



Comparison of the Performance of Solar Panels Designed in Three Different Ways under the Same Conditions

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Highlights

- This paper focuses on comparison of the performance of three various located solar panels.
- A comparison for solar panel designs is analysed empirically in the study.
- This study presents an analysis for solar panel selection and investment ideas.

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Abstract

Renewable energy sources such as solar energy have great potential to alleviate some of the negative environmental problems, including climate change, caused by intensive fossil fuel use. Solar energy will play an important part in future energy systems because of its rapid installation technology and lowering costs. In order to use solar radiation intensity in a wide range in the most efficient way, the plants must either be at an optimum angle in the area where they are installed or they should be designed with moving systems. In this study, performance and efficiency comparisons of solar tracking systems and fixed-designed systems based on real-field conditions have been made. In this way, price performance ratios can be determined clearly and it will be easier to decide on the types of power plants to be built. While solar tracking systems move according to the most efficient position that they can get from the sun through radiation sensors, they are designed with elements such as PLCs using multi-year solar data that operate with an open loop and based on meteorological data. In this study, three different power plant types designed as 1-axis, 2-axis, and fixed angle were controlled as open loop with PLC software and production differences between power plants were evaluated for 1 year. According to this research we have done, it has been concluded that 2-axis tracking systems produce approximately 32% more energy annually than a fixed-angle system, with an annual efficiency rate of 23% higher than a 1-axis system.

1. INTRODUCTION

Energy is the most important resource and strategic tool for all countries, affecting the shape of societies. The availability and cost of energy significantly affect our quality of life, the structure of national economies, international relations and the stability of our environment [1]. Energy is an important element for the economy of both our country and other world states. All governments and other international organizations are almost in a race with each other to obtain energy resources such as oil, natural gas, coal, etc. Energy is an indispensable part of industrialization and the daily lives of modern people. Therefore, energy needs are very important national and international agenda. Due to limited fossil energy resources, foreign dependency and environmental effects of fossil energy resources, producing safer, sufficient, cheaper, and cleaner energy is among the main problems of social life and the economy for countries. In our country, Turkey, whose industry, economy, and population are growing rapidly, the need for energy is constantly increasing in parallel with the growth. For this reason, it is of great importance to use the produced energy with high efficiency and to evaluate the potential of alternative and renewable energy sources as well as the existing energy sources.

In recent years, Turkey is among the countries that have developed with the policies it has implemented in the field of renewable energy. Although it is a useful way of obtaining energy, there are obstacles to renewable energy generation. The development of renewable energy requires removing these barriers and adopting appropriate practices to overcome them. Besides these problems, Turkey has a large renewable energy potential but lacks the implementation policy and the necessary tools, so resources cannot be used [2].

Turkey is located at the meeting point of the Asia, Europe, and Africa continents and acts as a bridge between Europe and Asia. Its size is 779,452 km². In 2020, Turkey's population was around 83 million. As a result of the social and economic development of the country, the energy demand of the country is constantly increasing [3]. According to the data of Turkey Electricity Distribution Inc., the development of the gross electricity generation by primary source by years in Turkey is given in Figure 1 below [4].

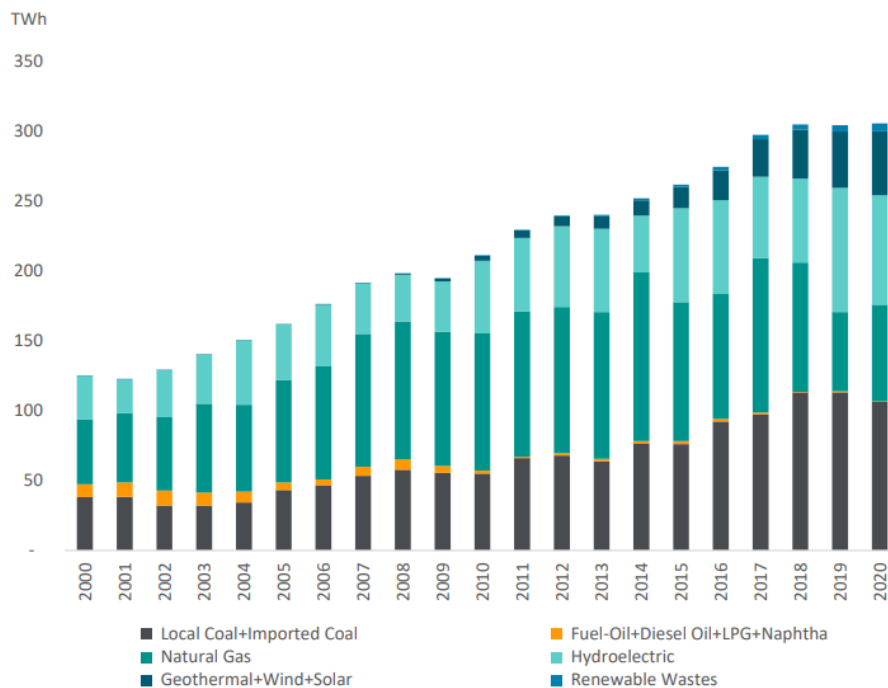


Figure 1. Development of total installed power according to resources in Turkey

Figure 2 demonstrates the ratios for installed power of renewable and non-renewable resources in Turkey regarding 2019 [5].

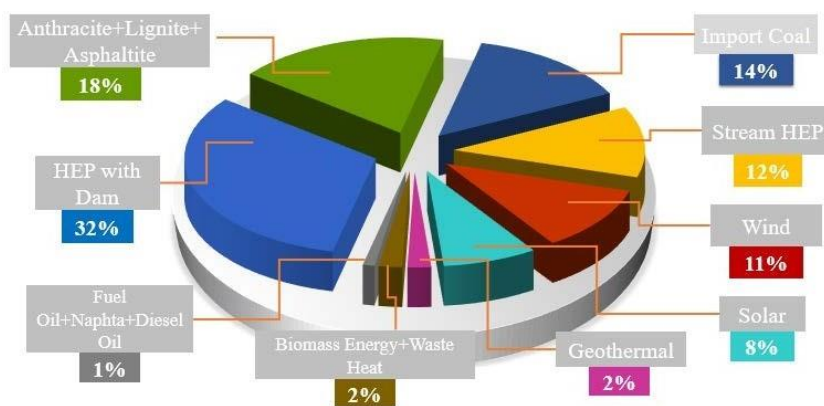


Figure 2. Installed power capacity of Turkey

Renewable energy is a topical issue in the world as well as in Turkey. Renewable energy sources are important in terms of being environmentally friendly with the carbon emission rates they emit into the atmosphere and reducing dependence on foreign sources. Renewable energy sources are primarily solar energy, but they can also include hydraulic, wind, geothermal, biomass, and wave energy. Although the most important energy type in this list is solar energy, it can be said that it has an indirect or direct effect on other energy types [6]. Annual solar radiation and monthly variation of Turkey's average daily sunshine duration are given in Figures 3 and 4.

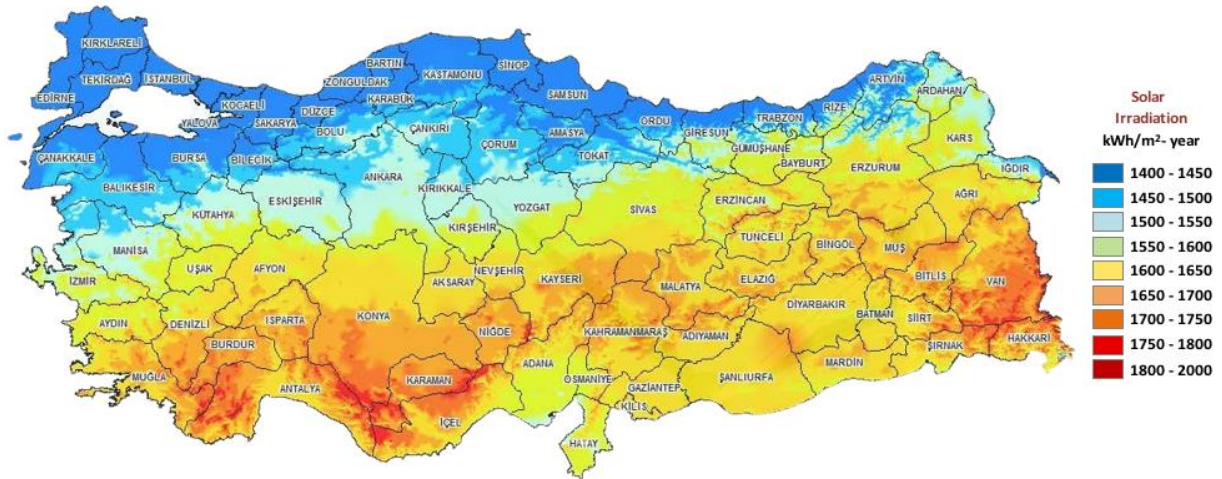


Figure 3. Annual solar radiation [7]

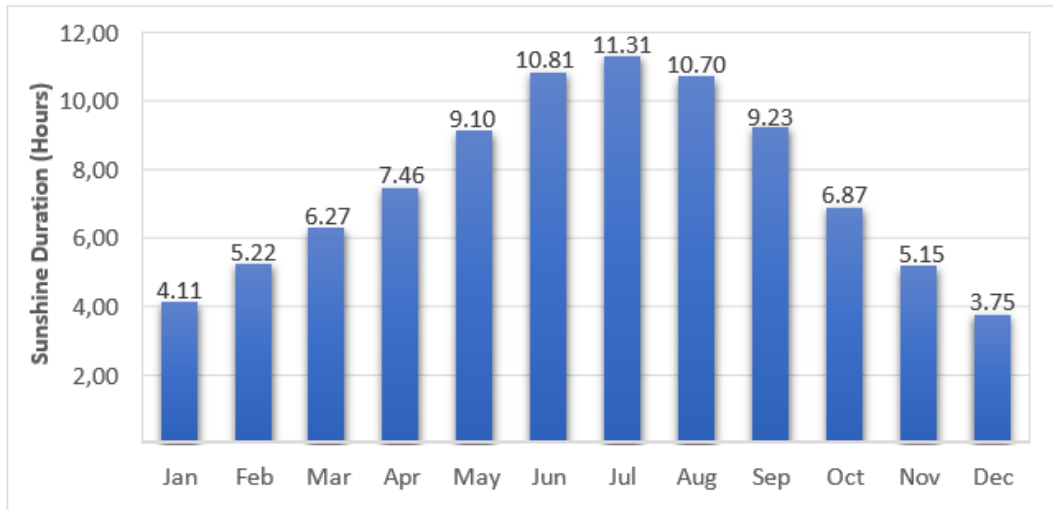


Figure 4. Average Daily Sunshine Duration [8]

When Figures 3 and 4 above are examined, the importance of Turkey's solar energy potential can be understood more clearly. According to the data given in Figure 2 above, the share of solar power plant (SPPs) in the country is around 8% [9]. Within the scope of the regulation published in the Official Gazette dated 12.05.2019 and numbered 30772, this ratio will increase much more with the new facilities to be implemented within the scope of the establishment of solar power plants for roof and facade applications, and the share of the sun will gain more importance in electricity generation [10]. The graphic shown in Figure 5 below expresses the development of the power plants installed with solar energy over the years in Turkey [11- 14].

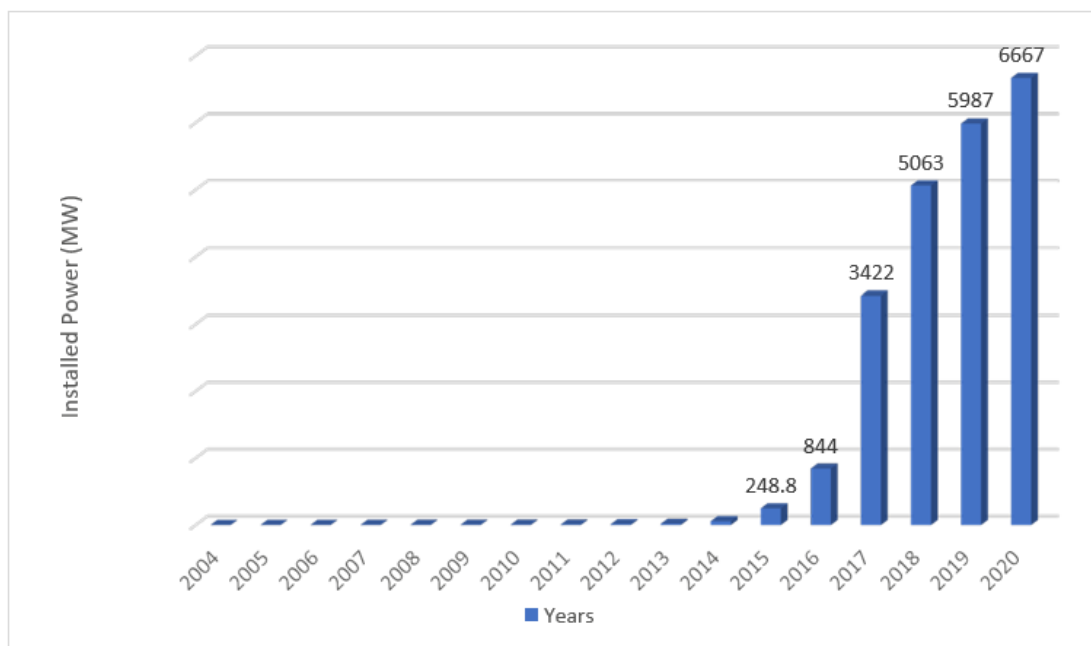


Figure 5. Development of the solar power plants in Turkey

As a result of irregular field layouts and installations, existing roof layouts, and inexperienced applications, the efficiency of solar panels, which are already inefficient, further decreases. In order to eliminate the negative effects of these and similar situations or to obtain the maximum value that can be obtained from inefficient panels, it is important that the power plant installations are achieved in optimum conditions before they are designed. Power plants built in our country are optimally designed with fixed-angle power plants as a result of simulation applied within the framework of mathematical modelling criteria arranged according to the past radiation values prepared in a computer environment. The aim of our study is to help investors decide in what way the plants can be established by making efficiency analysis and production calculations under real field conditions and with real values close to 100%, and to guide investors in feasibility studies.

In their studies, Bingöl et al. developed a microcontroller-based solar tracking systems in their studies. This system follows the position of the sun by working independently from the geography it is located in and ensures that the sun's rays are perpendicular to the panel surface [15]. J. Rizk and Y. Chaiko demonstrated in their study the potential benefits of a simple solar tracking system using a stepper motor and light sensor. With this method, it has increased the panel efficiency by keeping the solar panel always perpendicular to the sun rays [16]. Demirtaş carried out the design and application of a prototype of a PLC-controlled solar tracking system. It used an open-loop control system in this application. The results of the application showed that the mobile solar tracking system works approximately 34.5% more efficiently than the fixed system in terms of energy generation [17]. Sungur analysed the energy gain of fixed and mobile solar tracking systems in his study. Sungur calculated that a moving system with respect to a single axis had a 42.6% energy saving and emphasized that the cost would decrease when the number of panels started to be increased by increasing the number of panels. [18]. Khan et al. explained the microcontroller-based design methodology of an automatic solar tracker in their work. Light- dependent resistors are used as sensors for the solar tracker. The designed tracking system was created with a precise control mechanism to provide three ways of controlling the system [19]. Deb and Roy worked on the design of a tracking system for PV solar panels. They have provided the optimization of the return of solar energy to electricity by directing the PV panel to the real sun position with the uniaxial solar tracking device proposed here. An experimental model of the device was made and the system was set up with the help of a step motor that moves the PV panel according to the signals received from two efficient light sensors [20]. Zhan et al. designed a system that monitors the solar intensity on the panel with a PLC controlled monitoring system in their studies. With this system, the orientation angles and heights of the solar panels are controlled, so that the panels are allowed to receive the sun rays at every moment of the day. When the measured values of the solar tracking

system and fixed angle systems are compared, yield differences between approximately 8% and 25% have been observed [21].

In this study, a comparative efficiency analysis has been made conducted with solar power plants designed in three different types at the same power and location in the Kadirli district of Osmaniye. These three different power plant types are the first plant type is mounted at a fixed angle, the second plant type is designed to follow the North-South position, and the third plant type is designed to follow both the East-West position and the North-South position. The main goal of this study is here to decide what type of solar panel should be utilized for the most efficient generation and future investments.

2. SOLAR ENERGY

Solar energy is used as an alternative solution in more developed countries in order to reduce the environmental problems caused by fossil fuels. It is not possible to provide the energy requirements for industry, residential, or individual purposes from direct sunlight, as is the case with plants. For this reason, solar energy can be used by transforming it in various ways. The areas of use of solar energy include direct or indirect electricity generation, hot water generation, space heating and cooling, process heat energy for industrial establishments; and greenhouse heating [22].

Turkey has abundant in solar energy potential, with the advantage of its geographical location. According to the Solar Energy Potential Atlas of Turkey, the annual total sunshine duration is 2,741.07 hours, the average daily sunshine duration is 7.5 hours, the average annual total radiation intensity is 1527 kWh/m^2 - year and the average daily total irradiance is 4.2 kWh/m^2 [22]. These values actually shed light on how much solar potential Turkey has. Therefore, it is seen that investments to be made in renewable energy resources are of great importance both in terms of recovery in a short time and their contribution to our country's economy. When it is compared with Germany, which is located farther north than Turkey; the average annual sunshine duration is 1600 hours, and an average of 994,000 kWh of energy can be produced annually from a 1 MW power plant. This value reaches an average of 1.540.00 kWh in our country. Despite this, although Germany has a power plant with a value of 46,000 MW, this value is slightly above 5000 MW in our country [23]. Therefore, it is obvious that our country, which has many times more solar energy potential than Germany, should give more importance to such investments. In addition, Germany reached to 47.72 GW cumulative solar power capacity at the end of May 2019 and ranked 4th in the world. Germany has successfully supplied over 50% of the nation's daily energy demand from solar power [23].

2.1. Photovoltaic Systems

Solar cells are devices made of semiconductor materials that convert light energy from the sun directly into electrical energy. Silicon, used in the electronics industry, is also the most commonly used raw material in the solar cell structure. In terms of technology, monocrystalline, polycrystalline, and amorphous solar cells are used commercially. The efficiencies of solar cells in these structures are as follows: on a modular basis, 15-17%; 12-14%. It can be evaluated at 5-8%. For 1 cm^2 of battery area, the highest battery efficiencies were achieved in laboratories.

- Crystalline solar cells 25%
- Polycrystalline solar cells 20%
- Amorphous solar cells were measured at 13%.
- Apart from these single-joint solar cells, 33% efficiency was achieved with multi-joint (TANDEM) solar cells developed in the laboratory. The efficiency estimated to be reached theoretically is 40%.

Studies in literature have also been concentrated on solar cells that can replace traditional Si (silicon) solar cells that have been commercialized in recent years with equivalent efficiency but with cheaper and easier production technologies. New technologies such as photo-electrochemical polycrystalline titanium dioxide batteries, polymeric plastic batteries, and quantum solar cells with energy band gaps that can be produced to adapt to various wavelengths of the solar spectrum are being created [24].

Solar energy can be used for various purposes, such as generating heat or electricity. Solar energy can be used to generate electricity where there is no electricity network; it can be used to purify water in areas without access to clean water, and it can be used to meet the energy needs of satellites in space. Power plants installed with solar energy generally do not need much maintenance. Even just keeping the solar panels clean can be enough. Therefore, it needs to be cleaned as it gets dirty. Since there are no moving parts, wear and tear is less. Checking the cable connections at certain periods and cleaning the inverters can be sufficient for the maintenance of solar power plants. In addition to the advantages of solar energy, there are also disadvantages. The initial investment cost of a solar power plant installation can be high.

Solar energy can still be produced in cloudy and rainy weather, but the efficiency of the solar energy system will decrease considerably. Solar panels need sunlight directly to convert solar energy into electricity effectively. Therefore, it will have a negative impact on the yield from the panels on cloudy and rainy days. In addition, there will be no energy production during the night. Figure 6 and 7 below show the production graphs of two different days produced in the EMTA Kablo SPP-2 power plant in sunny and cloudy weather, respectively.

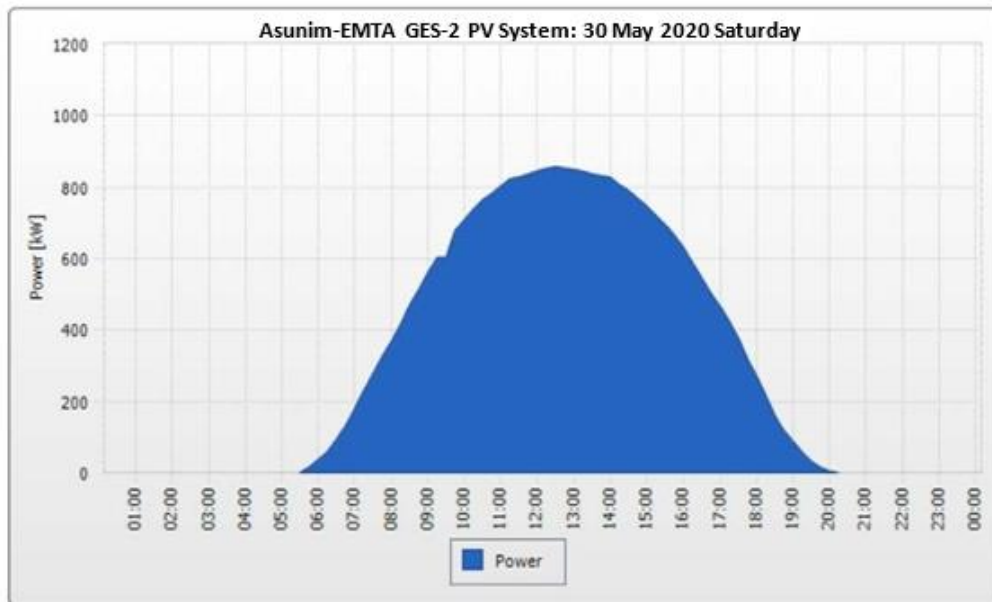


Figure 6. Graph of energy produced on a sunny day

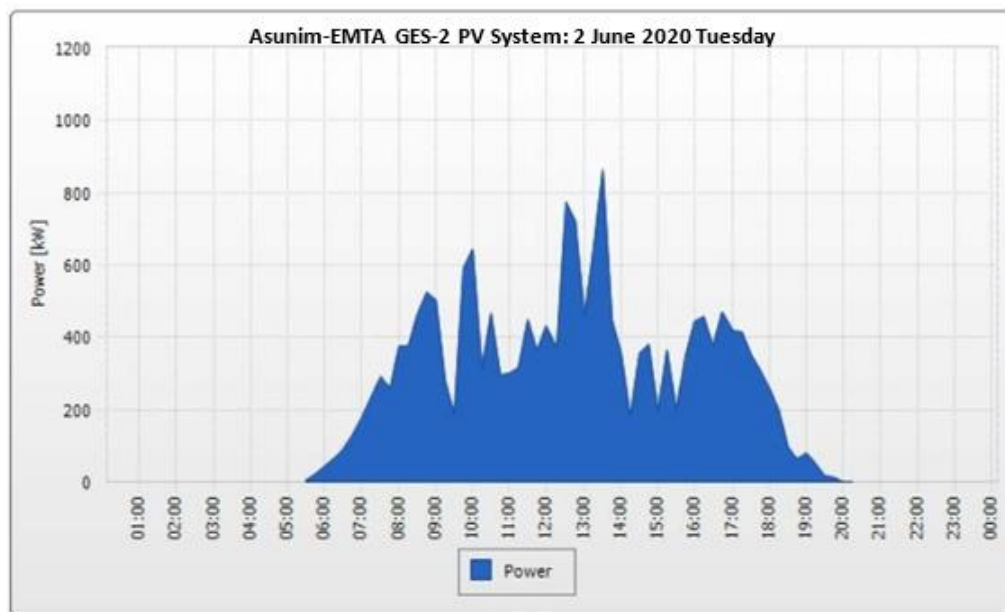


Figure 7. Graph of energy produced on a cloudy day

When Figures 6 and 7 are compared, it is clear that the energy obtained on a cloudy day decreases due to the less sunlight reaching the solar cells. Electricity generated from solar energy should either be used at the time it is produced, pressed into the system or stored with large batteries. Most systems only use solar energy during the day and meet their needs from the grid at night. The amount of electricity produced from solar energy is proportional to the number of panels. However, the problem here is that the panels take up a lot of space. A panel with 250 Wp power occupies an average of 1.6 m^2 area. Therefore, there is a practical limit to the amount of energy that can be produced.

3. MATERIAL AND METHODS

The solar tracking system is useful in a variety of solar energy applications where its advantages include not just increased power and efficiency compared to fixed systems, but also economic evaluations of large-scale solar energy applications. To maximize the solar radiation effects on the solar collectors and panels, the systems are oriented with optimal tilt angles towards the equator from the horizon. The tracking angles are determined by the location's latitude and climatic circumstances. Single-axis solar tracking systems and dual-axis solar tracking systems are the two primary types of solar tracking systems based on the degree of freedom of movement [25]. In this study, three solar power plants with the same power and location in Kadirli region of Osmaniye were compared for efficiency. First plant type is mounted at a fixed angle, second follows North-South, and third follows both East-West and North-South. Since each power plant is affected by the same temperature, the same pollution, and the same environmental conditions, only the production values have been compared. In each plant; 2 kW GoodWe brand inverters and three serially connected polycrystalline Yingli brand 255 Wp solar panels were used. At the same time, cable cross sections and lengths are kept equal. The retention of energy data is created by taking the data provided by SEMS Portal. In order to prevent possible data loss, a second data tracking was performed using KAEL brand energy analysers. In the system installed here, inverters are ON-GRID and connected directly to the network. Therefore, the grid data (voltage and frequency) is read by the inverter processors and at the start-up phase, it starts production at the same frequency and voltage level as the grid. In the event of a possible power outage or power failure for maintenance, since the inverters will not be able to receive feedback from the grid, they will not produce and there will be no feedback to the grid.

3.1. First Type of Plant

The established power plants in our country and in the world mainly consist of fixed angle systems. The installed plants with fixed angles can face the sun vertically only a few days of the year, and their production

values can only peak when the sun rays are steep. Therefore, the maximum power level that can be taken from the panels is almost never reached. The fixed-type power plant built in this project was established by examining the types of power plants in our region and having the same angle of view as them. It has been determined that the power plants installed in the aforementioned region are installed in the south direction at an angle of 25° to the sun. Our experimental plants were similarly established in the south direction, equivalent to those installed at an angle of 25° to the sun (Solar Power Plant-1). With the adjustable bolt mechanism on the table to which the solar panels are attached, the facility has been brought to a fixed angle and will remain the same throughout the year. In this section, the production data of only a south facing plant with a fixed view of 25° was obtained during the operation period. The image and annual production data of the Solar Power Plant-1 are shown in Figures 8 and 9 below.



Figure 8. View of Solar Power Plant-1

Figure 9 shows all the values that a facility established with panels of 765 Wp power can produce in the Kadirli district for one year. At this facility, with a power of 765 Wp , a total of 1041.55 kWh of energy was produced annually. If we compare the value of this power with a real power plant with a power of $1,200,000 \text{ Wp}$ and a power of 1 MWe ; approximately $1,683,803 \text{ kWh}$ of energy can be produced with a 1 MWe power plant.

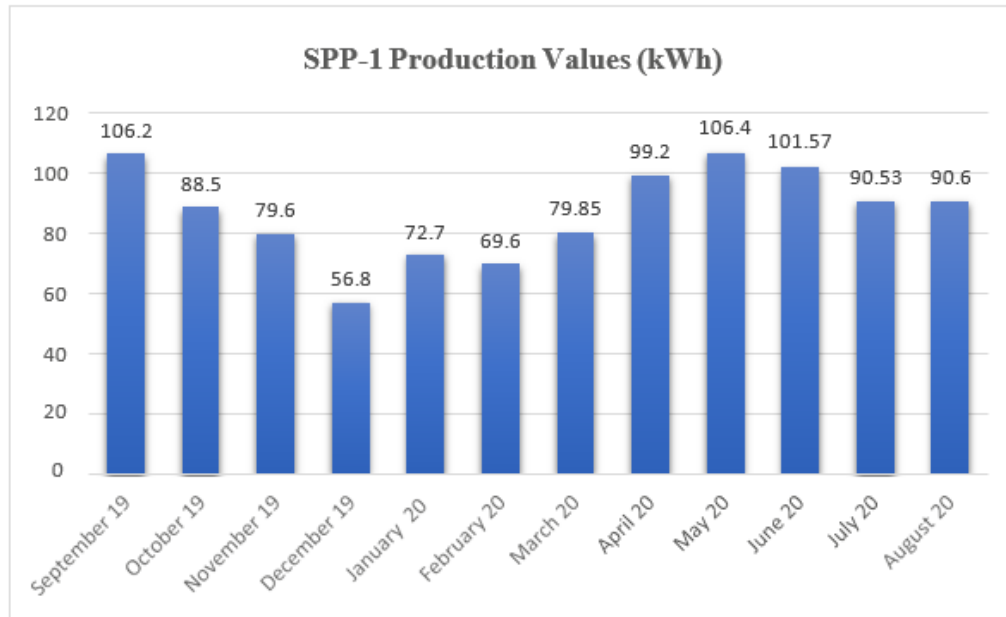


Figure 9. One year generation data of Solar Power Plant-1

3.2. Second Type of Plant

Solar Power Plant-2 follows the sun in a north-south direction. It was established according to the annual movement of the sun. The East-West position is fixed to the table with an adjustable sliding mechanism. The North-South location is designed to automatically track the annual sun position by a linear motor driven by 24V DC. This facility receives sunlight at an angle of 90° every day of the year at noon. For this reason, a more efficient power plant was built compared to fixed facilities. During the study period, the production differences between the fixed power plant and the production data received were evaluated. The following Figures 10 and 11 show the 1-Axis Tracking System, which is also named Solar Power Plant-2, and one-year SPP-2 production values.



Figure 10. View of Solar Power Plant-2

Figure 11 shows that a total of 1116.03 kWh of energy can be produced in one year. When we compare this value with a real 1-axis tracking power plant installed with a power of 1,200,000 Wp, we will be able to generate 1,750,635 kWh of energy from a 1-axis tracked power plant with 1 MWe installed power.

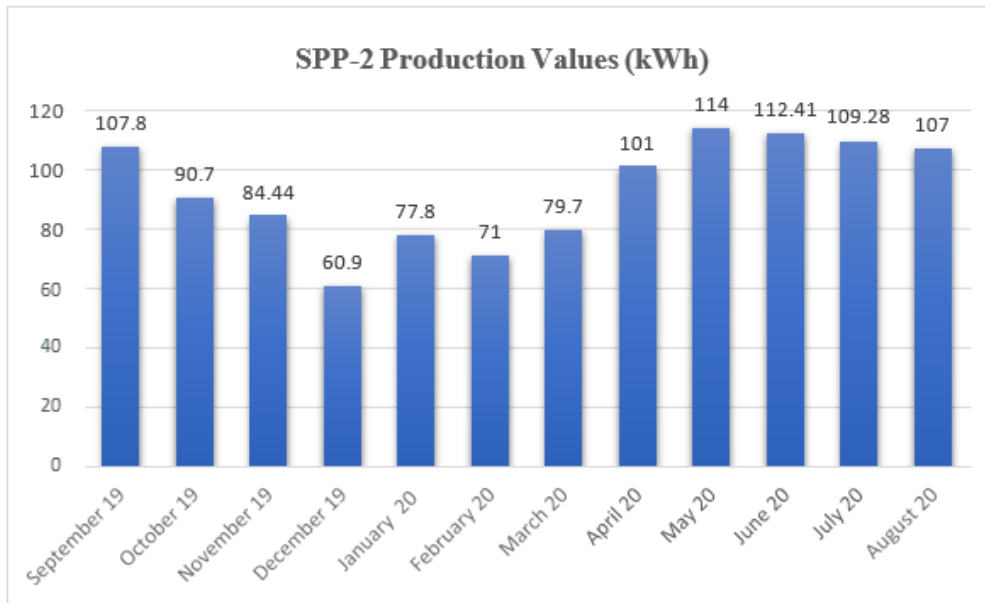


Figure 11. One year generation data of Solar Power Plant-2

3.3. Third Type of Plant

Solar Power Plant-3 was established as a power plant that positions itself according to the daily and monthly movements of the sun. A table was designed to track the sun with 24V DC linear motors following both the East-West position and the North-South position. Daily action; using the sunrise-sunset data of Boğaziçi University Kandilli Observatory and Earthquake Research Institute Astronomy Laboratory, the daily movement of the sun was monitored with software written with S7-1200 PLC. The solar tracking software was created by us, and it is aimed at following the sun in the most efficient way. It aims to design a stable algorithm by eliminating situations such as sensor malfunctions and light scattering caused by clouding. The seasonal variation was calculated in proportion to the annual movement of the sun in the North-South direction and controlled by the PLC to track the sun. In this way, it has been ensured that the sunlight is always perpendicular to the panels at a 90° angle at any time of the day and maximum efficiency is obtained from the sun. The program written for the annual movement was also used for the control of the Solar Power Plant-2. The production differences between them are evaluated by comparing the data obtained during the production period with the production data of other power plant types. The panels cannot fully receive the sun's rays due to environmental effects in our location during sunrise time in the morning and sunset in the evening. Therefore, tracking starts one hour after the sunrise in the morning, and the sun's tracking movement stops one hour before sunset. As a result, it was possible to track the sun in the 120° angle band during the day, not at an angle of 180°. In Figures 12 and 13 below, the 2-Axis tracking system, which is also named Solar Power Plant-3, and one-year SPP-3 production values are shown.



Figure 12. View of Solar Power Plant-3

Figure 13 shows that a total of 1373.31 kWh of energy can be produced in one year. When we compare this value with a real power plant installed with a power of 1,200,000 Wp, we will be able to generate 2,154,211 kWh of energy from a power plant with an installed power of 1 MWe.

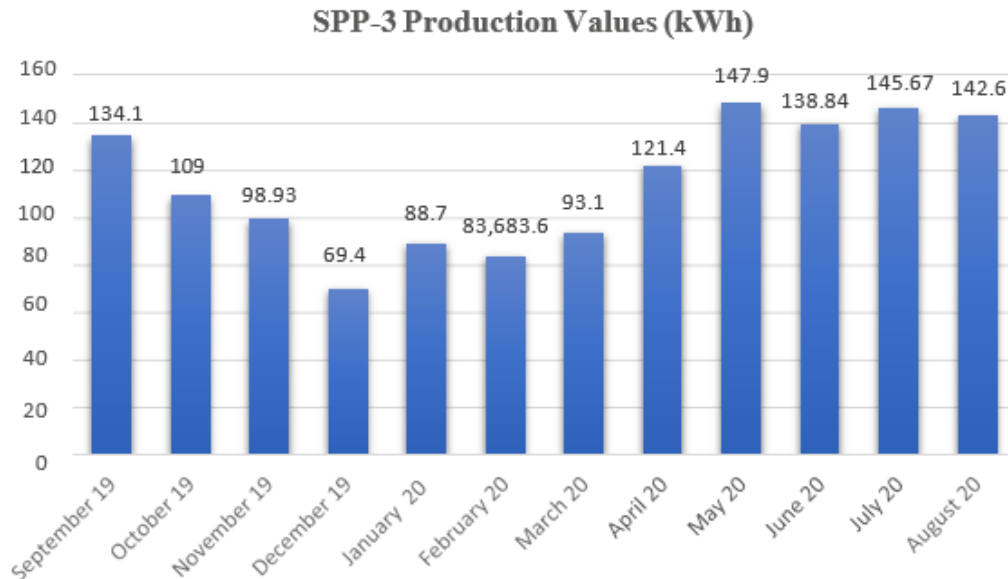


Figure 13. One year generation data of Solar Power Plant-3

4. RESULTS AND DISCUSSION

The fact that the energy obtained from fossil fuels is limited for future generations has forced people to find clean energy by using the power of nature. In this direction, solar energy, which forms the basis of all energy resources, stands out as the most important energy source among all resources. A feasibility study for solar energy systems is important in terms of seeing the future predictions of the investment owners. Therefore, how soon an investment returns as a profit will encourage more investments to be made in that area. This comparative efficiency analysis, on the other hand, is a study that will set an example for investment and

guide investment decisions.

If the results are examined depending on the constructed system, data on production values can be monitored online on the SEMS PORTAL page of GoodWe Inverters, or retrospective production reporting can be obtained. To prevent data loss, a second monitoring is performed using KANEL energy analysers at the same time. The above production values are the graphs created as a result of the data taken from both monitoring modules. In Figure 14 below, the comparative production values of the data taken over a year in total are given.

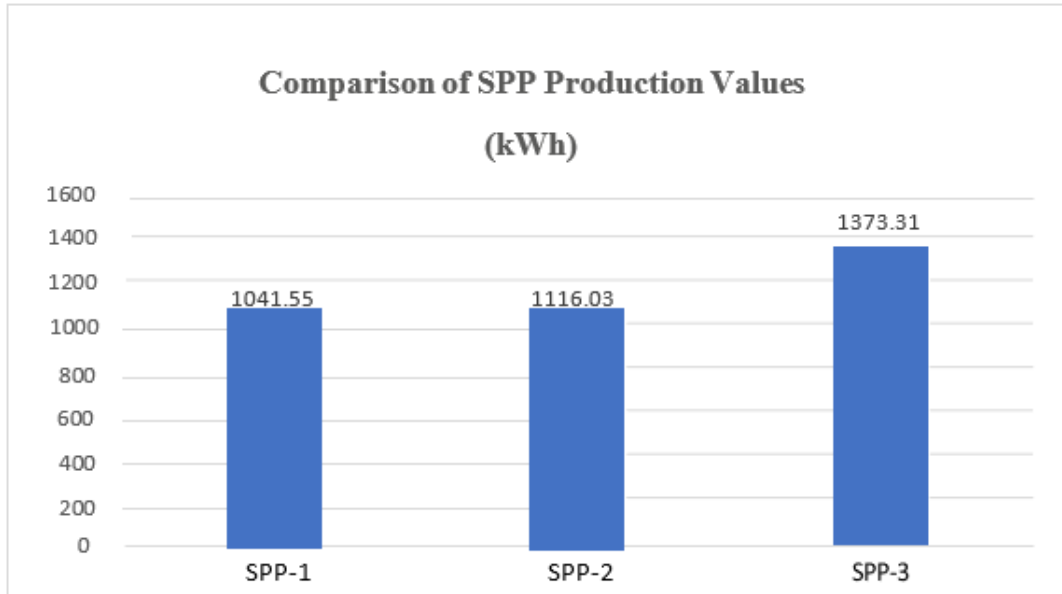


Figure 14. Comparative production values of power plants

Figure 14 shows that there are differences between the amounts of energy produced by three different systems in the same time periods. When the data in figure is analysed, it can be achieved the following results.

According to the production values, the produced electrical energy for three different solar power plants at the end of one-year were given in Figure 14.

- Total energy generation of SPP-1 facility: 1041.55 kWh
- Total energy generation of SPP-2 facility: 1116.03 kWh
- Total energy generation of SPP-3 facility: 1373.31 kWh

Comparison of production values of SPP-3 and SPP-1 power plants:

$$\frac{(1373kWh - 1041.55kWh)}{1041.55kWh} \cdot 100 = 31.85\%. \quad (1)$$

Comparison of production values of SPP-2 and SPP-1 power plants:

$$\frac{(1116.03kWh - 1041.55kWh)}{1041.55kWh} \cdot 100 = 7.15\%. \quad (2)$$

While the production difference between a 2-axis tracked system and a fixed system was found to be around

31.85%, the production difference between a 1-axis tracked system and a fixed system was found to be around 7.15%.

When we look at these values under real field conditions, the following results can be obtained.

- The amount of energy that a fixed power plant with a capacity of 1 *MWe* can produce in one-year: 1,633,803 *kWh*.
- The amount of energy that a 1 *MWe* 1-axis tracking plant can generate in one-year: 1,750,635 *kWh*.
- The amount of energy that a 1 *MWe* 2-axis tracked power plant can produce in one-year: 2,154,211 *kWh*.

Analysing the energy values obtained from the three systems above, it is observed that the fixed power plant produces the least energy compared to the others. It has been observed that the SPP-2, which has a 1-axis solar tracking system, produces 116,832 *kWh* more energy per year compared to the fixed system. SPP-3 with a 2-axis solar tracking system produces 403.558 *kWh* more energy per year compared to SPP-2 with a 1-axis solar tracking system. It is observed that the SPP-3, which also has a 2-axis solar tracking system, produces 520.408 *kWh* more energy per year compared to the SPP-1. When the electrical energy values obtained from these three systems are compared, as expected, the SPP-3 system gave the best result. The most important thing in this study is to determine the most suitable system considered by comparing the initial investment cost and the energy values obtained. According to the results obtained, it will be possible to determine how long the investment cost difference between the systems can be amortized and which system will be more efficient considering the life cycle costs.

5. CONCLUSION

This paper contains a study where shade, pollution, temperature, and other conditions are considered equal, and three different power plant types in the same climate and ambient conditions have been evaluated for the Kadırlı district of Osmaniye. Production data was collected separately for each power plant. Data collection processes were handled with the help of SEMS Portal and KAEL Energy analysers. According to the data obtained, it is concluded that a 2-axis power plant is 31.85% more efficient than a fixed power plant, and a 1-axis power plant produces 7.15% more energy than a fixed power plant in a one-year period. Considering that a power plant to be established as a result of the results calculated above will operate for an average of 25 years, it should be taken into account that a system with 2-axis tracking will yield more than 30% compared to a fixed power plant for 25 years, and investment decisions can be made accordingly.

As a 4 *MW* solar power plant operator and user, it can be said that the investment costs of a 1 *MW* power plant are around 700,000 *USD* for 2020. This amount corresponds to the installation cost of a fixed land establishment. A power plant installed on average land can generate 1,600,000 *kWh* of energy annually. With an investment of 910,000 *USD* and an additional 30% of the investment cost, a 2-axis tracked power plant can be installed and an annual average energy production value of 2,154,211 *kWh* can be increased. Therefore, with an energy surplus of up to 31% every year for 25 years, great contributions will be made to both the budget and our national economy. At this stage, investments made with the establishment of a solar track facility will yield an extra return of approximately 19,188 *USD* per year, considering energy unit prices of today.

In this study, three different solar power plants were compared in detail in terms of performance under the same conditions. When the literature is examined, it is seen that there are many studies in the field of theoretical and estimation of energy production efficiencies in solar energy systems. However, it is seen that there are not enough studies on experimental and real established systems. The most distinctive feature of this study is that three different systems with a power of 765 *Wp* were examined under the same conditions. When the literature is examined, it is clearly seen that there are no three different panel systems installed at such high power and compared with each other. This increases the importance of this study. The electrical energy values obtained from all three panel systems are given in detail on a monthly basis. One of the most important features of this study is that the data was obtained from real installation systems.

Thus, this study will provide a foresight for the newly established solar power plants to predict how the economy and efficiency will be. This study will enable the selection of the most suitable solar power plant by comparing the investment costs of the installed solar energy systems and the electrical energy values produced. Considering that the popularity of solar energy systems is constantly increasing today, it is expected that this study will make very important contributions to studies on similar topics.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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