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Condition Review on Photovoltaic Cell Cooling Techniques for Sub-Saharan African Region

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Abstract

Solar energy, a critical component of sustainable energy solutions, offers significant potential, especially in regions like Sub-Saharan Africa (SSA) that experience high solar irradiance. However, excessive heat and inefficient thermal management hinder the optimal performance of photovoltaic (PV) systems in these regions. High operating temperatures lead to thermal degradation, reducing both efficiency and lifespan of PV panels. This paper reviews the challenges of PV cooling in SSA, highlighting the urgent need for cost-effective cooling techniques to enhance efficiency and economic viability. It explores various methods to mitigate excessive heat and proposes a novel cooling technique tailored to the climatic conditions of SSA. The goal is to improve PV performance, extend panel lifespan, and support sustainable energy development in the region, addressing the pressing energy poverty that affects approximately 70% of SSA's population. This study underscores the importance of efficient PV systems in combating climate change and fostering economic growth in SSA.

Key words: *Photovoltaic PV, Cooling, Efficiency, Thermal Degradation, Phase Change Materials*

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I. Introduction

Solar energy, derived from the sun's abundant energy, offers many advantages that position it as a vital element of our sustainable energy future. It represents environmentally friendly technology, a robust energy resource, and one of the most significant forms of renewable and eco-friendly energy. The sun bestows an astounding 1.8×10^{11} MW of energy upon the Earth, a magnitude nearly a thousand times greater than the combined energy consumption from all other sources (Sheik *et al.,* 2022). Harnessing solar radiation to generate electricity emerges as a superior alternative to non-renewable fossil fuels. As technology advances rapidly, the demand for energy sources continues to surge. The depletion of traditional fossil fuels not only leads to energy shortages but also triggers numerous environmental pollution issues, which are primary impediments to the advancement of a sustainable society (Sun *et al.,* 2022). Ongoing advancements have been made to enhance the efficiency of PV solar cells, while concentrated solar technologies for electricity generation also demonstrate promising potential (Hayat *et al.,* 2019). Both concentrated solar power and solar photovoltaics continue to undergo continuous refinement to meet our evolving energy requirements (Li *et al.,* 2022).

The SSA region is characterized by its abundant solar energy resources, with some of the highest levels of solar irradiance in the world. This immense potential for solar energy has made photovoltaic (PV) systems an increasingly attractive solution for addressing the region's growing energy demands and combating climate change. However, one critical challenge that hinders the widespread adoption of PV technology in Sub-Saharan Africa is the issue of excessive heat and inefficient thermal management of PV panels.

As temperatures in Sub-Saharan Africa can soar to extreme levels, especially during the dry seasons, PV panels often operate at elevated temperatures, causing a decrease in their overall efficiency and lifespan. High operating temperatures can lead to a phenomenon known as the "thermal degradation" of PV cells, which not only reduces energy production but also shortens the operational life of the panels. Furthermore, inefficient cooling systems in PV installations can significantly affect the economic viability of solar power projects in the region.

Due to the significant influence of temperature on PV performance, much research has been dedicated to possible cost-effective ways to cool PV modules (Sajjad *et al.,* 2019; Dwivedi, *et al.,* 2020; Moner-Girona *et al.,* 2021 and Mohammed *et al.,* 2023). As the world recognizes the urgency of addressing climate change and reducing carbon emissions, there is a heightened demand for efficient and reliable PV systems, making the improvement of PV cooling techniques a critical focus in the quest for sustainable energy solutions. The difficulty in cooling PV modules is that the cooling system must not significantly increase the overall initial cost, and effectively increase the efficiency to be worthwhile. This paper aims to explore, design, and simulate a new technique for photovoltaic cooling systems tailored to the unique climatic conditions of the SSA region.

1.1 Access to Energy

Access to reliable and affordable energy is a fundamental driver of economic and social development. In Sub-Saharan Africa (SSA), a significant portion of the population, roughly 70%, continues to grapple with 'energy poverty,' where they lack access to basic electricity services (Quansah *et al.,* 2016). This situation not only hampers the well-being and quality of life for millions but also impedes economic growth and development prospects (Murshed *et al.,* 2022). One of the core issues hindering the implementation of large-scale energy projects in SSA is the exorbitant cost involved (Avila *et al.,* 2017 and IEA 2023).

According to Avila *et al.,* (2017), the electricity sector in SSA region presents a unique set of challenges. While sub-Saharan Africa contributes the least of any global region to greenhouse gas emissions (GHG), it is most vulnerable to climate change impacts such as droughts and reduced agricultural yields (Omotoso *et al*., 2023). Eustache *et al.,* 2023 opined that scattered pattern of rainfall and persistent drought leads to a reduced hydroelectric output as well as extended outages. Avila *et al.,* (2017) further challenges that are priority targets for reform in SSA electricity sector, with the aim of reaching affordable energy access and sustainability goals across the region.

1.2 Global Development in Solar Energy

The global landscape of photovoltaic (PV) solar energy has achieved a remarkable milestone in 2022, with the cumulative capacity of installed and commissioned PV systems surpassing 1.18 terawatts (TW). This significant achievement reflects a year-on-year growth of over 26%, a clear indication of the accelerating transition towards renewable energy sources (IEA, 2023). China continues to assert its dominance in the global solar arena, maintaining its position as the country with the largest installed PV capacity. In 2022 alone, China added a staggering 106 GW of solar capacity, constituting 44% of the total global additions. As a result, China's cumulative installed capacity reached a formidable 414.5 GW, a trend that has been consistent over the past decades, with impressive additions of 54.9 GW in 2021 and 48.2 GW in 2020. The European Union (EU) demonstrated a commendable surge in solar installations, with 38.7 GW of solar capacity added in 2022, a significant increase from the 27 GW registered in 2021 and 20 GW in 2020. Spain emerged as the leader in European solar growth, contributing 8.1 GW, followed closely by Germany (7.5 GW), Poland (4.9 GW), and the Netherlands (3.9 GW). Collectively, the EU secured its position as the second-largest market in terms of cumulative capacity, amassing 209.3 GW.

1.2.1 Global Penetration Rates and Contribution to Electricity Demand

A noteworthy aspect of the report is the examination of electricity production from PV in various countries. Nine countries achieved penetration rates exceeding 10% in 2022, signaling the growing influence of solar energy in their energy mix. Spain led the list with a remarkable 19% penetration rate, followed by Greece (17.5%), Chile (17%), and the Netherlands (15.9%). Australia (15.7%) and Honduras (12.9%) secured the fifth and sixth positions. Germany (12.4%) and Israel (12.3%) closely followed, with Japan marking the last position at 10.2%. The report highlighted that PV's contribution amounted to 6.2% of the world's total electricity demand, with the EU and China having penetration rates of 8.7% and 6.5%, respectively.

1.3 Development of solar energy in sub-Saharan Africa

On a global scale, an anticipated surge of over 1200GW in new solar capacity is projected to be added between 2022 and 2031. However, the Sub-Saharan Africa (SSA) region, despite its abundant solar potential, is poised to contribute only a modest fraction to this expansion, accounting for just below 1% of the overall growth. By 2031, it is forecasted that the SSA region will have approximately 8.6GW of new solar capacity, representing a mere 0.7% of the global increment (as shown in figure 1). The average temperature for SSA is 35.96^{0}C and should be brought down 25^{0}C which is the optimal operating temperature of PV for enhance its operation (EIA, IRENA, national sources, Fitch Solutions)

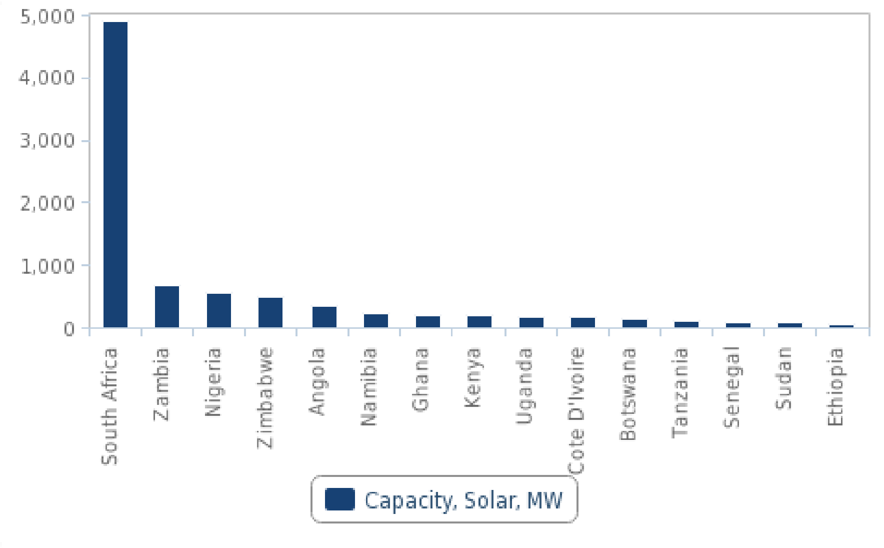

Figure 1: Net Change in Power Capacity by Market, 2022 – 2031
Source: Fitch Solutions (2022).

1.4 Photovoltaic Systems

Photovoltaic systems are systems that convert sunlight into electricity using photovoltaic cells. Al-Ezzi and Ansari (2022) define photovoltaic systems as systems that utilize solar power to generate electricity by converting the sunlight to direct current in solar cells or PV cells. These PV cells consist of semiconducting materials, specifically p-type and n-type layers. When exposed to sunlight, the cell initiates an electric field between these layers, generating both voltage and current. PV cells are typically categorized as either polycrystalline, composed of fragments from multiple silicon crystals, or monocrystalline, which are obtained by cutting a single, large crystal.

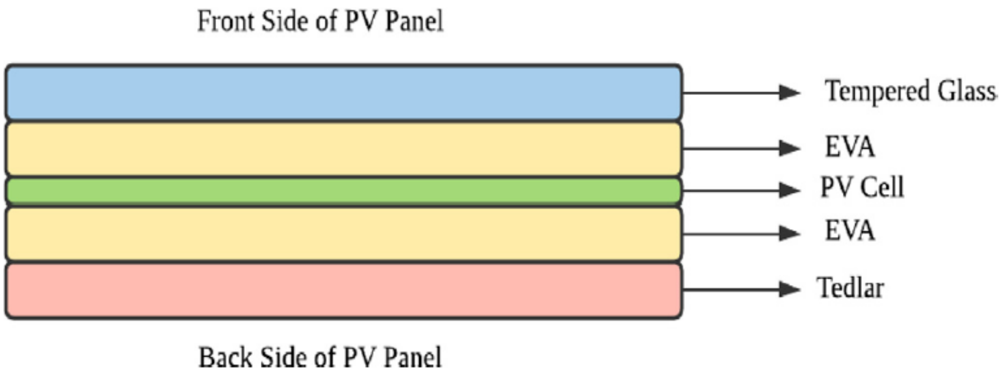

Figure 2: Schematic Diagram of a PV panel
Source: Sheik *et al.,* (2022)

The PV panel typically comprises of five distinct layers, as illustrated in Figure 2. The initial layer is composed of tempered glass, offering protection and durability. Beneath it lies the second layer, ethylene-vinyl acetate (EVA), which acts as an adhesive and encapsulant, binding the components together. The third layer consists of the PV cells, where the photoelectric effect happens as sunlight is converted into electricity. Below the PV cells, the fourth layer again features EVA, providing structural support and insulation. Finally, the bottommost layer is constructed from Tedlar foil, enhancing the panel's longevity and safeguarding it from environmental factors (Sheik *et al.,* 2022).

II. Literature Review

In the study by, Khan *et al.,* (2017) which investigated the efficiency of three distinct structures/materials: (i) silvered glass plane mirror; (ii) convex spherical mirrors; and (iii) aluminum (Al) foil as a reflector. They also compared four different cooling techniques, namely the water sprinkling system, passive heat sink method, active air fan method, and closed loop method, to enhance the output power. A revolutionary Bi reflector solar PV system (BRPVS) was proposed to manage the working of the reflectors.

In another study by Sukarno *et al.,* (2017) which intend to examine the 30-output power and efficiency from continuous cooling system, cooling system every one hour and non-cooling system of solar photovoltaic panel. The output power computed for the continuous cooling system was 68.8-Watt, cooling system every one hour was 65.11 Watt and 59.06 Watt for non-cooling system accordingly at University Malaysia Sabah (6°01'53.73"N, 116°07'14.98"E). The efficiency percentage of this system was 16.7%, 14.4% and 13% respectively. The maximum temperature for continuous cooling system panel was 38.9˚C at 2 pm, cooling system every one hour was 48.2˚C at 11 am and non-cooling system was found 53.3˚C at 1 pm. Power output measurement was conducted for 10 days from 13th to 22nd March 2016. The corresponding maximum global solar radiation was 1052.9 W/m² on 17th March 2016 at 2 pm whereas the highest hourly average was 970.17 W/m^2 at 1 pm. Therefore, it can be stated that normally output power for continuous cooling system is greater than non-cooling system.

Also, Syafiqah *et al.,* (2017) in their study which examines and discusses the PV panel with water- and air-cooling system. The air-cooling system was constructed behind the of PV panel meanwhile water-cooling system at front surface. The studies of both cooling systems were performed by utilizing ANSYS CFX and PSPICE software. The greatest temperature of PV panel without cooling equipment is 66.3 °C. There is a decrement of 19.2% and 53.2% in temperature with the air- and water-cooling system applied to PV panel.

Kumar and Dubey (2018) in their study on the efficiency improvement of photovoltaic panels by design improvement of cooling system using back water-cooling tubes used an array of water tube which were fitted to the back of solar panel to reduce its temperature and bring temperature to standard working point. Prior to this both air cooling model and water-cooling model conditions are examined under normal operating condition. After obtaining data for various model, the study analyzed back water-cooling tube array outcomes with the normal solar panel. The result shows a maximum photoelectric conversion efficiency difference of 2.6%, and temperature decreases of 1-2 degree Celsius, the output power generation efficiency increased by 0.5 to 1 % for the solar PV panel when using heat pipe for air-cooling,

Ebaid *et al.,* (2018) in their research which studied cooling of photovoltaic (PV) panels utilizing two nanofluids and water as a cooling medium with volume flow rate spanning from 500 to 5000 mL/min at concentrations (0.01 wt.%, 0.05 wt.%, and 0.1 wt.%) under different radiation intensity. Two types of nanofluids were used, namely Al_2O_3 in water -polyethylene glycol mixture at pH 5.7, and TiO_2 in water-cetyltrimethylammonium bromide mixture at pH 9.7, respectively. To cool the PV panel effectively, a heat exchanger with an aluminum rectangular cross-section was integrated into its rear surface, designed to accommodate various volume flow rates of the aforementioned cooling medium. The system underwent testing in the climate conditions of Jerash, Jordan. Flow characteristics, including the friction factor (f) and the product of the friction factor and Reynolds number, were examined for TiO2, Al2O3 nanofluids, and water as cooling media.

The study conducted by Harahap and Dewi (2019), Tashtoush and Al-Oqool (2019) delved into the exploration of three primary parameters pivotal to the effectiveness of the active cooling system. These parameters include the water flow rate, the setpoint temperature of the photovoltaic panel, and the maximum allowable temperature difference of the photovoltaic panel. By systematically investigating these variables, the researchers aimed to discern their individual and collective impacts on the cooling system's performance and its ability to regulate the temperature of the photovoltaic panel efficiently.

Shmroukh (2019) studied thermal regulation of photovoltaic panel installed in upper Egyptian conditions in Qena. The objective of the research is to design a cooling system for the suggested thin-film PV panel that will be deployed in a difficult environment location in Qena City, Upper Egypt. The goal is to achieve a feasible and tolerable level of electrical efficiency. In order to reach this objective, three distinct cooling systems and operating modes were examined: an open-loop water-based cooling system, a closed-loop water-based cooling system with a free-convection air-cooled heat exchanger, and a closed-loop water-based cooling system with a forced-convection air-cooled heat exchanger utilizing a DC fan.

Fayaz *et al.* (2019), thought of a novel design of a thermal collector made up of Aluminum. He conducted his experiment for PV, PVT, and PVTPCM systems to observe, evaluate and analyze efficiency under different operating conditions. The experiment comprising of the PVT-PCM system was done utilizing paraffin wax (commercial code name A44- PCM). For the PV-Thermal hybrid networks, water flows via serpentine thermal collector, which is passively driven by the above water tank.

Arifin *et al.,* (2020) performed numerical and experimental analyses to explore the decline in the operating temperature of PV panels using an air-cooled heat sink. The suggested heat sink was built as an aluminum plate with perforated fins that is mounted to the rear of the PV panel. A full computational fluid dynamics (CFD) simulation was done using the program ANSYS Fluent to ensure that the heat sink model operated appropriately. The impact of heat sinks on the heat transfer between a PV panel and the circulating ambient air was explored. The results demonstrated a large drop of the operating temperature of the PV panel and an improvement in its electrical performance.

Nebbali *et al.,* (2020) in their study which aimed to limit losses due to temperature rise in PV panels using a simple and autonomous air conditioning system comprised of a fan activated by the power produced by the panel. This fan blows ambient air on the back face of the panel. Experimental readings of the current intensity as well as voltage provided by the panel and its front face temperature ensure the validity of the numerical code. Numerical and experimental findings are in good agreement. As the primary findings of this autonomous cooling, in contrast to the uncooled panel scenario, the efficiency for difficult climatic condition improves of 29.52 % while the panel temperature lowers of 39.29 °C. Such results achieved with this quite simple autonomous cooling system on the improvement of the PV panel efficiency suggest interesting economic and commercial arguments.

Bhakre *et al*., (2021) reviewed the extensive investigation on the influence of the front surface, rear surface and combination of front and rear surface cooling on the water-based photovoltaic systems. The research also discusses diverse designs of solar thermal absorber collectors. The front surface cooling resolves two problems.

Metwally *et al.,* (2021) studied the annual performance of the photovoltaic active cooling system using the thermoelectric generator. The study developed a photovoltaic panel model that consists of an active cooling technique. Active cooling systems created model employs household water as a thermoelectric generator's heat sink, and the photovoltaic temperature represents a thermoelectric generator heat source.

Also, Agyekum *et al.,* (2021) carried out an experimental examination to access the influence of dual surface cooling of solar photovoltaic panel on the efficiency of the module. The research delved into investigating the efficacy of simultaneous dual surface cooling in enhancing the output performance of photovoltaic (PV) modules through experimental methods. Specifically, the study focused on implementing a cooling system that addresses both the front and rear surfaces of the PV module. To cool the rear surface effectively, a unique approach was adopted. A cotton wick mesh was utilized, designed to absorb water from a perforated pipe. Through capillary action, the absorbed water was efficiently transferred down the surface of the rear side of the PV module.

Nižetić *et al.,* (2021) conducted an experimental investigation concerning passively cooled freestanding silicon photovoltaic panels (PV), exploring various cooling configurations with the incorporation of phase change materials (PCM). The study involved the examination of PV panels (20Wp) under typical Mediterranean climate conditions, undergoing several months of field monitoring. The primary objective of the research was to reevaluate the traditionally employed passive cooling methods for PV systems, particularly in scenarios where phase change materials are utilized for cooling purposes (PV-PCM cooling systems).

Sornek *et al.,* (2022) Developed and tested water-cooling system dedicated to photovoltaic panels. The study aimed to enhance the efficiency of photovoltaic cells. However, it also delved into exploring other avenues for improving the energy output of current technologies, such as the implementation of cooling systems for photovoltaic modules. This approach can decrease the mean operation temperature of photovoltaic cells, leading to an increase in efficiency and energy produced. Water-based cooling (AW) systems, such as water-cooled panels or heat exchangers, are effective at dissipating heat. Water-cooling is often more efficient, as water can transfer heat more effectively than air.

Passive cooling methods leverage natural processes to remove heat from PV panels. These methods such as heat sinks (PHS), and thermal photovoltaic systems (PPVIT), designing panels with elevated gaps to allow airflow and prevent heat buildup (PPVI). Reflective coatings can also reduce heat absorption, while orientation and tilt adjustments optimize exposure (PPO) to cooler ambient air. On the contrary, active cooling, active cooling mechanisms employ technologies to manage temperature. They include air cooling (AA) involves fans or blower

There are other techniques used by combination of aforementioned techniques, each of the techniques has its own subsidiary. For example, AWC, it can be water spayed above (AWA) or below (AWB), similarly for air cooling it can be heat extraction (AAE) or fanning (AAF).

TABLE 1. Related literatures on PV cooling using different methods with efficiency improvements.

S/N	**Authors/ Year**	**SPV module details**	**Location and Tilt Angle**	**Cooling method**	**Test methodology**	**Efficiency enhancement**	**Results**
1.	Savvakis *et al.*, 2020	Mono-crystalline panel, 10Wp.	ReSEL facilities (35°31 ′ N, 24 °04 ′ E). Tilt angle 30°	PCM RT 27, PCM RT 31.	Experimental. PCM with Copper pipes	4.19%	The maximum temperature reference module is 61°C Reduction against the reference panel, with PCM27 and PCM31, was reduced by 6.4°C and 7.5°C
2.	Kumar *et al.*, 2020	Poly-crystalline panel, 12Wp.	Coimbatore, Tamilnadu. Tilt angle 26°	PCM - mass ratio 7:1:2- CaCo 3, SiC and Cu (Nanoparticle).	Experimental.	4.3%	Temperature reduction by combined PCM of PV panel by 2°C with a mean temperature of 4.4°C and performance efficiency enhanced by 2.2%.

4.	Singh *et al*., 2020	Mono-crystalline Panel, 175Wp.	Chennai, India (13 o N, 80 o E) Tilt angle 13°	PCM - Calcium chloride hexahydrate ($CaCl_2 .6H_2O$)	Experimental Conducted with two trials	First Trail 6.2% Second Trail 8.3%	In the first trial, the temperatures in the uncooled panel were 77.1°C and in the PCM-based panel 53.8°C, In the second trial, temperatures in the uncooled and PCM panel 64.4°C and 46.4°C, respectively.
5.	Sudhakar *et al*., 2020	Poly-crystalline Panel, 20Wp.	Chennai, India (13.01°N, 80.24°E)	PCM-OM 35	Experimental. One reference panel and another panel rear are filled with PCM	12.4%	Temperature reduction using PCM-T 32°C-49°C Reference panel temp 35°C-52 °C. Electrical efficiency reference panel 4%-7.5% and for PCM module 4.5% -8.5%.
6.	Xu *et al*., 2020	photovoltaic panel, 17Wp.	Shanghai, China (121.52° E, 31.27° N). Tilt angle 30°	PCM - Fatty Acid.	Experimental. PV Module, solar collector, dual-axis tracker, water tank.		Case 1 3.5% Case 2 3% Case 3 3.4% Case 4 2.9% Conducted two trails with a tracking system. the regulation temperature in case1 and case2 at 45°C and 50°C, respectively. Two trails with stationary position, in case3 and Case4 temperature regulation at 45°C and 50°C, respectively. Panel temperature
7	Abdollahi and Rahimi, 2020	Poly-crystalline Panel, 10Wp.	Kermanshah, Iran	PCM - Composed oil 82wt%% coconut oil and 18wt% sunflower oil. Composed PCM with nano PCM. Boehmite Nano powder (0.009w/w)	Experimental. Test conducted with a sun simulator	29.24% at I-690w/m2 26.88% at I-530w/m2 21.19% at I-410w/m2	Temperature reduction at irradiation I-410 w/m2 , for composed oil 20°C-32°C and with composed oil and nano PCM 20°C- 29°C. I-530w/m2, for composed oil-20°C- 40°C, with composed oil and nano PCM 20°C-35°C. I-690w/m2, for composed oil-20°C-49°C, with composed oil and nano PCM 20°C- 42°C. Electrical Efficiency. Composed oil - 21.1%, 26.8% and 29.24, with Composed oil and Nano PCM - 44.7%, 46.6% and 48.2%, respectively
8	Singh *et al*., 2020	C-Si type Panel	Varanasi, India Tilt angle 25°	PCM - OM32. Uncooled PV, PV-PCM. Air-PV-T-PCM,	Numerical.	19.75%	Panel temperature was reduced to 35% and 25% for Air-PVT-PCM panel and PV-PCM panel compared to reference panel.
9	Sarafoji *et al*., 2020	Multi-crystalline panel, 325Wp.	Haryana, India (10°8 N, 78°68 E)	ROM05-P	Experimental.	-	Setpoint for PSCS (Prototype solar cold storage system) 5 °C-7 °C and 7°C-15°C for 3hrs and 4hrs. Using PCM based system improves the compressor off time by 33.15%. Decreases the total power consumption by 16%. The system sustains a predetermined temperature for approximately 35% longer than a standard cold storage system.
10	Bayrak *et al*., 2020	Poly-crystalline Panel, 75Wp.	Elazig, Turkey	Extended Fines PCM - (Biphenyl) PCM2 - ($CaCl_2 \cdot 6H_2O$)	Experimental.	8.5%	Conducted test with Fin coverage of 25%, 75%, and 100%, compared with two PCM. PV-PCM-Fins with 100% coverage, power output of 42.56 watts and 46.18 watts for reference and PCM2 panels, respectively.

11	Shastry and Arunachala, 2020	Poly-crystalline Panel, 20Wp.	Manipal, India	PCM (OM-47)	Experimental.	9%	At Peak radiation 840 w/m^2 , for the reference panel, PVT-PCM, PVT-PCM-Metal matrix panel temperature reached 65°C, 44°C, and 41°C. At PVT flow rate of 150 l/min.
12	Hassan *et al.*, 2020	Mono-crystalline Panel, 30 Wp.	Taxila, Pakistan Tilt angle 33.7°	PCM - RT-35HC Graphene Nanoparticles (Sodium Dodecyl Benzene Sulphonate (SDBS)			By changing volume concentrations of graphene nanoparticles and flowrates (0.05%, 0.1%, 0.15%) (20, 30, 40 LPM), effective outcome is obtained with 0.1 vol% and 40LPM flowrate of nanoparticle concentration. Temperature reduction in the panel is found to be 23.9°C, 16.1°C, and 11.9°C with nanofluid-PVT-PCM, water-based PVT-PCM, and PV-PCM, respectively.
13	Rajvikram *et al.*, 2019	5Wp	Chennai, India	PCM-OM-29	Experimental.	Day-1: 3.36% Day-2: 3.27%	Test Conducted for two days PCM entrenched with Aluminum.
14	Li *et al.*, 2019	Mono-crystalline Panel, 100Wp.	Shanghai, China. (31 o 1’ 14”N, 121 o 26’11”E). Tilt angle 30°	PCM-35 PV, PV-PCM, PVT-PCM	Experimental.	5.18% - PV-PCM 3.66% - PVT-PCM	Total energy generated for two days trail PV-984watts, PV-PCM-1035watts, and PVT-PCM-1020watts.
15	Karthikeyan *et al.*, 2019	Crystalline panel, 310Wp	Thailand (16.7°N, 100.1°E)	PCM - Paraffin wax and Expanded graphite	Experimental/ Numerical Pure PCM paraffin wax (PV-PCM), Combined PCM Paraffin 75% and Expanded graphite 25% (PV-PCM)	At 2.5cm PCM 14.29% and PCM 14.7%. At 5cm thickness, PCM 14.1% and PCM 14.86%.	Test conducted on different thicknesses of PCM. Combined PCM gives better results than Pure PCM. At 2.5cm Thickness Efficiency Ref-PV temperature 52.98°C, PV with PCM temperature reduction 46.28°C, Average reduction 6.7°C
16	Abdelrahman *et al.*, 2019	Crystalline panel	Cairo, Egypt	PCM (RT35HC) Al_2O_3 with volume fraction of 0.1% to 0.7%.	Numerical	-	Panel temperature reduces to 20%–46.3% at the panel surface and rises to 52.3% by the nanoparticle’s addition. with heat, flux ranges from 279Watt/m^2 to 820 Watt/m^2 .
17	Nada *et al.*, 2018	Poly-crystalline Panel, 30Wp.	Dokky, Giza, Egypt Tilt angle 30°	PCM - RT55. NPCM - Al_2O_3 nanoparticles.	Experimental.	13.2% - PV-NPCM. 5.7% - PV-PCM	NPCM panel temperature was reduced by 10.6°C, whereas PV-PCM panel temperature was reduced by 8.1°C.
18	Su *et al.*, 2018	Multi-crystalline panel, 5Wp.	Hengqin island Macau (22° 09’50 ″ N, 113°33’28” E).	PCM - Paraffin wax	Experimental PCM is encapsulated in spheres and CPV-Dish concentrator.	10%	Enhancement in the thermal, electrical, and overall performance for the Concentrated PVT panel with PCM cooling can be higher than 5%, 10%, and 15%, respectively.
19	Nada and El-Nagar, 2018	Poly-crystalline panel, 30Wp.	Dokky-Giza, Egypt. Tilt angle 30°	PCM RT55, NPCM - Al_2O_3	Experimental PV, PV-building, PV-PCM, PV-NPCM-concentration 2%	7.1% - PV-PCM 14.2% - PV-NPCM	The peak temperatures of reference PV, PV-B, PV-PCM and PV-PCMN are 50°C, 75°C, 62°C, and 59°C. PV reference panel always has the lowest temperature due to exposure to the surrounding air.

20	Modjinou *et al.*, 2018	Crystalline panel, 135Wp.	Hefei, China. (31° N, 117° E) Tilt angle 32°	PCM salt hydrate, Micro-encapsulated PCM, Microchannel heat pipe (MCHP)	Experimental	7.95%	Investigation conducted with PVT, PVT-PCM, PVT-MCHP system. Overall efficiency enhanced by 36.71%, 35.5% and 31.78%, respectively.
21	Al-Waeli *et al.*, 2017	120Wp	Kuala Lumpur (2.9021° N, 101.7830° E) Tilt angle 14°	PCM - Paraffin wax-NPCM - SiC (silicon carbide particles), Nanofluid (water and SiC)	Experimental. Nanofluid flow 0.17kg/s,	13.70%	Panel surface reduced by 30°C by PVT-NPCM-Nanofluid, enhanced by open circuit voltage (Voc) from 13V-21V, and power output from 61.1watts to 120.7watts. at mass flow rate of 0.17kg/s.
22	Klugmann-Radziemska and Wcis ł o-Kucharek, 2017	Photovoltaic panel, 10Wp.	− Gdansk, Poland	PCM1: Paraffin 42–44 PCM2: RT 22 PCM3: Ceresin	Experimental	7%	Reference PV temperature reaches to 71°C PCM1 is selected for the test. Tested conducted with different thickness of 2cm, 3cm, and 4cm. temperature reduction of 65°C, 64°C, and 61°C.
23	Sardarabadi *et al.*, 2017	Mono-crystalline panel, 40Wp.	Mashhad, Iran (Latitude: 36° and Longitude: 59°). Tilt angle 30°	PVT-Deionized water and Zinc-oxide PCM paraffin wax (42°C-72°C)	Experimental	PVT Deionized water 7.07% Nano Fluid 8.12%. PVT-PCM Deionized water12.84 % Nano Fluid 13.29%	Test conducted by PVT and PVT-PCM using as Deionized water and Nano Fluid (zinc-oxide) at Constant Irradiation of 845.42W/m2
24	Kant *et al.*, 2016	-	City of Allahabad (Uttar Pradesh) (25.45° N, 81.85° E), Tilt angle 30°	PCM - RT35	Numerical	-	At Peak, PV without PCM temperature reaches to 60°C panel temperature with PCM (conduction) 58 °C, with PCM (Cond and Conv.) 55 °Cat Solar radiation 900w/m2.
25	Sharma *et al.*, 2016	-	Solar simulator	PCM - RT42 concentrated PV system (CPV).	Experiment	7.7%.	Test performed at. Indoor at constant irradiation of 1000 W/m2, building integrated photovoltaic (BIPV) – PCM integrated compared with Reference panel.
27	Stropnik and Stritih, 2016	Mono-crystalline panel, 250wp.	Ljubljana. Tilt angle 40°	PCM - RT28HC	Experimental and TRNSYS simulation software	7.3%	Reference panel temperature reaches to 70°C PV-PCM temperature reduce to 45 °C. Simulated Results. Temperatures of reference Panel 66°C PV-PCM 35°C.
28	Ho *et al.*, 2016	-	Taiwan	PCM - RT35 microencapsulated phase change material (MEPCM)	Numerical	1.48% - MEPCM1, 2.03% - MEPCM2	Using MEPCM1 with two layers thickness of 3cm, the melting point of 30°C, 26°C for layer1 and layer 2. MEPCM2 with two layers thickness of 5cm, the melting point of 30°C, 26°C for layer1 and layer 2.
29	Atkin and Farid, 2015	Mono-crystalline panel	New Zealand	PCM - Infused Graphite. Finned Air Cooling (heat Sink).	Experimental Case1, Reference PV Case2, NPCM Case3, Finned based Case 4, NPCM and heat sink	Case4. Experimental 9.83% - 12hrs 9.69% - 18hrs Simulation 12.9% -	Experiment conducted in laboratory and MATLAB Modelling for 12hrs, 18hrs. Case 4 most effective method compared to other cases.

						12hrs 11.2% - 18hrs	
30	Maiti *et al*., 2011	Crystalline panel, 10Wp	Kotri village, Rajasthan, India. Tilt angle 18.9°	PCM - Paraffin waxes, Reflectors - V-trough	Experimental Case1 PV - Reflectors Case2 PV-PCM - Reflectors	-	PV temperature in V-trough drops from 78°C to 62°C with PCM with composite aluminum turnings, Power output over the day is increased by 1.5 times.
31	Hasan *et al*., 2010	Poly-crystalline panel,	Ireland	PCM - RT20, Commercial blend (SP22), Capric Palmitic acid (C–P), Capric Lauric acid (C–L) and Pure salt hydrated (CaCl2 .6H2 O)	Experimental	-	PV panel temperature for reference. temp: 35 °C, RT-20 Temp: 21.3 °C, C-L temp: 20.78 °C, C-P Temp: 22.33 °C, CaCl2 Temp: 29.17°C, SP22 Temp: 22.97°C.
32	Huang *et al*., 2005	Crystalline panel	Belfast, UK (latitude 54° 36 ′ N)	PCM - RT25 (liquid) PCM - GR40 (solid) Aluminium fins in PCM container	Experimental. Case1 PV - PCM - fins Case2 PV - PCM	8.9%	PV panel temperature of Case1 ranges from 21°C-34°C and Case 2 ranges from 22°C-43°C
33	Ahmad *et al*., 2021	Mono-crystalline panel, 150Wp.	University of Sharjah (25°17 ′ N, 55°28 ′ E), Tilt Angle - 36°	PVT air cooling	Experimental	9%	Average panel temperature reduction form 56.36°C to 38.31°C average output power 73.4 watts to 79.5 watts, respectively.
32	Huang *et al*., 2005	Crystalline panel	Belfast, UK (latitude 54° 36 ′ N)	PCM - RT25 (liquid) PCM - GR40 (solid) Aluminum fins in PCM container.	Experimental. Case1 PV - PCM - fins Case2 PV - PCM	8.9%	PV panel temperature of Case1 ranges from 21°C-34°C and Case 2 ranges from 22°C-43°C
33	Ahmad *et al*., 2021	Mono-crystalline panel, 150Wp.	University of Sharjah (25°17 ′ N, 55°28 ′ E), Tilt Angle - 36°	PVT air cooling	Experimental	9%	Average panel temperature reduction form 56.36°C to 38.31°C average output power 73.4 watts to 79.5 watts, respectively.
34	Elbreki *et al*., 2020	Photovoltaic panel, 40Wp.	Bangi.,National University of Malaysia.	Air Cooling (fins) with Reflectors	Experimental	13.7%	lapping fins with an average panel temperature of 24.5°C which is lesser compared to the reference panel temperature. Power output performance high as 37.1watts.
35	Kabeel *et al*., 2019	Poly-crystalline panel, 130Wp.	Tanta city, Egypt. Tilt angle 30.47°	PV-reflector-Forced air cooled, PV-reflector-forced air cooled and water circulation.	Experimental. Air blower 10w DC, 61m3/hr. Water pump 5w DC, 12L/min	42%	Panel temperature reduced with PV-reflector using forced air-cooling 64°C-43°C With PV-reflector water cooling method 34°C-32°C With PV-reflector using combined air and water-cooling method temperature reduced to 33°C-29°C
36	Sajjad *et al*., 2019	Mono-crystalline panel, 40Wp.	Taxila. (33.7° N, 72.8° E). Tilt angle 47°	PVT - Air Cooling	Experimental	7.2%	In peak irradiation 1099 Watt/m2 Power output for the cooled panel is 32.5watts/ and 27watts in reference panel.
37	Firoozzadeh *et al*., 2019	Poly-crystalline panel, 60Wp.	Dezful, Iran	PVT - Finned cooling (passive)	Experimental	2.68%	Aluminum fin is attached to back side panel conducted test at two irradiances of 630 Watts/m2 and 420 Watts/m2 the

							temperature reduction of 7.4°C and 5°C was observed.
38	Kabeel and Abdelgaied, 2019	Poly-crystalline panel, 130Wp.	Tanta University, Tilt angle 30.47°	PVT - Air cooling, Reflector (RF), Water cooling.	Experimental Case1- PV Case2 -PV-RF Case3 - PVT-RF (Air) Case4 PV-R-(Water) Case5-PVT-R-(Air & water cooling)	Case5 - 39.69%	The PV surface temperature is 71.5°C 78.5°C, 65.2°C, 38.1°C, and 32.9°C for cases 1, 2, 3, 4, and 5, respectively.
39	Elminshawy *et al.*, 2019	Poly-crystalline panel, 250Wp.	Ort-Said, Egypt. Tilt angle 31°	PVT - Forced Air Cooling with Buried Heat Exchanger	Experimental	22.98%	Geothermal cooling system adopted, temperature of the panel drops to 8°C, 10°C, 11°C, and 13°C in comparison with the reference panel. for four different air flows, respectively, when rates of 0.022, 0.0248, 0.026 and 0.028 m3 /s.
40	Bayrak *et al.*, 2019	Poly-crystalline panel, 75Wp.	Firat University, Elazig Turkey	PVT - Air cooling	Experimental 10 different fins arrangements A1-A10	11.55%.	The performance of finned panels (A5-staggered array 7 cm × 20 cm) most effective compared to other arrangements. Temperature comparison for lowest and highest A5 – 45.42°C A10 – 62.52°C.
41	Grubi š i ć-Čabo *et al.*, 2018	Poly-crystalline panel, 50Wp	Croatia. Tilt angle 25o	PVT - Air cooling	Experimental.	12.9%	Two fin geometries were analyzed using Aluminum fins with Passive air colling method.
43	Tomar *et al.*, 2017	Crystalline panel, 60Wp.	IIT Delhi, New Delhi	PVT - Air-cooling (Active and passive)	Experimental Case 1: PV with channel integrated, Case 2: PV with glass to glass integrated, Case3: PV with duct integrated, Case 4: PV without duct.	10.41%	Case1 gives better performance than other cases, with yearly round, thermal and overall efficiency 34.35% & 61.52%.
44	Mojumder *et al.*, 2016	Poly-crystalline panel, 40Wp.	Kuala Lumpur, Malaysia	PVT Air collector with finned	Experimental	13.75%	Test conducted with for three cases, case1 with no fins, case2 with 2 fins, case 3 with four fins. For case4 at flow rate of 0.14 kg/s and 700 watt/m2 of irradiation, the maximal thermal performances enhanced by 56.1%
45	Chandrasekar and Senthilkumar, 2015	Mono-crystalline panel, 25Wp.	Tiruchirappalli, Tamil Nadu, India (78.6°E, 10.8°N),	PVT Air cooling with finned system	Experimental	14%	Conducted test by PVT passive method using fin arrangement. PV panel temperature is reduced by 12%.
46	Popovici *et al.*, 2015	Crystalline panel	-	PVT- Air cooling Heat Sink	Numerical analysis	-	Reference panel temperature reached to 56°C. Heat sink attached panel temperature drops to 10°C. when the highest power generated by the panel ranges from 6.9% to 7.5%, for the fin angles 90° to 45°, respectively.
47	Sarhaddi *et al.*, 2010	Crystalline panel	-	PVT - Air collector	Numerical	10.1%	Overall energy and thermal efficiency enhanced by 45% and 17.18%, respectively.

48	Yesildal *et al.*, 2022	Mono-crystalline panel, 50Wp.	Erzurum, Turkey	PVT - Spray water cooling	Experimental	11.43%	The maximum performance was achieved with a spraying period of 49.89s, nozzle airflow rate of 2m3 /h, spray flow rate of 0.0180 m3 /h, nozzle to panel distance 50 cm, for the solar irradiance of 700 W/m2
49	Kazem *et al.*, 2021	Mono-crystalline panel, 100Wp.	Sohar, Oman.	PVT - Water based cooling and nanofluid Silicon Carbide (SiC)	Experimental and Numerical	20.2%	The PV panel output power raises from 55.2Watt to 63.16Watt and 72.28Watt, for water and nanofluid based cooling. PV cell temperature reduced to 3.92% to15.26%, thermal efficiency enhanced by 29% - 43.3% for water and nanofluid based panels, respectively.
50	Hadipour *et al.*, 2021	Mono-crystalline panel, 85 Wp.	Semnan, Iran	PVT - Spray water cooling	Experimental	12.1%	Reference PV panel temperature reaches to 57.1°C Case1 study-flow water spray cooling 1.2l/min/m2 , Case2 pulse cooling (duty cycle) DC - 1, 0.52l/min/m2 , case 3 pulse cooling (duty cycle) DC - 0.5, 0.12l/min/m2 Temperature reduction 24.8°C , 25.7°C, and 26.5°C for Case1, 2, and 3, respectively.
51	Abdullah *et al.*, 2020	Poly-crystalline panel, 100Wp.	University Teknikal Malaysia Melaka (UTEM)	PVT-water based method	Experimental and numerical.	11.5%	Solar irradiation ranges between 500 - 1000 watt/m2 and with mass flow rates of 2 to 6 l/min. At 500 Watt/m2 with 6l/min, the maximal Electrical performance reaches 11.5%. At 1000 Watt/m2 with 5l/min, the maximum Thermal performance is 58.6%. At 1000 Watt/m2 with 5l/min, Total efficiency was enhanced by 66.8%.
52	Gomaa *et al.*, 2020	Crystalline panel	Jordan (32° N, 36° E), Tilt angle 26°	PVT-Water based cooling, PVT-Air-based Cooling	Experimental	10.2%	PV panel temperature reduction 58°C 55 °Cand 38°C for reference PV, water and fins cooling method, respectively. efficiency increased by 7% and 10.2% for water and fins cooling modules, accordingly.
53	Elminshawy *et al.*, 2019	Poly-crystalline Panel, 250 Wp.	Egypt (31°1 ′ N, 32° 1 ′ E)	PVT - Buried Water-cooling system. with CPV	Experimental.	29%	The temperature of the reference PV is 72°C Temperature reduction of 47.2°C 45.5 °C, 41.8 °C and 39.3°C at cooling water flow rates of 0.01, 0.02, 0.03 and 0.04 kg/s, respectively. The electrical efficiency of the CPV was enhanced about 7.2, 12.8, 18.5 and 29%, respectively.
54	Emam and Ahmed, 2018	Crystalline panel	-	PVT water-based (water jacket). PCM (n-octadecane paraffin).	Numerical	17.7%	Concentrated PV method has been analyzed with water jacket cooling system with CR20. PV surface temperature reaches to 56°C.
55	Chandrasekar *et al.*, 2013	Crystalline panel, 50 Wp.	Tilt angle 15°	PVT - Wick-Water based, aluminum oxide/water nanofluid and Copper oxide/water nanofluid	Experimental	21%	Throughout the day PV panel temperature reached 65 °Cand electrical efficiency of 9% without cooling. Temperature reduction was 45°C 59°C, 54°C by the combination of water, Copper oxide/water and aluminum oxide / water nanofluid, respectively.

				Volume-0.1% concentration			
56	Ahmad and Hussein, 2001	Mono-crystalline Panel, 50Wp	Cairo, Egypt Tilt angle 30°	Reflector	Experimental. One Reflector is placed south facing	60%	Temperature increased. At solar irradiation 900w/m2, Reference PV temperature-47°C Reflector PV tempertaure-57°C Power difference. For reference PV -38watts And Reflector PV -50watts fill factor in the reflector panel is reduced by 5%

Table 1 Summary of related works on existing PV cooling technologies

III. Conclusion

In conclusion, this review has highlighted the critical challenges faced by photovoltaic (PV) systems in the Sub-Saharan African (SSA) region due to excessive heat and inefficient thermal management. These issues significantly hinder the optimal performance and economic viability of PV systems, reducing their efficiency and lifespan. Given the high solar irradiance in SSA, there is a pressing need for innovative and cost-effective cooling techniques tailored to the region's unique climatic conditions. SSA is the region with high irradiance but less potential in the deployment of Photovoltaic system and this is largely associated to the low efficiency resulting to optimal utilization of the system. Developing a suitable PV cooling framework for the SSA will enhance the energy poverty within the region and reduce GHG. This paper presents a review on various method applied in the cooling of Photovoltaic system and is intended to develop the particular system for SSA. The system when design will improve system reliability, grid stability and interconnectivity, power system quality implementation especially with the DER integration to existing grid. Ultimately, this study underscores the importance of continued research and development in PV cooling technologies to ensure the successful deployment of solar energy systems in SSA, thus supporting the region's transition to a sustainable energy future in a deregulated electricity market.

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