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Floating Photovoltaic Performance Evaluation Using Novel Cooling System: Case Study

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ABSTRACT

Photovoltaic panels nowadays are considered one of the most important methods for generating electricity directly from the sun as a green energy resource. The photovoltaic cells convert about 20% of solar energy to electric power, and the rest is converted to heat that increases the cells temperature. The photovoltaic performance decreases by about 0.4%–0.5% for each 1°C increase in cell temperature. The main objective of this article is to mitigate the high temperature of floating PV cells in order to enhance their efficiency and power output using a novel water cooling design which use natural cold water from natural sources. ANSYS has been used to conduct a series of simulations under different boundary conditions like solar radiation, ambient temperature, and cooling water temperature at Duhok Dam Reservoir, KRI. The results of the proposed cooling module showed a significant increase in efficiency (1.26%–2.49%) and power performance (17.76–36.81W) and a significant increase in power (6.43%–14.89%) compared to the non-cooled module. Thus, using an active cooling method for floating panels could be a typical option to boost the output of the solar panels. The results of this research have outperformed other research, with a power increase rate of about 14.1%.

1. Introduction

The availability of energy is a key factor in determining the level of a nation's industrial growth. The amount of energy that individuals use is another factor that determines their style of life. Energy is essential for a wide variety of uses, including lighting, the operation of domestic appliances, industrial plants, transportation, and agricultural uses [1].

The necessity to employ renewable energy sources is very strong for many reasons. First is the rising energy demand. Second is the depletion of fossil fuels, and the last is the rising environmental pollution [2]. Across the globe, especially in nations where alternative energy sources are available, more people are turning to use these sources to satisfy their heating and electrical needs [3].

The use of photovoltaic technology to generate energy is one of the fastest growing industries today. The price of solar modules and other system components has decreased dramatically over the past 20 years. The technological developments have increased their efficiency, enhanced their reliability, and increased their output, all of which have contributed to lowering the cost of energy [4].

A photovoltaic panel converts the energy from sun-light into electricity. So far, the most effective solar panels available today can convert the solar energy they receive into electricity at an efficiency of 22.8%, which means that the remaining 81.2% is lost and converted to heat [5]. The high temperature of photovoltaic panels is one of the primary concerns that causes a reduction in the amount of electrical energy produced by 0.4–0.5% for every 1ºC increase in ambient temperature compared to that at 25 ºC [6]. The material used to construct the PV module might be damaged by a rise in temperature as a consequence of this energy being squandered as heat, which would decrease the cell life-time and conversion efficiency. When exposed to the sun, solar cells may become as hot as 70°C in the summer in mild climates like the Mediterranean and even higher than 75°C in hotter and drier locations [7]. Removing heat from PV cells using adequate cooling techniques is required to counteract the impacts of cell temperature and keep the operating temperature of the PV cells within the manufacturer's stated value. It is necessary to remove heat from the PV cells in order to improve their performance, and this is achieved by passive cooling and active cooling methods [8][9].

The first floating solar photovoltaic system was developed in Japan in 2007 on a small scale, and the first commercial system was installed in California in 2008. Installations above 1 MWp were not constructed until 2013. 62 GWp of FPV will be operational worldwide by 2030. 87% of global FPV capacity is in Asia [10]. Floating photovoltaic panels are reported to outperform land-based installations. Water cooling, either by immersing or spraying the panels, lowers the operating temperature and boosts module efficiency [11].

The high summer temperature in the proposed area (Duhok Dam Reservoir, Duhok, KRI) will increase the PV cells temperature to 70°C. Also, in the cold winter months, the cell temperature can reach more than 45°C which will decrease the performance of the PV module. In this paper, an active cooling method has been simulated using ANSYS to cool down the cell's temperature in order to improve its performance.

After the introduction, a literature of related works has been stated. Point 3 states the methodology of the study. In addition, Point 4 showed the governing equation used to calculate the efficiency and power output of the module, while point 5 showed the simulation process. Point 6 represents the results and discussion, as well as point 7 lists the conclusion of the research.

2. Related Works

Chin et al. used a plate which contains several internal water channels attached at the back surface of the PV panel. The results showed increase in panel efficiency 1.6% and reduction in temperature about 21.2°C[12]. Bevilacqua conducted back surface spray cooling with a maximum absolute improvement of 1.6%. Additionally, during hot months, the average percentage increase in daily energy can reach up to 8% [13]. Sexena et al test the front water cooling of PV module using indoor artificial radiation using for intermittent and continuous water cooling which enhanced power 18% for intermittent flow in comparison with non-cooled module and 29% more power for continuous flow [14]. Younas et al. conducted experimental study to cool PV module using simple steal cooling channels. At 895 W/m2 solar irradiation, the temperature dropped about

27.5°C and increase in efficiency about 1.6% with performance ratio boosted about 12.85%[15]. Bashir et al. evaluated to effect of using water cooling with Phosphorus-Silicon (p-Si) and Crystalline silicon (c-Si) module. The temperatures of non-cooled module were 13.6% and 7.2% lower than cooled modules causing increase in efficiency of c-Si and p-Si 13% and 6.2% Respectively [16]. Shalaby et al. tested experimentally active water cooling using cheap and simple materials the results showed increase in efficiency of 13.79% and also increase in power about 14.1% in comparison with non-cooled module [6]. Yildirim et al. made a simulation for thermal PV/T water based system under different water mass flow rates to study the thermal behavior of the system. The optimum power and efficiency enhancement achieved was 241.90W and 17.79% respectively after cooling in comparison with 215.29W and 15.84% for non-cooled module [17]. Pang et al. also evaluated the performance of water based PV/T and enhanced the electrical energy production about 11% in comparison with non-cooled panel [18]. Yang et al. studied experimentally the effect of geothermal energy to cool photovoltaic using U-shaped borehole heat exchanger. The results showed that the cooling process can enhance the efficiency about 14.3% [19].

3. The Proposed Cooling Module Methodology

The Jinko Cheetah JKM335M-60-V solar panel is proposed for this study. The proposed module offers great efficiency, good low-light performance, and a long lifespan due to its high-quality silicon crystals. The Proposed Panel can generate 250 W at Nominal Operating Cell Temperature (NOCT) and 335 W at Standard Test Conditions (STC). This will allow the cooled modules to generate power more than NOCT conditions. Table 1 demonstrates the specification of proposed solar panel.

The panel consists of five main layers, which are Glass, top and bottom Ethylene Vinyl Acetate (EVA), PV cell layer, and PolyVinyl Fluoride (PVF), plus the aluminum frame. Figure 1 depicts the layers of a PV panel.

This study proposed an active cooling technique that involves pumping naturally cold water from a non-depleted supply (dam reservoir). The water is circulated using a low-wattage DC pump at a steady flow rate via a polypropylene channel, where it flows in direct contact with the panel's back sheet before the water flows back to the reservoir. Polypropylene is recommended for manufacturing the channel because of its low density, thermal conductivity, and economy.

Table 1. Specifications of the PV module.

Parameter	STC	NOCT
Maximum Power (P_{max})	335Wp	250Wp
Maximum Power Voltage (V_{mp})	34.0V	32.0V
Maximum Power Current (I_{mp})	9.87A	7.82A
Open-circuit Voltage (V_{oc})	41.5V	38.4V
Short-circuit Current (I_{sc})	10.36A	8.74A
Module Efficiency STC (%)	20.08%	
Operating Temperature (°C)	-40°C~+85°C	
Temperature Coefficients of P_{max}	-0.37%/°C	
Nominal Operating Cell Temperature (NOCT)	45±2°C	

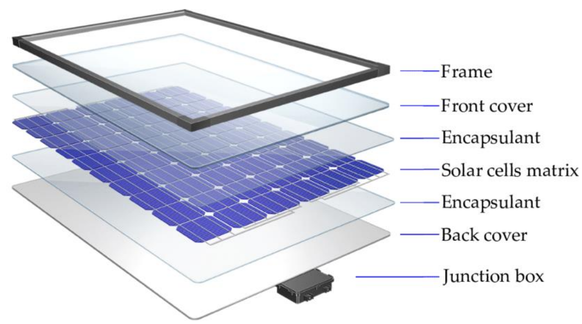

Figure 1: Represents the layers of PV panel

The cooling block has been designed using SolidWorks. It is a serpentine shaped channel with a rectangular inlet and outlet (115.75mm×10mm). The contact area between the water channel and the panel back PVF is 1.06 m2, which is about 63.75% of the panel area. Figure 2 shows the shape and details of the module with the cooling block.

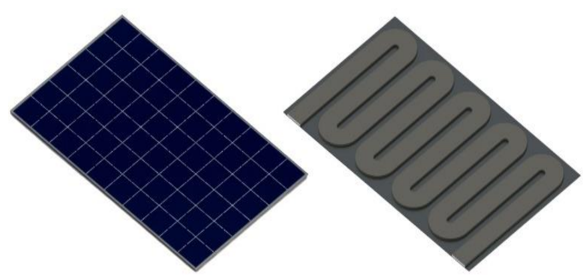

Figure 2. PV module with cooling channel

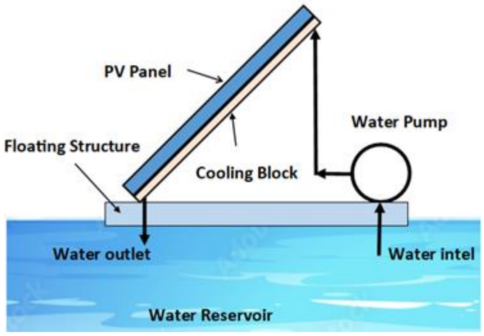

Figure 3. Schematic diagram of the cooling process.

4. Governing Equations

The following equation can be used to analyze the influence that temperature has on the electrical efficiency of the solar panel [20]:

$$\eta_{el} = \eta_r \times (1 - \beta(T_c - T_r) \qquad (1)$$

Where: -
η_{el}: Electrical efficiency of the panel.
η_r: Maximum panel efficiency of the panel.
β: Temperature coefficient at maximum power.
T_c: Cell temperature.
T_r: Cell reference temperature (25ºC).

After calculating the efficiency of the panel, power output can be calculated using equation (2):

$$\boldsymbol{P_{output} = P_{in\_total} \times \eta_{el}} \qquad (2)$$

Where Pin_total is the total solar radiation reaches the surface of the glass layer multiplied by the area of the panel:

$$P_{in\_total} = G_\beta \times Area_{panel} \qquad (3)$$

Where Gβ is the total solar radiation reaches panel at Duhok Dam reservoir coordinated (36.88, 43.00) which is estimated using the clear-sky radiation equations for inclined panels from the reference "Solar Engineering of thermal processes, Photovoltaic and Wind by Duffie and Beckman" [21].

5. Simulation Process

First, a simulation has been conducted on the non-cooled module in order to get the PV cell temperatures as a reference. The geometry has been imported to ANSYS workbench steady-state thermal in order to conduct simulation for the non-cooled module. The material properties have been assigned for each panel layer as depicted in Table 2. The heat flux absorbed by each layer was calculated using the optical characteristics mentioned in Table 3.

Table 2. Properties of PV layers

Layer	Thickness mm	Density (kg/m³)	Thermal conductivity (W/m.K)	Heat capacity (j/kg.K)
Glass	3.2	3000	1.8	500
PV	0.2	2330	148	677
EVA	0.3	960	0.35	2090
PVF	0.2	1200	0.2	1250

Simulation of the cooling module has been conducted using ANSYS Fluent. All panel layers have been suppressed except the cooling block. A mesh size of 2 mm has been applied to the block. The water flowrate assigned is 1000 L/h, which is equal to the velocity of 0.24 m/s. The type of flow is turbulent, as the Reynolds number is in the range of 2900–4800. The cooling water temperature of Duhok Dam reservoir at different months was obtained from previous research [22-23].

Table 3. Optical characteristics of layers used in photovoltaic systems

Material	ρ	τ	α	ε
Glass	7.3%	81.5%	11.2%	0.9
PV	3%	----	97%	----
EVA	4%	90%	6%	
PVF	----	----	----	0.87

*** ρ:Reflectivity, τ:Transmissivity, α: Absorptivity, ε: Emissivity**

After the simulations for the module and the cooling block were done, the two simulations were combined using system coupling to find out how the cooling water affected the proposed PV module and, by extension, the PV cell layer.

6. Results and Discussion.

The simulation has been conducted for 12 different conditions for each month at NOCT conditions for both non-cooled and cooled modules. In February, which has the coldest weather conditions (4°C ambient temperature), the temperature of the PV cell has decreased by about 16.87 °C, with a temperature decrease rate of 51.06%. The efficiency increased (1.25%) more than in the non-cooled module. The power increased by about 19.33 W, with an increase rate of 6.43% in comparison with the non-cooled module. In February, the water temperature, which is the lowest (7°C) among the other months, is the reason for the coldest temperature reached in the PV cell.

In July, the temperature decreased by about 33.56 °C, with a temperature decrease rate of 48.03%. The efficiency increased by 2.49% over the non-cooled module. The module generated (36.81 W) more power with a power increase rate of 14.89% in comparison with a non-cooled module. Although the difference in July is higher than February, the power production is less than February for many reasons. The ambient temperature in July is the highest, causing the non-cooled cell temperature to reach 70°C, which is higher compared with all other months.

Figure 3. depicts the effect of the ambient temperature or weather temperature, solar radiation on the PV cells temperature. The ambient temperature has direct effect on the PV cell as well as the solar irradiance. As the solar cell absorbs heat generated from energy that has not been converted to electric power, it also absorbs the heat from the surrounding which will indeed has more negative effect on the efficiency and power production of the module. The figure also depicts the effect of using water as cooling medium on the cell temperature which decreased the cell temperature up to 50%. The reduction of cells temperature certainly will enhance the performance of the PV module. It is shown that the cooling water has decrease the temperature of cells to near optimum temperature (25°C) at March, April and November. The temperature also decreased more than optimum in January, February and December. For other hot months, the cell temperature has been decreased to acceptable operation range which is under 40°C which will certainly improve the power production to acceptable range.

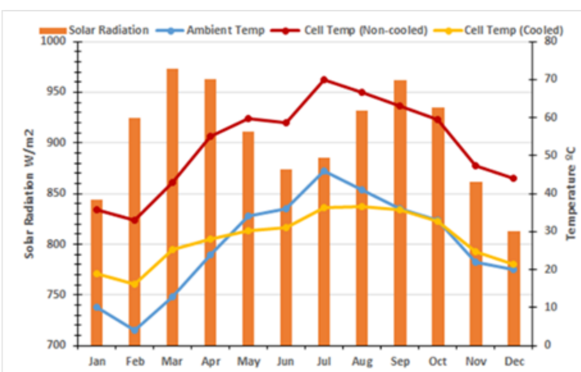

Figure 4: Solar radiation, Ambient Temp., and Cell Temp for non-cooled and cooled module.

Figure 4 depicts the improvement in amount of power production after cooling in comparison with a non-cooled module. The maximum power production for cooled modules was in March, and the minimum was in December. Also, the maximum improved module efficiency result was in February, and vice versa, it was in July. The power enhancement is a results for the temperature reduction of PV cells which cause the improvement in conversion process of solar radiation to electric power.

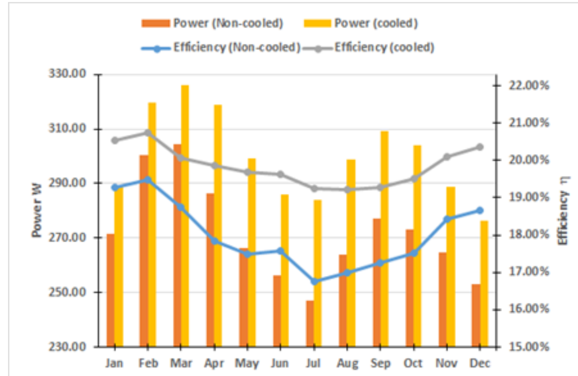

Figure 5: Efficiency and power output for non-cooled and cooled modules.

Figure 5 shows the effect of the cooling water temperature value on the cell temperature, which is the highest in July when the cell temperature reaches more than 70°C. Also, the lowest effect of cooling water on cell temperature is in February, when the cell temperature for a non-cooled module reached not more than 35°C.

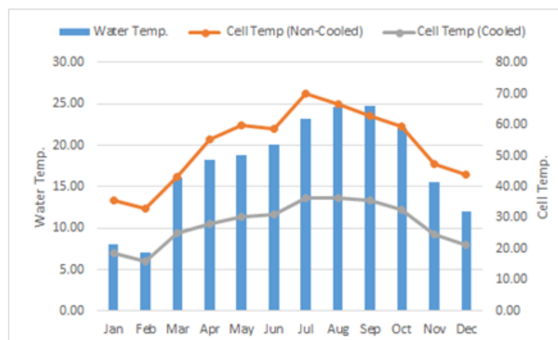

Figure 6: The effect of the cooling water temperature value on the cell temperature

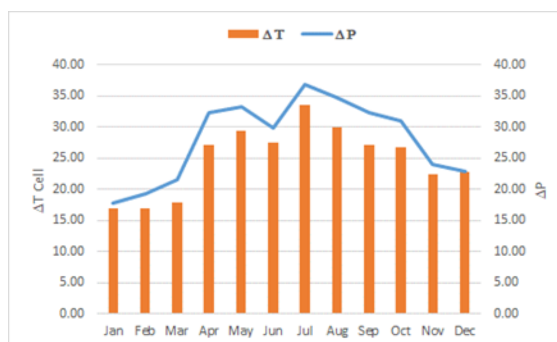

Figure 7: The relation between temperature reduction (ΔT_{cell}) and the power improvement (ΔP).

In Figure 6, the blue bars present the power improvement between non-cooled and cooled modules, while the orange bars present the temperature reduction between non-cooled and cooled modules. The figure shows that the highest temperature reduction at July (33.56°C) causes the highest power improvement at July, with 36.81 W more power than a non-cooled module.

7. The Comparative Analysis of the Proposed Cooling System

This section provides a comparison table for some cooling methods, module type, power increase rate (%), and ΔT_{cell} (Temperature difference between non-cooled and cooled modules) between the proposed cooling system and other existing related approaches in the literature as shown in Table 4.

Table 4. A comparative analysis table

Cooling Method	Module type	Power increase rate (%)
Back Surface Water Channel [12]	Poly-Si 80W	15.1
Back Surface Water Spray [13]	Mono-Si 245W	7.38
Font Surface water cooling [14]	Poly-Si 40W	29
Back Surface Heat Exchanger [15]	Poly-Si 50W	12.85
Back Surface Water Channel [16]	Mono-Si 40W	13
Back Surface PVC Channels [6]	Mono-Si 250W	14.1
Water Based PV/T [17]	Mono-Si 325W	12.36
Water Based PV/T [18]	Mono-Si 180W	11
Back Surface Water Spray [19]	Poly-Si 60W	14.3
Back Surface Serpentine Channel (proposed cooling system)	**Mono-Si 335W**	**14.89**

8. Conclusion

The Proposed cooling system and PV module have been simulated using ANSYS (Steady-State Thermal, Fluent, and System Coupling) depending on the physical characteristics of their layers and the Duhok Dam reservoir climate and solar conditions as boundary conditions. The solar irradiation, ambient temperature, and cooling water temperature have been taken as parameters to conduct the thermal analysis of the proposed module. Simulation has been conducted for 12 months on average. The results show a significant increase in efficiency and power output, especially during the summer months when the ambient temperature is high. Furthermore, the results recorded a decrease in the temperature of the module (16.87 to 33.56 °C), causing an increase in efficiency and power rate of about 6.43% to 14.89% in comparison with the non-cooled module. Plus, the results show that it is also significant to cool the panels in the winter months, but definitely at a lower improvement in performance, which recorded about 6.43% to 9.06%. Depending on the previous results, more numerical and experimental investigations are recommended for the current and different water channel shapes and dimensions in order to make more efficient panels, which can be the first brick to build a floating cooled farm in the proposed location.

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