Cooling Techniques in Solar Cells

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Non-concentrated photovoltaics (PV) have modest efficiency of up to around 20% because they utilise only a narrow spectrum of solar irradiation for electricity conversion. Therefore, recent advances employed multi-junction PV or concentrated photovoltaic (CPV) to widen the irradiation spectrum for conversion. CPV systems concentrate solar irradiation on the cell's surface, producing high solar flux and temperature. The efficient cooling of CPV cells is critical to avoid thermal degradation and ensure optimal performance.

concentrated solar cell | solar energy | electrical and thermal efficiency | CPV cooling mechanism | heat transfer enhancement

1. Introduction

Solar energy in the world's total energy mix has become much more significant over the past two decades [1][2][3]. Photovoltaic (PV) cells produce electricity directly from the sun's irradiation. They are an excellent alternative to decreasing the use of fossil fuels, which contributes to global warming [4][5][6]. On our planet, solar energy from direct sunlight is both the most widespread and the most easily accessible source of energy [7][8]. Sand, widely accessible globally, is the primary silicon source for PV cells [9]. Most PV systems consist of single-junction PV cells, which have become more cost-effective in recent decades. However, their efficiency is relatively low, around 20%, because they can only convert a narrow range of electromagnetic waves into electricity. Multi-junction PV cells, also known as concentrated photovoltaic (CPV) cells, have recently emerged as an alternative. The structure of multijunction CPV cells broadens the spectrum of electromagnetic waves that can be converted into energy, making them a more attractive option for the renewable energy community. CPV systems utilise equipment such as parabolic mirrors to concentrate and increase solar irradiation density up to 1000 times (1000 suns) at the CPV cell's surface.

2. Types and Classification of Cooling Techniques in Solar Cells

Research by [10] examines the cooling system using an active cooling system pump. It collects the heat from the PV and dissipates it utilising a convector or heat sink. Several researchers have highlighted that active cooling is more efficient and suitable for high concentrations. The authors of [10] experimented and reported that the output of a concentration solar panel is between 4.7 and 5.2 times that of the nonconcentrated cell. The results demonstrate that the solar cell temperature was reduced to below 60 °C, generating more electrical output. Research using parabolic concentrators to analyse heat transfer in photovoltaics has been conducted by [11]. Researchers found that the temperature of the concentrator aperture and the PV cell increased with the intensity of incident solar energy. A comparative analysis is presented in **Table 1** between the most commercially available photovoltaic and a concentrated multijunction solar cell based on the following references [12][13][14][15][16][17].

Table 1. Comparison between primarily used solar cells with concentrated multijunction solar cells.

Type of Solar Cell	Monocrystalline	Polycrystalline	Thin Film	Multi-Junction
Type of Material	Fragments from single wafer crystal	Fragments from different silicon crystals	Fragments from single wafer crystal	Combination of different semiconductors
Life Span	25 to 30 years	20 to 25 years	10 to 20 years	30 or more years
Efficiency	14 to 26%	12 to 21%	Very low	33.8 to 69.1
Appearance	Aesthetic	Non-aesthetic	Aesthetic	Aesthetic
Portability	Big, comes in different size	Big, comes in different size	Flexible lightweight	Lightweight, smaller size
Number of Junctions	1	1	1	It can have 2–7
Cost	High	High	Low	Higher

Research and development in CPV have highlighted the importance of effective cooling. The cooling system ensures that the cell operates within its optimal temperature. CPV cooling design typically has thermal resistance coefficients with good cell temperature uniformity for maximum efficiency [18]. Additionally, it is vital to consider the cooling system's power consumption, ease of installation, and high level of dependability. The selection of a cooling technique depends on the objective and operational environment [18]. However, the suitability of a cooling method is contingent on the solar concentration, location, installation, and system output requirements [19]. Researchers classify CPV cooling as either passive or active, depending on the geometry, coolant, and level of solar concentration [19]. Furthermore, CPV cooling can be categorised based on the nature of heat transfer, natural circulation and forced circulation, or the type of coolant as passive cooling and active cooling [7][20][21]. Researchers report that passive cooling is suitable for concentrations of less than 20 suns; in high concentrations, active cooling is necessary [22].

Natural circulation and forced circulation can be air-based cooling or water-based cooling. Air-based cooling is simple and cheaper [21]. However, it has a lower heat transfer coefficient which varies from 1–10 W/m2.KW/m2.K for natural circulation to 20–100 W/m2.K W/m2.K for forced circulation [18]. Water-based cooling has a better heat transfer coefficient of 200–1000 W/m2.K W/m2.K for natural circulation and 1000–1500 W/m2.KW/m2.K for forced circulation [11][23][24]. Ref. [25] stated heat pipe heat sink dissipates flux in CPV. Researchers reported that under 25 suns, the heat pipe and heat sink could cool CPV to 37.8 °C and 54.16 °C, respectively. They have highlighted that this cooling method is cost-effective due to its low energy consumption. The disadvantage of passive cooling is the size in terms of the heatsink area. Economically, the passive system is not viable because it requires a large amount of material, consisting of larger fins and plate areas depending on the concentration ratio [1][2][3][19][26][27]. Photovoltaic (PV) cells produce electricity directly from the sun's irradiation. They are an excellent alternative to decreasing the use of fossil fuels, which contributes to global warming [4][5][6]. On our planet, solar energy from direct sunlight is both the most widespread and the most easily accessible source of energy [7][19][26][27][28]. In other words, the greater the concentration ratio of the CPV, the larger the required heatsink. This has reduced the feasibility and attractiveness of using a PC system to cool a CPV. The use of active cooling (AC) to achieve temperature uniformity has been studied. With this method, the coolant circulates through the cooling system using an active cooling system pump. It collects the heat from the PV and dissipates it utilising a convector or heat sink. Several researchers have highlighted that active cooling is more efficient and suitable for high concentrations [25][29][30][31]. However, one of the limitations posed by AC includes temperature non-uniformity. **Table 2** summarises research availability and current challenges of CPV cooling.

Table 2. Limitations and challenges in existing methods of CPV cooling.

Cooling Technique	Method of Study	Concentration	Main Challenges	Reference
Heat Pipe and Fins	Experiment Theoretical Numerically Simulation	Lower Medium High *	Overheating, uncontrollable oscillatory thermal flows, reverse thermal flows, area-dependent cooling capacity, temperature non-uniformity	[18][19][32][33][34][35][36][37]
PCM	Experiment Theoretical Numerically Simulation	Lower Medium High *	Limited cooling capacity at higher concentrations, limited amounts of heat energy storage, acidic nature, issue of disposal after lifetime used, mass/weight cooling capacity dependant	[30][38][39][40][41][42]
Jet Impingement	Experiment Theoretical Numerically Simulation	Lower Medium High	System design complexity, draining spent flow, temperature non-uniformity, manufacturing costs	[43][44][45][46]

Cooling Technique	Method of Study	Concentration	Main Challenges	Reference
Immersion Liquid	Experiment Theoretical Numerically Simulation	Lower Medium High	Salt deposition issue, cell performance degression, pressure drop, type of liquid, increased weight, design architecture	[30][47][48][49][50][51][52]
Microchannel	Experiment Theoretical Numerically Simulation	Lower Medium High	Pressure drops, corrosion, temperature non-uniformity, higher manufacturing costs, more power requirements, more studies are needed to commercialise	[53][54][55][56][57][58]

Level of Research Reported in CPV cooling: = Good number of study available; = Limited number of study available; Level of Concentration (C): *Lower*: C < 20 suns, *Medium*: 20 < C < 100, *High:* C > 100. * With a hybrid system configuration.

... they have ... meration. ... pingement cooling, and heat pipes, can potentially enhance electrical and thermal performance. Researchers can utilise the organic Rankine cycle (ORC) to create a mutually beneficial scenario to achieve cell temperature reduction while enhancing system output by incorporating a heat recovery system into a CPV thermal system. However, various restrictions and challenges exist associated with implementing concentrated photovoltaic/thermal (CPV/T) hybrid systems, such as complexities related to design, initial costs, component compatibility, and a lack of available platforms integrated model packages for research purposes. Electroosmotic flow (EOF) is another method of improving heat transfer by inducing fluid motion through an electric field, enhancing convective heat transfer [59][60][61]. This approach can be beneficial in microfluidic channels and other critical applications. Researchers use magnetohydrodynamics (MHD) flow to enhance heat transfer. Applying an external magnetic field induces fluid motion and enhances convective heat transfer. MHD flow has been used in various heat transfer applications, such as nuclear reactors, liquid metal batteries, and plasma devices [58][59][60]. The limitations and research gaps of the current approach to heat transfer enhancement are summarised in **Table 3**.

Table 3. Heat transfer enhancement approach in thermal energy management (MHTE).

MHTE Approach	Area of Approach	Current State of Art	Research Gap and Limitations
Use of Nanofluid	Type coolant		Corrosion problems, stability issues, sedimentation issues, agglomeration issues, pressure drop, high cost
Hybrid Cooling	Overall system	*	Compatibility issues, cost economic viability, integrating components within a single system
Boiling Heat Pipes (PHP)	Phase change liquids		Limited modelling tools, no flow pattern control, little experimental work, and availability of components to measure flow.

MHTE Approach	Area of Approach	Current State of Art	Research Gap and Limitations
Magneto Hydrodynamics (MHD)	Type coolant and overall system		Limited experimental work, more numerical models and simulations research are required, and additional cost
Electro Osmotic Flow (EOF)	Porous material under the influence of an electric field		Limited modelling tools, effects of channel geometries on the EOF, design optimisation
Pulsating Flow	Flow and overall system		Limited theoretical study, more research is needed combined with porous media, contradicting results, additional cost due to using of solenoid valves, other means to provide pulsation can be explored, may lead to system complexity

Level of Research Reported: [icon] = Applied to CPV cooling, and a good number of studies are available; [icon]* = Good number of studies available with limited research in a ground couple/ ORC systems; [icon] = Limited number of studies available and have been in the field of electronics; [icon] = Studies available mainly in the field of medicine, electronics, and mechanical engineering but has not been applied to CPV cooling.

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