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# Performance analysis of a 500-kWp grid-connected solar photovoltaic power plant in Kahramanmaraş

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**Abstract:** In today's world, the daily need for and cost of energy sources increase and this forces industrial institutions to seek for new ways to generate their own energy. The developments in photovoltaic systems have recently drawn attention in the business world. Although their installation costs are high, they are environmentally friendly and profitable investments in the long run. The cost analysis of a large-scale photovoltaic generator in the climatic conditions of Kahramanmaraş will lead the way to new investments. In this study, the modeling and cost analysis of an on-grid photovoltaic generator of 500 kW, which was installed to provide energy for a textile factory located in the Pazarcık district of Kahramanmaraş Province (37.5 °N, 37.3 °E; altitude: 748 m), was performed. The findings suggest that the photovoltaic generator of 500 kW installed in the Pazarcık district of Kahramanmaraş Province in August 2013 produces 816,639 MWh energy and reaches its initial cost in 6.2198 years. Therefore, photovoltaic generators are significantly useful when the climatic conditions in Kahramanmaraş are taken into account.

**Key words:** Photovoltaic, cost analysis, solar energy

## 1. Introduction

Annual energy consumption in the world is 10 TWh and this is estimated to reach 30 TWh in 2050 [1]. The high cost of fossil fuels, which is the greatest source of energy, and global warming and environmental issues increase the importance of the use of clean and renewable energy sources [2]. Fossil fuels cannot definitely sustain the energy needs of the growing human population due to finite supplies and adverse effects of anthropogenic greenhouse gas emissions on the global climate [3,4]. Therefore, it is necessary to seek alternative forms of renewable energy [5–8] such as solar energy, which previously proved to be a sustainable solution to the energy needs of society [9,10]. Solar energy has recently come to the forefront among renewable energy sources. The sun is one of the most important natural resources in the world. Solar energy is clean, renewable, and abundant in most parts of our world and can also be converted into electrical energy by means of photovoltaic (PV) systems [11]. PV systems have become one of the most promising renewable energy systems that can invert solar energy to electricity [12]. PV arrays do not generate any toxic or harmful substances polluting the environment [13,14]. Another considerable feature of them is that they are low-maintenance. Depending on the development in PV technologies, the efficiency of PV arrays has improved and studies on PV systems have gradually increased. PV systems are occasionally operated in stand-alone mode and they feed fixed loads by stand-alone PV inverters

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[15–17]. PV systems are also interconnected to the grid. Interconnecting a PV system to a grid has become a popular design trend, and grid-connection types of PV inverters were proposed [18,19]. Therefore, various power electronics technologies are designed to convert DC to AC power for PV applications [20].

The amount of power produced by a PV system depends on the amount of irradiation to which it is exposed. As the sun's position changes throughout the day, the PV system must be adjusted so that it is always aimed precisely at the sun and, as a result, produces the maximum possible power [21–24].

PV systems should be optimally planned in order to avoid any technological or economic problems [25]. In addition, it is important to operate PV energy conversion systems close to the maximum power point in order to increase the output efficiency of PV arrays [26]. Thus, power electronics inverters are required for the maximum power point tracking algorithm, which provides maximum PV power. They are also needed to transfer the PV power to a load or to the grid.

In this study, the modeling and cost analysis of an on-grid photovoltaic generator of 500 kW, which was installed to supply a considerable amount of energy for a textile factory located in the Pazarcık district of Kahramanmaraş Province (37.5 °N, 37.3 °E; altitude: 748 m), was performed.

### 1.1. Kahramanmaraş's climate

Monthly climate figures required for PV system modeling in Kahramanmaraş are given in Table 1.

**Table 1.** Kahramanmaraş's climatic conditions [27].

| | Radiation values (total) $\left(kWh/m^2\right)$ | Radiation values (average) $\left(kWh/m^2\right)$ | Sunshine duration $(h)$ | Temperature (average) (°C) | Wind (average) $(m/s)$ |
|---|---|---|---|---|---|
| January | 59.70 | 1.92 | 4.21 | 4.43 | 2.10 |
| February | 77.40 | 2.76 | 5.47 | 4.97 | 2.30 |
| March | 125.10 | 4.03 | 6.61 | 9.03 | 2.50 |
| April | 152.70 | 5.09 | 7.85 | 13.91 | 2.50 |
| May | 188.70 | 6.08 | 9.57 | 20.19 | 2.60 |
| June | 204.30 | 6.81 | 11.49 | 26.01 | 3.30 |
| July | 203.10 | 6.58 | 12.07 | 30.36 | 3.60 |
| August | 180.00 | 5.80 | 11.43 | 29.25 | 3.00 |
| September | 151.80 | 5.06 | 10.13 | 24.03 | 2.60 |
| October | 113.40 | 3.66 | 7.55 | 18.00 | 2.00 |
| November | 72.00 | 2.40 | 5.56 | 10.78 | 1.80 |
| December | 54.30 | 1.75 | 3.86 | 5.91 | 1.90 |

Kahramanmaraş is an important area with a monthly average radiation of 131.875 $kWh/m^2$ and an average temperature of 16.405 °C along with an annual average sunshine duration of 2874 h.

Kahramanmaraş is a productive area in terms of solar energy with an annual radiation rate of 1582.5 $kWh/m^2$. Figure 1 displays the annual average radiation rates in Pazarcık on the map [27].

## 2. Photovoltaic generator

The PV system of 500 kW operates on a grid. Energy generated by the system is used by a textile factory. Missing energy is provided by the electrical network. In the system, 2001 pieces of polycrystalline PV panels of

250 W along with 8 inverters of 50 kW, 2 inverters of 13 kW, and 4 inverters of 10 kW were used. The system scheme is shown in Figure 2.

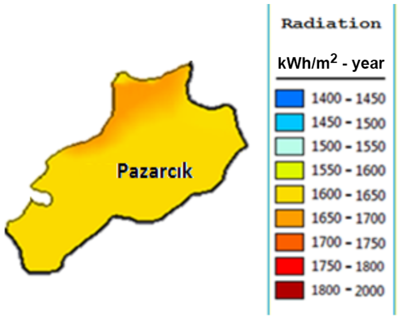

**Figure 1.** Pazarcık's radiation figures

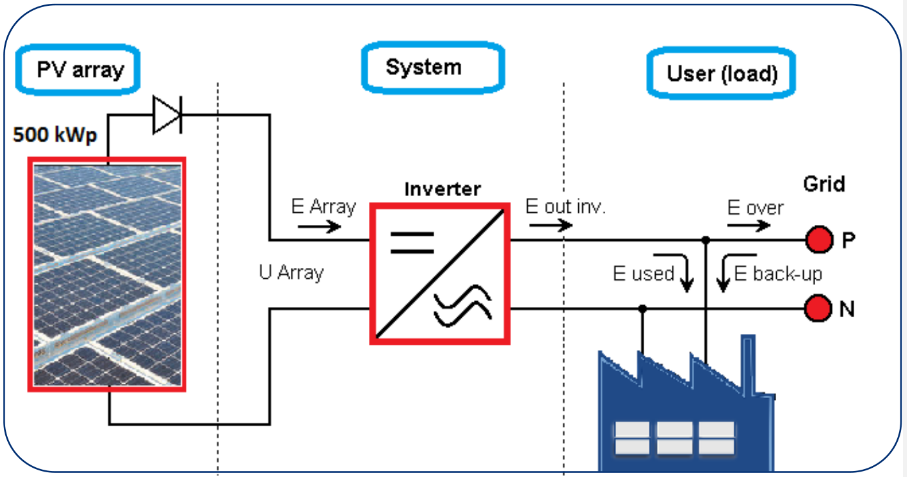

**Figure 2.** System scheme.

**Figure 3.** Photovoltaic generator installed on the roof of the textile factory.

### 2.1. Photovoltaic Panel

A part of the PV generator panels of 500 kW installed on the roof of a textile factory located in Pazarcık, Kahramanmaraş, is shown in Figure 3. The properties of the PV panel are displayed in Table 2. The maximum power of the panel is 250 W. Its nominal current is 8.28 A and nominal voltage is 30.2 V. Its efficiency is considerably high at 15.32%. Panels are located on the roof of the textile factory, and its footprint is important.

**Table 2.** Properties of the photovoltaic panels.

| | |
|---|---|
| Trademark | Soleos |
| Model | Soleos 250-9PJ |
| Solar cell | Si-poly |
| Maximum power at STC (Pmax) | 250 W |
| Optimum operating voltage (Vmp) | 30.2 V |
| Optimum operating current (Imp) | 8.28 A |
| Open circuit voltage (Voc) | 37.72 V |
| Short circuit current (Isc) | 8.81 A |
| Module efficiency | 15.32% |
| Length | 1650 mm |
| Width | 990 mm |
| Weight | 18.6 kg |

## 2.2. Modeling of photovoltaic panels

A solar cell is designed to convert sunlight to electricity. When light interacts with the solar cell, current and voltage are observed to generate electric power. The sunlight is absorbed in the solar cell and excites electrons to a higher energy state, and the excited electron moves to the electronic circuit and gives energy to the circuit. Energy conversion between sunlight and electronic circuit is performed by semiconductor materials with p-n junctions [28,30].

The theoretical equivalent circuit of a PV panel is realized by linear and nonlinear electronic components. The properties of each component are separately defined depending on the temperature and magnitude of solar energy for different PV panels. An equivalent circuit of the PV panel is represented by one diode and resistors and one current source [31].

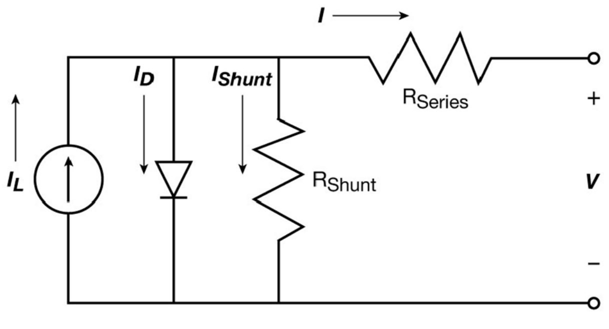

**Figure 4.** One-diode equivalent circuit for a PV cell.

If the Kirchhoff current law is applied to the circuit in Figure 4 [32],

$$I_{cell} = I_{ph} - I_D - I_{sh}. \tag{1}$$

The net electron, hole, and diode current with Boltzmann distribution are:

$$I_e = I_{eo}.(e^{\frac{qV_D}{kbT}} - 1), \tag{2}$$

$$I_h = I_{ho}.(e^{\frac{qV_D}{kbT}} - 1), \tag{3}$$

$$I_D = I_e + I_h = I_o.(e^{\frac{qV_D}{kbT}} - 1), \tag{4}$$

where q is the electron load ($1.602\times10^{-19}$ C), and k is the Boltzmann constant ($1.381\times10^{-23}$ J/K). The source current expression of the solar cell equivalent circuit shown in Figure 1 is obtained in Eq. (5) by applying Kirchhoff's voltage law [33–35]:

$$I_D = I_o\left(e^{\frac{qV_D}{mkT}} - 1\right) = I_o\left(e^{\frac{q(V_{pv}+I.R_s)}{mkT}} - 1\right). \tag{5}$$

$N_{PC}$ number of parallel panels in connected series with others constitutes the PV panels. Total voltage of the series PV array can be evaluated by adding the voltages of each PV. Total current of the shunt PV array is also calculated by adding currents of each PV for the fixed voltage [36].

$V_m =$ the voltage applied to the end of the module

$I_m =$ module current

$$V_M = N_{sc}V_{new} \tag{6}$$

$$I_M = N_{pc}I_{new} \tag{7}$$

$$I_{ph} = \left[I_{sc} + \alpha\left(T_c - 25\right)\right]\frac{G}{G_{ref}} \tag{8}$$

$$I_{cell} = I_{ph} - I_o\left(e^{\frac{q(V_{pv}+I.R_s)}{mkT}} - 1\right) - \frac{(V_{pv}+I.R_s)}{R_{sh}} \tag{9}$$

$$I_0 = I_{oref}\left(\frac{T_c}{T_{cref}}\right)^3 \exp\left[\left(\frac{q.E_g}{n.k_b}\right)\left(\frac{1}{T_{cref}} - \frac{1}{T_c}\right)\right] \tag{10}$$

$I_{cell}$ can be calculated by using Eqs. (8)–(10) to obtain the current of the solar cell:

$$I_{cell} = I_{ph.}(1 + C_0\left(T - 300\right)) - I_o\left(e^{\frac{q(V_{pv}+I.R_s)}{mkT}} - 1\right) - \frac{(V_{pv} + I.R_s)}{R_{sh}}, \tag{11}$$

where $I_{PV}$, $I_0$, $R_p$, and Rs denote the parameters of a single PV module. Series and parallel PV modules in a given SP array are represented by $N_{SC}$ and $N_{pc}$, respectively. The developed simulator is independent from the number of series/parallel arrays. In addition, it can also be used to observe the dependency of the system with respect to the shading, temperature, and diodes.

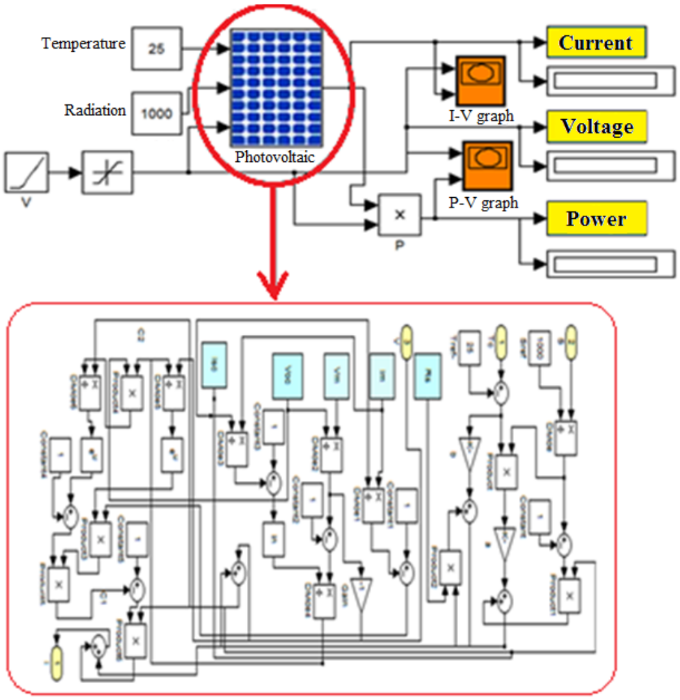

**Figure 5.** Selected PV panel type model in MATLAB/Simulink.

In this part, the selected PV panel is modeled in MATLAB/Simulink based on the extracted equations as shown in Figure 5. First, MATLAB/Simulink was used for the electrical model of the PV panel for which the mathematical model was completed. As in the experimental study, parameters such as solar radiation values, medium temperatures, etc. are encoded as inputs of the PV panel. These data are obtained from the experimental study. The same panel type and values are obtained from the experimental study. Thanks to this applied study, it can be understood how the characteristics of the PV panel change under different cell temperatures and the effects of changes on the PV panel are analyzed in detail.

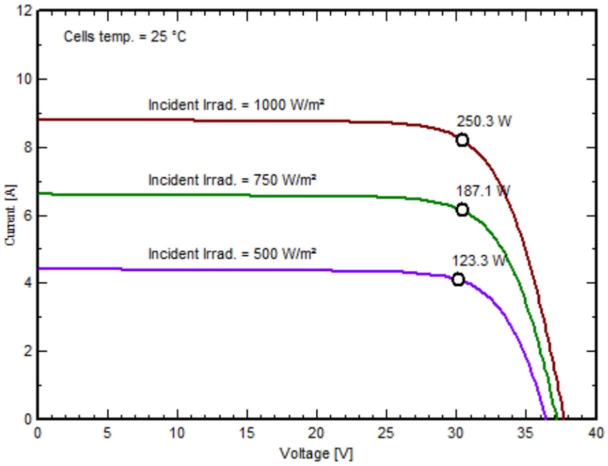

**Figure 6.** Change in current-voltage characteristics depending on the radiation.

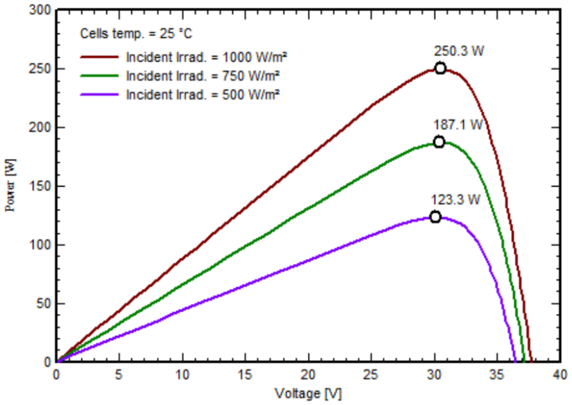

**Figure 7.** Change in power-voltage characteristics depending on the radiation.

Change in current-voltage characteristics of the panel used in the PV generator and change in power-voltage characteristics depending on the radiation are shown in Figures 6 and 7, respectively. While the panel generates 250.3 W at a temperature of 25 °C and radiation of 1000 W/$m^2$, it generates 187.1 W for 750 W/$m^2$ and 123.3 W for 500 W/$m^2$ [37].

The 2001 pieces of polycrystalline PV panel of 250 W used in the system were divided into three groups. The first group contains 1725 panels, 75 parallel panels connected to 23 series panels, while the third group includes 168 panels, 8 parallel panels connected to 21 series panels (Figure 8).

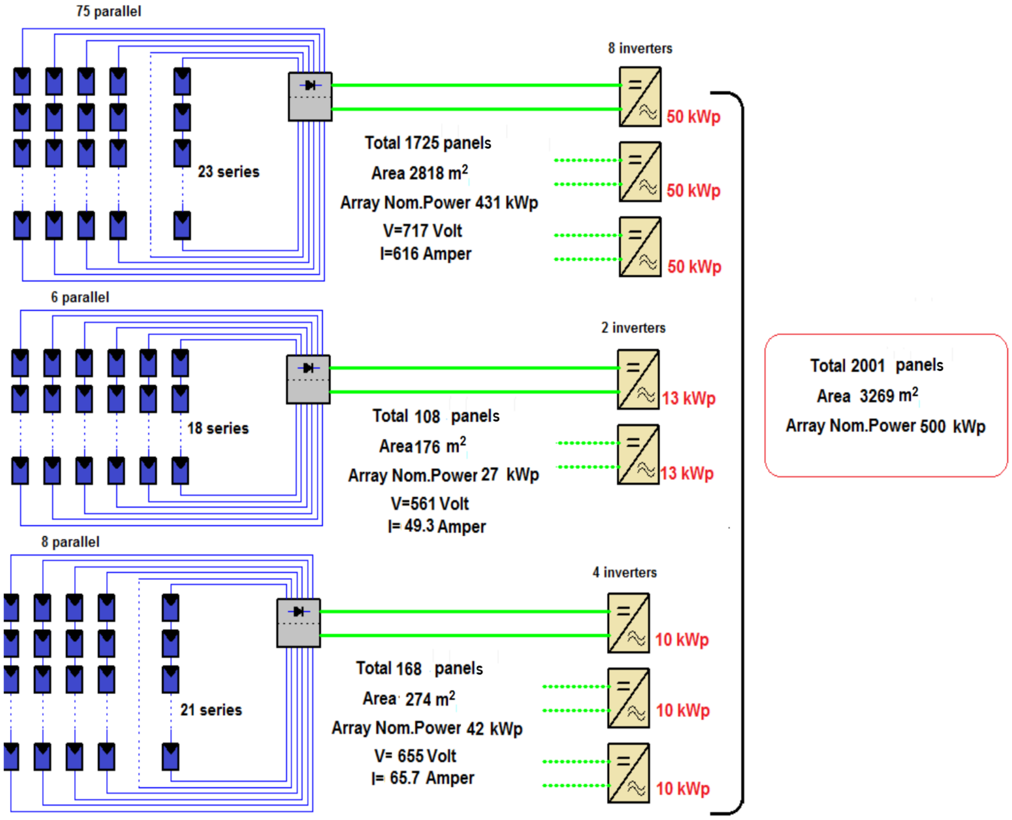

**Figure 8.** The structure of the PV generator.

The system, which started in August 2013, generated 479.7 MWh of energy within a period of 8 months. The system was estimated to generate 496.2 MWh at the beginning, and the success rate is 96.57%. The modeling is based on annual climate values, which helps to estimate the amount to be generated (Figure 9).

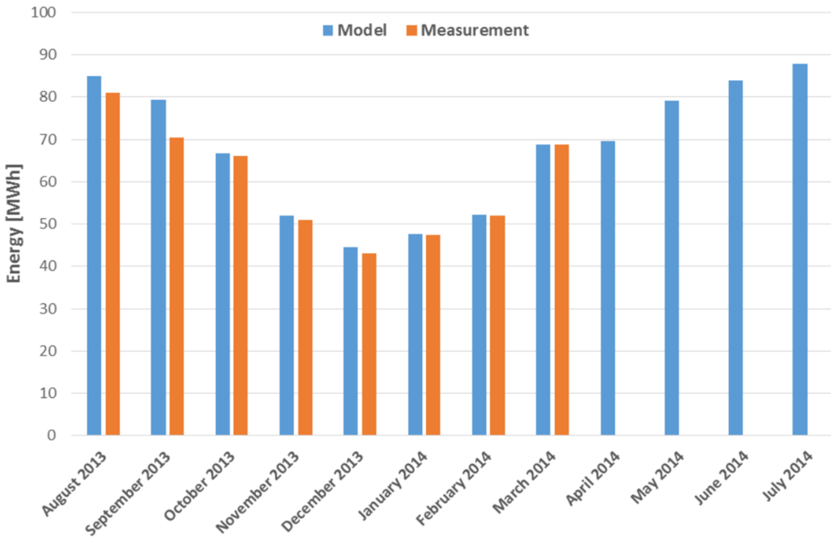

**Figure 9.** Energy generated by the system and results of the modeling.

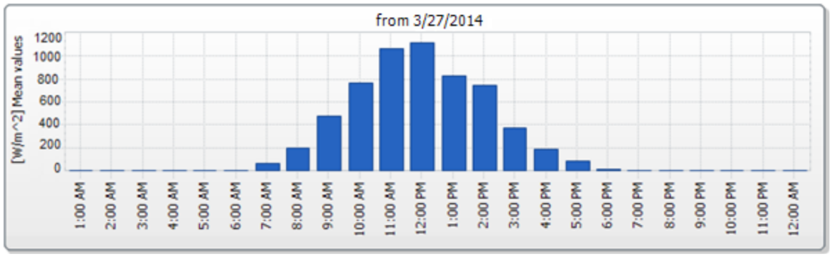

**Figure 10.** Radiation rates on 27 March 2014.

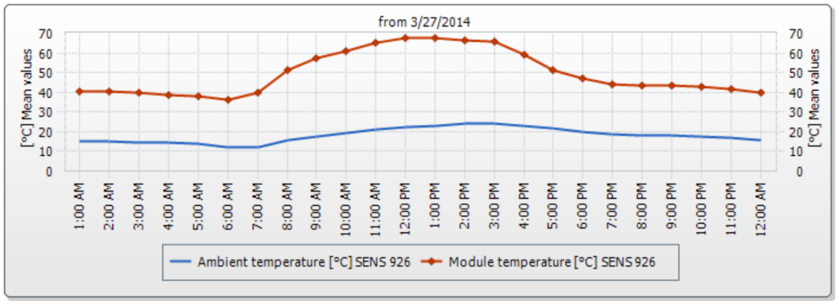

**Figure 11.** Temperature on 27 March 2014.

Radiation rates and temperature in Kahramanmaraş on 27 March 2014 are given in Figures 10 and 11, respectively [38].

## 3. Cost analysis

Although their installation costs are high at the beginning, PV generators are cost-effective in terms of operation and maintenance. The systems become more and more efficient thanks to technological developments, and costs are gradually reduced. The cost analysis of a PV system of 500 kW is given in Table 3. The installation cost of the system is 1,304,413.30 Turkish lira (TL; 1 TL = US \$0.36). PV panels include 73% of the cost while the inverter is 21% and other equipment is 6%. The system annually generates 816,639 MWh of energy. The net profit is 6,991,000 TL. The unit cost of energy is 0.119 TL. It pays off in 6.2198 years [39–42].

**Table 3.** Cost analysis of the system.

| | | | | |
|---|---|---|---|---|
| PV modules | | 400 TL | 2001 | 800,400 TL |
| Support | | 35 TL | 2001 | 70,035 TL |
| Inverter | 50 kW | 24,000 TL | 8 | 192,000 TL |
| | 13 kW | 8500 TL | 2 | 17,000 TL |
| | 10 kW | 6500 TL | 4 | 26,000 TL |
| Total | | 1,105,435 TL | | |
| Taxes | | 198,978 TL | | |
| Net investment | | 1,304,413 TL | | |
| PV cost (TL/W) | | 1.888 TL | | |
| System costs (TL/W) | | 2.608 TL | | |
| Production (kWh, 1 year) | | 816,639 TL | | |
| Production (kWh, 30 years) | | 24,499,170 TL | | |
| Fixed feeding tariff | | 0.33 TL | | |
| Total yearly income | | 269,491 TL | | |
| Total income | | 8,084,726 TL | | |
| Energy price increase (1 year) | | 2% | | |
| Maintenance cost (1 year) | | 7000 TL | | |
| Net profit | | 6,991,000 TL | | |
| Unit cost of energy (30 years) | | 0.1193 TL | | |
| Breakeven point (years) | | 6.2198 | | |

The annual financial balance of the photovoltaic generator is shown in Figure 11. It is assumed that the annual inflation rate is 6% and the energy price per unit will increase 2%. The electricity tariff is calculated as \$13.3, which is the amount paid by distribution companies for the energy generated by PV generators. From a different point of view, the electricity is actually supplied on the grid and energy generated by the system is transferred to the electricity network. The system begins to make a profit in the seventh year. Energy generated by the PV generator is valued at 269,490.87 TL in 2013 [43,44] (Figure 12).

## 4. Conclusion

A PV generator of 500 kW installed in the Pazarcık district of Kahramanmaraş Province in August 2013 to provide energy for a textile factory generates 816.639 MWh of energy and reaches its initial cost in 6.2198 years. This significant renewable energy source bears utmost importance in today's world where the need for and cost of energy is considerably high. In addition to its cost-efficiency, the system is also environmentally friendly. It does not lead to gas emission or contribute to global warming. Furthermore, PV generators may be a potential energy source for Turkey, which is dependent on foreign countries in terms of energy. In conclusion, it is observed that PV generators are significantly useful when Kahramanmaraş's climatic conditions are taken into account.

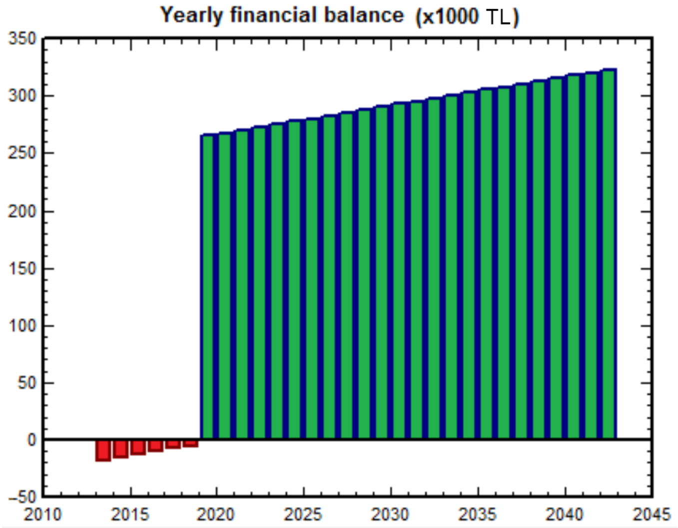

**Figure 12.** Yearly financial balance.

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