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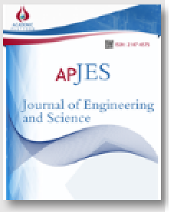

Electrical and Thermal Performance Analysis of a Linear Fresnel Reflector-Photovoltaic/Thermal System

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Abstract

A photovoltaic system integrated with linear Fresnel reflectors constitutes a very attractive energy generation system when combined with a cooling thermal system. In this study, a photovoltaic system using high efficiency and extremely durable monocrystalline solar cells is theoretically discussed. Although cheap but relatively less effective solar cells have been proposed, it has been shown that a very good cost-effective photovoltaic system can be produced by concentrating sunlight with a linear Fresnel reflector system and obtaining additional heat energy by cooling the photovoltaic panel. The electrical and thermal performance of the proposed system is theoretically analyzed under relatively low solar radiation conditions. Under the given climatic conditions and the average instantaneous solar radiation of 559 W/m^2 at the location, it is concluded that when a cooling mechanism is implemented, an average of 228.8 kWh of electricity and 1229.8 kWh of thermal energy can be obtained per month from the system.

Keywords: Solar radiation, concentrated solar photovoltaics, linear Fresnel reflector, PV cooling, CPV/T systems

1. INTRODUCTION

Photovoltaic (PV) cells convert sunlight directly into electricity. Therefore, photovoltaic power generation is a direct way of obtaining electricity from the Sun. However, due to the relatively low conversion efficiency and high costs, the PV systems are far from the traditional power generation systems in terms of wide usage. When compared to the levelized cost of energy (LCOE) on residential scale, PV power costs 204 €/kWh$_e$, coal-based power including tax, transmission and distribution costs 186 €/kW$_e$ and nuclear power costs 152 €/kWh$_e$ [1]. High investment costs, or total system costs of PV systems are still relatively high, although they start to decrease rapidly as a result of technology improvements and economies of volume and scale. Total system costs are composed of the sum of module costs and the expenses for the "balance-of system", including mounting structures, inverters, cabling and power management devices. While the costs of the module types with different technologies vary on a per watt basis, these differences are less significant at the system level, which also considers the efficiency and land-use needs of the technology [2].

On the other hand, concentrating the sunlight allows the use of less PV material. Systems operating under concentrated sunlight are called concentration photovoltaics (CPV). The crucial idea behind CPV is replacing the PV material, which is currently the most expensive part of the system, with cheaper optical elements. Sunlight can be concentrated by refraction, reflection, wavelength conversion, diffraction and laser action. Refraction is accomplished by lenses and reflection by mirrors (collectors) [3]. "The combination of photovoltaic (PV) technology, solar thermal technology and reflective or refractive solar concentrators has been a highly appealing option for developers and researchers since the late 1970s and early 1980s. The result is what is known as a concentrated photovoltaic thermal (CPVT) system which is a hybrid combination of concentration and photovoltaic/thermal (PV/T) systems. Several CPVT systems have been designed, studied, and demonstrated both theoretically and experimentally in literature. The results of these studies and demonstrations show that CPVT systems hold very high potential for market penetration in the energy sector due to their unique features" [4].

Concentrating solar collector usually has concave reflecting surfaces to intercept and focus the Sun's beam radiation to a smaller receiving area. The high temperature concentrating solar thermal systems, like parabolic trough and linear Fresnel, requires large open area and the system engineering is very complex. The Linear Fresnel Collector is a line focusing concentrating collector suitable for solar thermal power generation and production of process heat [5]. LFRs had a late development compared to the other technologies [6]. LFR arrays present some relevant advantages in the domain of concentrating solar power because of their simplicity, robustness and low capital cost [7].

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The first modern PV concentrator called SANDIA-II array was made at Sandia National Laboratories in 1977. It consists of 5 cm diameter Si PV cells combined with acrylic Fresnel lens with 32 suns [8]. Integrating PV and concentrating collectors is such an attractive and old idea [9] because the CPVTs are highly efficient system compared to PV and concentrated solar collector systems. To reflect the incoming sun rays onto PV surface with lesser loss obviously makes such system more efficient. Therefore, in CPV systems mostly parabolic trough collectors are used [10-20]. The idea of using LFRs in a CPV system is very rare with new design of LFR-like systems and there is no any study regarding the coupling of traditional LFR systems and PVs in the literature. Vivar et al. developed a CPVT system based on LFR idea. They built an enclosed system by putting a micro LFR collector and a very small hybrid PV/T system inside an envelope which is not a traditional way of using LFRs as it is given in Figure 1. [21].

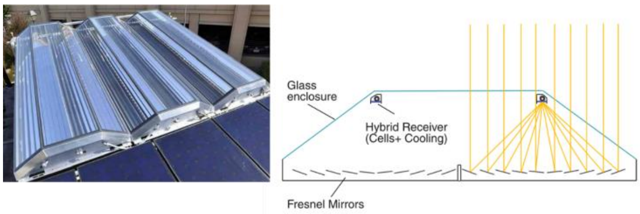

Figure 1. Micro-concentrator system on Santa Clara University Solar Decathlon House, 2010 [21].

Yang et al. designed an LFR-like CPVT system and analyzed it experimentally [22]. Although they used flat mirrors as it is in a traditional LFR system, but they made a parabolic trough collector indeed as it is showing in Figure 2.

Figure 2. One unit of CPVT prototype [22].

Du et al. developed a CPV test device using flat mirrors as it is in a traditional LFR systems, but it was a parabolic trough collector rather than a traditional LFR as it is shown in Figure 3 [23].

Figure 3. Experimental set-up of water-cooled CPV module [23].

Zhang et al. designed a linear flat mirror concentrator (LFMC) aimed at low cost linear concentrating photovoltaic systems for economic green power [24]. Although they used a traditional LFR system, since they used a PV panel immersed in liquid. Therefore, their system was not a CPV/T system which is showing in Fig.4.

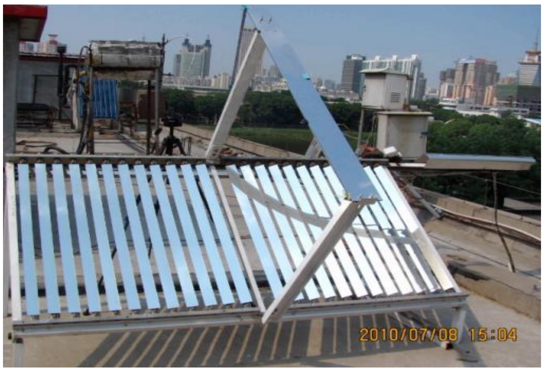

Figure 4. The mini-scale LFMC [24].

Rosell et al. studied on a similar system without analyzing it detailly. They have focused on to determine the output water temperature experimentally [25]. Their system is given in Fig.5.

Figure 5. PV/T system at the University of Lleida terrace [25].

Liu et al. considered an LFR-like system to build a CPV/T system [26]. However, they kept PV and thermal part separately by using a beam splitter for the incoming solar radiation. Therefore, their system cannot be accepted as a CPV/T system. The details of their system are showing in the Fig.6.

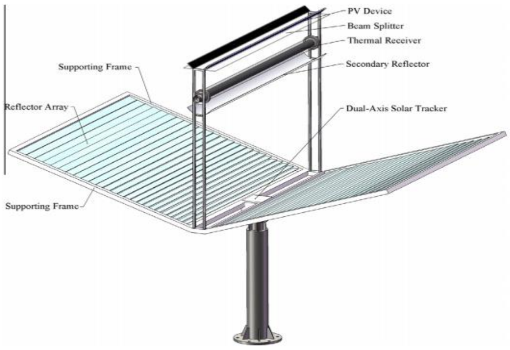

Figure 6. The mini-scale LFMC [26].

Photovoltaic cell production technology has been greatly improved and the PV efficiencies consequently increased. Si-based solar cells with back point contact [27] reached an efficiency record of 27.6%, and some manufacturers used this type of solar cells under more than 400 X-concentrations [28]. Commercial PV panels convert 10-27 % of the incident sunlight into electricity [29], depending on the solar cells that are used in panels. The remaining solar radiation is converted into heat, which significantly increases the temperature of the PV module and reduces the PV efficiency. This heat can be removed naturally or there may be a need of a cooling system which converts PV system into a PV-thermal (PV/T) system.

In this paper, a photovoltaic system with traditional linear Fresnel reflectors (LFR) integrated with a cooling mechanism is studied. Concentration of solar radiation onto a PV panel by using an LFR system is a new application in the literature. It is shown that a highly effective CPV/T system can be produced by combining a linear Fresnel reflector system with a PV panel as the receiver and a cooling system. The proposed system is considered together with low solar radiation conditions. Under the given weather conditions, it is concluded that it is possible to obtain on average 224.8 kWh of monthly electrical and 78.1 kWh of monthly thermal energy when a cooling system is integrated into PV system.

2. SOLAR ENERGY POTENTIAL IN ISTANBUL, TURKEY

The system is discussed for the city of Istanbul in Turkey. Therefore, here in this section, solar energy potential in Istanbul are given in details. Turkey has 7.5 hours/day of insolation duration and 4.18 kWh/m^2-day of solar radiation annually. Turkey's total global solar radiation is given in Fig.7 [30].

Figure 7. Total solar radiation on Turkey [30].

Istanbul is located between latitude 41.0082°N and the longitude 28.9784°E by having comparatively low solar radiation and insolation hours given in Fig.8.

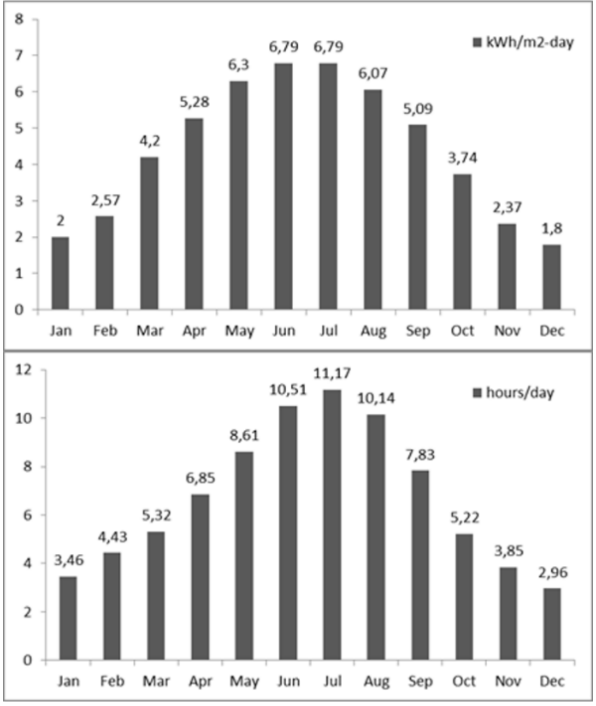

Figure 8. The monthly and average daily global solar insolation and average daily insolation hours in Istanbul [30].

It can easily be said that the solar radiation for Istanbul is relatively low. The reason for deciding to study on such low-level data in the paper is to give an idea to those who want to apply this system to the locations with higher solar energy values.

3. A PV/T SYSTEM INTEGRATED WITH LINEAR FRESNEL REFLECTORS

A conventional Linear Fresnel Power system consists of planar mirrors arranged one after the other. The Sun's rays fallen on the mirrors are focused on a receiver which is at a certain height (Figure 9). Thus, the fluid in the receiver is heated for the usage of later on. It is possible to reach high temperatures of 400 ^{o}C with this system [31].

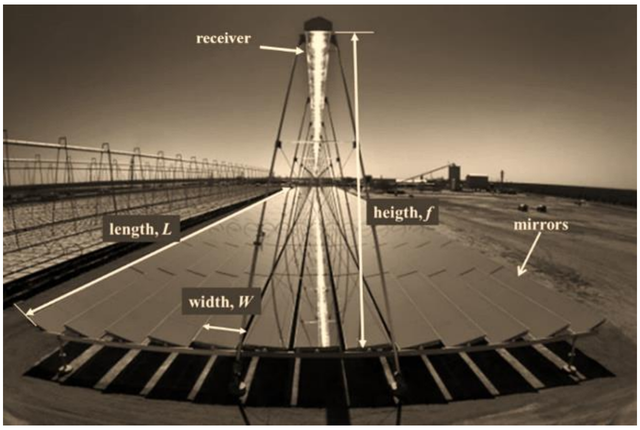

Figure 9. Reliance Areva Power's concentrated solar power [32].

In this study, for the sake of obtaining a CPV/T system, the thermal receiver of a traditional LFR system is replaced by a PV/T panel, as it is shown in Figure 10.

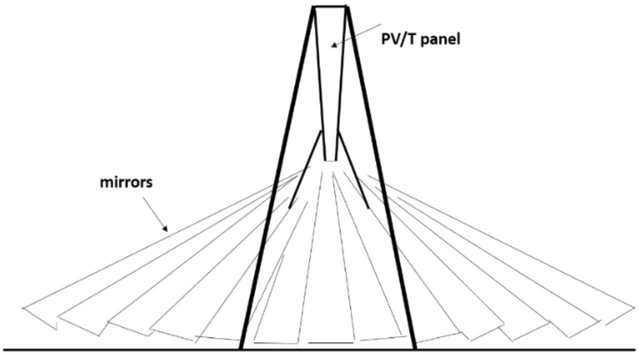

Figure 10. A CPV/T system using LFRs with PV/T receiver.

A representative view of the PV/T panel is introduced in Figure 11.

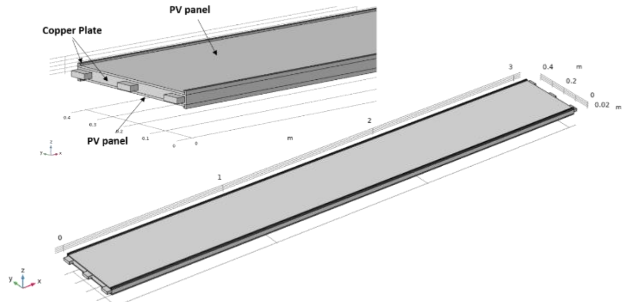

Figure 11. A representative view of the receiver of an LFR-CPV/T system.

The considered LFR-CPV/T system consists of 10 mirrors in total, as 5 mirrors on each side of the collector area. Although in an LFR system, tracking does not supply a perfect reflection [33], in this study, all the calculations are done by considering the mirrors as tracking the hourly position of the Sun on the representative day of the given month. Hence, rather than dealing with the values of each specific day in a given month, it is assumed that each and every day of a given month has the same solar energy values like direct normal radiation and sunshine duration by considering the solar radiation in every day is same as the representative day of the months.

The technical specifications of the considered LFR system are given in Table 1.

Table 1. Technical properties of the LFR system

Property	**Value**
#of Mirrors, N	10
Mirror Length, L	3 m
Mirror Width, W	0.3 m
Gap between the adjoint mirrors	0.2 m
Receiver Height, f	3.31 m
Reflectivity of mirrors in full spectrum, ρ	98%

It is assumed a highly reflective aluminum lighting sheet is used in the mirrors [34]. To avoid the shading and blocking losses in the mirror area, the gap between the adjoint mirrors is selected as 0.2 m.

Although, it is offered to use multi-junction solar cells for concentrated solar light, multi- or mono-crystal silicon (p-Sci, m-Si) solar cells can also be used for relatively low concentrated solar light. Therefore, here in this study, a highly efficient PV panel with 21.7% efficiency made of Monocrystalline-Si is considered as the part of the receiver of the system [35,36]. Under standard test conditions (STC) of AM1.5, 1000 W/m^2 at ambient temperature of 25ºC, the specifications of the PV panel are given in Table 2.

Table 2. Technical properties of the PV panel.

Property	**Value**
Length	3 m
Width	0.4 m
PV area, A_{pv}	1.2 m^2
Efficiency, η_{nom}	21.7%
Emissivity of PV panel, ε	0.91
Rated voltage, V_{mpp}	77.6 V
Rated current density, J_{sc}	2.803 A/m^2
Power @ max. power point, P_M^{STC}	261 W
Power temperature coefficient, β	-0.29 %/ºC

To avoid the end-loss in the receiver, its width is selected as 0.4 m after optical optimization calculations which they are not given in this paper.

In the calculations, only the direct solar radiation is taken into account, since the mirrors are facing opposite to the ground and so the contribution from diffuse radiation can easily be neglected.

When sunlight is concentrated onto a PV panel, the instant PV temperature, T_{pv}, rises which can be calculated by the following equation [37];

$$(1-\eta_{nom})E_{pv} = h_w(T_{pv}-T_a)+\varepsilon\sigma(T_{pv}^4-T_a^4) \quad (1)$$

where η_{nom} is the nominal efficiency of PV panel, E_{pv} is the concentrated power density reflected by LFR onto the PV panel in W/m^2, h_w is the convective heat transfer coefficient $\approx 11.4+5.7v\ W/m^2K$ for the air, v is the average wind speed, T_{pv} is the temperature of PV panel at E_{pv}, T_a is the ambient temperature in K, ε is the emissivity of PV panel and σ is Stefan-Boltzmann constant which is equal to $5.67\times 10^{-8}\ W/m^2K^4$.

The average of daily solar energy for Istanbul is obtained as in Table 3 for each month.

Table 3. Monthly average daily solar energy and weather data for Istanbul [38]

Month	Number of the days	Representative day of the month	Av. wind speed (m/s)	Av. instant Solar radiation (W/m^2)	Sunshine duration (hours)	Average ambient temp. (ºC)	Mains water temp. T_{in}, (ºC)
January	31	17	4.81	491.33	3.46	6.00	10.2
February	28	16	4.81	493.12	4.43	6.10	9
March	31	16	4.36	671.05	5.32	7.70	9.5
April	30	15	4.03	655.18	6.85	12.00	11.8
May	31	15	3.97	621.95	8.61	16.70	15.4
June	30	11	4.28	549.14	10.51	21.40	19.2
July	31	17	4.78	516.70	11.17	23.80	21.9
August	31	16	4.78	508.83	10.14	23.80	22.9
September	30	15	4.92	552.55	7.83	20.10	22.4
October	31	15	4.36	609.00	5.22	15.70	19.8
November	30	14	4.25	523.25	3.85	11.70	16.9
December	31	10	4.83	516.89	2.96	8.20	13.2

The power output of the PV panel at maximum point for a given power density E_{pv} and temperature T_{pv} is [37] calculated through following equation as,

$$P_{out} = P_M^{STC}\frac{E_{pv}}{1000}\left[1+\beta(T_{pv}-25)\right] \quad (2)$$

Such a high energy, E_{pv}, certainly rises the PV temperature and the elevated PV temperature clearly reduces the power output. Thus, the efficiency of PV can be obtained by following expression;

$$\eta_{pv} = \frac{P_{out}}{E_{pv}.A_{pv}} \quad (3)$$

Reflected concentrated solar energy E_{pv} received by the bottom PV panel, the bottom PV temperature at E_{pv} calculated by Eq. (1), T_{pv} are given in the Table 4.

Table 4. Elevated temperature of bottom PV panel due to E_{pv}.

Month	**E_{pv} (W/m^2)**	**T_{pv} (ºC)**
January	3521.25	67.3
February	3534.08	67.6
March	4809.26	94.4
April	4695.52	99.8
May	4457.37	100.4
June	3935.56	92.6
July	3703.07	86.8
August	3646.67	85.9
September	3960.00	86.5
October	4364.55	94.0
November	3750.01	80.9
December	3704.43	72.2
Average	**4006.81**	**85.7**

To avoid reduction in output electrical power and efficiency, obviously it is necessary to cool the PV panel down. Cooling by convection and radiation heat transfer is not enough as it is in a stand-alone PV panel. Therefore, using a cooling system is inevitable. In literature, various types of cooling mechanisms for a concentrated PV system has been studied [39-54]. Selection of the working fluid in the cooling system depends on the intended use of the thermal energy obtained. In this study, since the PV surface area to be cooled is small, it is assumed that water, which is considered as a coolant, flows through a single channel in an absorber metal panel sandwiched between the top and bottom PV panels as it is shown in the Fig. 12. To distribute the inlet water homogeneous in the plate, the inlets considered as manifolded.

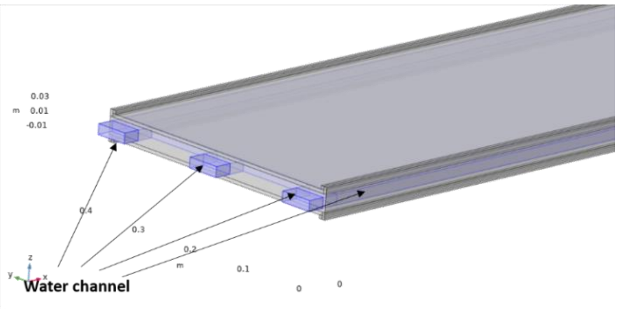

Figure 12. PV and thermal configuration of the receiver.

The portion of the incoming energy converted into electrical energy is about $\eta_{nom}E_{pv}$ for the bottom PV panel. The

$(1-\eta_{nom})E_{pv}$ segment of the incoming energy is converted into thermal energy and the heat transfer mechanisms in the domain is shown in the Fig. 13.

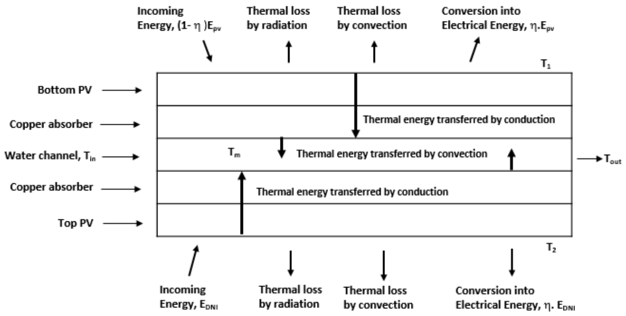

Figure 13. Heat transfer mechanisms in PV/T receiver

The detailed mathematical descriptions of the heat mechanisms given in the Fig. 10 are as follows for the bottom (concentrated) and top direct PV respectively;

$$(1-\eta_{nom})E_{pv} = h_w(T_1 - T_a) + \varepsilon\sigma(T_1^4 - T_a^4) + \frac{1}{R}(T_1 - T_m) \tag{4}$$

$$(1-\eta_{nom})E_{DNI} = h_w(T_2 - T_a) + \varepsilon\sigma(T_2^4 - T_a^4) + \frac{1}{R}(T_2 - T_m) \tag{5}$$

where T_1 and T_2 is the both sides surface temperature of the receiver, R is the thermal resistance along the receiver and T_m is the mean water temperature which is given as follows theoretically;

$$T_m = \frac{T_{out}+T_{in}}{2} \tag{6}$$

In this study despite T_m can be calculated iteratively, after doing some preliminary study, it was seen that it is 5 °C above the water inlet temperature, T_{in}. Therefore, in the calculations, T_m is obtained according to this asssumption by considering T_{in} given in Table-3. The Eqs. (4) and (5) gives the thermal energy balance. In these equations, the thermal portion of the incoming energy onto the receiver's both sides respectively are given by;

$$(1-\eta_{nom})E_{pv} \tag{7}$$

$$(1-\eta_{nom})E_{DNI} \tag{8}$$

The heat lost by radiation is expressed as;

$$\varepsilon\sigma\left(T_i^4 - T_a^4\right), i = 1,2 \tag{9}$$

The heat lost by convection is given by;

$$h_w(T_i - T_a),\ i = 1,2 \tag{10}$$

And finally, the heat transferred into the coolant is given by the term of;

$$\frac{1}{R}(T_i - T_m),\ \mathrm{i} = 1,2 \tag{11}$$

Where the thermal resistance R is given as follows;

$$R = \frac{L_{pv}}{k_{pv}} + \frac{L_{abs}}{k_{abs}} + \frac{1}{h_w} \tag{12}$$

The parameters given in the Eq. (12) are expressed in the Table 5.

Table 5. Thermal and mechanical properties of the receiver [55].

Property	**Thickness, *L*, (m)**	**Heat transfer coefficient, *k*, *h***
Photovoltaic, (pv)	225.10^{-6}	148 W/m.K
Copper absorber, (abs)	10^{-2}	400 W/m.K
Water, (w)	-	450 W/m^2.K

Heat transfer processes in the system is also carried out numerically by using finite element method. As an example, temperature distribution on the bottom-PV surface for the month April is obtained as in the Fig.14.

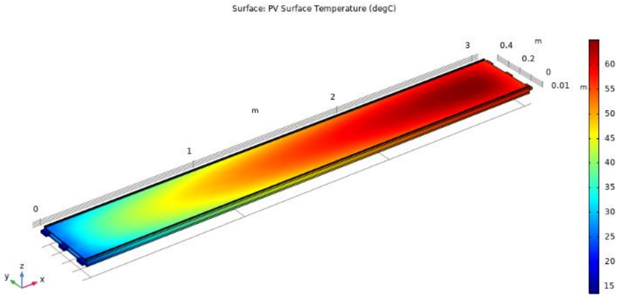

Figure 14. Temperature distribution on the bottom-PV surface of the receiver.

For this example, the velocity streamline of the flow is obtained as in the Fig.15.

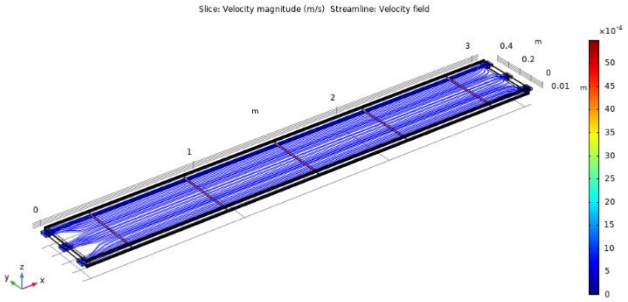

Figure 15. Velocity streamline of the flow.

After applying the heat transfer mechanisms to decrease the temperature of the PV receiver, the obtained simulation results of the PV/T system for 12 months are given in Table 6.

Table 6. The electrical and thermal performance of the system

Month	Bottom PV temperature after cooling (ºC)	Top PV temp. (ºC)	Total Instant Pout (W)	Daily Electrical Energy (kWh/d)	Output temperature of water (ºC)	Daily Thermal Energy (kWh/d)
1	37.6	29.4	1012.1	3.5	38.9	13.9
2	37.8	29.6	1015.2	4.5	39.1	17.9
3	49.2	38.1	1335.7	7.1	52.3	33.2
4	51.1	40.1	1296.3	8.9	55.0	45.9
5	51.5	41.1	1228.8	10.6	55.9	59.0
6	49.2	40.2	1092.2	11.5	53.8	68.2
7	47.8	39.3	1032.0	11.5	52.0	69.2
8	47.4	39.0	1017.4	10.3	51.5	62.0
9	47.7	38.6	1104.1	8.6	51.4	47.8
10	49.6	39.5	1210.2	6.3	53.4	33.6
11	43.1	34.4	1060.3	4.1	45.9	19.9
12	40.1	31.5	1057.0	3.1	41.5	13.1

By comparing the bottom PV temperature given in Table-6 to Table-4, the significant amount of decrease, hence increase in power output, can be seen clearly. Besides, it is also noticeable that by increasing the electrical output of the system, a considerable amount of thermal energy is obtained from the system. Thermal energy, thermal efficiency and overall system efficiency are given as follows respectively;

$$Q_{th} = \frac{\dot{m}.c_p}{A_{pv}}.(T_{out} - T_{in}) \tag{13}$$

$$\eta_{th} = \frac{Q_{th}}{E_{pv}} \tag{14}$$

$$\eta_s = \eta_{pv} + \eta_{th} \tag{15}$$

Where η_{pv} is the total electrical energy efficiency of the LFR-CPV/T system. The mass flow rate, $\dot{m}$, for water is selected as 0.02 kg/s and the specific heat is $c_p = 4186$ Ws/kgK.

Electrical, thermal and overall efficiencies of the system are given in Table 7.

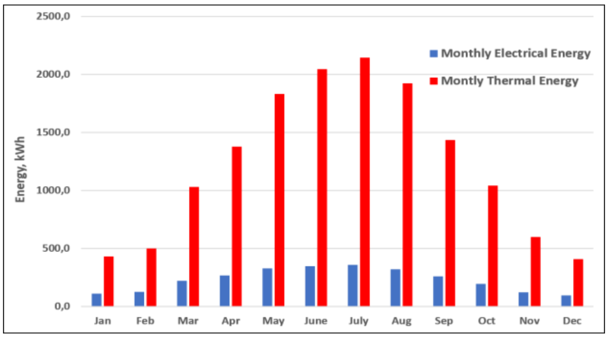

Figure 16. The daily averaged monthly total produced electrical and thermal energy.

Table 7. The electrical, thermal and overall system efficiency

Month	Electrical Energy Efficiency (%), η_{pv}	Thermal Energy Efficiency (%),η_{th}	Overall system efficiency (%),η_s
1	21.2	47.4	68.6
2	21.2	47.6	68.8
3	20.6	54.1	74.7
4	20.5	59.4	79.9
5	20.4	64.0	84.4
6	20.5	68.8	89.3
7	20.6	69.7	90.3
8	20.6	69.8	90.4
9	20.6	64.1	84.7
10	20.5	61.4	81.9
11	20.9	57.5	78.4
12	21.1	49.9	71.0

The daily averaged monthly total produced electrical and thermal energy are given in the Fig. 16.

Under concentrated solar radiation, the average instant LFR-PV power output is obtained as 1121.8 W. This would be 292 W under only DNI. Therefore, to produce the same amount of power under DNI, a PV panel with 4.6 m^2 surface area should be used. This means that by the presented configuration in this study, the electrical performance of the PV panel of 1.2 m^2 is increased by 383% and achieves up to 90% overall system efficiency. To give a clear clue about the results obtained in the present study, the study done by Amanlou et al. on a concentrated PV/T system by using a LFR-like system together with PV panel with 10% efficiency [56] is considered. They used a single-crystalline silicone PV panel of 0.80 m^2. The panel was cooled by air flow. Their system is showing in Fig.17.

Figure 17. The PV/T collector and Fresnel reflector [56].

With such a system, they have increased the electrical performance of the system by 36%. Another study for comparison is done by Yang et al [22]. They have designed a quasi-parabolic trough collector by using flat mirrors in the system to build a low concentrating photovoltaic/thermal system (Fig.2). They achieved a 59% overall system efficiency as the summation of electrical and thermal efficiencies.

4. CONCLUSION

In this study, a PV/T system with a conventional linear Fresnel reflector is introduced as a new application of a concentrated solar energy system and its performance is obtained under solar conditions of the city of Istanbul in Turkey. Under the given solar radiation conditions which is instantaneously 559 W/m^2 at the location, the system yields 228.8 kWh of average monthly electrical and 1229.8 kWh thermal energy. These results can competitively be compared with the results obtained in the studies given in the literature. When these results are considered that the daily electrical consumption is about 2 kWh and thermal energy usage (for heating) is about 4 kWh per capita in Turkey, for such a small system this amount of energy would be enough for domestic and even for small-size commercial usages with a few modules of the presented system. Without a cooling system, PV temperature in proposed concentrating system reaches up to 100^{o}C which is much higher than the optimal working temperature of a PV panel. As it is very well known that the efficiency of PV panels drops drastically parallel to the elevated PV temperatures. Hence, considering an LFR-PV system with a cooling system does not only increase the PV power generation, but also increases the overall system efficiency up to 90% due to an additional thermal energy system for the intention of cooling the PV receiver. When compared with a photovoltaic system under direct sunlight with 292 W of generated power, the power generated by proposed LFR-PV system is about 4 times higher, which is 1121.8 W on average in the case study. The result would be much more remarkable when the system is sized-up. Therefore, since this type of system is more affordable than a conventional photovoltaic system, it can be considered as an alternative power supply in convenient areas. It is also expected to realize this purposed configuration of the CPV/T by an R&D company named SUNOVA Project Consultancy and Construction Company and verify the performance results in this study.

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