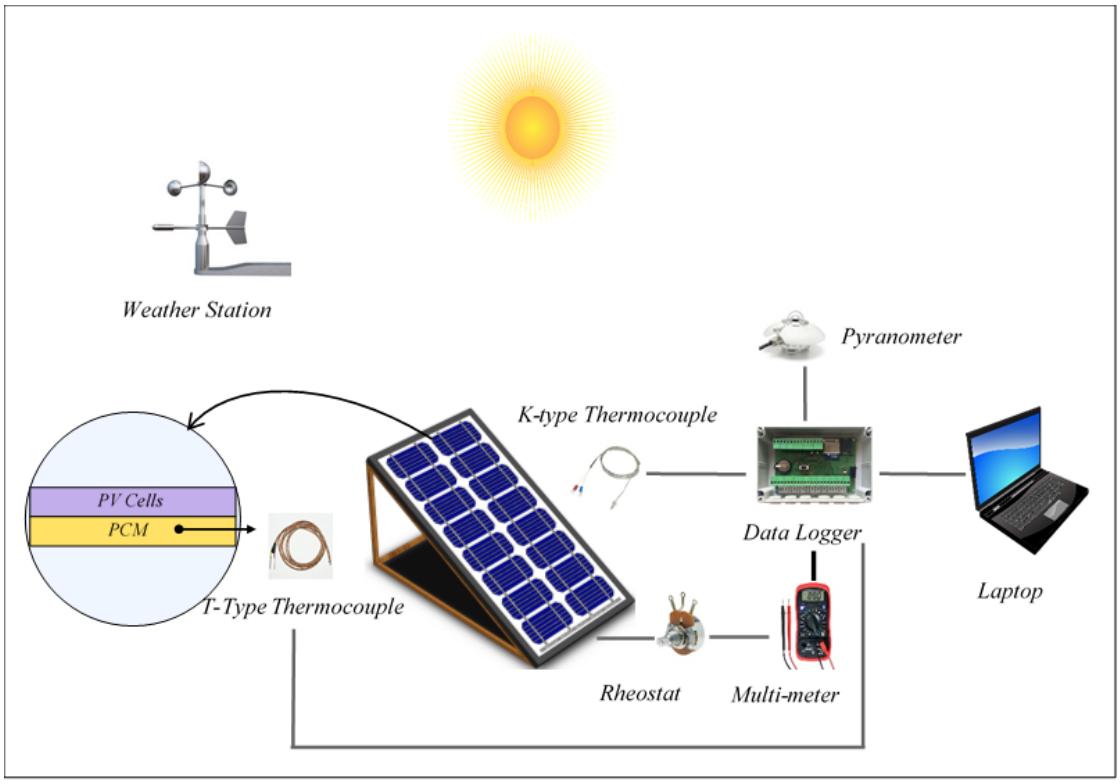

Fig. 8: Schematic Representation of an Experimental Setup for Cooling Photovoltaic Using Cooling PCM.

The following table provides an overview of cooling techniques involving Phase Change Materials (PCMs) applied in photovoltaic systems. It highlights the materials and tools utilized, along with their impact on PV performance

Table 7: PCM Cooling in Photovoltaic Systems: Materials, Measurements, and Outcomes.

Authors	Cooling Methodology	PV Technology	Cooling Materials	Measurement Tools	Key Findings
Hassan et al. [76]	Different types of PCM with different sizes and materials of PCM enclosures have been studied	Polycrystalline silicon PV cells	Perspex (MARCRYL CLEAR from Vink Plastics) container, Aluminum container, Phase change materials (RT20, SP22, CL, CaCl2, and CP)	Differential scanning calorimetry (DSC), GR262 solar simulator, A Kipp and Zonen CM6B pyranometer, T-type copper-constantan thermocouples, Data Logger	Temperature decreased by 18°C for 30 minutes and by 10°C for 5 hours under 1000 W/m2 insolation.
Jungwoo Park et al. [77]	PCM application in vertical PV modules	Polycrystalline silicon solar cell 10.9 Wp	Paraffinic hydrocarbon PCM, Transparent acrylic plates, Aluminum plate, Battery (enclosed type).	Solar controller, LED bulb, Thermal couple thermometer, Pyranometer (LP PYRA 02 AC, Delta OHM), Data logger & data storage, Weather station, Power meter (HPM-300A, AD Power)	There was an increase of 1.0-1.5% in electric power during the winter season.
Ahmad Hasan et al. [78]	PV with PCM and internal fins	Polycrystalline ethylene vinyl	Sheet of aluminum alloy (1050A) for PCM	Differential scanning calorimetry (DSC)	PV output increased by 7.2%

		acetate (EVA) encapsulated 40 WP Microsol PV panel (MM0025)	container, Epoxy resin, Polystyrene sheets for insulation, Commercial PCM RT42, Internal fins	to find thermophysical properties of PCM, T-type copper–constantan thermocouples calibrated in ice-bath, Apogee pyranometer (model # SP-110), weather station (Starmeter-WS1041), NI compact Rio (NI cRIO-9073) data acquisition system.	at peak and 5% on average.
S.R. Mousavi Baygi et al. [79]	PV with PCM embedded in several enclosures	Volta Max photovoltaic solar panels with a capacity of 40W	Polyethylene glycol 1000 (PEG1000) as PCM, Eight rectangular-shaped aluminum containers	Hukseflux pyranometer (SR12), Thermocouples of PT100, Temperature sensor Six pt-100 sensor, laser thermometer	The electrical efficiency of the system improved by up to 8%.
Karthikeyan Velmurugan et al. [80]	PV with PCM in different container thicknesses	5 Wp Polycrystalline	Lauryl Alcohol (LA) and Cetyl Alcohol (CA) organic PCM, PCM containers with different thickness, Glass wool insulation	T-type thermocouple, Data Logger, Pyranometer, Multimeter, Computer	Eutectic PCM can reduce the photovoltaic temperature by 10.3 °C.
Mohammad Rezvanpour et al. [81]	Sandwich model used for the PV-PCM panel	5 Wp Monocrystalline	CaCl2-6H2O (Calcium Chloride Hexahydrate) PCM, Transparent plexiglass with 8 mm thickness, Screws, Strong high-temperature heat glue, Aluminum structure	Arduino Mega2560, SD card module, 1 GB ram, Resistors (15Ω, 68Ω, 82Ω, 4.7 kΩ), LM35 thermocouples	The maximum temperature drop was 26.3 °C (38% decrease). The power increased by 1.16 W (24.68% of the increase).
Leila Siahkamari et al. [82]	Nano-PCM with copper tubes attached to the back side of the PV panel	10 Wp monocrystalline silicon photovoltaic module (BTM-4208SD)	steel frame to handle the PV module, copper microchannel tubes, pure sheep fat as PCM, CuO nanoparticles, Water tank, water pump	Metal Halide lamp (l HID-T400 W/D), Pyranometer (Tes1333R), Thermometer (BTM-4208SD)	The maximum power generated increased by about 24.6% to 26.2% compared to the no-cooling system and 5.3% to 12% compared to paraffin wax.
Peter Atkin et al. [83]	PCM-infused graphite with aluminum fins installed at the rear side of the PV	Monocrystalline silicon solar panel	Paraffin wax RT40 PCM, High conductivity graphite blocks, Finned heat sink	Two 500 W halogen lamps, Voltage control device, Differential scanning calorimetry (DSC)	The overall efficiency increased by about 12.97% while the least improvement was found by PCM or fins alone.
Farouk Hachem et al. [84]	Pure or combined PCM to cool the PV	30W Polycrystalline PV panel	PV stand, Aluminum PCM container, Petroleum jelly	K-type Thermocouples, Variable resistive load, Ampere-	The η_el increased by an average of 3% when pure PCM

	module from the back side		PCM, Copper and graphite powders, Aluminum flat plate, RTV grey silicon	meter, Voltmeter, Solar meter	was used and by an average of 5.8% when using combined PCM.
Ali H.A. Al-Waeli et al. [85]	Nano-PCM with cooling pipes to cool the PV module from the back side	The model type is STF-120P6 with a rated power of 122 Wp	SiC nanofluid, Paraffin wax, Cooling pipes, Cooling tank filled with water, Cooling tank filled with PCM/nano-SiC, Heat exchanger, Water pumps, Insulation	Apogee meter pyranometer, K-type thermocouple, Data acquisition system, Multi-meter, Polysulphone-flow meter, Density tester, Viscometer, KD2 Pro analyzer to measure thermal conductivity.	The highest efficiency of the photovoltaic module was 13.7%, while the efficiency of the conventional module was 7.1%.
A. Hasan et al. [86]	Cooling of the PV module by different types of PCM embedded in aluminum enclosures with inner fins	65 W polycrystalline EVA encapsulated PV panels	Aluminum rectangular metallic containers having internal fins, Epoxy resin glue, Eutectic mixture of capric–palmitic acid (PCM1), Salt hydrate CaCl2_6H2O (PCM2)	Differential scanning calorimetry (DSC), T-type copper–constantan thermocouples, Analogue data logger, A pyranometer	The best results were found by CaCl2-6H2O which lowered the photovoltaic temperature by 3-4°C. CaCl2-6H2O resulted in a 3% greater energy saving compared to capric-palmitic acid in Vehari, Pakistan.
Lippong Tan et al. [87]	Cooling of the PV module by PCM enclosed in an aluminum enclosure with internal fins	BP Solar, model: SX320M	PCM paraffin wax (RT 27), Four aluminum enclosures with different numbers of inner fins (0-3-6-12)	Handheld pyranometer 105HP, An AR856 handheld anemometer, An electronic load device (BK Precision 8540), An Agilent 349070A data logger unit	The temperature was reduced by 15°C. The electrical efficiency improved by 5.39%.
M. Rajvikram et al. [88]	Photovoltaic cooling by PCM in aluminum enclosures and outer fins	5Wp polycrystalline solar PV panels	Hydrogen sulfate HS29 as PCM, Aluminum container, Black anodized heat sink, C-type clamp	Multimeters (voltmeter & amperemeter), Installation meter (KM-SPM-11), FLIR cameras	The maximum output power of about 1.48W was produced using the PCM and finned heat. The maximum efficiency using PCM and finned heat is 17.03%.
T. Wongwuttanasatian et al. [89]	PV module cooling by PCM embedded in various shaped enclosures	20 W polycrystalline PV modules	Palm wax was used as the PCM, Grooved box, Tubed box, Finned box	K-type thermocouples, pyranometer, Multimeters	PV-PCM with a finned enclosure lowered the temperature by 6.1°C. PV-PCM with a finned enclosure improved the electrical efficiency by 5.3%.
Preeti Singh et al. [90]	PCM in improved containers	175Wp monocrystalline silicon PV panels	Aluminum containers, Calcium chloride hexahydrate	Pyranometer (Kipp and Zonen Delft, model- CM11), Electronic load	Temperature can be reduced from 77°C to 54°C. Electric

			(CaCl2.6H2O) as PCM, Thermal conductive paste (Buyyart, model DRG-102)	controller (Prodigit model- 3311F), K-type thermocouples, Data logger, Multimeters	generation can be increased by 6.2% in January and 8.3% in June.
Rajan Kumar et al. [91]	External fins attached to the PCM container	10 Wp Polycrystalline PV modules	PCM container made from Al 6061 sheet, Fins made from Al 6061 sheet, Paraffin wax granules as PCM	Solar Simulator: halogen lamps (500 W×2), multimeters, Lux meter (intensity meter), Infrared thermometers & Hg thermometer	Electrical efficiency improved by 5.16% using PCM, and by 6.59% using PCM and external fins.
Mohamed Sharaf et al. [92]	PCM with aluminum foam matrix is embedded in an aluminum enclosure	20 Wp Silicon solar PV module (SM-20P)	RT42 paraffin as PCM, Aluminum container, A rubber gasket with silicone sealant, Aluminum foam matrix	T-type thermocouples, Davis 6153EU Vantage Pro II weather station, Ampere and voltmeter meter, Data logger type A NI 9321, digital multimeter	The temperature in December, January, and February decreased by 4%, 7.4%, and 13.2%, respectively. Power in December, January, and February increased by 1.85%, 3.38%, and 4.14%, respectively.
Mohammad Amin Vaziri Rad et al. [93]	The PCM is contained in several independent aluminum enclosures	20 Wp polycrystalline silicon PV panels	The PCM used was Rubitherm® RT28HC, Aluminum containers, Epoxy glue	Data logger (PICO TC-08), K-type thermocouples, Apogee SP-420 pyranometer, Resistors (15Ω), Yocto-Watt device	PV performance improved by 10.7%.
Mohammad Amin Vaziri Rad et al. [94]	PCM with aluminum shavings embedded in a metal enclosure with water-cooling tubes	25 Wp mono-silicone photovoltaic panel	Salt hydrate phase change material, Industrial aluminum shavings, Copper-plate, Aluminum paste, Pipes, Metal container, Fiberglass foam insulation, Heat exchanger, Insulated water tank, Mini pump	Solar Power Meter (TES 1333), k-type thermocouples, Thermometer (LUTRON - TM-946), Multimeter (VICTOR VC97)	The porous media of aluminum shavings reduced the PCM melting time by about 19%-25%, which reduced the temperature by 24°C. Electric efficiency improved by 2.5%.
P. Sudhakar et al. [95]	PCM with a water-cooling system	20Wp polycrystalline silicon panel	Insulated water tank, thermosyphon pipe, OM 35 PCM	Pyranometer (Hukeflux LP02), RTD sensors, J-type thermocouples for water temp., data acquisition system (Agilent 34972A), digital multimeter (Mastek MAS 830L)	Lowered cell temperature by 5.4°C, and Improved output power by 13.54% and electrical efficiency by 12.4%.

The table provides an overview of various studies focusing on forced convection cooling techniques applied to photovoltaic (PV) systems. These investigations explore different cooling methods to enhance the performance of PV systems and cover a range of methodologies, PV types, materials, measurement tools, and key findings. Notably, the prevalent PV panel size used

in these studies varies between 5Wp and 40Wp, with many falling within this power capacity range. The most frequently employed measuring tools include K-type thermocouples, pyranometers, data loggers, multimeters, and anemometers. One common observation across these studies is the improvement in electrical efficiency that ranges between 3-13%. Additionally, the utilization of phase change materials (PCMs) and other cooling techniques resulted in a notable reduction in temperature and contributed to enhanced PV system performance.

3.4. Thermoelectric Cooling Methods

The thermoelectric technique is an advanced technology in cooling photovoltaics, actively regulating PV module temperatures to enhance solar energy conversion efficiency while also generating electricity from waste heat. In this section, we explore its methods, materials, tools, and its dual role in improving solar power and sustainable energy generation. Fig. 9 depicts an experimental setup utilizing thermoelectric cooling, heat sinks, DC fans, and a cooling duct to enhance photovoltaic system efficiency. Thermoelectric modules actively regulate PV temperatures, while heat sinks dissipate excess heat, and DC fans optimize airflow. Measuring tools like a hotwire anemometer, K-type thermocouples, a rheostat, a multimeter, a data logger, and a pyranometer monitor airflow, temperatures, resistance, and solar radiation. This setup combines active temperature control with data collection for improved PV performance and electricity generation from waste heat.

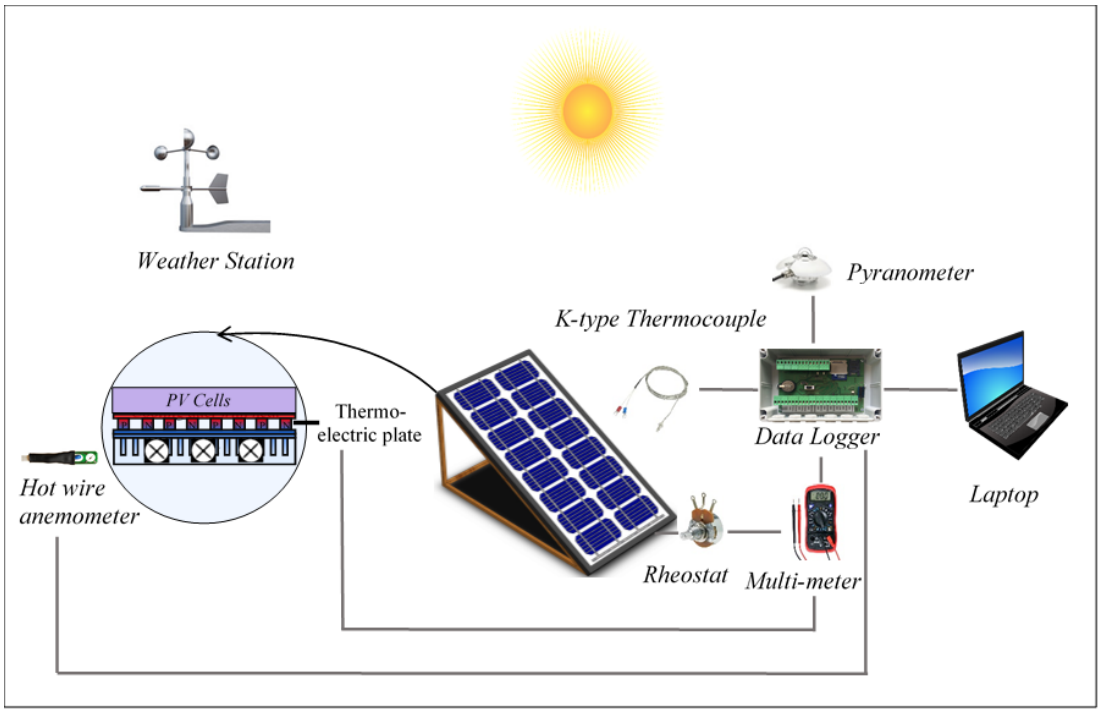

Fig. 9: Schematic Representation of an Experimental Setup for Cooling Photovoltaic Using Thermoelectric With Heat Sink and Cooling Duct.

The following table presents an overview of cooling methods with a primary focus on thermoelectric (TE) techniques applied in photovoltaic systems. These approaches employ thermoelectric modules to manage the temperature of PV panels. The table summarizes the methodologies, materials, tools, and significant findings related to TE-based cooling, highlighting their impact on enhancing solar energy conversion efficiency.

Table 8: Thermoelectric Cooling in Photovoltaic Systems: Materials, Measurements, and Outcomes.

Authors	Cooling Methodology	PV Technology	Cooling Materials	Measurement Tools	Key Findings
Alireza Akbar et al. [96]	PV with thermoelectric module, aluminum plate, copper pipes	Crystalline silicon (c-Si) PV module	TE module TEC-1206 AC, liquid pump, Copper pipes Water, SiO2-H2O, and Ag-H2O, An aluminum plate, Silicone adhesives	Solar simulator, Thermal sensors (LM 35), Arduino board, Multimeters, (ProsKit MT-1210)	Temperature reductions: 1.77°C (water), 9.76°C (SiO2-H2O), 13.17°C (Ag-H2O) Efficiency improvements: 13.09% (water), 16.17% (SiO2-H2O), 20.68% (Ag-H2O)
M. Benghanem et al. [97]	PV with thermoelectric module, heat sink, cooling fan	Solar mini-panels	Thermoelectric module (TEM), Heat sink Cooling Fan, Electronic load	ReRa Tracer Software, Pyranometer (Kipp & Zonen), K-Type Thermocouple, Digital Multimeter	Solar cell efficiency decreases by 0.5% for each °C increase in temperature.
Wei Pang et al. [98]	PV with TE module and heat sink	Monocrystalline silicon photovoltaic module 10 W	Thermoelectric generator SP1848, Pin fin, and plate-fin heat sink	1000 W halogen tungsten lamp (QVF137), Lithium battery, Inverter, a resistor with 1 kΩ Data acquisition system (Agilent 34970A), Thermal resistor (RTC103)	Effective structure: PV/TE with heat sink, reducing cell temperature by ~8°C. TE module shows a cooling performance of approximately 27%.
Rouhollah Salehi et al. [99]	PV with TE module and heat sink	(10 W) solar panel	Thermoelectric module, Heat sink,	Thermometer, Pyranometer, Multimeter	Average temperature reduction of 10°C. Average efficiency and power increase of 10.50%.
Tengfei Cui et al. [100]	CPV/TE with heat sinks	Single-junction GaAs solar cells	Fresnel lens, paraffin as PCM, Copper-made container, TE generator (TEP1-1264-1.5), Copper-made water-cooling heat sinks, Aluminum air cooling heat sink, Thermal conductive adhesive, A sunlight tracer, Double-axis stepper motor	Temperature sensors, pressure sensors, High-precision electronic load (N3302A), Pyrheliometer, and pyranometer (PC-2-T)	PV-PCM-TE with water cooling had higher efficiency compared to air cooling in the same working environment.
Ershuai Yin et al. [101]	PV/TE with PCM and water-cooling block	PV cell is a 3-junction GaAs PV cell (GaInP2/GaAs/Ge)	Fresnel lens, Double-axis sunlight trace, system TE generators, PCM plate (Parafin), Graphite composite, Copper foam	Laser power meter VLP-2000-200W, Pyrheliometer and pyranometer PC-2-T, Thermocouples K-type, Data	Temperature reduction of about 30°C compared to the CPV-TE hybrid system. Output power increased by

			composite, Water cooling block	acquisition unit 34972A, Electronic load IT8511+	23.52% compared to the CPV-TE hybrid system.
Fatemeh Rajaee et al. [102]	PV/TE with Co3O4/water nanofluid and PCM	5 W polycrystalline silicon cell	TE generators SP1848-27145, Co3O4/water nanofluid Heat sinks, Heat conductive paste, Copper pipes, Paraffin wax Al2O3, powder Magnetic stirrer, Pump AC/220-240V/ 8W	K-type thermocouple sensors, TES-133 pyranometer, Multimeters UT71C/D/E, Data record device TESTO-177-T4, UK	Using PCM and 1% nanofluid enhanced overall electrical efficiency by 4.52%.

The table shows a range of PV cell types, including crystalline silicon (c-Si) PV modules, monocrystalline silicon PV modules, gallium arsenide (GaAs) single-junction solar cells, and triple-junction GaAs PV cells. They range from small-sized 5W polycrystalline silicon cells to 10W monocrystalline silicon modules. This diversity highlights the adaptability of cooling technologies across different PV technologies. In terms of materials, the studies use a wide range of components, including thermal modules, heat sinks, copper tubing, paraffin wax, nanofluids, and more, each performing unique roles in temperature control and heat dissipation. The comprehensive suite of measurement instruments, including pyranometers, multimeters, thermocouples (K-type), data loggers, hot anemometers, and infrared cameras, allows researchers to comprehensively evaluate the performance and efficiency of cooling methods in diverse PV applications. In addition, the results in the table show a significant range, from temperature reductions of about 1.77°C to 30°C and efficiency improvements ranging from about 4.52% to 20.68%.

3.5. Heat pump and heat pipe techniques

In addition to the previously discussed cooling methods, heat pipes, and heat pumps are noteworthy technologies that contribute significantly to enhancing the efficiency of a PV system. The main difference between these methods is their passive and active nature. Heat pipes, being passive devices, transfer heat efficiently without mechanical components, relying on phase changes. They excel at maintaining constant temperatures and are valuable in solar panels and electronics. In contrast, heat pumps are active devices that require energy input to move heat and are versatile, serving both heating and cooling purposes. Fig. 10 depicts an experimental setup utilizing heat pump and heat pipe techniques to enhance photovoltaic system efficiency. Heat pumps actively regulate PV temperatures by transferring excess heat away from the panels, while heat pipes facilitate efficient thermal management by rapidly conducting heat, respectively. Measuring tools like K-type thermocouples, a pyranometer, a multimeter, a rheostat, a data logger, and a laptop monitor temperatures, solar radiation, electrical resistance, and data collection, respectively. This setup combines active and passive cooling methods with comprehensive data monitoring to improve PV performance and maximize electricity generation from enhanced thermal management.

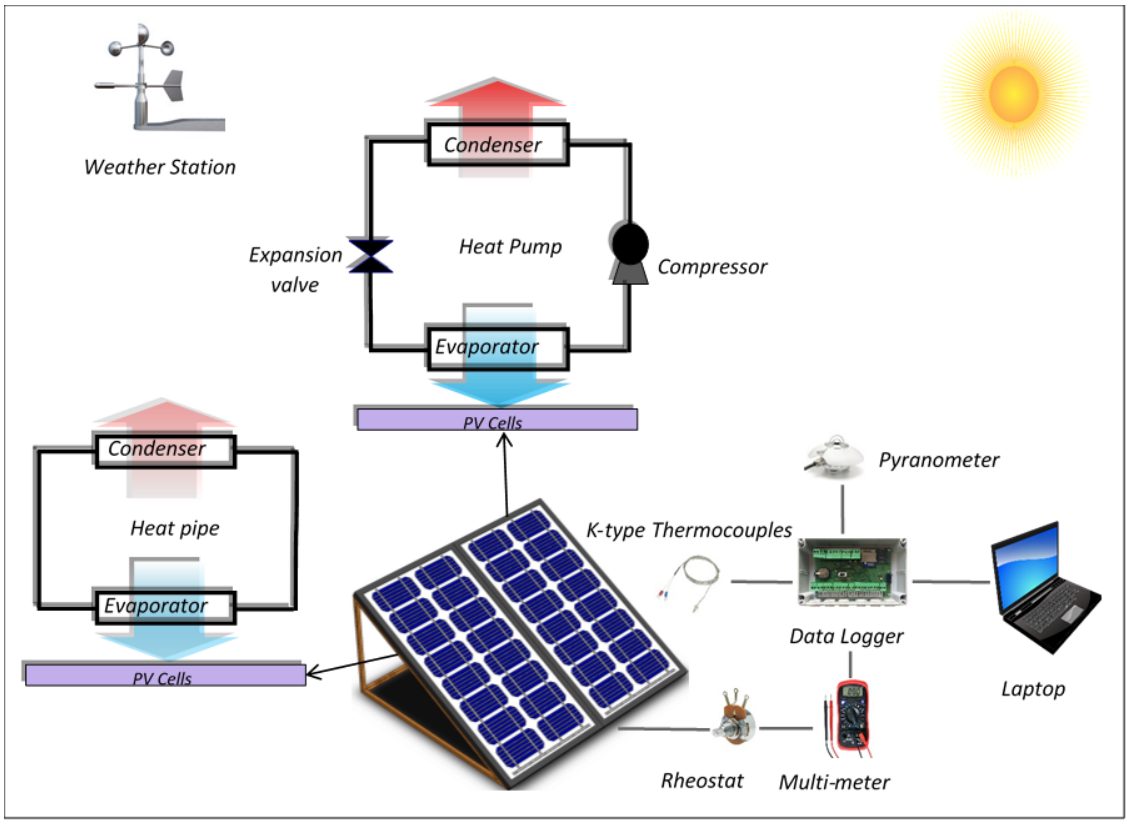

Fig. 10: Schematic Representation of an Experimental Setup for Cooling Photovoltaic Using Heat Pump and Heat Pipe Techniques.

Below is a summary table focusing on these technologies, outlining their methodologies, materials, tools, and important results, with an emphasis on their impact on increasing the efficiency of solar energy conversion.

Table 9: Various Cooling Techniques in Photovoltaic Systems: Materials, Measurements, and Outcomes.

Authors	Cooling Methodology	PV Technology	Cooling Materials	Measurement Tools	Key Findings
H. Jouhara et al. [103]	Flat Heat Pipes (Heat Mat)	PV/T	Heat Mat, Intermediate Fluid (60% Water and 40% Glycol),	K-Type Thermocouples, Pyranometer, National Instruments Data Acquisition System	Achieved a thermal efficiency of 50% for the PV/T mat, and a 15% increase in electrical output.
Meysam Moradgholi et al. [104]	Heat Pipe (Thermosyphon Type)	Single Crystal Silicon	Aluminum Thermosyphons, Fiberglass Insulation,	MPPT1 Device (0.1 W Accuracy), Solarimeter Device (Solar 300), Laser Thermometer (0.1°C Accuracy), PT100 Thermocouple (0.1°C Accuracy), Gauge (1-3 Bar Range)	Improved thermal efficiency by 16.35% with methanol and 45.14% with acetone. Enhanced average electrical power by 5.67% with methanol and 7.7% with acetone.

Qu Minglu et al. [105]	Dual-Source Heat Pump (DSHP)	Mono-Crystalline Si Solar Cells	Dual-Source Heat Pump, Copper Components, Thermally Conductive Silicone Rubber, Heat Storage Tank	Utilized Pre-Calibrated T-Type Thermocouples, PT100 Resistance Temperature Device (Class A), PWM Digital Power Meter	Reduced PV/T plate temperature by up to 45°C and increased electrical conversion efficiency by 10.3%.
Hongbing Chen et al. [106]	PV Panels with a Small Heat Pump	Amorphous Silicon (8.03 Wp)	Heat Pump System, Glass Vacuum Tube, Aluminum Sheet, Copper Tube	Employed Pyranometer, Power & Energy Monitor, Pressure Transducer, Thermocouple Type K, PT100 Temperature Sensor, Data Logger, Flow Indicator, Rheostat, Resistance (10Kohm and 100Kohm)	Improved electrical efficiency of PV panels by up to 1.9%.

The table presents the heat pipes, and heat pump cooling techniques for photovoltaic systems, highlighting the materials and measurement tools used. Materials include heat pipes, thermosyphons, heat pumps, and PV panels. Measurement tools encompass thermocouples, pyranometers, data acquisition systems, and more, enabling precise temperature monitoring and electrical output assessment. These diverse materials and tools showcase the potential for enhancing PV system efficiency through effective temperature management.

4. Results and discussion

4.1. Energy and Economic Study

Based on several cooling techniques found in the literature, we shall now delve into the methodology used for the systematic comparison and evaluation of these techniques applied to photovoltaic panels. To accomplish this comparative analysis, several important assumptions were made, which include factors such as a PV panel area of 1 m2, a power output of 210 Wp, an assumed average daily sunlight exposure of 10 hours, and an average radiation level of 800 W/m², an efficiency rate of 21% at standard test conditions (STC), and an actual efficiency of 10.50% in the absence of cooling, derived from previous experimental data. Furthermore, this methodology takes into account the average PV panel temperature of 53°C and the ambient temperature of 30°C.

To conduct this comparative analysis, we adopt an analytical approach that involves calculating the output power of PV panels under different cooling methods, using the assumptions we have made. It then involves subtracting the energy consumed by active cooling methodologies to determine the net electrical energy produced. In addition, cost evaluation is incorporated into the analysis, allowing a comprehensive comparison of the performance and cost-effectiveness of each cooling method.

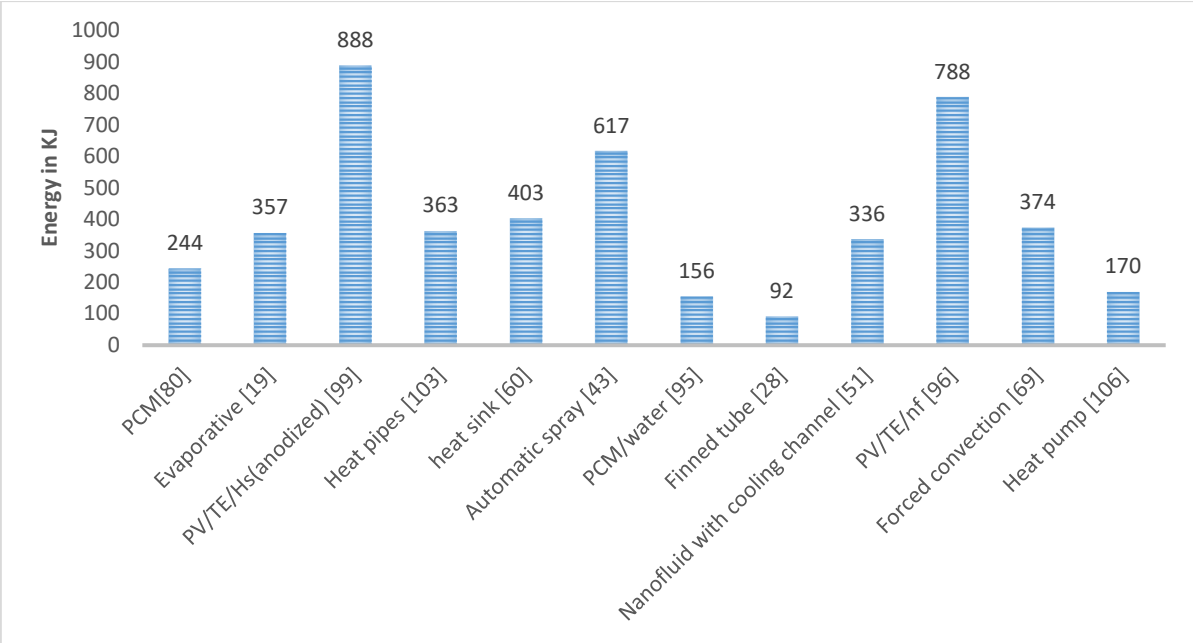

Fig. 11: Comparative Analysis of Electrical Energy Savings Achieved Through Various Cooling Methods.

Analyzing Fig. 11, which depicts the net electrical energy calculation for a PV panel with different cooling technologies, it becomes clear that these approaches yield significantly different results in terms of net energy gains, taking into account both additional energy production and consumption. Passive cooling technologies, including PV/TE/Hs (anodized), auto-spray, heat sink, and heat pipes, display significantly high net energy gains, achieving values of 888 kJ, 617 kJ, 403 kJ, and 363 kJ, respectively, with minimal electrical energy consumption. Among the active cooling methods, nanofluid with a cooling channel leads with a significant net additional energy output of 336 kJ, while forced convection follows closely with 374 kJ, taking into account their respective energy consumption.

Fig. 12: Comparative Cost Savings Analysis Across Various Cooling Methods.

By analyzing the cost data presented in Fig.12 for different PV cooling technologies, a clear distinction can be made between passive and active approaches in terms of their associated costs. Passive cooling techniques generally show lower initial costs, with options such as PCM and evaporative cooling priced at $35 each. In contrast, active cooling methods tend to involve higher initial investments, with PV/TE/nf (Photovoltaic/Thermoelectric with nanofluids) being the most expensive at $155, followed by a heat pump at $90. The choice of cooling technology should not only be based on initial cost but also consider factors such as energy efficiency and long-term operational benefits. This analysis paves the way for a discussion of the energy efficiency ratios associated with these cooling methods, highlighting their performance beyond cost.

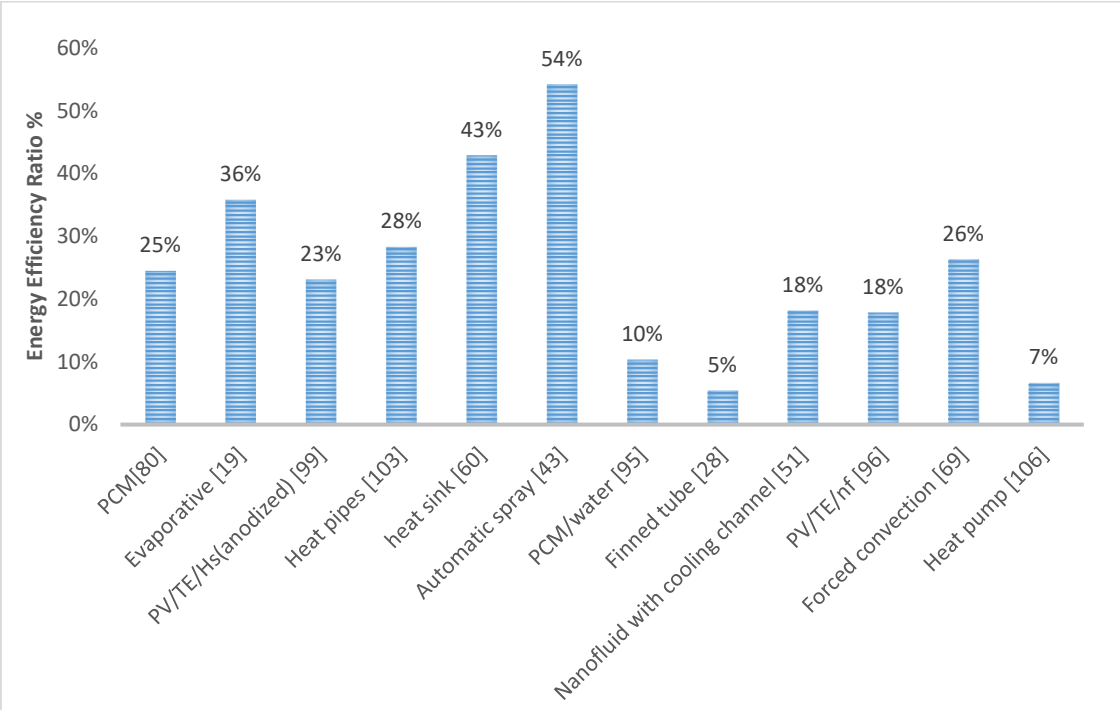

Fig. 13: Comparative Analysis of Energy Efficiency Ratios Among Diverse Cooling Techniques.

Fig. 13 represents the "Cooling Energy Efficiency Ratios". These ratios help evaluate and compare the effectiveness of various cooling techniques in providing cooling or temperature control while considering their electrical energy input. By calculating and comparing these ratios for different cooling systems, it becomes easier to identify which methods are the most energy-efficient. This information is invaluable for making informed decisions when selecting cooling technologies, ensuring that the chosen method not only effectively manages temperature but also minimizes energy consumption and associated costs.

In the realm of cooling techniques, various factors come into play. Heat sinks stand out with an impressive energy efficiency ratio of 43%, underscoring their pivotal role in passive cooling. In challenging environments, such as dusty or dirty climates, automatic spray systems, boasting a remarkable energy efficiency ratio of 54%, not only excel in cooling but also ensure cleanliness and performance. Active cooling techniques, such as systems with cooling channels, have the unique ability to generate surplus thermal energy while cooling, enhancing overall utility. However, passive cooling methods like evaporative cooling (36%) and phase change materials (PCM) (25%) often exhibit higher energy efficiency ratios compared to active techniques, making them attractive unless specific thermal energy production is required. Additionally, passive techniques can also harness extra power through thermoelectric (TE) elements, although they tend to be relatively expensive, adding complexity to the decision-making process.

4.2. Advantages and Disadvantages of The Main Cooling Techniques

The following table provides a detailed comparison of the main cooling techniques used for photovoltaic panels. This comparison considers various factors such as cost, efficiency, and maintenance requirements, alongside specific cooling materials and types of PV technology employed.

Table 10: Advantages and Disadvantages of The Main Cooling Techniques

Cooling Technique	Advantages	Disadvantages
Evaporative Cooling	Low initial cost, effective in dry climates, low water consumption, low or no power consumption	A complex system, with reduced effectiveness in humid climates, allows dust to adhere to PV
Water Pipes and Channels	Efficient heat dissipation, versatile application, extracted heat can be reused	Requires water circulation systems, potential for corrosion and leaks, high power consumption (pumps)
Water Spray	The rapid cooling effect, keeps the PV surface clean, and effective in hot conditions	Requires water consumption, maintenance of spray nozzles and water pumps
Water Nanofluid	Enhanced thermal conductivity, effective heat transfer	Nanofluid preparation and stability, potential clogging in channels, heat exchanger required, risk of sedimentation.
Natural Air Cooling	Passive system with low operational cost, minimal maintenance required	Limited effectiveness in high temperatures, added mass (heat sink) can cause cracks in PV.
Forced Air Cooling	Effective in moderate climates, enhances convective heat transfer	Requires energy for fans, noise and vibration issues, maintenance of fans
PCM	High thermal storage capacity, uniform temperature regulation, efficient passive cooling	Dependent on ambient air conditions, limited operational lifetime, criticality of phase change transition temperature, very low thermal conductivity
Thermoelectric Cooling	Potential for energy generation	High cost, requires very high-temperature gradient, requires other cooling techniques (fans, heat sink, PCM, water)
Heat Pump	Very efficient heat transfer, suitable for varied climates	Initial installation cost, maintenance of heat pumps, high power consumption
Heat Pipe	Passive cooling system with a good cooling effect	Depending on the evaporation point of the liquid and the ambient temperature. Requires maintenance.

In summary, each cooling technique presents distinct benefits and limitations. The choice of cooling method should be based on specific environmental conditions, efficiency improvements desired, cost considerations, and maintenance capabilities. This detailed comparison helps in making an informed decision for selecting the most suitable cooling technique for optimizing the performance and longevity of photovoltaic systems.

5. Closure

In summary, the present study provided a comprehensive exploration of different PV system cooling approaches, with each approach thoroughly examined through dedicated experimental setups. It is worth noting that the research exposed covered a wide range of PV sizes, technologies, and measurement instruments, enhancing the comprehensiveness of the findings. Moreover, it was observed that in the case of expensive cooling techniques such as thermoelectric methods, the size of the PV panels utilized was notably smaller, typically ranging between 5 W to 10 W. In contrast, more cost-effective cooling approaches like evaporative techniques incorporated larger PV panel sizes, ranging from 25 to 320 Wp, thereby providing results that are more practical and applicable to real-world scenarios. Throughout the investigation, a variety of PV technologies were employed, with crystalline types such as polycrystalline and monocrystalline being the predominant choices. Furthermore, the primary tools utilized for measurement and data collection encompassed a range of temperature sensors (including K, J & T-type thermocouples, PT100 thermometers, infrared thermometers, infrared cameras, LM 35 sensors, and others), power meters (such as multimeters, voltage and current sensors, MPPT controllers, and others), Pyranometers for solar intensity measurement, data loggers for comprehensive data collection, and an assortment of weather stations, anemometers, flow meters, and other relevant tools. Additionally, various cooling materials were employed to design specific cooling techniques for each method. These settings have played a pivotal role in accurately evaluating the performance and efficiency of cooling technologies. Furthermore, the subsequent analysis in the energy section has offered valuable insights into the net energy gains, cost-effectiveness, and energy efficiency ratios associated with these methods. Passive cooling technologies, exemplified by phase change materials, heat sinks, and evaporative cooling, have shown commendable energy efficiency and cost-effectiveness, especially under diverse PV setups. Conversely, active cooling methods, although they require initial investments, offer promising ways to significantly improve energy production. These diverse selections have significantly enriched the breadth of our research and contributed to the comprehensive understanding of the cooling methods under examination. In progressing toward a sustainable energy future, improving PV system performance through effective temperature management remains a top priority, and our study provides a solid foundation of knowledge to guide these endeavors.

6. Conclusions

In conclusion, this study offers a comprehensive exploration of photovoltaic system cooling methods, underscoring the pivotal role of experimental setups in ensuring precise data collection and analysis. These setups enabled comprehensive assessments across diverse PV sizes, technologies, and measurement tools. Within this framework, various cooling materials were identified, providing essential insights into net energy gains, cost-effectiveness, and energy efficiency related to cooling methods.

Passive cooling technologies such as PV/TE/Hs (anodized), auto-spray, heat sink, and heat pipes demonstrate substantial net energy gains of 888 kJ, 617 kJ, 403 kJ, and 363 kJ, respectively, with minimal electrical energy consumption. Conversely, active cooling methods like nanofluid with cooling channels and forced convection exhibit notable net additional energy outputs of 336 kJ and 374 kJ, respectively, taking into account their energy consumption.

A comparative cost analysis highlights lower initial costs for passive techniques such as PCM and evaporative cooling at $35 each, compared to higher investments required for active methods like PV/TE/nf ($155) and heat pumps ($90). The selection of cooling technology should consider not only initial costs but also energy efficiency and long-term operational benefits.

Energy efficiency ratios further underscore the performance of different cooling techniques in managing temperature control relative to their electrical energy input. Passive methods like heat sinks (43%) and automatic spray systems (54%) excel in energy efficiency, ensuring effective cooling and system cleanliness. In contrast, active techniques such as cooling channels and thermoelectric elements offer surplus thermal energy production but require careful consideration due to their higher costs and complexity.

As we advance toward sustainability, this study emphasizes the crucial role of experimental setups in achieving precise data collection and highlights the benefits of passive cooling techniques like heat sinks, PCMs, evaporative, and sprayer cooling compared to active methods. This knowledge aids in making informed decisions when selecting cooling technologies based on project requirements and environmental conditions, optimizing PV system performance, and supporting sustainable energy solutions. Additionally, this paper contributes to the domain by providing a comprehensive summary that guides engineers, researchers, and readers in initiating their studies or experiments, thereby advancing research and development in PV cooling technologies. The uniqueness of this review lies in its detailed focus on the materials used in various cooling techniques, the corresponding measuring tools, and a thorough comparison based on energy and economic aspects.

7. Future Recommendations

1. Conduct a comparative experimental study involving PV systems with various cooling methods, including standard PV, PV with heat sinks, and PV with forced convection. This research will provide valuable insights into the performance differences and energy efficiency of these cooling techniques.

2. Undertake a comprehensive comparative experimental study encompassing PV systems with different cooling approaches, such as standard PV, PV with phase change materials (PCM), PV with composite PCMs, and PV with heat sinks. This investigation will shed light on the advantages and disadvantages of these cooling methods in real-world applications.

3. Initiate a comparative experimental study involving PV systems utilizing distinct cooling strategies, including standard PV and PV with evaporative techniques. This research will help in evaluating the effectiveness of evaporative cooling in enhancing PV system performance.

4. Carry out a comparative experimental study focusing on PV systems with various cooling methods, such as standard PV and PV with spray cooling techniques. This study will contribute to a deeper understanding of the benefits and limitations of spray cooling in the realm of PV systems.

5. Undertake an economic and environmental study to assess the ecological impact of different PV cooling technologies. Investigate the environmental footprint, sustainability, and long-term implications of these cooling methods to guide environmentally responsible decisions in PV system design and operation.

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