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Modeling and Performance Analysis of a Rooftop Photovoltaic System for Batman: Impact of Seasonal Shading on Energy Efficiency

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ABSTRACT

The increasing depletion of conventional energy resources and the escalating environmental impacts necessitate a transition to renewable energy sources. Among these, solar energy emerges as a sustainable and viable alternative, with photovoltaic (PV) systems offering efficient energy conversion. This study focuses on the modeling and performance simulation of a rooftop PV system designed for the Batman Dicle Elektrik Dağıtım A.Ş. (DEDAŞ) building. The primary objectives are to mitigate energy costs and enhance environmental sustainability by harnessing solar energy. The PV system was designed and analyzed using PVsyst software, incorporating various shading scenarios to assess performance impacts. Simulation results indicate that shading significantly affects energy production, particularly during winter months, with losses reaching up to 28% in December. Conversely, in summer, shading effects are minimized, resulting in a 4% energy loss in June. The findings highlight the importance of accounting for local climatic and geographical factors in PV system design, demonstrating the potential for optimizing renewable energy utilization in similar projects.

1. Introduction

The rapid increase in energy demand and the depletion of fossil fuels have led to the search for new energy production solutions. The environmental impacts of fossil fuels contribute to global warming and climate change, leading to problems such as air and water pollution and habitat destruction. Renewable energy sources offer sustainable solutions as an alternative to these damages; solar energy in particular stands out with its low carbon emissions and continuous energy production capacity. Grid-connected photovoltaic (PV) systems are systems that convert sunlight into electricity and transfer this energy to the electricity grid. These systems have the advantages of being environmentally friendly, increasing energy security, offering low operation and maintenance costs, reducing energy costs and scalability. Turkey is a country with high solar energy potential, with an average annual solar radiation of 1527 kWh/m², making solar electricity generation sustainable. Batman province has this potential with an annual solar radiation of 1700-1800 kWh/m² and offers favorable conditions for solar energy projects. Grid-connected PV systems to be installed in Batman can increase local energy production and ensure energy security, while creating new job opportunities and reducing energy costs. This study aims to optimize this potential by addressing the modeling and simulation of a rooftop grid-connected PV system for Dicle Elektrik Dağıtım A.Ş. building. The data to be obtained will be evaluated in terms of energy generation capacity, economic evaluation and environmental impacts and will serve as a reference for similar projects. Solar energy technologies, especially photovoltaic (PV) systems, have received significant attention in the field of sustainable and environmentally friendly energy generation. This chapter provides a comprehensive review of the existing literature on the design, performance analysis and economic evaluation of rooftop grid-connected photovoltaic systems. The review will cover a wide range of topics from PV system component selection, system design, energy efficiency and performance analysis to economic evaluation methods. The studies in the literature include technical and economic aspects of PV systems, simulation techniques and application examples, and focus on current developments worldwide. For instance, Mohammed M.A et al. (2024) investigates the LVRT capabilities and control algorithms of three-phase grid-connected PV systems, while Mishra P.R et al. (2024) describes the role of PVSyst software in system performance evaluation. In other studies, topics such as energy flow and losses analysis, shade losses and seasonal optimization of rooftop systems are addressed with PVsyst. PVsyst software is widely used in the design of solar energy systems with its large database and user-friendly interface. Many studies in Turkey have used PVsyst to examine solar photovoltaic system designs and provide data to optimize system performance according to local conditions. Among the examples, studies carried out in Bursa compared the performance of systems installed with different PV technologies and analyzed their energy generation capacity and efficiency.

Mohammed M.A et al. (2024) focus on the modeling of three-phase grid-connected photovoltaic systems. The authors investigate the low-voltage operation (LVRT) capability and the control algorithms used in these systems. This suggests solutions aimed at improving the stability and efficiency of grid-connected systems. The paper by Mishra P.R et al. (2024) and Ciftci, S et. al. (2020) describes how PVSyst software is used for performance evaluation of grid-connected photovoltaic systems. The authors emphasize that PVSyst is a powerful tool for analyzing power generation losses and simulating system efficiency. Rawat R. et al. (2019) analyze the energy flow and losses of a grid-connected 30.5 kWp PV system using PVsyst simulation software. The authors focus on component selection and performance evaluation. Vidur P.R et al. (2022) discusses shading losses, layout and system design of rooftop solar systems. This study provides important information on system scaling and simulation methods. Dong H. et al. (2023) investigate how rooftop PV systems can be optimized by taking seasonal effects into account. The authors analyze the effects of energy storage strategies and seasonal generation fluctuations on system performance.

In the literature, there are many studies on the applications of PVsyst. Kumar et al. (2021) studied the office energy load requirements of the mechanical engineering department of an engineering college in Bikaner, India, and designed a standalone PV system to meet these requirements. In their study, they determined the average annual energy requirement of the system as 1086.24 kWh using PVsyst software and found that the amount of energy obtained through solar panels was 1143.6 kWh. The amount of energy provided to the user was recorded as 1068.12 kWh, and it was emphasized that the decreasing power capacity of the system occurred due to various losses. In a similar study, Baqir et al. (2022) conducted the design and performance analysis of a 700 kWp grid-connected PV system in Daykundi province of Afghanistan. Mohammadi and Gezegin (2022) investigated the design and simulation of a 5 MW solar power plant in Ghor province of Afghanistan. The main objective of the study is to evaluate the capacity of generating electrical energy from local resources to provide reliable and sustainable energy to an area in the center of Ghor province that is not connected to the national electricity grid. Sharma et al. (2018) investigated the solar photovoltaic system design of an academic institution using PVsyst software. The basis of the study is how the performance of photovoltaic systems is affected by factors such as geographical location, solar radiation, module type and orientation. Siregar et al. (2020) (2020) presented the design and simulation of a 600 m² solar PV system at the University of Sumatera Utara, Indonesia. This study revealed that the optimal design using Si-Mono 310 Wp panels produced 144.21 MWh of energy per year. The effects of partial shading on energy and exergy efficiency for photovoltaic panels were studied by Bayrak et al. Badea et al Maximizing solar photovoltaic energy efficiency: Extensive work has been done on investigating MPPT techniques based on shading effects.

Extensive studies have been conducted by Albatayneh on enhancing the energy efficiency of buildings by shading with PV panels in semi-arid climate zone.

In Cakmak (2022), PVsyst simulation program has enabled many studies on solar photovoltaic system design in Turkey. İzgi and Özcan (2020) presented the monthly and annual performance analysis of a 1 MW grid-connected photovoltaic power plant installed in Osmangazi district of Bursa using mono-crystal, poly-crystal and thin film technologies. In the first phase of the research, a detailed shading analysis was carried out to determine the suitability of the area for PV installation. This analysis was performed using Google Sketchup and PVsyst software. In the next stage, PVsyst and PV*SOL software were used to simulate the performance of three different photovoltaic technologies. For performance evaluation, parameters such as string efficiency, final efficiency, PV efficiency and performance ratio were considered. In another study by Demiryürek et al. (2020), the data of Lebit Enerji's solar power plant with an installed capacity of 200 kWp were transferred to the PVsyst V6.67-TRIAL program and simulation was performed. This simulation data was compared with the actual generation data. The simulation report analyzes the losses in the system; various factors such as thermal losses, cabling losses, shading losses and panel losses were evaluated. As a result of the analysis, a difference of approximately 0.56% was found between simulation data and actual generation values. This finding provides important contributions to feasibility studies for PV systems in the design phase, and can also guide revision studies to increase the efficiency of existing systems. In the study by Kılıç and Kurtaran (2023), a rooftop photovoltaic system with an installed capacity of 11.06 kWp was designed to meet the energy needs of an environmental consultancy firm with an area of 864.55 m² in Osmangazi district of Bursa. According to the performance analysis performed with PVsyst 7.3.4 simulation program, it was determined that the system can generate 14,602.63 kWh of electricity per year. The electrical energy transferred to the grid is observed as 13,714 kWh when system losses are taken into account. The performance rate was calculated as 81.69% and the loss rate as 18.31%. Factors such as high module temperature, insufficient sunshine duration and inefficiency of system components caused system losses. In July and August, a decrease in the efficiency of the panels was observed due to high temperatures. In the study by Etci and Bilhan (2021), the model of two different systems producing electricity from solar energy in Konya province was created and production data were compared. In Marhraoui (2019), while the annual energy production of the fixed-axis system was determined as 193.7 MWh/year, this value was calculated as 232.4 MWh/year in the dual-axis system. It was determined that the biaxial system produced 16.7% more energy than the fixed axis system. In Sancar and Altinkaynak (2021) and Eklas (2018), rooftop photovoltaic systems are considered for Isparta province and six different simulations are performed with different roof types and orientation angles. These studies provide important data for the design of solar photovoltaic systems in Turkey and provide guidance for optimizing system performance according to local conditions.

This literature review will strengthen the scientific background of the study on the modeling and simulation of rooftop PV system for DEDAŞ building by highlighting the critical factors in the design of solar energy systems and the necessary strategies to optimize the system performance.

The motivation for this study stems from problems such as global warming and climate change caused by increasing energy demand, depletion of fossil fuel reserves and environmental impacts of traditional energy sources. In the search for sustainable energy solutions, solar energy, which has low carbon emissions and is widely available, stands out. In this context, modeling and simulation of a rooftop PV system was performed for the DEDAŞ building in a region with high solar radiation potential such as Batman. The study aims to reduce energy production costs and increase environmental sustainability. The proposed method aims to address the performance losses encountered by PV systems due to shading effects. It has been determined that losses of up to 28% in energy production occur especially in winter months due to low sun angle and long shadows. In summer months, the shading effect decreases and losses drop to 4%. This problem shows the lack of system designs that take into account local climatic and geographical conditions and that shading analyses are not sufficiently integrated into the design processes. Existing diagnostic methods generally address PV system designs in general terms and do not consider local conditions in detail. Shading effects, seasonal differences or the effects of local sun angles on energy production are not sufficiently examined. As a result, design processes and simulation results cannot provide optimum performance in real life. The proposed method of this study offers several advantages over existing approaches. These are; the system design was carried out considering the specific solar radiation profile and shading conditions of Batman. In addition, shading effects were analyzed in detail under different seasons and scenarios using PVsyst software. The study provides a directly applicable reference for similar projects by taking a real application such as the DEDAŞ building as a basis.

2. Photovoltaic Systems

Photovoltaic systems consist of interconnected components designed to fulfill specific purposes. These purposes can range from meeting the power needs of a small device to supplying electricity to the main distribution grid. Photovoltaic systems are classified according to the diagram shown in Figure 1. The two main categories in this classification are stand-alone and grid-connected systems (Messenger, 2018). In stand-alone systems, solar power generation is directly matched to load demand (Akcan E.,et. al, 2020).

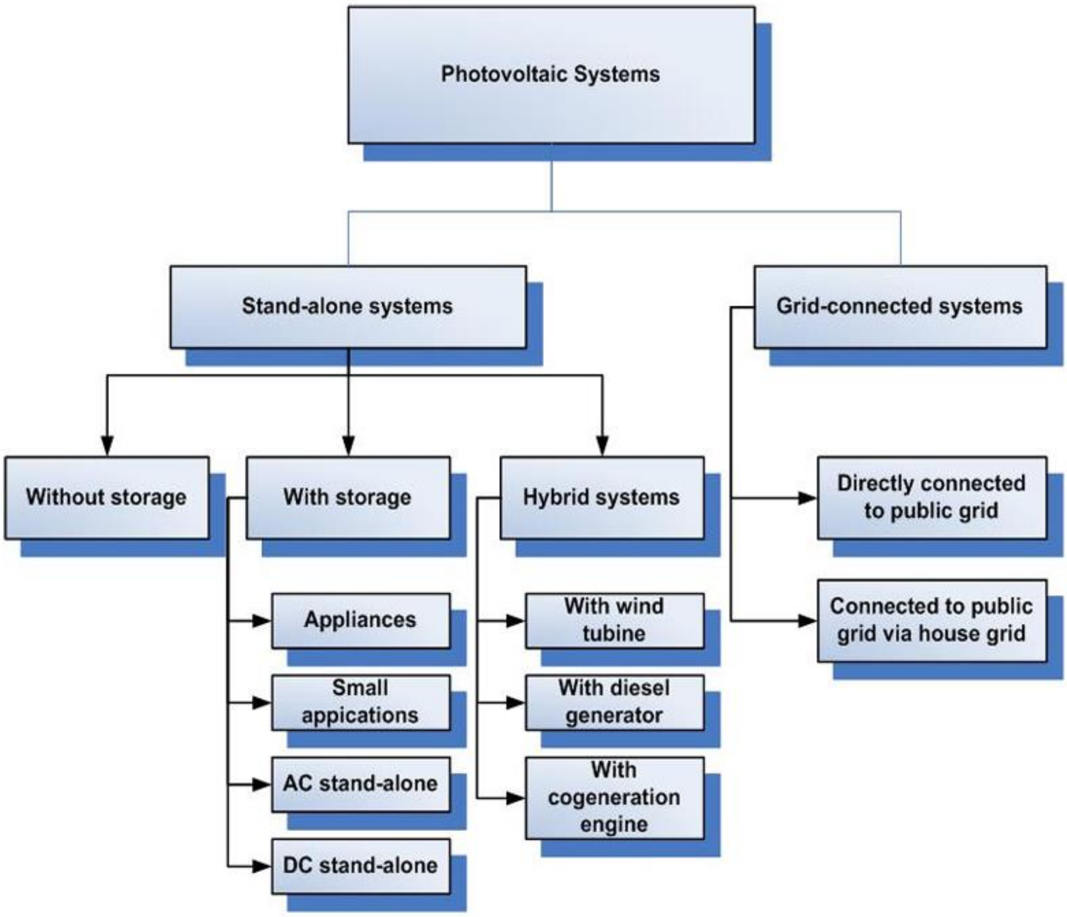
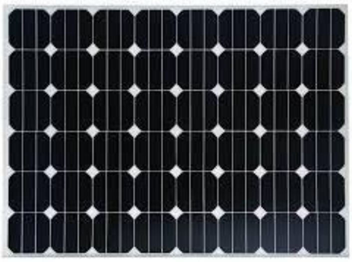
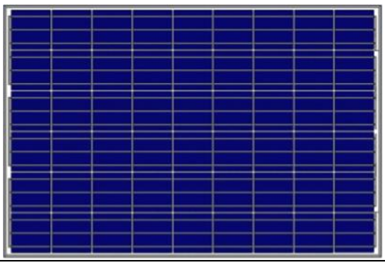
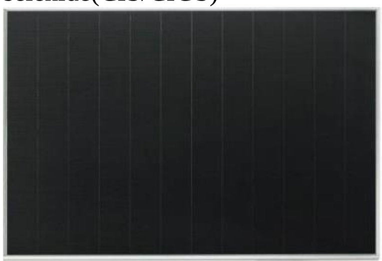


Figure 1. Classification of PV systems (Dzimano, 2008)

2.1 Advancements in Photovoltaic Cell Materials: Crystalline, Thin-Film, and Emerging Alternatives

PV cells are composed of semiconductor materials made of two basic types of materials: crystalline and thin film. Most PV cells are silicon-based, but in the near future other thin-film materials are likely to overtake silicon PV cells in terms of cost and performance (Archer, 2014). PV materials generally belong to one or more of the following classes: crystalline, thin-film, amorphous, multijunction, organic or photo-chemical.

Table 1. Strengths and shortcomings of different photovoltaic technologies (Makarova, 2017)

PV Technology	Strengths	Weaknesses
Monocrystalline Silicon (mono-Si): 36 % of market share 	efficiency: 15-20 % (21.5 % as current maximum) - durability up to 25 years - space-efficient	- the highest price - sensitivity to ambient temperature (performance decrease significantly with an increase of ambient temperature) - sensitivity to shading issues, snow and dirt - wasteful manufacturing process
Polycrystalline Silicon (p-Si veya m-Si): 55 % of market share 	-simple, cost-efficient and not wasteful manufacturing process -insignificant intolerance to high ambient temperature	- impurities and efficiency of 13-16 % - not space efficient - energy extensive manufacturing process
Thin-film (TFSC): - Amorphous silicon (a-Si) - Cadmium telluride (CdTe) - Copper indium gallium selenide(CIS/CIGS) 	- cost-efficient and simple manufacturing process - flexible configurations applicable different installations - high tolerance to shading issues and variation of ambient temperature	- low efficiency: 9-12 % - low space efficiency - high degradation rate

Mono-crystalline silicon cells used to occupy a dominant position in the photovoltaic market in the past, but have nowadays been overtaken by polycrystalline silicon. Mono-crystalline silicon was popular due to its high stability and desirable physical, chemical and electronic properties; moreover, its success in microelectronics has had a positive impact on the PV industry. However, polycrystalline silicon has become the most widely used material due to its lower cost. Since the cost of silicon accounts for a large part of the total cost of the solar cell, the production processes of polycrystalline silicon reduce the cost and enable the formation of large crystalline structures. As a result, this leads to the production of cheaper cells with lower efficiency, while the ease of assembly offsets the disadvantage of low efficiency.

2.2 Features, Limitations, and Applications in PV System Design and Simulation

PVsyst is a software package designed for the study, sizing and data analysis of solar photovoltaic systems. It covers grid-connected, stand-alone, pump systems and DC grid PV systems and includes a large database of meteorological data and PV system components. PVsyst is recognized worldwide as a standard software for PV systems design and simulation. The software simulates with inputs such as PV arrays, inverter models and battery packs and produces results with various parameters, which can

be reported monthly, daily or hourly. Actual component prices and additional costs can be used for economic evaluation (Cakmak F. 2024).
However, PVsyst has some limitations: the screen cannot be made full size, it cannot perform detailed shadow analysis and it does not provide a single line diagram. PVsyst version 6.8 (Figure 2) is preferred for system design and analysis and provides simulation result reports for off-grid or grid-connected energy systems. Thanks to the 3D application of the software, shading effects on the system can also be modeled. PVsyst offers a large database of brands and manufacturers and users can manually enter technical data for missing elements. Furthermore, meteorological data can be synthetically generated with the Meteonorm 7.2 tool (PVsyst, 2024).

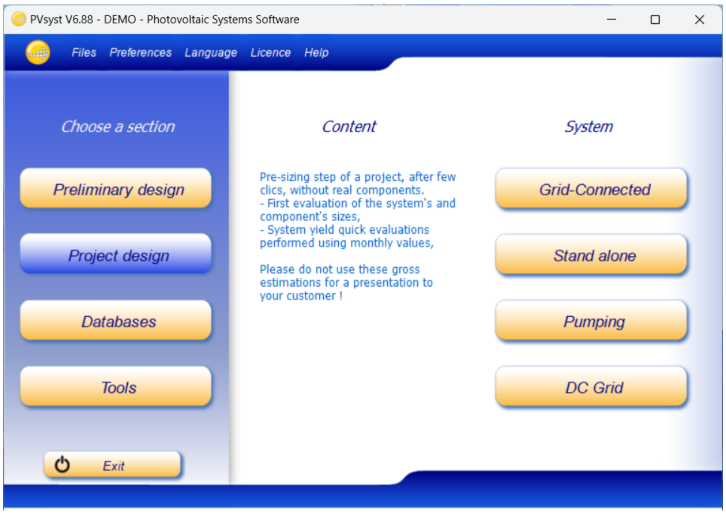


Figure 2. PVsyst screen capture

3. Project Design of Photovoltaic System with PVsyst

Before starting the PVsyst simulation, some preliminary definitions should be made to the software. In the start screen of the PVsyst software shown in Figure 2, the "Grid-connected" option should be selected since a grid-connected system will be built for the DEDAŞ building SPP plant in Batman province. After this selection, the main screen shown in Figure 3 opens. On this screen, there are sections where general information about the project is defined (PVsyst, 2024). The first step is to define the project name. Then, the meteorological data of the region is provided by entering the coordinates from the "Weather database" tab on the interface. The technical and economic information required for the energy system such as the brand, model, number, orientation, user needs, losses that may occur in the system, 3D shading analysis and economic analysis of the panel and battery are defined in the "Main parameters" tab on the interface. When all options turn green, the simulation is started by clicking on the "Run simulation" option. In the next step, the meteorological data of the region where the photovoltaic energy systems will be installed must be generated through the resources available in the system database. PVsyst simulation software can generate meteorological data through various databases. These databases include Meteonorm 7.2, NASA-SSE, PVGIS TMY and NREL/NSRBD TMY (PVsyst, 2024). In this study, the area where DEDAŞ SPP will be installed was selected on the map and Meteonorm 7.2 data of the region in question were taken. These data are shown in Table 1. The total annual global irradiation in the region where the SPP plant will be built is 1548.2 kWh/m2 and the highest temperature is 31.9 °C on average in July. In the table containing meteorological data created by the software, extra data can be added and removed as needed. These data also include horizontal diffuse irradiation, wind speed, turbidity and humidity.

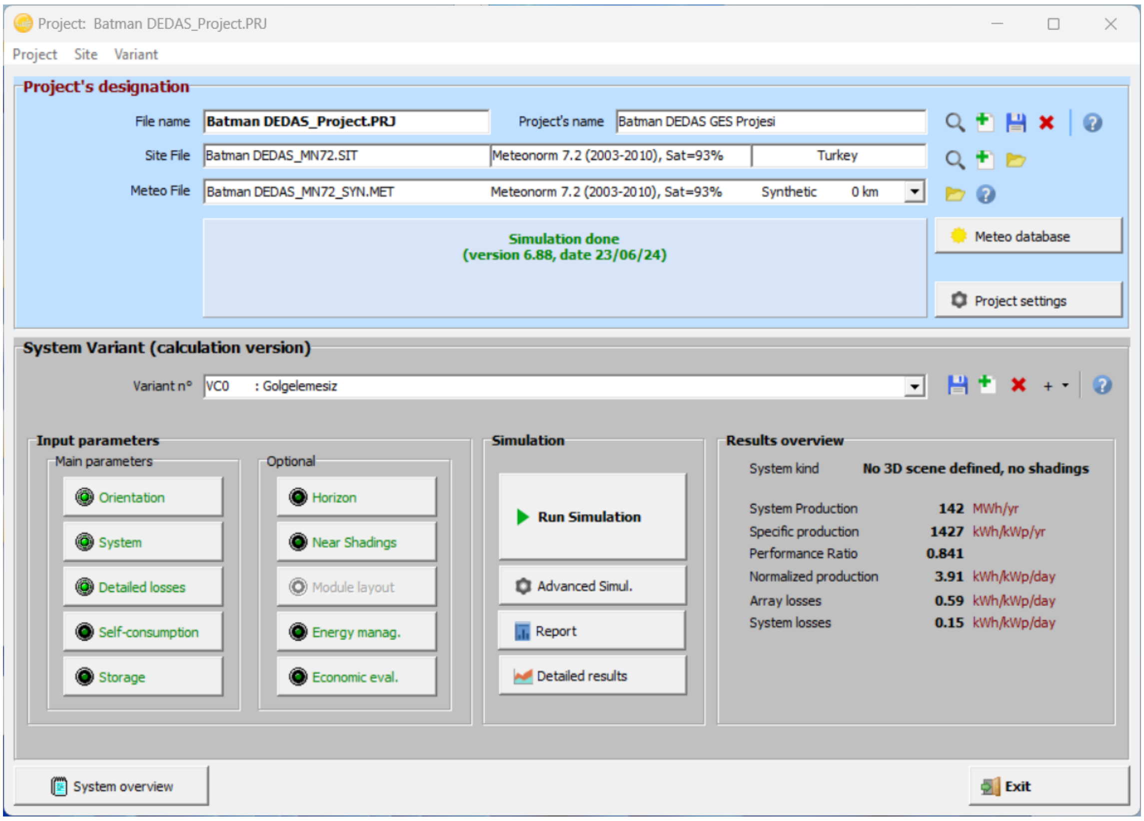


Figure 3. Creating the Project with PVsyst

Table 1. Meteonorm 7.2 Data for Batman DEDAŞ region

	Global Horizontal Irradiation	Horizontal Diffuse Irradiation	Temperature
	kWh/m^2.month	kWh/m^2.month	°C
January	55,5	32,2	2,4
February	70,5	38,0	4,8
March	112,8	58,0	10,1
April	141,0	66,2	14,2
May	181,7	79,1	20,1
June	204,7	69,3	27,2
July	208,0	76,5	31,9
August	193,6	75,4	31,1
September	153,6	53,4	25,1
October	103,5	47,2	19,0
November	70,0	32,0	10,0
December	53,3	30,0	4,7
YEAR	**1548,2**	**657,3**	**16,7**

Diagrams showing the output power distribution of the plant without shading and under shading conditions are presented in Figure 4. In these diagrams, it is possible to examine the power provided by the system to the grid in the range of 0 kW to 100 kW. The obtained results reflect the determining effect of the inverter performance in this power range. Since the same inverter is used in both scenarios, the differences between the shaded and unshaded cases are minimal and do not have a significant impact on the output power of the system. This similarity demonstrates how effective the inverter's power transfer capacity is in compensating for the possible variations of the shadowing effect and points to the stability of the power distribution. Graphs showing the annual loss diagrams of the plant without and with shading are presented in Figure 4 and Figure 5. In both scenarios, it is assumed that an equal amount of global radiation, i.e. 1548 kWh/m², is reflected to the collector and the percentage loss of radiation is shown in detail.

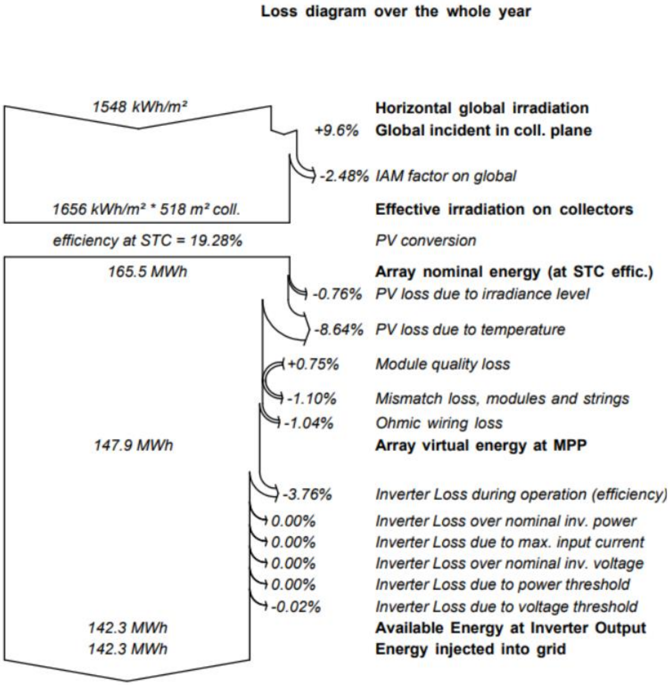


Figure 4. Simulation Loss Diagram without Shading

While the losses due to temperature were calculated as 8.64% in the unshaded condition, these losses reached a similar value of 8.45% in the shaded condition. Similarly, losses due to the inverter were 3.76% in the unshaded condition and 3.88% in the shaded condition. Losses due to module quality and ohmic wiring remained constant in both scenarios.

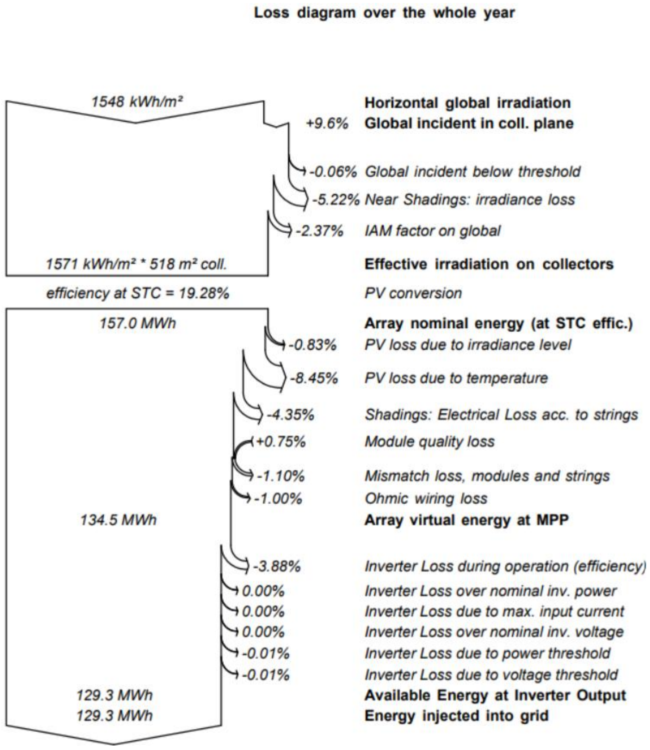


Figure 5. Simulation Loss Diagram with Shading

The main variation is observed in the losses due to shading. In the simulation without shading, shading losses were 0%, while in the simulation with shading, losses due to near shading effects were 5.22% and losses due to shading of other panels in the same array were 4.36%. These findings highlight the significant impact of shading on system efficiency and the importance of optimizing shading management.

Diagrams showing the daily energy production of the facility under both unshaded and shaded conditions are presented in Figure 6. In this graph, instances where energy production values display a linear distribution can be interpreted as high system performance. In the second diagram, which examines the shading effect, the irregular and scattered placement of data points indicates losses in energy production and demonstrates the negative impact of shading on PV system performance. This irregularity causes disruptions in the continuity and stability of the energy production process under shaded conditions, leading to notable decreases in system efficiency.

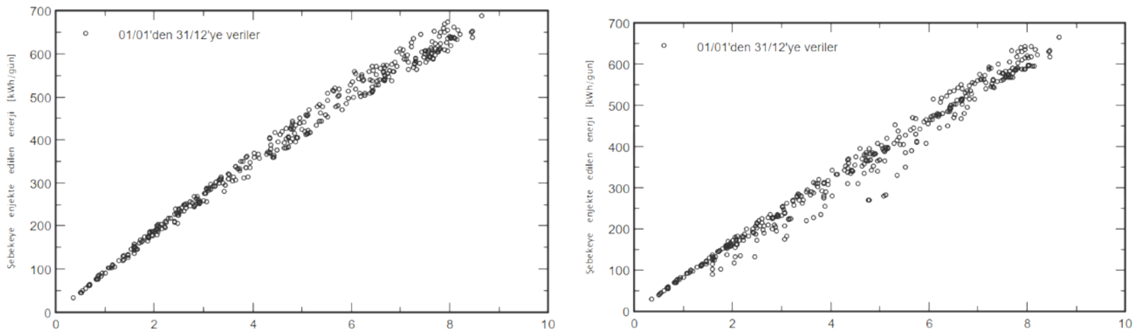


Figure 6. Daily Energy Production Diagrams for Simulations Under Unshaded and Shaded Conditions kWh/m^2

In the facility simulation report, an analysis of the monthly production graphs for unshaded and shaded conditions, as shown in Figure 7, reveals significant differences, especially during October, November, December, January, February, and March, when solar angles are lower and shading effects increase. Although there is not a large difference in the normalized production values of the system during these months, it was found that the energy loss, when considering shading, is proportionally quite significant.

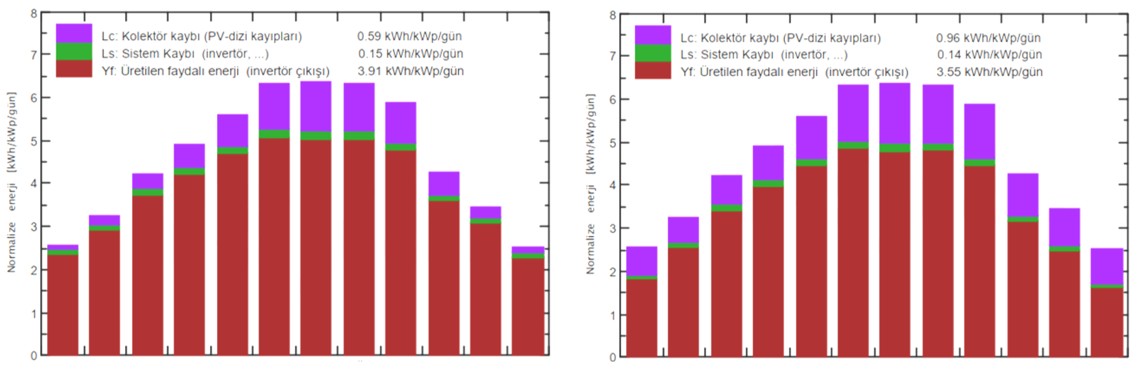


Figure 7. Production Graphs for Simulations Under Unshaded and Shaded Conditions (12 Months)

During periods when solar rays arrive at more horizontal angles, shading reduces the effective surface area of the panels, inhibiting radiation absorption and restricting energy production. This study uniquely emphasizes the quantification of shading impacts under varying solar altitude angles, particularly during winter months, where long shadows intensify energy losses. Unlike prior research, which often generalizes shading effects without considering seasonal and angular variations, our findings underscore the disproportionate impact of low solar angles on monthly production losses. These results provide a novel perspective, revealing the critical importance of incorporating detailed shading analyses into PV system performance evaluations, especially under suboptimal solar conditions.

4. Conclusion

This paper presents a detailed analysis of the photovoltaic (PV) system planned to be installed on the roof of Batman DEDAŞ building using PVsyst 7.2 simulation software. The study aimed to evaluate the effects of shading factor on the performance of the PV system, energy production capacity and economic returns. According to the simulation results, the annual energy generation capacity of the PV system in the absence of shading was determined as 142.3 MWh and the performance ratio of the system was calculated as 84.06%. The positioning of the panels with a tilt angle of 32° and an azimuth angle of 22° provides optimum solar radiation, resulting in a high energy generation potential. In the simulations performed under the shading effect, the annual energy production was calculated as 129.3 MWh and the performance ratio decreased to 76.33%. In particular, the shading caused by the buildings on the south of the building and the series connection of the panels caused a 5.22% energy loss in energy production and 4.36% energy loss in series connected panels. Analysis of the monthly energy production graphs shows that the loss of energy production due to shading is significant between October and February. In particular, the shadowing that occurs in December when the sun's rays are at the most horizontal angle caused a 28% loss in energy production. On the other hand, in June, when the sun's rays come at steeper angles and the shadowing effect is minimal, the loss rate in energy production is relatively low at 4%.

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