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Techno-Economic Evaluation of a Photovoltaic System for Industrial Facility: A Case Study in Edirne, Turkey

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Highlights

- Photovoltaic system is a cost-effective, environmentally friendly, and sustainable energy source for industrial applications.
- The capacity factor of the PV system is 14.8%.
- The annual average rate of solar energy utilization of the photovoltaic system is 20%.

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Abstract

System solutions such as the use of renewable energy are used as energy management applications to implement the necessary measures to eliminate energy waste, losses, and inefficiencies in industrial facilities, to meet the needs of heating, cooling, ventilation, electricity, hot water, and lighting energy completely or partially. In this study, it is planned to obtain some of the electrical energy consumed as an energy efficiency increasing application in the industrial facility located in Edirne, from solar energy, which is a renewable energy source. With the 910 kW Photovoltaic (PV) system planned to be installed in the industrial facility, it is aimed to obtain approximately 20% of the electricity need of the facility with solar energy. Thus, because of the use of renewable energy in electricity production, 543.7 tCO_2 greenhouse gas emissions will be reduced, equivalent to 99.6 unused cars and pickup trucks per year. With the PV system installation, 1,183.0 MWh/year (101.737 TOE/year) energy savings and 318,376.66 $/year cost savings will be achieved. The payback period of the system is 2.7 years.

Endüstriyel Tesis İçin Bir PV Sisteminin Tekno-Ekonomik Değerlendirmesi: Türkiye-Edirne'de Bir Vaka Çalışması

Makale Bilgileri

Makale Tarihçesi:

Geliş: 4 Aralık 2024

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Anahtar Kelimeler:

Fotovoltaik;

Enerji Yönetimi;

Güneş Enerjisi,

Ekonomik Analiz.

Öz

Endüstriyel tesislerde enerji israfı, kayıpları ve verimsizliklerin giderilmesi için gerekli önlemlerin uygulanması, ısıtma, soğutma, havalandırma, elektrik, sıcak su ve aydınlatma enerjisi ihtiyaçlarının tamamen veya kısmen karşılanması için yenilenebilir enerji kullanımı gibi sistem çözümleri enerji yönetimi uygulamaları olarak kullanılmaktadır. Bu çalışmada, Edirne'de bulunan sanayi tesisinde enerji verimliliğini artırıcı bir uygulama olarak tüketilen elektrik enerjisinin bir kısmının yenilenebilir bir enerji kaynağı olan güneş enerjisinden elde edilmesi planlanmıştır. Sanayi tesisine kurulması planlanan 910 kW Fotovoltaik (PV) sistem ile tesisin elektrik ihtiyacının yaklaşık %20'sinin güneş enerjisi ile elde edilmesi hedeflenmektedir. Böylece elektrik enerjisi üretiminde yenilenebilir enerji kullanımı sayesinde yılda 99,6 adet kullanılmayan otomobil ve kamyonete eşdeğer 543,7 tCO_2 sera gazı salımı azaltılmış olacak. PV sistem kurulumu ile 1.183,0 MWh/yıl (101,737 TEP/yıl) enerji tasarrufu ve 318.376,66 $/yıl maliyet tasarrufu sağlanacaktır. Sistemin geri ödeme süresi 2,7 yıldır.

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1. Introduction

In the world, 50% of primary energy consumption is realised in industry (AEO, 2018). At this point, it gains importance in terms of increasing efficiency and energy saving with energy management in industry. In Turkey, where the electricity consumption in the industry has a share of more than 35%, the utilization of renewable energy sources for electricity generation has been one of the objectives (enerji.gov.tr). Within the scope of efficiency-enhancing practices in industrial facilities, electricity generation systems based on renewable energy resources are established to meet part of the energy need. In order to meet the electricity, and lighting energy needs in buildings, system solutions such as the use of renewable energy sources are analysed by the designers at the project stage.

PV systems are a suitable power generation system for industrial applications. In 2020, the worldwide PV system capacity was 773.2 GWp (Statista). Owolabi et al. analysed the PV plant in Nigeria and proved that it is a viable option. Mukisa et al. evaluated rooftop PV system for industrial plants. Obeng et al. investigated the campus application of a thin film (CdTe) solar PV system. Farangi et al. investigated the economic analysis of PV system. Kumar et al. investigated the fulfilment of the energy needs of an educational building with a PV system. Chang et al. analysed the rooftop PV system for different buildings. Sajid et al. analysed a photovoltaic (PV) system to meet the electricity demand of an industrial plant. Rajput and Dheer conducted experiments on a 100 kWp PV system with the mathematical model they developed.

In the literature, there are studies on energy analysis in industrial plants (Andrews and Johnson, 2016) and environmental impact (Cheng et al., 2019). The management team in the plant is also an important factor (Tiller, 2012). Sola and Mota analysed the factors affecting energy management in industrial facilities from these perspectives. A study developed by Martin et al. (2012) shows that better energy efficiency and productivity are strongly related to management practices. According to a study developed by Neves et al., the market also influences the adoption of an environmental management system (ISO 14001). Marimon and Casadesús (2017) conducted research on the application of ISO 50001 in industrial plants. The impact of energy management activities in an industrial company was analysed by Schulze et al.in 2016. Backlund et al. (2012) found that retrofit works in Industrial plant are more energy efficient for energy intensive industries. Tollander and Ottosson (2010) argue that energy management practices in industries are scarce. Energy efficiency practices in industrial plant should be developed both in terms of theoretical contributions and practical case studies (Worrell et al., 2009; Yin, 2009). Schulz and Stehfest (1980) showed that energy management practices in industry are beneficial both financially and environmentally (Klugman et al., 2009). Other studies show potentials for total energy savings (Karlsson et alç, 2009; Thollander et al., 2007). The application of cogeneration systems in industrial plants is seen as a solution (Marshman et al., 2010). Rudberg et al (2013) investigated the preconditions for energy management in industrial plant.

The aim of the study is to obtain a part of the electrical energy consumed as an energy efficiency improving application in the industrial facility from solar energy, which is a renewable energy source. In this study, the PV system, which is an electricity generation system from solar energy that can be used in integration with the buildings, will be installed on the roof of the facility where the study is carried out. Within the scope of the study, a system that will provide electrical energy conversion from solar energy with a power of 910 kW consisting of 2000 grid-connected PV panels on a total area of 4,550 m^2 on the roof of 4 buildings of the industrial facility will be installed and the electricity production of this system will be monitored for a period of two years. Using the obtained data, system performances, capacity factors, energy production efficiencies, levelled electricity costs will be determined. The performance and economic analysis of the PV system, which is designed to be installed, are theoretically examined for real field conditions. This study sets an example for future studies by providing methodology and information on how to improve energy efficiency by generating electricity from renewable energy sources, not only for industrial plants in Turkey, but also for other industrial plants around the world.

2. Material and Methods

2.1. Site Description

The closed volume of the industrial facility located in Edirne; Turkey is 14,339 m^2. It is located at 41^o latitude, 26^o longitude geographical coordinates. Figure 1 shows the location of the industrial facility. Table 1 summarises the Industrial facility 's location and heating characteristics in Edirne.

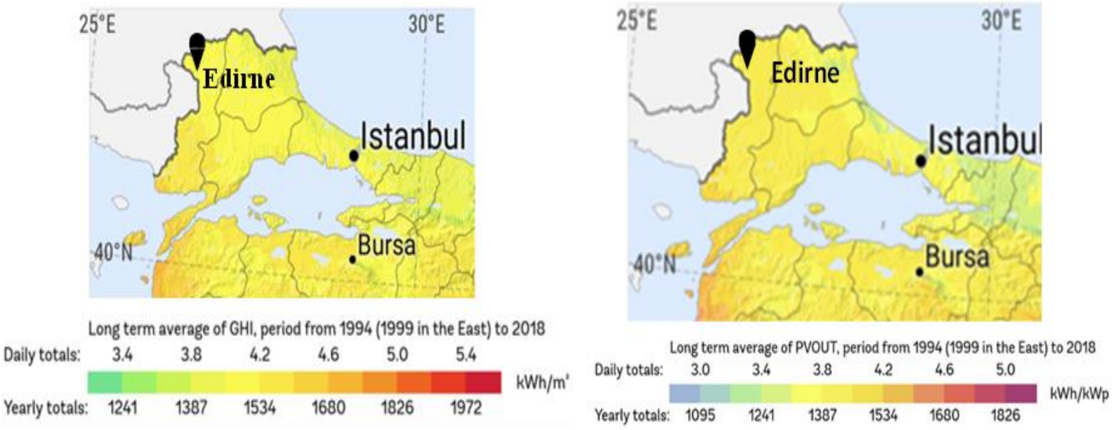
Figure 1. Location of the industrial facility in Edirne, Turkey (earth.google.com)

Table 1. Industrial facility location's climate data

Parameter	Unit	Edirne
Latitude	ºN	41.7
Longitude	ºE	26.6
Elevation	m	51
Earth temperature amplitude	ºC	21.8
Average annual air temperature	ºC	13.5
Annual relative humidity	%	69.5
Heating design temperature	ºC	-5.6
Cooling design temperature	ºC	33
Total heating degree days	ºC·d	2,212
Total cooling degree days	ºC·d	2,009
Annual average horizontal solar radiation	kWh/m^2/d	3.91
Annual atmospheric pressure	kPa	99.3
Annual average wind speed	m/s	1.9

-Solar energy potential

Figure 2 provides a summary of global horizontal radiation and estimated PV power potential in shopping mall location. It represents the average daily/yearly electricity generation totals obtained from 1 kW-peak solar power plant. Figure 3 shows the monthly average ambient temperature and solar radiation of the industrial facility site in Edirne, Thrace.



(a) (b)

Figure 2. a) Global horizontal radiation and **b)** Photovoltaic power potential in Edirne, Turkey (Shopping mall location) (globalsolaratlas.info)

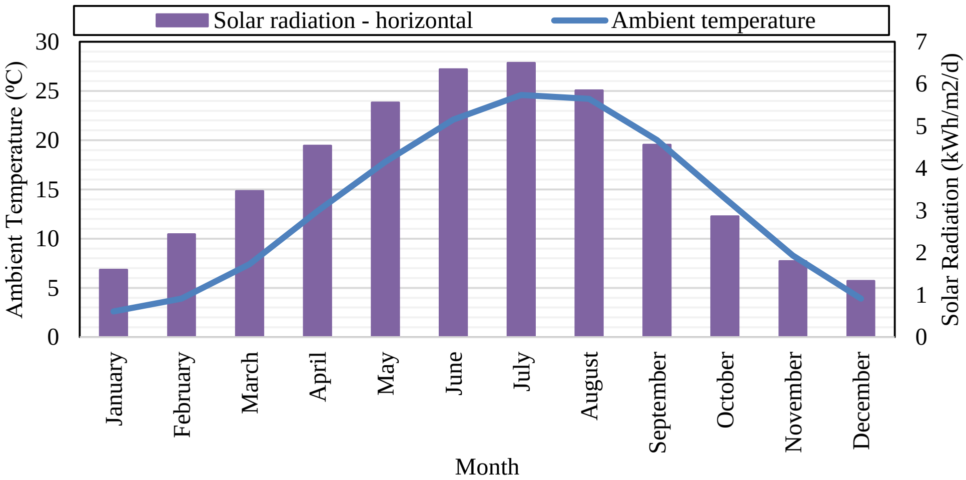


Figure 3. Monthly average ambient temperature and solar radiation in Edirne, Turkey (retscreen-database)

2.2. Energy Production, Consumption, and Cost of the Industrial Facility

The total energy consumption of the industrial facility in 2020 is 3,825.6 TOE, the total energy consumption in 2021 is 3,139.79 TOE, and the total energy consumption in 2022 is 3,825.6 TOE. The facility's total energy consumption average for the last 3 years is 3,477.81 TOE. In Figure 4, the monthly energy consumption of the industrial facility in 2022 and the monthly production of the industrial facility in 2022 in Figure 5 are given. There is a linear variation between total energy consumption and production. Figure 6 shows the distribution of total production and energy consumption in the months of 2022. Considering the production and energy consumption in the industrial facility, it has been determined that production is mostly directly proportional to coal consumption. Figure 7 shows the total production and consumption trend graph in the months of 2022.

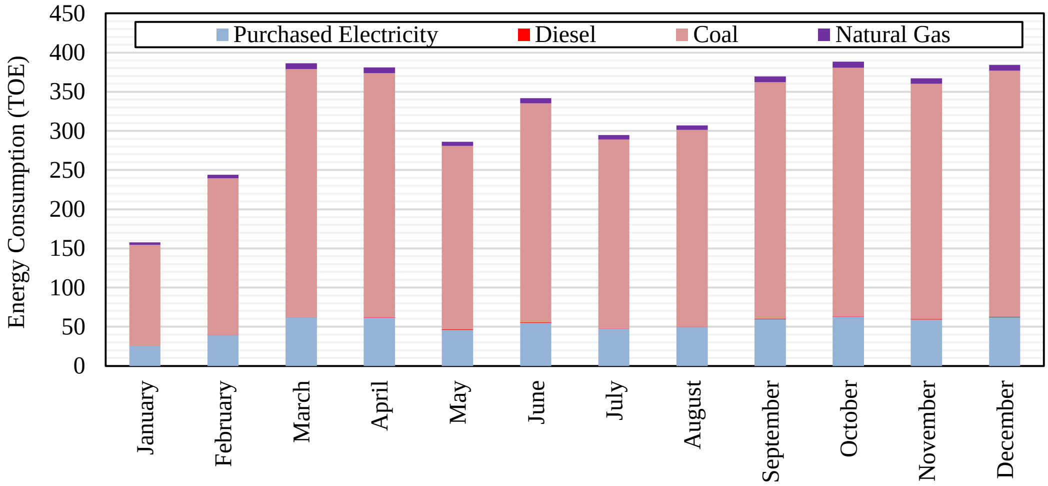


Figure 4. Energy consumption of industrial facility in the months of 2022

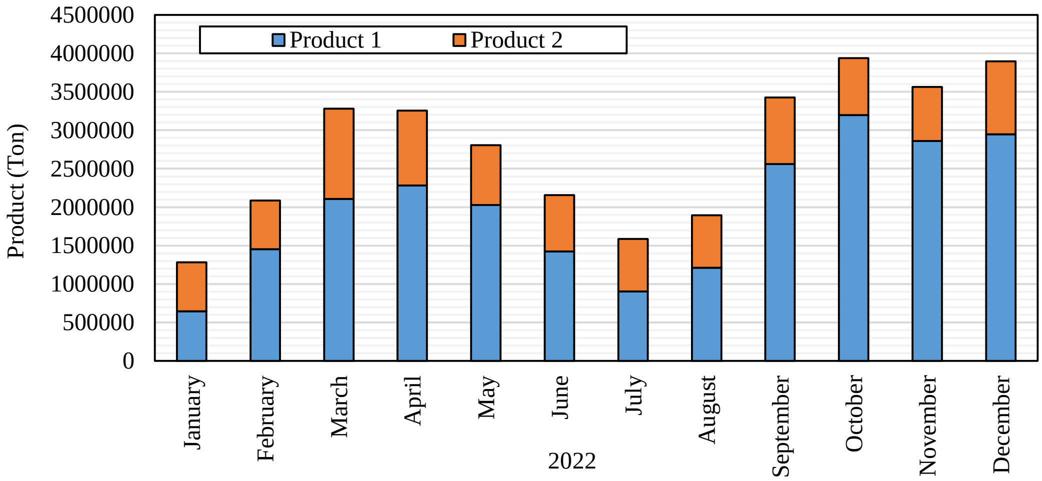


Figure 5. Production of the industrial facility in the months of 2022

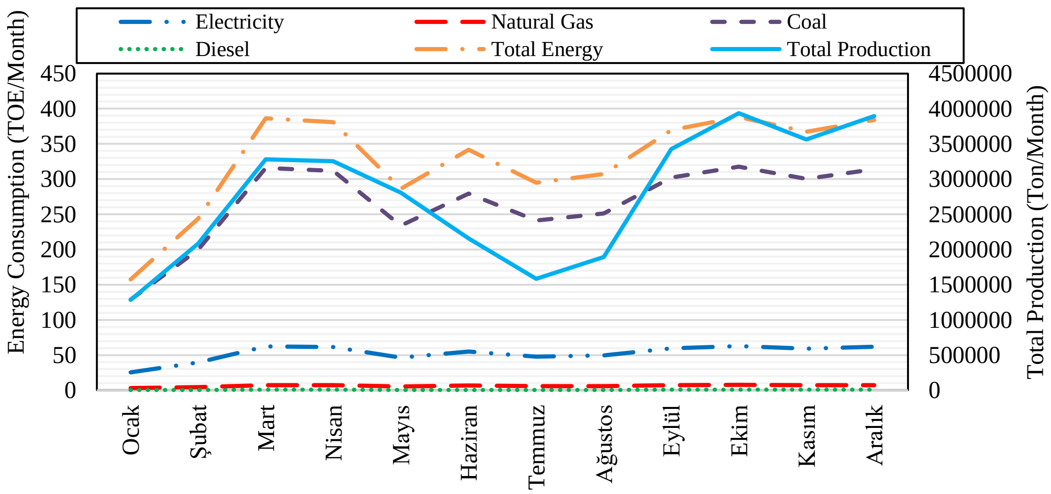


Figure 6. Distribution of total production and energy consumption in the months of 2022

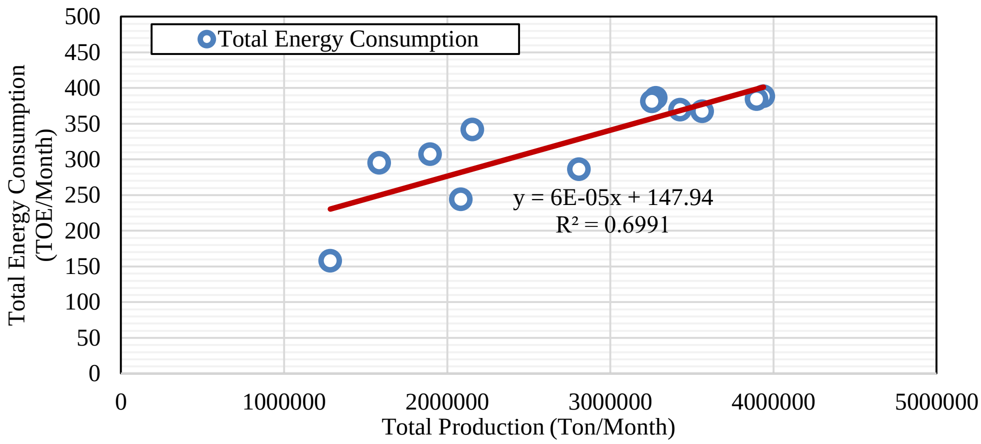


Figure 7. Total production and consumption trend graph in 2022

Table 2 shows the average energy consumption and costs of the industrial facility for the years 2020-2021-2022. It is seen that 43.4% of the energy cost is spent on electrical energy. At this point, it will be an energy efficiency enhancing application to produce electricity with a renewable energy source within the boundaries of the industrial facility to reduce the energy cost.

Table 2. Energy consumption and costs (average of 2020-2021-2022)

Energy (Purchased)	Consumption				Cost		Unit Cost
	Amount	Unit	TOE	Total%	$	Total%	$ / TOE
Electricity (purchased)	7,327,940.0	kWh	630.20	16.13	1,983,764.23	43,4%	3,147.83
Coal	15,977.0	Ton	3,195.4	81.77	2,529,340.37	55,3%	791.56
Natural gas	91,233.0	Sm^3	75.27	1.93	51,547,848.60	1,1%	684.84
Diesel	8,000.0	Lt	6.77	0.17	9,101.85	0,2%	1,344.44
Total			3,907.64	100	2,046,943.27	100	5,968.67

In order to determine the total amount of energy used in the factory, it is necessary to take into account the changes in production as well as consumption, and for this purpose, the 'Specific Energy Consumption' for each month should be calculated. Specific energy consumption is the amount of energy used to obtain a unit of product and can be expressed by Equation 1. SEC is specific energy consumption [TOE/Ton], EC is energy consumption [TOE] and P is production [Ton].

$$SEC = EC/P \tag{1}$$

Performance evaluation is done by regularly comparing the expected energy usage with the actual energy consumption values. SEC values can be used to evaluate this. These are especially important for monitoring the impact of various operating conditions on factory production performance. The growth of SEC indicates poor performance and unnecessarily increased energy consumption. Figure 8 shows the specific energy consumption and total production diagram of the industrial facility in 2022. It has been determined that as the total production increases in the industrial facility, the specific energy consumption decreases, and this indicates that the performance of the industrial facility is good.

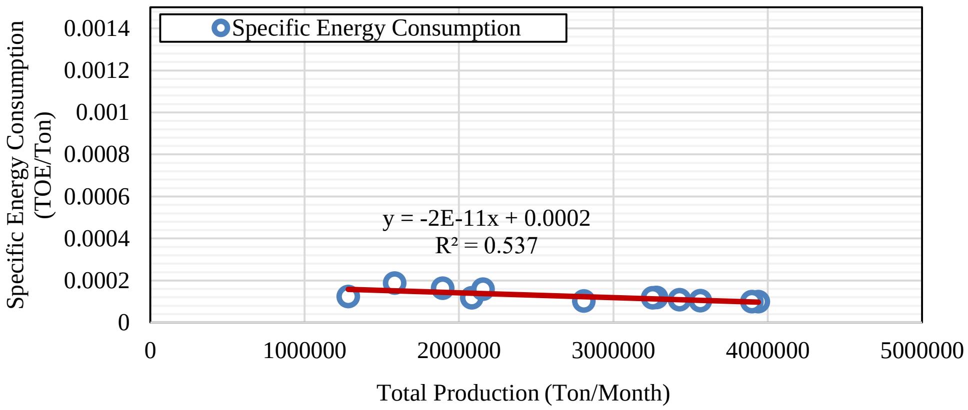


Figure 8. Total production and specific energy consumption in 2022

2.3. Simulation tool description

RETScreen Software is software used worldwide to evaluate energy production, cost analysis and greenhouse gas emission reductions for renewable energy technologies (Clean Energy Project Analysis).

2.4. PV system description and components

-Electrical load

The annual electrical energy consumption of the industrial facility is 7,327.94 MWh equivalent to 630 TOE. This consumption amount constitutes 16.13% of the total annual energy consumption of the facility. Electric energy consumption costs 1,983,764.2 $ per year. The cost of electrical energy consumption constitutes 43.4% of the annual total energy consumption cost. The annual electricity consumption cost of the industrial facility is 3,147.83 $/TOE. With the efficiency enhancing project, it is aimed to generate some of the electrical energy needs of the facility with renewable energy sources, to save money and to reduce CO_2 emissions. There is an area of 4,550 m^2 suitable for PV system installation in the roof areas of the facility.

-PV system design

The technical properties of PV module are shown at Table 3. Photovoltaic panels are flat plate monocrystalline type, with a lifetime of around 25 years, being specified the capital price is 950 $/kW.

Table 3. Technical properties of PV module

Properties	Value
Cell type	Monocrystalline
Power	455 W
Maximum Power Voltage	1000 V/1500 V DC
Maximum Power Current	9.60 A
Open Circuit Voltage	50-40 V
Short Circuit Current	11.43 A
Efficiency	20.14 %
Number of cells	72
Power rating	0 W / 5 W
Working range	-40ºC ~ +85ºC
Dimensions	2096 x 1039 x 35 mm
Area	2.275 m^2
Warranty	25 Years
Power tolerance	0 ~ 5 W
Weight	19 kg
Front surface	Low iron tempered glass 3.2 mm
Cable	4 mm^2 (IEC)/12AWG(UL), 900 mm
Certificate	IP67

Table 4. PV system technical specifications

Proposed case power system		
Solar tracking mode	-	Fixed
Slope	°	32
Azimuth	°	0
Annual solar radiation - horizontal	MWh/m²	1.43
Annual solar radiation - tilted	MWh/m²	1.58
Photovoltaic		
Type	-	mono-Si
Power capacity	kW	910
Efficiency	%	20
Nominal operating cell temperature	°C	45
Temperature coefficient	% / °C	0.4
Total solar collector area	m²	4,550
Number of total solar collectors	piece	2,000
Miscellaneous losses	%	6.98
Inverter		
Efficiency	%	95
Capacity	kW	100x9
Miscellaneous losses	%	3.0
Summary		
Capacity factor	%	14.8
Electricity exported to grid	MWh	1,183

The features of the designed PV system are shown in Table 4. The tilt angle of the PV modules to be installed on the roof of the industrial facility is fixed and 32º. There are 2000 PV panels in the energy production system.

3. Results and Discussion

Figure 9 shows the pre-application energy consumption and energy costs ratios in the industrial facility, and Figure 10 shows the post-application energy consumption and energy costs. 16.1% of the energy consumed in the industrial facility is electrical energy and electrical energy is purchased. With the PV system installation, an average of 16.14% of the electrical energy consumed will be produced and 7% savings will be made in energy costs. Table 6 shows the monthly electrical energy and monthly earnings produced by the PV system. Figure 11 shows the monthly electrical energy and solar radiation produced by the PV system. Table 5 shows the monthly electrical energy produced by the PV system and monthly earnings. The capacity factor of the system is 14.8%. Electric energy costs produced and purchased are shown in Figure 12.

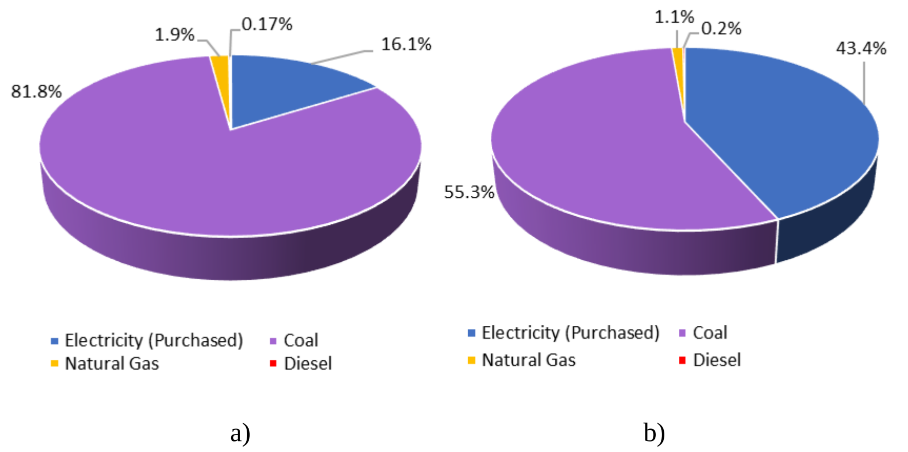


Figure 9. Before PV installation a) Energy consumption and b) Energy costs rates

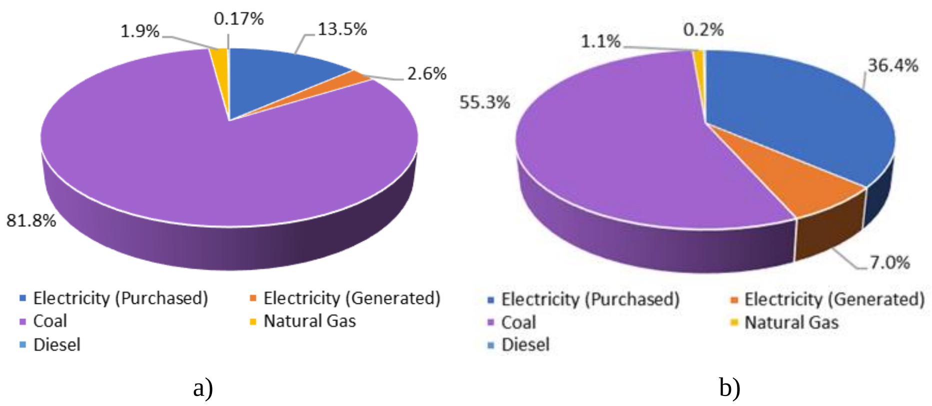


Figure 10. After PV installation a) Energy consumption and b) Energy costs

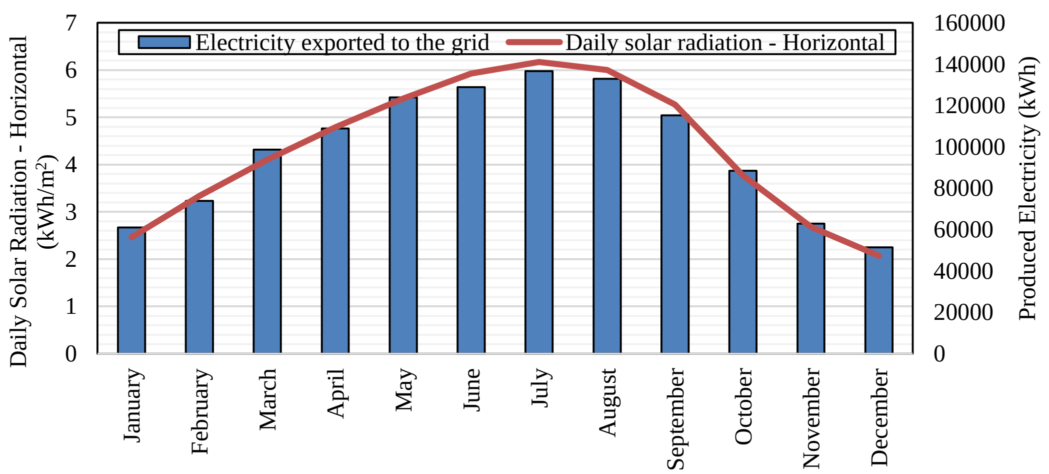


Figure 11. Monthly electrical energy and solar radiation produced by the PV system

Table 5. Monthly electrical energy produced by the PV system and monthly earning

Month	**Electricity exported to grid** (kWh)	**TOE**	**Monthly earning** **($)**
January	61,050.0	5.25	16,547.93
February	73,920.0	6.36	20,036.42
March	98,610.0	8.48	26,728.77
April	108,830.0	9.36	29,498.96
May	123,880.0	10.65	33,578.34
June	128,940.0	11.09	34,949.88
July	136,690.0	11.76	37,050.56
August	132,900.0	11.43	36,023.26
September	115,310.0	9.92	31,255.40
October	88,480.0	7.61	23,982.98
November	62,940.0	5.41	17,060.23
December	51,460.0	4.43	13,948.51
Annual	1,183,000.0	101.74	318,376.66

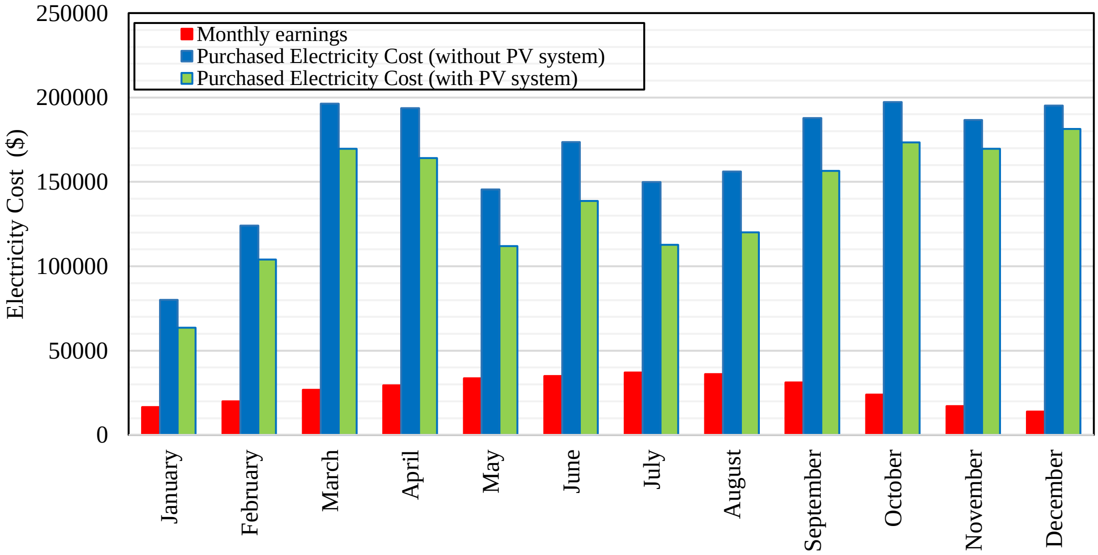


Figure 12. Electric energy costs produced and purchased

The electrical energy values and costs purchased before the PV system installation in Table 6 and after the PV system installation in Table 7 are given. With the installation of the PV system, a total of 318,376.66 $ financial gain is achieved annually. Figure 13 shows the monthly solar energy utilization rate (solar fraction). The annual average rate of solar energy utilization of the PV system is 20%.

Table 6. Purchased electrical energy and costs (without PV system)

Month	**Purchased Electrical Energy (kWh)**		**Purchased Electricity Cost ($)**
	Energy (kWh)	**Energy (TOE)**	
January	295,599.1	25.42	80,123.75
February	457,691.8	39.36	124,059.85
March	724,285.8	62.29	196,321.58
April	714,615.3	61.46	193,700.34
May	536,785.2	46.16	145,498.53
June	640,580.8	55.09	173,632.90
July	552,875.4	47.55	149,859.87
August	575,775.9	49.52	156,067.17
September	692,804.7	59.58	187,788.46
October	728,097.3	62.62	197,354.71
November	688,479.7	59.21	186,616.16
December	720,348.3	61.95	195,254.30
Annual	7,327,940.0	630.20	1,986,277.64

Table 7. Purchased electrical energy values and costs (with PV system)

Month	Electricity (kWh)		Electricity (TOE)		Purchased Electricity Cost ($)
	Purchased	Produced	Purchased	Produced	
January	234,549.1	61,050.0	20.171	5.250	63,575.82
February	383,771.8	73,920.0	33.004	6.357	104,023.44
March	625,675.8	98,610.0	53.808	8.480	169,592.81
April	605,785.3	108,830.0	52.097	9.359	164,201.38
May	412,905.2	123,880.0	35.510	10.654	111,920.19
June	511,640.8	128,940.0	44.001	11.089	138,683.02
July	416,185.4	136,690.0	35.792	11.755	112,809.30
August	442,875.9	132,900.0	38.087	11.429	120,043.91
September	577,494.7	115,310.0	49.664	9.917	156,533.06
October	639,617.3	88,480.0	55.007	7.609	173,371.73
November	625,539.7	62,940.0	53.796	5.413	169,555.93
December	668,888.3	51,460.0	57.524	4.426	181,305.79
Annual	6,144,940.0	1,183,000.0	528.461	101.737	1,665,619.09

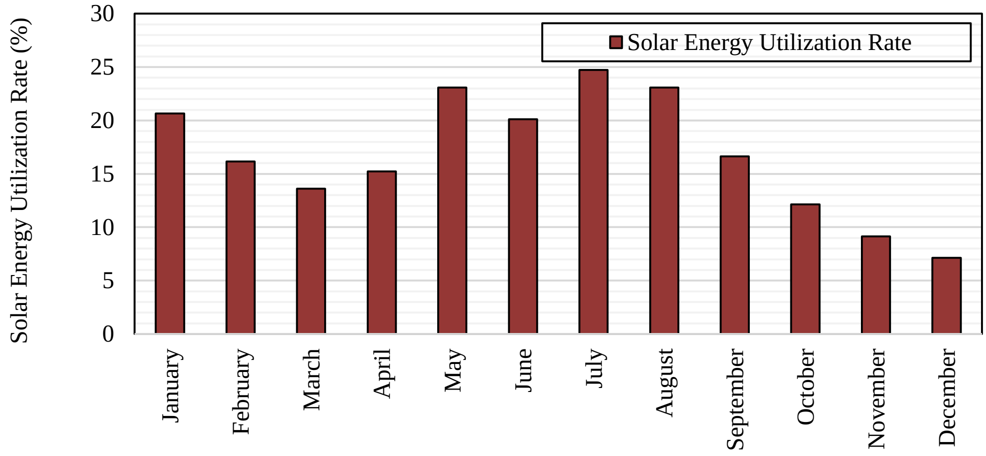


Figure 13. Utilization rate of solar energy (solar fraction)

3.1. Economic analysis

It is envisaged that the planned investment will be made with the own budgetary resources of the industrial facility. Table 8 contains PV system information. The PV system is designed as a roof application with a power of 910 kW. Table 10 includes the study savings. With the PV system installation, 1,183.0 MWh/year (101.737 TOE/year) energy savings and 318,376.66 $/year cost savings will be achieved. The payback period of the system is 2.7 years. Figure 14 shows the PV system cumulative balance diagram. Figure 15 and Figure 16 show the monthly average earning and expense. Table 9 contains the necessary data for the economic evaluation of the study.

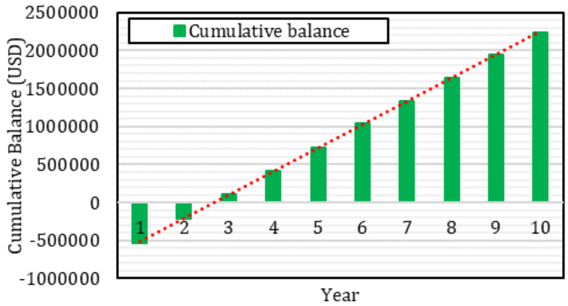


Figure 14. PV system cumulative balance

Table 8. PV system information

PV system information	
Study	910 kW Roof PV Solar Energy System
Electricity Purchase Unit Price	0.27 $/kWh
Distribution Price Unit Price	0.026 $/kWh
Annual Consumed Electricity	675,000.00 kWh
System Installed AC Power	910.00 kW
System Installed DC Power	910.00 kW
Annual Electricity Generation Potential	1,183,000.00 kWh
Unit Price	950.00 $/kW
Investment Cost	864,500.00 $
Investment Value Equity Ratio / Amount	100.00% / 864,500.00 $
Depreciation Period of Investment (Month / Year)	32 months / 2.7 years
10 Year Total Savings Amount	3,100,908.68 $
Performance Time of PV Power Plant	25 years

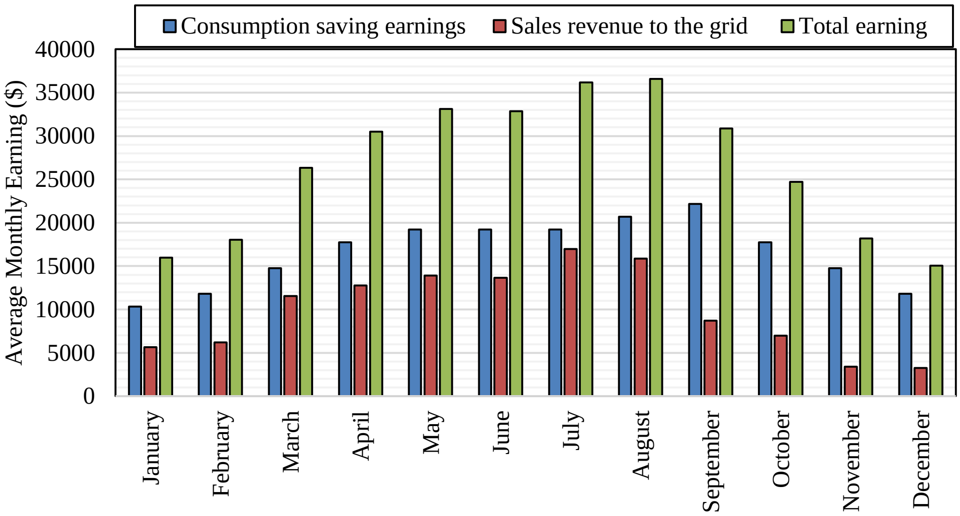


Figure 15. Average monthly earning

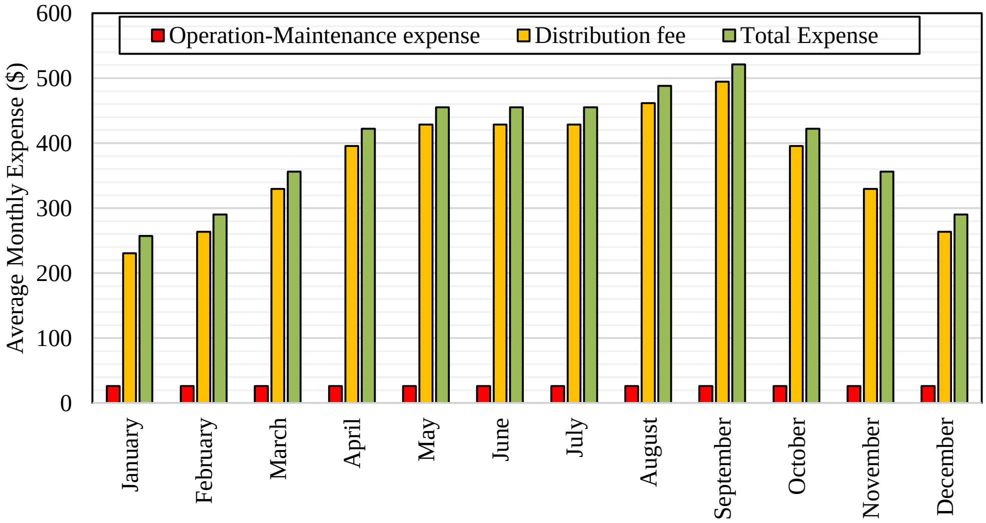


Figure 16. Average monthly expenses

Table 9. Necessary data for the economic evaluation

Economic evaluation	
Investment cost ($)	864,500.0
Consumption saving earning ($)	199,472.3
Sales revenue to the grid ($)	118,904.4
Total earning ($)	318,376.7
Operation-Maintenance expense ($)	316.6
Distribution fee ($)	4,452.5
Total expense ($)	4,769.1
Scrap value ($)	216,125.0
Discount rate	10%
Project life	25 years

3.2. Impact Analysis

Impact analysis is a process in which the significant impacts of the PV system analysed in the study on the environment are identified. It is used to determine the extent to which carbon dioxide (CO_2) and other greenhouse gas emissions released into the atmosphere are reduced by PV system installation. The effects of the proposed application on the environment or other equipment and systems. and the CO_2 emission reduction due to the savings to be made are given in Table 10.

Table 10. Impact analysis of the PV system

Emission Analysis	Unit	Value
Country - region	-	Turkey
GHG emission factor	tCO_2/MWh	0.459598
Produced electricity	MWh	1,183.0
Net annual GHG emission reduction	tCO_2	543.7

Annual net GHG emissions reductions equivalent to 543.7 tCO_2 equivalent to 99.6 unused cars and pickup trucks.

4. Conclusions

In order to meet a part of the energy needs of industrial facilities. energy efficiency-enhancing practices are carried out by establishing electricity generation systems based on renewable energy sources. which are established within a maximum of ten kilometers from their facilities.

The following is the study's main conclusion:

-By installing a solar PV system with a capacity of 910 kW on the roof of the industrial facility in Edirne, Turkey. 1,183.0 MWh/year electrical energy can be produced annually.

-Thus, 20% of the electricity need of the facility will be produced using renewable energy sources and the emission of 543.7 tCO_2 to the atmosphere will be prevented.

-The payback period of the system is 2.7 years.

-The average annual earning of the system is 318,376.66 $/year and its annual expense is 4,769.13 $/year.

While making the economic analysis of the system payback period method, net present value method, benefit/cost method and internal rate of return methods are used. According to each cost analysis method, the PV system study in the industrial facility is acceptable.

To ensure the continuity of the positive effect after the PV system installation, the personnel responsible for the system should be assigned and the personnel should be trained in PV system operation and maintenance. The system should be examined with periodic checks to be made on a regular basis. After the installation of the PV system, the performance of the system should be determined by measuring data such as electrical values and temperature on the system for the first two years and making system analysis. At the same time, since the temperature significantly affects the PV panel efficiency, the efficiency reduction due to the temperature increase can be calculated by measuring the panel surface temperatures.

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