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Research Article

Performance Analysis of a PV Power Plant Installed on the Roof

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Abstract: Today, increasing energy costs and environmental concerns direct industrial facilities to sustainable energy sources. In this context, PV Power Plants (PVPP) installed on the roofs of factories offer an environmentally friendly and economical energy production solution. Rooftop solar power plants allow factories to utilize their existing rooftop areas, while meeting a significant portion of their electricity needs and providing significant savings on energy bills. It also contributes to environmental sustainability by reducing carbon emissions. However, there are some difficulties in system installation, such as the suitability of the roof structure, initial investment cost and bureaucratic processes. Considering all these factors, rooftop solar power plant applications have become a strategic investment for factories due to their long-term economic benefits, energy supply security and environmental gains. This study aims to investigate the energy saving performance and environmental impacts of a PVPP installed on the roof of a factory in Düzce, Türkiye. The results show that in the months when solar radiation is intense in Düzce, the electricity used from PVPPs is higher than the electricity used from the grid. However, an average of 46.02% of the energy needed in the factory for 8 months was provided by the PVPP installed on the roof. From an economic perspective, the payback period of the installed solar power plant system is calculated as approximately 3 years. From an environmental perspective, with the installation of the PVPP, CO_2 emissions have decreased by 1,100 tons compared to the past. This value means that the factory emits 76% less CO_2 compared to the factory before the installation of the PVPP. As a result, it is seen that the PVPP placed on the roof of the factory contributes significantly to economic and environmental aspects.

Keywords: *Factory, Energy, Solar power plant, Environment*

I. INTRODUCTION

Solar energy systems are considered one of the most important energy sources of the 21st century and have a critical role in meeting global energy needs (Panwar et al., 2011). Solar energy technologies are becoming increasingly important in line with the goals of reducing dependence on fossil fuels, combating climate change and building a sustainable energy future (Holechek et al., 2022). Today is considered a "turning point" for photovoltaic (PV) technology, and the widespread use of solar energy systems brings about a significant transformation in the energy sector (Shahsavari & Akbari, 2018).

The basis of solar energy systems are PV cells that convert sunlight directly into electrical energy (El Hammoumi et al., 2022). These cells are made from semiconductor materials and produce electric current when exposed to sunlight (Singh et al., 2021). Solar panels or modules are created by combining PV cells and these panels are designed for use in various application areas (Parida et al., 2011).

The development of solar energy systems has led to the emergence of different technologies and application areas (Parida et al., 2011). Crystalline silicon solar cells are one of the most widely used technologies in the solar industry (Ballif et al., 2022). There are two main types: monocrystalline and polycrystalline. Using crystalline silicon on glass offers the potential to increase efficiency while simplifying manufacturing processes (Razykov et al., 2011; Ayadi et al., 2022). These types of solar cells are commonly used in a variety of applications, including residential, commercial buildings, and solar power plants (PVPP). Thin-film solar cells have the potential to be used in areas such as portable devices, wearable technology and space applications, thanks to their ability to be produced using less material and to be applied to flexible surfaces (Parida et al., 2011). They can be produced using different materials such as amorphous silicon (a-Si), cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) (Kabir et al., 2018). The efficiency of thin film solar cells is generally in the range of 3-8% (Razykov et al., 2011).

Multi-junction solar cells are designed to achieve higher efficiency by absorbing light of different wavelengths more efficiently (Kabir et al., 2018; Kannan and Vakeesan, 2016). These types of solar cells are often used in areas requiring

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high performance, such as space applications and concentrated PV systems (Verduci et al., 2022). They can be manufactured using materials such as gallium arsenide (GaAs) and indium phosphide (InP) (Razykov et al., 2011).

Sensitized solar cells generate electricity using a dye or organic molecule that absorbs light (Parida et al., 2011; Kabir et al., 2018; Kannan & Vakeesan, 2016). This type of solar cell offers low-cost production potential and flexible design possibilities. Sensitized solar cells can be easily combined with electrochromic cells, thus offering potential for smart windows and other innovative applications (Parida et al., 2011).

Concentrated PV systems generate electricity by concentrating sunlight and focusing it on a smaller area using mirrors or lenses. These systems are used to achieve high efficiency, especially in sunny areas (Kolamroudi et al., 2022). Concentrated PV systems can be combined with thermoelectric generators (TEGs) to increase the overall efficiency of the system and improve its thermal stability (Parida et al., 2011; Singh, 2013).

Hybrid systems provide more reliable, efficient and sustainable solutions by combining different energy sources (Parida et al., 2011; Kannan & Vakeesan, 2016; Singh, 2013):

PV/T (photovoltaic-thermal) systems produce both electrical and thermal energy and can be integrated into buildings (Şirin et al., 2023). These systems are particularly suitable for applications such as hot water production, space heating and cooling (Parida et al., 2011; Singh, 2013; Mekhilef et al., 2011; Pfenninger et al., 2014).

Photovoltaic-wind-diesel hybrid systems are used to meet energy needs especially in off-grid regions (Shezan et al., 2016). These systems are supported by diesel generators and battery storage systems to balance the variability of solar and wind energy (Parida et al., 2011; Kannan & Vakeesan, 2016; Singh, 2013).

PV-hydro hybrid systems can create a continuous and reliable energy source by combining solar energy and hydroelectric energy (Parida et al., 2011; Singh, 2013). These systems offer potential for energy generation and storage, especially in regions where water resources are abundant (Singh, 2013).

PV-fuel cell production systems offer the opportunity to store and transport energy by producing hydrogen through electrolysis with solar energy (Parida et al., 2011; Kannan & Vakeesan, 2016; Singh, 2013). These systems are particularly suitable for long-term energy storage and portable energy needs (Parida et al., 2011).

The widespread use of solar energy systems and their effective use bring with them various challenges (Parida et al., 2011; Kannan & Vakeesan, 2016; Ang et al., 2022). Climatic conditions, air pollution, sunshine duration and geographical location are factors that directly affect system performance (Parida et al., 2011; Kannan & Vakeesan, 2016; Singh, 2013; Pfenninger et al., 2014; Ang et al., 2022). Factors such as cloudiness, temperature and humidity can reduce the electricity generating capacity of solar panels (Parida et al., 2011; Kannan & Vakeesan, 2016). The variability of solar and wind energy sources can complicate the design and sizing of hybrid systems (Parida et al., 2011; Kannan & Vakeesan, 2016; Ang et al., 2022). Battery storage systems or other energy storage solutions may be required to balance fluctuations in energy production (Parida et al., 2011; Singh, 2013). The initial investment cost of solar energy systems may be a barrier for some applications (Parida et al., 2011; Kannan & Vakeesan, 2016; Ang et al., 2022). However, costs are gradually decreasing thanks to technological advances and economies of scale (Parida et al., 2011; Kannan & Vakeesan, 2016; Oni et al., 2024). The integration of grid-connected PV systems may create some challenges in terms of grid stability and security. Grid operators must use advanced control and management systems to manage fluctuations in solar power generation and ensure grid reliability (Parida et al., 2011; Kannan & Vakeesan, 2016; Ang et al., 2022).

Future developments aim to make solar energy systems more efficient, economical, reliable and accessible (Kabir et al., 2018). Efforts are being made to increase the efficiency of solar cells through new materials and nanotechnology (Parida et al., 2011; Kannan & Vakeesan, 2016; Oni et al., 2024). New generation technologies such as perovskite solar cells and organic solar cells offer the potential for high efficiency and low cost (Bati et al., 2023). Advances in energy storage technologies will ensure that solar energy is available around the clock and contribute to grid stability (Parida et al., 2011; Kannan & Vakeesan, 2016; Singh, 2013). Different storage solutions such as battery storage systems, hydrogen production and thermal energy storage are being developed (Parida et al., 2011; Singh, 2013). The widespread use of smart grid technologies will facilitate the integration of solar energy systems into the grid and increase energy efficiency (Parida et al., 2011; Ellabban et al., 2014). Smart meters, demand response programs and advanced grid control systems will enable more effective management of solar energy production (Ellabban et al., 2014). The development of low-carbon energy carriers will enable solar energy to be transported over long distances and used in different sectors (Parida et al., 2011; Kannan & Vakeesan, 2016). Energy carriers such as hydrogen, ammonia and synthetic fuels offer potential solutions for the storage and transportation of solar energy (Parida et al., 2011).

Adopting solar energy systems offers far-reaching advantages that are not limited to energy production alone, but also include environmental benefits, economic opportunities and social development (Algarni et al., 2023). Solar energy has a much lower carbon footprint than fossil fuels and is a clean energy source when it comes to reducing greenhouse gas emissions and combating climate change (Olabi & Abdelkareem, 2022). In reducing dependency on fossil fuels and increasing energy security, solar energy reduces the need for energy imports and increases the security of energy supply, as it is a local resource. In creating new job opportunities and supporting local economies, the solar energy sector creates

employment in different areas such as production, installation, maintenance and research. In providing electrification and improving the quality of life in rural areas, solar energy can provide a cost-effective and reliable source of electricity for people living in off-grid areas. In contributing to a sustainable energy future, solar energy is a clean, safe and sustainable energy source for future generations (Parida et al., 2011; Kannan & Vakeesan, 2016; Ang et al., 2022).

In conclusion, solar energy systems are a rapidly developing technology that has the potential to revolutionize the energy sector. Past and present progress demonstrates future potential and proves that solar energy is an indispensable resource for a sustainable energy future.

The strategic importance of integrating solar energy systems onto factory rooftops represents a fundamental paradigm shift in operational sustainability and cost management, transcending a mere energy transition (Reddy et al., 2024). For industrial facilities, rooftops have evolved from idle spaces into active production centers that contribute directly to cash flow (Berto et al., 2018). In the current global context, where supply chains are being reshaped by regulations such as the European Green Deal and the Carbon Border Adjustment Mechanism (CBAM), these self-consumption systems do not only provide significant savings on electricity expenditures but also offer a competitive advantage in international markets by minimizing the corporate carbon footprint (Erdogdu, 2025; Fratean & Dobra, 2018). In this regard, the utilization of solar energy in manufacturing plants stands out as the most rational investment tool, enabling facilities to declare energy independence at the intersection of environmental responsibility and economic efficiency (Gholami, 2024).

The main objective of this study is to quantitatively analyze the economic gains and environmental impacts of integrating rooftop PV power plants (PVPPs) in high-energy-density production facilities. The inclusion of renewable energy sources in production processes is of strategic importance in line with the goals of optimizing energy costs and industrial decarbonization. Although there is a vast body of knowledge in the literature regarding general industrial applications, studies focusing on the specific production dynamics and energy consumption profiles of plants are limited. This research evaluates the performance of PVPPs by considering operational variables specific to the sector and aims to fill this literature gap by providing an empirical data set for practitioners and policymakers. The second section of the study discusses the solar energy potential of Turkey and Düzce. The third section discusses the results obtained from electricity production and consumption data, as well as environmental data. The conclusion section summarizes the findings and offers recommendations for policymakers to promote the widespread adoption of solar energy systems.

II. SOLAR ENERGY POTENTIAL OF TÜRKİYE AND DÜZCE

Türkiye has a surface area of 783,562 km^2. It has great strategic importance and influence in the region due to its location between the European and Asian continents. Türkiye's energy needs have been increasing since the 1980s with increasing living conditions, population (approximately 84 million) and growing economy. Two main factors appear at the forefront in Türkiye's energy policy. One of these is high fossil fuel dependency and the other is high-energy imports. Most of the oil and natural gas imported is due to insufficient domestic reserves. Türkiye, which has high-energy imports, is neighboring countries that have 75% of the world's fossil fuel reserves. Türkiye has a 1% share in world energy demand and is the country with the highest average energy demand growth among OECD (Organization for Economic Co-operation and Development) countries. Türkiye's energy needs are largely met by fossil fuels (Erat et al., 2021).

Renewable energy sources have the largest share in installed energy capacity with 57.28%. Natural gas follows with 23.7%. Hydropower has the largest share among renewable energy sources. According to the data for 2023, hydraulic energy has 28.82%, natural gas with 23.7%, coal with 20.3%, solar energy with 14.08%, wind energy with 10.64%, geothermal energy with 1.52% and other energy sources with 0.94% installed capacity (TEİAŞ, 2025).

Türkiye's energy policy is based on reducing fossil fuel dependency due to its commitment to reduce greenhouse gas emissions by 21% under the Paris Agreement due to climate change. In addition, due to the negative impact of oil and natural gas price movements on the economy and the risk of depletion of fossil fuels in the coming years, many studies are being carried out on renewable energy sources. The renewable energy source that can play the most important role in reducing the share of fossil fuels in energy production is solar energy. Due to its location, Türkiye is very efficient in terms of solar energy. Tükiye's solar energy potential atlas is given in Figure 1. Türkiye's annual sunshine duration is 2741 hours and an average of 7.5 hours per day. Sunshine durations of Türkiye by month are given in Figure 2. The highest sunshine duration in Türkiye is in June with 11.31 hours, while the lowest sunshine duration is in December with 3.75 hours. The annual total incoming solar energy is 1527 kWh/m^2 year and the daily average is 4.18 kWh/m^2 day. Türkiye's global radiation values by month are given in Figure 3. The highest solar radiation is in June with 6.57 kWh/m^{2}day, and the lowest solar radiation is in December with 1.59 kWh/m^{2}day.

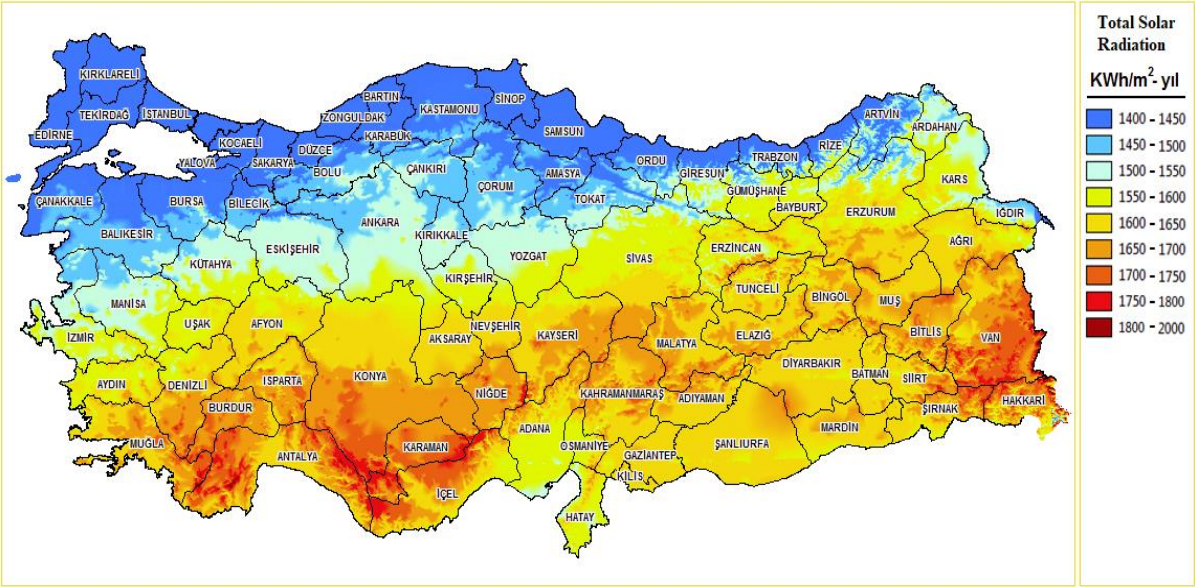


Figure 1. Türkiye's solar energy atlas.

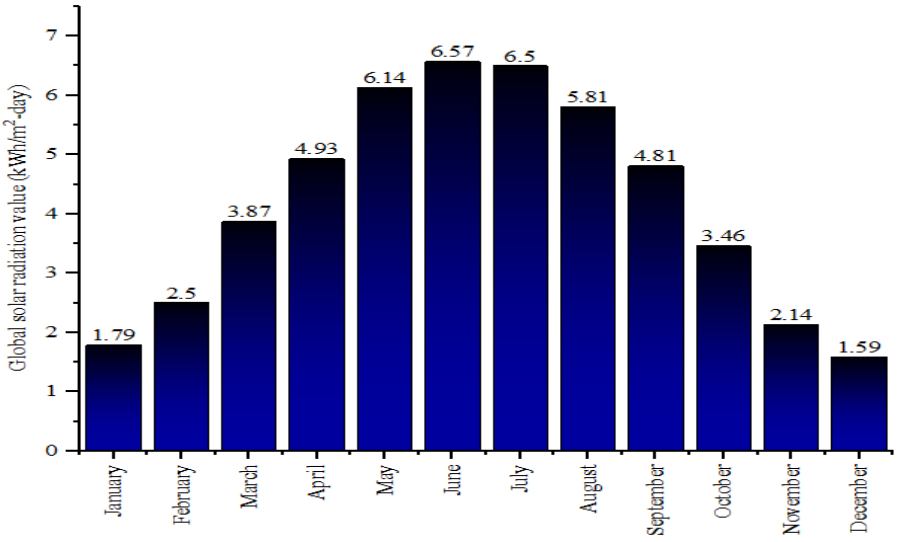


Figure 2. Solar radiation values of Türkiye by month.

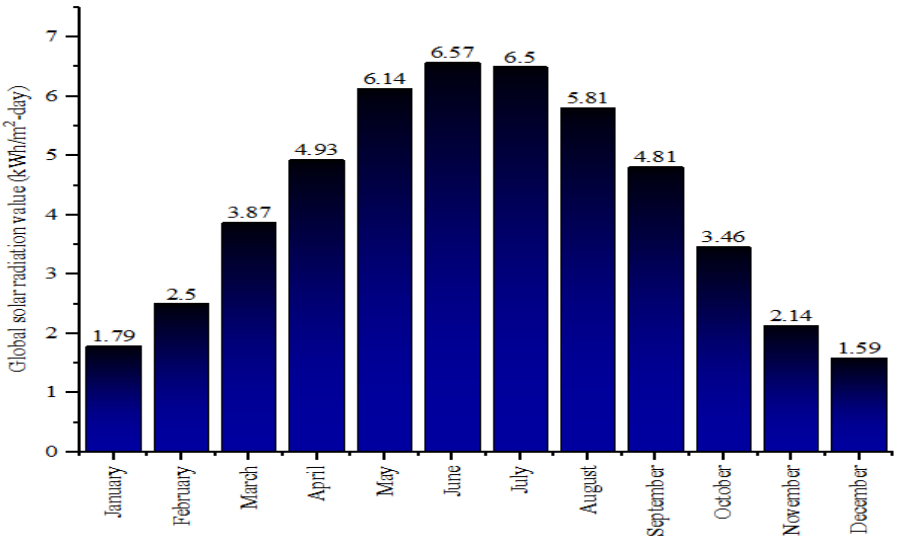


Figure 3. Sunshine durations in Türkiye by month.

Düzce province is located in the Western Black Sea Section of the Black Sea Region. The Western Black Sea Region covers the western part of the Black Sea Region, the east of the Marmara Region and part of the transition region to Central Anatolia, and is located roughly between 40°-42° north latitude and 30°-33° east longitude. Düzce province is located in the west and north of Bolu province, east of Sakarya province and southwest of Zonguldak province. It is bordered by the Black Sea to the north. Düzce's altitude is 146 m. Along Efteni Lake and Büyük Melen the altitude drops to 112 m. Due to its location in the Black Sea Region, Düzce's solar energy potential is below the Türkiye average. Figure 4 shows the solar radiation map of Düzce province, taken from the Solar Energy Potential Atlas data prepared by the Ministry of Energy. Monthly changes in radiation intensity for Düzce province are given in Figure 5 and in sunshine durations in Figure 6. When Figures 2 and 3 are evaluated together, it is seen that the average daily solar radiation amount of Düzce is 3.68 kWh/m^2-day and the average daily sunshine duration is 6.48 hours. In this case, although Düzce data is below the Türkiye average, it seems to have a higher potential than many European cities.

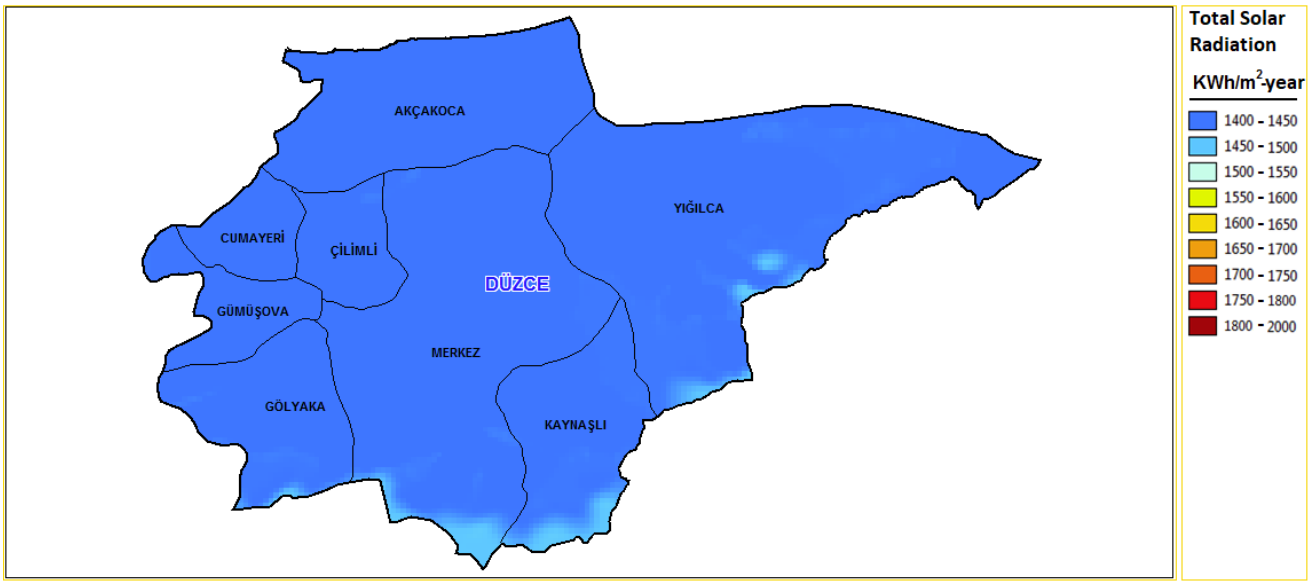


Figure 4. Solar energy atlas of Düzce.

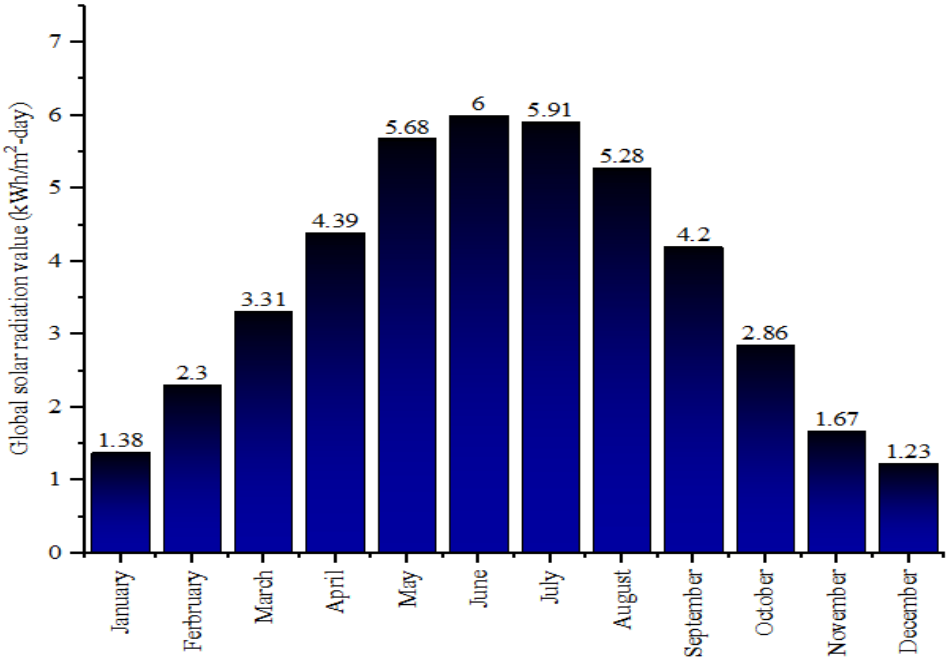


Figure 5. Solar radiation values of Düzce by month.

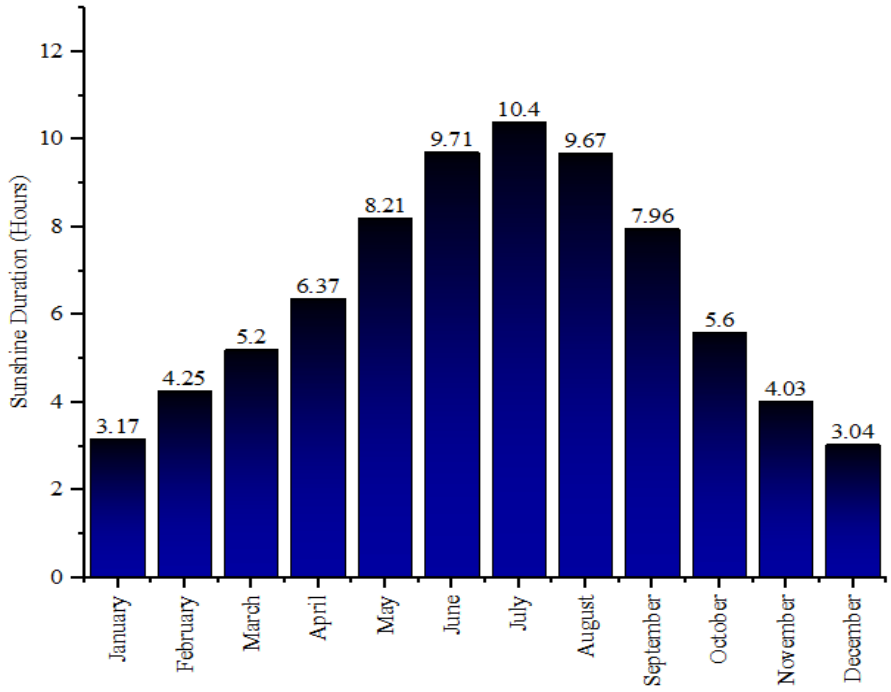


Figure 6. Sunshine durations of Düzce by month.

In the study, the general view of the Fibrobeton company campus, where solar energy panels were placed on its roof, is given in Figure 7. 2700 photovoltaic solar panels were placed on the roof of Fibrobeton's factory in Düzce. It was established as a PVPP with a total energy production capacity of 1560 MWh. The panels installed on the roof are positioned at a 10% angle.



Figure 7. General view of the facility with solar panels installed on its roof.

The payback period for a solar energy system is simply calculated by dividing the cost of the system by the annual savings it provides. The basic equation is as follows:

$$Payback\ Period\ (Year) = \frac{Total\ Investment\ Cost\ (₺)}{Annual\ Energy\ Savings\ (₺/year)} \quad (1)$$

The total investment cost in the equation is obtained by multiplying all expenses made for the installation of the solar power plant (panel, inverter, assembly, engineering, connection, permits, etc.), and the annual energy savings are obtained by multiplying the amount of electricity (kWh) produced by the solar power plant per year by the unit price of the electricity to be purchased (₺/kWh).

$$Annual\ Savings = Annual\ Production\ (kWh) \times Electricity\ Unit\ Price\ (₺/\text{kWh}) \quad (2)$$

Every 1 kWh of electricity produced by solar energy prevents a certain amount of carbon emissions by replacing electricity taken from the grid (mostly from fossil fuels). The average emission factor for grid electricity in Türkiye is approximately 0.43 kg CO_2/kWh (this value may vary by country and year) (Vlaović et al., 2023).

$$Annual\ CO_2\ reduction\ (kg) = E \times EF \quad , \quad (3)$$

III. RESULTS AND DISCUSSIONS

In this study, the energy consumption and environmental performance of the PVPP installed on the roof of a factory in Düzce province were examined. Performance evaluation was made from the data taken in the first 8 months (January-August) of 2023. Then, the results obtained from the graphs were interpreted.

The total energy consumption of the factory in January-August 2023 is given in Figure 8. As seen in the figure, the highest energy consumption was measured as 142,964.06 kWh in February, while the lowest energy consumption was measured as 106,074.33 kWh in April. The factory's 8-month energy consumption average was determined as 124,451.66 kWh. It is seen that the energy consumption of the factory in the winter months is higher than the energy consumption in the spring and summer periods.

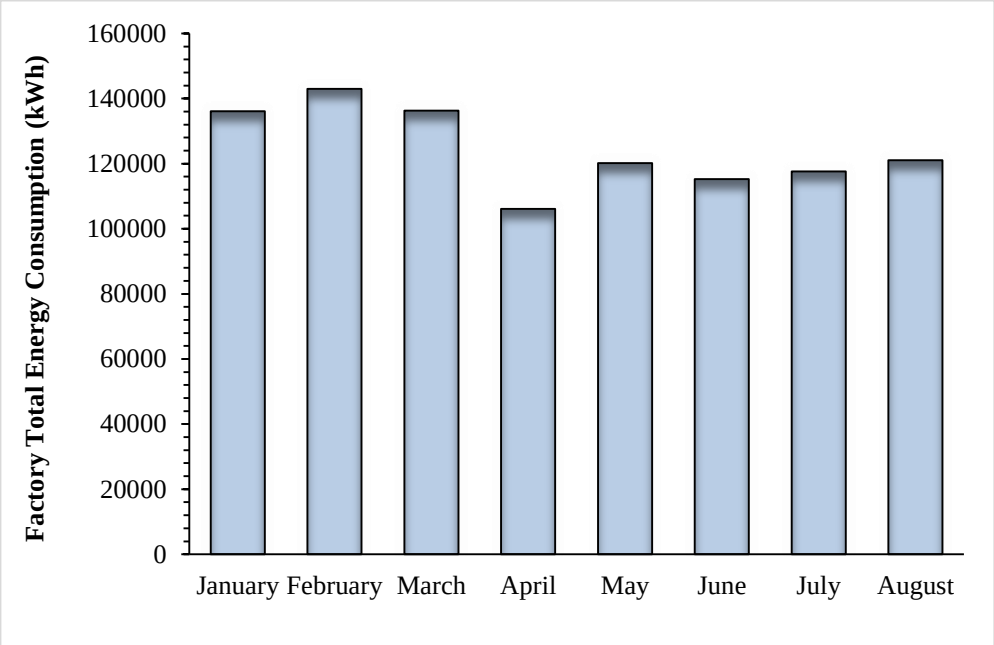


Figure 8. Total energy consumption of the factory by month.

It is planned to reduce the energy consumption values of the factory, as seen in Figure 8, by placing solar panels on the roof of the factory in order to benefit from renewable energy sources. The electricity production obtained from the PVPP installed on the roof of the factory is given in Figure 9. The lowest value in the factory's PVPP electricity production was 46,253.12 kWh in January, and the highest electricity production was 269,080.32 kWh in July. The factory's 8-month average PVPP electricity production was determined as 140,678.62 kWh. Considering these electricity production values, although PVPP electricity production does not meet the entire electricity consumption of the factory, it helps to reduce energy consumption to a great extent.

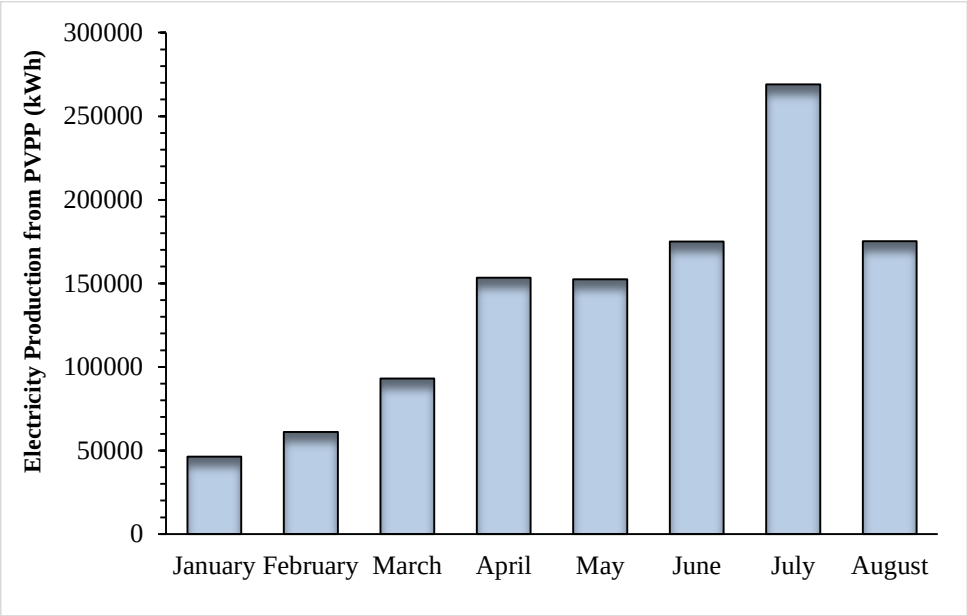


Figure 9. Electricity production from rooftop PVPPs by month.

The amount of electricity used from the PVPP in the factory by month is given in Figure 10. As seen in Figure 10, the lowest electricity use from the PVPP was 34,806.02 kWh in January, while the highest electricity use was 72,753.95 kWh. The average electricity used by the factory from PVPPs over the last 8 months was determined as 54,657.41 kWh. Here, it is seen that while some of the electricity produced from the solar power plant is used directly, some of it is given to the grid.

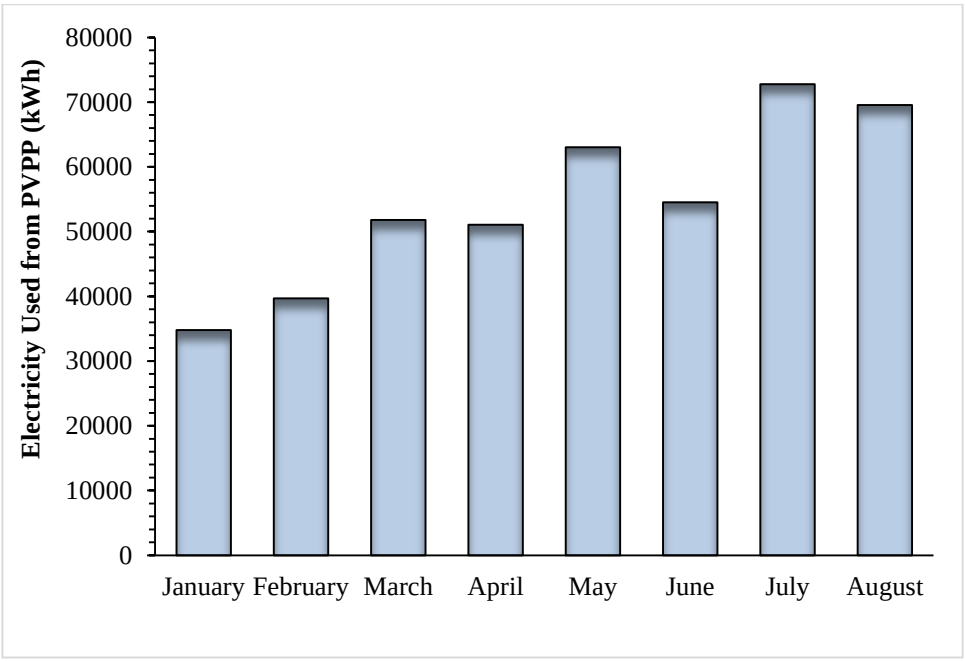


Figure 10. Electricity usage from the PVPP installed on the roof of the factory according to the months.

While some of the electricity obtained from the PVPP in the factory is used directly, some of it is given to the grid. The amount of electricity given to the grid from the PVPP is given in Figure 11. As seen in Figure 11, the lowest amount of electricity given to the grid from the PVPP was determined as 11,447.1 kWh in January, and the highest was determined as 190,126.05 kWh in July. The average electricity given to the grid from the PVPP for 8 months was 75,708.77 kWh.

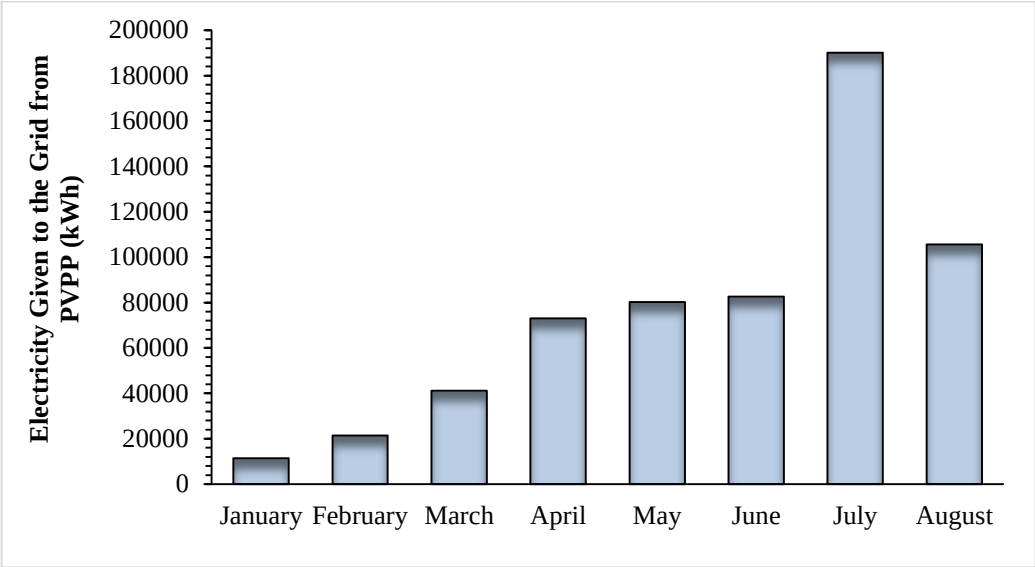


Figure 11. The amount of electricity given to the grid from the PVPP.

When the electricity produced from the PVPP in the factory did not meet the total consumption amount, electricity was consumed from the grid. The amount of electricity used from the grid when electricity production from the PVPP is insufficient is given in Figure 12. As seen in Figure 12, the lowest amount of electricity used from the grid was determined as 34,763.93 kWh in July, and the highest was determined as 103,274.03 kWh in February. The average amount of electricity used from the grid for 8 months was calculated as 65,473.02 kWh. Inversely proportional to Figure 9, more electricity was used from the grid in the months when solar power plant production was low, while less electricity was used from the grid in the months when solar power plant electricity production was high.

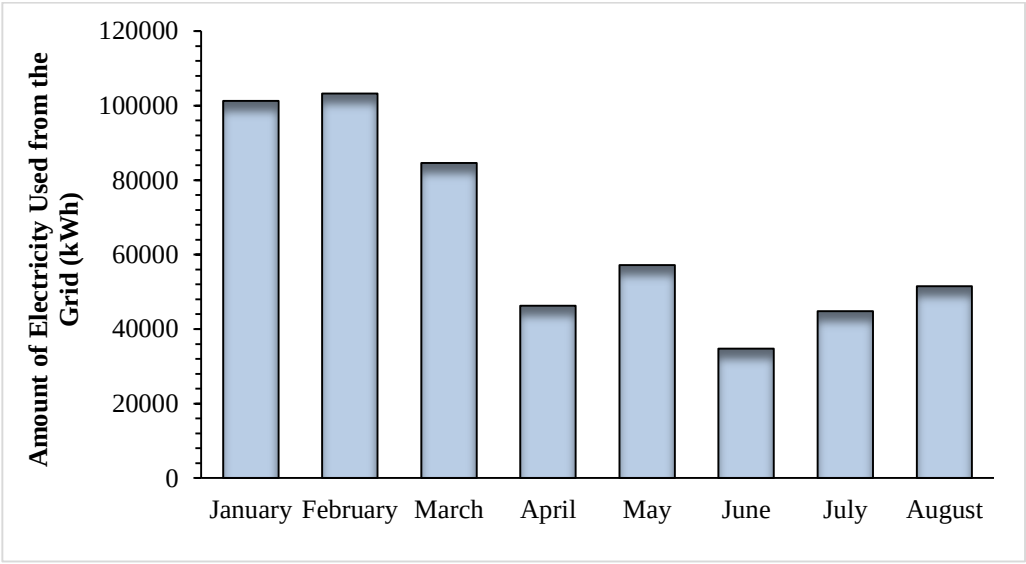


Figure 12. The amount of electricity used by the factory from the grid.

When the obtained data is evaluated, Although Düzce's solar potential is below the Turkish average (daily average of 3.68 kWh/m^2), this value is typical for industrial roofs in the Marmara and Black Sea transition zones. Simulations for university buildings across Turkiye show even higher values, such as 1336 kWh/kWp. Fibrobeton's efficiency demonstrates that the project was realistically designed despite the low radiation levels in the region. In the literature and industrial standards (IEC 61724), ideal PR values are generally expected to be in the 75%-85% range (Cabral et al., 2024; Reich et al., 2012). The 52% rate in Fibrobeton seems quite low compared to a standard solar power system. This situation may be due to the low panel slope of 10% mentioned in the text, the cloudy climate of Düzce, or possible shading/soiling factors on the roof. Self-consumption rates in the industrial sector are generally around 57-60% (Martínez-Calahorro et al., 2020; Pedrero et al., 2021). The lower rate of fiber-reinforced concrete (38.8%) suggests that the solar power capacity (1.1 MWp) was designed to be higher than the factory's instantaneous daytime load, or that the factory's shift system did not perfectly coincide with the peak hours of the sun (load shift).

IV. CONCLUSION

In this study, the performance and environmental benefits of the PVPP installed on the roof of a factory in Düzce province in meeting the electricity needs of the factory were evaluated. A comment was made on how the situation before and after the use of PVPPs in the factory changed. The critical information obtained as a result of the study is given below:

- Factories are generally high energy consuming facilities. Thanks to solar power systems, free energy is obtained from the sun. It provides significant financial savings in electricity bills due to the cheap electricity obtained. In terms of investment cost, the company can amortize the cost spent for the solar power plant in approximately 3 years.
- The percentage of electricity produced from PVPPs in the factory was over 50% between May and August. While the electricity used from PVPPs was 46.02% on average for 8 months, which obtained from the grid was determined as 53.99%.
- Since solar energy is a clean and renewable energy source, it significantly reduces fossil fuel usage. It contributes to environmental sustainability by reducing CO_2 emissions. The factory, which carries out environmentally friendly production, is strengthened in terms of both legal advantages and brand image. It is anticipated that the factory will reduce 1100 tons of CO_2 emissions annually, thanks to the PVPP used.
- Energy independence and security of the factory has been ensured with the use of PVPPs. The factory's dependence on the grid has decreased with the use of PVPPs. It has become a reliable backup energy source against power outages. The factory will be less affected by fluctuations in energy prices.
- The factory's monthly performance rate (PR) is 52%, while its specific efficiency is 1560 kWh/kWp.

PVPPs installed on factory roofs offer significant advantages in terms of reducing energy costs for industrial facilities and enabling environmentally friendly production. Thanks to the use of solar energy, fossil fuel dependency decreases, carbon emissions decrease and significant savings are made on energy bills. Additionally, the use of roofs saves space by eliminating the need for additional land. However, some difficulties may be encountered during the installation of these systems. In particular, the structural suitability, static bearing capacity and insulation status of roofs should be analyzed in detail in advance. Additionally, the initial investment cost can be high and bureaucratic permits during the installation process can take time. However, factors such as adverse weather conditions or shading may affect system efficiency. Despite all these factors, rooftop PVPPs are a very valuable energy solution for factories when long-term gains and sustainability goals are taken into account.

The widespread adoption of PVPPs is a multifaceted transformation process requiring not only increased capacity but also the modernization of all components of the energy system. The first and most critical step for policymakers is to integrate energy storage systems into production within a legal and financial framework to increase grid resilience. Instead of fixed purchase guarantees, hybrid tender models that incentivize storage and dynamic pricing mechanisms will enhance supply security by minimizing the risks stemming from the intermittent nature of solar energy.

Secondly, in addition to large-scale power plants, the focus should be on the "distributed energy" model. Removing bureaucratic hurdles for rooftop installations and establishing digital "one-stop" approval mechanisms will accelerate consumers' transition to becoming "producer consumers". At this point, increasing smart grid investments and making AI-powered production forecasting systems mandatory will enable the centralized synchronization of thousands of small-scale resources included in the system.

Finally, in order to prevent land-use conflicts, "sectoral integration" policies should be prioritized. Special incentive categories should be created for Agrivoltaics applications, which enable energy production while protecting agricultural land, and for Floating PVPP projects, which utilize water surfaces such as dam reservoirs. These approaches will both support the development of the local technology ecosystem (panel, inverter, and software production) and maintain a balance between environmental sustainability and energy independence.

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Author Contributions: For multi-author articles, the specific contributions of each author should be indicated using their initials, for example: Conceptualization, G.Y.; Methodology, G.Y.; Software, G.Y.; Investigation, G.Y.; Data Curation, M.M.; Writing—Original Draft, M.M.; Writing—Review & Editing, A.E.G.; Visualization, A.E.G.; Supervision, A.E.G.

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