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Experimental Investigation of Photovoltaic–Thermoelectric Generator (PV-TEG) Integrated Hybrid System Performance

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Keywords
Hybrid system, Photovoltaic, Thermoelectric generator, Solar energy, Harvesting.

Abstract
A coupling of photovoltaic (PV) and thermoelectric generator (TEG), called the photovoltaic-thermoelectric (PV-TEG) hybrid system, is a promised technique to influentially make wider the utilize of solar radiation that falling on the upper surface of the PV and harvesting the wasted heat in the PV via the TEG module to increase the total output power and boosted (PV-TEG) system comprehensive performance. The combination of photovoltaic and thermoelectric apparatus demands specific interest since the solar cell with the thermoelectric device own an inverse relation with temperature. Therefore, the research study was been experimental. Firstly, the optimum design of (PV-TEG) hybrid system performance was tested experimentally in the indoor environment inside the Graduate Studies Laboratory of the College of Engineering, University of Kerbala to validate the correctness of the chosen system. Secondly, The (PV-TEG) performance was emulate with the solar cell system alone and the photovoltaic/ thermal system performance. The results appeared that the PV- 50 items of TEG as model of hybrid system generated an electrical power was higher by (31.66 % and 16.5 %) compared with that of the traditional photovoltaic only and the PV/T system experimental under the same operating conditions. The electrical output power (Eel) and electrical efficiency (ηel) of the PV-TEG hybrid system were higher than that of the PV module and PV/T system in all tests. The Eel is about (20.21) W and ηel is about 5.83 % in experimental tests.

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1. Introduction

These days, the fast integration of renewable energy advances into the worldwide energy supply foundation is fundamental due to the developing concerns concerning worldwide warming and climate alter issues. Sun-oriented energy collecting has developed a promising arrangement to embrace a clean and economical power generation demonstration inside this system. Photovoltaic

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innovation, which converts sun-powered energy straightforwardly into electrical power, is the foremost solid among other sun-based transformation choices because the absence of dynamic parts, low servicing requirements, and noiseless operation (D.N. Kossyvakis, G.D. Voutsinas 2016). In any case, despite the colossal advance made by photovoltaic cells to date, particularly (commercially accessible sun-powered cells as crystalline PV cells), their restricted proficiency between (10%-20%), The wide range of incoming solar radiation is not used, resulting in a large loss of energy during the conversion process. As a result, most of the retained energy is changed into warm energy, which leads to higher PV temperatures and thus a decrease in throughput due to the temperature coefficient. For an instant, under higher operating temperatures, the output power of crystalline photovoltaic cells could reduce by 0.4 percent to 0.65 percent for each 1 degree Celsius (He et al. 2013). In addition, this waste energy cuts short the life of the PV. Therefore, the solar cell operating temperature can be maintained at an acceptable level by using thermal management devices for a cooling PV module, such as passive or active coolintechniques(Hashim 2015).

Then it is called a combined photovoltaic/thermal (PV/T) system. Many (PV/T) hybrid systems have been studied for regaining the heat dispersion from the solar panel and using it for thermic employments like the warming of water that becomes less, water distillation, and environment heating(Darkwa et al. 2019). Generally, PV/T systems increase overall energy output (electrical energy + thermal energy) than photovoltaic and low-grade thermal energy contrasted to thermal systems employed alone. So it becomes necessary to find a device that converts waste heat straight into electric energy, like a thermoelectric TE device. A thermoelectric generator (TEG) is an ecologically safe, solid-state heat engine that converts waste heat into electrical power by the Seeback effect depending on the temperature variance between TEG's cold and hot side (Darkwa et al. 2019) and (Hashim, Lafta Rashid, and Jawad Kadham n.d.). Different researchers are examining viability of using thermoelectric generators in diverse applications, for instance waste heat recovery from automobiles(Imran and Hashim 2020) , Ovens (Hashim 2018).

Lately, Since the great plane of attention in like hybrid systems and their large potential for improved performance compared to solar cell systems, there has been an increase in the numbering research papers emitted on PV-TEG (M W Aljibory 2021). Mainly, the PV-TE can be separated into two types of designs: splitting of spectrum (Ju et al. 2012) and direct coupling. The PV and TEG are connected directly and parallelly in the direct coupling method. A sink of heat is linked to the base of the TEG, and the PV is put right above it. The shorter wavelengths are absorbed by the PV, whereas the longer wavelengths are absorbed via the TEG, so the PV is placed over the TEG(Huen and Daoud 2017). Furthermore, the PV's unabsorbed solar energy passes through the PV to the TEG below when using the direct connection approach. It acts as a heat source for the TEG, generating electricity(Dallan, Schumann, and Lesage 2015).

However, based on previous surveys in most investigations, coupling a TEG module to a prototype solar cell as a hybrid system has improved the performance of solar cells and the PV-TEG system efficiency. This improvement is attributed to removing excess heat from the solar system, which enhances the efficiency of the photovoltaic system, rather than adding the singular PV efficiency and TEG systems, since the increase in the number of thermoelectric modules coupled with the photovoltaic panel does not directly increase the output power. The reason is the nonlinear relationship between TEG and the PV cell and the effect of the cooled TEG medium. Therefore, the current research aims to investigate the optimum model system performance of a photovoltaic hybrid system with 50 items of TEG unit numbers. Also, comparing the performance of a (PV-TEG) hybrid system with a simple PV system alone and that of a PV system with a thermal system (PV/T) under the same boundary conditions using an efficient cooling system.

2. Description and Operation of Systems

2.1. Description of Systems

In the current study, the sample of three-dimension has been evolved to research the overall thermal performance of PV, PVT, and PV-TEG structures. Figure 1depicts the simulated optimum model of system(PV-TEG) with numbers and distribution of TEG items. The simplest distinction among the PV-TEG and PV/T structures is the lack of the layer of TE module in the PV/T system. The hybrid system (PV-TEG) consists of Mono-crystalline silicon photovoltaic (m-Si) PV cells. Besides its lower cost, Monocrystalline types can accomplish the most elevated efficiency compared to polycrystalline silicon and amorphous silicon(Darkwa et al. 2019). The PV cells are attached to the top of thermoelectric generator TEG modules (the hot side) via a conductive plate from aluminum to transmit the heat from the PV panel to the TEG hot side (Hashim, Bomphrey, and Min 2016) as well as a heat exchanger (shell and tube water collector) with cooling water under the cold side of TEG to increase the temperature difference between the high-temperature side and low-temperature side of TEG. The PV module, as illustrated in figure(2a), forms of five strata, viz: glass, ethylene-vinyl acetate (EVA), monocrystalline silicon cell, EVA, and TPT (Tedlar polyester Tedlar) from upper to lower in the order. The TEG selected type of (the TEC-12715) module. It was a sufficient option to be used as a heat generator as it is available on the local market, operating under the maximum temperature of hot side is 70℃, and its minimized price liken to other thermo- electric devices (Riahi et al. 2020). The TEG consists of the following layers as offered in figure (2b): ceramic, 127 pairs of n-type and p-type thermoelements composed of (Bi_2Te_3) semiconductor materials that supply the electrical connexion in the TEG, and ceramic provides thermal conductivity (Mahmoudinezhad et al. 2018). The heat exchanger is selected shell and tube type or known (Serpentine flow design) as shown in figure (2c), it consists of copper pipes that linked at the bottom of the absorber (aluminum plate) (Zhou, Ke, and Deng 2018)and (Abdulameer Sachit et al. 2019).

2.2. System Operation

Amid operation, sun oriented light strikes the upper surface of the photovoltaic module, so one division of the sun oriented radiation is changed over to PV power; another division is lost to the around such as through radiation and convection from the glass layer, and the remaining vitality is transmitted to the TEG module through conduction warm exchange. At last, agreeing to the Seebeck impact, a parcel of the warm vitality ingested by the TEG module changes over to power. At the same time, the heat exchanger evacuates the larger part of the warm from the working water that streams through it. Figure 3 outlines the vitality pathway for the reenacted PV-TEG framework. Table 1 shows the geometrical dimensions of the components in the above systems(Dallan et al. 2015) and (Gu et al. 2019).

Figure 1. Simulated Hybrid System (PV-TEG)

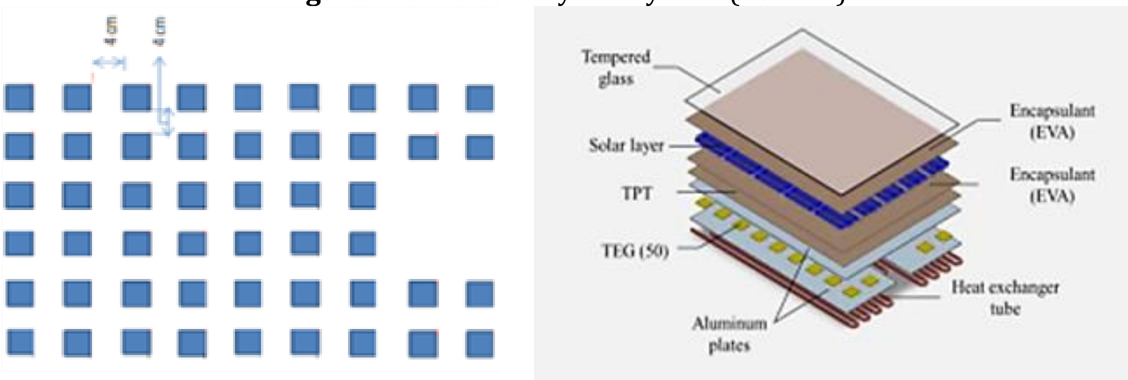


Figure 2. (a) PV layers, (b) TEG- layers, and (c) Heat exchanger components (Aluminum plate with copper pipe)

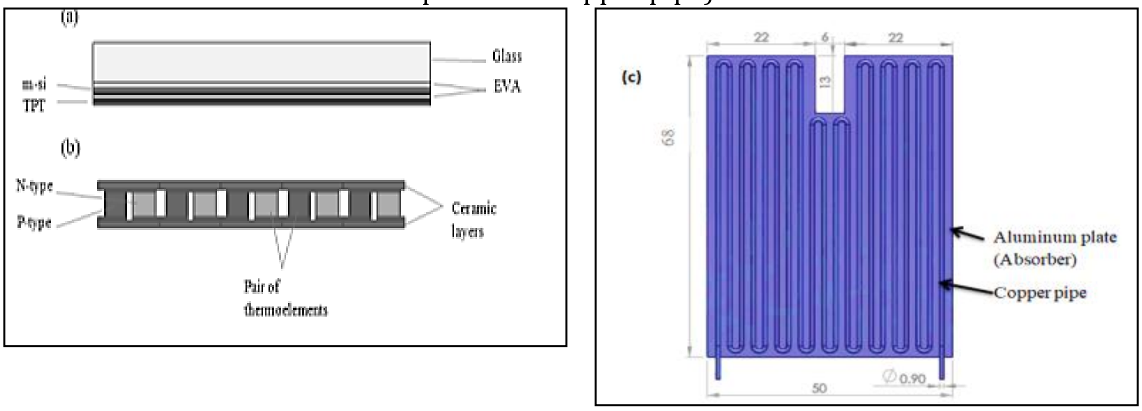


Figure 3. Illustrates the energy pathway for the simulated PV-TEG system.

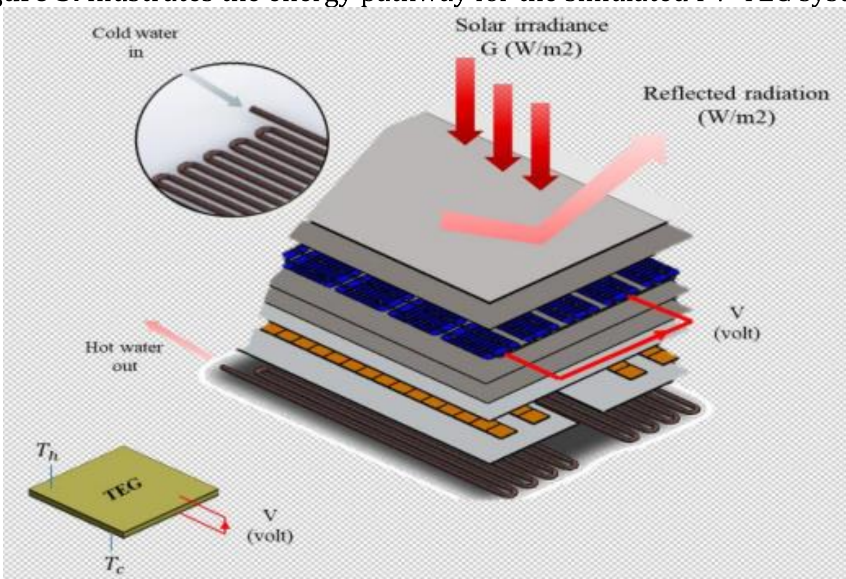


Table 1. Geometrical dimensions of the PV Panel, the heat exchanger system, and TEG system

Parameters	Dimensions (m)
PV panel	
Top Glass Layer	0.510 x 0.680 x 0.003
EVA Layer	0.510 x 0.680 x 0.0005
PV Cell Layer	0.510 x 0.680 x 0.0003
EVA Layer	0.510 x 0.680 x 0.0005
Tedlar Layer	0.510 x 0.680 x 0.0005
Thermal Concentrator(Conductive Plate)	0.500 x 0.680 x 0.002
TEG Module	
Ceramic	0.040 x 0.040 x 0.0005
Thermoelectric Element (P-N) 127 Pair	0.040 x 0.040 x 0.002
Ceramic	0.040 x 0.040 x 0.0005
Heat Exchanger (Sheet and Tube)	
Aluminum plate (absorber)	0.510 x 0.680 x 0.002
Copper pipe	
Length	9.660
Diameter	0.0127
Thickness of pipe	7.2 x10^-4

3. Experimental Work

The indoor experimental setup was built-up at Graduate Studies Laboratory of the College of Engineering, University of Kerbala during a Autumn day in Iraq. The optimum model of (PV – with 50 units of TEG) hybrid system was tested under the 1000 (W/m^2) solar flux generated by the solar simulators of 4 halogen lamps and shown in Figures(4, 5, and 6) show the test rig, detailes of experimental rig, and the schematic diagram of the experimental setup of the hybrid system. The main components are the mono-crystalline photovoltaic panel, the 50 items of Thermoelectric module, and the heat exchanger that was designed and built in the laboratory as shown in figure (7). In addition of the solar simulators, and measuring insruments.

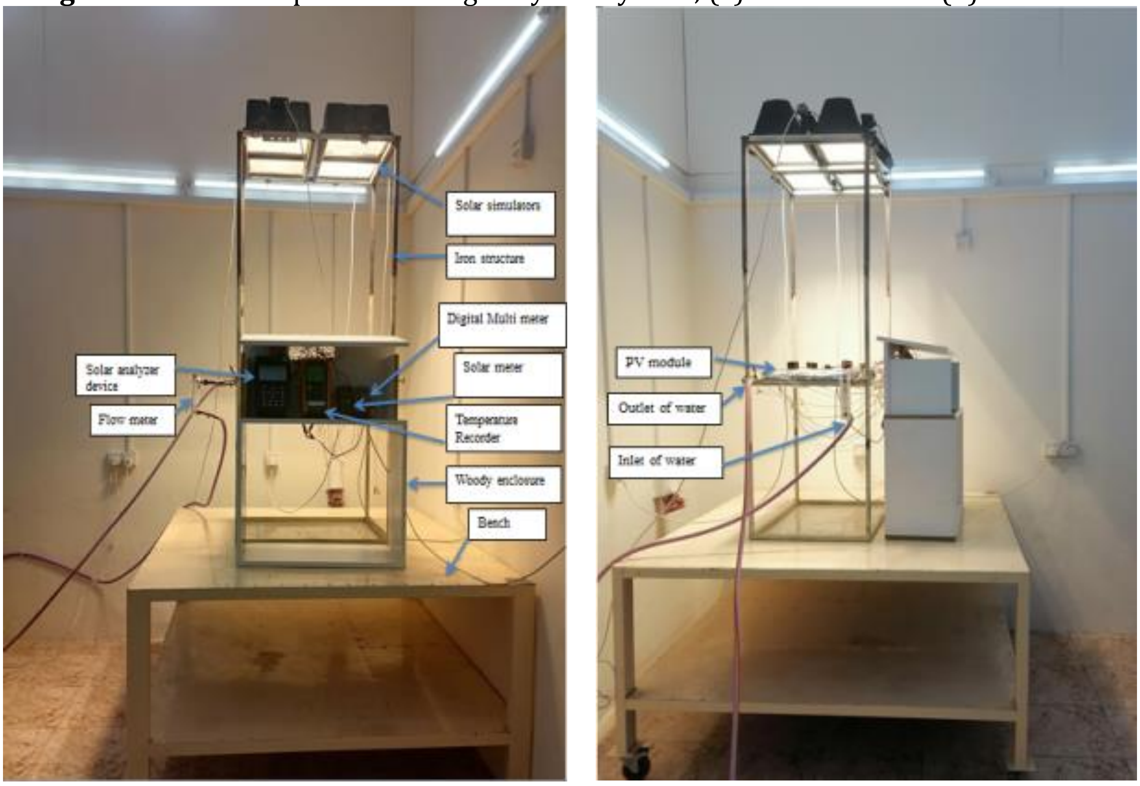
The Different types of measurement instrumentations are used in the experimental work as shown below:

- Thermocouples type (k) with the accuracy of a dvice ± 0.25 °C.
- Termperature recorder type Lutron BTM-4208SD with the accuracy of a dvice is ± (0.4 % + 0.5) °C.
- Solar module analyzer type (PROVA 200A) with the accuracy of a dvice are ± (1%) V and ± (1%) A.
- Flow meter type (ZYIA) with range (1-10) litter /min, was utilized to measure the water flow rate
- Solar Meter Type TES132 with the accuracy of a dvice is ± (5%) W/m2 ±0.38 /°C from 25°C.
- Digital multimeter type TMT 4600, This advice has been used to measure two or more electrical values principally voltage (volts) DC and AC voltage range: 200V- 600V. DC current (amps) range: 200μA-10A and resistance

(ohms)range: 200Ω - 2MΩ. It is a standard diagnostic tool for technicians in the electrical/electronic.

Water flow rate used in this study was calculated by using a simulation analysis developed by ANSYS FLUENT software for heat exchanger with main boundary conditions, as shown in the Table (2). Figure (8) shows the optimum volume flow rate of cooling fluid 7 (l/min), at which the temperature of the Aluminum sheet in the heat exchanger decreased to the lowest value. Whereas, any increment in the flow rate of running water inside the heat exchanger will not effect on the temperature distribution of the heat exchanger surface.

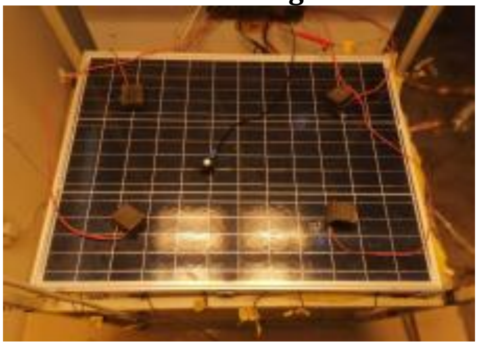
Figure 4. Parts of Experimental Rig of hybrid system; (a)Front view and (b) Side view



(a) Front View of Experimental Rig

(b) Side View of Experimental Rig

Figure 5. Details of Experimental Rig Parts



(a) Sensor of Solar Meter, Insolated thermocouples and connected rods of Digital Multimeter

(b) TEG modules arrangement

(c) Instruments of Experimental Rig

Figure 6. Schematic diagram of the PV -TEG integrating system.

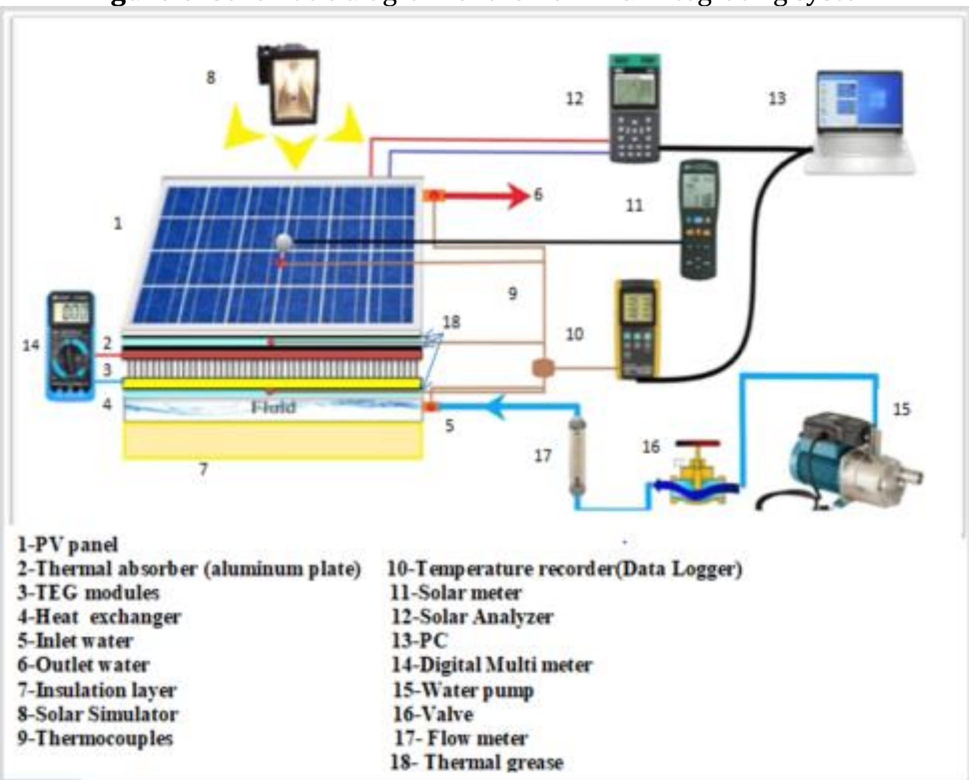


Figure 7. Heat exchanger manufacture stages

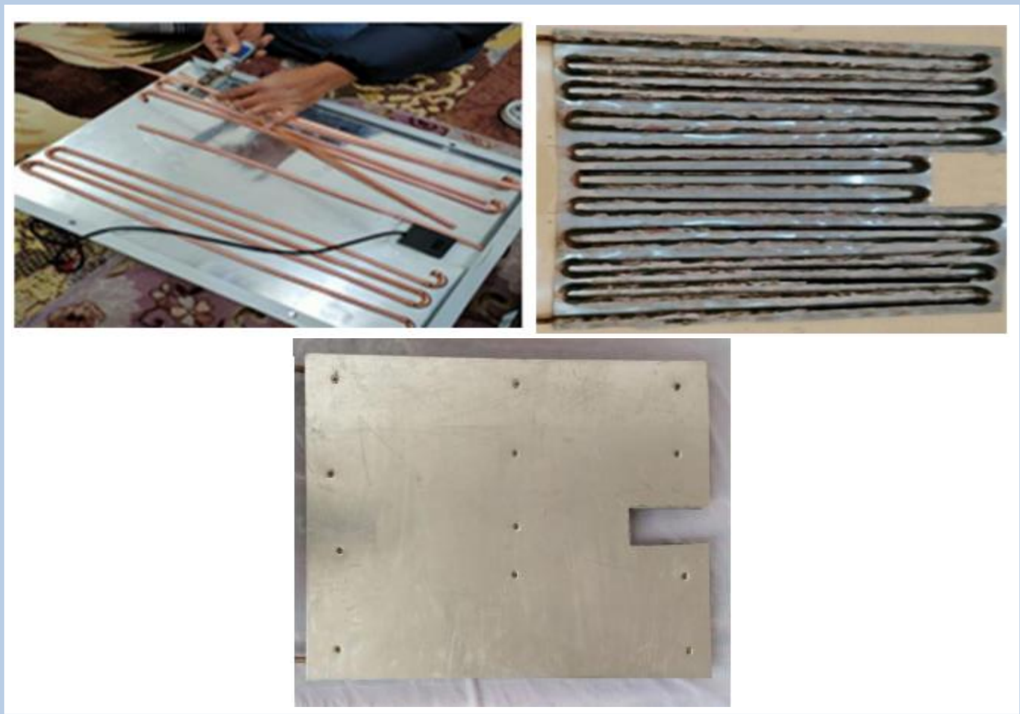
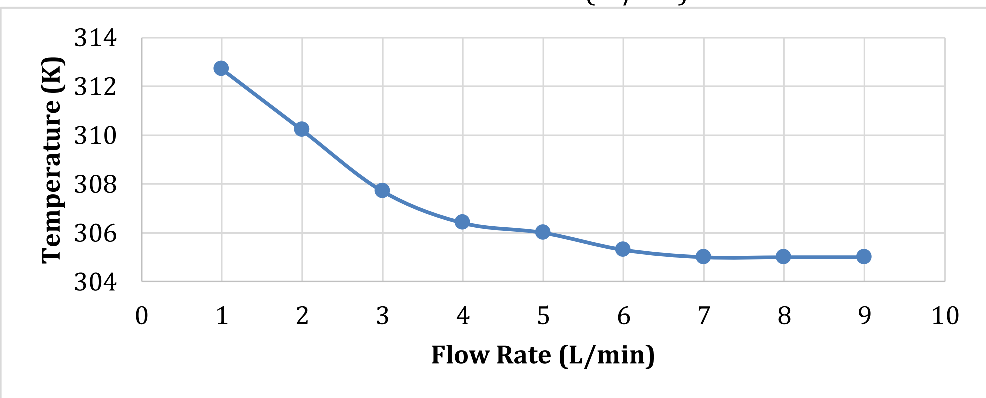


Table 2. Test Conditions

Solar irradiance	1000 W/m2
Ambient temperature	28 °C
Wind speed	0 m/s
Inlet cooling water temperature	20°C
Flow rate range	1-9 (l/min)
Coolant	Water

Figure 8. Temperature distribution average on heat exchanger surface with volume flow rate at solar radiation 1000 (W/m2)



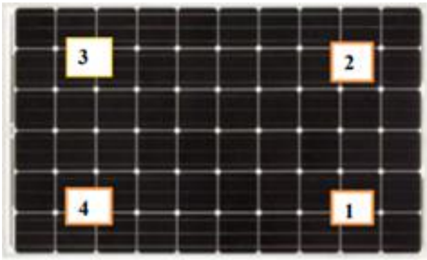
3.1. Test Rig Building

Generally, iron structures are constructed to support the PV module, the water PV/T system, and the PV -TEG hybrid system individually. In addition to all experimental rig components and measurement instrumentations that were previously mentioned. Moreover, the solar simulators are fixed on top of the iron structure and bonded with caution to avoid falling. the light of solar simulators is exposed normally down on the PV module that is installed and fixed on the slide part in the structure. In both a PV/T system and photovoltaic- thermoelectric coupling system, the flow meter device is fixed perpendicularly to the horizontal plane to measure the flow rate of inlet cooling water.

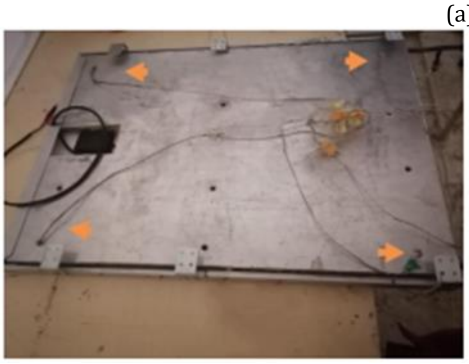
Control gate valve to supply chosen flow rate at the constant head. The four insulated and calibrated thermocouples are distributed on the PV panel front surface; a schematic diagram of the locations of thermocouples connection is shown in figure (9-a). Six thermocouples are tied, two at inlet-outlet water pipe positions and four on the back surface of the heat exchanger aluminum plate, as shown in figure (9-b). In addition, in the hybrid system, with two thermocouples are attached to the aluminum plate (thermal concentrator) by placing them in a made incision in the plate surface, as shown in figure (9-c). Next, all thermocouples are connected with a thermometer, and the wires of the PV module are connected to the solar analyzer. In addition, the solar meter is fixed on the photovoltaic surface to measure solar irradiance.

The PV panel is separately attached to the front side of an aluminum plate operating as the thermal concentrator to extract more heat from the backside of the PV panel. Subsequently, the 50 items of thermoelectric generator modules are sandwiched between the aluminum plate's backside and the front side of a heat exchanger. The thermic contact between contact areas is realized with the thermal grease tape. The thermocouples (Th) are stuck in the made incision in the aluminum plate that are assumed to be the temperature of TEG hot side. Furthermore, the other thermocouples (Tc) are fixed at the backside of the heat exchanger aluminum plate that are assumed to be the temperature of thermoelectric cold side.

Figure 9. Schematic diagram of locations of thermocouples connection on the: (a) PV module, (b) heat exchanger, and (c) Aluminum plate (thermal absorber)



(a) PV module



(b) Thermocouples location on the plate heat exchanger

(c) Thermocouples location on the Aluminum

3.2. Test Procedures

The PV, PV/T, and PV-TEG experimental measurements started in November 2021 in the laboratory. The experimental indoor tests are taken in the controlled room, at constant environment temperature Ta=28 ˚C and wind speed =0 m/s, for three systems (PV only, PV/T system, and PV-TEG hybrid system). Firstly, for the Photovoltaic system moving the solar panel up or down and using the solar meter to record the radiation intensity. At the same time, Four thermal isolated thermocouples have been fixed on the front surface of the PV panel and connected to Temperature Measurement Data Logger device. In addition, Solar Module Output Measurement has been linked with the PV panel to measure the PV electrical properties. After two hours of system operation to reach a steady state, the measured readings such as a temperature, current (I_{mp}), voltage (V_{mp}), electrical power of PV panel (P_m), and efficiency have been recorded at each solar radiation value. Second, the PV/T system has been tested in the same laboratory conditions that had been mentioned previously with the solar simulator and solar meter to determine the solar radiation at 1000 (W/m^2) at the volume flow rate of 7 (l/min). Following procedures are followed:

- The gate valve is adjusted at the chosen value of the volume flow rate of water input to the heat exchanger.
- Water is supplied to the system and connected -to the thermocouples of the PV/T system with a temperature recorder. In addition, the sensors of the solar meter is set up connect at specific place.
- Waiting a five minutes until the temperature of the PV module in the system reaches stability.
- Read temperatures of the front surface of PV module, PV/T system, and inlet and outlet water that get out to heat sink by calibrated thermocouples type k.
- Record the temperature of ambient around the experimental rig every five minutes to make sure it stays stable.
- Evaluate the electrical efficiency of the PV/T system by using the calculation equation of electrical efficiency that will be hinted at formerly.
- Download readings of instruments by hand recording on a computer to offer and compare it with a traditional photovoltaic system.

Finally, the PV -TEG hybrid system is tested in the same laboratory conditions. Bismuth Telluride TEG 50 pieces are set on the back surface of the aluminum plate and closely arranged in series for high voltage generation, as shown in figure (10). The hot sides of TEG modules is paste to the aluminum plate, whereas the TEG cold sides is touched the upper surface of the thermal exchanger. After that, all formed test steps have been repeated. The PV panel output energy and electrical efficiency have been evaluated. As well as, the electric energy of TEG modules has obtained by measuring the total open voltage of the TEG items with Digital Multi meter. It is also possible to roughly estimate the total power produced by TEG modules by using the formula (Hashim 2015):

$P_{TEG} = V_{oc} * I$ (1)

Where Voc is the voltage of a thermoelectric generator and was given by:

$Voc = \alpha_{np} * \Delta T\ R_L\ /(R_{in}+RL\ )$ (2)

Where R_L is the load resistance, R_{in} is the internal resistance of TEG, $\Delta T= (T_h - T_c)$ is the temperature difference across the two junctions, and α np is referred to as the Seebeck coefficient. The electric current (I) flowing through the thermoelectric generator was given by:

$\boldsymbol{I} = (\boldsymbol{s}\ /(\mathbf{1}+\boldsymbol{s})\ ^{\mathbf{2}}\ )(\boldsymbol{\alpha_{np}}*\Delta \boldsymbol{T})\ ^{\mathbf{2}}\ /\boldsymbol{R_{in}}$ (3)

Where $s = R_L/R_{in}$ is the ratio of the load resistance to the device's internal resistance. The power output depends on the ratio s, and the maximum power output was obtained at the matched load (i.e., when $R_L = R_{in} = 2.05\Omega$) So total output P_{TEG} of all thermoelectric modules (Zhu et al. 2016):

$P_{TEG} = Voc^2/(4R_{in}*M)$ (4)

Where M is the TEG modules number. The hybrid system's total power and overall efficiency are compared with that of the PV only and PV/T system. The improvement ratio and the deviation (difference) percentage are calculated as (Al-saleh and Yousif 2009):

$The\ improvement\ ratio = (Final\ value - Starting\ value)\ /Starting\ value\ *100\%$ (5)

So, the total output electrical power of the hybrid system Eel , that is obtained by using (Mahmoudinezhad et al. 2018):

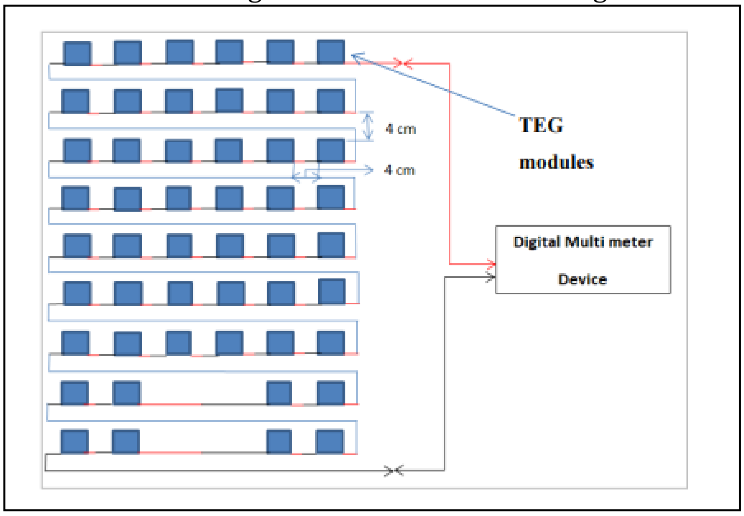
$E_{el} = P_{\mathrm{m}} + P_{TEG}$ (6)

The total electrical conversion efficiency (ηel) of the (PV-TEG) coupled system is given (Saleh et al. 2021) and (Babu and Ponnambalam 2018):

$\eta el = (P\mathrm{m}+P_{TEG}\ )/(A_{PV}*G)$ (7)

Where (G) and (A_{PV}) are the input solar radiation and the area of photovoltaic panel, respectively.

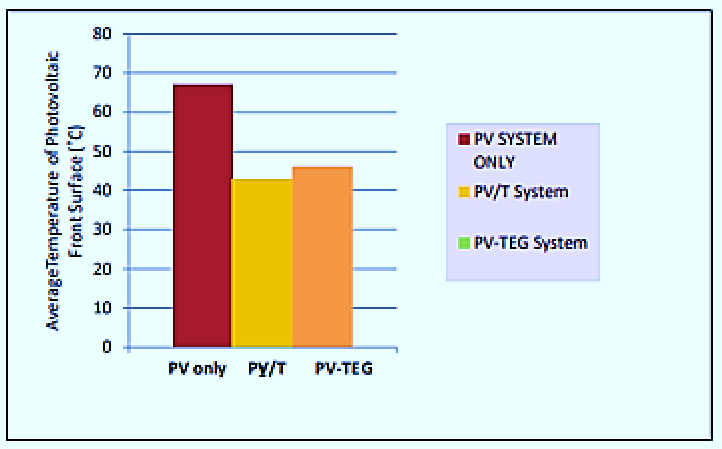
Figure 10. Schematic diagram of TEG modules arrangement and tying



4. Results and Discussion

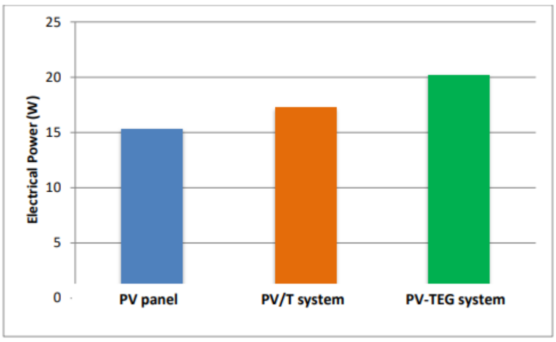
The experimental results include temperature measurements, electrical measurements, and performance calculations from measurements. Figure (11) compares the average temperature of the photovoltaic panel surface for the solar panel only, solar cells /thermal system, and the hybrid system. Also shows that the average temperature of photovoltaic panel surface in PV-only system is 67(℃) higher compared with other systems because absenting the cooling device, while in the PV -TEG hybrid system is about 44.4(℃) slitely higher compared with that of PV/T system because existing thermoelectric modules layer that works as resistance and causes temperature rising of photovoltaic panel.

Figure 11. Comparison between the average temperatures of photovoltaic front side in three system (PV Only, PV/T and PV-TEG)

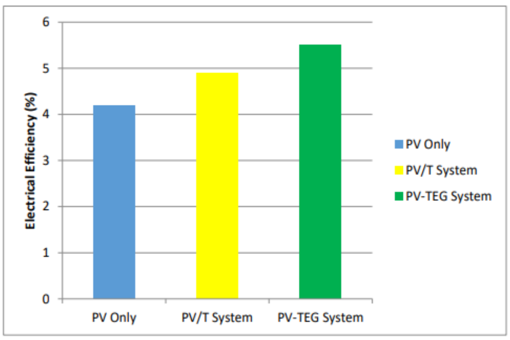


Figures (11) shows the maximum power (Pm) and the electrical efficiency of the solar panel of PV only, PV/T collector, PV - TEG hybrid system, and thermoelectric modules and solar panel integrating system. The above figures display the total power and overall efficiency of PV-TEG are more than by the power of all test systems due to the additional energy generated from the thermoelectric converting the heat absorbed from the solar panel into electrical energy. the output power of the PV-TEG model is higher by 31.66% and 16.5% compared with the traditional photovoltaic only and the PV/T system, respectively, under the same operating conditions.

Figure 11. The electrical output power and efficiency of three systems (PV only, PV/T, and PV-TEG) in an experimental test.



(a) The electrical energy



(b) The electrical efficiency

Conclusion

Generally, the Photovoltaic – thermoelectric hybrid system is one of the effective and promising strategies for collecting the waste warm within the sun powered cells, changing over it into extra electrical vitality, and diminishing the sun based cells' working temperature of the sun oriented cells, hence making strides their proficiency and keeping up their life span. The ideal number of TEG modules to maximize the combined framework yield control beneath certain working conditions was assessed and examined.

In this study, the performance for hybrid system with commercial PV, TEG modules, and heat exchanger (Shell and Tube) type under the same operating conditions was done experimentaly. The model PV-50 TEG hybrid system with heat exchanger type (absorber plate and tube) produces additional energy, experimentaly are higher by (31.66 % and 16.5 %) compared with the traditional PV and the PV/T system, respectively. The generated Pel of PV panel is a bout 15.35 (W), PV/T is a bout 17.24 (W). The generated Pel of PV panel in the PV PV-TEG is a bout 17.81 (W) and generated power by TEG modules is 2.4 (W), So the total electrical power of hybrid system is 20.21(W).

Nomenclature

G	solar irradiance, W/m^2
Z	figure of merit, K^{-1}
k	thermal conductance (w/K)
Th	hot side temperature of TEG (K)
Tc	cold side temperature of TEG (K)
Tsc	PV temperature (K)
Apv	area of PV panel
ATE	area of thermoelement
ΔT	temperature difference between cold surface and hot surface of TEG

Subscripts

El	Electrical
mp	Maximum power piont

Greek symbols

α	Seebeck coefficient (V/K)
η	Efficiency
σ	Electrical conductivity coefficient ($\Omega{-1}$ $m{-1}$)
v	The wind speed (m/s)

Abbreviations

Bi_2Te_3	bismuth telluride
EVA	ethylene vinyl acetate PV photovoltaic
PV-TE	photovoltaic-thermoelectric
TE	thermoelectric
TEG	thermoelectric generator
TPT	Tedlar polyester tedlar
PV	Photovoltaic

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