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Technical and Economic Analysis of Photovoltaic System Designed for a Public Building in Turkey

A. Talat Inan*

*Department of Mechanical Engineering, Faculty of Technology, Marmara University, Goztepe Kampusu, Istanbul, Turkey

(ainan@marmara.edu.tr)

‡ A. Talat İnan, Marmara University, Goztepe Kampusu, Kadikoy 34722 Istanbul, Turkey, Tel: +90 216 336 5670,

Fax: +90 216 337 8987, ainan@marmara.edu.tr

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Abstract- The use of renewable energy sources is a clean and sustainable solution in order to meet increasing energy needs. Photovoltaic systems can produce electricity directly from solar energy which the fastest growing types of renewable energy in Turkey. The use of photovoltaic systems in public buildings will contribute to awareness of renewable energy as well as supporting the electricity consumption of these buildings. In this study, a photovoltaic system has been designed for a public building in Istanbul to compare electricity consumption with a traditional system. The system was designed and simulated with PV*SOL software. As a result of the comparison, environmental and economic analysis have been made. Roof of the four blocks and the open car park located on south side of the building were set for installation of the system. The cost of the system having installed capacity of 3.259 MW is supposed to be USD 2,705,586. Payback time would be 5.3 years. Performance coefficient of the system is expected to be 86.3%. Annual 4.10 GWh electrical energy for the building can be produced by photovoltaic system. Economic and environmental evaluations have been carried out for the designed photovoltaic system.

Keywords Photovoltaic system, public building, rooftop, car park, Istanbul.

1. Introduction

As a result of energy use, problems such as rapid depletion of natural resources, environmental problems, climate change and high cost in production may occur. Therefore, solutions are sought for these problems in order to reduce the burden of energy costs on the economy and to protect the environment through efficient use of energy. Energy efficiency studies are carried out in public buildings, residences and production facilities. In this context, each country carries out strategic plans to increase energy efficiency in line with its strategic objectives and works to implement determined methods. One of these actions is to determine the energy saving potential in public buildings and to promote the use of on-site production and renewable energy resources in buildings. For example, it can be said that 10% of total energy consumption for public buildings in Korea must be met from new or renewable energy sources [1]. Building energy management systems in the world and in Turkey, solar energy is also one of the fastest growing renewable energy sources. According to the National Energy Agency's renewable energy reports, the amount of annual energy produced by solar energy in the world is low compared to the amount of energy obtained through wind, geothermal and hydraulic resources. Looking at the average increase rate of renewable energy source compared to the previous year between 1990 and 2015, the sun was first to surpass all other renewable energy sources [2]. When the number of employment and investment costs in the sector are examined, solar energy technologies are the fastest growing and developing renewable energy technology, even the amount of production is small at the moment [3]. Photovoltaic systems, which can generate electricity directly from solar energy, will contribute to the awareness of society in renewable energy as well as to support electricity consumption.

Table 1 shows the average amount of solar radiation per square meter for some countries and the electricity production values obtained from solar energy [4]. For given geographic location in Turkey, solar energy is an indispensable renewable energy source.

Table 1. The average amount of solar radiation per square meter for some countries and electricity production values obtained from solar energy.

Location	London	America SW	America NE	Australia	Germany	Japan	China NW	**Turkey**
Radiation (kWh/m²)	2.5	5.5	2.5	5.3	2.7	3.6	6.2	**4.2**
Installed Power (GW)	0.11	50		11.1	45.6	50	174	**3.4**

Photovoltaic systems in which the energy coming from the Sun is converted directly into electrical energy. Installation cost of photovoltaic systems is the highest among other renewable energy systems [5]. The efficiency of photovoltaic systems at the point of today's technology is also low. Photovoltaic systems have the advantages of not having mechanical and moving parts, lack of noise, no pollution, no elevated temperatures and long life [6].

In this study, a photovoltaic system was designed for a public building with a high electricity consumption established on 125,000 m^2 area in Istanbul. A simulation was performed with PV*SOL software. Technical, environmental and economic analysis of the system was studied according to the simulation results.

Public buildings are spread over a covered area of 80,000 m^2, consisting of 7 blocks namely A, B, C, D, E, F and G. Six blocks are located above ground, F block is underground and used as closed parking. The layout of the blocks is shown in Fig. 1. There is an open parking area in the south of the buildings [7].

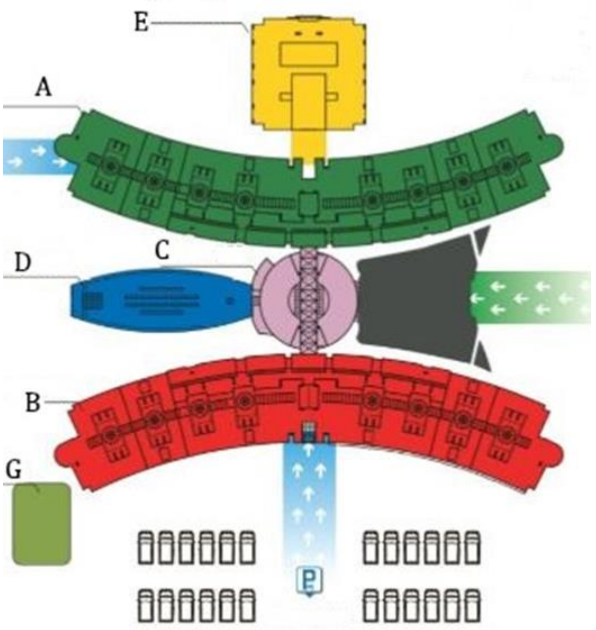

Fig. 1. The layout of the public building

Electricity consumption of the public building is 15,736,419 kWh and 14,910,128 kWh for 2017 and 2018, respectively. The distribution of annual electricity consumption values by months is shown in Fig. 2. Especially in January, July and August, electricity consumption is high. The high electricity consumption of the building in these months is related to the excessive use of air conditioning for heating or cooling. Electrical load of the building does not vary widely annually except for air conditioning units.

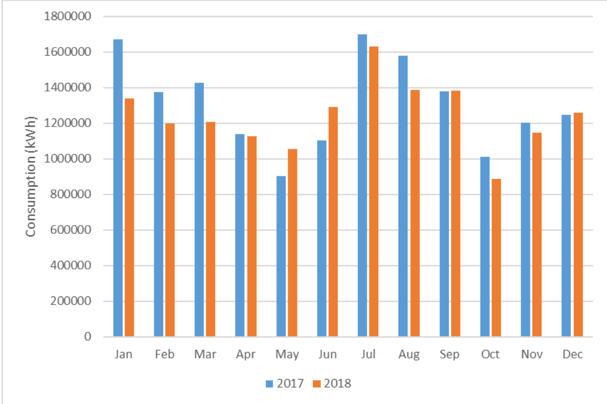

Fig.2. Monthly distribution of the electricity consumption of the public building.

2. Methodology

There is many software to use designing of photovoltaic solar systems. In this study, PV*SOL software was used. PV*SOL software was developed by German-based Valentin-Software. The software gets meteorological data from the MeteoSyn system. A trial version of the software is used for this study.

First of all, it is necessary to determine the system type and the region where the system will be installed. The designed system is grid dependent. The location of the system can be selected via satellite over the internet. There are around 8,000 pieces of solar radiation data based on measurements made between 1986 and 2005 (outside Germany). MeteoSyn software calculates solar radiation values by interpolation using measurement data at the closest locations to the user's location [8].

2.1. Calculation of Irradiance

The software uses the following input parameters to calculate the solar radiation on the oblique plane; time (day and hour), radiation from the global horizontal plane, position information (latitude and longitude), mounting information (inclination and azimuth angles of inclined plane), shading and albedo. The path followed for the determination of the solar radiation to the oblique plane where shading taken into account is shown in Fig. 3.

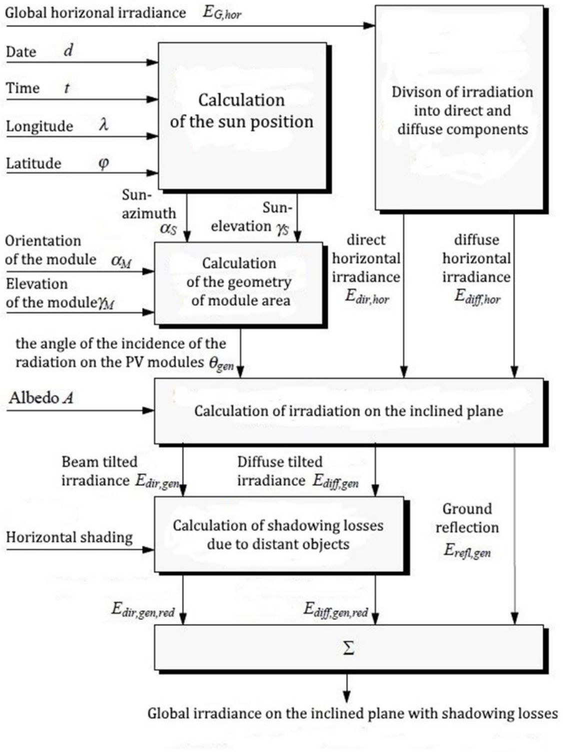

Fig. 3. Flow diagram of solar radiation calculation from inclined plane.

The software determines the position of the Sun in the calculation of hourly solar radiation. The position of the sun is expressed in two angles; solar azimuth angle (αs) and solar elevation angle (γs). These angles vary depending on the latitude and longitude of the study as shown in Fig. 4 during the day.

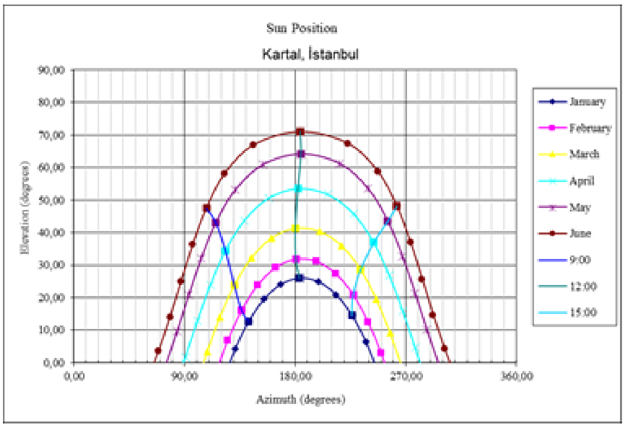

Fig. 4. Sun position for Istanbul, Turkey.

Non-atmospheric solar radiation (E_{extra}) is the value measured as solar radiation from the solar radiation to the perpendicular surface just outside the Earth's atmosphere. The distance between the Sun and the Earth varies due to the eccentric trajectory drawn by the Earth around the Sun, and depending on this variability, non-atmospheric solar radiation also changes throughout the year. The average value during the year is 1367 W/m^2 and this value is called the Solar constant (E_0). nth day of the year non-atmospheric radiation value is calculated as follows [9].

$$E_{extra} = E_0 \cdot \left(1 + 0.033 \cdot cos\left(2\pi \cdot \frac{n}{365}\right)\right) \qquad (1)$$

The amount of solar radiation reaching the earth decreases depending on the emission and absorption characteristics of the atmosphere. The radiation ($E_{G,hor}$) reaching the horizontal plane consists of two terms, depending on these characteristics of the atmosphere;

$$E_{G,hor} = E_{dir,hor} + E_{diff,hor} \qquad (2)$$

Here; $E_{dir,hor}$ is the direct radiation from the horizontal plane and $E_{diff,hor}$ is the diffuse beam that comes into the horizontal plane [10]. The software obtains the radiation value that reaches the horizontal plane through the MeteoSyn system, as previously mentioned, as either interpolated directly from the measured values or from the measurement stations near the location.

Diffuse radiation from the horizontal plane is related to the clarity of the atmosphere and the calculated in three diverse ways according to the clarity index k_T value [11];

for $kT \leq 0.3$

$$E_{diff,hor} = E_{G,hor} \cdot (1.020 - 0.254 \cdot k_T + 0.0123 \cdot sin\gamma_S)$$

for $0.3 < kT < 0.78$ (3)

$$E_{diff,hor} = E_{G,hor} \cdot (1.400 - 1.749 \cdot k_T + 0.177 \cdot sin\gamma_S)$$

for $kT \geq 0.78$

k_T value; the ratio of radiation coming to the plane to the non-atmospheric radiation;

$$k_T = \frac{E_{G,hor}}{E_{extra}} \qquad (4)$$

The location of the photovoltaic modules is determined by the user. Two angle values that define the layout of a module; azimuth (α_E) and slope (γ_E) angles of the module. Figure 5 shows the angles of positioning the module [12]. The angle of inclination (θ_{gen}) is the angle between the normal of the module and the solar radiation, and the cos (θ_{gen}) is calculated as follows;

$$\cos(\theta_{gen}) = -cos\gamma_S \cdot sin\gamma_E \cdot sin\gamma_E \cdot cos(\alpha_S - \alpha_E + \pi) + sin\gamma_S \cdot cos\gamma_E$$

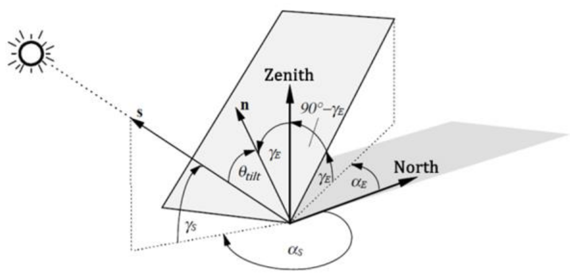

Fig. 5. Calculation angle of sun incidence onto an inclined surface.

The irradiance onto an inclined surface ($E_{G,gen}$) consists of three components and is calculated as follows;

$$E_{G,gen} = E_{dir,gen} + E_{diff,gen} + E_{refl,gen} \quad (6)$$

$E_{dir,gen}$ is the direct radiation to the inclined surface; $E_{diff,gen}$ is the diffuse radiation to inclined surface and $E_{refl,gen}$ is the reflected radiation to the inclined surface.

Direct radiation from the inclined plane is obtained by multiplying the direct radiation from the horizontal plane by the ratio of solar zenith angle and the angle of incidence. The software calculated the radiation from the horizontal plane and the diffuse radiation component of this radiation as previously described. The software calculates the direct radiation from the equation (2) to the horizontal plane. Thus, direct radiation to the inclined plane can also be calculated;

$$E_{G,gen} = E_{G,hor} \cdot R_b \quad (7)$$

Here, the ratio of the solar zenith angle and the angle of incidence is called the geometric factor and is expressed by the symbol Rb.

$$R_b = \frac{cos\theta_{gen}}{cos\,\theta_z} \quad (8)$$

Diffuse radiation from an inclined plane is calculated by the software on the Hay & Davies model as follows [13];

$$E_{diff,gen} = E_{diff,hor}\left[k_t R_b + (1-k_t)\frac{1+cos(\gamma_E)}{2}\right] \quad (9)$$

The reflected radiation value from the inclined plane is calculated as follows;

$$E_{refl,gen} = E_{G,hor} \cdot A \cdot \frac{1}{2} \cdot (1 - cos\gamma_E) \quad (10)$$

Here, *A* is the albedo. Albedo is defined as the reflection coefficient of the ground. Table 2 shows the albedo values according to different site properties [14].

Table 2. Albedo values for different environments

Surface	**Albedo**	**Surface**	**Albedo**
Grass (July, August)	0.25	Asphalt	0.15
Lawn	0.18…0.23	Wood	0.05…0.18
Dry grass	0.28…0.32	Shrubbery and sandy surfaces	0.10…0.25
Uncultivated fields	0.26	Water surface (γs>45)	0.05
Plain earth	0.17	Water surface (γs>30)	0.08
Gravel	0.18	Water surface (γs>20)	0.12
Concrete, clean	0.30	Water surface (γs>10)	0.22
Concrete, weathered	0.20	Fresh snow cover	0.80…0.90
Cement, clean	0.55	Old snow cover	0.45…0.70

With the sum of these three components the software calculates incoming solar radiation onto the module. One of the most crucial factors in determining the amount of electrical energy produced by photovoltaic modules is the amount of solar radiation.

2.2. Calculation of generated electricity

Besides the amount of solar radiation, the other key factor in calculation of the electrical energy to be produced is the characteristic of the photovoltaic module. The software has about 13,000 module characteristics in its own database and the new module can be added by the user as a new module. The photovoltaic module model used in this study is a model found in the database of the software.

The two most principal factors that reveal the characteristic of a photovoltaic module are solar radiation and operating temperature. Figure 6 shows the graph of the change in the module efficiency of the solar radiation and operating temperature in the software database. The software determines the amount of electrical energy produced by the module by using this characteristic.

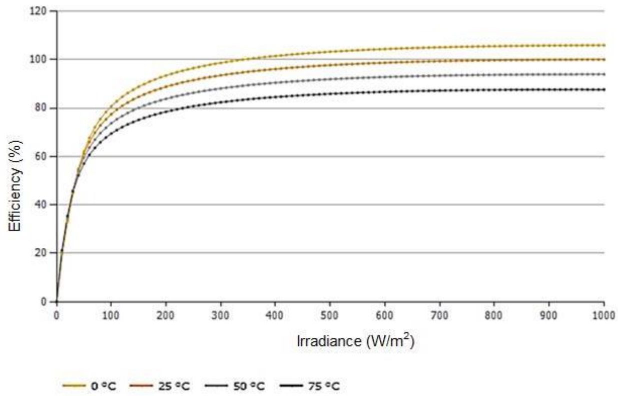

Fig. 6. Module characteristic with varying irradiation and temperature.

The operating temperature of the photovoltaic module is calculated by the software as follows;

$$T_{modul} = T_{amb} + DT \cdot \frac{E}{E_{STC}} \quad (11)$$

Here T_{modul} is the operating temperature of the photovoltaic module, T_{amb} is the ambient temperature, *E* is the solar radiation in the operating condition and E_{STC} refers to the amount of solar radiation under standard test conditions. The E_{STC} value is 1000 W/m^2. DT coefficient; it depends on the module installation and can be defined as the temperature increase under 1000 W/m^2 of the module. Table 3 shows the DT coefficients according to the mounting method [15].

Table 3. DT values for different installation types.

DT	Installation situation
29 K	Roof-parallel, well ventilated
32 K	Roof-integrated – rear-ventilated
43 K	Roof-integrated – not ventilated
28 K	Mounted – roof
22 K	Mounted – free area

PV*SOL software has 3D design editor. 3-dimensional objects can be drawn on the satellite map. In this way, the closest realistic simulation can be made to calculate the amount of shading. For roof areas of drawn 3D buildings, the software can automatically stack the maximum number of modules on the roof. In addition, the proper inverter configuration is done automatically. There are 3,100 inverter model features in software database.

2.3. Meteorological data

The public building is located at 40° 54' North latitude and 29° 10' East longitude. According to the MeteoSyn system, solar radiation for the selected location is 1350.7 kWh/m^2 per year. The average annual temperature is 15.4°C. According to the results obtained by interpolation of MeteoSyn software, the distribution of solar radiation perpendicular to the horizontal surface in the location of the public building is shown in Fig. 7.

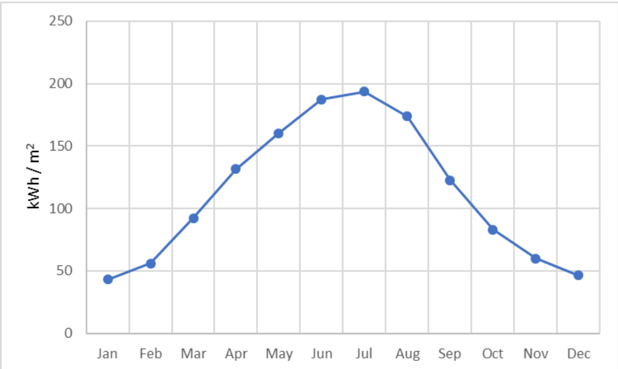

Fig. 7. Monthly average solar radiation on the horizontal surface in Istanbul.

Albedo value for simulation of photovoltaic system is taken as 20%. The pollution factor was omitted.

2.4. Capacity and Location Selection

The photovoltaic system designed for public buildings consist of roofs and parking space. The simulation was executed through two separate files as the system in the roofs and the system in the parking lot. The reason for this, the software is not able to make shadowing calculations in very large systems. If the size of the shading calculations reaches the limit, it warns the user.

As mentioned before, the buildings consist of different blocks. The roofs suitable for the installation of the photovoltaic system are the roofs of E, A and B blocks. There are different roof elements on these roofs such as elevator and machine rooms, ventilation systems, glass domes. The ones that are at the height to affect the shading are added to the drawing in three dimensions. Those whose height is insignificant so as not to affect shading is marked as the area where module placement cannot be made.

The photovoltaic system designed for the parking area will be installed on steel construction. For the software, this system was defined as the building height and the simulation was carried out in this way. The G-block roof which is located next to the open car park area, is also included in this system.

2.5. Design of the system

2.5.1. Photovoltaic modules

The system chosen for photovoltaic modules is produced in Turkey and has carbon footprint certification. Module specifications are given in Table 4 [16].

Table 4. Characteristics of the module.

Module	CSUN275-60P
Maximum Power	275 W
Dimensions (Length x Width)	1640 x 990 mm
Open Circuit Voltage	38.4 V
Maximum Power Voltage	31.3 V
Short Circuit Current	9.27 A
Module Efficiency (STC)	16.94 %
Power Temperature Coefficient	-0.408%/K

When designing the system for building roofs, the 3-dimensional drawings of buildings are used to automatically fill the roof area with the maximum number of modules. The photovoltaic modules are placed with a 30° inclination. The default value regarding distance between the two module rows is 1 m. As a result, the module layout for roofs is shown in Fig. 8.

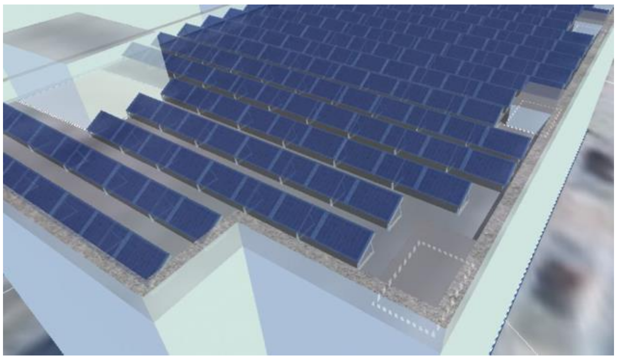

Fig. 8. Mounting the modules on the roof.

The roof shapes of the blocks are considered in installation of the modules on the southern façade. The modules are arranged according to the facades of the building. The module is positioned at angles ranging from -20° to 20° relative to the southern facade of the rows. The total number of roof systems is 6784. Eight modules were placed on block E roof, 2993 units on block A and 2976 modules on block B. The module layout of the roof system is shown in Fig. 9.

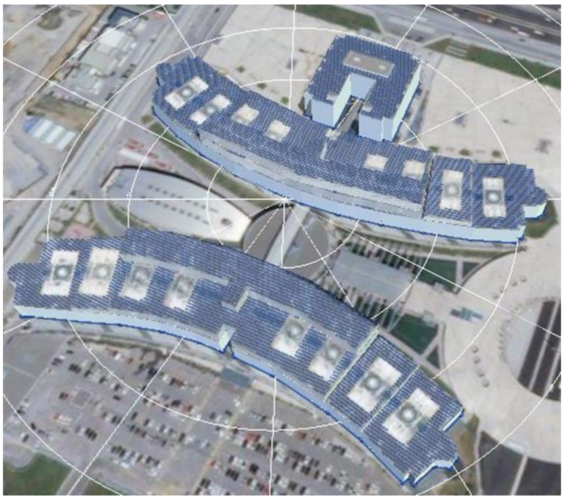

Fig. 9. Mounting the modules on the roof.

The second simulation, which completes the photovoltaic system designed for the public building is for G block roof and open parking area. The settlement in these areas was made with the maximum number of modules and the automatic filling feature. While 483 modules were placed on the G block roof, 4584 modules were placed in the open car parking area where consists of two parts. The layout of the modules is shown in Fig. 10.

Fig. 10. Mounting the modules on car parking area.

The canopy type photovoltaic system considered for the parking area is shown in Fig. 11 [17]. The modules are arranged in parallel with the modules in the block E roof system.

Fig. 11. The canopy type photovoltaic system for car parking area.

2.5.2.Inverters

The module has automatically determined the appropriate inverter configuration for the software modules upon the creation of the layout plans. The software can be selected from the inverter data list and the inverter brands and models can be selected for the configuration. By entering the model of the inverter, which is deemed suitable for the system, the software has determined the number of inverters required for the system as 96. The inverter characteristics are given in Table 5 [18].

Table 5. Characteristics of the inverter.

Inverter	**Furinous ECO 27-0-3**
Max. Input Current	47.7 A
DC Input Voltage Range	580-1,000 V
Number of DC Connections	6
Max. Output Power	27,000 W
Max. Efficiency	98.3%

2.6. Economic analysis

The software performs the cost calculations with the net present value method. The net present value C_{PV} is calculated as follows;

$$C_{PV} = Z \cdot b \tag{12}$$

Here, Z is the payment sequence, and b is a function called net value factor. The net value factor function depends on the lifetime T, the principal repayment period q, and the price change factor r [19];

$$b(T,q,r) = \begin{cases} \dfrac{1-(r/q)^T}{q-r}, & r \neq q \\ \dfrac{T}{q}, & r = q \end{cases} \tag{13}$$

3. Analysis

3.1. Electricity generation

As a result of the simulation, it was calculated that a total of 4,101,760 kWh of electrical energy could be produced by the photovoltaic system to be established. The distribution of the electrical energy to be produced is shown in Fig. 12. Electricity generation is the highest in July with 502,674.6 kWh. The month with the lowest electricity generation is January with 189,344.5 kWh. As mentioned before, in Fig. 7, the highest monthly average solar radiance is in July and the lowest in January. The electricity generation values are matching with the graph of the monthly solar radiance in Istanbul.

As a result; while the capacity factor of the photovoltaic system designed on the roof is calculated as 86.8%, the capacity factor of the system designed for the parking area is calculated as 85.9%.

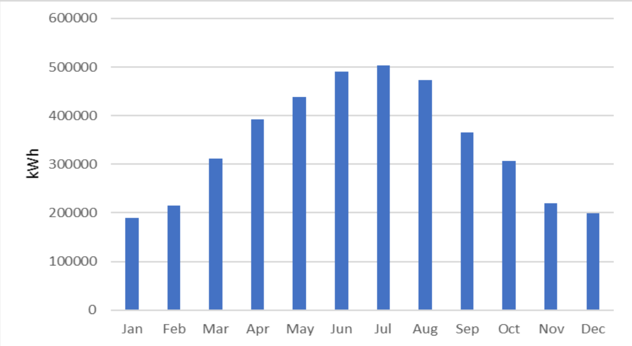

Fig. 12. Monthly distribution of electrical energy to be produced

As a result of these values, it can be said that 26.8% of the electricity consumption of the public building could be obtained from the sun. The ratio of electricity to be produced to consumption is shown in Table 6 on a monthly basis.

Table 6. The ratio of the electricity to be produced monthly in the public building to consumption

Month	Generated Energy (kWh)	Supply percent
Jan	189,344.5	12.6%
Feb	214,487.5	16.7%
Mar	311,716.8	23.7%
Apr	391,957.8	34.6%
May	438,506.3	44.8%
Jun	491,012.5	41.0%
Jul	502,674.6	30.2%
Aug	472,408.3	31.9%
Sep	364,755.8	26.4%
Oct	306,245.2	32.2%
Nov	220,346.3	18.8%
Dec	198,304.3	15.8%

3.2. Economic analysis

The costs of equipment and labor which constitute the expenses of the system to be installed are shown in Table 7. The total cost of the system is USD 2,705,586. The electricity cost of the public building is USD 125 /MWh. According to this value, the system saves USD 512,720 annually. Payback time of the system is 5.3 years.

Table 7. Cost analysis of the system

Equipment	Number	Unit price	Total ($)
Module	11851	190	2,251,690
Inverter	96	2176	208,896
Cable	~52500 m	-	50,000
Workmanship	-	-	75,000
Others	-	-	100,000

3.3. Environmental analysis

The use of solar energy in electricity generation is a clean method in terms of greenhouse gas emissions. During the operation of photovoltaic systems, greenhouse gas does not emit. Overall GHG (Greenhouse Gas) emissions factor in Turkey for electricity generation is 0.460 tCO_2/MWh [20]. According to this value, the amount of annual greenhouse gas emission reduction is 1886.8 tons.

4. Conclusion

As a result of the design, calculation and simulation of the photovoltaic system for a public building in Istanbul, the system could generate 4,101.7 MWh of electricity annually. Thus, 26.8% of the annual electricity consumption of the public building would be met by the photovoltaic system. By taking into account the cost of electricity at the public building, this system would save USD 512,720 per year. Payback time of the system would be 5.3 years.

It shows that photovoltaic systems are a suitable solution for clean and sustainable energy for public buildings having high electricity consumption during working hours. It has also been observed that photovoltaic systems could provide considerable amounts of savings for public buildings.

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