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A Cost-Effective Theoretical Novel Configuration of Concentrated Photovoltaic System with Linear Fresnel Reflectors

Araştırma Makalesi / Research Article

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ABSTRACT

A simple yet newly-configured theoretical concentrated photovoltaic system integrated with linear Fresnel reflectors is discussed in this study. The concentration of solar radiation onto a comparatively smaller photovoltaic panel by using linear Fresnel reflectors yields a very high rate photovoltaic power production and a cost effective system even at locations of a relatively low-rate solar radiation region. The proposed configuration for the concentrated photovoltaic power system with linear Fresnel reflectors is novel in the literature. To examine the system as a case study, this system is assumed to be located in Istanbul, Turkey, where the average daily global solar radiation is known as low. Under the given solar radiation conditions, although no any cooling system is considered for this system, it is concluded that 153.7 kWh of average monthly obtained electrical energy in such a small system would be enough for domestic and even for small size industrial usages. When it is compared to a photovoltaic system under direct sunlight, this system costs 38.3% less for the same amount of power produced. The result would be much more remarkable when the system is sized-up.

Keywords: Solar radiation, concentrated solar photovoltaics, linear Fresnel reflector.

Uygun Maaliyetli Lineer Fresnel Yansıtıcılı Özgün Bir Yoğunlaştırılmış Fotovoltaik Sistemin Teorik Yapılanışı

ÖZ

Bu çalışmada lineer Fresnel yansıtıcılarla entegre basit fakat özgün bir konfigürasyona sahip teorik konsantre bir fotovoltaik sistem ele alınmıştır. Doğrusal Fresnel yansıtıcılar kullanılarak güneş ışınımının nispeten daha küçük bir fotovoltaik panel üzerine yoğunlaşmasıyla güneş enerjisinin nispeten düşük olduğu lokasyonlarda dahi düşük maaliyetli ve çok yüksek bir fotovoltaik güç üretimi sağlanabilir. Önerilen bu doğrusal Fresnel reflektörlü konsantre fotovoltaik güç sistemi konfigürasyonu literatürde yenidir. Sistemi bir örnek olay ile incelemek amacıyla bu sistemin günlük ortalama güneş ışınımının düşük olarak bilindiği İstanbul'da olduğu varsayılmaktadır. Verilen güneş radyasyonu koşulları altında, bu sistem için herhangi bir soğutma sistemi gözönüne alınmadığı halde, böylesi küçük bir sistemde aylık ortalama 153,7 kWh elektrik enerjisinin evsel ve hatta küçük boyutlu endüstriyel kullanımlar için yeterli olacağı sonucuna varılmıştır. Doğrudan güneş ışığı altındaki bir fotovoltaik sistem ile karşılaştırıldığında bu sistemin, üretilen aynı miktardaki güç için % 38,3 daha az maliyeti olduğu görülmektedir. Bu sistemden elde edilecek sonuçlar, sistem daha büyük boyutlarda düşünüldüğünde çok daha dikkat çekici olacaktır.

Anahtar Kelimeler: Güneş radyasyonu, yoğunlaştırılmış fotovoltaik sistemler, doğrusal Fresnel yansıtıcılar

1. INTRODUCTION

Because of the shortage of the fossil fuels, the renewable energy sources are being more attractive day after day. The origin of the most of the renewable energy sources is the Sun. Solar energy can be used directly or indirectly, for heating, cooling, lighting, drying and generating electricity. One of the most common ways of obtaining electrical energy from the sun is the photovoltaic (PV) power generation. However, the PV power still cannot compete with traditionally produced power because of high production and installation prices. Besides, nowadays the availability of silicon material is being a concern. Therefore, many solar companies are reducing their dependence on silicon [1-4].

On the other hand, the concentrated sunlight significantly reduces the usage of PV material. The use of PV under concentrated sunlight is called as concentration photovoltaics (CPV). The key idea behind CPV is to replace the area of active material, which currently is the most expensive, with optic elements that can be manufactured cheaper. At large concentrations, the cell size is reduced considerably (i.e. 500 – 1000 times as compared to one sun modules), allowing a cost distribution scheme different from traditional photovoltaics [5-7]. This technology is usually classified according to its concentration ratio, number of times that

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the sunlight is concentrated, as low (<10 suns), medium (10-100 suns), high (100-2000 suns), and ultra-high (>2000 suns) [8].

Concentrator systems can be also classified as a function of the strategy used for concentrating sunrays. They can be refractive, using lenses, or reflective, using mirrors. Moreover, if sunrays are concentrated onto a point, those systems are called point-focus, and if sunrays are concentrated onto a line, they are called line-focus [9]. Basically, there are two types of solar collectors, non-concentrating or stationary, and concentrating. 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. These systems are used for power generation using high pressure steam. The temperature is around 400 oC [10]. The Linear Fresnel Collector is a line focusing concentrating collector suitable for solar thermal power generation and production of process heat [11]. Linear Fresnel reflectors had a late development compared to the other technologies [12]. Linear Fresnel collector arrays present some relevant advantages in the domain of concentrating solar power because of their simplicity, robustness and low capital cost [13].

Photovoltaic cell production technology has been greatly improved and the PV efficiencies consequently increased. Si-based solar cells with back point contact [14] reached an efficiency record of 27.6%, and some manufacturers used this type of solar cells under more than 400 X-concentrations [15].

The use of compound III–V semiconductors brings the development of multi-junction solar cells: two or more p–n junctions are monolithically integrated into a single device. The utilization of these cells allows a better usage of the solar spectrum as each one of the junctions is optimized to capture the radiation of a different part of the spectrum. Based on the spectral response, the theoretical limit efficiency of silicon cells is 31%, whereas multi-junction cells could reach 86% [16]. Current records for laboratory-multi-junction cell are 46% from Soitec, 45.7% from NREL, 44.4% from Sharp, and 43.4% from Fraunhofer-ISE [17].

In this study, a concentrated photovoltaic system integrated with linear Fresnel reflectors (LFR) is considered. The idea of concentrating the solar radiation onto a PV panel by using a LFR system is new in the literature. Concentration of the solar radiation onto a comparatively smaller PV panel by using LFR yields a high rate photovoltaic power production and a cost effective system even at the locations of a relatively low-rate solar radiation regions. As a case study, this system is assumed to be located in Istanbul, Turkey in where the average daily global solar radiation is known to be low.

2. ELECTRICITY CONSUMPTION AND SOLAR ENERGY POTENTIAL IN ISTANBUL, TURKEY

In the cities in Turkey, average monthly electricity consumption per capita varies in between 47-638 kWh and the average electrical energy consumption is 199 kWh/capita in Istanbul as of 2014 [18]. There are 5,577,636 residential subscribers in Istanbul. On average, 29.71% of the total consumption in Istanbul is realized as residential usage. Thus, the average monthly residential use of electricity is 163.34 kWh per residence in Istanbul city in 2016. Monthly residential consumption is given in Table 1 [19].

Table 1. Monthly residential electricity consumption in Istanbul in 2016 [19].

Month	Total (MWh)	Res. (%)	Residential use (MWh)	kWh per residence
Jan	3404730.30	33.24	1131732.35	202.91
Feb	3227780.56	30.89	997061.41	178.76
Mar	3138517.00	29.25	918016.22	164.59
Apr	2876791.15	29.99	862749.67	154.68
May	2798860.62	29.29	819786.28	146.98
Jun	2871255.74	28.70	824050.40	147.74
Jul	2861989.69	29.69	849724.74	152.34
Aug	3343937.46	28.54	954359.75	171.10
Sep	2646496.50	28.36	750546.41	134.56
Oct	2958911.71	27.41	811037.70	145.41
Nov	3120202.64	30.47	950725.74	170.45
Dec	3470141.66	30.63	1062904.39	190.57
Average	3059967.92	29.71	911057.92	163.34

Turkey has 7.5 hours/day of annual insolation duration and 4.18 kWh/m2-day of annual solar radiation. Turkey's total global solar radiation is given in Fig.1 [20].

Figure 1. Total solar radiation on Turkey [20]

Also, the monthly average daily global solar insolation on a horizontal surface and insolation hours of Turkey is given in Fig.2.

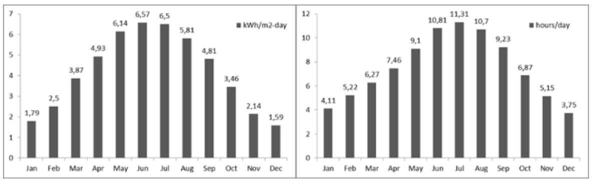

Figure 2. The monthly, average daily global solar insolation and average daily insolation hours of Turkey [20].

On the other hand, it is known that the existing meteorological data is lower than the actual solar energy data of Turkey. General Directorate of Renewable Energy (EIE) and Turkish State Meteorological Service (DMI) have been taking new measurements since 1992 to determine the more accurate solar energy data. The collected data shows that the actual solar energy radiation values are 20-25% higher than the existing data [21].

Istanbul city of Turkey 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.3.

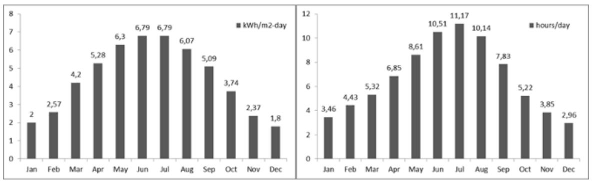

Figure 3. The monthly, average daily global solar insolation and average daily insolation hours in Istanbul [20]

3. A PV SYSTEM INTEGRATED WITH LINEAR FRESNEL REFLECTORS

A linear Fresnel reflector system consists of mostly flat mirrors. These mirrors form a parabola-like shape to reflect the incoming solar radiation onto a receiver which is placed at the focal point of the mirror system. A typical LFR system is shown in the Fig.4. In the system, the mirror tracks the sun to reflect the Sunlight onto an elevated boiler tube system (thermal receiver) to produce steam without the costs and pollution of fossil-fired boilers.

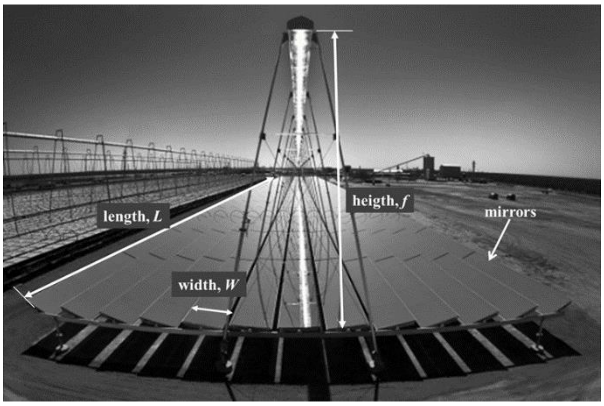

Figure 4. Areva Power's concentrated solar power [22]

In this study, thermal receiver of the LFR system is replaced by a PV panel. In the LFR system considered, there are 10 mirrors in total, as 5 mirrors on each side. In a LFR system, tracking is not an easy job, it does not supply a perfect reflection [23]. In this study, all the calculations are done by considering the solar radiation on the representative day of the month and at solar noon. However, to correct this assumption, average daily solar radiation value is taken into account. Hence, the solar radiation is assumed having the same value at every sun shining hours in a day. The technical specifications of the LFR system are given in Table 2.

Table 2. Technical properties of the LFR system

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

A very high efficient PV panel with 24.2□0.7% efficiency is considered as the receiver of the system [24-26]. However, for the sake of being conservative in the calculations, the efficiency of the panel is taken as 19.6%. Under standard test conditions (STC) of AM1.5, 1000 W/m2 at 25oC of ambient temperature, the specifications of the PV panel are given in Table 3.

Table 3. Technical properties of the PV panel.

Property	Value
Length	3 m
Width	0.3 m
Efficiency, η_{nom}	19.6%
Open circuit voltage, V_{oc}	68.2 V
Short circuit current, I_{sc}	6.39 A
Power @ max. power point , P_M^{STC}	345 W
Power temperature coefficient, β	-0.29 %/°C

Solar power on a collector-mirror is given as [27];

$$P_{col} = I_b . W . L . \sum_{i=0}^{N} \cos(\theta_i) \tag{1}$$

Where I_b is the direct normal irradiance (DNI) (W/m^2), L is the length of the mirror (m), W is the width of the mirror (m), N is the number of mirrors in the system and θ_i is the tilt angle of the i^{th} mirror. i=0 refers the first mirror (if there is any, otherwise refers the central point of the mirror system) in the centre of the system incident and reflected rays are as sketched in Fig.5.

Figure 5. Incident and reflected rays on/from mirrors [22].

For the calculations, all of the geometrical parameters involved are given as in the Fig. 6 [28].

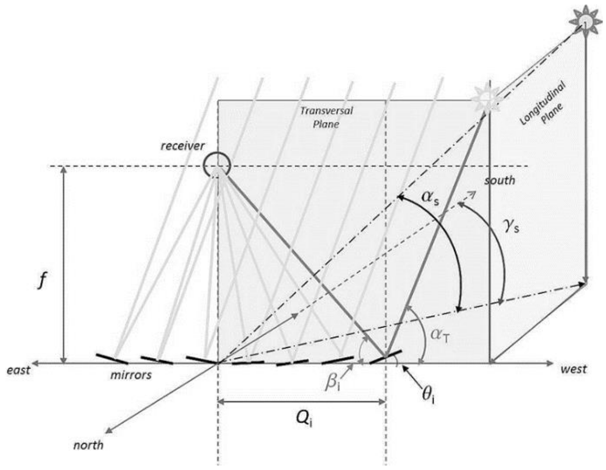

Figure 6. Geometrical structure of an LFR system.

Angles related to tilt angle of a mirror at right and left hand sides are shown in figures 7a and 7b respectively.

$$\beta_i = \arctan\left(f/Q_i\right) \tag{4}$$

The angles α_s and γ_s refer the solar altitude and solar azimuth angles respectively, and Q_i is the distance of the i^{th} mirror from the center of the LFR system.

The distance of the mirror is calculated with the following formulas [29];

$$S_i = \frac{\left(Q_{i-1} + W\cos\theta_{i-1} + \frac{W}{2}\right).W\sin\theta_{i-1}}{f - W\sin\theta_{i-1}} \tag{5}$$

$$Q_i = Q_{i-1} + W\cos\theta_{i-1} + S_i \tag{6}$$

where, S_i is the gap between adjacent mirrors.

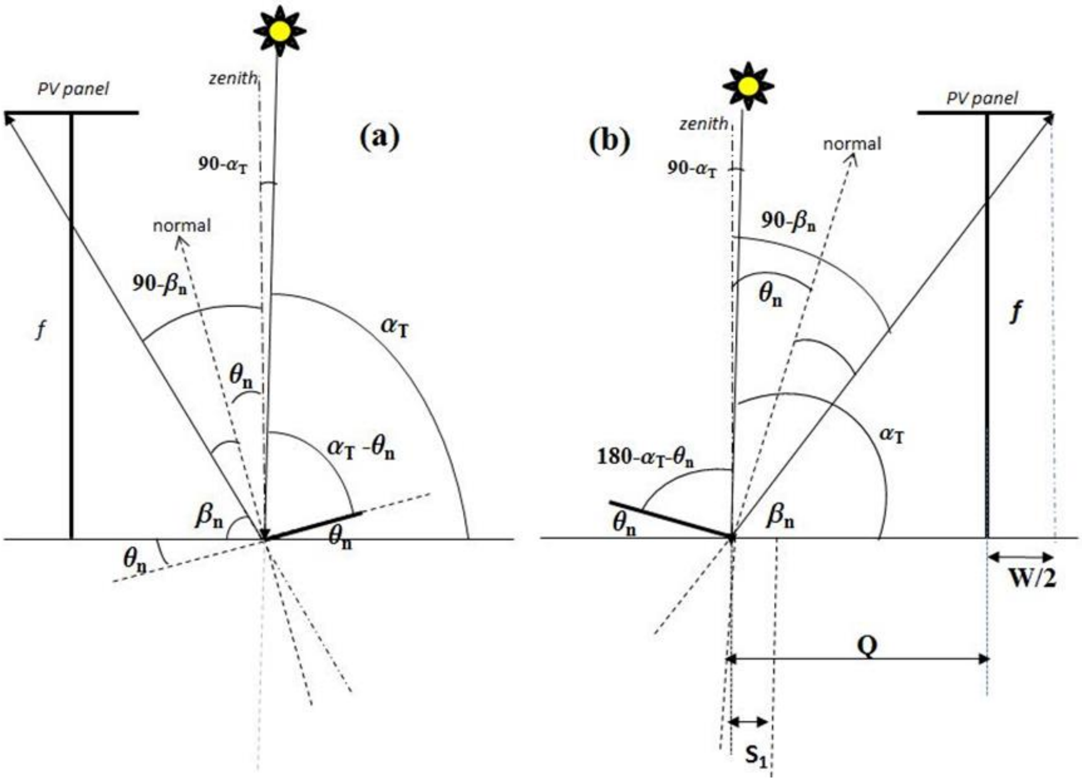

Figure 7. Angles related to tilt angle of the mirrors at (a) right and (b) left hand side of the LFR system.

The tilt angle of the i^{th} mirror at right hand side is defined as [27]:

$$\theta_i = \frac{\alpha_T - \beta_i}{2} \tag{2}$$

where the transversal solar altitude angle α_T and the angle β_i are defined as;

$$\alpha_T = \arctan\left(\tan(\alpha_s)/\sin\gamma_s\right) \tag{3}$$

The tilt angle of the i^{th} mirror at the left hand side is obtained as;

$$\theta_i = 90 - \frac{\alpha_T + \beta_i}{2} \tag{7}$$

The calculation starts with the following initial values of $S_1 = 0, \quad \theta_0 = 0,$

$Q_0 = Q_1 = W/2 + f\tan\xi_0$. $\xi_0 = 16'$ is the angular radius of the Sun disk.

In the calculation of solar energy collected by the mirror system and then reflected onto a PV panel, the solar angles on the representative day of each month in the given location at solar noon is assumed as the same in other days of the month and solar global radiation and insolation hour as monthly average daily values. Besides, it is assumed that, DNI is $\gamma = 90\%$ of the global solar radiation during the insolation hours. Also, since the PV receiver facing to the ground, the contribution from diffuse radiation can easily be neglected. Therefore, in the calculation, only the direct radiation can be taken into account.

When sunlight is concentrated onto PV panel, then the instant PV temperature, T_{pv} rises as it can be calculated by the following equation [30];

$$C(1-\eta_{nom})E_{ar}\mu_i = h(T_{pv}-T_a)+2\sigma(T_{pv}^4-T_a^4) \quad (8)$$

where $C = S_{col}/S_{pv}$ is geometric concentration ratio (S_{col} and S_{pv} are the collector and PV area respectively), η_{nom} is the nominal efficiency of PV panel, E_{ar} is the average reflected power density by each of the mirror, $E_{pv} = C.E_{ar} = (P_{col}/S_{col}^e).\gamma$ is power density on PV panel in W/m^2, μ_i is the portion of total solar spectrum (45 % visible light, 9% UV and 46% IR), *h* is the convective heat transfer coefficient of the process ($\approx 2.8+3v$ $\mathrm{W/m^2}K$ for air, *v* is the average wind speed), T_{pv} is the temperature of PV panel at E_{pv}, T_a is ambient temperature in K (assumed 298.15 K) and σ is Stefan-Boltzmann constant which is 5.67×10^{-8} $\mathrm{W/m^2}K^4$.

The effective collector area which is smaller than the real area of collectors $S_{col}^r = N.W.L$ is defined in terms of tilt angle θ_i as;

$$S_{col}^e = W.L.\sum_{i=0}^{N}\cos(\theta_i) \quad (9)$$

Monthly average daily solar data on Istanbul is obtained as in Table 4.

Table 4. Monthly average daily solar data on Istanbul.

Month	representative day of the month	Av. Wind speed (m/s)	Global radiation (W/m^2-d)	Sunshine duration (hours)	Av. instant global radiation (W/m^2)	Av. DNI (W/m^2)	Solar azimuth angle (degree)	Solar altitude Angle (degree)
January	17	4.81	2000	3.46	578.03	520.23	179.91	28.36
February	16	4.81	2570	4.43	580.14	522.12	179.92	36.82
March	16	4.36	4200	5.32	789.47	710.53	179.71	47.42
April	15	4.03	5280	6.85	770.80	693.72	179.90	58.90
May	15	3.97	6300	8.61	731.71	658.54	179.65	67.95
June	11	4.28	6790	10.51	646.05	581.45	179.34	72.10
July	17	4.78	6790	11.17	607.88	547.09	179.74	70.11
August	16	4.78	6070	10.14	598.62	538.76	179.76	62.60
September	15	4.92	5090	7.83	650.06	585.06	179.84	51.87
October	15	4.36	3740	5.22	716.48	644.83	179.70	40.35
November	14	4.25	2370	3.85	615.58	554.03	179.83	30.69
December	10	4.83	1800	2.96	608.11	547.30	179.73	26.08

The power output of the PV panel at maximum point for a given power density E_{pv} and temperature T_{pv} is [30] calculated through following equation as,

$$P_{out} = P_M^{STC}\frac{E_{pv}}{1000}\left[1+\beta(T_{pv}-25)\right] \quad (10)$$

The elevated PV temperature clearly reduces the power output thus the efficiency of PV which is obtained by following expression;

$$\eta_{pv} = \frac{P_{out}}{E_{pv}.A_{pv}} \quad (11)$$

The monthly total produced electrical energy by the LFR-PV system can be calculated as;

$$E_\Sigma = h_s D_n P_{LFR} \quad (12)$$

where h_s is the sunshine duration hours per day and D_n is the numbers of the day and P_{LFR} is the instant power output of LFR-PV concentrating system in regarding month.

E_{pv} is the instant power density on PV panel, T_{pv} is the PV temperature at the power density of E_{pv}, P_{DNI} is the instant power output of the PV panel under

DNI , η_{pv} is the LFR-PV system efficiency and E_Σ is the monthly total produced electrical energy by the LFR-PV system. The values of each property are calculated as above and given in Table 5.

Table 5. Performance of LFR-PV system.

Month	**E_{pv} (W/m^2)**	**T_{pv} (°C)**	**P_{DNI} (W)**	**P_{LFR} (W)**	η_{pv} **(%)**	E_Σ **(Wh/month)**
January	5313.99	137.6	104.1	760.5	15.9	81572.3
February	5314.03	137.6	104.5	760.5	15.9	94334.9
March	5313.93	140.8	142.2	750.1	15.7	123700.0
April	5314.06	143.2	138.9	742.2	15.5	152512.0
May	5314.01	143.7	131.8	740.7	15.5	197692.0
June	5313.96	141.4	116.4	748.2	15.6	235895.0
July	5314.04	137.8	109.5	759.8	15.9	263106.0
August	5314.02	137.8	107.9	759.8	15.9	238845.0
September	5314.02	136.9	117.1	763.0	16.0	179231.0
October	5313.87	140.8	129.1	750.1	15.7	121373.0
November	5313.92	141.6	110.9	747.4	15.6	86329.3
December	5313.72	137.5	109.6	760.9	15.9	69822.9
Average	**5313.96**	**139.7**	**118.5**	**753.6**	**15.8**	**153700.0**

Under concentrated solar radiation, the average LFR-PV power output is 753.6 W. This would be 118.5 W under the DNI. Therefore, to produce the same amount of energy under DNI, 5.7 m^2 of PV panel should be used.

Compared to other technologies, the investment costs per square meter of collector field using LFR technology tend to be lower because of the simpler solar field construction. The Fresnel design uses less expensive reflector materials and absorber components. It has the lower optical performance and thermal output, but this is offset by lower investment and operating & maintenance costs. Linear Fresnel Reflectors (LFR) CSP technology is the most economical (flat mirrors) and the most adaptable (flexible production parameters) of all solar technologies [31]. Cost data for the LFR-PV system components is presented in Table 6. For the cost calculations the current rate is taken as 1€=1.136US$ (22/04/2017).

Table 6. Cost data [32, 33].

Component	**Unit Price**	**Area (m^2)**	**Average P_{out} (W)**	**Total Price (USD)**
PV (high efficient, mono-Si)	622 USD/m^2	5.70	753.6	3560
LFR (complete system)	160 €/ m^2	9.01	-	1638
PV for LFR system	622 USD/m^2	0.90	753.6	560
LFR+PV	-	-	-	2198

4. CONCLUSION

In this study, a PV system with linear Fresnel reflectors is introduced as a novel configuration of CPV and its performance is obtained under solar conditions of Istanbul city of Turkey. Under the given solar radiation conditions, although no any cooling system is considered for the system, the concluding 153.7 kWh of average monthly obtained electrical energy in such a small system would be enough for domestic and even for small-size commercial usages. Without a cooling system, PV temperature in proposed concentrating system reaches up to 140 oC which is much higher than 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 a LFR-PV system with a cooling system would not only increase the PV power generation, but also make the overall system efficiency increased due to the additional thermal energy system via cooling system. When compared with a photovoltaic system under direct sunlight, the power generated by proposed LFR-PV system would be about 7 times higher which is averagely 753.6 W in the case study and would cost 38.3% less with the same amount of power generated by a PV system under the DNI. 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.

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