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Experimental analysis of a cooling system effect on photovoltaic panels' efficiency and its preheating water production

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Highlights

A high reliability-low complexity PV/T is developed to reach high overall efficiency.

The cooling system does not impose water head losses and water waste.

Equipping a PV with the water coolant enhances PV efficiency from 10.9% to 12.3%.

The measured data reveals the average thermal efficiency of PV/T is around 49.4%.

The payback period in the given boundary conditions is estimated 1.7 years.

Abstract

This paper addresses a low complexity and high efficient cooling system applicable on photovoltaic (PV) system leading to enhance electrical efficiency and provide preheated water. The developed system consists of a PV, a cooling water system establishing a uniform surface temperature, and a solar water heater. According to the proposed system characteristics, the setup is constructed based on a single mono-crystalline solar panel to absorb more solar radiation intensity and generate more electrical energy per area in compare to a poly-crystalline panel. The preheated water produced by absorbed heat from the photovoltaic is conducted to a solar water heater to satisfy domestic hot water demand. The experimental results show the electrical, thermal and overall energy efficiencies are boosted to 12.3%, 49.4%, and 61.7%, respectively. The results are obtained on July in Tehran, Iran. Moreover, comparing the performance of the cooling system with the conventional systems reveals that the proposed system has higher efficiency originated from the uniform minute holes in the implemented shower stuck on the panel back. Furthermore, if the heat transferred to water in the cooling system is utilized, the payback period is estimated 1.7 years; otherwise, the payback period exceeds 8.7 years if only PV conversion efficiency is included.

Keywords: Payback period; Photovoltaic/Thermal Systems; Renewable Energy; Solar Energy.

Introduction

Trends of energy consumption, global warming, air pollution, greenhouse gas emission, depletion of fossil energy resources, and the fluctuations in fossil fuel energy prices lead to increase the share of renewable energies in energy supply systems. In the meantime, one of the most accessible and clean renewable energy sources is solar energy. The main application of solar energy has allocated to heat generation via thermal collectors, and electricity generation via photovoltaic systems. Although the use of solar energy has been increased, there are some obstacles that influence on the share of solar energy carrier among the other energy carriers, such as high capital cost, low efficiency and requiring storage systems (such as batteries) due to the difference between supply and demand curves. A large number of research papers have been published on photovoltaic/thermal (PV/T) collectors since 1970s to overcome the barriers [1].

A PV/T collector consists of photovoltaic and solar thermal systems producing electricity and heat simultaneously. The conversion efficiency improvement is attained through lowering PV surface temperature. The heat removed from the panel might be transferred to water or air collection for utilization unit [2]. The primary merits of PV/T collectors can be mentioned that are higher energy efficiency per the area, integration of heat and power generation as well as lower capital cost coincided with two independent systems.

Several experimental and theoretical studies about PV/T collectors have been carried out. Most studies have been conducted to improve PV electrical efficiency and its thermal efficiency. A comprehensive review on the hybrid PV/T solar collectors has been carried out by T. T. Chow [2]; the following research focused on analysis of problems, models, and experimental results that conducted by H. A. Zondag et al. [3], D. W. de Vries [4], P.G. Charalambous et al. [5]. Furthermore, C. Lamnatou and D. Chemisana [6] investigated the aforementioned studies with the emphasis on the environmental aspects.

J. Prakash et al. [7] studied a hybrid PV/T solar system from a theoretical viewpoint. In this system, air and water are directed to a duct placed below the solar panel surface; as a result, the temperature of solar panel will be reduced by extraction of heat from the panel. Thereby, the electrical efficiency is enhanced noticeably by the applied mechanism. It is concluded that the thermal efficiency varies in a range of 50% to 67% while water is used as the cooling fluid. The mentioned improvement is reduced in a range of 17% to 51% if the cooling water is substituted with cooling air. The lower heat transfer rate between the absorber plate and the flowing air in compare to the water causes the decrement in the thermal efficiency. H. Saitoh et al. [8] did experimental and analytical research on simultaneous power and heat generation with a hybrid solar collector. The result demonstrates that electrical conversion efficiency is around 10%-13%. In case of brine temperate around 20C, the collector efficiency and overall efficiency (electrical conversion efficiency + collector efficiency) are obtained 40-50% and 50-60%, respectively, while if the brine temperature reaches 40C, the collector efficiency and overall efficiency decrease to 20% and 30%, respectively. The study shows that the hybrid collector has the advantage of higher exergy efficiency. S. Dubey and G. N. Tiwari [9] developed an integrated combined system of a PV/T solar water heater customized for New Delhi climate. It is observed that PV/T with flat plate collector partially covered with PV module has better thermal and average cell efficiency. Moreover, distinguishable enhancement in the efficiency from 33% to 64% is achieved due to glazing area increment. M. Abdolzadeh and M. Ameri [10] developed a PV/T water collector set up to increase the flow rate of a photovoltaic water pumping system that is performed by spraying water over the photovoltaic cells. Experimental results demonstrate that spraying water over the cells increases the performance indexes. The improvement of average PV cell efficiency, subsystem efficiency, and total efficiency are reported 3.26%, 1.40%, and 1.35%, respectively. Improving PV electrical efficiency transfers a higher power to the pump that means increasing water flow rate. Coupling a PV with the suggested cooling system, to a pump, can provide 644L/h flow rate at 16m head, while if the cooling system is inactive, the flow rate drops to 479L/h at 16m head. F. Sarhaddi et al. [11] quantify the thermal and electrical indexes of a typical PV/T air collector. Some corrections are done on heat loss coefficients for improving the PV/T air collector thermal model. The result exhibits that overall energy efficiency of PV/T air collector reaches 45%. A. Fudholi et al. [12] investigated the energy generated by PV/T water collector in the condition that solar radiation is about 500-800$\frac{W}{m^2}$. The results reveal that PV electrical efficiency, PV thermal efficiency, and the PV/T water collector can reach to 13.8%, 54.6% and 68.4%, respectively when the water flow rate is 0.041 kg/s and solar radiation is on the maximum solar radiation ($800\frac{W}{m^2}$). A. Ibrahim et al. [13] designed a building integrated PV/T system to produce both electricity and hot water which is implemented in a building. It should be mentioned that this paper was based on energy efficiency, exergy efficiency, and potential of exergetic improvement according to the metrological condition of Malaysia. The results demonstrate that the PV/T energy efficiency varies between 55% and 62%. Furthermore, the variation of PV/T exergy efficiency is from 12 to14%. C. Colangelo et al [14] developed a thermal analysis of a new PV/T solar panel using RADTHERM THERMOANALITICS software. Several combinations of water flow rates and different panel configurations have been investigated to determine the best performance in terms of optimal PV efficiency and available thermal energy. G. Popovici et al. [15] developed a numerical model to investigate effect of air cooled heat sinks on PV conversion efficiency improvement. The heat sink that is attached at the back of PV panel is composed from a ribbed wall with specific dimensions. The results reveal in case of equipping 80W PV with 16% nominal efficiency with the best configuration of the air cooled heat sink designed in the paper, the efficiency improvement is around 7.6%. The results presented is obtained at solar radiation $500\frac{W}{m^2}$. G. S. Nizˇetic´ et al. [16] developed a cooling system spraying over both sides of the panel. The improved electrical efficiency of a mono crystalline photovoltaic is reported 16.3% when the temperature decreases from 54C to 24C and the both sides of PV are cooled down. While if the back surface is cooled down, the efficiency improvement is reached 14%. M. Proell et al. [17] presented a novel concept for improving the thermal efficiency of PV/T through concentrating sunlight with compound parabolic concentrator reflectors to attain a higher radiation power. The experiments were implemented at ZAE Bayern in Garching, Germany. The results exhibit the thermal efficiency of equipped PV/T with maximum power point tracking is enhanced to 34% thermal efficiency in compare to a glazed flat plate PV/T with 17% thermal efficiency when there is 60K temperature difference between ambient and the collector although the electrical efficiency drops noticeably from 15% to 9% because of temperature increment and a non-uniform flux distribution caused by the reflectors. R. Tripathi and G. N. Tiwari [18] developed a single experimental set up which was fully covered with concentrated PV/T collector. This experiment was done with the objective of achieving both thermal and electrical energy at the same time in IIT Delhi, India. Two cases are taken into account on the basis of receiver rotation regarding sun movement. The first case is allocated to a fixed position and the second is the manual maximum power point tracking technique. As expected, the second case shows a better performance. Furthermore, the thermal energy difference between the second case and the first case is 25%, while the exergy difference is around 19%.

Although utilizing cooling systems on PV can enhance the electrical efficiency and as well as give an opportunity to have a heat source, penetrating these systems depends on their return ratio. Some studies consider payback period, such as following:

S. Tselepis and Y. Tripanagnostopoulos [19] studied an economic analysis of hybrid PV/T and comparison with standard PV module for a domestic system in climate condition of Athens, Greece. The results demonstrate that the payback period for ac-Si PV system and a-Si PV system is 25 and 29 years, respectively; whereas they are shortened to 10 and 6 years in the case that the panels are integrated with the thermal system, respectively. J. J. Michael et al. [20] carried out a brief overview on the different solar flat plate PV/T technologies. The energy payback period of the PV/T system in the Italian climate would be 2 years, compared with 4.3 years for the solar thermal collector and 3.4 years for the PV system.

Besides the abovementioned considerations in association with equipping PV with a cooling system, the challenging issues and the obstacles should be observed. The conventional problems are access to water (in order to lower PV cell temperature) and as well as hot water demand especially in the case of PV power plants, concern about isolating water from electric junctions, difficulties originated from integrating the system to the fossil fuel fired water heater and restrictions in transportation due to fragility insulation layer injected in the cooling system. Moreover, some cooling systems [10,16] disperse/spray water on PV glass that leads to emerge tracks on the glass due to water minerals, that causes the PV conversion efficiency might be dropped out because of reducing irradiation to the cells and loading effect originating from non-uniform tracks. In addition, cleaning the tracks and water vapored from the glass impose operational costs.

This research is oriented to explore the electrical and thermal performance of a new PV/T system on the outdoor solar test facility at Sharif Energy Research Institute (SERI) in Tehran, Iran. Thereby, an experimental setup of PV/T is constructed based on a single mono-crystalline solar panel which a rectangular container has been attached to the back of it. The container is equipped with the uniform minute holes on the implemented shower stuck on the panel back in order to extract higher heat from the panel. Besides, a single solar water heater was constructed for this project and integrated into the system to compensate for the lack of heat that is required for sanitary hot water. Moreover, the study is targeted to introduce a commercial product customized for remote areas, since the PV/T design has harmony with the area conditions and requirements. As known, energy carrier transmission costs to low population remote areas with no economic justification is a barrier for the areas to have access to national electricity/gas Networks. Providing access to energy carriers is a key factor in the sustainable development of the regions especially through available renewable energy resources in those regions. Therefore, the integrated system should comprise the following properties:

1) Supplying heat and electrical energy demanded: a part of the required heat for sanitary hot water is provided through water cooling the photovoltaic panel. The water outlet from cooling system as water preheated, is directed to a solar water heater (that have effect on the solar water heater dimensions. It is equivalent to the investment cost reduction of the solar water heater) or a water heater using fossil fuel (Fuel consumption saving and in consequence of it, operational cost reduction are resulted in).

2) High reliability with negligible maintenance cost: During 13 year lifespan estimated for the cooling system, it should not require planned maintenance (expect limited cleaning programs).

3) Low capital cost: the investment cost should be inexpensive enough to compete with the conventional fossil energy conversion technologies.

Moreover, the stated properties for a coolant system to be installed in remote areas, it should have low head losses unlike coolant systems spraying water on PV surfaces and as well as negligible water consumption unlike coolant systems spraying water on front PV surface, open loop coolant systems or coolant systems that cooling water is in exposed to atmosphere. Briefly, the distinction between the coolant system developed in the study and similar coolant systems, are lower head losses (therefore there is no need to consume energy to supply the required pressure), zero water consumption in the coolant system (no water is wasted or vaporized during cooling PV), high efficiency, higher reliability (due to low complexity design) and its economic justification.

Methodology

The short-circuit current I_{sc} and the open-circuit voltage V_{oc} are two key characteristics of the I–V curve for a PV module. Changing in the incident solar irradiance and the ambient air temperature influences on I_{sc} and V_{oc} parameters. The open-circuit voltage increases just a little with increasing solar irradiance and decreases with raising module temperature which causes decreasing in the maximum electrical power remarkably. On the other hand, short-circuit current increases a little with increasing module temperature. Therefore, it is crystal clear that fluctuation in solar irradiance and module temperature changes the electrical efficiency of the PV module [21]. As a result, decreasing the panel surface temperature by water or air flow is an effective way in order to increase the electrical efficiency of the photovoltaic panel.

Many models have been developed to estimate the nonlinear behavior of PV, one of the popular models is an equivalent single diode circuit. According to the model as explained in [10, 11], PV module electrical behavior is described by quantifying the light current (I_L), the diode current (I_D), the shunt current (I_{sh}), and the saturation reverse current (I_0). Equations (1) to (8) are to compute the mentioned parameters:

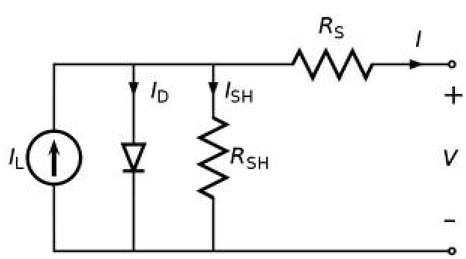

Fig. 1. equivalent single diode circuit [11]

$$I_{pv} = I_L - I_D - I_{SH} \quad (1)$$

$$I_{pv} = I_L - I_O \left[\exp\left(\frac{V_{pv}+I_{pv}R_S}{V_t}\right) - 1\right] - \frac{V_{pv}+I_{pv}R_S}{R_{SH}} \quad (2)$$

$$V_t = \frac{kt}{e} \quad (3)$$

Where t, k, and e are the absolute temperature of the cell, the Boltzmann's constant (1.381e-23 J/K) and the electron charge (1.602e-19 J/V), respectively. The equation (4) can be substituted with equation (2) when the below assumptions are applied.

I. The resistance (R_{SH}) paralleled with current supply is ignored
II. The PV current (I_L) and short-circuit current (I_{SC}) are equal
III. Expression of $\exp\left(\frac{V_{pv}+I_{pv}R_S}{V_t}\right)$ is much greater than zero.

$$I_{pv} = I_L - I_O \left[\exp\left(\frac{V_{pv}+I_{pv}R_S}{V_t}\right)\right] \quad (4)$$

Open circuit voltage is estimated by equation (5)

$$V_{OC} = V_t \ln\left(\frac{I_{SC}}{I_O}\right) \quad (5)$$

Finally, the PV current is determined by putting equations (5) in equation (4):

$$I_{pv} = I_{SC} \left[1 - \exp\left(\frac{V_{pv} - V_{OC} + I_{pv}R_s}{V_t}\right)\right] \quad (6)$$

The equation (6) states that photovoltaic cell current depends on the output voltage and radiated light on the photovoltaic surface. The short-circuit current is a function of light intensity that is computed by equation (7).

$$I_O = I_{SC} \exp\left(-\frac{V_{OC}}{V_t}\right) \quad (7)$$

$$I_{sc}(G) = \frac{I_{sc-r}}{G_r} G_{eff} \quad (8)$$

WhereI_{sc-r}, G_r and G_{eff} are the short-circuit current, the light intensity at standard conditions and effective radiation intensity, respectively.

The voltage operation is considered a linear function of temperature calculated by equation (9).

$$V_{oc-pv}(T_c) = V_{oc-r} + (T_c - T_{c-r})\mu_{voc} \tag{9}$$

In above, V_{oc-r} and μ_{voc} are standard voltage and voltage temperature coefficient, respectively, given by its manufacturer. T_C is collector temperature that can be calculated by equation (10)

$$T_C = T_a + \frac{(NOCT - T_o)}{800\ {}^{W}/_{m^2}} \times G_{eff} \tag{10}$$

Where NOCT is operating temperature given by the manufacturer. Finally, the panel efficiency is calculated according to the equation (11)

$$\eta = \frac{I_{pv}\ V_{pv}}{A\ G} \tag{11}$$

Where G is solar radiation intensity $[\frac{w}{m^2}]$ and A is panel area $[m^2]$. In addition, the thermal energy efficiency is calculated by equation (12).

$$\eta_{th} = \frac{\dot{m}\ C\ (T_f - T_{in})}{A\ G} \tag{12}$$

Where $\dot{m}, T_f, T_{in}, C,$ and S are the amount of input water flow rate to the panel, the output water temperature of the panel, the input water temperature to the panel, the heat capacity of water and the hybrid collector area, respectively. The solar water heater efficiency can be calculated by equation (11) if the required parameters related to the solar water heater are substituted in the equation (11).

Experimental set-up

The experiment has been carried out in Tehran, Iran (35.6892° N, 51.3890° E), on July. The experiment is performed by a PV module with 36-mono crystalline cells. The PV specification is listed in Table 1.

Measurement equipment

The hourly solar radiation power was reported by Iran Meteorological Organization on July. In addition, the hourly temperature is measured by a data logger system with DS18b20 temperature sensors that the resolution for all temperature sensors is configured on 12 bits. The measurement was performed on the top, bottom, and middle of the PV/T collector. So, the average of them was estimated as the final measurement.

Table 1: Specification of PV module

Characteristics	Value
Cell type	Mono-crystalline Si
Model name	NE-080T1J
Number of cells	36
Maximum power rating(P_{max})	80.0 W
Short circuit current(I_{Sc})	5.15 A
Open circuit voltage(V_{oc})	21.6 V
PV Efficiency	12.5%
Voltage at point of maximum power (V_{mpp})	17.3 V
Current at point of maximum power (I_{mpp})	4.63 A

Preparing the container is the most effective step to design the hybrid system for directing water to the coolant. Three possible materials were investigated through three defined criteria for fabricating the container (copper, aluminum, and iron). The criteria are thermal conductivity, density and capital cost of the metal. Regarding the criteria, the container made of aluminum was selected (copper container has the highest density and price among three containers. Moreover, the iron container has the second rank in density and the lowest thermal conductivity among three containers).

The container dimensions are 0.9(m)*0.45(m)*0.01(m) that is placed in the PV frame below the PV terminal in order to isolate electrical junctions from the water. The silicone glue is used to connect the container to the back of PV due to its high adhesion and the low heat resistance. In addition, the shower is connected with minute holes to the back of the container in order to possess maximum possible surface in exposed to cooling water and sprinkling the entire the back of the panel uniformly. The schematic diagram of the

PV/T panel is given by fig. 2. It should be mentioned that input water entered to the panel through the shower with minute holes from the top of the panel and flow to the bottom of it. The output water from the bottom flows through the solar water heater with $0.5\ m^2$ effective area. As a result, this system is configured to absorb and transfer heat from the solar panel in order to keep the panel at the desired temperature.

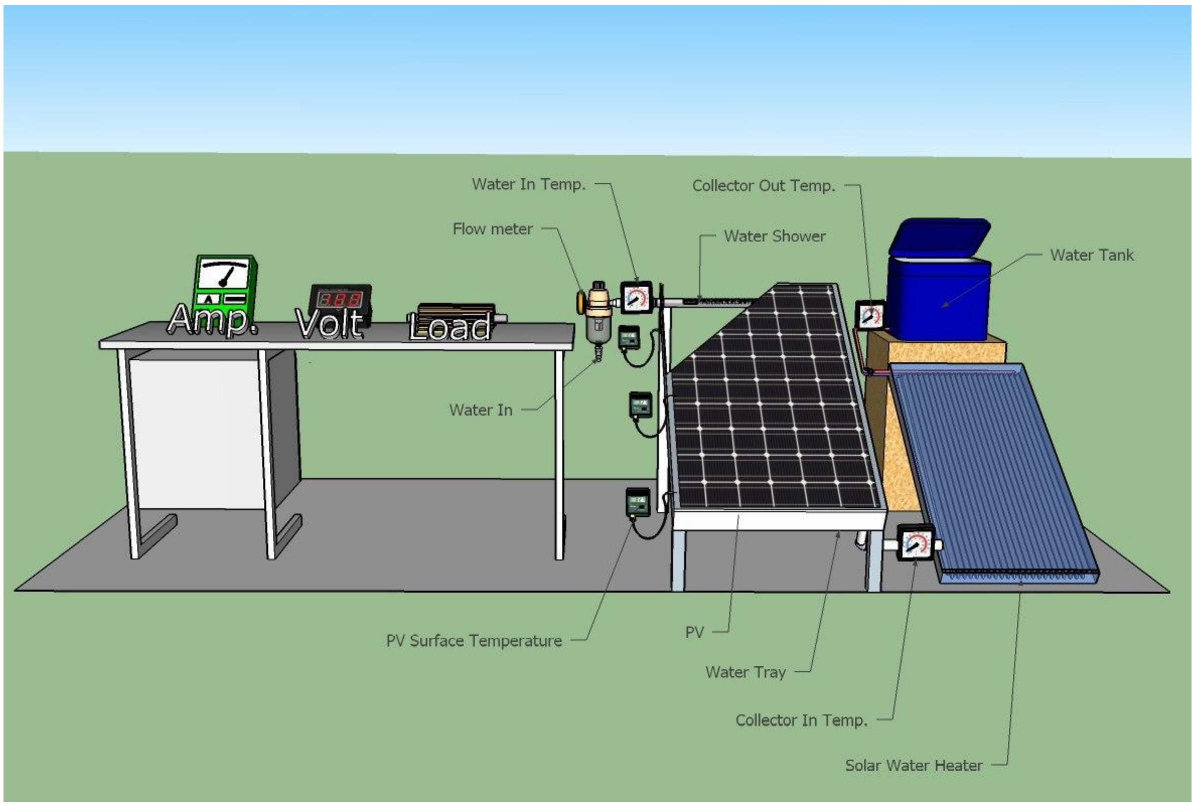

Fig. 2. Schematic of the system

Fig. 3 Shows the photograph of the experimental system where it is installed at the roof of SERI. In addition, the PV/T was installed with a 31°tilting angle relative to the horizontal plane facing south. So, preheated water is flowed in the water heater and moved toward the storage box with a 50 liter capacity for storing hot water.

Fig. 3. PV/T collector system

Results

The experimental results of the PV/T system in Tehran's climate are presented in the following. The coolant system effect on the electrical efficiency of the photovoltaic panel is quantified. Moreover, PV/T collector produces hot water to be consumed by medium-sized family while the generated electricity was connected to a dummy load as well via DC/AC inverter. Fig. 4 comprises the total solar radiation falling on the PV modules.

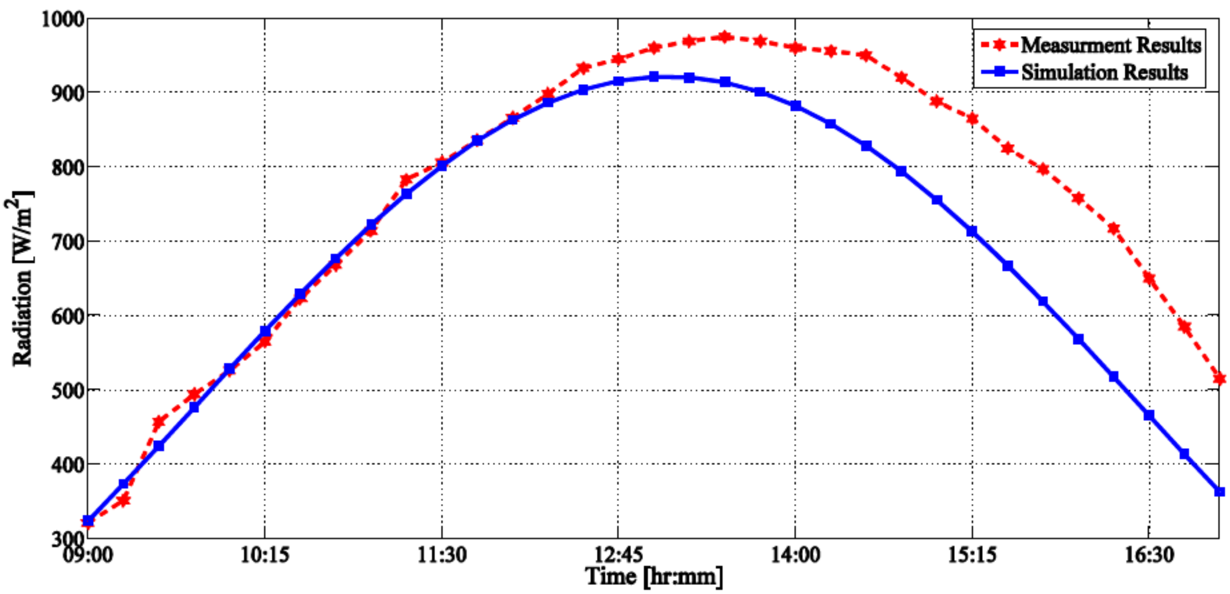

Fig. 4. The total solar radiation on a typical day

As seen in the above figure, there is a noticeable difference between the simulation results and measurements after 12 p.m. that originates from the heat accumulated on the sensor that influences on stating a higher irradiation than the reality.

Fig. 5 envisages effect of the coolant on the PV power. The power varies during the day. It reaches its maximum at 1 p.m. when global irradiance reaches its maximum.

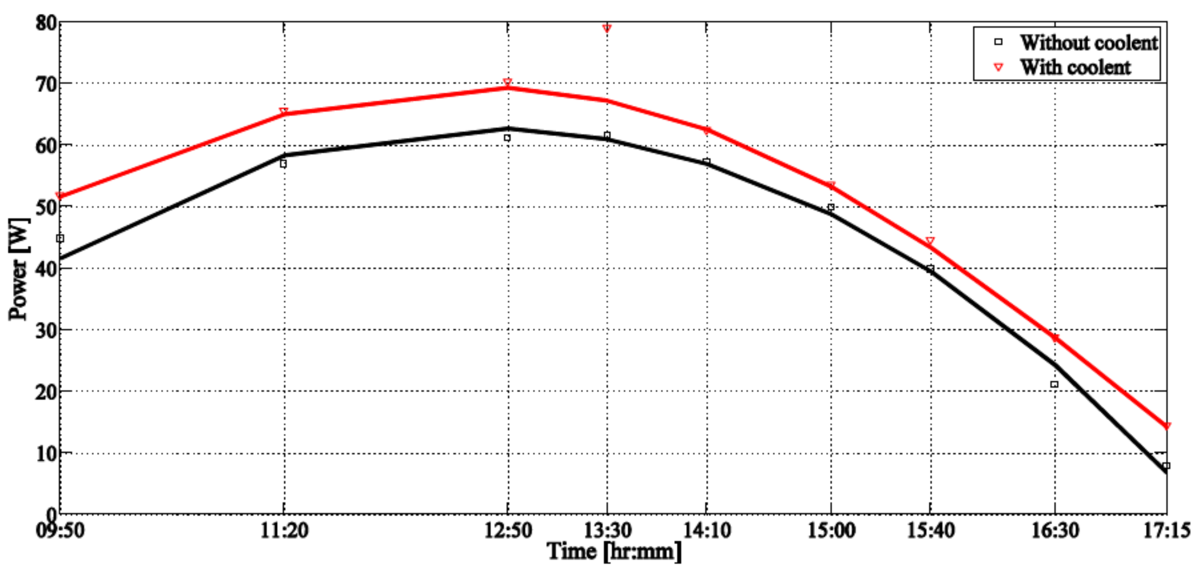

Fig. 5. The effect of the coolant on PV power

The experimental values of the ambient temperatures, the photovoltaic cell with and without coolant and the output water from PV/T are shown in fig. 6.

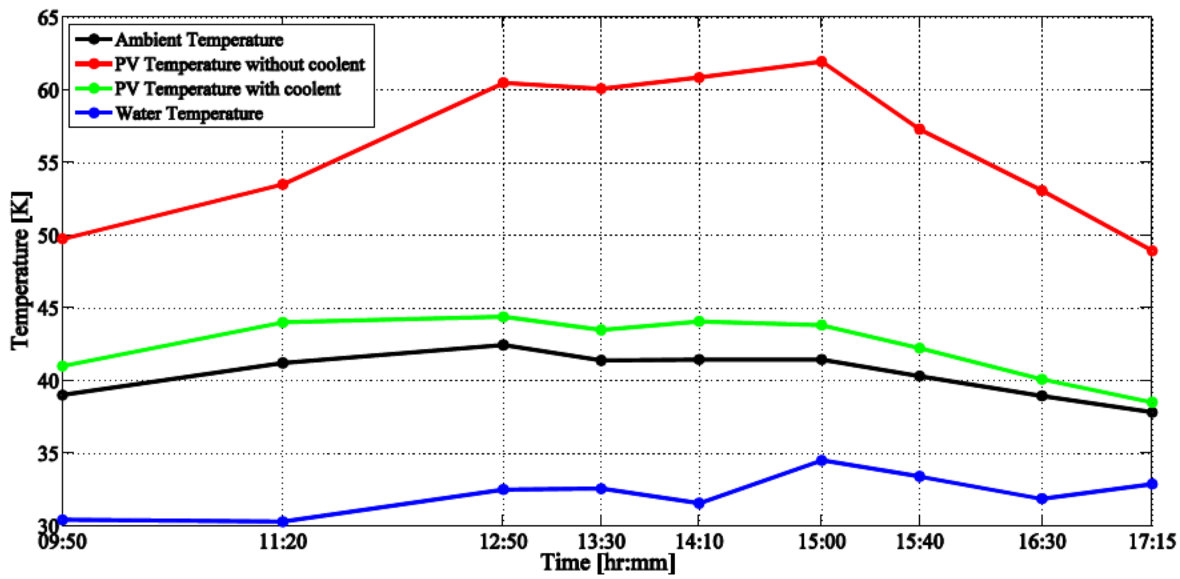

Fig. 6. Temperatures of ambient, PV and output water

Fig. 7 shows the electrical efficiency of the photovoltaic panel with and without coolant system.

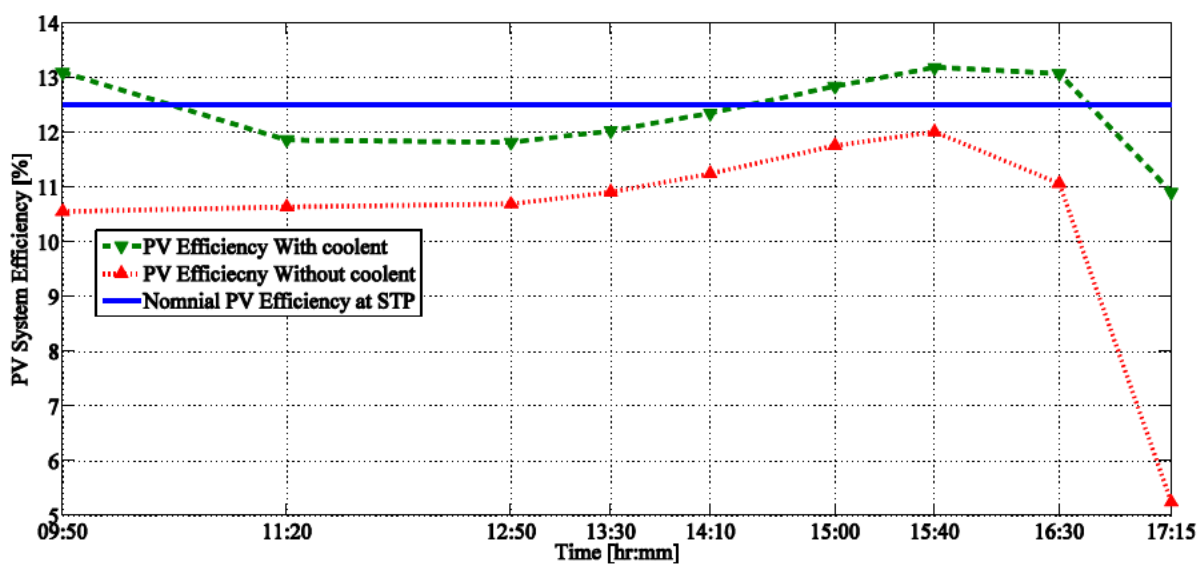

Fig. 7. The electrical efficiency of the photovoltaic panel

According to the above figure, average PV efficiency in case of equipping with coolant system can be reached to 12.3% that shows 1.6% is lower than in the nominal efficiency (12.5%). However, the average efficiency of PV without coolant is 10.9%. Finally, the coolant system enhances 12.8% average conversion efficiency. The role of the cooling system in the conversion efficiency improvement has acceptable agreement with the cooling system developed by S. Nizˇetic´ et al. [16]. Although the cooling system developed by S. Nizˇetic´ et al. [16] yields higher conversion efficiency in compare to this study, the water flow and water head loss in this study is lower. Moreover, water cooling panel in this study against the cooling system presented by S. Nizˇetic´ et al. [16] is not in exposed of atmosphere therefore water consumption in cooling system is zero.

The average thermal efficiency is approximated 49.4% that leads overall system efficiency is around 61.7% that is in harmony with the overall efficiency of the PV/T water collector reported by A. Ibrahim [13]. In spite of the low complexity cooling system presented in this paper, it achieves high efficiency such as A. Fudholi et al [12] and B.J. Huang et al. [22]. B.J. Huang et al. [21] reach to 9.5% for conversion efficiency and 50% for thermal efficiency. Although the thermal efficiency reported by B.J. Huang et al [22] has 0.6% higher efficiency, the lower PV conversion efficiency in comparison with this study remains a greater thermal load that increases its thermal efficiency. Furthermore, A. Fudholi et al. [12] reports conversion efficiency in range of 11.9-12.4% and thermal efficiency around 41.1-48% in table 8. As seen, the conversion efficiency is in the same range with the PV efficiency used in this study; however, the thermal efficiency presented in this paper has slightly higher efficiency due to direct heat exchange between water and PV surface.

Although integrating PV with the cooling system lead to higher power efficiency along with supplying a part of thermal demand, commercializing the cooling system depends on the payback period. The utilized heat recovery system from PV takes advantage of lower cost in comparison to the other commercialized systems with preserving its efficiency. In case that gas FOB[1] price is $10\frac{¢}{Nm^3}$, electricity price is $16\frac{¢}{kWh}$ [23], and 1 Iranian Rail equals 0.00002$. The capital cost is obtained $20\ \frac{¢}{W}$ (it should be mentioned the cooling system is insulated). The payback period of the cooling system is influenced from using or wasting the output water energy, if output water is used as water inlet to the solar water heater or a gas-fired water heater, the payback period is estimated 1.7 years; otherwise, the payback period is exceeded than 8.7 years that shows the developed cooling system can be interesting for home application.

Conclusions

In this study, a mono-crystalline silicon solar is equipped with a coolant system and solar water heater which enhances electrical PV efficiency and produce heat power simultaneously. The comparison between PV system performance and PV/T system performance has been taken with experimental setup and simulation model. Moreover, the system performance was compared to the PV module. Based on the measured data, the main achievements are summarized in the following:

The average efficiency of the PV without the cooling system is 10.9 % while equipping the PV with cooling system improves the electrical efficiency to 12.3%. In this case, the average thermal efficiency of the PV/T is calculated 49.4%. Therefore, the overall average efficiency reaches 61.7%. If the system is coupled with a gas fired water heater instead of the solar water heater, the payback period is obtained 1.7 years.

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[1] Free On Board

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Abstract

This paper addresses a low complexity and high efficient cooling system applicable on photovoltaic (PV) system leading to enhance electrical efficiency and provide preheated water. The developed system consists of a PV, a cooling water system establishing a uniform surface temperature, and a solar water heater. According to the proposed system characteristics, the setup is constructed based on a single mono-crystalline solar panel to absorb more solar radiation intensity and generate more electrical energy per area in compare to a poly-crystalline panel. The preheated water produced by absorbed heat from the photovoltaic is conducted to a solar water heater to satisfy domestic hot water demand. The experimental results show the electrical, thermal and overall energy efficiencies are boosted to 12.3%, 49.4%, and 61.7%, respectively. The results are obtained on July in Tehran, Iran. Moreover, comparing the performance of the cooling system with the conventional systems reveals that the proposed system has higher efficiency originated from the uniform minute holes in the implemented shower stuck on the panel back. Furthermore, if the heat transferred to water in the cooling system is utilized, the payback period is estimated 1.7 years; otherwise, the payback period exceeds 8.7 years if only PV conversion efficiency is included.

Keywords: Payback period; Photovoltaic/Thermal Systems; Renewable Energy; Solar Energy.

Introduction

Trends of energy consumption, global warming, air pollution, greenhouse gas emission, depletion of fossil energy resources, and the fluctuations in fossil fuel energy prices lead to increase the share of renewable energies in energy supply systems. In the meantime, one of the most accessible and clean renewable energy sources is solar energy. The main application of solar energy has allocated to heat generation via thermal collectors, and electricity generation via photovoltaic systems. Although the use of solar energy has been increased, there are some obstacles that influence on the share of solar energy carrier among the other energy carriers, such as high capital cost, low efficiency and requiring storage systems (such as batteries) due to the difference between supply and demand curves. A large number of research papers have been published on photovoltaic/thermal (PV/T) collectors since 1970s to overcome the barriers [1].

A PV/T collector consists of photovoltaic and solar thermal systems producing electricity and heat simultaneously. The conversion efficiency improvement is attained through lowering PV surface temperature. The heat removed from the panel might be transferred to water or air collection for utilization unit [2]. The primary merits of PV/T collectors can be mentioned that are higher energy efficiency per the area, integration of heat and power generation as well as lower capital cost coincided with two independent systems.

Several experimental and theoretical studies about PV/T collectors have been carried out. Most studies have been conducted to improve PV electrical efficiency and its thermal efficiency. A comprehensive review on the hybrid PV/T solar collectors has been carried out by T. T. Chow [2]; the following research focused on analysis of problems, models, and experimental results that conducted by H. A. Zondag et al. [3], D. W. de Vries [4], P.G. Charalambous et al. [5]. Furthermore, C. Lamnatou and D. Chemisana [6] investigated the aforementioned studies with the emphasis on the environmental aspects.

J. Prakash et al. [7] studied a hybrid PV/T solar system from a theoretical viewpoint. In this system, air and water are directed to a duct placed below the solar panel surface; as a result, the temperature of solar panel will be reduced by extraction of heat from the panel. Thereby, the electrical efficiency is enhanced noticeably by the applied mechanism. It is concluded that the thermal efficiency varies in a range of 50% to 67% while water is used as the cooling fluid. The mentioned improvement is reduced in a range of 17% to 51% if the cooling water is substituted with cooling air. The lower heat transfer rate between the absorber plate and the flowing air in compare to the water causes the decrement in the thermal efficiency. H. Saitoh et al. [8] did experimental and analytical research on simultaneous power and heat generation with a hybrid solar collector. The result demonstrates that electrical conversion efficiency is around 10%-13%. In case of brine temperate around 20C, the collector efficiency and overall efficiency (electrical conversion efficiency + collector efficiency) are obtained 40-50% and 50-60%, respectively, while if the brine temperature reaches 40C, the collector efficiency and overall efficiency decrease to 20% and 30%, respectively. The study shows that the hybrid collector has the advantage of higher exergy efficiency. S. Dubey and G. N. Tiwari [9] developed an integrated combined system of a PV/T solar water heater customized for New Delhi climate. It is observed that PV/T with flat plate collector partially covered with PV module has better thermal and average cell efficiency. Moreover, distinguishable enhancement in the efficiency from 33% to 64% is achieved due to glazing area increment. M. Abdolzadeh and M. Ameri [10] developed a PV/T water collector set up to increase the flow rate of a photovoltaic water pumping system that is performed by spraying water over the photovoltaic cells. Experimental results demonstrate that spraying water over the cells increases the performance indexes. The improvement of average PV cell efficiency, subsystem efficiency, and total efficiency are reported 3.26%, 1.40%, and 1.35%, respectively. Improving PV electrical efficiency transfers a higher power to the pump that means increasing water flow rate. Coupling a PV with the suggested cooling system, to a pump, can provide 644L/h flow rate at 16m head, while if the cooling system is inactive, the flow rate drops to 479L/h at 16m head. F. Sarhaddi et al. [11] quantify the thermal and electrical indexes of a typical PV/T air collector. Some corrections are done on heat loss coefficients for improving the PV/T air collector thermal model. The result exhibits that overall energy efficiency of PV/T air collector reaches 45%. A. Fudholi et al. [12] investigated the energy generated by PV/T water collector in the condition that solar radiation is about 500‐800$\frac{W}{m^2}$. The results reveal that PV electrical efficiency, PV thermal efficiency, and the PV/T water collector can reach to 13.8%, 54.6% and 68.4%, respectively when the water flow rate is 0.041 kg/s and solar radiation is on the maximum solar radiation (800$\frac{W}{m^2}$). A. Ibrahim et al. [13] designed a building integrated PV/T system to produce both electricity and hot water which is implemented in a building. It should be mentioned that this paper was based on energy efficiency, exergy efficiency, and potential of exergetic improvement according to the metrological condition of Malaysia. The results demonstrate that the PV/T energy efficiency varies between 55% and 62%. Furthermore, the variation of PV/T exergy efficiency is from 12 to14%. C. Colangelo et al [14] developed a thermal analysis of a new PV/T solar panel using RADTHERM THERMOANALITICS software. Several combinations of water flow rates and different panel configurations have been investigated to determine the best performance in terms of optimal PV efficiency and available thermal energy. G. Popovici et al. [15] developed a numerical model to investigate effect of air cooled heat sinks on PV conversion efficiency improvement. The heat sink that is attached at the back of PV panel is composed from a ribbed wall with specific dimensions. The results reveal in case of equipping 80W PV with 16% nominal efficiency with the best configuration of the air cooled heat sink designed in the paper, the efficiency improvement is around 7.6%. The results presented is obtained at solar radiation 500$\frac{W}{m^2}$. G. S. Nizˇetic´ et al. [16] developed a cooling system spraying over both sides of the panel. The improved electrical efficiency of a mono crystalline photovoltaic is reported 16.3% when the temperature decreases from 54C to 24C and the both sides of PV are cooled down. While if the back surface is cooled down, the efficiency improvement is reached 14%. M. Proell et al. [17] presented a novel concept for improving the thermal efficiency of PV/T through concentrating sunlight with compound parabolic concentrator reflectors to attain a higher radiation power. The experiments were implemented at ZAE Bayern in Garching, Germany. The results exhibit the thermal efficiency of equipped PV/T with maximum power point tracking is enhanced to 34% thermal efficiency in compare to a glazed flat plate PV/T with 17% thermal efficiency when there is 60K temperature difference between ambient and the collector although the electrical efficiency drops noticeably from 15% to 9% because of temperature increment and a non-uniform flux distribution caused by the reflectors. R. Tripathi and G. N. Tiwari [18] developed a single experimental set up which was fully covered with concentrated PV/T collector. This experiment was done with the objective of achieving both thermal and electrical energy at the same time in IIT Delhi, India. Two cases are taken into account on the basis of receiver rotation regarding sun movement. The first case is allocated to a fixed position and the second is the manual maximum power point tracking technique. As expected, the second case shows a better performance. Furthermore, the thermal energy difference between the second case and the first case is 25%, while the exergy difference is around 19%.

Although utilizing cooling systems on PV can enhance the electrical efficiency and as well as give an opportunity to have a heat source, penetrating these systems depends on their return ratio. Some studies consider payback period, such as following:

S. Tselepis and Y. Tripanagnostopoulos [19] studied an economic analysis of hybrid PV/T and comparison with standard PV module for a domestic system in climate condition of Athens, Greece. The results demonstrate that the payback period for ac-Si PV system and a-Si PV system is 25 and 29 years, respectively; whereas they are shortened to 10 and 6 years in the case that the panels are integrated with the thermal system, respectively. J. J. Michael et al. [20] carried out a brief overview on the different solar flat plate PV/T technologies. The energy payback period of the PV/T system in the Italian climate would be 2 years, compared with 4.3 years for the solar thermal collector and 3.4 years for the PV system.

Besides the abovementioned considerations in association with equipping PV with a cooling system, the challenging issues and the obstacles should be observed. The conventional problems are access to water (in order to lower PV cell temperature) and as well as hot water demand especially in the case of PV power plants, concern about isolating water from electric junctions, difficulties originated from integrating the system to the fossil fuel fired water heater and restrictions in transportation due to fragility insulation layer injected in the cooling system. Moreover, some cooling systems [10,16] disperse/spray water on PV glass that leads to emerge tracks on the glass due to water minerals, that causes the PV conversion efficiency might be dropped out because of reducing irradiation to the cells and loading effect originating from non-uniform tracks. In addition, cleaning the tracks and water vapored from the glass impose operational costs.

This research is oriented to explore the electrical and thermal performance of a new PV/T system on the outdoor solar test facility at Sharif Energy Research Institute (SERI) in Tehran, Iran. Thereby, an experimental setup of PV/T is constructed based on a single mono-crystalline solar panel which a rectangular container has been attached to the back of it. The container is equipped with the uniform minute holes on the implemented shower stuck on the panel back in order to extract higher heat from the panel. Besides, a single solar water heater was constructed for this project and integrated into the system to compensate for the lack of heat that is required for sanitary hot water. Moreover, the study is targeted to introduce a commercial product customized for remote areas, since the PV/T design has harmony with the area conditions and requirements. As known, energy carrier transmission costs to low population remote areas with no economic justification is a barrier for the areas to have access to national electricity/gas Networks. Providing access to energy carriers is a key factor in the sustainable development of the regions especially through available renewable energy resources in those regions. Therefore, the integrated system should comprise the following properties:

1) Supplying heat and electrical energy demanded: a part of the required heat for sanitary hot water is provided through water cooling the photovoltaic panel. The water outlet from cooling system as water preheated, is directed to a solar water heater (that have effect on the solar water heater dimensions. It is equivalent to the investment cost reduction of the solar water heater) or a water heater using fossil fuel (Fuel consumption saving and in consequence of it, operational cost reduction are resulted in).

2) High reliability with negligible maintenance cost: During 13 year lifespan estimated for the cooling system, it should not require planned maintenance (expect limited cleaning programs).

3) Low capital cost: the investment cost should be inexpensive enough to compete with the conventional fossil energy conversion technologies.

Moreover, the stated properties for a coolant system to be installed in remote areas, it should have low head losses unlike coolant systems spraying water on PV surfaces and as well as negligible water consumption unlike coolant systems spraying water on front PV surface, open loop coolant systems or coolant systems that cooling water is in exposed to atmosphere. Briefly, the distinction between the coolant system developed in the study and similar coolant systems, are lower head losses (therefore there is no need to consume energy to supply the required pressure), zero water consumption in the coolant system (no water is wasted or vaporized during cooling PV), high efficiency, higher reliability (due to low complexity design) and its economic justification.

Methodology

The short-circuit current $\mathrm{I_{sc}}$ and the open-circuit voltage $\mathrm{V_{oc}}$ are two key characteristics of the I–V curve for a PV module. Changing in the incident solar irradiance and the ambient air temperature influences on $\mathrm{I_{sc}}$ and $\mathrm{V_{oc}}$ parameters. The open-circuit voltage increases just a little with increasing solar irradiance and decreases with raising module temperature which causes decreasing in the maximum electrical power remarkably. On the other hand, short-circuit current increases a little with increasing module temperature. Therefore, it is crystal clear that fluctuation in solar irradiance and module temperature changes the electrical efficiency of the PV module [21]. As a result, decreasing the panel surface temperature by water or air flow is an effective way in order to increase the electrical efficiency of the photovoltaic panel.

Many models have been developed to estimate the nonlinear behavior of PV, one of the popular models is an equivalent single diode circuit. According to the model as explained in [10, 11], PV module electrical behavior is described by quantifying the light current (I_L), the diode current ($\mathrm{I_D}$), the shunt current ($\mathrm{I_{sh}}$), and the saturation reverse current (I_0). Equations (1) to (8) are to compute the mentioned parameters:

[Figure. 1. About here [11]]

$$I_{pv} = I_L - I_D - I_{SH} \tag{1}$$

$$I_{pv} = I_L - I_O \left[\exp\left(\frac{V_{pv} + I_{pv}R_S}{V_t}\right) - 1\right] - \frac{V_{pv} + I_{pv}R_S}{R_{SH}} \tag{2}$$

$$V_t = \frac{kt}{e} \tag{3}$$

Where t, k, and e are the absolute temperature of the cell, the Boltzmann's constant (1.381e-23 J/K) and the electron charge (1.602e-19 J/V), respectively. The equation (4) can be substituted with equation (2) when the below assumptions are applied.

I. The resistance (R_{SH}) paralleled with current supply is ignored

II. The PV current (I_L) and short-circuit current (I_{SC}) are equal

III. Expression of $\exp\left(\frac{V_{pv} + I_{pv}R_S}{V_t}\right)$ is much greater than zero.

$$I_{pv} = I_L - I_O \left[\exp\left(\frac{V_{pv} + I_{pv}R_S}{V_t}\right)\right] \tag{4}$$

Open circuit voltage is estimated by equation (5)

$$V_{OC} = V_t \ln\left(\frac{I_{SC}}{I_O}\right) \tag{5}$$

Finally, the PV current is determined by putting equations (5) in equation (4):

$$I_{pv} = I_{SC} \left[1 - \exp\left(\frac{V_{pv} - V_{OC} + I_{pv}R_s}{V_t}\right)\right] \tag{6}$$

The equation (6) states that photovoltaic cell current depends on the output voltage and radiated light on the photovoltaic surface. The short-circuit current is a function of light intensity that is computed by equation (7).

$$I_O = I_{SC} \exp\left(-\frac{V_{OC}}{V_t}\right) \tag{7}$$

$$I_{sc}(G) = \frac{I_{sc-r}}{G_r} G_{eff} \tag{8}$$

Where I_{sc-r}, G_r and G_{eff} are the short-circuit current, the light intensity at standard conditions and effective radiation intensity, respectively.

The voltage operation is considered a linear function of temperature calculated by equation (9).

$$V_{oc-pv}(T_c) = V_{oc-r} + (T_c - T_{c-r})\mu_{voc} \quad (9)$$

In above, V_{oc-r} and μ_{voc} are standard voltage and voltage temperature coefficient, respectively, given by its manufacturer. T_C is collector temperature that can be calculated by equation (10)

$$T_C = T_a + \frac{(NOCT - T_o)}{800\ ^{W}/_{m^2}} \times G_{eff} \quad (10)$$

Where NOCT is operating temperature given by the manufacturer. Finally, the panel efficiency is calculated according to the equation (11)

$$\eta = \frac{I_{pv}\ V_{pv}}{A\ G} \quad (11)$$

Where G is solar radiation intensity $[\frac{w}{m^2}]$ and A is panel area $[m^2]$. In addition, the thermal energy efficiency is calculated by equation (12).

$$\eta_{th} = \frac{\dot{m}\ C\ (T_f - T_{in})}{A\ G} \quad (12)$$

Where $\dot{m}$, T_f, T_{in}, C, and S are the amount of input water flow rate to the panel, the output water temperature of the panel, the input water temperature to the panel, the heat capacity of water and the hybrid collector area, respectively. The solar water heater efficiency can be calculated by equation (11) if the required parameters related to the solar water heater are substituted in the equation (11).

Experimental set-up

The experiment has been carried out in Tehran, Iran (35.6892° N, 51.3890° E), on July. The experiment is performed by a PV module with 36-mono crystalline cells. The PV specification is listed in Table 1.

Measurement equipment

The hourly solar radiation power was reported by Iran Meteorological Organization on July. In addition, the hourly temperature is measured by a data logger system with DS18b20 temperature sensors that the resolution for all temperature sensors is configured on 12 bits. The measurement was performed on the top, bottom, and middle of the PV/T collector. So, the average of them was estimated as the final measurement.

[Table 1 about here]

Preparing the container is the most effective step to design the hybrid system for directing water to the coolant. Three possible materials were investigated through three defined criteria for fabricating the container (copper, aluminum, and iron). The criteria are thermal conductivity, density and capital cost of the metal. Regarding the criteria, the container made of aluminum was selected (copper container has the highest density and price among three containers. Moreover, the iron container has the second rank in density and the lowest thermal conductivity among three containers).

The container dimensions are 0.9(m)*0.45(m)*0.01(m) that is placed in the PV frame below the PV terminal in order to isolate electrical junctions from the water. The silicone glue is used to connect the container to the back of PV due to its high adhesion and the low heat resistance. In addition, the shower is connected with minute holes to the back of the container in order to possess maximum possible surface in exposed to cooling water and sprinkling the entire the back of the panel uniformly. The schematic diagram of the PV/T panel is given by fig. 2. It should be mentioned that input water entered to the panel through the shower with minute holes from the top of the panel and flow to the bottom of it. The output water from the bottom flows through the solar water heater with $0.5\,m^2$ effective area. As a result, this system is configured to absorb and transfer heat from the solar panel in order to keep the panel at the desired temperature.

[Figure. 2. about here]

Fig. 3 Shows the photograph of the experimental system where it is installed at the roof of SERI. In addition, the PV/T was installed with a 31°tilting angle relative to the horizontal plane facing south. So, preheated water is flowed in the water heater and moved toward the storage box with a 50 liter capacity for storing hot water.

[Figure.3. about here]

Results

The experimental results of the PV/T system in Tehran's climate are presented in the following. The coolant system effect on the electrical efficiency of the photovoltaic panel is quantified. Moreover, PV/T collector produces hot water to be consumed by medium-sized family while the generated electricity was connected to a dummy load as well via DC/AC inverter. Fig. 4 comprises the total solar radiation falling on the PV modules.

[Figure. 3. about here]

As seen in the above figure, there is a noticeable difference between the simulation results and measurements after 12 p.m. that originates from the heat accumulated on the sensor that influences on stating a higher irradiation than the reality.

Fig. 5 envisages effect of the coolant on the PV power. The power varies during the day. It reaches its maximum at 1 p.m. when global irradiance reaches its maximum.

[Figure. 4. about here]

The experimental values of the ambient temperatures, the photovoltaic cell with and without coolant and the output water from PV/T are shown in fig. 6.

[Figure. 5. about here]

Fig. 7 shows the electrical efficiency of the photovoltaic panel with and without coolant system.

[Figure. 7. about here]

According to the above figure, average PV efficiency in case of equipping with coolant system can be reached to 12.3% that shows 1.6% is lower than in the nominal efficiency

(12.5%). However, the average efficiency of PV without coolant is 10.9%. Finally, the coolant system enhances 12.8% average conversion efficiency. The role of the cooling system in the conversion efficiency improvement has acceptable agreement with the cooling system developed by S. Nizˇetic´ et al. [16]. Although the cooling system developed by S. Nizˇetic´ et al. [16] yields higher conversion efficiency in compare to this study, the water flow and water head loss in this study is lower. Moreover, water cooling panel in this study against the cooling system presented by S. Nizˇetic´ et al. [16] is not in exposed of atmosphere therefore water consumption in cooling system is zero.

The average thermal efficiency is approximated 49.4% that leads overall system efficiency is around 61.7% that is in harmony with the overall efficiency of the PV/T water collector reported by A. Ibrahim [13]. In spite of the low complexity cooling system presented in this paper, it achieves high efficiency such as A. Fudholi et al [12] and B.J. Huang et al. [22]. B.J. Huang et al. [21] reach to 9.5% for conversion efficiency and 50% for thermal efficiency. Although the thermal efficiency reported by B.J. Huang et al [22] has 0.6% higher efficiency, the lower PV conversion efficiency in comparison with this study remains a greater thermal load that increases its thermal efficiency. Furthermore, A. Fudholi et al. [12] reports conversion efficiency in range of 11.9-12.4% and thermal efficiency around 41.1-48% in table 8. As seen, the conversion efficiency is in the same range with the PV efficiency used in this study; however, the thermal efficiency presented in this paper has slightly higher efficiency due to direct heat exchange between water and PV surface.

Although integrating PV with the cooling system lead to higher power efficiency along with supplying a part of thermal demand, commercializing the cooling system depends on the payback period. The utilized heat recovery system from PV takes advantage of lower cost in comparison to the other commercialized systems with preserving its efficiency. In case that gas FOB[1] price is $10\frac{¢}{Nm^3}$, electricity price is $16\frac{¢}{kWh}$ [23], and 1 Iranian Rail equals 0.00002$. The capital cost is obtained $20\ \frac{¢}{W}$ (it should be mentioned

[1] Free On Board

the cooling system is insulated). The payback period of the cooling system is influenced from using or wasting the output water energy, if output water is used as water inlet to the solar water heater or a gas-fired water heater, the payback period is estimated 1.7 years; otherwise, the payback period is exceeded than 8.7 years that shows the developed cooling system can be interesting for home application.

Conclusions

In this study, a mono-crystalline silicon solar is equipped with a coolant system and solar water heater which enhances electrical PV efficiency and produce heat power simultaneously. The comparison between PV system performance and PV/T system performance has been taken with experimental setup and simulation model. Moreover, the system performance was compared to the PV module. Based on the measured data, the main achievements are summarized in the following:

The average efficiency of the PV without the cooling system is 10.9 % while equipping the PV with cooling system improves the electrical efficiency to 12.3%. In this case, the average thermal efficiency of the PV/T is calculated 49.4%. Therefore, the overall average efficiency reaches 61.7%. If the system is coupled with a gas fired water heater instead of the solar water heater, the payback period is obtained 1.7 years.

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Table

Table1: Specification of PV module

Characteristics	Value
Cell type	Mono-crystalline Si
Model name	NE-080T1J
Number of cells	36
Maximum power rating(P_{max})	80.0 W
Short circuit current(I_{Sc})	5.15 A
Open circuit voltage(V_{oc})	21.6 V
PV Efficiency	12.5%
Voltage at point of maximum power (V_{mpp})	17.3 V
Current at point of maximum power (I_{mpp})	4.63 A

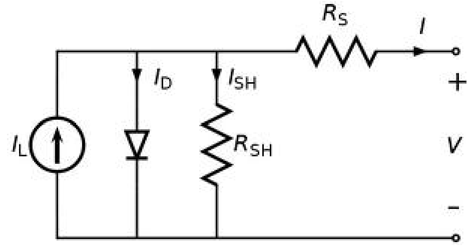

Figure.1. equivalent single diode circuit

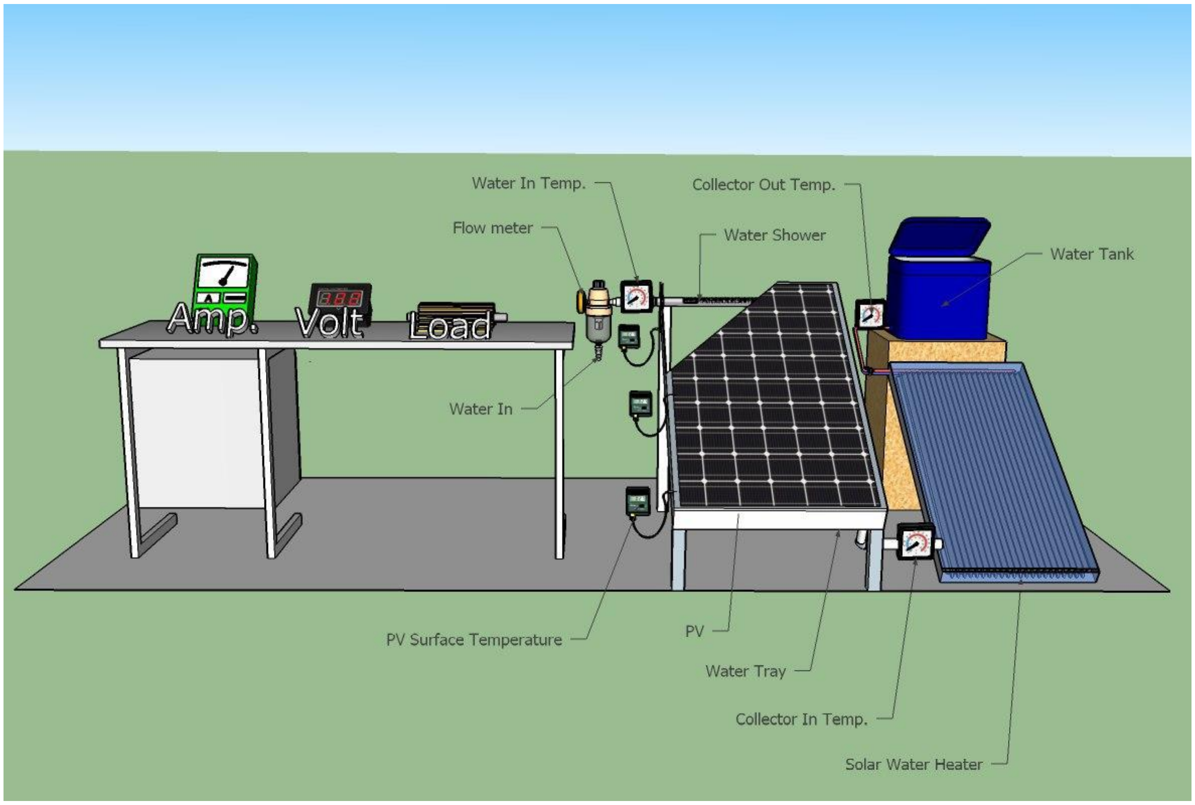

Figure.2. Schematic of the system

Figure.3. PV/T collector system

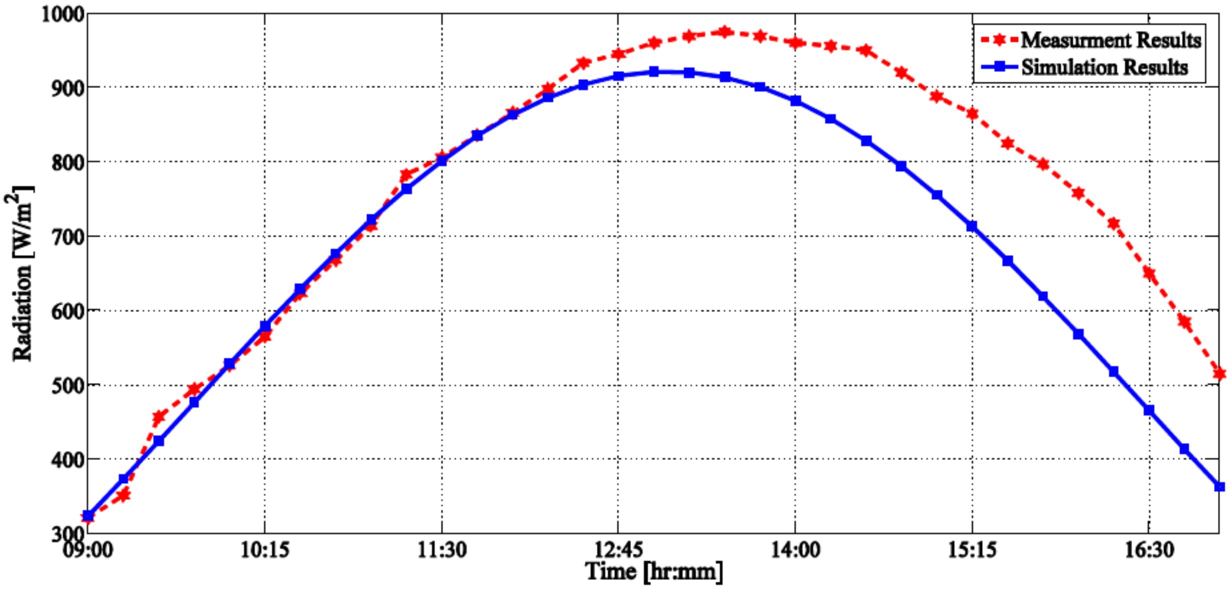

Figure.4. The total solar radiation on a typical day

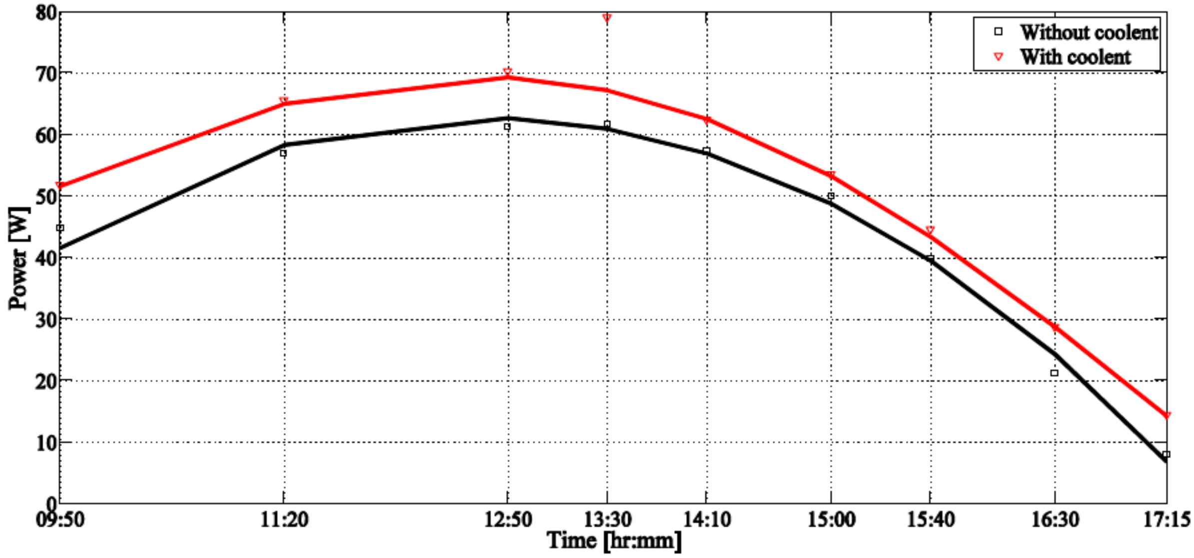

Figure.5. The effect of the coolant on PV power

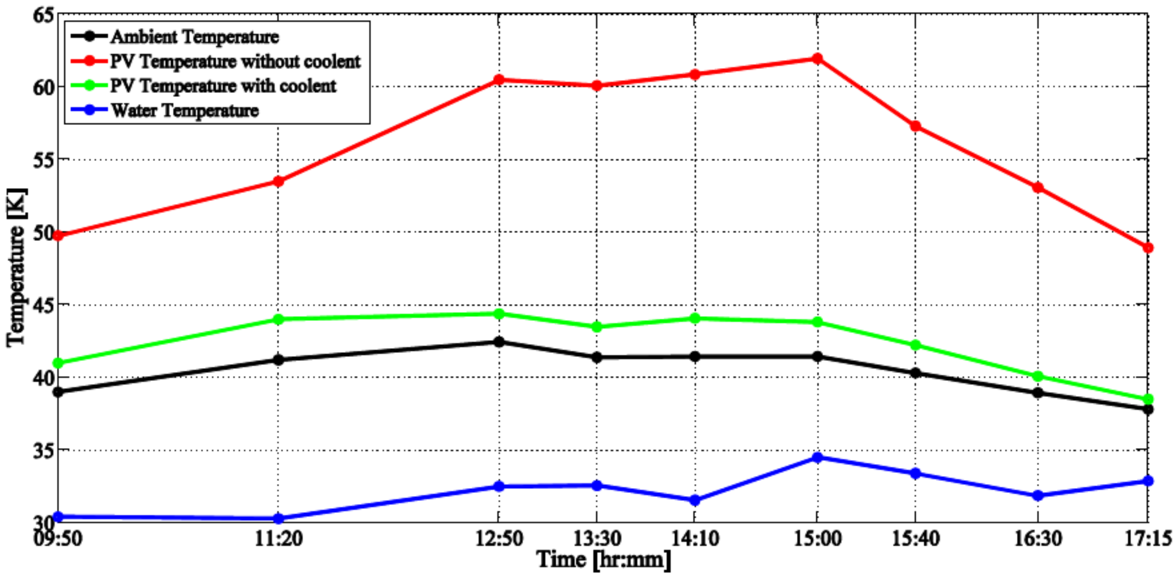

Figure.6. Temperatures of ambient, PV and output water

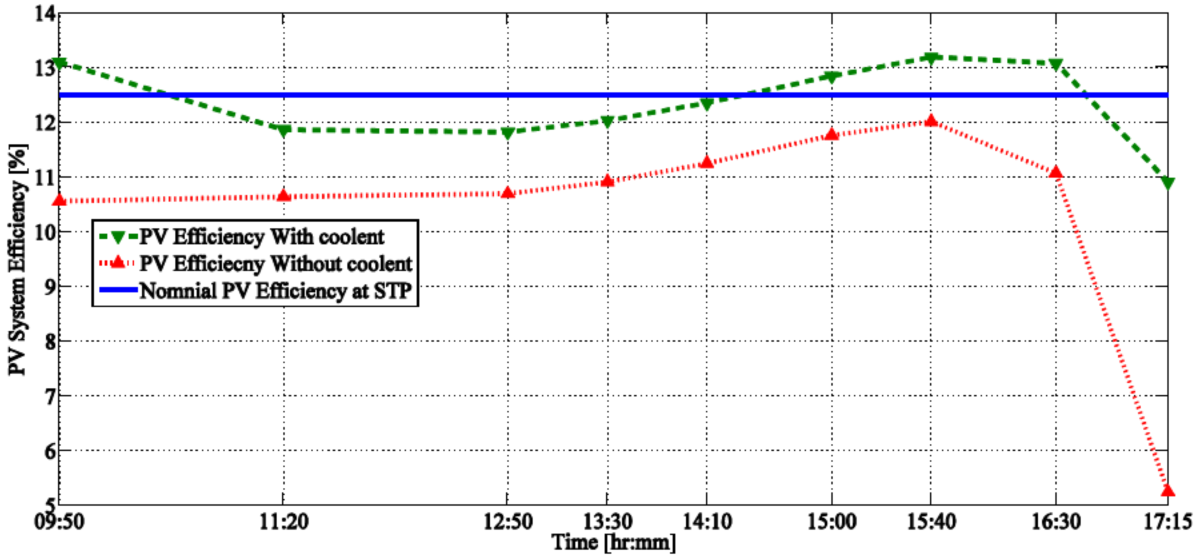

Figure.7. The electrical efficiency of the photovoltaic panel