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Investigation of power generated from a PVT-TEG system in Iranian cities

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Abstract

In the present paper, the possibility of using thermoelectric power generating modules (TEG) to convert the heat generated by the photovoltaic / thermal collector (PVT) to electricity in Iranian cities has been investigated. Thermal modeling of PVT-TEG system has been performed. The hot side of the TEG module is connected to the top of the air duct, which is connected to the back of the solar panel. Air flows through the duct and cools the cold part of the TEG modules. TEG modules convert the generated temperature gradient into electricity. Therefore, generating additional electricity from the generated heat improves the performance of the system. To evaluate the performance of the PVT-TEG system, nine cities with different climates from Iran (Bander Abbas, Birjand, Bojnurd, Bushehr, Esfahan, Hamedan, Jask, Kerman and Kermanshah) have been considered. Meteorological data for each city were used for the studies. The results show that the efficiency of the system depends on the temperature and the intensity of radiation. The electricity produced by the proposed system in Kerman is 1.66 times that of Bojnurd. Increasing the number of TEG modules increases the amount of electricity produced. Kerman city has the highest TEG efficiency (1.58%)and Bojnurd city has the highest PVT efficiency(9.15%).

Keywords: Thermoelectric Power; Photovoltaic; Solar Irradiance; PV-TEG.

Introduction

In order to deal with the rapid growth of electricity demand and to prevent the destructive environmental problems caused by the use of fossil fuels, many efforts have been made to develop the use of renewable energy. Solar power supply methods are generally divided into two categories[1, 2].Thermal systems that indirectly convert the sun's thermal energy into electrical energy, and photovoltaic systems in which the sun's radiant energy is converted directly into electrical energy. Photovoltaic cells are high-efficiency converters that their efficiency decreases under the influence of heat and as the operating temperature rises.

One of the methods to reduce the power drop due to rising cell temperature is the use of a combined photovoltaic-thermal system.

Cha´vez-Urbiola et al. [3] investigated the feasibility of using thermoelectric generators in hybrid systems. They experimentally evaluated four different types of systems, all of which had photovoltaic modules, thermoelectric modules, and heat extraction ducts, with and without light concentrators. The studied thermoelectric generators were of bismuth trillium type, which were considered for temperature difference of 50 to 200 degrees Celsius. According to their results, the efficiency of thermoelectric generator is linearly dependent on the temperature difference between hot and cold thermoelectric

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plates and reaches about 4% at a temperature difference of 155 ° C. Also, the generating power is directly related to the power of 2 temperature differences on the thermoelectric side.

Miljkovic et al. [4] combined a thermoelectric generator with linear parabolic solar collectors to generate electricity and heat at the same time. They use a thermosyphon system as a heat absorber in the other part of the generator, which by controlling the temperature of the cold surface, transfers the heat received from it to the lower cycle for storage. In an experimental study, Hassasnniadoon et al. [5] used thermoelectric modules in the heat transfer paths from the solar heat absorber surface to the solar water heater water storage. Their experimental results show that the maximum amount of thermoelectric power is 1.08W under a radiation intensity of 98,705 W/m^2, and in this case the thermal efficiency of the system is about 58.51%.

Deng et al. [6] modeled the heat flux distribution using finite element methods for the thermoelectric generator. According to their work, the outputs of the photovoltaic and thermoelectric generator increase due to the simultaneous integrated design. The total output power of their system is 393 MW, which is twice the output power of the cell alone.

Li et al. [7] introduced a new solar system consisting of a solar cell and a thermoelectric generator. This system is able to use a wide range of solar radiation by using the existing methods in separating solar wavelengths. They studied different thermoelectric parameters and found that the higher the temperature gradient between the two thermoelectric sides, the higher the efficiency. Lin et al. [8] combined photovoltaic-thermoelectric system with the help of temperature analysis of different points and the output power was investigated for both combined and non-combined modes.They observed that the photovoltaic cell in combination with the thermoelectric module had a higher temperature than the single state and also that the efficiency of the combined system was lower than the efficiency of the photovoltaic system.

Zhang et al. [9] developed a numerical model for the analysis of a combined photovoltaic-thermoelectric system under concentrated radiation. They studied different types of crystalline silicon, thin-layer silicon and polymer cells. The effect of temperature on the photovoltaic cell efficiency was investigated according to the semiconductor equations and the result was that polymeric thin layer silicon cells are suitable for concentrated composite systems and polymer cells are suitable for non-concentrating systems.

Panga et al. [10] experimentally investigated the thermal performance of a combined photovoltaic-thermoelectric system and found that the use of a heat sink behind the thermoelectric module thermally improved the performance of the system.

Wu et al. [11] theoretically analyzed the performance of a combined photovoltaic-thermoelectric system with nanofluid flow as a heat sink for a thermoelectric module in two states with and without glass. Their results show that when the thermoelectric efficiency reaches its maximum, the optimal value of the electrical charge resistance becomes greater than its corresponding value with the maximum overall efficiency. In addition, the use of nanofluids due to the higher thermal conductivity, better results shows in comparison with water.

Fisac et al. [12] experimentally evaluated the performance of a photovoltaic module for two independent modes in combination with thermoelectric generators. Their results show that with increasing temperature of photovoltaic modules, their efficiency decreases.

Vishal et al. [13] optimized thermoelectric cooling for active cooling in a solar cell. The results of the experiment show that for the intensity of radiation at an efficiency of 0.8-1 kW / m^2 and at a temperature of 25 to 45 ° C, the electrical efficiency of the solar cell increases by about 8.1%.

Mohammad Ali[14] studied the cooling methods of photovoltaic cells used in the last 5 years, such as nanofluids, the use of phase change materials, and based on the studies, it was concluded that PV / PCM systems due to the long payback period of up to 20 years,when working in a connection, become more expensive and less practical. Other research has been done on the use of phase change and nanofluidic materials to cool the photovoltaic system[15-17].

According to the previous literature, it can be said that few studies have been performed to evaluate the effectiveness of the proposed methods for cooling the photovoltaic system in different climates. In this paper, in order to recover heat and increase the performance of photovoltaic cells, a thermoelectric module is used, which captures the heat of the photovoltaic cell and converts it into electricity. The effect of environmental conditions on the efficiency of the photovoltaic system - thermoelectric module in several cities of Iran has been studied to determine which city is suitable for using this system. Bandar-e Abbas, Bushehr, Esfahan, Kerman, Shiraz, and Yazd are chosen for study. Thermal modeling of the PV-TEG system has been performed. Meteorological information has been used for each city to achieve the actual performance of the proposed system.

2. Modeling of PV-TEG system

A schematic of TEG modules and PV-TEG system is illustrated in Figures 1 and 2. Part of the heat from the photovoltaic cell is fed to the TEG module, part of which is converted to electricity, and the rest is released into the air through the fins. In the following, thermal modeling of different parts of the PV-TEG system is discussed.

2.1.TEG modeling

In this case, the device includes a PV solar with Tedlar layer covered by an aluminium sheet which combined with a TEG which integrated as a power generator and regenerator cooling due to temperature gradient, TEG is a solid-state device convert energy directly by conducting of flue gas and humidified flue gas due to base of TEG which work with seebeck effect. simultaneously, the properties of TEG such as thermal, semiconductor and Electrical of TEG has been combined for performance of device.in thermal property, the temperature gradient has been occurred in both two sides of this module. The semiconductor property of device has been made of two semiconductors, p- and n-type, which these two types has no similarity to each other, electrical modules connection in TEG is in series form but, thermal modules connection in TEG is parallel. The TEG generation performance occurred in low-temperature wet flue gas by supplying heat at the one of ending and moves thorough the external electricity circuit flows. [2, 18].The design TEG has been done Najafi et and Woodbury [19] which the dimension of TEG has been chosen as $W_{fin} \times W_{fin} \times th_{fin} = 40 \times 40 \times 3.2 \quad mm$ which shown in figure 1.the fin has been installed in the cold side of TEG and the number of fin has been selected $N_{fin} = 100$ with diameters of $D_{fin} = 1.5 \quad mm$ and with length of $L_{fin} = 15 \quad mm$.

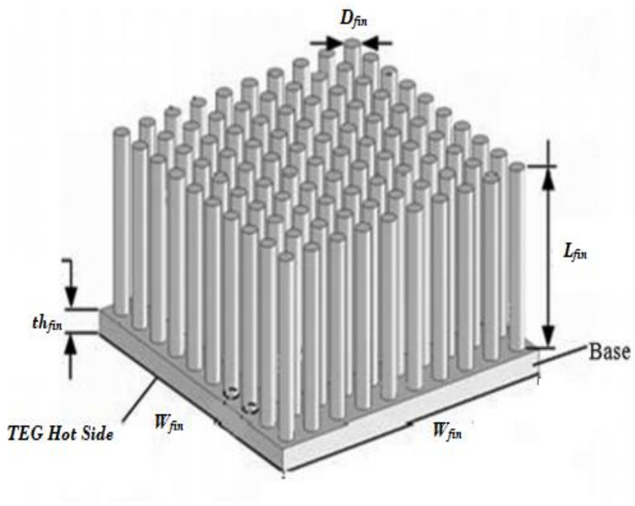

Fig 1. Illustration of TEG modules.
Thermoelectric module properties shown in table 1.

Table 1. TEG properties.[19]

Parameters	Value
S_{TEG}	0.05V/K
Z_{TEG}	0.002 1/K
R_{TEG}	0.97 Ω
K_{TEG}	25 W/m/K

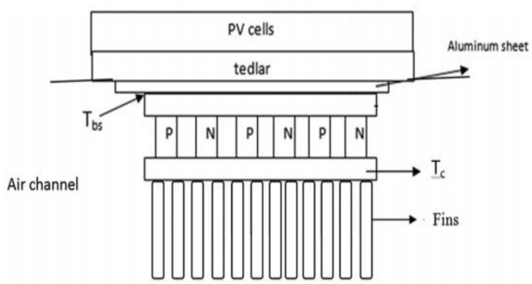

Fig 2. Modelling of PVT-TEG system combination.

The output generative power due to TEG has been described as. [18]

$$P_{TEG} = S_{TEG} I_{TEG} \left(T_{bs} - T_c\right) - I^2{}_{TEG} R_{TEG} \tag{1}$$

Where T_{bs}, T_c, I_{TEG}, R_{TEG} and S_{TEG} are the temperature of backside of tedlar , temperature of cold side, electrical current , TEC electrical resistance and Seebeck coefficient, respectively. It is assumed that the temperature of the hot surface, T_h , is equal to T_{bs} . Temperature of backside of tedlar is extracted by[4]:

$$T_{bs} = \frac{h_{p1}\left(\alpha\tau\right)_{eff} G + U_{tT} T_{amb} + h_f T_f}{U_{tT} + h_f} \tag{2}$$

Where U_{tT} , h_f , h_{p1}, T_{amb}, T_f , G and $\left(\alpha\tau\right)_{eff}$ are thermal heat transfer coefficient, convection heat transfer coefficient of fluid, penalty factor, temperature of ambient, temperature of fluid, amount of solar irradiation and the product of effective absorptivity and transmittivity, respectivly. The location of the mentioned temperatures is shown in figure 2.The total power has been generated by TEG can be calculated by:

$$P_{total,TEG} = P_{TEG} N_{TEG} \tag{3}$$

Where, N_{TEG} is the number of TEG modules.

The highest I_{TEG} for possible power of TEG has been optimal in equation (4) [18]

$$I_{TEG} = \frac{S_{TEG}\left(T_{bs} - T_c\right)}{2R_{TEG}} \tag{4}$$

In TEG the heat supplied in hot $\left(Q_h\right)$ and which a small part of heat supplied has been convert to the power $\left(P_{TEG}\right)$ and the rest rejective heat dissipated to backside of tedlar and fins in TEG module $\left(Q_C\right)$ which can be shown in equation (5) .[19]

$$Q_h = P_{TEG} + Q_c \tag{5}$$

The heat supplied due to the hot side of tedlar in the TEG module presumed as by a heat conduction transfer in equation (5).

$$Q_h = \frac{K_{TEG} A_{TEG}\left(T_{bs} - T_c\right)}{th_{TEG}} \tag{6}$$

2.2. PV panel modeling

The performance of the PV-TEG system depends on two system of TEG module and PV system. Earlier the TEG module has been described. Ordinarily, The PV cells make from materials such as photovoltaic cell materials, combination silicon with crystalline silicon (c-Si) and thin film silicon thin-film (pSi) photovoltaic cell, polymer photovoltaic cell materials, and copper indium gallium selenide (CIGS) photovoltaic cell materials. At first, the sun radiated sunlight to concentrate on the glass where covered by the concentrator which absorbed by the PV cells.[20] the number of 36 TEG has been installed beck side of PV panel with dimension of $1200 \times 527 \times 34 \quad mm$,thickness of silicon solar cell equals to $L_{si} = 300 \times 10^{-6} \quad m$,the thickness of glass cover equals to 0.003 m and the thickness of tedlar equals to 0.0005 m, the Characteristics of the PV panel are presented in table 2.

Table 2. Characteristics of the PV panel.[19]

Parameters	Value
$I_{m,ref}$	8.8
$V_{m,ref}$	8.5
$I_{sc,ref}$	9.6
$V_{oc,ref}$	10.9
G_{ref}	1000W/m^2
μ_f , current temperature coefficient	2.06 mA/C
μ_V , current temperature coefficient	-0.077 V/C
$\eta_{el,ref}$	12%
K_{si} , conductivity of silicon solar cell	0.036 W/m/K
K_g , conductivity of glass cover	1 W/m/K
K_T , the conductivity of tedlar	0.033 W/m/K
β_c , packing factor	0.85
τ_g , the transmissivity of glass cover	0.95
ε_g , the emissivity of PV	0.88
α_T , the absorptivity of tedlar	0.5

The radiation power depends on sky temperature where the chosen formula for effectiveness temperature of sky defined as ,[21]

$$T_{sky} = 0.0552 T_{amb}^{\ 1.5} \tag{7}$$

The temperature of cell in PV system has been estimated as [22]

$$T_{cell} = \frac{(\alpha\tau)_{eff}\, G + U_T T_{amb} + U_T T_{bs}}{U_t + U_T} \tag{8}$$

An average mean temperature has been considered through the ducts as the fluid temperature by calculating average of T_{in} ducts and T_{out} .

$$T_m = \frac{T_{in} + T_{out}}{2} \tag{9}$$

The summation of the overall heat loss, consist of all of heat loss such as radiative, convective, and conductive losses and the rate of electrical energy, in the top surface of the PV cell to the ambient the overall heat transfer from the PV cell to the back surface of the tedlar, which it is available of thorough the PV module. Defined as the rate of available solar energy[22].

$$\dot{Q}_{loss} = U_t\left(T_{cell} - T_{amb}\right)A_{pv} + \varepsilon_g \sigma A_{pv}\left(T^4{}_{cell} - T^4{}_{sky}\right) + U_T\left(T_{cell} - T_{bs}\right)A_{pv} \tag{10}$$

$$\dot{Q}_{elec} = \tau_g \beta_c \eta_{el} G.A_{pv} \tag{11}$$

$$\dot{Q}_{sol} = \dot{Q}_{loss} + \dot{Q}_{elec} \tag{12}$$

Where, U_T considered as the total conductive heat transfer coefficient due to air through the tedlar to ambient of the solar which has been assumed by:

$$U_T = \left[\frac{L_{si}}{K_{si}} + \frac{L_T}{K_T}\right]^{-1} \tag{13}$$

Another heat transfer coefficient U_t due to air through the glass cover to ambient of the solar cell, which contains both of conduction and convection losses, which defined as,

$$U_t = \left[\frac{L_g}{K_g} + \frac{1}{h_{conv,t}}\right]^{-1} \tag{14}$$

Also, the back loss thermal coefficient due to flows of air to ambient in the channel can be calculated,

$$U_b = \left[\frac{L_i}{K_i} + \frac{1}{h_{conv,b}}\right]^{-1} \tag{15}$$

The total thermal coefficient has been defined as:

$$U_{tT} = \left[\frac{1}{U_T} + \frac{1}{U_t} \right]^{-1} \tag{16}$$

An energy balance in back surface of the tedlar can be estimated some parameters.

$$U_T \left(T_{cell} - T_{amb} \right) A_{pv} = h_{amb} \left(T_{bs} - T_m \right) A_{pv} - P_{total,TEG} \tag{17}$$

Another equation based on the energy balance can be written as,

$$\dot{m} C_P \left(T_{out} - T_{in} \right) + U_b \left(T_{out} - T_{amb} \right) A_{PV} = h_{amb} \left(T_{bs} - T_m \right) \left(A_{pv} - A_{TEG} N_{TEG} \right) + N_{TEG} Q_c \tag{18}$$

in order to calculate power generation of solar, photocurrent should be considered as a function of solar irradiation, which has been defined as,[23]

$$I_{ph} = \frac{G}{G_{ref}} \left[I_{ph,ref} + \mu_f \left(T - T_f \right) \right] \tag{19}$$

The saturation current depends on the short-circuit current temperature coefficient and the open-circuit voltage temperature coefficient which, can be written by

$$I_0 = \frac{I_{sc,ref} + \mu_f \left(T - T_f \right)}{\exp\left[\frac{V_{oc,ref} + \mu_V \left(T - T_f \right)}{n N_s K_B T} \right] - 1} \tag{20}$$

In equation (20), (n) is the diode quality coefficient which can be given by,

$$n = \frac{q\left(V_{m,ref} - V_{oc,ref} \right)}{N_s K_B T_{ref}} \frac{1}{\ln\left(1 - \frac{I_{m,ref}}{I_{sc,ref}} \right)} \tag{21}$$

where, q is electrons charge equals to $1.602 \times 10^{-19} C$ .the open circuit voltage can be calculated by,

$$V_{oc} = \frac{N_s K_B T}{q} \ln\left(1 - \frac{I_{sc}}{I_0} \right) \tag{22}$$

Hence, the maximum power should be calculated the maximum of current and voltage in the following equations.

$$V_{mpp} = \frac{N_s K_B T}{q} \ln\left(\frac{N_s K_B T}{q I_0} \frac{I_{sc}}{V_{oc}} \right) \tag{23}$$

$$I_{mpp} = I_{ph} + I_o - \frac{N_s K_B T}{q} \ln\left(\frac{I_{sc}}{V_{oc}} \right) \tag{24}$$

$$P_{mpp} = V_{mpp} I_{mpp} \tag{25}$$

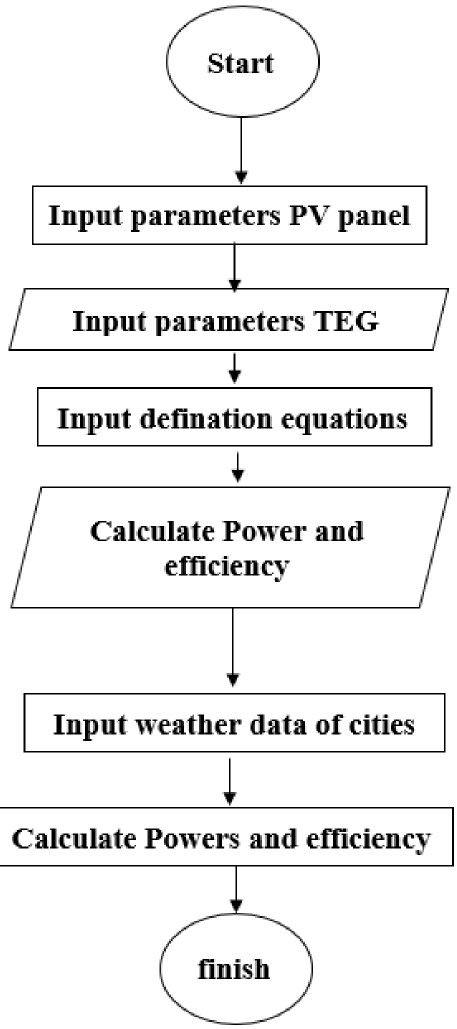

Fig 3. Flowcharts of methodology.

3. Results

At first, for investigation of the present study, it must be compared with a similar pervious study. Fig.3 shows the solution process in the present study.The production capacity of the photovoltaic system and TEG modules (the number of modules is equal to 36) in terms of solar radiation intensity in the present study has been compared with the previous literature and is shown in Figures 4 and 5. The results of the present study are very close to the results of Najafi and Woodbury[19] and there is less than 7% deviation between the results. The results show that with increasing solar radiation intensity, the production capacity of photovoltaic cells and TEG modules has increased.

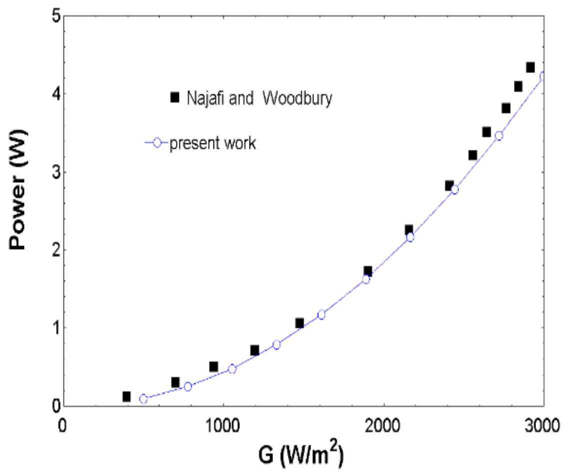

Fig 4. Power generation of PV panel in terms of the intensity of solar radiation

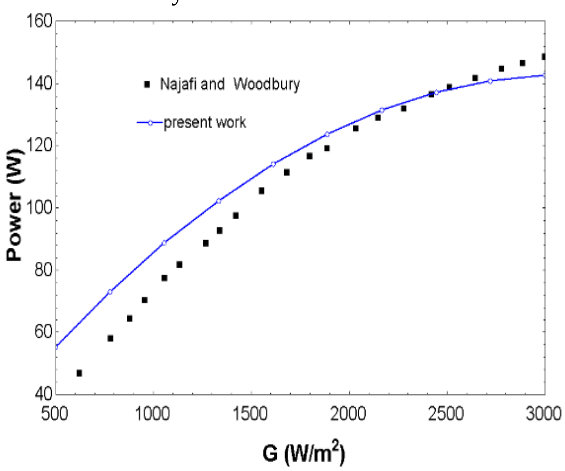

Fig 5. Power of 36 modules of TEG in terms of the intensity of solar radiation

Using modeling, the effect of radiation intensity on temperature T_{cell}, T_c and T_{bs} has been investigated and is shown in Fig.6. Results show $T_{cell} > T_{bs} > T_c$ and three temperatures increase with increasing radiation intensity. Temperature difference $(T_{bs} - T_c)$ causes power generation in the TEG module. As the intensity of the radiation increases, this temperature difference increases and leads to more power generation by TEG modules.

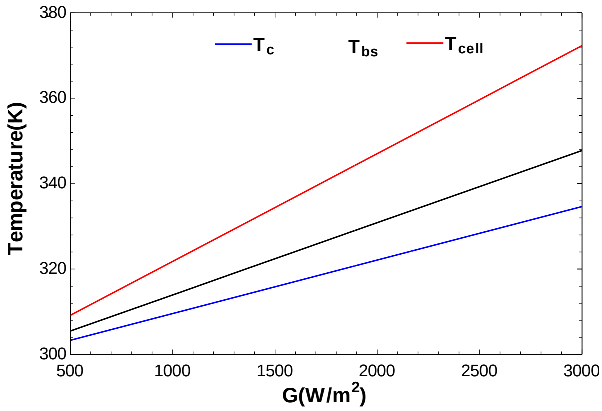

Fig 6. Temperature with Different solar irradiannce.

In this study, it is assumed that the number of thermoelectric modules is equal to the number of solar cells. The production capacity of each module does not increase as the number of modules is shown in Figure 7. It is observed that with increasing the number of modules, the production capacity of each module decreases. The reason for this behavior is that the output tone of each module depends on the temperature difference $(T_{bs} - T_c)$, which decreases as the number of modules increases. Although the power of each module decreases with increasing number of modules, but the total power generated by all modules increases with increasing number of modules. As the number of TEG modules increases, the temperature of the solar cell decreases and the photovoltaic cell produces more power. The number of TEG modules on the power generation of each photovoltaic cell and all photovoltaic cells is shown in Figures 8 and 9. Also, from Figures 7, 8 and 9, it can be well seen that the production capacity of the TEG module and the photovoltaic cell are a strong function of the intensity of solar radiation and increase with increasing radiation intensity. Using modeling and meteorological information, the performance of PVT-TEG system in 9 selected cities in Iran has been studied. According to the average annual radiation intensity based on meteorological information [24], Kerman and Esfahan have the highest radiation intensity among 9 selected cities. The temperature of the solar cell, temperature of cold side of TEG ,and the temperature of hot side of TEG in the backside of tedlar of TEG are calculated for all 9 selected cities and is shown in Figure 10.

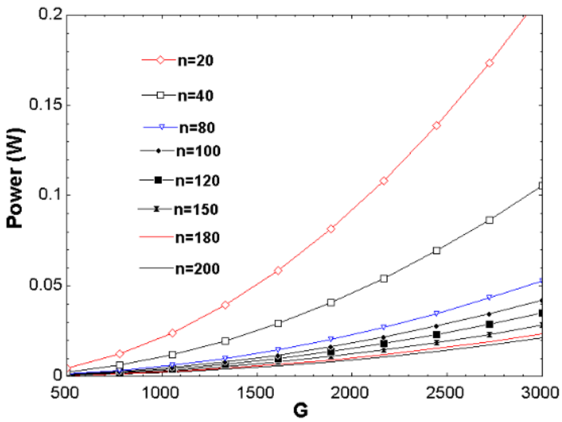

Fig 7. Power generation by each TEG module in different solar irradiannce.

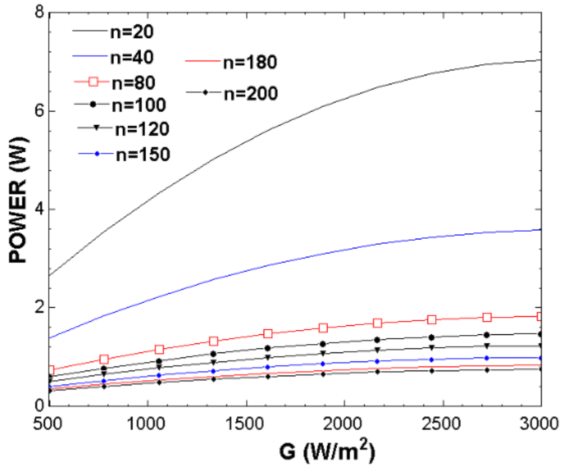

Fig 8. Power generation by each PV cell in different solar irradiannce.

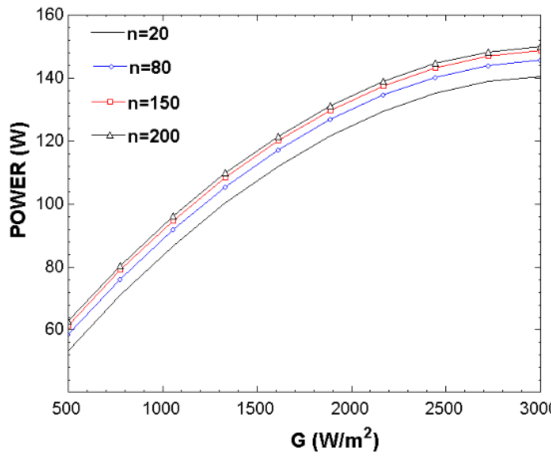

Fig 9. Power generation by PV cell in different solar irradiannce.

The generation capacity of each module is shown in Figure 11 by changing the number of thermoelectric modules for the 9 selected cities. As the number of modules increases, the amount of power output of each module decreases. The highest production capacity of each module is related to Kerman city and the lowest amount is related to Bojnurd city, which confirms that the production capacity of the modules is strongly dependent on the intensity of sunlight. The intensity of radiation in Kerman and Esfahan is close to each other, but the temperature of these two cities is different, and finally the production capacity of the TEG module in Esfahan is less than in Kerman.

Changes in photovoltaic cell production capacity for 9 selected cities by changing the number of TEG modules are shown in Figure 12. It is observed that with increasing the number of modules, the cell production capacity has also increased. The city of Kerman has the highest production capacity and the city of Bojnurd has the lowest production capacity. The total production capacity of TEG modules for the case where the number of modules is equal to 36 for all cities is calculated and shown in Figure 13. Most of the production capacity is related to the cities of Kerman, Esfahan and Bandar Abbas.

The efficiency of the photovoltaic cell and the efficiency of the TEG module for all 9 cities are calculated and shown in Figure 14. The results show that the highest efficiency of photovoltaic system is related to Bojnurd city and its value is 9% and the lowest PV efficiency is related to Kerman city and 8.1%. The highest efficiency of the TEG module is related to the city of Kerman or the amount and the lowest value of this efficiency is related to the city of Bojnurd.

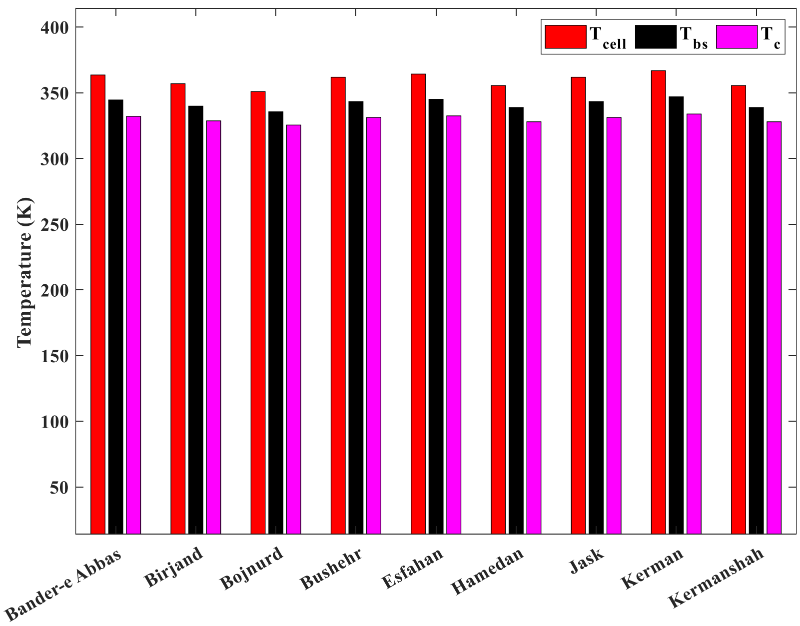

Fig 10. Temperature with Different solar irradiannce.

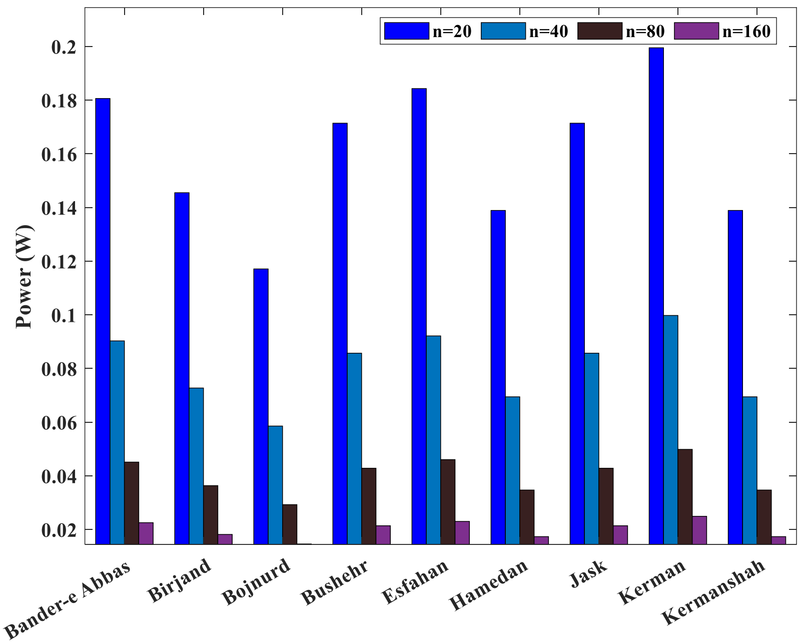

Fig11 .power generated for each module by variation number of TEG module in 9 cities of Iran.

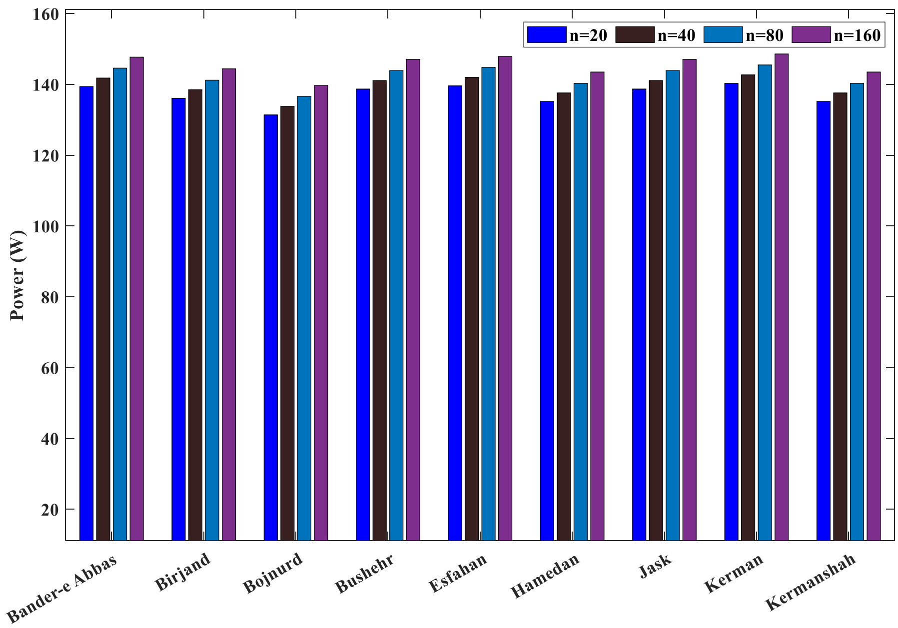

Fig 12.generation of power by PV cell with variation number of TEG modules in 9 location of Iran

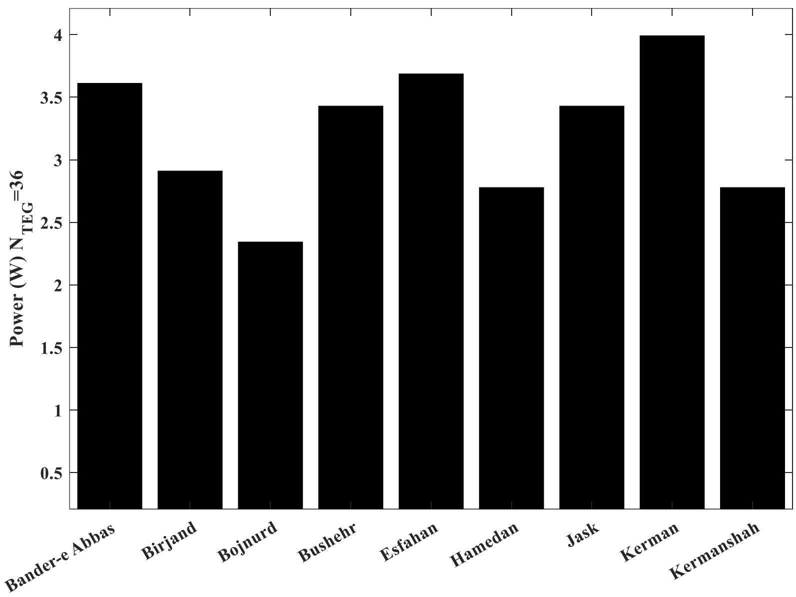

Fig 13. generation of power by 36 TEG modules.

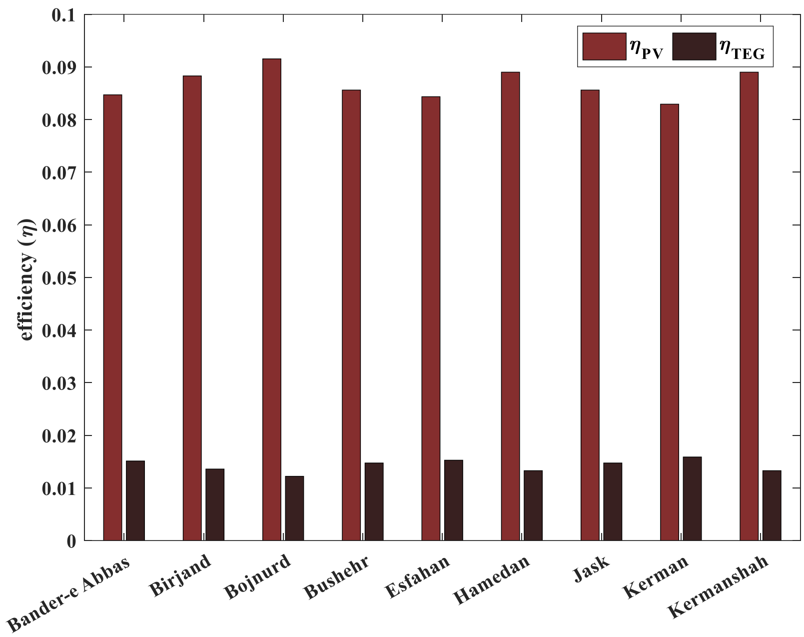

Fig.14. efficiency of PV and TEG for cities.

4. Conclusion

In this study, the effect of environmental conditions on the efficiency of PVT-TEG combined system has been investigated. Thermal modeling of the system has been done and the performance of PVT-TEG system has been investigated for 9 selected cities in Iran. The findings of these results are summarized below:

- Temperature analysis shows that the temperature of the photovoltaic cell is always higher than the hot surface temperature of the TEG module. The output power of the TEG module strongly depends on the temperature difference between the two levels. The lower the temperature of the PV cell, the higher its efficiency.
  As the intensity of radiation increases, the production capacity of the PV-TEG system increases.
  As the number of TEG modules increases, the power of each TEG module decreases and the power of each PV cell increases. Among the selected cities, Kerman has the highest production capacity and Bojnurd has the lowest production capacity. The highest efficiency of photovoltaic cells occurred in Bojnurd and the highest efficiency of TEG module occurred in Kerman. The first environmental parameter affecting the production capacity of the PVTEG system is the intensity of the sun's radiation, followed by the ambient temperature.
- In this paper, study of possibility combination of TEG with PV cell has been investigated. The temperatures parameters and power generation of TEG and PV cell has been considered, the most related parameters to the temperature and generated power was the level of solar irradiance. The results show that with increasing intensity of solar radiation, the amount of production power increases. As the number of TEG modules increases, the cell temperature decreases and the PV cell will generate more power. The reason for the decrease in the growth rate of the output power of the PVC panel is the increase in temperature.
- After all, the feasibility of installation of PV-TEG in 9 cities of Iran has been compared. The highest PV efficiency was for Bonjnord with amount of 0.09154 and the lowest PV efficiency was for Kerman with value of 0. 08293. Kerman has the most Generated power and Esfahan has the least generated power in those 9 cities.

Nomenclature

N_s	number of cells
K_B	Boltzmann constant= $1.38\times10^{-23} J/K$
I	electrical current, A
Q_c	rate of heat transfer removal, W
Q_h	rate of heat transfer supplied, W
I_0	Saturation current , A
V_w	wind velocity, m/s
A	surface area , m^2
G	solar irradiation, W/m^2
h	Convection heat transfer coefficient, $W.K^{-1}.m^{-2}$
K	thermal conductivity, $W/K/m$
n	diode quality coefficient
P	Power W
q	electrons charge 1.602 10^-19 C
R	thermal resistance, K/W
S	seebeek coefficient
T	temperature, K
th	thickness, m
W	width, m

Greek symbol

ε	emissivity
α	absorptivity
μ	current temperature, mA/C
η	efficiency
β_c	packing factor

τ	transmittivity
Subscript	
amb	ambient
b	base
bs	backside
el	PV efficiency
g	glass
in	input
mmp	maximum power point
oc	open circuit
out	output
PV	photovoltaic
ref	reference
sc	short circuit
si	silicon
T	tedlar
TEG	Thermoelectric module

5. References

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