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Cooling channel effect on photovoltaic panel energy generation

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ABSTRACT

It is a well-known fact that even though the electricity generation is higher when the solar radiation is high on a photovoltaic panel, its efficiency drops as its temperature increases. In this study, it is intended to achieve cooling effect using an air duct placed under a photovoltaic panel, thereby increase its efficiency. Hourly electricity generation, PV efficiency and cell temperature values over a year are calculated using annual temperature and radiation data by using MATLAB and PV Sol software. Maximum cell temperature for the uncooled case is determined as 57.91 °C on July 21st at 1p.m. as a result of hourly calculations. The incident solar radiation is 976 W/m^2 when the panel reached its maximum temperature. The PV panel and cooling channel are modelled in ANSYS Fluent software and cooling effect was investigated for different air velocities and air-cooling channel geometries for the hour when maximum cell temperature is reached. Environmental analyses are also made. It is observed that with finned cooling channel, it is possible to cool PV temperature more than with the flat cooling channel. Cooling the PV panel from its maximum cell temperature to 39.82 °C with 5 m/s air velocity and 82 fins cooling channel is achieved and new PV panel efficiency is recorded as 18.92 %. Environmentally considerations show that the use of solar energy provides the reduction of coal and natural gas-based CO$_2$ emissions as 15 and 8 tons, respectively.

1. Introduction

In today's society, the effective use of renewable energy is becoming mandatory with the increase of human population and environmental issues. The most important issue in today's world is the efficient usage of energy. Erkan et al. (2018) indicated that decreasing the initial costs, reducing and recovering waste energy and efficient usage of energy are the main research topics. The consumption of fossil fuels causes environmental pollution and global warming, which are the most importants problem that emerged in our age. However, solar energy is an important renewable energy source, with its abundance, simple technology to use, and environment friendly nature. Because of these reasons, the use of solar energy, which is a clean, endless and low-cost source of energy, has increased in the past years. Photovoltaic (PV) panel studies have also been increased day by day. Researchers often emphasize that one of the improvement studies for the PV panels is to increase the efficiency of PV cells by cooling.

There are two types of energy that can be produced from solar energy: electrical energy and thermal energy. The electrical energy can be produced by using PV cells which directly convert a part of the incident solar irradiance to electricity. The remaining part of the solar irradiation is converted into heat, which increases the temperature of the cells and reduces the performance of the PV module. There are many ways to cool a PV module for increasing efficiency. The cooling of PV cells is divided into five main topics; passive cooling techniques, heat pipe cooling, active cooling methods, nano-fluid cooling and thermoelectric cooling. Erkan et al. (2018) mentioned that cooling with a channel method can be active or passive. Active systems use energy consuming equipment such as pump or fan, but passive systems do not require any energy consuming equipment.

There had been many researches related to cooling processes of PV panels, such as Mittelman et al. (2009) who aimed cooling the PV panel with radiation and free convection. Similarly, Palumbo (2013) developed the cooling channel that worked with natural convection by using air as cooling material and he tested his system with different air velocities using fans. Kaiser et al. (2014) aimed to provide an open-air channel for PV panel to achieve cost effective system. Moreover, they used a ventilation system to record temperature differences by sending different air velocities. Baloch et al. (2014) stated the working principle of a cooling for photovoltaic by using jet impingement. Irwan et al. (2015) developed a solar simulator with halogen lamps to analyse the performance of a PV panel with and without air cooling mechanism. Baloch et al. (2015a) observed the behavior of thermal and electrical

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Nomenclature

A	Cross Sectional Area (m^2)
A_{PV}	PV Panel Area (m^2)
E_i	Hourly PV Electricity Generation (W)
G_{ref}	Ground Reflection
I_d	Diffuse Radiation (W/m^2)
I_G	Global Radiation (W/m^2)
I_T	Hourly Radiation Incident of the Tilted PV Panel (W/m^2)
k	Ventilation coefficient
n	Day Number
n_{pv}	Number of PV Panel
R_b	The ratio of beam radiation on the inclined surface to a horizontal surface
T	Temperature (°C)
T_a	Ambient Temperature (°C)
T_c	Cell Temperature (°C)
T_{ref}	Reference Temperature (°C)
$\dot{v}$	Volumetric Flow Rate (m^3/s)
w	Hour Angle (°)
w_s	Sunset Hour Angle (°)
Greek Letters	
β	Slope angel of PV (°)
δ	Declination Angle, Solar Radiation Coefficient (°)
η	Efficiency (%)
$\eta_{mp,ref}$	PV Panel Efficiency(%)
μ_{mp}	Temperature Coefficient of Maximum Power Point
ρ	Density (kg/m^3)
ρ_g	Ground Reflectivity

properties for a cold PV system and a combined duct cooling PV system in Dharan climate. Baloch et al. (2015b) aimed to obtain low and uniform temperature on the PV panel using a convergent water channel cooling. According to their study, water consumption was found to be dependent on the application of PV systems. Zeyad et al. (2018) focused on evaporative cooling using water. In their system, water was supplied from a tank by gravity to the back of the PV panel. Wu et al. (2018) built a three-dimensional numerical model of the water-cooled PV/T system with cooling channel on the PV panel. Erkan et al. (2018) investigated the cooling of a single crystalline photovoltaic cell using computational fluid dynamics method by taking water as a cooling material. Bayrak et al. (2019) experimentally investigated the performance of a polycrystalline 75 W PV panel with a cell structure in Elazığ, Turkey climatic conditions. They analyzed system performances such as temperature, power and efficiency by applying different fin parameters to PV panels. Wu et al. (2019) worked to investigate the effect of cooling channel position on heat transfer and thermoelectric behaving of air-cooled PV/T systems. Zheng et al. (2019) focused on the passive air-cooling system for PV, they showed the effect of channel geometry on the cooling performance of the system. Han et al. (2019) investigated two-dimensional numerical analysis of the fluid flow and heat transfer behaviors of the natural convection driven by the buoyancy force in the passive cooling air duct formed by the two vertical parallel walls. Piotrowskia et al. (2020) presented a technical and economic analysis of the efficiency and durability of PV panels with and without a cooling system and they observed an improvement of 3% in the cell efficiency of cooled down panels. Amber et al. (2020) evaluated the performance of the passive cooling technique by using circular and rectangular fins applied to the rear surface of the PV panels. The efficiency obtained by applying rectangular and circular fins increased by 14.5% and 13.2% compared to the reference module, respectively. As a result, the rectangular fins are decided for PV installations. Egab et al. (2020) investigated the reduction of the panel temperature using an air-cooled heat sink. The system consists of rectangular fins and rectangular fins with holes. According to the results, the temperature of the PV panel with fins decreased by 50% compared to the PV panel without fins. Arifin et al. (2020) designed an aluminum plate with perforated fins mounted to the back of the panel in order to reduce the operating temperature of the PV panel. According to CFD analysis, the average temperature of the PV panel decreased from 85.3° C to 72.8° C when 1.5 m / s of air was given to the heat sink and the electrical efficiency increased by 2.6%. Consequently, the effects of the heat sink on the heat transfer area and heat transfer performance were understood. We develop our cooling design and pursue performance analysis on a specific PV panel, selected as Panasonic N330. The PV panel cells are monocrystalline silicon and have 19.4% efficiency under standard test conditions (air mass = 1.5, Radiation = 1000 W/m^2, cell temperature = 25 °C). A cooling channel is used to cool the PV cell with the air blown by the help of a fan. The inclined PV panel is located in İzmir. In summer season, due to high radiation, cell temperature increases rapidly. Cell temperature calculations are performed with MATLAB. According to temperature rising, efficiency of PV module is decreasing. Therefore, in order to prevent this, PV panel must be cooled. For this reason, cooling channel is installed under the PV panel. Analyses with ANSYS Fluent software are performed using the solar irradiation at the time when maximum PV temperature is reached and considering cooling channels with different air velocities and different geometries. Studies in literature are primarily focused on theoretical and numerical assessments of PV cooling systems using various cooling materials such as air, water and ethanol–water mixture, as can be seen on the above literature survey. Even though there are systematic studies available in the literature that compare various channel types such as flat plate and finned plate using air, Maleki et al. (2020) stated that other forms of channels, such as zig-zag and wavy-shaped one, would be advantageous. Additionally, according to the same authors, optimization studies on the channel's geometrical qualities, as well as other operating conditions, would be advantageous in order to reach thermal solutions with environmental analysis. As far as the authors' best knowledge, the investigation of curved fins was not been performed in detail in any other study. Additionally, the main objective of this study is based on the lack of optimization studies and making performance analyses with channel design since they are new and open in development. Moreover, this study focuses on improving PV panel performance by lowering panel surface temperatures using various air channels such as flat plate, finned plate and curved plate geometries and to determine the best design. More specifically, in this study, detailed cell temperature, electricity generation and PV efficiency are investigated, the optimum channel is selected and environmental analyses are made. In the determination of the optimum channel, net electricity gain (increase in PV electricity generation minus fan electricity use to provide cooling) value was taken into consideration, which greatly makes the results more reasonable. Hence, it can be said that the present study provides a very detailed numerical analysis about the effect of the use of flat and especially curved finned cooling channels on the electricity generation performance of PVs. The evaluation of the impact of curved finned cooling channel can be considered as an addition to the literature. Moreover, considering the net electricity generation increase (electricity generation increase due to the cooling minus electricity consumption of the fan in order to provide cooling), the best cooling channel option with the best air velocity value is determined as the result of the study, which can also be considered as a novelty. Finally, the environmental analyses show the benefit of the use of solar energy in terms of sustainability and environmental friendliness of the renewable energy.

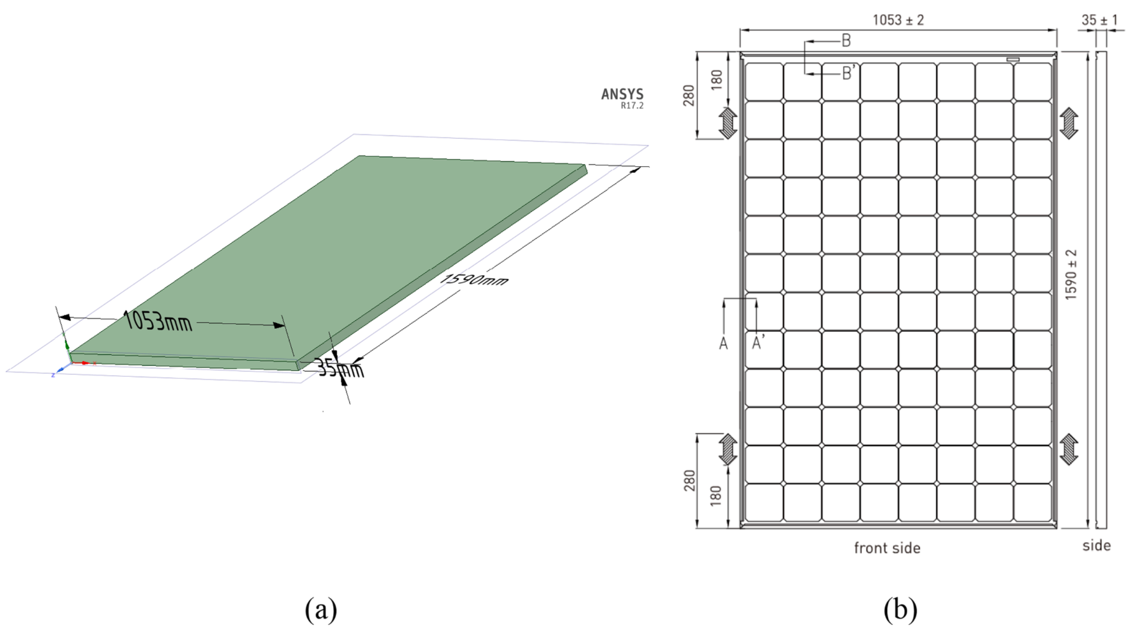


Fig. 1. Schematic description of PV panel (a) Ansys-Fluent model, (b) Dimensions of the PV panel (Panasonic Module HIT Datasheet, 2021).

2. Description of the system

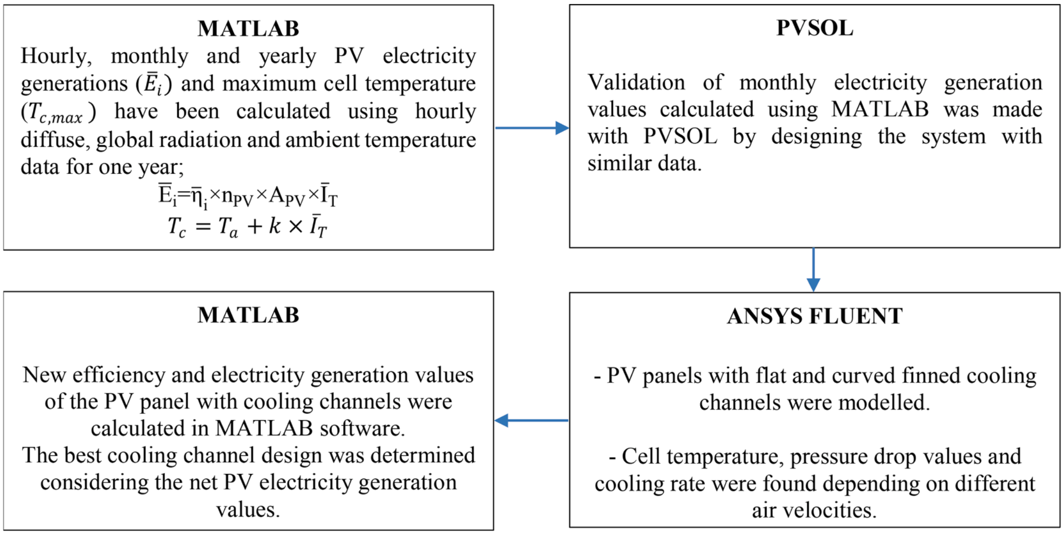
The inclined Panasonic N330 PV panel is located with 30° angle in İzmir, Turkey. Panasonic N330 has monocrystalline silicon cells and a 19.7% efficiency. PV panel has 1053 mm width, 1590 mm length and 45 mm thickness. The PV panel with cooling channel is constituted of layers of glass, airgap, PV cells, aluminum plate and cooling channel. The thicknesses of these layers are 10 mm, 20 mm, 1 mm, 4 mm and 10 mm, respectively. For all surfaces, except the upper surface, convective heat transfer with the ambient air at 25 °C is assumed. Cooling channel material is aluminum and current cooling fluid is air. The outlet pressure of the cooling channel is accepted as atmospheric pressure.

When photons from the sun arrives the PV panel, it activates electrons, causing them to separate from their atoms. If the conductors are connected to the solar cells, an electrical circuit is formed, and electricity is generated by the flow of electrons in the circuit. Electricity generation reduces the efficiency of the system by allowing cells to heat up over time. While generating electricity, air flows simultaneously through the cooling channel for the cooling process. The air sent into the cooling channel continues along the channel and takes heat from the PV panel. At the end, heated air leaves the channel and the PV panel has been cooled. The geometrical dimensions of the evaluated PV and its Ansys-Fluent model are presented in Fig. 1.

3. Analysis

In the first part of the research, a comprehensive numerical analysis of the PV panel is performed using MATLAB software to simulate time-dependent changes. Hourly diffuse, global radiation and ambient temperature data for one year were used to calculate hourly electricity generation and panel temperature values. For the design, the reference temperature was taken as 25 ^{0}C and the slope angle of the PV was taken as 30°. It is aimed to calculate the monthly electricity generation of this PV panel and to compare them with the values obtained in the PV Sol software. Consequently, the change in the cooling amount, PV electricity generation and efficiency depending on the velocity of the air supplied to the evaluated cooling channels are observed.

In the second part of the study, analyses are made using ANSYS



MATLAB

Hourly, monthly and yearly PV electricity generations ($\bar{E}_i$) and maximum cell temperature ($T_{c,max}$) have been calculated using hourly diffuse, global radiation and ambient temperature data for one year;

$$\bar{E}_i=\bar{\eta}_i\times n_{PV}\times A_{PV}\times \bar{I}_T$$

$$T_c = T_a + k \times \bar{I}_T$$

PVSOL

Validation of monthly electricity generation values calculated using MATLAB was made with PVSOL by designing the system with similar data.

ANSYS FLUENT

- PV panels with flat and curved finned cooling channels were modelled.

- Cell temperature, pressure drop values and cooling rate were found depending on different air velocities.

MATLAB

New efficiency and electricity generation values of the PV panel with cooling channels were calculated in MATLAB software.
The best cooling channel design was determined considering the net PV electricity generation values.

Fig. 2. Steps of the analyses in the present study.

Fluent software. Cooling channel designs are investigated according to the parameters calculated in the previous section. The designs are created with different geometrical shapes and different air velocities. The considered geometrical shapes of the cooling channel are flat channel, channel with flat fins and channel with curved fins. After cooling analyses in ANSYS Fluent software, air pressure drops encountered during the air flow through the cooling channel and new cell temperatures of the PV panel are recorded. New efficiencies of the PV panel and new electricity generations with cooling channels are calculated in MATLAB software. Fan powers required for the system are found. The optimal design is chosen by calculating net production by subtracting fan power required for air flow inside the cooling channel from PV electricity generation. The number of panels for a typical house roof installation is taken into consideration and environmental analyses are also performed. The procedure followed in the study is summarized in Fig. 2.

3.1. *Electricity generation analyses*

The hourly electricity generation formula and steps of the calculations are performed according to Duffie and Beckman (2013) listed by Eqs. 1–9 as follows;

- Declination Angle (δ):

$$\delta = 23.45 \times sin\left(360 \times \frac{284+n}{365}\right) \tag{1}$$

where, n is the day number in the year from 1 to 365.

- Hour Angle (w):

$$w = (Solar\ Time - 12) \times 15^{o} \tag{2}$$

where, solar time is hours of the day from 1 to 24.

- Sunset Hour Angle (w_s):

$$w_s = min\begin{bmatrix} arccos(-tan\phi tan\delta) \\ arccos(-tan(\phi-\beta)tan\delta) \end{bmatrix} \tag{3}$$

where, ϕ is latitude of Izmir and β is slope angel of PV.

- The ratio of beam radiation on the inclined surface to a horizontal surface for the collector directed south in the northern hemisphere (R_b):

$$R_b = \frac{cos(\phi-\beta)cos\delta cosw + sin(\phi-\beta)sin\delta}{cos\phi cos\delta cosw + sin\phi sin\delta} \tag{4}$$

- Hourly radiation incident of the tilted PV panel ($\overline{I}_T$):

$$\overline{I}_T = \left(\overline{I}_G - \overline{I}_d\right)R_b + \overline{I}_d\left(\frac{1+cos\beta}{2}\right) + \overline{I}_G\rho_g\left(\frac{1-cos\beta}{2}\right) \tag{5}$$

where, $\overline{I}_G$ is the global radiation, $\overline{I}_d$ is the diffuse radiation and ρ_g is ground reflection.

If $|w|>|ws| => \overline{I}_T = 0$

- Cell temperature (T_c):

$$T_c = T_a + k \times \overline{I}_T \tag{6}$$

where, T_a is the ambient temperature for each hour and k is the ventilation coefficient, taken as 0.2 (Erkan et al., 2018)

- Hourly PV efficiency ($\overline{\eta}_i$):

Table 1
Evaluated data used in calculations.

Ground Reflection	0.2
Slope Angle of PV (β)	30°
Latitude of Izmir (ϕ)	38.4
PV efficiency ($\eta_{mp,ref}$)	19.7%
Reference Temperature	25 °C
Global Radiation	1000 W/m^2
Number of PV	1
PV Area	1.67 m^2

$$\overline{\eta}_i = \eta_{mp,ref} \times \left(1 - \mu_{mp}\left(T_c - T_{ref}\right) + \delta.ln\left(\frac{\overline{I}_T}{G_{ref}}\right)\right) \tag{7}$$

where, $\eta_{mp,ref}$ is PV panel efficiency, μ_{mp} is the temperature coefficient of maximum power point efficiency which is 0.00258 and T_{ref} is the reference temperature.

- Hourly PV electricity generation ($\overline{E}_i$):

$$\overline{E}_i = \overline{\eta}_i \times n_{PV} \times A_{PV} \times \overline{I}_T \tag{8}$$

where n_{PV} is the number of PV and A_{PV} is PV area.

- Some amount of solar radiation has been absorbed by glass and PV cells. Therefore, net heat flux (W/m^2) is:

$$Heat\ Flux = Glass\ Transmissivity \times Incoming\ Radiation \tag{9}$$

Data used in PV electricity calculations are presented in Table 1.

3.2. *System and software analysis*

3.2.1. *PV simulation using MATLAB*

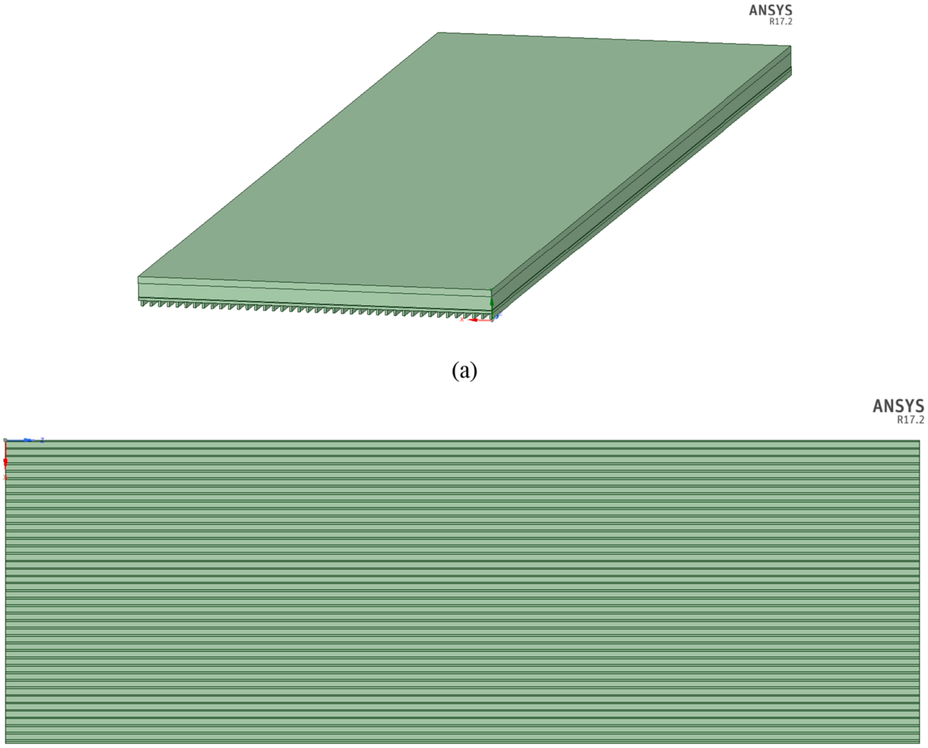
Using hourly diffuse, global radiation and ambient temperature data for one year, declination angle (δ), hour angle (w), sunset hour angle (w_s), beam radiation (R_b), hourly radiation incident ($\overline{I}_T$), cell temperature (T_c), hourly PV efficiency ($\overline{\eta}_i$), hourly PV electricity generation ($\overline{E}_i$) and maximum cell temperature ($T_{c,max}$) are calculated in MATLAB. The maximum cell temperature is encountered as 57.91 °C. These values are also compared with the results obtained from PV Sol software to make the validation of the results of the code written in MATLAB software. Moreover, the panel efficiency and electricity generation values, which depend on the new cell temperature (resulting from the created cooling effect of the channels), are calculated using the same formula.

3.2.2. *PV simulation using PV Sol software*

In PV Sol software, the system is designed with two PV panels. Set up type was 3D, grid-connected PV system and Panasonic N330 PV panels are selected. Climate data are chosen for İzmir/Çiğli covering the period of January to December 2018. The system is located on a roof with 30 °angle. A single inverter is used in the system. Cable losses are taken as 1% and there is no energy transfer from the grid to the system.

3.2.3. *Numerical model on ANSYS Fluent*

Software analyses are made based on the maximum cell temperature, which is 57.91 °C, because as it was mentioned earlier that the main aim of this study is to provide cooling which compensate the temperature rising of the PV. ANSYS Fluent analyses for the case with flat cooling channel are made for different air velocities, which are 5, 7 and 10 m/s. The air velocity value is taken as 3 and 5 m/s for the cases with flat or curved fins. Furthermore, after the determination of the cooling channel that provides the best PV panel efficiency and electricity generation, an environmental analysis is performed taking the number of panels as 30 Panasonic N330 330 W panels (the total capacity is 9.9 kW). The selection of the PV number is determined considering the installation of



(a)

(b)

Fig. 3. View of PV panel and cooling channel with 82 flat fins in ANSYS Fluent (a) Front view of half PV and cooling channel, (b) Bottom view of half PV and cooling channel.

unlicensed roof-top on grid solar power plant limit of 10 kW in Turkey. In the ANSYS Fluent software, firstly, flat plate cooling channel is taken into consideration with different air velocity values. Then, flat finned cooling channel is evaluated with different air velocities. Finally, curved finned cooling channel is taken into account with the same air velocity values. Fan power consumption values in order to supply the required air volumetric flow rate and pressure drop values are also calculated and considered. As a result, the curved finned cooling channel is found to provide the best cooling amount. In order to obtain better analysis results, as many as possible mesh elements are used and 1,717,100 and 1,816,400 and 5,281,744 meshes were generated for cooling channel with 71 flat fins, 82 flat fins and curved fins with 30 mm fin distance, respectively. Half of the system is modelled and one side surface of the system is defined as symmetry in order to be able to use finer meshes, which result in more accurate outcomes. Moreover, the heat transfer coefficient on all outer surfaces (defined as wall) is 5.8 W/m^{2}K, the heat flux on the top surface is defined as 597 W/m^2. This heat flux value is determined with the help of inclined radiation that is coming to the surface of the panel (975.97 W/m^2), the slope angle of the panel area of the PV panel (30°), absorptivity of the PV cell and transmissivity of the glass.

The model with a flat plate channel is consisted of the glass layer on the top, the air layer between the glass and the absorber, the cooling channel layer and the cooling air layer. The model view of the PV with flat fins, which includes only the half of the PV and the channel due to symmetrical conditions, is illustrated in Fig. 3. Similarly, the model with curved finned cooling channel, which includes only the half of the PV and the channel, can be seen in Fig. 4.

The main geometrical dimensions of the models with cooling channels are summarized in Table 2.

3.3. Environmental analysis

There are many reasons for using renewable energy types in the world and preferring solar energy systems is one of the best ways to contribute to a healthier environment. Solar energy is the most abundant and ready energy source and can be used unlimitedly. Also, solar systems do not necessarily need water to work, thus, it does not play a role in the consumption of water resources. Moreover, an important advantage for the environment is that it does not release chemicals such as carbon dioxide, methane and nitrous oxide to the atmosphere, and does not cause air pollution and health problems. The calculations of carbon dioxide emissions from coal and natural gas that are prevented as a result of PV panel installation are shown in the results part by using data given in Table 3.

Total amount of CO_2 emission from source;

$$Electricity\ Generation \times CO_2\ Emission\ Value \tag{10}$$

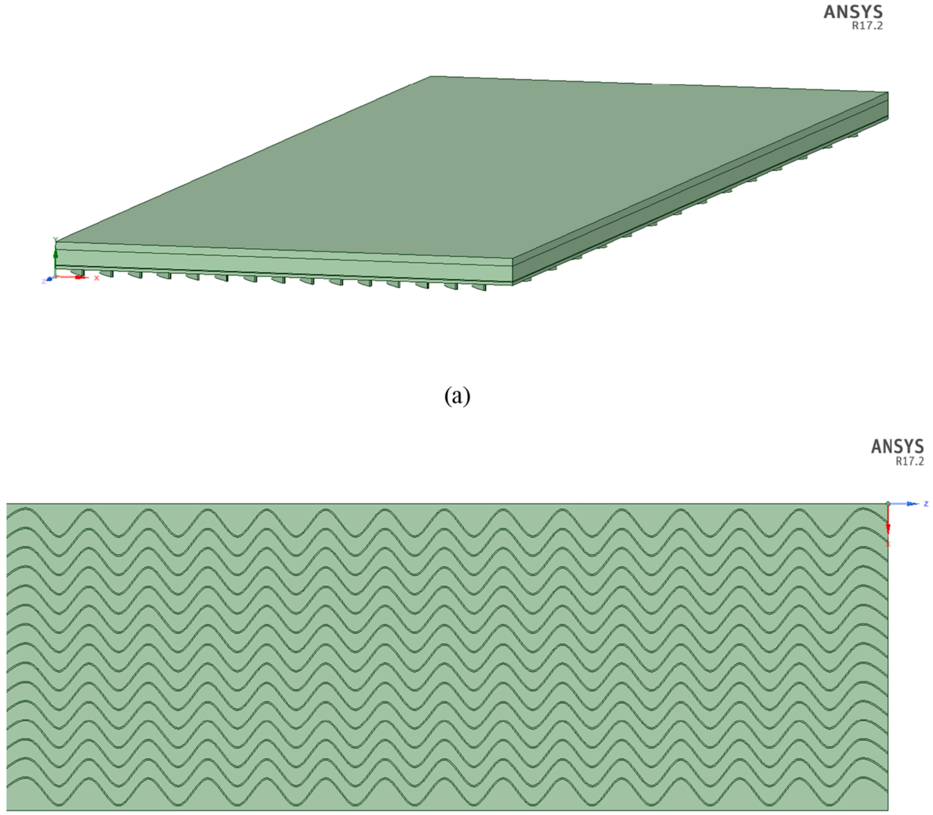
where, *Electricity Generation* in GWh and CO_2 *Emission Value* in tons/GWh.

4. Validation of the model

Baloch et al. (2015a,b) analyzed a convergent water channel cooling which aimed to obtain low and uniform temperature on the PV panel surface. They made evaluations for an uncooled PV system and a converged channel-cooled PV system due to the climate of Saudi Arabia during June and December. Before cooling the PV string, the maximum temperature was recorded as 71.2 °C and 48.2 °C in June and December, respectively.

The mesh methods applied in this study are similarly applied to the study of the Baloch et al. (2015a,b) and the obtained results are compared with their outcomes.

As it is seen in the Table 4, when water with a temperature of 27 °C is



(a)

(b)

Fig. 4. View of PV panel and cooling channel with curved fins (with 30 mm fin distance) in ANSYS Fluent (a) Front view of half PV and cooling channel, (b) Bottom view of half PV and cooling channel.

Table 2
Geometrical dimensions of the models with cooling channels.

Dimensions	Fin Type Flat		Curved
	71 fins	82 fins	
Length	1590 mm		
Thickness	5 mm	3 mm	1.5 mm
Installation spacing	10 mm		30 mm
Curvature radius	–	–	26.5 mm

Table 3
CO_2 emission values (Enerji Atlası, 2020).

Source	Approximately CO_2 emission (tons-CO_2/ /GWh)
Coal	888
Natural gas	499

Table 4
Comparison of water outlet temperatures and cell temperatures between the applied mesh methods into Baloch et al. (2015a,b)

	Water velocity (m/s)	Water outlet temperature (°C)	Cell temperature (°C)
Results of Baloch et al. (2015a,b)	0.012	30.50	45.10
Present study results	0.012	29.77	42.79

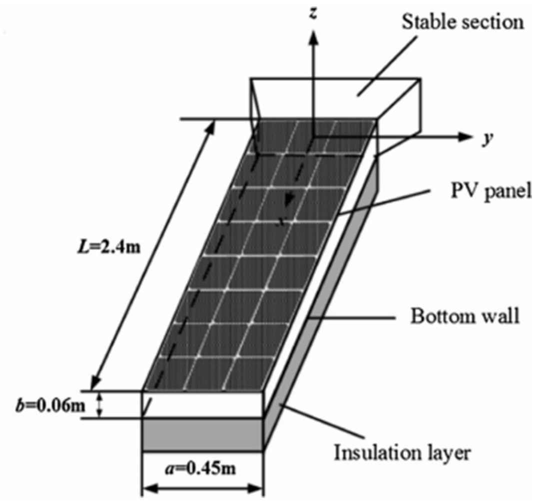


Fig. 5. Geometry of PV panel with cooling channel in the study of Wu et al. (2019).

given to the cooling channel at a velocity of 0.012 m/s, the water outlet temperature is found to be 29.77 °C, while the temperature of the cell before cooling (which is 71.2 °C) is found to drop to 42.79 °C after cooling in the applied mesh methods in Baloch et al. (2015a,b).

In the study of Baloch et al. (2015a,b), the temperature of the water entering the cooling channel at a velocity of 0.012 m/s increased from 27 °C to 30.5 °C. The cell temperature decreased from 71.2 °C to 45.1 °C. Looking at the results obtained in the present study and the values given

Table 5
Comparison of air temperatures at different locations with the results given by Wu et al. (2019)

Location	x = 0 *m*	x = 0.5 *m*	x = 1 *m*	x = 1.5 *m*	x = 2 *m*	x = 2.4 *m*
Results of Wu et al. (2019)	298.15	298.81	299.19	299.52	299.83	300.03
Present study results	298.15	298.50	298.90	299.33	299.76	300.10

by Baloch et al. (2015a,b), it can be seen that both the cell temperature and water outlet temperature values are near in both studies.

Another validation is made with the study of Wu et al. (2019). The investigated geometry view is presented in Fig. 5.

They numerically studied the effect of cooling channel location on the heat transfer properties and thermoelectric performance of PV/T systems. Air was used as the cooling fluid and air inlet temperature was 25 °C, while the ambient temperature was taken as 20 °C. Air inlet velocity to the channel was taken as 0.93 m/s and wind velocity was considered as 1 m/s. Similar mesh applications were applied to the model of Wu et al. (2019) study and 428,400 volume elements are created. The mesh number in Wu et. al (2019) was 421,200. The insulation layer is not modeled in Fluent, because the bottom surface is defined as insulation, so there is no need to draw the insulation as a volume. The wind effect is considered by defining convection to the side walls of the model. The convection coefficient is calculated as 9.5 (W/m^{2}K) using the formula given in Wu et al. (2019), which considers the wind velocity and the free steam temperature is taken as 20 °C as this is the ambient temperature.

As a result, the air temperature at different locations (namely at the inlet, at x = 0.5, 1, 1.5, 2 and 2.4 m from the inlet) were compared with the values given in Wu et al. (2019) in Table 5. It can be seen that very similar results were obtained with the ones presented in Wu et al. (2019).

The air temperature contours at the defined locations are presented in Fig. 6. The heating of air is clearly observed in this figure.

As a result of two different comparisons, it can be clearly seen that the using of the current modeling and meshing strategy gives reliable outcomes. Therefore, it can be said that the results obtained in the present investigation are reliable.

5. Results

In this section firstly, monthly electricity generation of the PV is presented (Fig. 7a). Secondly, comparison of electricity generation data calculated with MATLAB and PV Sol is made (Fig. 7b and Table 6). Next, heat transfer characteristics and temperature differences occurred during heat transfer between PV and cooling channel are examined using the calculated data from ANSYS Fluent software. Finally, all results and graphs from Fluent software are discussed.

As it is seen in Table 6, monthly electricity generation values, which are calculated in MATLAB, are almost the same as the values found by PV Sol. The maximum electricity generation is seen in July with 56 kWh. The PV reaches its maximum temperature at July 21st at 1p.m. The values about the PV and solar radiation at this time are summarized in Table 7.

When the highest cell temperature which is 57.91 °C is reached, PV panel efficiency is found to be 18%, solar radiation is seen as 975.97 W/m^2 and electricity generation is calculated as 293 W.

The effect of cooling with a flat plate cooling channel is investigated firstly using Ansys-Fluent software. The cell temperature, the PV temperature drop due to cooling, the electricity generation value as a result of the cooling effect and the relevant PV efficiency are summarized for different air velocities in Table 8. In the numerical calculations, residual values smaller than 1×10^{-3} for continuity, 1×10^{-6} for momentum equations and 1×10^{-8} were considered for the converged solution.

As it is seen in Table 8, the highest amount of cooling is provided with 10 m/s air velocity and the electricity generation is increased significantly. For the 5 m/s air velocity case, electricity generation is increased from 293 W to 302.95 W so that 3.4% increase has been happened. With 7 m/s air velocity, electricity generation is risen from 293 W to 307.01 W, which means an increase of 4.78%. Finally, with 10 m/s air velocity, electricity generation is increased from 293 W to 310.4 W so that 5.94% increase has occurred. As an expected result, when the air velocity increases, the cooling effect and hence the electricity generation increases for flat plate cooling channel. After completing flat plate analysis, different geometrical shapes for cooling channel are considered. Flat finned and curved finned cooling channel effect are investigated.

In Table 9, it is clearly seen that, the channel with flat fins provides much more cooling than the flat plate channel. The cooling effect observed with 82 fins and 3 m/s air velocity is close to the case with flat plate cooling channel with 5 m/s air velocity. Additionally, a similar cooling is achieved for the case with 71 flat fins, 5 m/s air velocity and for the case with flat plate cooling channel, 7 m/s air velocity. In the case with 82 flat fins and 5 m/s air velocity, almost the same cooling value is observed as the case with flat plate cooling channel and 10 m/s. The air velocity is limited with 5 m/s in this section considering that the flat fins

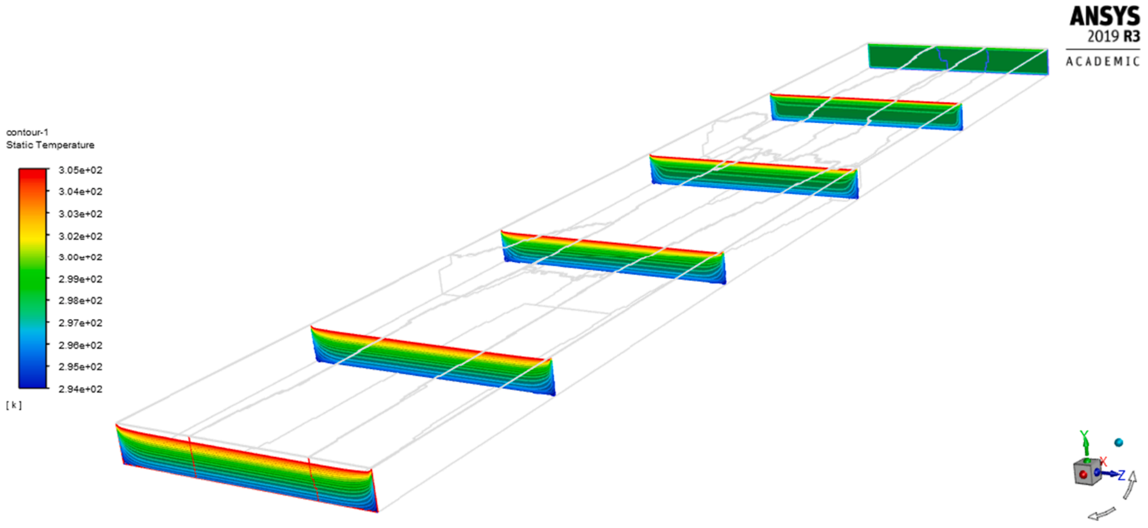


Fig. 6. Air temperature contours at the defined locations.

Financial Analysis

Return on Assets	11,02 %
Total Payment from Utility	124,64 ₺/year
Accrued Cash Flow (Cash Balance)	1.306,99 ₺

Tech. Quality of the PV System

PV Generator Energy (AC grid)	1.054 kWh/year
Spec. Annual Yield	1.596,33 kWh/kWp
Performance Ratio (PR)	82,8 %

System integration

Energy from Grid	0 kWh/year	Grid Feed-in	1.054 kWh/year

the country in which the climate data record is located.

System Type, Climate and Grid

Type of System	3D, Grid-connected PV ...
Climate Data	IZMIR/CIGLI(CV/AFB), ...
Resolution of the ...	1 h
AC Mains	230 V, 3-phase, cos φ = 1
Maximum Feed-in ...	No

3D Design

Arbitrary Building ...

Module Data	VBHN330SJ47
Manufacturer	Panasonic
Number of PV Mo...	2
PV Generator Out...	0,66 kWp
Inclination	30°
Orientation	173°
Installation Type	Mounted - Roof

Configuration

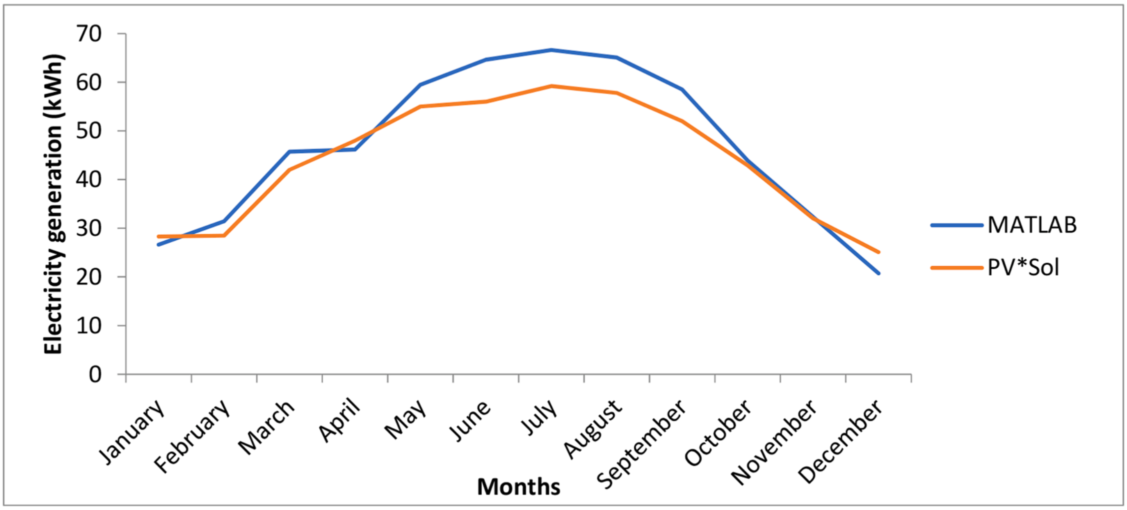
Arbitrary Building ...

1 x Inverter 1	DMI 800/50
Manufacturer	Dorfmüller
Configuration	MPP 1: 2 x 1

Cables

Total Loss	1 % (6,6 W)

(a)



(b)

Fig. 7. Comparison of monthly electricity generation based on MATLAB and PV Sol (a) Monthly electricity generation graph in PV Sol, (b) Monthly electricity generation graph in MATLAB and PV Sol.

Table 6
The comparisons of electricity generation values between MATLAB and PV Sol

Months	MATLAB	PV Sol
January	26.61 kWh	28.3 kWh
February	31.42 kWh	28.5 kWh
March	45.73 kWh	42 kWh
April	46.18 kWh	48 kWh
May	59.51 kWh	55 kWh
June	64.63 kWh	56 kWh
July	66.60 kWh	59.2 kWh
August	65.07 kWh	57.8 kWh
September	58.50 kWh	52 kWh
October	43.91 kWh	42.9 kWh
November	32.30 kWh	32 kWh
December	20.73 kWh	25.1 kWh
Total	561.19 kWh	526.8 kWh

Table 7
MATLAB result for the day in which maximum PV temperature is encountered.

At Maximum Cell Temperature: 57.91 (°C)	
PV Efficiency (%)	18
Solar Radiation (W/m^2)	975.97
Electricity Generation (W)	293

will create high pressure drop if the air velocity is increased more. Additionally, as nearly the same amount of cooling with the flat plate is achieved with a slower air speed when the fins are used, higher air velocity values are considered unnecessary as they can dramatically increase the needed fan power consumption.

In Fig. 8, the temperature distribution on the PV module is given. As, symmetry condition is taken in the model, the right surface represent the middle area of the PV.

Table 8
Comparison of the results for air velocities of 5 m/s, 7 m/s and 10 m/s for the case with flat plate cooling channel.

Inlet Velocity (m/s)	Cell Temperature (°C)	PV Temperature Drop (°C)	Electricity Generation (W)	PV Efficiency (%)
5	46.40	11.51	302.95	18.59
7	41.49	16.42	307.01	18.84
10	37.40	20.51	310.40	19.04

As it is seen in Table 10, if curved finned cooling channel is mounted to PV module assembly, higher cooling effect is reached. It can be seen that the PV efficiency takes a higher value than 19%, when the air velocity is 5 m/s. The curved shape of the fins provides a longer way for the air inside the cooling channel and the disturbance effect makes the heat transfer even higher compared to flat fins. In this part of the study, the same air velocity values are used as the ones used in flat fins part of the study. At the first look, it can be said that the use of curved fins is more advantageous as they provide higher cooling effect and thus higher electricity generation. The values calculated for the flat plate, flat fins and curved fins are summarized in Table 11.

For each cooling channel design, a decrease in cell temperature is observed when the air velocity increases. Consequently, electricity generation and panel efficiency are increased. The highest panel efficiency, which is 19.08%, is reached with curved finned cooling channel.

Even though the increasing air velocity increases the electricity generation of the PV, it also increases the air pressure drop through the cooling channel. The net electricity generation increase should also be taken into account by considering the electricity consumption of the fan to supply the required air volumetric rate with the required pressure

Table 9
Comparison of the results with 3 m/s and 5 m/s air velocities for flat finned cooling channel.

	Inlet Air Velocity (m/s)	Cell Temperature (°C)	Temperature Difference (°C)	Electricity Generation (W)	PV Efficiency (%)
71 Fins	3	49.74	8.17	300.18	18.42
	5	41.36	16.55	307.12	18.84
82 Fins	3	47.48	10.43	302.05	18.53
	5	39.82	18.02	308.40	18.92

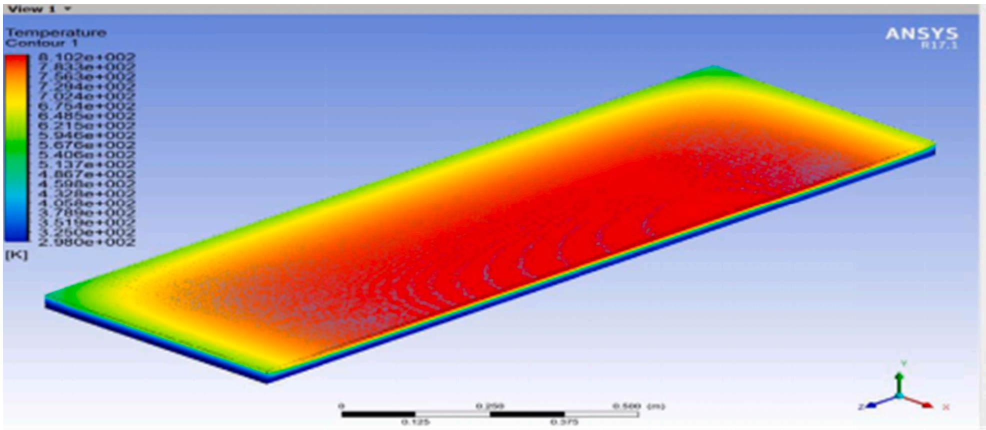


Fig. 8. Temperature contour of the PV module with 82 fins for 5 m/s in ANSYS Fluent.

Table 10
The results with 3 m/s and 5 m/s air velocities for curved fined cooling channel.

Fin Distance (mm)	Inlet Velocity (m/s)	Cell Temperature (°C)	Temperature Drop (°C)	Electricity Generation (W)	PV Efficiency (%)
30	3	42.61	15.30	306.09	18.78
	5	36.66	21.25	311.01	19.08

Table 11
The results of all types geometry.

	Inlet Velocity (m/s)	Cell Temperature (°C)	Temperature Drop (°C)	Electricity Generation (W)	PV Efficiency (%)
Flat Plate					
	5	46.4	11.51	302.95	18.59
	7	41.49	16.42	307.01	18.84
	10	37.40	20.51	310.40	19.04
Flat Fins					
71 Fins	3	49.74	8.17	300.18	18.42
	5	41.36	16.55	307.12	18.84
82 Fins	3	47.48	10.43	302.05	18.53
	5	39.82	18.02	308.40	18.92
Curved Fins					
30 mm	3	42.61	15.30	306.09	18.78
	5	36.66	21.25	311.01	19.08

Table 12
Pressure Drops, Volumetric Flow Rate and Required Fan Power according to the all types of geometry.

Channel Geometry	Pressure Drop (Pa)	Volumetric Flow Rate (m^3/s)	Fan Power (W)
Without fins (5 m/s)	56.83	0.05265	2.99
Without fins (7 m/s)	96.97	0.07371	7.41
Without fins (10 m/s)	175.05	0.10530	18.43
With 71 fins (3 m/s)	58.49	0.01156	0.67
With 71 fins (5 m/s)	126.41	0.01970	2.49
With 82 fins (3 m/s)	56.15	0.01284	0.72
With 82 fins (5 m/s)	121.25	0.02140	2.59
30 mm (3 m/s)	415.78	0.01525	6.34
30 mm (5 m/s)	1124.55	0.02542	28.58

value. In Table 12, the required fan power for different cases are given.

Pressure drop values are calculated with ANSYS Fluent Software by taking difference of inlet and outlet pressure values of air into consideration.

$$\Delta P(Pa) = P_{outlet} - P_{inlet} \tag{11}$$

The calculations of the required fan power and net electricity generation are calculated as;

$$Fan\ power(W) = \Delta P(Pa) \times \dot{V}(m^3/s) \tag{12}$$

$$Net\ generation = Electricity\ generation(W) - Fan\ power(W) \tag{13}$$

From Table 12, it can be clearly seen that even though the increase in heat transfer provides a high electricity generation efficiency for the case with curved fins, the increasing air pressure drop may surpass this increase as there will be a high fan electricity consumption. For this reason, the net electricity generation increase for each case is investigated in order to see which case is optimum. The net electricity generation for all investigated cases are summarized in Table 13.

The results presented in Table 13 show an interesting point. Although the use of curved fins provides higher PV electricity generation values, the maximum net electricity is accomplished with the use of cooling channel with 82 flat fins. The reason of this is that fan power depends on pressure drops and volumetric flow rate in the air channel. Moreover, pressure drops increase with increasing air velocity. In the study, the required fan power increased when the number of fins is increased for the same air velocities and when the curved fin air channel geometry is used. The highest fan power was observed when curved fin geometry is used and 5 m/s air velocity is given. Because the pressure drop increases depending on the air velocity and therefore more fan power is needed. It is concluded that the most efficient cooling channel design is the one with 82 flat fins with 5 m/s air velocity. This design provides a net electricity generation of 305.81 W, which represents a 4.37% increase compared to 293 W with the PV with no cooling channel.

For 30 PV panels without cooling channel, annual electricity generation is calculated as 16,835 kWh. A 3.37% yearly loss assumption is made. The annual electricity generation for 30 PV panels with cooling channel (82 fins and 5 m/s air velocity) is calculated as 17,400 kWh.

888 tons of carbon dioxide emerges as a result of burning coal for 1 GWh electricity generation in coal-based power generation plants. By putting a cooling channel, 506.2 kg coal based, or 270 kg natural gas-based carbon dioxide emissions are prevented compared to the case without cooling channel. Considering the use of 30 PVs with a cooling channel with flat fins, 15,451.2 kg coal based and 8,682 kg natural gas-based CO_2 emissions are prevented, respectively, while 17,400 kWh electricity is generated for an unlicensed PV panel station. In the case of PV use without cooling channel, 14,945 kg coal based and 8,390 kg natural gas-based CO_2 emissions can be prevented, respectively, with 16,835 kWh electricity generation, as can be seen in Fig. 9.

6. Conclusion

In this study, the monthly electricity generation, panel efficiency, solar radiation and cell temperatures are found in MATLAB software by using the hourly solar and temperature data of 2018 for İzmir, Turkey. The cooling channel is designed by adhering to the highest cell temperature. It is observed how much electricity generation and panel efficiency increase can be achieved depending on the drop in cell temperature by sending air at different velocities to this channel by performing simulations in ANSYS Fluent software. Different geometrical shapes for the cooling channel are tried such as the plate channel, the channel with flat fins and the channel with curved fins. At the end, higher cooling effect is observed on the PV with these new channels. Pressure drop values are also discussed.

As a conclusion, it is observed that, it is possible to cool the PV with curved finned cooling channel more than with the flat finned cooling channel. It is also observed that the maximum cooling of the PV panel is encountered with the cooling channel design with curved fins and 5 m/s air velocity. In this case the temperature of the PV is decreased to 36.66 °C from its maximum cell temperature, which is recorded as

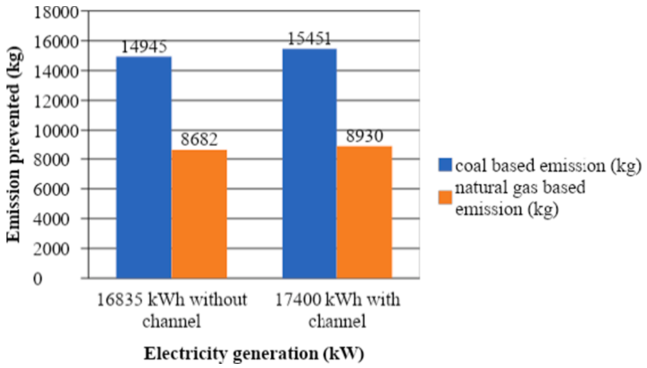


Fig. 9. Prevented emission values using PV panel with and without cooling channel.

Table 13
Net Electricity Generation of all types of geometry.

Channel Geometry	Without cooling	Without fins (Flat channel) (5 m/s)	Without fins (Flat channel) (7 m/s)	Without fins (Flat channel) (10 m/s)	With 71 flat fins (3 m/s)	With 71 flat fins (5 m/s)	With 82 flat fins (3 m/s)	With 82 flat fins (5 m/s)	With Curved fins (3 m/s)	With Curved fins (5 m/s)
Electricity Generation (W)	293	302.95	307.01	310.40	300.18	307.12	302.05	308.40	306.09	311.01
Fan Power (W)	–	2.99	7.41	18.43	0.67	2.49	0.72	2.59	6.34	28.58
Net Generation (W)	–	299.96	299.60	291.97	299.51	304.63	301.33	305.81	299.75	282.43

57.91 °C. However, the maximum net electricity generation is found for the case with the cooling channel with 82 flat fins and 5 m/s air velocity, when the fan power requirement is taken into account. The higher pressure drop values created by the curved fins make this design less efficient.

Lastly, the use of solar energy decreased CO_2 emissions significantly. The PV with the cooling channel with 82 fins can prevent 15,451.2 kg coal based and 8,682 kg natural gas-based CO_2 emissions, respectively.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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