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Research Article

Thermal Regulation Methods Aimed to Elevate Photovoltaic Panel Performance: A Review

Umit Kemalettin Terzi and Taha Furkan Ozturk

Abstract— **Commercially used solar modules convert about 14 to 24% of sunlight into electrical energy. The remaining energy is kept in the panels which is converted into heat energy and increases the panel temperature. However, the increase in temperature caused by this input reduces the power output of the solar panel, i.e. in crystalline silicon cells it is about 0.40%/°C. And the resulting thermal stress also reduces the panel life. Therefore, it would be a smart solution to dissipate the heat generated on the photovoltaic system by cooling the panels with various methods in order to reduce the solar panel temperature and increase the module performance. This paper presents a summary study to review the significant researches on improving performance of photovoltaic systems. Among these researches, there are studies aiming to reduce the high operating temperature seen on the solar cell surface and to balance the inhomogeneous heat distribution such as cooling of a PV panel with natural and forced liquid and air, heat pipe, phase change material and thermoelectric module. Besides these studies, researches aiming to make optimum use of sunlight by reducing reflection, pollution and photo-angular effects, which are parameters that have weakening effects on the electrical performance of solar cells, are reviewed as well.**

Index Terms—**Efficiency, Photovoltaic (PV) cell, PV module cooling, Solar energy.**

I. INTRODUCTION

ACCORDING TO the researches of the International Energy Agency, the population growth trend in the world, the rate of economic development and the increase in energy consumption per capita are conceived as the main factors that will cause the worldwide energy consumption to increase by 71% between 2003 and 2030 [1].The foremost solution to meet this expected increase in energy demand and to reduce the climate change problems it may bring is the use of renewable energy resources, which science and policy makers in the world have jointly reached [2].

UMIT KEMALETTIN TERZI, is with Department of Electric and Electronics Engineering Faculty of Technology, University of Marmara, Istanbul, Turkey,(e-mail terzi@marmara.edu.tr).
https://orcid.org/0000-0002-2306-6008

TAHA FURKAN OZTURK, is with is with Department of Electric and Electronics Engineering Faculty of Technology, University of Marmara, Istanbul, Turkey, (e-mail: tahaozturk@marun.edu.tr).
https://orcid.org/0000-0002-2306-6008
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Renewable energy sources are defined as clean, green, nature-friendly and waste-free energy sources due to their natural existence. Resources used in this field are classified as hydropower, solar, wind, geothermal, bioenergy and wave energy [3]. Medium and long-term plans have been prepared to reduce the use of fossil fuels in the world and to increase the share of renewable energy sources in production. With the Climate Change Framework Convention - Kyoto Protocol, which entered into force as a result of the negotiations held at the United Nations in 2005, countries aim to increase the use of renewable energy technologies that remove carbon dioxide, to reduce greenhouse gas emissions by limiting the use of fossil resources and to increase energy efficiency [4]. However, although the relevant agreements introduce principles to countries to reduce the use of some energy sources, global electrical energy production increased by 10% on average in the 5-year period covering 2017-2021, reaching 27,295 TWh at the end of 2021 [5]. Consequently, photovoltaic electricity generation is considered as one of the most powerful options among renewable energy technologies to solve the energy dilemma that will be experienced in the future. So much so that the use of solar energy systems has been increasing in recent years in a wide range from wearable personal devices to transportation vehicles and from applications as small as chargers to power plants as large as solar farms [6].

Photovoltaic electricity generation is carried out using solar cells made from semiconductor material such as silicon. The working principle of solar cells is based on the photovoltaic phenomenon. In other words, they produce direct current by directly converting the solar radiation falling on them into electrical energy [7]. A typical silicon solar cell can produce as much as 0,5 volts of electricity. Solar cells can form module, string and array by connecting each other in series or parallel. Thus, the power output is raised by increasing the current and voltage values they produce. In this way, the output voltage can be attained 12, 24, 48 V or higher [8].

The most important features of photovoltaic (PV) cells to be taken into account are the current (A) and voltage (V) values they produce, and in order to speak of the electrical properties of the cells, firstly, it is necessary to define their current-voltage characteristic. The operating points of the PV cell at different currents, voltages and the maximum power point are determined by means of the open circuit voltage (Voc), the short circuit current (Isc) and a regulated load. When the terminals of a PV cell are short-circuited, the maximum current measured is called the short-circuit current and is denoted as Isc. When a cell is left open circuit, the voltage measured at its terminals is called the open circuit voltage and is denoted as Voc. Fig.1 shows I-V and P-V curves for a PV cell. In order to utilize a PV system more efficiently, it is necessary to keep the output power of the solar module at its maximum possible value. The area of the largest rectangle under the current-voltage characteristic curve is equal to the maximum power and it can be calculated as it is in Eq.(1). The unit of maximum power is Watt-peak (Wp). The voltage and current at the maximum power point are expressed as V_{mpp} and I_{mpp}, respectively. The I_{mpp} value is 95% of I_{sc} and the V_{mpp} value is 80% of V_{oc} [9-11].

$$\text{Pmax} = \text{Pmpp} = \text{Vmpp x Impp} \qquad (1)$$

The measure of quality and ideality of the PV cell is the Fill Factor which is denoted as FF and it can be calculated as it is in Eq.(2). It is the ratio between the maximum power of the PV cell and the highest power value that it can theoretically produce. The Fill Factor, which is equal to 1 in an ideal PV cell, is in practice between 0.5 and 0.80 for silicon cells and a maximum of 0.89 for GaAs cells [12,13].

$$FF = \frac{Pmax}{Pt} = \frac{Vmpp\ x\ Impp}{Voc\ x\ Isc} \qquad (2)$$

The conversion efficiency of the PV cell is principally defined as the ratio of the maximum energy provided by the solar cell and the energy of the light shining on the cell. This value is simply the percentage of converting solar energy to usable electricity on the unit surface of the cell. Efficiency, which is denoted as η and can be calculated as it is in Eq.(3), is a significant plate-mark used to compare the electrical performance of the PV system with other [14].

$$\eta = \frac{Pmax}{Pin} = \frac{Vmpp\ x\ Impp}{Pin} = \frac{(Voc\ x\ Isc)\ x\ FF}{Pin} \qquad (3)$$

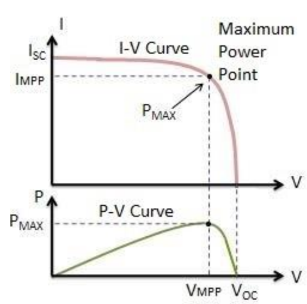

Fig.1. I-V and P-V curves for a PV cell [9]

Due to direct sunlight and environmental effects which PV modules are exposed, the shape of the I-V curve is influenced, the peak power value decreases and the efficiency of the photovoltaic system diminishes. Since commercially used solar modules convert approximately 14% to 24% of sunlight into electrical energy [15], increasing this efficiency and thus enabling PV technologies to become cost competitive with traditional energy sources are one of the main goals of researches investigated in the literature and solar cell industry.
Many factors affect the performance of photovoltaic devices in real environmental conditions, different from those specified in standard test conditions (STC). Karamanav [16] studied the types of solar cells, their working principle and photovoltaic conversion principles and examined the parameters affecting the performance of PV cells. According to his study, it is stated that the external factors that cause the change in the power output of PV devices operating in outdoors can be counted as photo-angular factor, solar radiation, spectral factor and temperature. In this study the change of the I-V values of a monocrystalline solar cell, which can produce 3.6 V and 60 mA at its maximum power point, experimentally investigated under a constant temperature (T=21°C) and a constant light source (150W) which was being moved between 0°-180°. The presented experimental results showed that in order to obtain the best efficiency from the photovoltaic cell, the angle of the light source should be 90°, and when the light angle is 0° and 180°, it is concluded that its performance is at a minimum level. The current and voltage values depending on different angles of incident light are given in Table 1.

TABLE I
I-V VALUES DEPENDING ON DIFFERENT ANGLES OF INCIDENT LIGHT [16]

Angle, [^{0}]	Current, [mA]	Voltage, [V]
0	2.7	1.95
30	9.5	2.28
45	18.7	2.84
60	35.2	3.01
90	42.8	3.25
120	35.2	3.01
135	18.7	2.84
150	9.5	2.28
180	2.7	1.95

Albayrak [17] investigated the dependency of PV module efficiency with solar irradiation and temperature. The I-V and P-V characteristics of a 260 W polycrystalline solar panel were examined by measurements taken under water-cooled and uncooled operating conditions at high ambient temperature and radiation, low ambient temperature and radiation levels which were 1000 W/m^2 and 33 ^oC, 400 W/m^2 and 24 ^oC, respectively. It was observed that as the ambient temperature and solar intensity decreased, the energy efficiency obtained from the panel with cooling decreased. An increase of 13% was achieved in electrical efficiency compared to the uncooled operating condition. In the study carried out under the condition of high sun intensity and ambient temperature, a power increase of 22.5% was obtained. Fig.2 shows P-V characteristic of PV cell for different irradiation values.

Zhu et al.[18] studied experimentally improvement of electrical and thermal performance of hybrid PV system by applying nanofluid prepared with MgO and ionized water in different mass ratio and layer thicknesses from the upper surface of a solar panel. In the study carried out outdoors, the solar cell temperature, the temperature difference between the input and the output and the output power of the cell of the hybrid system were investigated. When the optical properties of nanofluids prepared in different mass ratios and layer thicknesses were examined, it was observed that the visible light transmittance decreased with increasing mass ratio and film thickness. It has been stated that the reasons for this are the increase in the number of nanoparticles per unit volume, the scattering of the incident light and its absorption by the nanofluid. Thus, it was observed that the electrical power output of the hybrid system decreased due to the decrement in the useful solar radiation reaching the solar cell. Fig.3 demonstrates typical spectral responses from a variety of PV cell technologies [19].

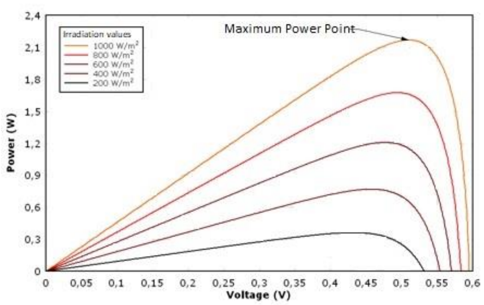

Fig.2. P-V characteristic of PV cell for different irradiation values [17]

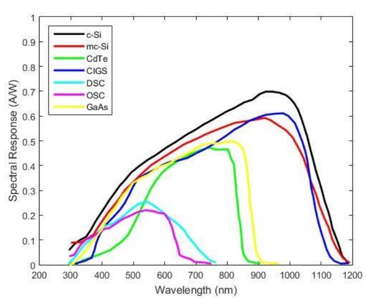

Fig.3. Typical spectral responses from a variety of PV cell technologies [19]

Skoplaki and Palyvos [20] presented an overview of documented sources about correlation of operating temperature and energy conversion process of PV modules. In their study, it is stated that the module operating temperature plays a dominant role in the photovoltaic energy conversion. It was emphasized that both the electrical efficiency and the power output of a PV module decrease depending on the operating temperature. Efficiency of a PV cell under an operating temperature (T_C), which is denoted as η_C, can be calculated as it is in Eq.(4). Here the values η_{Tref} and β_{ref} are the quantities given normally by the photovoltaic module manufacturer. Fig.4 shows the correlation between cell temperature and P-V characteristics of photovoltaic module at constant solar irradiation.

$$\eta_C = \eta_{Tref}\left(1 - \beta_{ref}(T_C - T_{ref})\right) \quad (4)$$

As a result of aforementioned external factor it is important to state that cooling techniques are required on the large scale to regulate the PV module's thermal management in order to increase the module performance while reducing its temperature. Among these techniques, there are significant studies, such as cooling of a PV panel by liquid and air circulations, heat pipe, phase change material and thermoelectric module and utilizing aluminum fins, nano and other types of material on front and rear surface of module.

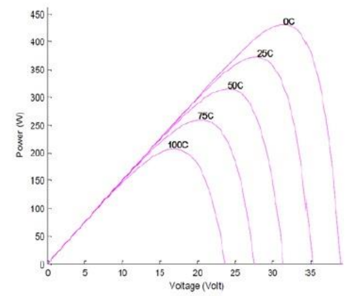

Fig.4. Correlation between cell temperature and P-V characteristics of PV module at constant solar irradiation [21]

II. COOLING BY LIQUID AND AIR CIRCULATION

Altınışık [22] experimentally investigated the change in electricity generation in a PV system with 100 W nominal power output that is intermittently cooled with water in the form of sprinkler. The water required for panel cooling was supplied from the mains water system whose flow rate was gauged as 20 L per minute, and the solar intensity, temperature, current and voltage data were measured for cooled and uncooled operations under high and low ambient temperature and solar irradiation, which were 33 °C, 1000 W/m^2 and 22 °C, 700 W/m^2 respectively. Fig.5 shows the experimental setup suggested in his work. As a result of the study in which the cooling system was active for 13 minutes in the condition of high solar energy and ambient temperature the solar panel's temperature measured from front surface was reduced from 51 °C to 26 °C, and the power value, which was 52.45 W before the commencing of the cooling process, was increased to 65.31 W at the end. In the lower ambient conditions the cooling system remained active for the same time and the front surface temperature was reduced from 43.8 °C to 25 °C. The power value was increased from 38 W to 42.4 W. Thus, it has been observed that significant energy efficiency can be restored by cooling the panels.

Kızılkan [23] stated that if a solar panel is cooled with water from the front surface, the access of the useful solar radiation to the panel surface can be partially diminished due to the water film on the surface. For this reason, the change in power output of a 250 W PV panel caused by cooling with mains water along the back surface was investigated. The experiments were repeated for two consecutive days in the morning and afternoon hours in August. In all experiments, the solar radiation level was measured as approximately 822 W/m^2, and the back surface of the solar panel was cooled homogeneously with water at a flow rate of 0.5 L per minute for 20 minutes. The most significant values of power output in the uncooled, cooled states and power increase were 100.1 W, 115.07 W and 14.97 W, according to the results of study carried out in the morning of the second day trial. Additionally, a 21,1 °C temperature drop achieved while the surface temperature was decreased from 57 °C to 35.9 °C in the second day trial conducted in the afternoon. Another work on the experimental analysis of liquid cooling of PV cells was done by Al-Mamoori [24] wherein he investigated the effectiveness of thermal management of a PV cell by water spray nozzles on front and rear surface at flow rates 1, 2 and 3 L/m. In the study, the output power and efficiency changes of the 100 W photovoltaic panels, which were cooled by water obtained passively with the help of gravity from a tank placed at a height, were examined. Each examinations were carried out for consecutive three days in August while the relevant data were measured and recorded. As a result of the tests, the measurements obtained with the cooling methods were compared with the uncooled reference panel and each other. Additionally, by means of results the superiority of the two cooling methods over each other was evaluated. It was observed that electrical properties are significantly improved by the cooling methods used, especially at the flow rate 3 L/m which was assessed as the most promising and feasible among the others. The output power increased from 50.93 W to 80.08 W for cooling from the front surface and to 75.26 W for cooling from the rear surface. Although the efficiency of the uncooled panel was 9.7%, the efficiency of the panels increased to 14.31% and 13.57% with cooling from the front and rear surfaces. In the light of the evaluations, it has been revealed that front-side cooling is more effective in increasing panel performance than rear-side cooling. The quantitative data of experimental methods used as cooling technology proposed by the author are briefly listed in Table 2.

In order to better a 20 W polycrystalline PV panel's performance Akman [25] experimentally carried out two different cooling methods by which an array of channels made of polyamide material and a serpentine made of copper pipe were attached the rear surface of panels. For this purpose, an experimental setup was established wherein solar radiation, voltage, current and temperature values of PV panels cooled with aforementioned methods and uncooled reference panel were measured on four different days in September. Fig.6 shows the setup suggested in his work. As the result of the experiments it was observed that the highest rear surface temperatures of panels were 59.53 °C, 43.90°C and 29.23°C on the fourth day with a radiation value of 775 W/m² for the reference panel and panels cooled with serpentine and channels. The electrical power and efficiency values produced by each panel at these temperature values were 11.80W, 13%; 14.44W, 16% and 15.23 W, 17%, respectively.

Albayrak [17] investigated the change of PV cell efficiency with different solar irradiation and temperature conditions over the course of cooling a 260 W polycrystalline solar panel, which was mounted on an aluminum mechanical assembly, with mains water which flowed at 20 L/min on panel's back surface. The increment of power output was observed by measuring the panel pre-temperature values, ambient temperature, current and voltage during the tests carried out for two different days in May and July. In the first experiment the conditions were recorded as 33°C of ambient temperature and 1000 W/m^2 of sun intensity and the average panel front surface temperature was measured as 51 °C. With the presented method, the front surface temperature of the panel, which was cooled for 13 minutes, was decreased to 26 °C. While the power output of the PV panel was 145.5 W before the cooling process commenced, it was recorded as 178.3 W at the end of the process. Thus, an efficiency increase of 32.8 W and 22.5% was achieved. In the latter experiment operated in the morning the outdoor conditions were recorded as 24°C of ambient temperature and 400 W/m2 of sun intensity. Before the cooling method was applied the average panel front surface temperature and the output power of PV panel were measured as 46 °C and 110.3 W, respectively. As a result of the 5-minute cooling process, the panel surface temperature was reduced to 30°C and the panel power was increased to 141.3 W. By the presented method, a power increase of 41.3 W, that is, a 28.1% increase in efficiency, was achieved.

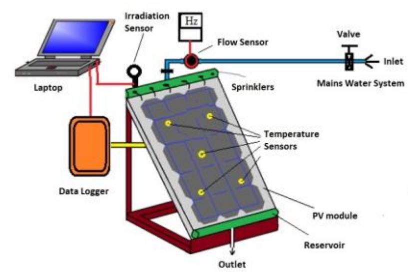

Fig.5. The experimental setup suggested by Altınışık [22]

Yaver [26] tested a forced liquid circulation technique in order to mitigate the adverse effect of the surface temperature of the solar panel on the electricity production efficiency in hybrid photovoltaic systems in the Turkish city of Hatay. In the proposed setup water cooled by a compressor cooling system was used as the coolant liquid and was circulated between PV/T module and the water tank with the help of a DC pump. In the study, to determine the electricity production efficiency of the system, the current and voltage values produced under cooling and non-cooling conditions were measured for 6 days in June. With results of the measurements carried out during all tests, it was observed that the solar radiation value varied between 600-1000 W/m^2, the module surface temperature varied between 51.6-75.2 °C in the uncooled system and 33.3-61.5 °C in the cooled system. The highest electricity production efficiency of the system was calculated as 6.1% in the uncooled case and 9.3% in the cooled one. When these measured efficiencies were compared, it was seen that the efficiency increased by 52.6% with the presented cooling technique. In addition, it has been determined that the most suitable surface temperature for PV solar modules to operate with high efficiency should be between 45-55 °C.

Another experimental work aiming to increase photovoltaic panel efficiency was an innovative design developed by Delibaş [27]. In his study, as a unique system design, cellulosic sponges capable of absorbing and dispersing liquid up to 10 times its weight were mounted on the rear surface of the PV panel. By this method It was aimed to remove the high heat on the photovoltaic system by spraying water over these sponges through nozzles and take advantage of the enthalpy of evaporation. In the research conducted in a laboratory condition, 300 – 400 – 500 W/m2 radiation intensities were taken into account and 0.5 lt of water was sprayed at 10, 20 and 30 minute intervals at 0°, 25° and 35° panel tilt angles. The schematic representation of the experimental setup is as shown in Fig.7. After each cooling processes performed with the proposed design were examined, it was understood that the effectiveness of the technique in PV panels became more significant as the angle of inclination increases. This increment became even more prominent, especially under high radiation intensity. So much so that the average temperature of the panel with a 35° tilt angle was 65 °C, while the average temperature of the panel with a 0° tilt angle was 83 °C under 500 W/m^2 radiation intensity. Moreover, the highest efficiency increase and temperature decrease were achieved in the parameters with a 20-minute spray interval, while the change between the parameters of 10, 20 and 30 minutes was insignificant. The lowest panel temperature and highest power output were measured at 35° panel tilt, and the highest panel temperature and lowest power output were measured at 0° panel tilt in all cases with integrated sponge. Fig.8 shows the changes of the average power produced depending on radiation intensities and spray intervals.

Teo et al. [28] carried out an experimental inquiry for active and passive performance of air cooling method designed for a hybrid photovoltaic system. In the model developed to actively cool the PV cells, a parallel channel array with an inlet/outlet manifold was installed behind the solar panel in order to provide homogeneous air flow distribution, and air ventilation was provided by a blower fan with a flow rate of 0.055 kg/s. Without applying the cooling technique, the panel surface temperature was recorded as 68 °C through the sensors at the bottom of the panel, and the system efficiency at this temperature was calculated as 8.6%. However, in the tests carried out under the proposed active cooling method, it was determined that the temperature value decreased to 38 °C and the photovoltaic system efficiency reached 12.5%. Moreover, the heat transfer simulation model developed with computational fluid dynamics (CFD) was compared with the actual temperature profile of the solar panel. The consistency of the values measured in the experiments and the values calculated in the developed model was observed.

TABLE II
THE QUANTITATIVE DATA OF EXPERIMENTAL METHODS USED AS COOLING TECHNOLOGY PROPOSED BY AL-MAMOORI [24]

System	Max Power Output P (W)	Improvement in Max Power Output P (%)	Max panel temperature reduction T_{pv} (°C) - Front	Max panel temperature reduction Tpv (°C) - Rear	Electrical Efficiency η (%)	Improvement in Electrical Efficiency η (%)
Without Cooling	50.93	-	66	70	9.70	-
Upper Cooling 1L/m	61	19.77	51	56	11.52	18.76
Upper Cooling 2L/m	70	37.60	45.2	47	13.17	35.77
Upper Cooling 3L/m	80.08	57.23	36	40	14.3	47.52
Lower Cooling 1L/m	55.6	9.16	54.6	52	10.50	8.24
Lower Cooling 2L/m	66.08	29.74	49	45.5	12.34	27.21
Lower Cooling 3L/m	75.26	47.77	41	37	13.57	39.89

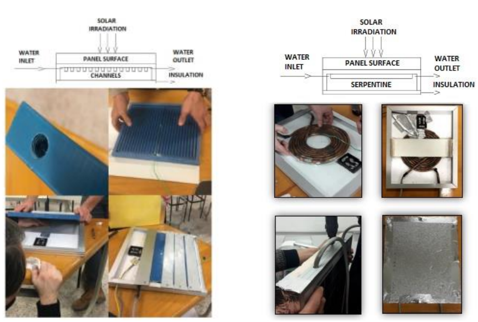

Fig.6. The experimental setup suggested by Akman [25]

Kaiser et al. [29] stated that one of the economical methods that can be applied to reduce the negative impact of building integrated photovoltaic system due to temperature is to leave an open air channel under the solar panel for ventilation. Tests were carried out to evaluate the effect of air ducts with 3 different aspect ratios on the panel temperature under natural and 3 different forced ventilation conditions through a test setup. The power output and electrical efficiency of the system were determined by evaluating the effects of solar radiation, channel size, and forced air velocity on the module temperature with the measurements obtained in the tests. These evaluations were found to be compatible with the results presented in the literature. According to the results obtained it was shown that the higher channel aspect ratio leads to the lower the panel temperature, in case of natural ventilation (V = 0.5 m/s) the critical channel aspect ratio (b/l) should be 0.11 to diminish overheating of the PV device, a 19.13% of increment of output power can be achieved when comparing 6 m/s forced air speed with natural ventilation at 0.0825 channel aspect ratio under

25 °C ambient temperature and 1000 W/m^2 solar radiation condition.

Eker [30] grouped the ideal tilt angles of the PV systems installed in the Turkish city of Bursa according to their monthly, seasonal and annual values. By the means of a simulation program the correlation between the cooling effect of wind on cell temperature, produced power output and efficiency of photovoltaic system were numerically investigated. It was stated in her work that wind affects panel temperatures, thus affecting panel efficiency. The correlation between wind and panel temperature was calculated as it is in Eq.(5) [31].

$$T_c = T_a + w\,(0.32/(8.91 + 2\,v_f))I_T \qquad (5)$$

T_c, T_a, w, V_f and I_T in the formula are, respectively; panel cell temperature, atmospheric temperature, installation coefficient, wind speed and instantaneous radiation (W/m^2). For the monthly average maximum air temperature averages (T_a) and monthly wind speed averages (V_f) of Bursa, 22-year monthly average data for Bursa province between 1983 and 2005 were used. By utilizing these data, the cell efficiency was calculated as follows in Eq.(6) [32].

$$\eta_C = \eta_T\left(1 - \beta_{ref}(T_C - T_r)\right) \qquad (6)$$

η_c is the efficiency of the PV panel cell, η_T is the efficiency of the panel cell at the reference temperature, β_{ref} is the temperature coefficient and T_r is the reference temperature. These values are accepted as η_T =0.16, T_r=25 °C, w=1, β_{ref} = 0.004 1/°C. To calculate the electrical energy produced the following formula was used as in Eq.(7) [32]

$$\eta_C = E/H_T \qquad (7)$$

Here, η_c is accepted as the panel efficiency, E is the electrical energy produced (MJ/m^{2}day), H_T is the total daily radiation falling on the inclined plane (MJ/m^{2}day). The cell temperature and efficiency for windless condition were calculated as in Eq.(8) and Eq.(9) [33]. T_{nom} was accepted as 45 °C.

$$T_c = T_a + (T_{nom} - 20)I_T/800 \qquad (8)$$

$$\eta_C = (-0.05T_c + 12.757)/100 \qquad (9)$$

After the outcomes of simulation were examined it was identified that the annual solar radiation values are at most according to the monthly optimum tilt angles at which the panels are installed. The maximum electrical energy is produced in July and the minimum in January. The system is least efficient in August and most efficient in January. When the effect of wind cooling effect on panel efficiency compared to windless weather conditions was examined, it was determined that the panel efficiency under the cooling effect of the wind was approximately 4.8% higher throughout the year. Therefore, it was found that the panels under the cooling effect of the wind produced more electrical energy.

Erdemir [34] measured meteorological data including wind speed and direction, ambient and panel surface temperature, humidity and solar irradiation belonging to 5 different locations with different altitude values around Konya and Karaman provinces of Türkiye. The effect of the aforenamed variables on the panel power output were experimentally studied by the means of a mobile PV experiment kit which were transported to these locations during tests. After completion of the experimental study, sensitivity analysis was performed by utilizing artificial neural networks connection weights method (CWM) and the holdback input randomization method (HIPR) to perform numerical evaluation. In the sensitivity analysis performed, three different impact values were calculated for each input and their average was taken. Thus, a more reliable comparison was provided by making calculations according to two different methods. While evaluated jointly for five different locations the order of influence of the parameters was numerically determined from high to low as solar irradiation, ambient temperature, humidity, panel surface temperature, instantaneous wind speed, wind speed and wind direction.

Fidan [35] built a hybrid photovoltaic system in which mains system water and air were utilized as coolant. The system efficiency calculations were experimentally carried out in the condition of Turkish city of Batman while conducting a comparative analysis with uncooled PV panel in the outdoor tests under high radiation in August and September. The current and voltage values were recorded in order to determine the amount of the change of efficiency while coolants separately circulated through three arrays of channel made from epoxy glass material whose heights ranged from 3 mm to 5 mm equipped on the rear side of PV panel. The circulation's flow rates varied from 1.8 m/s to 3 m/s for air and from 0.016 l/s to 0.032 l/s for water. In the light of data recorded by measurements of the experiments, the most favorable results were obtained with 3 mm duct height, 0.016 m/s water flow rate and 1.8 m/s air speed in which the efficiencies of the systems were 9.5%, 11.4% and 12.3% for PV, PV/T-air and PV/T-water, respectively. Thus, it was seen that water has a better cooling effect compared to air.

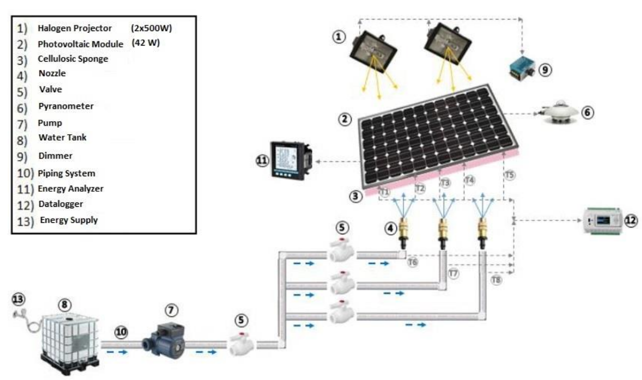

Fig.7. The experimental setup suggested by Delibaş [27]

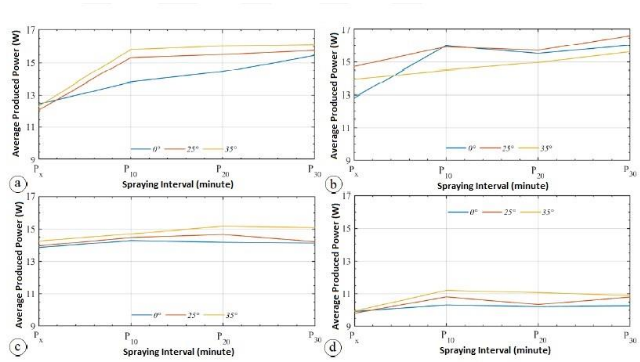

Fig.8. Average power produced depending on radiation intensities and spray intervals [27]

III. UTILIZING FINS, NANO AND OTHER TYPES OF MATERIAL ON THE SURFACES OF MODULE

Zhu et al. [18] studied experimentally improvement of performance of a hybrid photovoltaic system by applying Nano fluids prepared with MgO and ionized water in 0.02% wt, 0.06% wt and 0.1% wt mass ratios. In the proposed technique the Nano fluid actively circulated 2 or 4 mm layer thicknesses between the glass additionally mounted on the top of a 25 W solar panel and the its upper surface. The outdoor experiments held in November showed that the hybrid photovoltaic system with a 0.02% wt Nano fluid generated approximately 4.5 W more than that with a 0.1% wt Nano fluid when the layer thickness was adjusted to 4 mm. Thus, it was interpreted that the power output decreased with the increment of the mass fraction of the Nano fluid. Another experiment in which the mass fraction of Nano fluid was 0.02% wt showed that the hybrid system with a layer of 2 mm thickness produced roughly 0.5 W more than that with a 4 mm. It was inferred that the thickness of Nano fluid layer hindered the solar radiation from reaching the PV cell. Therefore, the produced power decreased.

Özdemir [36] conducted a experimental examination on the effects of Nano technological particles on the electrical performance of PV panels. In his study the proposed cooling method was actively implemented by the circulation of Nano fluids prepared by mixing TiO_2 and Al_2O_3 nanoparticles of different volumetric fractions, i.e. 0,01%, 0,1% and 1%, with deionized water through copper pipes with high thermal conductivity on the rear surface of panel. In the outdoor tests carried out in June and July, the improvement of the performance of the PV system was examined by comparing the electrical values of the cooled panel with the values of uncooled case. In the lights of the values examined, it was seen that TiO_2 Nano fluid was more promising in improving efficiency than Al_2O_3 Nano fluid and the volumetric ratio of 0.01% was the optimal value wherein 7.30%, 7.32% and 8.17% were the achieved efficiency for water, Al_2O_3 and TiO_2, respectively.

In another study in which Nano technological particles was utilized to increase the photovoltaic system performance Özhan [37] stated that the pollution on the panel front surface caused by environmental factors such as dust and dirty rain attenuated the efficiency and decreased the output power. Therefore, he conducted an experimental analysis on hydrophobic coating prepared by nanoparticles which applied on panel upper surface in order to minimize PV system's power loss. To assess the effects of his proposed method on the electrical performance four off-grid PV systems were built by identical 25 W panels, DC loads and data loggers. The photovoltaic modules in the first system were coated with hydrophobic nanomaterial (Nasiol C), the modules in the second system were coated with a different brand of hydrophobic nanomaterial (Nano Z Nano-Cam GL2), and the third and fourth systems were not applied with any coating. Thus, performance data with and without coating were compared to evaluate its effects. The study was carried out for 8 weeks in the outdoor for both the system that tracks the sun with an east-west axis and the fixed system with 30° tilt angle to the South. The measurements showed that the hydrophobic coating displayed a negative effect on the system with sun tracker and provided 1.7% lower power output. This is attributed to the fact that it became more polluted due to rain. Conversely, for the inclined fixed system, the coating had a positive effect of 2.8% on power output. It was evaluated that the positive effect was occurred because the mounting angle was greater than 15º, which is the sliding angle of the hydrophobic material.

Another experimental work examining the effects of the hydrophobic coating on the photovoltaic panel efficiency was done by Sarkın [38]. In his study it was researched how to prevent the loss of electrical efficiency caused by reduced light transmittance caused by reflection back from the protective glass and pollutants such as sand, dust and organic waste. For this purpose, coatings with 5 different formations was prepared with a solution containing SiO_2 and TiO_2 nanoparticles. A hydrophobic surface with anti-reflective and self-cleaning properties was produced by applying a 3D printer to the photovoltaic panel. Fig.9 shows the hydrophobic surface coating process and hydrophobic surface formation. In the outdoor tests performed on 5 homogeneously distributed coatings with 84% light transmittance, 3.122 - 8.477 μm thickness, on the PV panel, 2 models were found to be successful and were revealed to be 4.654% and 8.7% more efficient than the uncoated panel.

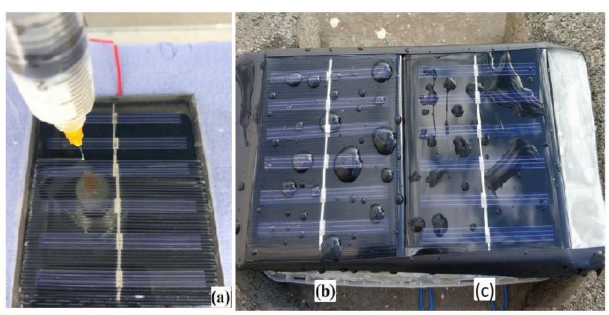

Fig.9. (a) The hydrophobic surface coating process, (b) hydrophobic surface formation, (c) the uncoated surface [38]

Jagathdarani et al. [39] proposed a novel hybrid photovoltaic system in which two changes in the design of the conventional solar panel were made. First, the Tedlar layer on the back surface of the solar panel was replaced with the toughened glass layer in order to better the transfer of heat energy to the bottom layer of the panel. Thus, it was aimed to prevent the temperature increase in PV cells and the decrease in PV panel efficiency when the solar panel was exposed to solar radiation due to the Tedlar layer not being a good thermal conductor. Secondly, a thermal system supported by natural water circulation, which works passively by means of the water tank placed at height, was attached on the underneath of newly designed PV panel. In this proposed thermal system a flat plate thermal collector was designed which consisted of six arrays of copper fins with 0.04 mm reflector sheet thickness. Fig.10 shows the experimental setup and the thermal collector system proposed by the authors. During outdoor tests, the output characteristics of the new design hybrid photovoltaic systems and the conventional solar panel were monitored for 7 hours using software and the average values for the hour were compared with each other. It was observed that under 927W/ m^2 solar radiation the new design solar panel provided a maximum electrical power output of 46.68 W, while this value was 42.77 W in the conventional panel. It is demonstrated with this method that the electrical efficiency of the PV panel is improved. In addition, efficient use of energy is ensured by storing thermal energy in the hot water tank.

Fig.10.The experimental setup and the thermal collector system [39]

Ayaz [40] investigated to what extent three solar panel glasses with different characteristics, i.e., comfort, synergy and tempered-polished, can change the photovoltaic system performance while an aluminum material is applied to the bottom of the panel for cooling purposes. In the first stage of his research, an experimental study was carried out by measuring the current, voltage and surface temperatures of the 60W monocrystalline solar panel and 7 different cases were discussed. In the second stage, the correlation of obtained data and power output were examined with feed forward back propagation method of artificial neural network while 10 different stochastic models were developed. According to the test results, it was determined that glass types reduce the output power. The highest power loss was 68.93% in the comfort glass test when the aluminum material was installed at the bottom and the least power loss, 1.21%, occurred when only the aluminum material was installed at the bottom. It was concluded that the glass samples used in the tests increased heating and reduced power output due to the high iron content in their structures and the glass coatings not preventing reflection. After stochastic models were examined by a comparative analysis, it was determined that the highest power production was in the comfort glass with 8302.7 W in the second model, in the synergy glass with 5664.6 W in the tenth model, and in the tempered-polishing glass in the other models.

Yüksel [41] conducted a numerical study on fins placed at different lengths and intervals underneath of PV to investigate the improvement of passive thermal regulation with a commercial computational fluid dynamics (CFD) software. The analyses were carried out with a two-dimensional numerical model for 8 hours at 4 different radiation values determined according to the meteorological records of Izmir province of Türkiye, i.e. 1000, 500, 300, 200 W/m^2. In the analysis examining the effect of half and full-length 5, 25 and 40 fins modeling conducted to increase heat transfer in passive coolant material on the PV system, it was found that increasing the number of fins provides a homogeneous temperature distribution in the coolant and a more uniform temperature along the panel surface. Fig. 11 shows temperature contours along the panel surface under 500 W/m^2 solar radiation at the 20000th second during the tests for 5, 25, 40 full and half fin configurations. It is observed that hot spots on the panel surface are eliminated and the panel surface temperature is reduced. According to the comparison of 40 full fins and finless cases the increment in the output power were 5 W/ m^2 for 1000 W/ m^2 radiation, 0.75 W/ m^2, 0.2 W/ m^2 and 0.1 W/ m^2 for 500, 300 and 200 W/ m^2, respectively. Although increasing the number and length of fin had initially tendency to improve the PV power output, it was found that increasing the heat transfer rate caused the average coolant substance temperature to increase and melt faster. After complete melting was achieved, it was shown that by rapidly increasing the panel surface temperature, it reduced the power output value below the reference model, which was without fin.

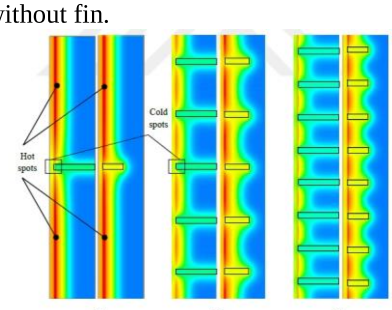

Fig.11. Temperature contours (a) 5, (b) 25, (c) 40 full and half fin configurations [41]

Bayrak et al. [42] conducted an experimental analysis in which 10 different cooling layouts mounted on the back of a 75 W polycrystalline solar panel were undergone comparison according to their superiority over improving efficiency and output power. In their study aluminum fins with 3 different layouts, i.e. located in the middle, right and left, right, middle and left, were utilized in order to elevate PV panel's performance. The size and layouts of aluminum fins are displayed in Fig. 12. The surface temperatures of uncooled panel and panels cooled with fin arrangements were recorded as 48.3 °C, 47.5 °C, 46.7 °C and 46.1 °C, respectively. According to the serial tests carried out under the same climatic conditions, the cooling method performed with aluminum fins installed on the right, left and middle of the rear side of panel was stated as the most successful arrangement by production of 47.88 W output power with a conversion efficiency of 9.23%. Additionally, it was emphasized by the authors that having low investment cost, being simple to install and requiring zero maintenance made aluminum fins more preferable among the other cooling arrangements.

In other similar study utilizing aluminum finned wall on the rear of a 50W monocrystalline panel in order to improve passive thermal regulation of PV system was experimentally carried out by Ekiz [43]. In this work two types of aluminum fins, i.e. plain and embossed, were produced to elevate the heat transfer of passive thermal controller which was used as coolant. The technical drawing of proposed fins can be seen in in Fig. 13. As a result of the experimental examination, the maximum temperature values were 45.32°C for uncooled case, 40.61°C for the prototype with plain fins and 39.48°C for the prototype with embossed fins. The electrical power outputs were observed as 27.95W, 30.99W and 32.77W, respectively. Thus, with proposed prototypes it can be seen that there is significant drop in the panel surface temperature and increment in power output as well as efficiency.

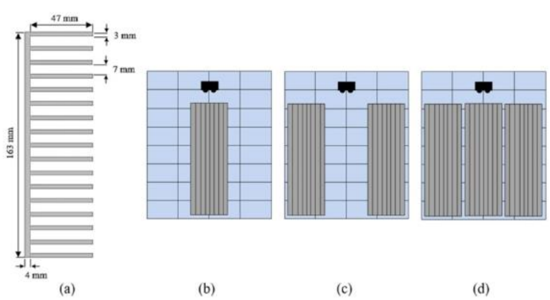

Fig.12. (a) The size of fins, (b) in the middle, (c) in the right and left, (d) in the right, middle and left [42]

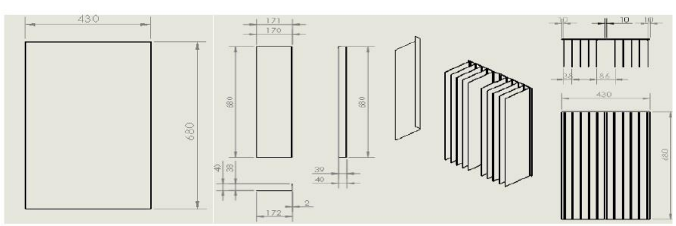

Fig.13. The technical drawing of fins proposed by Ekiz [43]

Türk [44] researched the degree to which 2 different cooling systems were successful in reducing the drop in PV panel output power caused by high temperature of summer conditions occurred in Turkish city of Edirne. During the outdoor tests the electrical output values and temperature changes in the 260W polycrystalline panels which were equipped with 30 pieces of aluminum fins and thermoelectric generators were observed for 3 months. By the means of data obtained from the experiments, it was recorded that 100402.70 kWh energy was generated with the reference panel, 108970.38 kWh with the fin-cooled panel and 108762.97 kWh with the thermoelectric-cooled panel. Although close output powers were obtained as a result of experiments, the author noted that the passive cooling method with aluminum fins is more suitable when the cost factor is taken into account.

IV. PHASE CHANGE MATERIAL (PCM) AS A PASSIVE THERMAL REGULATOR

Phase Change Material (PCM) is adjoined in the cavity underneath of solar panel as a passive thermal regulator due to its ability by which it can store a large amount of heat as latent energy and keep the panel temperature at a certain range while being melted by excessive heat which solar radiation caused [45].

Yüksel [41] developed one dimensional mathematical model to evaluate effect of three different thickness of PCM, i.e. 3, 2 and 1 cm, on increasing the electrical efficiency of PV panel. The comparative investigation was carried out between uncooled case and passive thermal regulator mounted underneath of panel during constant and variable irradiation conditions. Fig. 14 displays the mathematical model of PV panel with PCM cooling and the thermophysical properties of the model can be seen in Table 3. In the examination carried out under constant solar radiation conditions of 300, 500, 700 and 1000 W/m^2 applied for eight hours, it was observed that the panel temperature could be kept at a lower temperature for a longer time in case of PCM. Also, it was understood that increasing the thickness of the PCM will prevent temperature increases over longer periods of time. Additionally, it was shown that the drop in efficiency was significantly prevented in inquires with increased phase changer thickness in high irradiance conditions such as 1000 and 700 W/m^2. According to the comparative analysis PCM-cooled system produced 9 W/m^2 more than the uncooled case under the highest irradiation. For variable irradiance values, boundary conditions were defined based on Turkish city of Izmir. Analysis was made for 4 different months, i.e. January, April, July and October, which symbolized seasons of the year. Best performance was obtained for October during tests. The panel temperature was reduced by 9 K by placing 3 cm of PCM and approximately 6% of power increase was achieved.

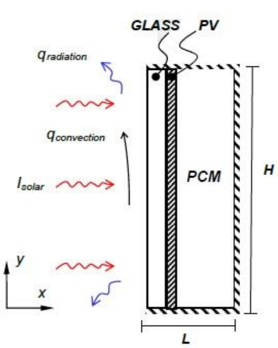

Fig.14. The mathematical model of PV panel with PCM cooling proposed by Yüksel [41]

TABLE III
THE THERMOPHYSICAL PROPERTIES OF THE PROPOSED MODEL [41]

Material	Specific Heat (J/kgK)	Density (kg/m³)	Thermal Conductivity (W/mK)	Latent Heat (J/kg)	Melting Temperature (K)
Glass	500	1.95	1.8		
PV/Plastic	1255	2.28	0.1		
PCM	2000	2.84	0.2	184000	300

Similarly, in another study, Şen [46] planned to regulate the temperature on the photovoltaic panel surface by using calcium chloride hexahydrate (CaCl2·6H2O) as a phase changing substance and examined the effect of the method on the efficiency of a 125W panel. During the outdoor tests carried out in Batman province of Turkey in August the highest radiation value was measured as 981W/m^2 and under that radiation condition the current, voltage and power values with an utilized phase-changing substance and uncooled case were obtained as 4.78 A, 4.75 A; 15.78 V, 15.7 V; 75.45 W, 74.69 W, respectively. Thus, the efficiency increase in the PV panel was measured as 2.95% and the maximum increase for current and voltage was achieved by 1.46% by the means of PCM.

In their experimental study Bayrak et al. [42] focused on the evaluations of two PCMs, i.e. Biphenyl and CaCl2·6H2O, which were examined for performance improvement of a 75 W polycrystalline PV system under the same solar irradiation. In their work the PCMs with two different melting temperatures which were above and below of solar module surface temperature were purposely chosen to determine the effect on output power of system. Under maximum radiation condition which was recorded as 1024.9 W/m^2 during the outdoor experiments the highest output powers for reference panel, PCMs as Biphenyl and CaCl2·6H2O were measured as 45.38 W, 40.54 W and 46.01 W, respectively. It was observed that mounting a PCM with a higher melting temperature, i.e. Biphenyl, than the panel operating temperature had an adverse effect on the efficiency. Thus, it was understood that although PCMs can be provided in broad range of melting temperatures they should be utilized according to surface temperature of the PV system on which cooling method is applied.

Özbaş [47] tested a passive cooling method to improve a 5 W polycrystalline PV panel's performance by utilizing paraffin wax as PCM. The experiments were conducted under laboratory conditions using an incandescent lamp as solar simulation for 2 hours and the average solar irradiation was recorded as 1035 W/m^2. By the means of passive thermal regulation technique the produced heat was absorbed for approximately 70 minutes, whereas panel operating temperature was increased afterward because of PCM heat storage property. Nevertheless, the average upper surface temperature of cooled panel as being 53.6 ◦C stayed below the reference panel's temperature which was recorded as 54.9 ◦C under the same test conditions. Moreover, it was observed that the generated voltages were as 7.699 V and 7.714 V on average for the reference panel and cooling method. Thus, a 2% of increment in the conventional PV's efficiency was achieved by utilizing paraffin as PCM.

In another experimental study, similar to the previous research, Ekiz [43] utilized paraffin as a passive thermal regulator mixed with aluminum sawdust and equipped with two different types of fins in order to elevate its heat transfer rate. The experimental results showed that two designs achieved 11.8% and 16.5% decreases in panel temperature and 10.9% and 17.25% improvements on electrical power output compared to the uncooled case. Table 4 shows the thermodynamic properties of PCMs used in the aforementioned studies.

TABLE IV
THERMODYNAMIC PROPERTIES OF PCMs USED IN THE REVIEWED STUDIES

PCM	Melting Temperature (°C)	Thermal Condition (W/mk)	Latent Heat (J/g)	Purity (%)
Biphenyl [42]	69.17	0.11	132.79	99.00
CaCl2·6H2O [42,46]	1255	0.19	213.12	97.00
Paraffin [43,47]	2000	0.2	266.00	98.5

V. INNOVATIVE COOLING TECHNOLOGIES: HEAT PIPES

Heat pipes have emerged as an important research area in recent years in order to cool surfaces and achieve uniform temperature distribution on surfaces due to their unique characteristics. In its most general form, a heat pipe is a closed-volume passive device that allows heat to be transferred from one region to another by transport, taking advantage of the liquid-vapor phase change of the working fluid inside [48]. Fig. 15 shows a picture of a conventional heat pipe [49].

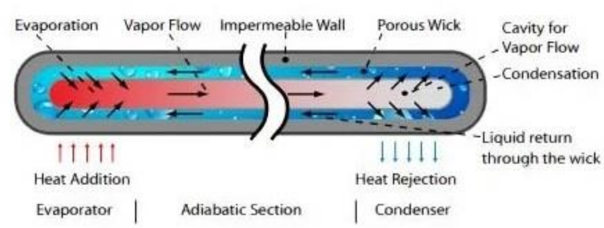

Fig.15. A conventional heat pipe [49]

In order to investigate the thermal and electrical performance of a hybrid photovoltaic system with integrated heat pipe, Rejeb et al. [50] performed mathematical modeling and simulation analysis under the hot climatic conditions of Sharjah city, United Arab Emirates. The data belonging to the mathematical model in which the behavior of the heat pipe in a hybrid PVT system was studied using discrete system equations solved by the finite element method was compared with the experimental data in the literature [51]. Thus, the mathematical model was verified. In the light of estimations developed by the model, it was determined that the maximum monthly electrical energy production for a hybrid photovoltaic system with integrated heat pipe was 116 kWh, and 102 kWh for uncooled reference PV panel. It was shown that the use of heat pipes in hybrid photovoltaic systems provides better electricity generation compared to the reference solar panel.

Datkayeva [52] studied the change in operating temperature and power output of a 10 W solar panel as a result of the use of heat pipes integrated as passive coolant. In the research 6 copper heat pipes with a diameter of 0.8 mm, 4 of which are 42 cm and 2 of which are 29 cm long, were manufactured. Ethanol and pure water were used as working fluids in the heat pipes for cooling the panels and compared with a reference panel. The condenser part of the heat pipes was sized as 11 cm and the evaporator part was as 31 cm while filling ratio of working fluid was 1/3. Water was preferred for heat transfer purposes in the back part of the system covered with an aluminum cover and the cavity was filled with 650 ml of water. Fig. 16 shows the size of heat pipes and the preparation of the experimental set-up. The average values of the output power were measured as 8.32 W, 8.27 W and 8.25 W for the panels using working fluid pure water, ethanol and the reference panel, respectively. As a result of the data obtained during the outdoor tests, it was shown that the power output of the pure water-based panel was higher than ethanol and reference panel.

Fig.16. The experimental setup by Datkayeva [52]

Li et al. [53] compared experimentally rectangular and trapezoidal types of micro heat pipes (RMHP and TMHP) with the same cross-sectional area to assess to what extent the hybrid photovoltaic system performance was changed. For the 2-day outdoor tests conducted on May 4 and July 5, 20 groups of micro heat pipes entire sized in the length of 950 mm, width of 80 mm and thickness of 3 mm were placed behind the PV panel installed at 45◦ tilt angle and R141b was used as a working fluid with a 25% filling ratio. The section diagrams belonging to both heat pipes are shown in Fig. 17. According to the measurements made during the experiment, the average efficiency value of the solar panel cooled by a rectangular cross–section micro heat pipe was 12.4% and the average electrical power was 137.5 W. The values for the same measurements are 11.9% and 132 W for the trapezoidal heat pipe solar panel, respectively. Thus, it was perceived that the electrical performance of the RMHP is better than TMHP.

In a laboratory condition Özbaş [47] tested two thermosyphon type heat pipes charged by different working fluids of 16.66% filling ratio, i.e. ionized water and methanol, with a 400 W solar simulator for 2 hours. In his passive thermal regulator designs the thermosyphons were manufactured by copper pipes having sizes of 8 mm diameter and 0.7 mm thickness. Each design consisted of 3 thermosyphons which were grouped as two 40 cm and one 30 cm length. The cavity underneath of PV panel where heat pipes were embedded were filled with PCM in order to obtain homogenous thermal distribution and then sealed by an aluminum plate and insulation. Fig. 18 displays the proposed experimental design by the author. During the laboratory tests, the surface temperature on the front glass of the panels were averagely measured as 54.9 ◦C, 49.5 ◦C and 50.5 ◦C, respectively, for the reference panel and panels used water and methanol as working fluid. According to the comparison with the uncooled reference panel the designs with water and methanol as working fluid obtained an efficiency improvement of 6% and 4%.

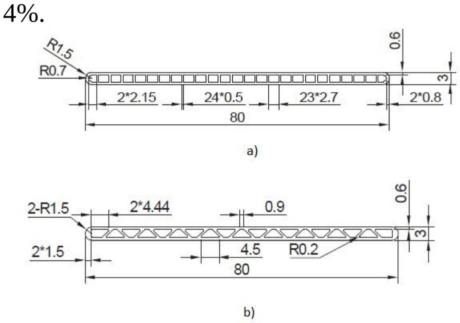

Fig.17. The section diagrams (a) RMHP, (b) TMHP [53]

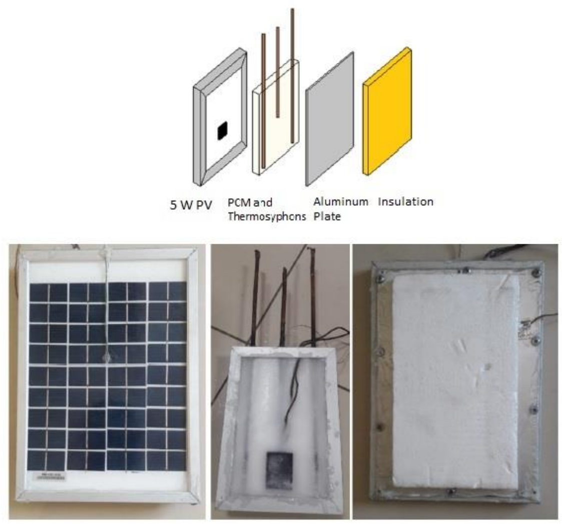

Fig.18. The proposed experimental design by Özbaş [47]

Chen et al. [54] conducted an experimental study on thermal regulation performance of a high-concentrating PV system equipped with a GaAs solar cell and a thermosyphon type heat pipe and compared its results with the simulation analysis of the numerical model developed in their work. The change in cell temperature and electrical efficiency were investigated for four values of concentration, and temperature of saturation and five values of working fluid filling ratio associated with the thermosyphon manufactured by copper of 1.2 mm thickness and its evaporation end was designed as a cuboid sized 40 x 40 x 20 mm3. The schematic diagram of thermosyphon is shown in Fig. 19. According to test results it was concluded that the performance of the system was dependent to temperature of saturation in the evaporator end. Lower temperature enabled the heat pipe to dissipate the heat produced by solar irradiation, while higher temperature hindered the heat pipe to function. The most favorable result recorded while the temperature of saturation kept 312.15 K as the lowest and filling ratio was 55% wherein the electrical efficiency rose to 30.9% and cell temperature was 326 K.

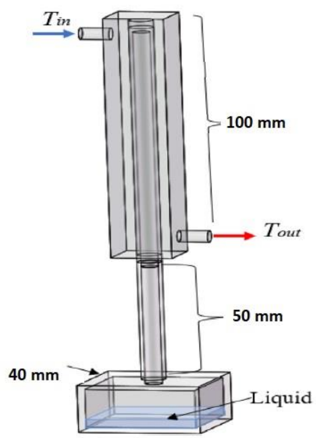

Fig.19. The schematic diagram of thermosyphon by Chen et al. [54]

VI. THERMOELECTRIC COOLING

Bozkurt [55] stated that it is possible to prevent the temperature increment and electrical performance attenuation caused by the operating conditions of the solar panel by taking advantage of the fact, known as the Peltier effect, that if thermoelectric module is supplied with direct current its one surface heats up and the other surface cools down. In the experimental study conducted, the power and efficiency values of two 10 W solar panels with the same characteristics, one of them was mounted with a thermoelectric equipment, were measured in order to analyze to what extent the cooling effect made a performance change on the system. According to the outdoor tests conducted between 10:00 and 15:00 for 2 days in April, an average increase of 6% and 5.5% were obtained respectively in the power and efficiency values of TEM integrated to PV panel.

Bayrak et al. [42] aimed to elevate a 75 W polycrystalline solar panel performance by harnessing different layouts of TEM underneath of panel. During the outdoor experimental tests held under the summer climate conditions in Turkish city of Elazığ, the current and voltage data were recorded from reference and cooled panels on whose rear surface 6, 8 and 12 pieces of TEM were installed. Fig. 20 shows different layout schemes and electrical connectors of PV-TEMs. The experiments showed that the more TEM were placed on back of PV module the more temperature drop on surface were obtained. The highest temperature decrement was gained by TEM-12 which was 2.7 °C under 995.924 W/m2 of solar radiation. The highest electrical power of uncooled PV and PV-TEM panels were 46.45 W, 47.60 W, 48.35 W and 48.64 W, respectively.

Türk [44] employed 30 pieces of thermoelectric generator (TEG) on back surface of a 260 W polycrystalline PV module to enable additional electricity generation, known as the Seebeck effect, by utilizing waste heat produced on cell surface by solar radiation. Besides that, aluminum fins were mounted to the lower surfaces of TEG modules in order to create a temperature difference between their surfaces. Fig. 21 shows the installation of thermoelectric generators and aluminum fins on the back surface of the photovoltaic panel. The total electrical energy obtained from standard and PV-TEG panels was recorded in outdoor tests conducted under meteorological conditions of the Turkish city of Edirne from 07:00 in the morning to 19:00 in the evening between July and September. As results of the 3 month lasted trials standard PV panel produced 100402.70 Wh, while PV-TEG panel did 108762.97 Wh. The proposed model obtained an 8.32% of improvement in electrical power generation.

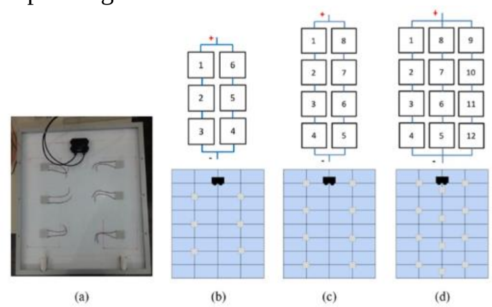

Fig.20 (a) Electrical connectors of PV-TEMs, (b) 6, (c) 8, (d) 12 pieces of TEM [42]

In order to examine the effects of shading and temperature on a PV system Özmen [56] compared the efficiencies of a reference panel, a shaded panel and an unshaded panel with passive coolant. In the research two sets of experiments were prepared consisting of equivalent polycrystalline panels with 10 W rating. One of the sets had its front surface area of 4 cm^2 shaded and the other set had a TEM mounted on its back surface. During the field tests conducted on June 2 from 8:00 to 19:00 in the Turkish city of Denizli the maximum and average power outputs of panels were measured as, respectively, 9.378 W and 5.756 W; 8.723 W and 5. 262 W; 9.651 W and 6.013 W. The maximum efficiencies were listed as 13.47%, 12.58% and 13.89%.

Song et al. [57] developed three prototypes of hybrid photovoltaic systems by utilizing amorphous silicon (a-Si), cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) solar cells coupled with TEG modules. In their work it was aimed to generate additional electrical energy by leveraging heat energy produced by unabsorbed part of solar radiation spectrum. Also, in order to lower the temperature of cold surface of TEG module, so that its performance could enhance, paraffin as PCM with 50℃ of melting point was combined into the hybrid system. In this aspect, numerical and experimental methods were both conducted to assess at which extent the systems' performance improved. Furthermore, the rear surface temperatures of the reference panel without TEG module and the prototypes underwent a comparative analysis. Fig. 22 shows the prototypes proposed by the authors. The employed methodologies showed the outcomes for CdTe, a- Si and CIGS cells as follows. The hybrid PV systems' temperatures were respectively 44.0℃, 40.5℃, and 39.3℃ on average. Moreover, the combining of PV cell, PCM and TEG modules in a hybrid system resulted in more decreased cell temperature benchmarked with standard PV system. The average decrement of back surface temperature were 4.70℃, 2.32℃ and 3.43℃, respectively. The efficiencies were averagely 19.7%, 12.7% and 21.9%. According to juxtaposition of the hybrid systems it was concluded that the system with CIGS cell showed superiority on thermal management.

Fig.21.The installation of (a) thermoelectric generators (b) aluminum fins on the back surface [44]

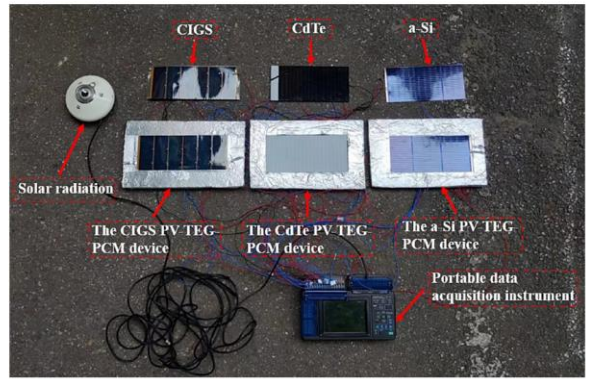

Fig.22. The experimental setup of the prototypes proposed by Song et al. [57]

VII. CONCLUSION

A comprehensive review of investigations carried out with various experimental and numerical methodologies has been provided for thermal regulation aimed to elevate photovoltaic panel performance by this paper. The examinations have shown that majority of these researches are successfully able to dissipate the heat produced by unabsorbed part of solar radiation spectrum. As a result of the review some essential points have been concluded as follows:

By the liquid circulation and spraying methods applied on both surfaces of a PV module significant improvement on its performance can be achieved. Among the examined techniques the highest temperature drop can be obtained as 30.3 °C by means of forced circulation. And the highest efficiency increment can be realized as 52.6% with such methodologies. On the other hand the liquid cooling with natural circulation is also effective in elevating the PV module performance and decreasing the panel surface temperature. With the proposed technique a 47.52% of efficiency improvement and a 21.1 °C of temperature decrement on rear surface might be yielded at the highest extent.

Although there is a perception that the cooling with water from the front surface of the solar panel might hinder the access of the useful solar radiation due to the water film on the surface, the experiments shows that the front-side cooling is more effective in increasing panel performance than rear-side cooling.

Thermal management with air ventilation can provide promising outcomes on the PV performance. By means of forced ventilation a 30 °C temperature drop and a 45.34% efficiency improvement can be obtained. Investigation shows that wind as a medium of natural air cooling might elevate approximately a panel efficiency as 4.8% compared to windless condition throughout the year. It is also crucial to note that PV panel integrated on building should have sufficient air gap between roof and its panel whose ratio (b/l) should be 0.11 in order to evade overheating.

Then investigation conducted to evaluate the superiority of active water and air cooling reveals that water has a better cooling effect compared to air.

The investigations show that deploying nanotechnological materials in a photovoltaic system for elevating its performance have merits and demerits. Due to higher thermal conductivity properties, nanofluids can be beneficial to dissipate the heat energy produced on PV panel surfaces and improve the system efficiency. However, applying such method on front surface can decrease the electrical power output of PV system as well. Since increment of mass fraction and layer thickness of nanofluids can scatter and absorb the ray of light, by this way, hinder its access into the PV cell. On the other hand, by utilizing nanoparticles in producing hydrophobic coating can conduce to elevate the efficiency for 8.7%. As a rule, in order to harness positive effect from this method the tilt angle of PV panel should be greater that the sliding angle of hydrophobic material. For this reason the hydrophobic coating method is more promising in PV system with fixed tilt angle rather than with sun tracker which can provide 1.7% lower power output.

In order to have a better heat transfer through the bottom of PV panel the Tedlar layer can be replaced with glass or aluminum plate as heatsink. The experiments display that the glass layer supported by a flat plate thermal collector can obtain a 9.14% of improvement in electrical power output. However, the aluminum material installed at the rear surface without a heat absorbing setup might lead to power loss when it is compared to a conventional solar panel. When the effects of different types of glasses, i.e. comfort, synergy and tempered-polished, placed on the front surface of the solar panel on the output power are examined, it is seen that they might not prevent the reflection of the sun rays from the front surface of the panel due to their high iron content. In consequence, they might increase heating and reduce the power output.

Trials of integration of aluminum fins by various configurations with their numbers and geometry display that increasing the number and surface area of fins provides a more uniform temperature along the panel surface and eliminates hot spots on it. By applying such a method 5.84 °C of temperature decrement and 17.24% of improvement in electrical power output can be achieved. When the fins are combined with a coolant substance, such as a PCM, in order to increase the thermal conductivity they cause the average temperature of coolant to rise and the substance to melt faster. And this leads rapid temperature rising in the panel surface and power output drop below the value of panel without cooling.

In the market PCMs can be found in broad range of melting temperatures, however, they should be preferred according to surface temperature of the PV system on which cooling method is utilized. The experiment shows that choosing a PCM with a melting temperature that is incompatible with the panel operating temperature leads to a 10.66% of decrement in electrical power output. The comparative investigation aiming to evaluate the effect of various thickness of PCM on the electrical efficiency of PV panel highlights that utilizing a PCM with thicker layer hinders the rising of surface temperature over longer periods of time. Also, the drop in efficiency can be significantly prevented by the increased thickness in even higher irradiance conditions. Coupling a PCM with a equipment of higher thermal conductive properties can conduce to more temperature decrement and performance improvement in a PV system. The experiment reveals that PCM mixed with aluminum sawdust and equipped with embossed aluminum fins has 16.5% drop in panel temperature and 17.25% improvement on electrical power output compared to the reference panel.

The critical factors which the performance of PV system equipped with heat pipe is dependant to can be counted as type and filling ratio of working fluid, sizing and cross-sectional area of heat pipe and temperature of saturation in the evaporator end. The heat pipe design with water as working fluid has superiority over the designs with methanol and ethanol. When rectangular and trapezoidal types of micro heat pipes with the same cross-sectional area are compared rectangular micro heat pipe demonstrates better performance under the same environmental conditions. The temperature of saturation in the evaporator end affects the operating temperature on average. When the temperature of saturation is lower degree the surface temperature can be kept lower and electrical efficiency can be yielded higher. The filling and concentration ratios are strongly related to each other. Although at the lower concentration ratios than 300 the filling ratio has a trivial influence on the surface temperature, at the concentration ratio over it 55% of filling ratio can keep the surface temperature 5 K lower than other filling ratios.

The comparative analyses reveal that performance of PV system improves by increment of number of TE modules harnessed. By utilizing the Peltier effect a 75 W PV panel equipped with 12 pieces of TE can obtain a 4.71% of improvement in electrical power output. By the means of the Seebeck effect a 260 W PV panel equipped with 30 pieces of TE can obtain a 8.32% of performance increment. As a-Si, CdTe and CIGS types of PV modules coupled with TEG module and Paraffin are benchmarked according to their surface temperature and efficiency measured under same meteorological conditions CIGS shows superiority with 35.87 °C and 21.9% values over others.

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BIOGRAPHIES

UMIT KEMALETTIN TERZI Zonguldak, in 1968. He received the B.S degree from Marmara University Technical Education Faculty Electrical Education Department in 1989. He received the M.S. degree in 1994 and the Ph.D. degree in 2000 from the Department of Electrical Education of the Institute of Pure and Applied Sciences of Marmara University.

From 1989 to 1996, he was a Research Assistant and from 1996 to 2000 a Lecturer at Marmara University. He worked as an Assistant Professor between 2000 and 2013, an Associate Professor between 2013 and 2020 at Marmara University. Currently, he is working as a Professor at the Department of Electrical and Electronic Engineering of the Faculty of Technology of Marmara University and continues to work as the Head of the Department at the Department of Electrical Education of the Faculty of Technical Education. His research interests include power systems, renewable energy, electrical machinery and nanomaterials.

TAHA FURKAN OZTURK Istanbul, in 1984. He received the B.S. degrees in electrical engineering from Kocaeli University in 2007 and he is currently pursuing the M.S. degree in Electrical and Electronic Engineering in the Faculty of Technology of Marmara University. His research interests include electrical power generation, transmission and distribution, renewable energy and nanotechnology. His M.S. degree thesis interests nanotechnology applications on renewable energy sources.