

Title	Experimental analysis of a cooling system effect on photovoltaic panels' efficiency and its preheating water production
Authors	Fakouriyan, Samaneh;Saboohi, Y.;Fathi, A.
Publication date	2018-09-18
Original Citation	Fakouriyan, S., Saboohi, Y. and Fathi, A. (2019) 'Experimental analysis of a cooling system effect on photovoltaic panels' efficiency and its preheating water production', Renewable Energy, 134, pp. 1362–1368. https://doi.org/10.1016/j.renene.2018.09.054 .
Type of publication	Article (peer-reviewed)
Link to publisher's version	https://doi.org/10.1016/j.renene.2018.09.054 - 10.1016/j.renene.2018.09.054
Rights	© 2018 Elsevier Ltd. This manuscript version is made available under the CC-BY-NC-ND 4.0 license https://creativecommons.org/licenses/by-nc-nd/4.0/ - https://creativecommons.org/licenses/by-nc-nd/4.0/
Download date	2024-05-07 03:31:39
Item downloaded from	https://hdl.handle.net/10468/13866

Title Page

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

Samaneh Fakouriyan *

Department of Energy Engineering, Sharif University of Technology, Azadi Ave., Tehran,
1459777611 Iran.

Email: Samane.fakourian@gmail.com

Yadollah Saboohi

Department of Energy Engineering, Sharif University of Technology, Azadi Ave., Tehran,
1459777611 Iran.

Email: Saboohi@sharif.edu

Amorhossein Fathi

Sharif Energy Research Institute (SERI), Sharif University of Technology, Azadi Ave., Tehran,
1459777611 Iran.

Email: amirhossein.fathi87@gmail.com

***Corresponding author:** Samaneh Fakouriyan

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.

1 Abstract

2 This paper addresses a low complexity and high efficient cooling system applicable on
3 photovoltaic (PV) system leading to enhance electrical efficiency and provide preheated
4 water. The developed system consists of a PV, a cooling water system establishing a
5 uniform surface temperature, and a solar water heater. According to the proposed system
6 characteristics, the setup is constructed based on a single mono-crystalline solar panel to
7 absorb more solar radiation intensity and generate more electrical energy per area in
8 compare to a poly-crystalline panel. The preheated water produced by absorbed heat from
9 the photovoltaic is conducted to a solar water heater to satisfy domestic hot water
10 demand. The experimental results show the electrical, thermal and overall energy
11 efficiencies are boosted to 12.3%, 49.4%, and 61.7%, respectively. The results are
12 obtained on July in Tehran, Iran. Moreover, comparing the performance of the cooling
13 system with the conventional systems reveals that the proposed system has higher
14 efficiency originated from the uniform minute holes in the implemented shower stuck on
15 the panel back. Furthermore, if the heat transferred to water in the cooling system is
16 utilized, the payback period is estimated 1.7 years; otherwise, the payback period exceeds
17 8.7 years if only PV conversion efficiency is included.

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

20

21

22

23

1 Introduction

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

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

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

26 J. Prakash et al. [7] studied a hybrid PV/T solar system from a theoretical viewpoint. In
27 this system, air and water are directed to a duct placed below the solar panel surface; as a
28 result, the temperature of solar panel will be reduced by extraction of heat from the panel.
29 Thereby, the electrical efficiency is enhanced noticeably by the applied mechanism. It is

1 concluded that the thermal efficiency varies in a range of 50% to 67% while water is used
 2 as the cooling fluid. The mentioned improvement is reduced in a range of 17% to 51% if
 3 the cooling water is substituted with cooling air. The lower heat transfer rate between the
 4 absorber plate and the flowing air in compare to the water causes the decrement in the
 5 thermal efficiency. H. Saitoh et al. [8] did experimental and analytical research on
 6 simultaneous power and heat generation with a hybrid solar collector. The result
 7 demonstrates that electrical conversion efficiency is around 10%-13%. In case of brine
 8 temperate around 20C, the collector efficiency and overall efficiency (electrical
 9 conversion efficiency + collector efficiency) are obtained 40-50% and 50-60%,
 10 respectively, while if the brine temperature reaches 40C, the collector efficiency and
 11 overall efficiency decrease to 20% and 30%, respectively. The study shows that the hybrid
 12 collector has the advantage of higher exergy efficiency. S. Dubey and G. N. Tiwari [9]
 13 developed an integrated combined system of a PV/T solar water heater customized for
 14 New Delhi climate. It is observed that PV/T with flat plate collector partially covered with
 15 PV module has better thermal and average cell efficiency. Moreover, distinguishable
 16 enhancement in the efficiency from 33% to 64% is achieved due to glazing area
 17 increment. M. Abdolzadeh and M. Ameri [10] developed a PV/T water collector set up to
 18 increase the flow rate of a photovoltaic water pumping system that is performed by
 19 spraying water over the photovoltaic cells. Experimental results demonstrate that spraying
 20 water over the cells increases the performance indexes. The improvement of average PV
 21 cell efficiency, subsystem efficiency, and total efficiency are reported 3.26%, 1.40%, and
 22 1.35%, respectively. Improving PV electrical efficiency transfers a higher power to the
 23 pump that means increasing water flow rate. Coupling a PV with the suggested cooling
 24 system, to a pump, can provide 644L/h flow rate at 16m head, while if the cooling system
 25 is inactive, the flow rate drops to 479L/h at 16m head. F. Sarhaddi et al. [11] quantify the
 26 thermal and electrical indexes of a typical PV/T air collector. Some corrections are done
 27 on heat loss coefficients for improving the PV/T air collector thermal model. The result
 28 exhibits that overall energy efficiency of PV/T air collector reaches 45%. A. Fudholi et al.
 29 [12] investigated the energy generated by PV/T water collector in the condition that solar
 30 radiation is about $500-800 \frac{W}{m^2}$. The results reveal that PV electrical efficiency, PV thermal
 31 efficiency, and the PV/T water collector can reach to 13.8%, 54.6% and 68.4%,

1 respectively when the water flow rate is 0.041 kg/s and solar radiation is on the maximum
 2 solar radiation ($800 \frac{W}{m^2}$). A. Ibrahim et al. [13] designed a building integrated PV/T system
 3 to produce both electricity and hot water which is implemented in a building. It should be
 4 mentioned that this paper was based on energy efficiency, exergy efficiency, and potential
 5 of exergetic improvement according to the metrological condition of Malaysia. The results
 6 demonstrate that the PV/T energy efficiency varies between 55% and 62%. Furthermore,
 7 the variation of PV/T exergy efficiency is from 12 to 14%. C. Colangelo et al [14]
 8 developed a thermal analysis of a new PV/T solar panel using RADTHERM
 9 THERMOANALITICS software. Several combinations of water flow rates and different
 10 panel configurations have been investigated to determine the best performance in terms of
 11 optimal PV efficiency and available thermal energy. G. Popovici et al. [15] developed a
 12 numerical model to investigate effect of air cooled heat sinks on PV conversion efficiency
 13 improvement. The heat sink that is attached at the back of PV panel is composed from a
 14 ribbed wall with specific dimensions. The results reveal in case of equipping 80W PV
 15 with 16% nominal efficiency with the best configuration of the air cooled heat sink
 16 designed in the paper, the efficiency improvement is around 7.6%. The results presented is
 17 obtained at solar radiation $500 \frac{W}{m^2}$. G. S. Nizetic et al. [16] developed a cooling system
 18 spraying over both sides of the panel. The improved electrical efficiency of a mono
 19 crystalline photovoltaic is reported 16.3% when the temperature decreases from 54C to
 20 24C and the both sides of PV are cooled down. While if the back surface is cooled down,
 21 the efficiency improvement is reached 14%. M. Proell et al. [17] presented a novel
 22 concept for improving the thermal efficiency of PV/T through concentrating sunlight with
 23 compound parabolic concentrator reflectors to attain a higher radiation power. The
 24 experiments were implemented at ZAE Bayern in Garching, Germany. The results exhibit
 25 the thermal efficiency of equipped PV/T with maximum power point tracking is enhanced
 26 to 34% thermal efficiency in compare to a glazed flat plate PV/T with 17% thermal
 27 efficiency when there is 60K temperature difference between ambient and the collector
 28 although the electrical efficiency drops noticeably from 15% to 9% because of
 29 temperature increment and a non-uniform flux distribution caused by the reflectors. R.
 30 Tripathi and G. N. Tiwari [18] developed a single experimental set up which was fully
 31 covered with concentrated PV/T collector. This experiment was done with the objective of

1 achieving both thermal and electrical energy at the same time in IIT Delhi, India. Two
2 cases are taken into account on the basis of receiver rotation regarding sun movement. The
3 first case is allocated to a fixed position and the second is the manual maximum power
4 point tracking technique. As expected, the second case shows a better performance.
5 Furthermore, the thermal energy difference between the second case and the first case is
6 25%, while the exergy difference is around 19%.

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

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

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

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

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

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

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

27 Moreover, the stated properties for a coolant system to be installed in remote areas, it
28 should have low head losses unlike coolant systems spraying water on PV surfaces and as
29 well as negligible water consumption unlike coolant systems spraying water on front PV

1 surface, open loop coolant systems or coolant systems that cooling water is in exposed to
 2 atmosphere. Briefly, the distinction between the coolant system developed in the study
 3 and similar coolant systems, are lower head losses (therefore there is no need to consume
 4 energy to supply the required pressure), zero water consumption in the coolant system (no
 5 water is wasted or vaporized during cooling PV), high efficiency, higher reliability (due to
 6 low complexity design) and its economic justification.

7 Methodology

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

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

23

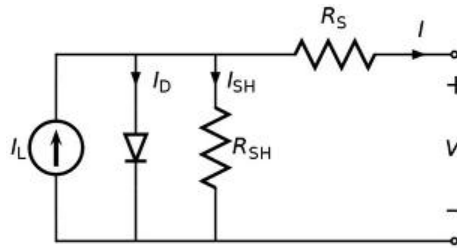


Fig. 1. equivalent single diode circuit [11]

24

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

$$I_{pv} = I_L - I_0 \left[\exp \left(\frac{V_{pv} + I_{pv} R_S}{V_t} \right) - 1 \right] - \frac{V_{pv} + I_{pv} R_S}{R_{SH}} \quad (2)$$

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

1 Where t , k , and e are the absolute temperature of the cell, the Boltzmann's constant
 2 (1.381×10^{-23} J/K) and the electron charge (1.602×10^{-19} J/V), respectively. The equation (4)
 3 can be substituted with equation (2) when the below assumptions are applied.

4I. The resistance (R_{SH}) paralleled with current supply is ignored

5II. The PV current (I_L) and short-circuit current (I_{SC}) are equal

6III. Expression of $\exp \left(\frac{V_{pv} + I_{pv} R_S}{V_t} \right)$ is much greater than zero.

$$I_{pv} = I_L - I_0 \left[\exp \left(\frac{V_{pv} + I_{pv} R_S}{V_t} \right) \right] \quad (4)$$

7 Open circuit voltage is estimated by equation (5)

$$V_{OC} = V_t \ln \left(\frac{I_{SC}}{I_0} \right) \quad (5)$$

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

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

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

$$I_0 = I_{SC} \exp \left(- \frac{V_{OC}}{V_t} \right) \quad (7)$$

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

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

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

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

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

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

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

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

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

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

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

17 Experimental set-up

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

1 Measurement equipment

2 The hourly solar radiation power was reported by Iran Meteorological Organization on
3 July. In addition, the hourly temperature is measured by a data logger system with
4 DS18B20 temperature sensors that the resolution for all temperature sensors is configured
5 on 12 bits. The measurement was performed on the top, bottom, and middle of the PV/T
6 collector. So, the average of them was estimated as the final measurement.

7

8

Table 1: Specification of PV module

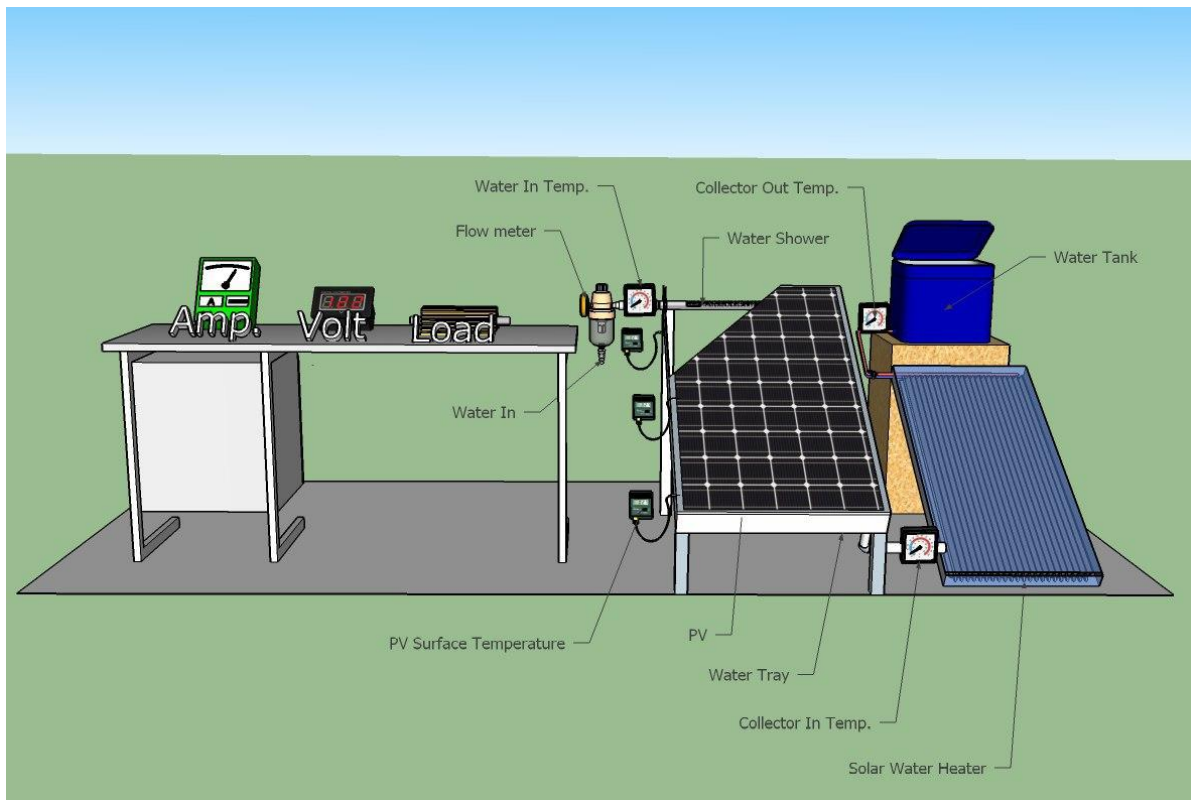
Characteristics	Value
Cell type	Mono-crystalline Si
Model name	NE-080T1J
Number of cells	36
Maximum power rating(P_{max})	80.0 W
Short circuit current(I_{sc})	5.15 A
Open circuit voltage(V_{oc})	21.6 V
PV Efficiency	12.5%
Voltage at point of maximum power (V_{mpp})	17.3 V
Current at point of maximum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

9

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

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

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



6
7 **Fig. 2.** Schematic of the system

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



Fig. 3. PV/T collector system

1 **Results**

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

7

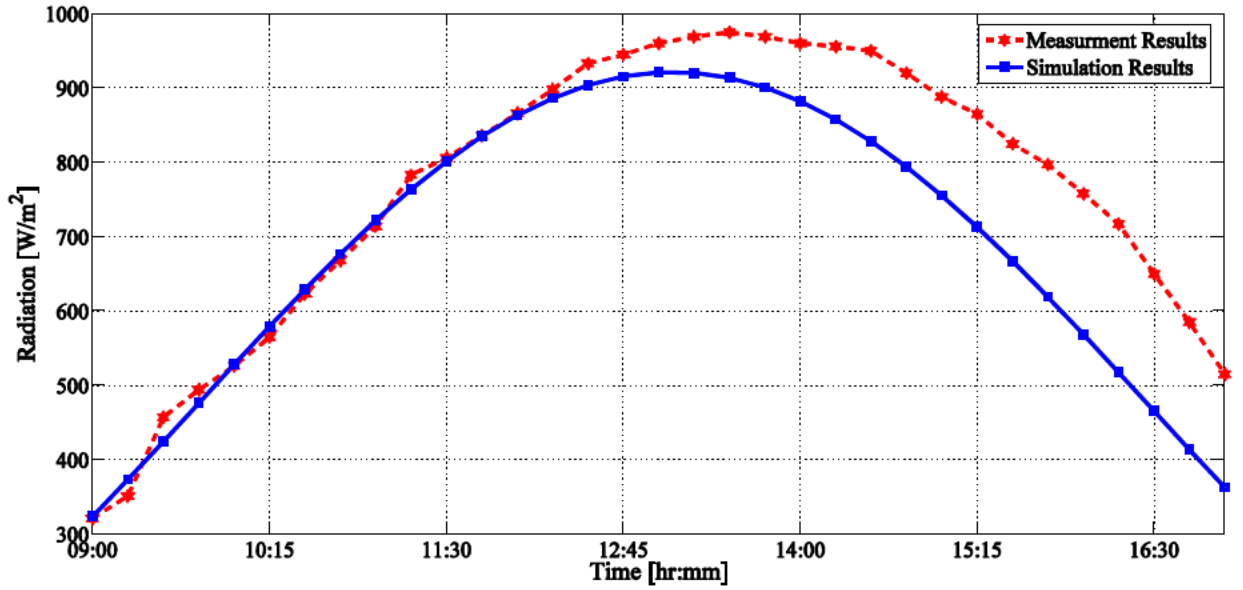


Fig. 4. The total solar radiation on a typical day

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.

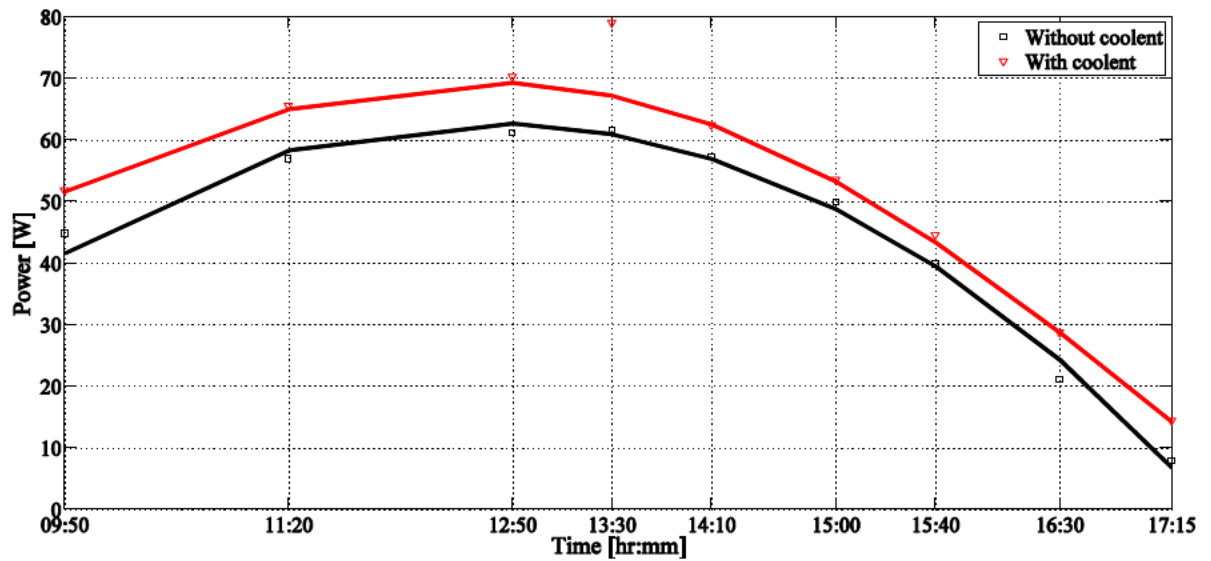


Fig. 5. The effect of the coolant on PV power

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

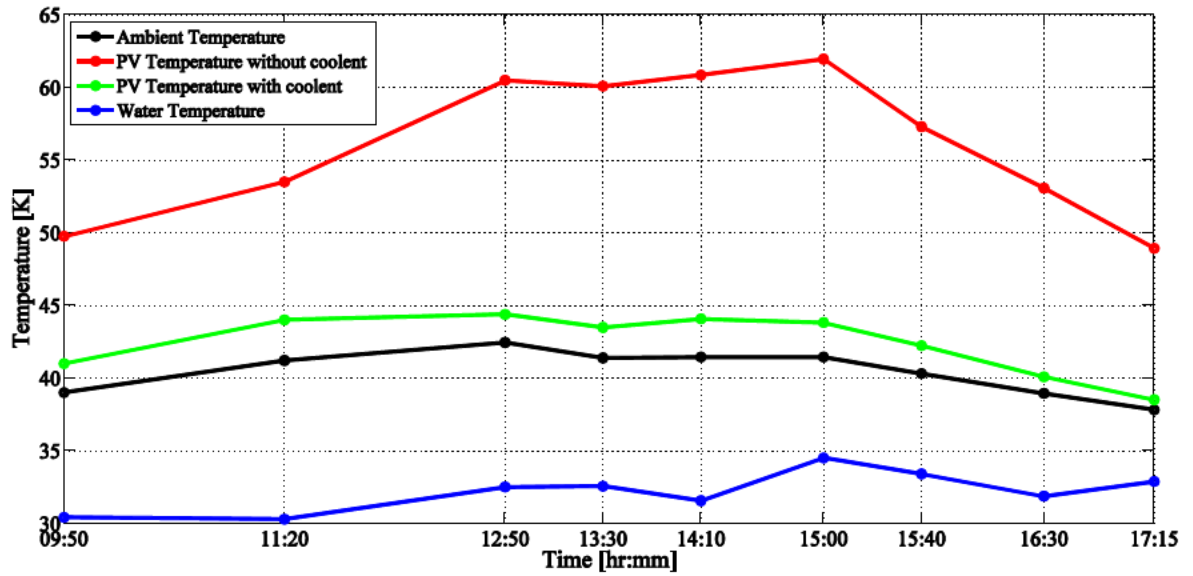


Fig. 6. Temperatures of ambient, PV and output water

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

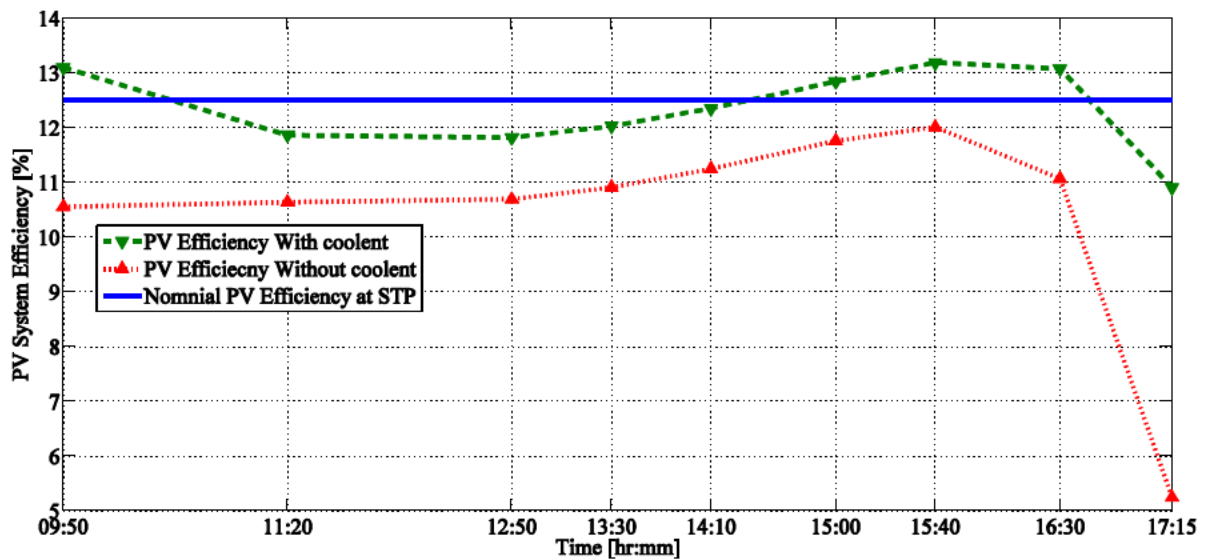


Fig. 7. The electrical efficiency of the photovoltaic panel

1 According to the above figure, average PV efficiency in case of equipping with coolant
2 system can be reached to 12.3% that shows 1.6% is lower than in the nominal efficiency
3 (12.5%). However, the average efficiency of PV without coolant is 10.9%. Finally, the
4 coolant system enhances 12.8% average conversion efficiency. The role of the cooling
5 system in the conversion efficiency improvement has acceptable agreement with the
6 cooling system developed by S. Nizetic' et al. [16]. Although the cooling system
7 developed by S. Nizetic' et al. [16] yields higher conversion efficiency in compare to this
8 study, the water flow and water head loss in this study is lower. Moreover, water cooling
9 panel in this study against the cooling system presented by S. Nizetic' et al. [16] is not in
10 exposed of atmosphere therefore water consumption in cooling system is zero.

11 The average thermal efficiency is approximated 49.4% that leads overall system efficiency
12 is around 61.7% that is in harmony with the overall efficiency of the PV/T water collector
13 reported by A. Ibrahim [13]. In spite of the low complexity cooling system presented in
14 this paper, it achieves high efficiency such as A. Fudholi et al [12] and B.J. Huang et al.
15 [22]. B.J. Huang et al. [21] reach to 9.5% for conversion efficiency and 50% for thermal
16 efficiency. Although the thermal efficiency reported by B.J. Huang et al [22] has 0.6%
17 higher efficiency, the lower PV conversion efficiency in comparison with this study
18 remains a greater thermal load that increases its thermal efficiency. Furthermore, A.
19 Fudholi et al. [12] reports conversion efficiency in range of 11.9-12.4% and thermal
20 efficiency around 41.1-48% in table 8. As seen, the conversion efficiency is in the same
21 range with the PV efficiency used in this study; however, the thermal efficiency presented
22 in this paper has slightly higher efficiency due to direct heat exchange between water and
23 PV surface.

24 Although integrating PV with the cooling system lead to higher power efficiency along
25 with supplying a part of thermal demand, commercializing the cooling system depends on
26 the payback period. The utilized heat recovery system from PV takes advantage of lower
27 cost in comparison to the other commercialized systems with preserving its efficiency. In

1 case that gas FOB¹ price is $10 \frac{\text{¢}}{\text{Nm}^3}$, electricity price is $16 \frac{\text{¢}}{\text{kWh}}$ [23], and 1 Iranian Rail
2 equals 0.00002\$. The capital cost is obtained $20 \frac{\text{¢}}{\text{W}}$ (it should be mentioned the cooling
3 system is insulated). The payback period of the cooling system is influenced from using or
4 wasting the output water energy, if output water is used as water inlet to the solar water
5 heater or a gas-fired water heater, the payback period is estimated 1.7 years; otherwise, the
6 payback period is exceeded than 8.7 years that shows the developed cooling system can be
7 interesting for home application. **Conclusions**

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

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

19 Acknowledgment

20 The paper received funding from Sharif Research Energy Institute (SERI). The support
21 of SERI is kindly acknowledged.

¹ Free On Board

1 References

- [1] S. A. Kalogirou, "Solar energy engineering processes and systems," 2th Edition, Elsevier, 2013.
- [2] T. T. Chow, "A review on photovoltaic / thermal hybrid solar technology." *Applied Energy*, vol. 87, no. 2, pp. 365–379, 2010.
- [3] H. A. Zondag, D. W. de Vries, W. G. J. van Helden, R. J. C. van Zolingen, and A. A. van Steenhoven, "The thermal and electrical yield of a PV-thermal collector." *Solar Energy*, vol. 72, no. 2, pp. 113–128, 2002.
- [4] De Vries, D.W "Design of a photovoltaic / thermal combi-panel." *Eindhoven University of Technology*, Ph.D Thesis, 1998.
- [5] P. G. Charalambous, G. G. Maidment, S. A. Kalogirou, and K. Yiakoumetti, "Photovoltaic thermal (PV/T) collectors: A review." *Applied Thermal Engineering*, vol. 27, pp. 275–286, 2007.
- [6] C. Lamnatou and D. Chemisana, "Photovoltaic/thermal (PV/T) systems: A review with emphasis on environmental issues." *Renewable Energy*, vol. 105, pp. 270–287, 2016.
- [7] J. Prakash, "Transient Analysis of a photovoltaic -thermal solar collector for co-generaion of hot air/water." *Energy Conversion and Management*, vol. 35, no. 11, pp. 967–972, 1994.
- [8] H. Saitoh *et al.*, "Field experiments and analyses on a hybrid solar collector." *Applied Thermal Engineering*, vol. 23, pp. 2089–2105, 2003.
- [9] S. Dubey and G. N. Tiwari, "Thermal modeling of a combined system of photovoltaic thermal (PV / T) solar water heater." *Solar Energy*, vol. 82, pp. 602–612, 2008.
- [10] M. Abdolzadeh and M. Ameri, "Improving the effectiveness of a photovoltaic water pumping system by spraying water over the front of photovoltaic cells." *Renewable Energy*, vol. 34, pp. 91–96, 2009.
- [11] F. Sarhaddi, S. Farahat, H. Ajam, A. Behzadmehr, and M. M. Adeli, "An improved thermal and electrical model for a solar photovoltaic thermal (PV / T) air collector." *Applied Energy*, vol. 87, pp. 2328–2339, 2010.
- [12] A. Fudholi, K. Sopian, M. H. Yazdi, M. H. Ruslan, A. Ibrahim, and H. A. Kazem, "Performance analysis of photovoltaic thermal (PV/T) water collectors." *Energy Conversion and Management*, vol. 78, pp. 641–651, 2014.
- [13] A. Ibrahim, A. Fudholi, K. Sopian, and M. Y. Othman, "Efficiencies and improvement potential of building integrated photovoltaic thermal (BIPVT) system." *Energy Conversion and Management*, vol. 77, pp. 527–534, 2014.
- [14] G. Colangelo, D. Romano, G.M.Tina, "Performance Evaluation of a New Type of Combined Photovoltaic – Thermal Solar Collector." *Solar Energy Engineering*, vol. 137, pp. 1–12, 2015.

- 1 [15] C. G. Popovici, S.V. Hudişteanu, T.D. Mateescu and N.C. Chereche, "Efficiency
2 improvement of photovoltaic panels by using air cooled heat sinks." *Energy*
3 *Procedia*, vol.85, pp: 425-432, 2016.
- 4 [16] S. Nižetić, D. Čoko, A. Yadav, and F. Grubišić-Čabo, "Water spray cooling
5 technique applied on a photovoltaic panel: The performance response." *Energy conversion*
6 *and management*, Vol. 108, pp. 287-296, 2016.
- 7 [17] M. Proell, P. Osgyan, H. Karrer, and C. J. Brabec, "Experimental efficiency of a
8 low concentrating CPC PVT flat plate collector." *Solar Energy*, vol. 147, pp. 463–469,
9 2017.
- 10 [18] R. Tripathi and G. N. Tiwari, "Annual performance evaluation (energy and
11 exergy) of fully covered concentrated photovoltaic thermal (PV/T) water collector: An
12 experimental validation." *Solar Energy*, vol. 146, pp. 180–190, 2017.
- 13 [19] S. Tselepis and Y. Tripanagnostopoulos, "Economics analysis of hybrid
14 photovoltaic/thermal solar systems and comparison with standard pv modules."
15 *Proceedings of the international conference PV in Europe*, pp. 7-11.
- 16 [20] J. J. Michael, S.Iniyan, R.Goic,"Flat plate solar photovoltaic–thermal (PV/T)
17 systems:A reference guide." *Renewable and Sustainable Energy Reviews*,pp62-38,2015.
- 18 [21] M. Mattei, G. Notton, C. Cristofari, M. Muselli, and P. Poggi, "Calculation of the
19 polycrystalline PV module temperature using a simple method of energy balance."
20 *Renewable Energy*, vol. 31, pp. 553–567, 2005.
- 21 [22] B.J. Huang, T.H. Lin, W.C. Hung, and F.S. Sun, "Performance evaluation of solar
22 photovoltaic/thermal systems." *Solar energy*, vol. 70, pp. 443-448, 2001.
- 23 [23] SATBA, Renewable Energy and Energy Efficiency Organization, Retrieved from.
24 http://www.satba.gov.ir/suna_content/media/image/2016/09/4815_orig.pdf ,2018.
- 25
- 26

1 **Abstract**

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

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

20

21

22

23

1 **Introduction**

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

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

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

28 J. Prakash et al. [7] studied a hybrid PV/T solar system from a theoretical viewpoint. In
29 this system, air and water are directed to a duct placed below the solar panel surface; as

1 a result, the temperature of solar panel will be reduced by extraction of heat from the
2 panel. Thereby, the electrical efficiency is enhanced noticeably by the applied
3 mechanism. It is concluded that the thermal efficiency varies in a range of 50% to 67%
4 while water is used as the cooling fluid. The mentioned improvement is reduced in a
5 range of 17% to 51% if the cooling water is substituted with cooling air. The lower heat
6 transfer rate between the absorber plate and the flowing air in compare to the water
7 causes the decrement in the thermal efficiency. H. Saitoh et al. [8] did experimental and
8 analytical research on simultaneous power and heat generation with a hybrid solar
9 collector. The result demonstrates that electrical conversion efficiency is around 10%-
10 13%. In case of brine temperate around 20C, the collector efficiency and overall
11 efficiency (electrical conversion efficiency + collector efficiency) are obtained 40-50%
12 and 50-60%, respectively, while if the brine temperature reaches 40C, the collector
13 efficiency and overall efficiency decrease to 20% and 30%, respectively. The study
14 shows that the hybrid collector has the advantage of higher exergy efficiency. S. Dubey
15 and G. N. Tiwari [9] developed an integrated combined system of a PV/T solar water
16 heater customized for New Delhi climate. It is observed that PV/T with flat plate
17 collector partially covered with PV module has better thermal and average cell
18 efficiency. Moreover, distinguishable enhancement in the efficiency from 33% to 64% is
19 achieved due to glazing area increment. M. Abdolzadeh and M. Ameri [10] developed a
20 PV/T water collector set up to increase the flow rate of a photovoltaic water pumping
21 system that is performed by spraying water over the photovoltaic cells. Experimental
22 results demonstrate that spraying water over the cells increases the performance indexes.
23 The improvement of average PV cell efficiency, subsystem efficiency, and total
24 efficiency are reported 3.26%, 1.40%, and 1.35%, respectively. Improving PV electrical
25 efficiency transfers a higher power to the pump that means increasing water flow rate.
26 Coupling a PV with the suggested cooling system, to a pump, can provide 644L/h flow
27 rate at 16m head, while if the cooling system is inactive, the flow rate drops to 479L/h at
28 16m head. F. Sarhaddi et al. [11] quantify the thermal and electrical indexes of a typical
29 PV/T air collector. Some corrections are done on heat loss coefficients for improving the
30 PV/T air collector thermal model. The result exhibits that overall energy efficiency of
31 PV/T air collector reaches 45%. A. Fudholi et al. [12] investigated the energy generated

1 by PV/T water collector in the condition that solar radiation is about $500\text{-}800\frac{W}{m^2}$. The
 2 results reveal that PV electrical efficiency, PV thermal efficiency, and the PV/T water
 3 collector can reach to 13.8%, 54.6% and 68.4%, respectively when the water flow rate is
 4 0.041 kg/s and solar radiation is on the maximum solar radiation ($800\frac{W}{m^2}$). A. Ibrahim et
 5 al. [13] designed a building integrated PV/T system to produce both electricity and hot
 6 water which is implemented in a building. It should be mentioned that this paper was
 7 based on energy efficiency, exergy efficiency, and potential of exergetic improvement
 8 according to the metrological condition of Malaysia. The results demonstrate that the
 9 PV/T energy efficiency varies between 55% and 62%. Furthermore, the variation of
 10 PV/T exergy efficiency is from 12 to 14%. C. Colangelo et al [14] developed a thermal
 11 analysis of a new PV/T solar panel using RADTHERM THERMOANALITICS
 12 software. Several combinations of water flow rates and different panel configurations
 13 have been investigated to determine the best performance in terms of optimal PV
 14 efficiency and available thermal energy. G. Popovici et al. [15] developed a numerical
 15 model to investigate effect of air cooled heat sinks on PV conversion efficiency
 16 improvement. The heat sink that is attached at the back of PV panel is composed from a
 17 ribbed wall with specific dimensions. The results reveal in case of equipping 80W PV
 18 with 16% nominal efficiency with the best configuration of the air cooled heat sink
 19 designed in the paper, the efficiency improvement is around 7.6%. The results presented
 20 is obtained at solar radiation $500\frac{W}{m^2}$. G. S. Nizetic' et al. [16] developed a cooling
 21 system spraying over both sides of the panel. The improved electrical efficiency of a
 22 mono crystalline photovoltaic is reported 16.3% when the temperature decreases from
 23 54°C to 24°C and the both sides of PV are cooled down. While if the back surface is
 24 cooled down, the efficiency improvement is reached 14%. M. Proell et al. [17] presented
 25 a novel concept for improving the thermal efficiency of PV/T through concentrating
 26 sunlight with compound parabolic concentrator reflectors to attain a higher radiation
 27 power. The experiments were implemented at ZAE Bayern in Garching, Germany. The
 28 results exhibit the thermal efficiency of equipped PV/T with maximum power point
 29 tracking is enhanced to 34% thermal efficiency in compare to a glazed flat plate PV/T
 30 with 17% thermal efficiency when there is 60K temperature difference between ambient

1 and the collector although the electrical efficiency drops noticeably from 15% to 9%
2 because of temperature increment and a non-uniform flux distribution caused by the
3 reflectors. R. Tripathi and G. N. Tiwari [18] developed a single experimental set up
4 which was fully covered with concentrated PV/T collector. This experiment was done
5 with the objective of achieving both thermal and electrical energy at the same time in IIT
6 Delhi, India. Two cases are taken into account on the basis of receiver rotation regarding
7 sun movement. The first case is allocated to a fixed position and the second is the
8 manual maximum power point tracking technique. As expected, the second case shows a
9 better performance. Furthermore, the thermal energy difference between the second case
10 and the first case is 25%, while the exergy difference is around 19%.

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

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

23 Besides the abovementioned considerations in association with equipping PV with a
24 cooling system, the challenging issues and the obstacles should be observed. The
25 conventional problems are access to water (in order to lower PV cell temperature) and as
26 well as hot water demand especially in the case of PV power plants, concern about
27 isolating water from electric junctions, difficulties originated from integrating the
28 system to the fossil fuel fired water heater and restrictions in transportation due to
29 fragility insulation layer injected in the cooling system. Moreover, some cooling systems
30 [10,16] disperse/spray water on PV glass that leads to emerge tracks on the glass due to

1 water minerals, that causes the PV conversion efficiency might be dropped out because
2 of reducing irradiation to the cells and loading effect originating from non-uniform
3 tracks. In addition, cleaning the tracks and water vaped from the glass impose
4 operational costs.

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

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

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

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

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

12 **Methodology**

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

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

28 **[Figure. 1. About here [11]]**
29

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

$$I_{pv} = I_L - I_0 \left[\exp \left(\frac{V_{pv} + I_{pv} R_s}{V_t} \right) - 1 \right] - \frac{V_{pv} + I_{pv} R_s}{R_{SH}} \quad (2)$$

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

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.

$$I_{pv} = I_L - I_0 \left[\exp \left(\frac{V_{pv} + I_{pv} R_s}{V_t} \right) \right] \quad (4)$$

Open circuit voltage is estimated by equation (5)

$$V_{OC} = V_t \ln \left(\frac{I_{SC}}{I_0} \right) \quad (5)$$

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).

$$I_0 = I_{SC} \exp \left(-\frac{V_{OC}}{V_t} \right) \quad (7)$$

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

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

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

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

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

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

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

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

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

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

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

17 **Experimental set-up**

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

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.

7 [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 m² 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.

26 [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

1 horizontal plane facing south. So, preheated water is flowed in the water heater and
2 moved toward the storage box with a 50 liter capacity for storing hot water.

3 [Figure.3. about here]

4 **Results**

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

11

12 [Figure. 3. about here]

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

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

18 [Figure. 4. about here]

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

21 [Figure. 5. about here]

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

24 [Figure. 7. about here]

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

1 (12.5%). However, the average efficiency of PV without coolant is 10.9%. Finally, the
2 coolant system enhances 12.8% average conversion efficiency. The role of the cooling
3 system in the conversion efficiency improvement has acceptable agreement with the
4 cooling system developed by S. Niẑetic' et al. [16]. Although the cooling system
5 developed by S. Niẑetic' et al. [16] yields higher conversion efficiency in compare to
6 this study, the water flow and water head loss in this study is lower. Moreover, water
7 cooling panel in this study against the cooling system presented by S. Niẑetic' et al.
8 [16] is not in exposed of atmosphere therefore water consumption in cooling system is
9 zero.

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

23 Although integrating PV with the cooling system lead to higher power efficiency along
24 with supplying a part of thermal demand, commercializing the cooling system depends
25 on the payback period. The utilized heat recovery system from PV takes advantage of
26 lower cost in comparison to the other commercialized systems with preserving its
27 efficiency. In case that gas FOB¹ price is $10 \frac{\text{¢}}{\text{Nm}^3}$, electricity price is $16 \frac{\text{¢}}{\text{kWh}}$ [23], and 1
28 Iranian Rail equals 0.00002\$. The capital cost is obtained $20 \frac{\text{¢}}{\text{W}}$ (it should be mentioned

¹ Free On Board

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

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

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

17 **Acknowledgment**

18 The paper received funding from Sharif Research Energy Institute (SERI). The support
19 of SERI is kindly acknowledged.

1 **References**

- 2 [1] S. A. Kalogirou, “Solar energy engineering processes and systems,” 2th Edition,
3 *Elsevier*, 2013.
- 4 [2] T. T. Chow, “A review on photovoltaic / thermal hybrid solar technology.”
5 *Applied Energy*, vol. 87, no. 2, pp. 365–379, 2010.
- 6 [3] H. A. Zondag, D. W. de Vries, W. G. J. van Helden, R. J. C. van Zolingen, and
7 A. A. van Steenhoven, “The thermal and electrical yield of a PV-thermal collector.”
8 *Solar Energy*, vol. 72, no. 2, pp. 113–128, 2002.
- 9 [4] De Vries, D.W “Design of a photovoltaic / thermal combi-panel.” *Eindhoven*
10 *University of Technology*, Ph.D Thesis, 1998.
- 11 [5] P. G. Charalambous, G. G. Maidment, S. A. Kalogirou, and K. Yiakoumetti,
12 “Photovoltaic thermal (PV/T) collectors: A review.” *Applied Thermal Engineering*, vol.
13 27, pp. 275–286, 2007.
- 14 [6] C. Lamnatou and D. Chemisana, “Photovoltaic/thermal (PV/T) systems: A review
15 with emphasis on environmental issues.” *Renewable Energy*, vol.105, pp.270-287, 2016.
- 16 [7] J. Prakash, “Transient Analysis of a photovoltaic -thermal solar collector for co-
17 generaion of hot air/water. ” *Energy Conversation and Management*, vol. 35, no. 11, pp.
18 967–972, 1994.
- 19 [8] H. Saitoh *et al.*, “Field experiments and analyses on a hybrid solar collector.”
20 *Applied Thermal Engineering*, vol. 23, pp. 2089–2105, 2003.
- 21 [9] S. Dubey and G. N. Tiwari, “Thermal modeling of a combined system of
22 photovoltaic thermal (PV / T) solar water heater.” *Solar Energy*, vol. 82, pp. 602–612,
23 2008.
- 24 [10] M. Abdolzadeh and M. Ameri, “Improving the effectiveness of a photovoltaic
25 water pumping system by spraying water over the front of photovoltaic cells.”
26 *Renewable Energy*, vol. 34, pp. 91–96, 2009.
- 27 [11] F. Sarhaddi, S. Farahat, H. Ajam, A. Behzadmehr, and M. M. Adeli, “An
28 improved thermal and electrical model for a solar photovoltaic thermal (PV / T) air
29 collector.” *Applied Energy*, vol. 87, pp. 2328–2339, 2010.
- 30 [12] A. Fudholi, K. Sopian, M. H. Yazdi, M. H. Ruslan, A. Ibrahim, and H. A. Kazem,
31 “Performance analysis of photovoltaic thermal (PV/T) water collectors.” *Energy*
32 *Conversation and Management*, vol. 78, pp. 641–651, 2014.
- 33 [13] A. Ibrahim, A. Fudholi, K. Sopian, and M. Y. Othman, “Efficiencies and
34 improvement potential of building integrated photovoltaic thermal (BIPVT) system.”
35 *Energy Conversation and Management*, vol. 77, pp. 527–534, 2014.
- 36 [14] G. Colangelo, D. Romano, G.M.Tina, “Performance Evaluation of a New Type of
37 Combined Photovoltaic – Thermal Solar Collector.” *Solar Energy Engineering*, vol.
38 137, pp. 1–12, 2015.

- 1 [15] C. G. Popovici, S.V. Hudişteanu, T.D. Mateescu and N.C. Chereche, "Efficiency
2 improvement of photovoltaic panels by using air cooled heat sinks." *Energy*
3 *Procedia*, vol.85, pp: 425-432, 2016.
- 4 [16] S. Nižetić, D. Čoko, A. Yadav, and F. Grubišić-Čabo, "Water spray cooling
5 technique applied on a photovoltaic panel: The performance response." *Energy*
6 *conversion and management*, Vol. 108, pp. 287-296, 2016.
- 7 [17] M. Proell, P. Osgyan, H. Karrer, and C. J. Brabec, "Experimental efficiency of a
8 low concentrating CPC PVT flat plate collector." *Solar Energy*, vol. 147, pp. 463-469,
9 2017.
- 10 [18] R. Tripathi and G. N. Tiwari, "Annual performance evaluation (energy and
11 exergy) of fully covered concentrated photovoltaic thermal (PV/T) water collector: An
12 experimental validation." *Solar Energy*, vol. 146, pp. 180-190, 2017.
- 13 [19] S. Tselepis and Y. Tripanagnostopoulos, "Economics analysis of hybrid
14 photovoltaic/thermal solar systems and comparison with standard pv modules."
15 *Proceedings of the international conference PV in Europe*, pp. 7-11.
- 16 [20] J. J. Michael, S.Iniyan, R.Goic,"Flat plate solar photovoltaic-thermal (PV/T)
17 systems:A reference guide." *Renewable and Sustainable Energy Reviews*,pp62-38,2015.
- 18 [21] M. Mattei, G. Notton, C. Cristofari, M. Muselli, and P. Poggi, "Calculation of the
19 polycrystalline PV module temperature using a simple method of energy balance."
20 *Renewable Energy*, vol. 31, pp. 553-567, 2005.
- 21 [22] B.J. Huang, T.H. Lin, W.C. Hung, and F.S. Sun, "Performance evaluation of solar
22 photovoltaic/thermal systems." *Solar energy*, vol. 70, pp. 443-448, 2001.
- 23 [23] SATBA, Renewable Energy and Energy Efficiency Organization, Retrieved from.
24 http://www.satba.gov.ir/suna_content/media/image/2016/09/4815_orig.pdf ,2018.
- 25
- 26

Table 1: Specification of PV module.....2

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.....2

Figure. 2. Schematic of the system.....3

Figure. 3. PV/T collector system.....4

Figure. 4. The total solar radiation on a typical day.....5

Figure. 5. The effect of the coolant on PV power.....6

Figure. 6. Temperatures of ambient, PV and output water.....7

Figure. 7. The electrical efficiency of the photovoltaic panel.....8

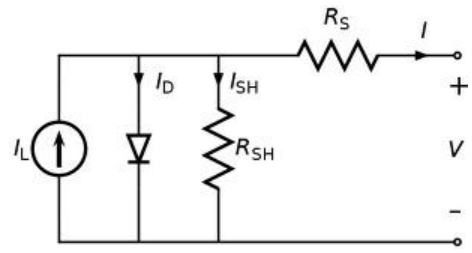


Figure.1. equivalent single diode circuit

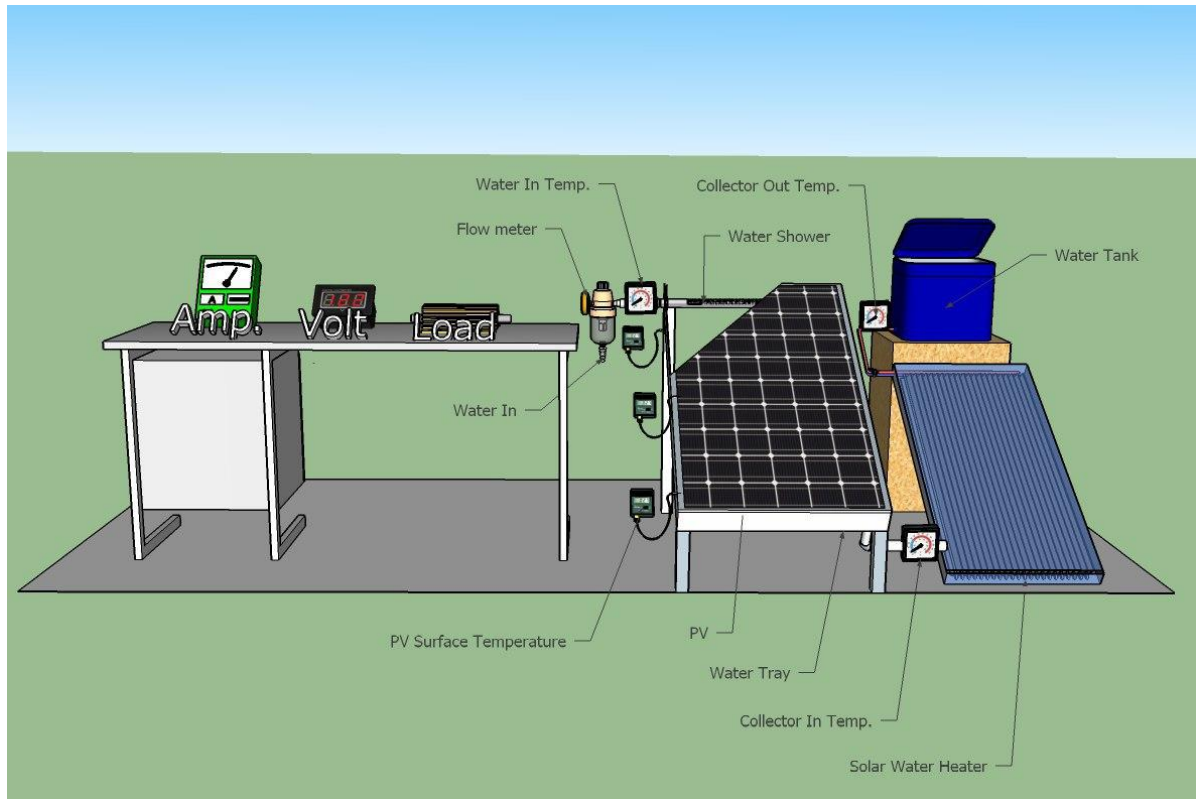


Figure.2. Schematic of the system



Figure.3. PV/T collector system

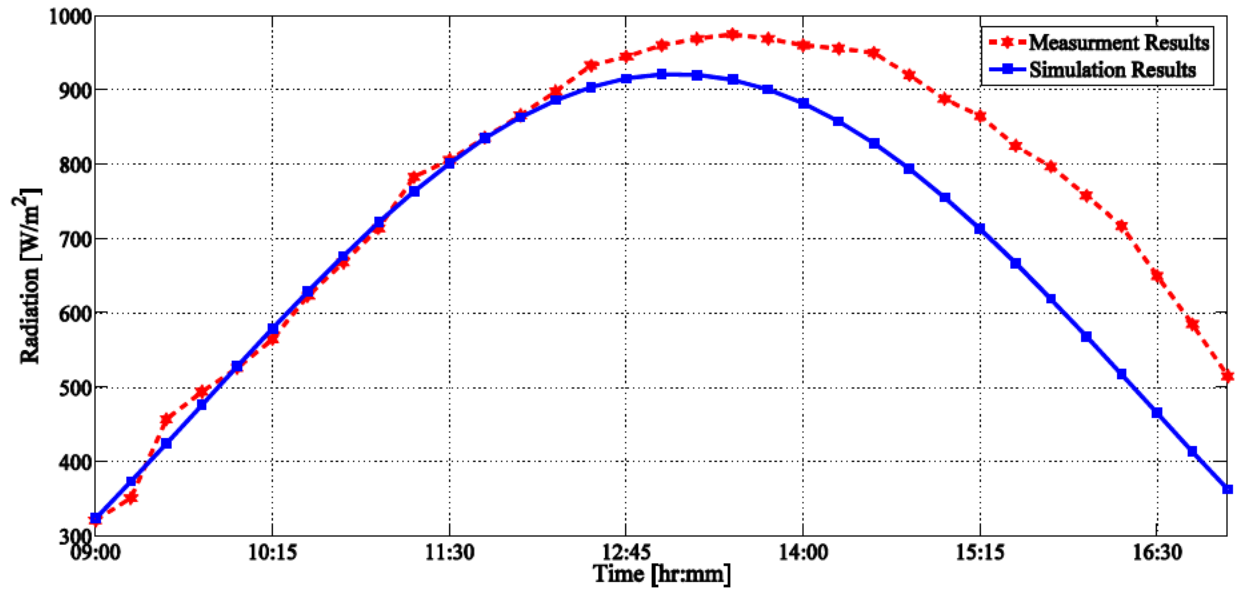


Figure.4. The total solar radiation on a typical day

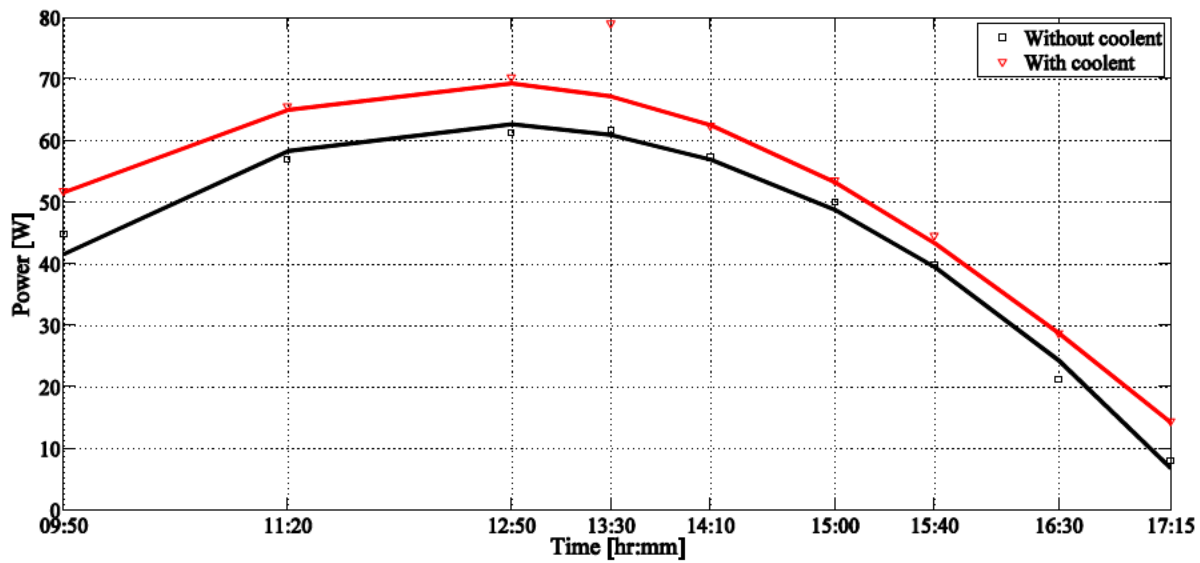


Figure.5. The effect of the coolant on PV power

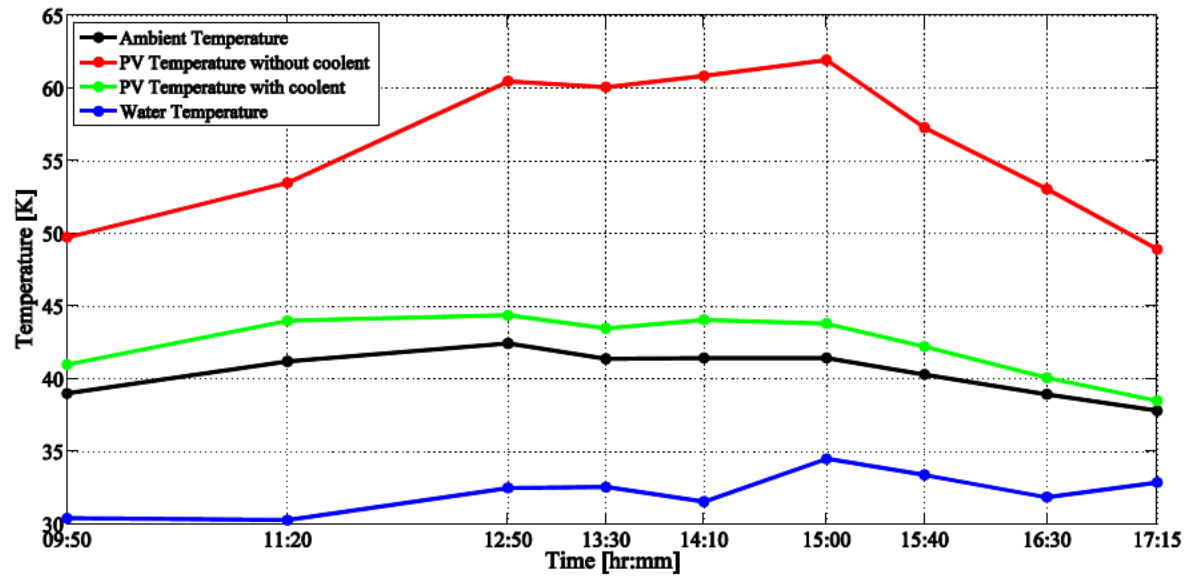


Figure.6. Temperatures of ambient, PV and output water

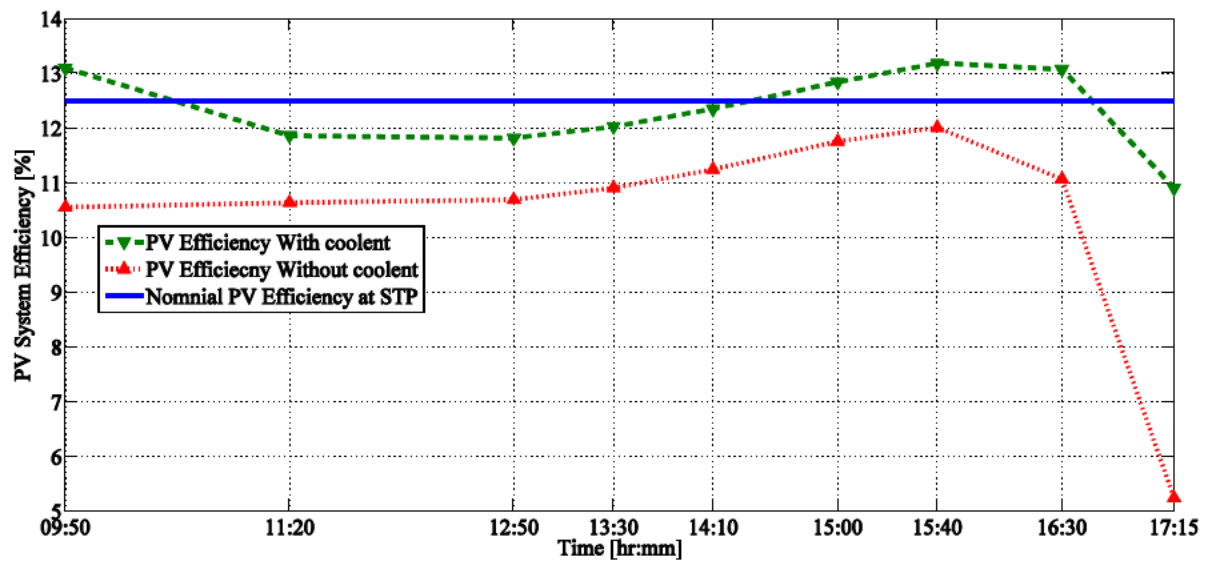


Figure.7. The electrical efficiency of the photovoltaic panel