Simulation and Performance Analysis of PV-Based Electricity Generation in Bursa

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Abstract: The continuous growth of the human population, advancements in technology, and the expansion of various sectors such as industry enterprises have resulted in a consistent increase in global energy demand. The finite nature of fossil fuel reserves, combined with the adverse effects of global warming and climate change, has prompted a global shift toward sustainable and environmentally friendly energy sources. The region in question possesses considerable potential in terms of renewable energy resources. Turkey, in particular, benefits from a high level of solar energy potential and generates electricity from solar radiation through photovoltaic (PV) systems. In this study, two different scenarios were simulated using PVsyst software. PV panels were installed on the rooftop of a building located on a university campus in Bursa, both in a horizontal configuration and at the optimum tilt angle of 34°, which is determined based on the geographic and climatic characteristics of Bursa province. Simulation results obtained from PVsyst indicated that PV panels installed at the optimum tilt angle generated 370,237 kWh/year, yielded higher energy efficiency and achieved a payback period of 4.501 years.

Keywords: *Renewable Energy, Solar Energy, Photovoltaic Panels, Optimum Tilt Angle.*

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I. INTRODUCTION

Energy is considered a fundamental indicator of development and progress across civilizations. Developed countries generally demonstrate significantly higher levels of energy production and consumption compared to less developed nations. Historically, humanity has relied on fossil fuels to meet its energy needs. However, the finite nature of fossil fuel reserves and their profound negative impacts on global warming and climate change have necessitated a transition toward sustainable and environmentally friendly energy sources. Renewable energy systems have garnered increasing attention in recent years. Turkey, in particular, possesses substantial potential for the development and utilization of renewable energy resources.

Located between 36°–42° north latitudes and 26°–45° east longitudes, Turkey lies within the solar belt, allowing it to receive substantial amounts of solar radiation annually. According to the Solar Energy Potential Atlas of Turkey [1], the average annual total sunshine duration is 2741 hours, and the average annual total solar irradiation is estimated at 1527.46 kWh/m². This considerable solar energy potential, spread across a vast geographical area, provides favorable conditions for the development of renewable energy resources. The southern regions of Turkey, characterized by higher solar radiation levels and longer sunshine durations, are particularly suitable for solar energy investments.

Figure 1 presents the solar energy potential atlas of Turkey, where provinces are color-coded according to their solar radiation levels.

Figure 2 presents the monthly global solar radiation values in Turkey. The data reveal a clear seasonal variation, with the highest radiation recorded in June and the lowest in December. This trend reflects the country’s geographic location and its exposure to the solar belt, indicating a substantial potential for solar energy utilization throughout the year, particularly during the summer months when solar radiance reaches its peak. Figure 3 illustrates the monthly average sunshine durations across Turkey, with the longest sunshine duration observed in July and the shortest in December.

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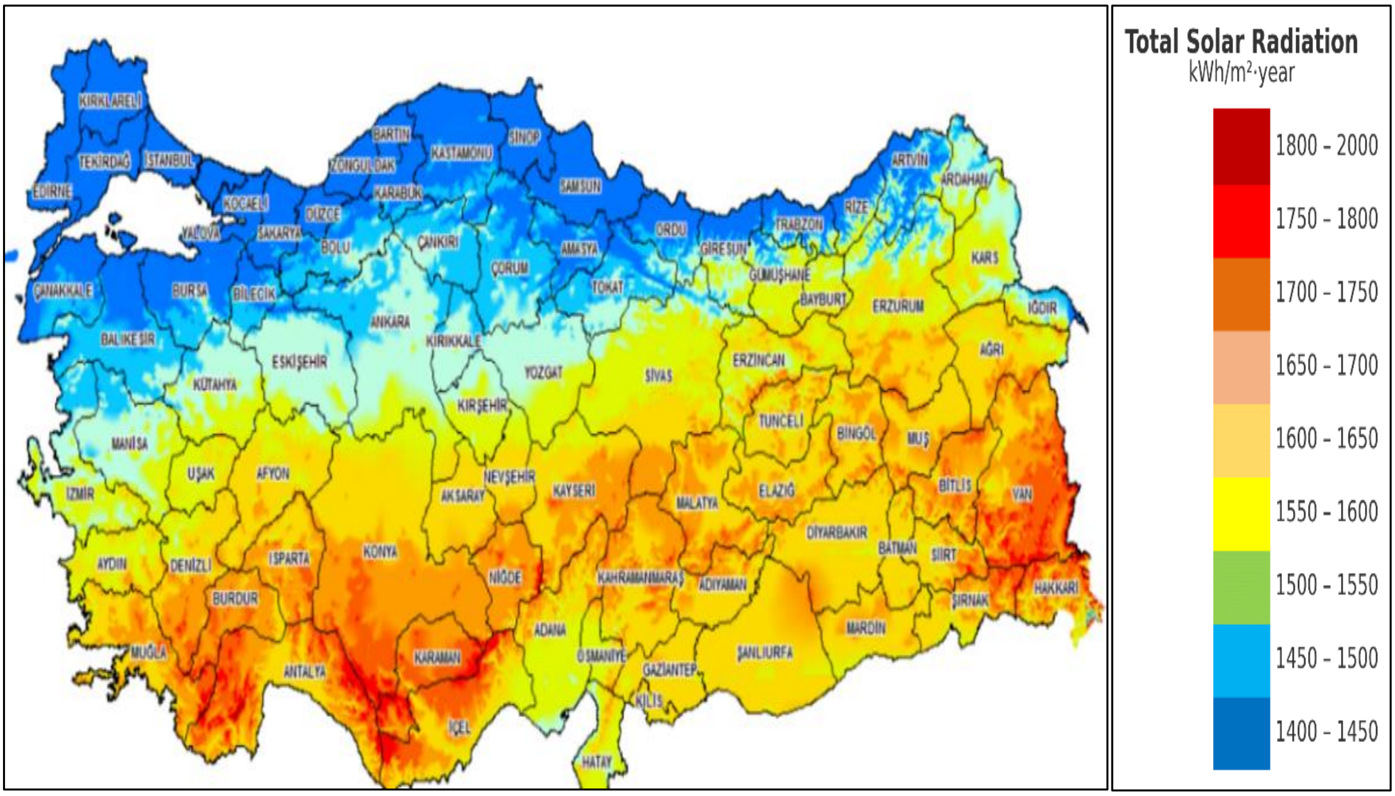

Fig 1 Solar Energy Potential Atlas of Turkey [1]

Figure 2 presents the monthly global solar radiation values in Turkey. The data reveal a clear seasonal variation, with the highest radiation recorded in June and the lowest in December. This trend reflects the country's geographic location and its exposure to the solar belt, indicating a substantial potential for solar energy utilization throughout the year, particularly during the summer months when solar irradiance reaches its peak. Figure 3 illustrates the monthly average sunshine durations across Turkey, with the longest sunshine duration observed in July and the shortest in December.

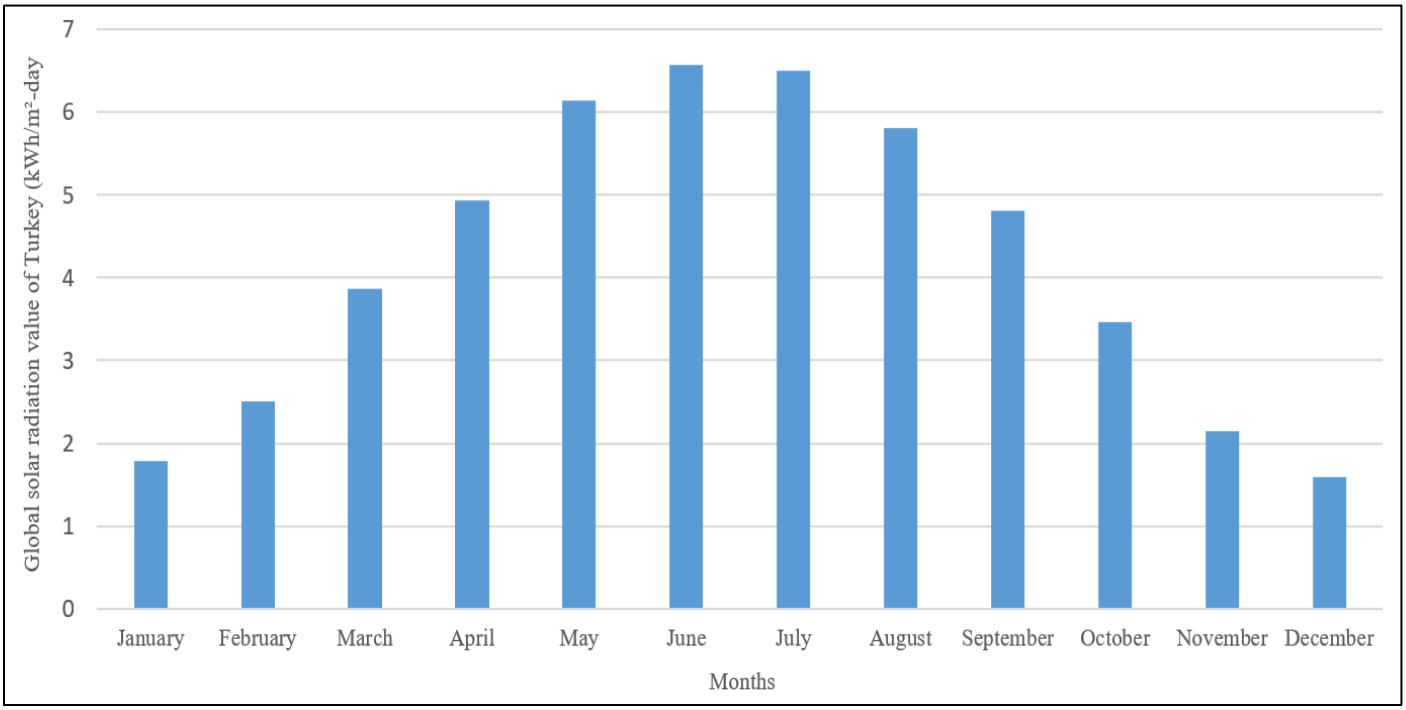

Fig 2 Turkey's Monthly Global Solar Radiation Values [1]

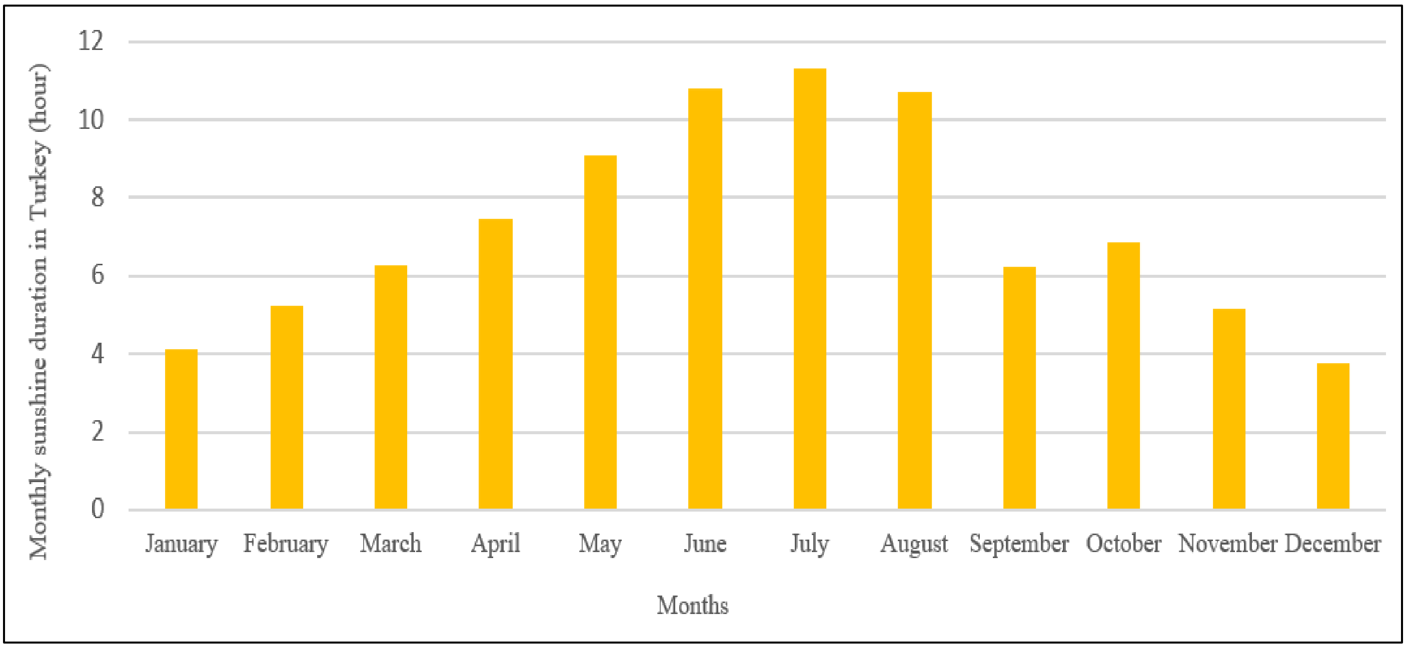

Fig 3 Monthly Sunshine Duration in Turkey [1]

The global transition to sustainable energy sources has accelerated the adoption of PV systems. Bursa, with its combination of industrial and urban areas, offers a favorable geographical context for the development of solar energy. While numerous studies have focused on the technical feasibility of PV systems, comprehensive analyses of different panel configurations under local climatic conditions remain limited. This study aims to address this gap by performing a detailed simulation and performance analysis of PV-based electricity generation in Bursa. Specifically, the performance of PV systems installed on the rooftop of the Ali Durmaz Mechanical Engineering building was evaluated and compared for different configurations, including horizontal (0°) and optimum tilt angles. Analysis of energy production under both horizontal and optimum tilt conditions demonstrates the potential efficiency gains achievable through proper system orientation. The findings provide valuable insights for investors and engineers regarding the feasibility and benefits of implementing PV systems in urban areas, thus facilitating informed decision-making in renewable energy investments.

II. LITERATURE SURVEY

Growing interest in solar energy, as one of the leading renewable energy sources, has led to a substantial increase in research on PV systems. Nevertheless, the high installation costs of these systems continue to stimulate studies aimed at their optimization. In this study, simulations and calculations were carried out using PVsyst software; accordingly, this section presents a comprehensive literature review of the software's capabilities and its applications in PV system analysis.

Bouzguenda et al.[2] focused on the design of a 2 kW off-grid PV system at King Faisal University, aiming to highlight Saudi Arabia's need for clean and renewable energy sources. The system's design, simulation, and both technical and economic analyses were conducted using PVsyst software.

Demiryürek [3] employed PVsyst software to simulate the 200 kWp Lebit Enerji solar power plant (SPP) in Siirt..By comparing the simulation results with the plant's actual power generation data, the analysis revealed an approximate deviation of 0.56% between the simulated and actual values.

Irwan et al. [4] evaluated an off-grid PV system using PVsyst software. The simulation of the off-grid PV system configuration was performed with this software, and annual energy consumption, power losses, and total energy flow were calculated.

Haydaroğlu and Gümüş [5] utilized PVsyst software to simulate a 250 kWp SPP installed at Dicle University. Their analysis showed that the highest irradiance was recorded in August, which correlated with the plant's peak efficiency. By comparing the actual power generation data with the simulation results, they found a significant deviation during December and January. Notably, the actual generation values were consistently higher than the simulated values, with the exception of January.

Kınalı [6] conducted performance analyses of SPP in the Konya and Karaman provinces using actual design models and generation data. The simulations were performed with PVsyst, PV*SOL, and PVGIS software. Within the study, the outputs of these simulation programs were compared with measured generation data from three ground-mounted SPP with capacities ranging from 250 kW to 1 MW in Konya and Karaman, in order to assess the reliability of the software for feasibility studies and project financing.

Kumar et al. [7] conducted a performance analysis of a 250 kWp PV system in Pune, India, utilizing PVsyst simulation software. The researchers employed a two-stage

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methodology to investigate the effect of panel tilt angles on energy production. In the first stage, the tilt angle was kept fixed, whereas in the second, it was optimized monthly. The study then comparatively evaluated the impact of these two scenarios on both energy production and system performance.

Mathew and Hossain [8] evaluated and compared the performance of a 25 MW grid-connected solar PV power plant in Chandigarh, India, using different PV technologies, including crystalline silicon and thin-film modules. PVsyst software was employed for system simulation, and the analysis indicated that CIGS (Copper Indium Gallium Selenide) modules achieved higher energy efficiency.

Rout and Kulkarni [9] conducted a case study on a 2 kW rooftop SPP in Odisha, India. The primary aim of the study was to analyze the performance characteristics of small-scale PV systems and to assess their technical feasibility. PVsyst simulation software was employed for system design and performance analysis.

Sarı and Özyiğit [10] designed and analyzed ten SPP across five districts in Sivas province, employing PVsyst software. For each site, two different panel types were modeled: a 10 MW monocrystalline and a 9.999 MW polycrystalline system. The results indicated that the highest annual electricity generation was achieved in the Gürün district, while the lowest was observed in the Zara district.

Şahin and Salihmuhsin [11] performed a performance analysis of the Göksun Municipality's SPP using PVsyst software. A comparison of the actual generation data with the simulation results revealed minimal discrepancies, which highlights the high accuracy of PVsyst simulations.

While existing studies in the literature mostly focus on power plants or off-grid systems, this study evaluates building-integrated PV configurations in Bursa under local climatic conditions. In this study, PV panels were installed on the rooftop of the Ali Durmaz Mechanical Engineering Building at Bursa Uludağ University using PVsyst 7.4 simulation software. Two installation configurations were modeled: a horizontal layout and another at the optimum tilt angle. For both scenarios, the amount of electricity generated and the system costs were analyzed in detail. Following these evaluations, the configuration providing higher efficiency was identified, and the simple payback period was calculated based on the most efficient system setup. In this way, the economic feasibility and investment payback of the PV system were comprehensively assessed.

III. MATERIAL AND METHODS

PV cells, which constitute the core component of a PV system, are composed of semiconductor materials. Their operating principle relies on the photoelectric effect, a phenomenon in which these materials directly convert light energy into electrical energy.

Photons constitute the solar radiation that reaches the Earth, each carrying varying amounts of energy depending on their wavelengths.Upon reaching the surface of the PV cell, a portion of these photons is reflected while another portion is absorbed by the surface; the remaining photons penetrate into the cell. Among those that enter the cell, photons with sufficient energy excite electrons within the semiconductor material, thereby initiating electrical conductivity.

Depending on their characteristics, PV cells convert the solar radiation reaching their surface into electrical energy with an efficiency ranging between 5% and 30%. When multiple cells are interconnected in series or parallel configurations, they form a PV module. The combination of multiple modules results in a PV panel, and the aggregation of panels constitutes a solar array. These arrays can be designed to generate electrical output ranging from very low to significantly high wattage levels, depending on the system configuration [12].

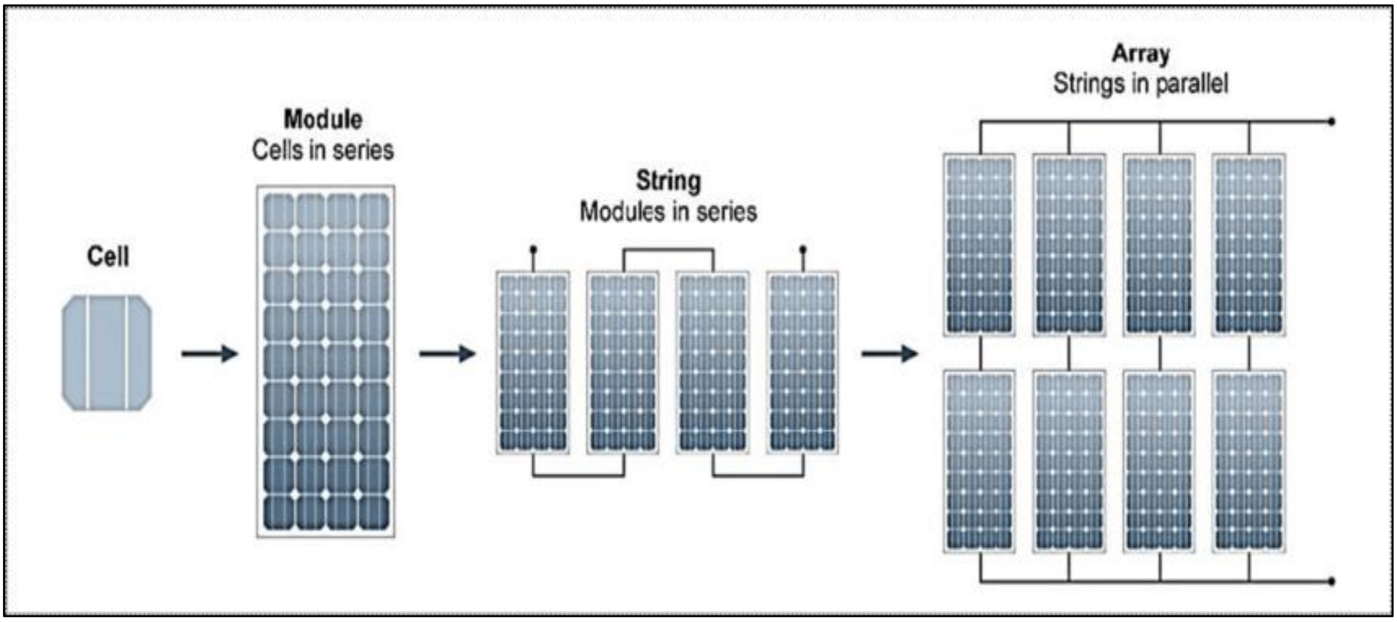

Fig 4 PV Cell, Module and Array Designs [13]

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➢ *PV System Components*

PV systems exhibit various differences depending on their intended applications; however, the fundamental equipment used remains largely similar. These systems generally consist of PV panels, batteries, charge controllers, and inverters.

- *PV Panel*

Solar panels convert solar irradiance into electrical energy via the embedded PV cells. These PV cells are interconnected in series and/or parallel arrangements to constitute the panels. The functionality of these panels relies on the PV effect, whereby semiconductor materials generate free charge carriers (electrons and holes) upon exposure to sunlight, enabling the direct conversion of photon energy into electrical current.

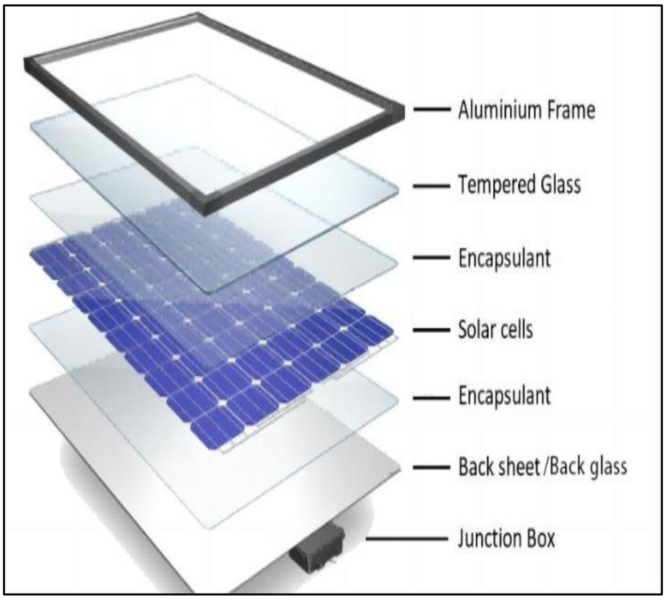

Fig 5 Solar Panel Structure [14]

A solar panel possesses a multi-layered structure designed to convert sunlight into electrical energy. The tempered glass layer allows the transmission of sunlight while providing protection against environmental factors. The EVA (ethylene-vinyl acetate) layer encapsulates and secures the PV cells in place. These PV cells convert incident solar radiation directly into electrical energy. Another EVA layer positioned beneath the PV cells provides additional support and enhances the mechanical integrity of the structure. Located at the bottom of the panel, the backsheet protects the module against moisture, ultraviolet (UV) radiation, and thermal stress. The entire assembly is enclosed within an aluminum frame, which safeguards the panel against mechanical impacts and ensures structural stability during installation. Positioned on the rear side of the panel, the junction box contains the electrical terminals for outputting direct current (DC) and houses bypass diodes to prevent reverse current flow.

- *Battery*

Batteries, commonly used in off-grid PV systems, serve the purpose of storing electrical energy generated from solar power. In the absence of sunlight, the stored energy is utilized to meet the electrical demand. Batteries function by converting electrical energy into chemical energy during charging, and then reconverting chemical energy into electrical energy when needed. In PV applications, lead-acid and nickel-cadmium batteries are frequently preferred due to their reliability and suitability for energy storage.

- *Inverter*

Inverters, also known as power converters, are essential components in PV systems, responsible for converting the direct current (DC) generated by solar panels into alternating current (AC) for end-use or grid integration. In addition to energy conversion, modern inverters record and monitor energy production data. They also filter voltage fluctuations from the grid, thereby reducing faults in motors and mechanical components, minimizing maintenance costs, and extending equipment lifespan. Moreover, by decreasing reactive power, inverters contribute to additional energy savings and improved system efficiency.

- *Charge Controller*

The primary function of the charge controller in a PV system is to prevent reverse current flow from the battery to the solar panel, particularly during nighttime or daytime periods with insufficient solar irradiance, when the panel voltage drops below the battery voltage.

- *Auxiliary Equipment*

In addition to core components such as batteries and inverters, PV systems require various auxiliary components to ensure proper energy generation and system functionality. These include diodes, fuses, cables, mounting hardware, and electrical connectors.

➢ *The Solar Energy Potential of Bursa Province*

Bursa is located in the Southern Marmara subregion of the Marmara Region, between 40° north latitude and 29° east longitude. The city lies at an average altitude of approximately 100 meters above sea level and features a transitional climate between the Mediterranean and Black Sea climates. This geographical and climatic positioning provides favorable conditions for the utilization of solar energy systems.

Figure 6 shows the global solar radiation data for Bursa's Nilüfer district, indicating that the maximum value is recorded in June, while the minimum occurs in December. This seasonal variation can be explained by the higher solar angle and longer daylight hours in summer, which increase radiation, whereas the lower solar angle and shorter daylight hours in winter reduce the amount of radiation.

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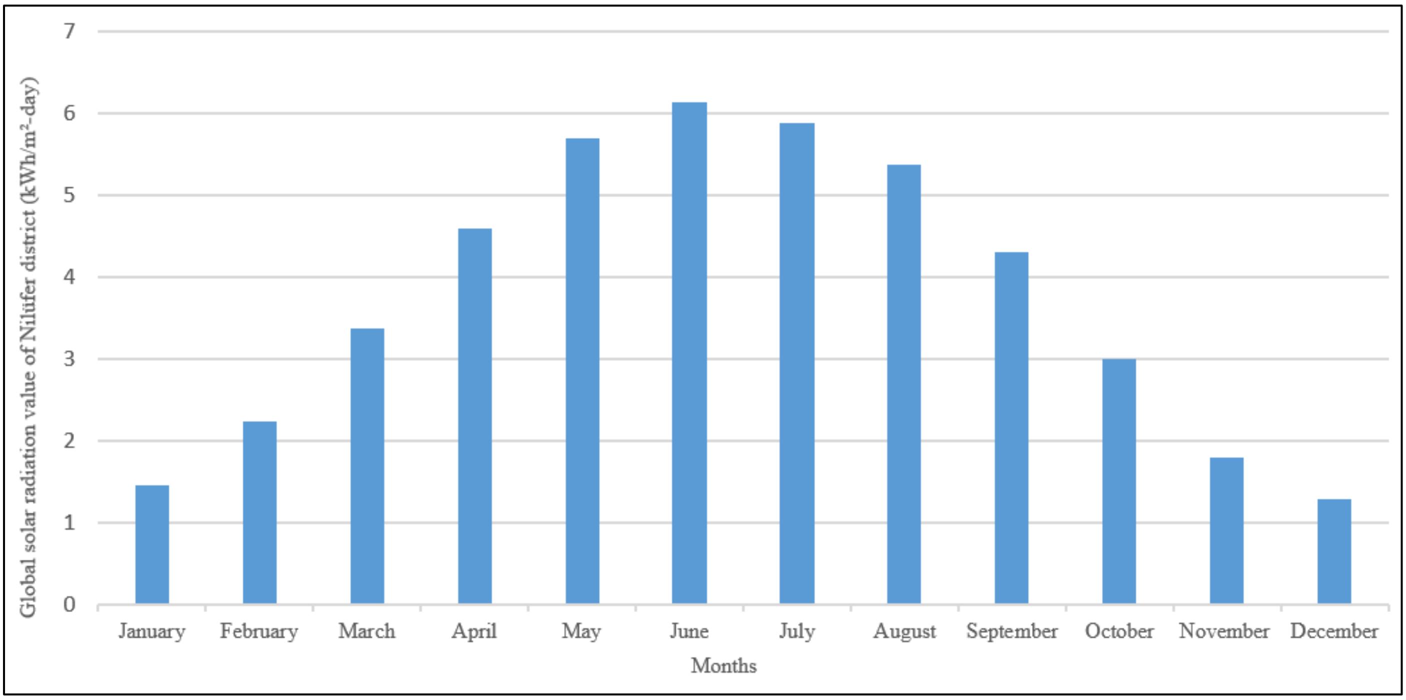

Fig 6 Global Solar Radiation Value of Nilüfer District

Figure 7 illustrates the monthly sunshine duration in Bursa's Nilüfer district. The data indicate that the longest sunshine duration occurs in July, while the shortest is observed in December. Extended sunshine hours during the summer months enhance the solar energy potential, whereas the shorter durations in winter reduce this potential.

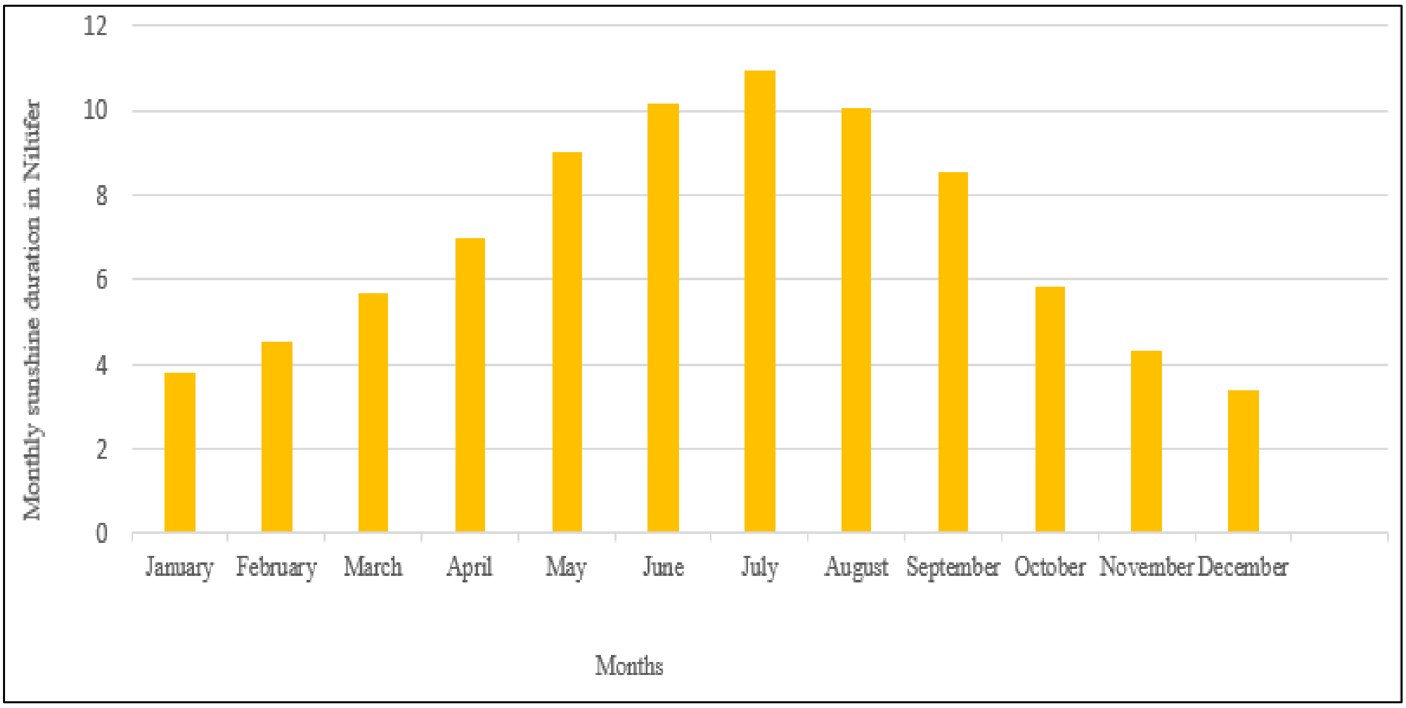

Fig 7 Monthly Sunshine Duration in Nilüfer

- ➢ *The Ali Durmaz Mechanical Engineering Building*

The Ali Durmaz Mechanical Engineering building, which is the subject of this study, is located in the Nilüfer district of Bursa, within the Görükle Campus of Uludag University. The building has a suitable rooftop surface area and accessibility for the installation of a PV system.

Figure 8(a) presents a visual representation of the building under study. Figure 8(b) illustrates the SketchUp-based design of the Ali Durmaz Mechanical Engineering building, which serves as the primary subject of this study.

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Fig 8(a) The Ali Durmaz Mechanical Engineering Building [15]


Fig 8(b) Front View of the Studied Building Modeled Using SketchUp Software

Figure 9. (a) presents a Google Earth image of the building under study. Roof measurements were extracted from this image, and the design developed in SketchUp based on these measurements is shown in Figure 9(b)

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Fig 9(a) Google Earth Image of Building [16]

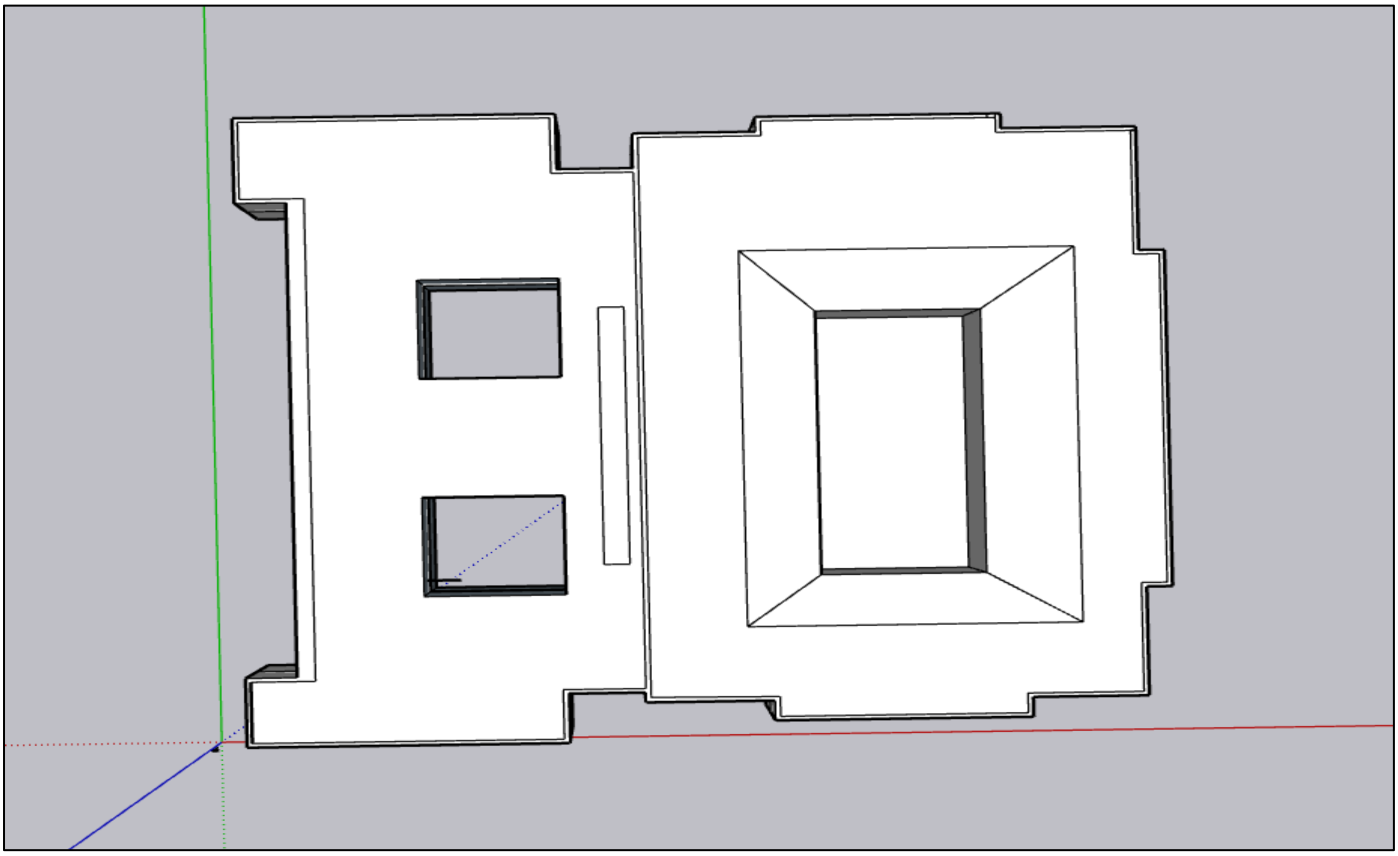

Fig 9(b) SketchUp-Rendered Rooftop Design

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➢ *PVsyst Simulation Software*

PVsyst is a simulation software developed in the C programming language at the University of Geneva, Switzerland.[17]. It is widely used for the design, simulation, and performance analysis of PV systems. The software enables detailed simulations of solar-powered irrigation systems, off-grid energy systems, and grid-connected systems. PVsyst contains an extensive database of various types of solar panels and inverters, and its 3D application allows for shading analysis, calculating the impact of shading on system performance. The results are presented as comprehensive reports containing both graphical and tabular data, which can be exported for use in other software platforms.[18]Using PVsyst, a wide range of data can be obtained, including annual, monthly, and daily energy production, system efficiency, loss analysis, climatic and radiation parameters, as well as economic outcomes.

- *Preliminary Design:*

This module is intended for a quick preliminary assessment prior to the installation of a PV system. By entering basic system parameters, it provides initial estimates of potential energy production.

- *Project:*

Offering a more comprehensive scope than the preliminary design, this module enables an in-depth evaluation of the project. It incorporates critical analyses, including the selection of meteorological data for the installation site, detailed system design, shading modeling, and loss calculations [19]

- *Grid-Connected:*

This module focuses on the design of grid-connected PV systems. It evaluates annual solar energy production, the amount of energy injected into and drawn from the grid, system efficiency, and energy losses.

- *Off-Grid:*

This module is dedicated to the design of standalone PV systems that operate independently from the grid.

- *Tools:*

This section provides a wide range of functions essential for the design, simulation, and performance analysis of PV systems.

- *Pumping:*

Designed for the simulation of solar-powered water pumping systems operating without energy storage units, this module is particularly relevant for irrigation and water supply applications.

- *Databases:*

The PVsyst databases store meteorological datasets used in PV system simulations, along with user-generated and customized component data.

IV. RESULTS

➢ *Horizontal Placement of PV Panels*

- At the initial stage, the system type is selected on PVsyst startup screen. For the design presented in this study, the grid-connected system configuration was chosen.
- In the second stage, the geographical coordinates of the area where the PV system will be installed are entered. If the location is not available in the PVsyst database, the coordinates are manually selected using the interactive map. Once the coordinates are determined, meteorological data are retrieved from the database. This step is of great importance for the accuracy of the simulation, as it generates the data that determine the annual solar potential of the region where the system will be installed.

Figure 10 presents the monthly meteorological parameters obtained from the Meteonorm database based on the specified coordinates. These parameters include global horizontal irradiation (GHI), horizontal diffuse irradiation (DHI), air temperature, wind velocity, atmospheric turbidity (Linke Turbidity), relative humidity, and other relevant meteorological data. Such information provides essential input for the design and performance analysis of solar energy systems.

- As presented in Figure 11, the orientation step in PVsyst was configured by defining the “Field Type” as a fixed tilted plane in accordance with the system design. The panel tilt was set to 0° (horizontal), while the azimuth angle was defined as 0°, a configuration selected due to its ability to maximize irradiation gain in south-oriented systems.
- In PVsyst, the selection of the required panels and batteries for the PV system is carried out through the “System” menu. This menu contains technical information about the panels and inverters, along with a list of available models, which can be selected together with their quantities. By entering the available area or the planned power capacity, the software calculates the required number of panels. If the desired panel or inverter specifications are not included in the database, they can be manually added.

As shown in Figure 12, the PV system incorporates 805 horizontally installed CWT430 108TN10 panels, selected for their high conversion efficiency, self-cleaning capability, anti-reflective glass, performance under low irradiance, durability, economic feasibility, and domestic production. In addition, seven HUAWEI SUN2000-50KTL-M3 inverters were chosen for their high efficiency and intelligent monitoring features to enhance overall system performance.

Figure 13 presents data from the PV system simulation, where the daily input-output diagram illustrates energy production and consumption, the performance ratio (PR) evaluates overall system efficiency, and system output power distribution along with string temperature provide essential information on potential losses and thermal conditions, contributing to the optimization of system efficiency and reliability.

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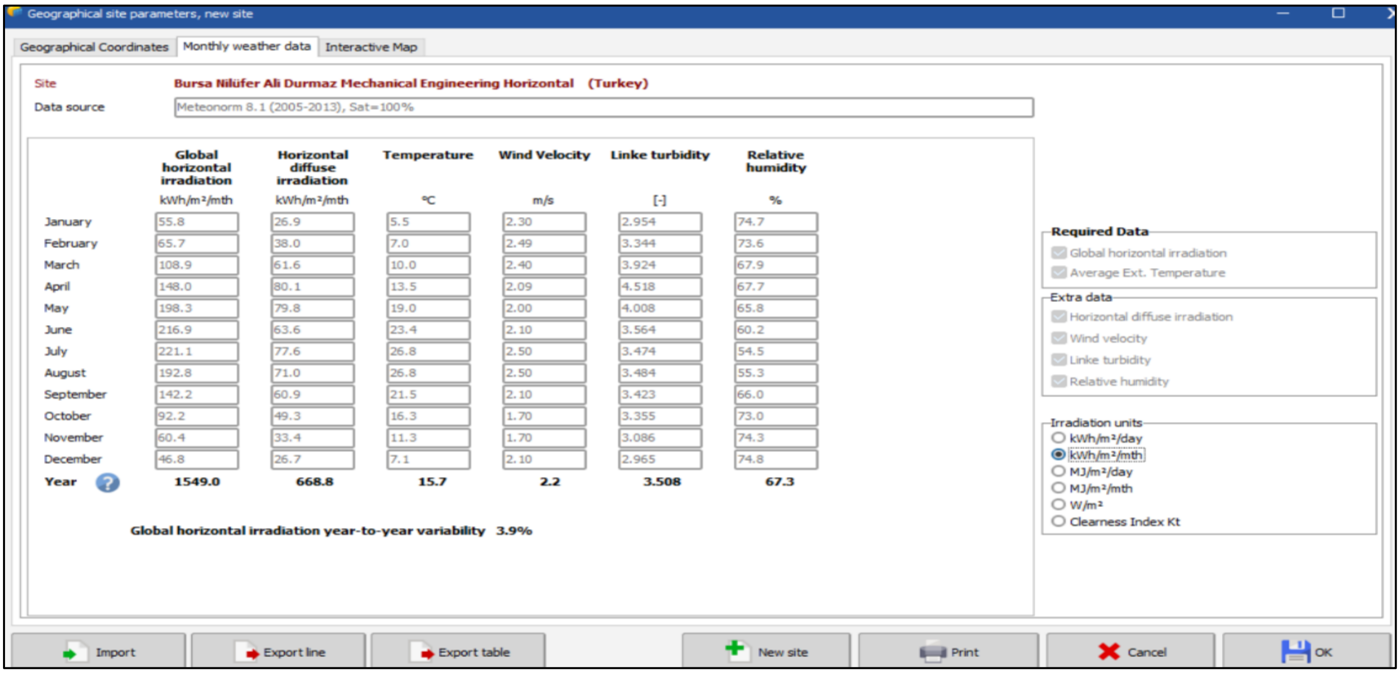

Fig 10 Meteonorm 8.1 Data

The graph demonstrates an almost linear relationship between the daily system energy (kWh/day) and the global horizontal irradiance (kWh/m²/day). This indicates that the system operates efficiently in proportion to solar irradiance and that the selection of panels and inverters has been well optimized. A performance ratio of 0.87 confirms that system losses are low. Fluctuations in the system output power distribution reflect the differences in irradiance between winter and summer months. Furthermore, the array temperature increases with higher irradiance levels.

After all input data are entered, the simulation process is initiated. At this stage, PVsyst calculates the system's energy production capacity on an hourly or monthly basis. It provides outputs such as specific yield (kWh/kWp), energy production (kWh/year), performance ratio, annual gain and loss graphs, and energy flow diagrams. These data are significant for conducting the annual performance analysis of the system and evaluating the economic feasibility of the investment. According to the graphs presented in Figure 14, the PV system demonstrates reliable performance throughout the year, with monthly energy production peaking in the summer months and reaching a minimum in winter, consistent with seasonal variations in solar irradiance. PV array and system losses are low, indicating well-optimized equipment selection. The performance ratio (PR) remains stable at an average of 0.87, with slight reductions during the summer due to temperature-induced panel efficiency losses. Energy production and grid injection also follow seasonal trends, and overall, the system exhibits high performance with low losses and an optimized design.

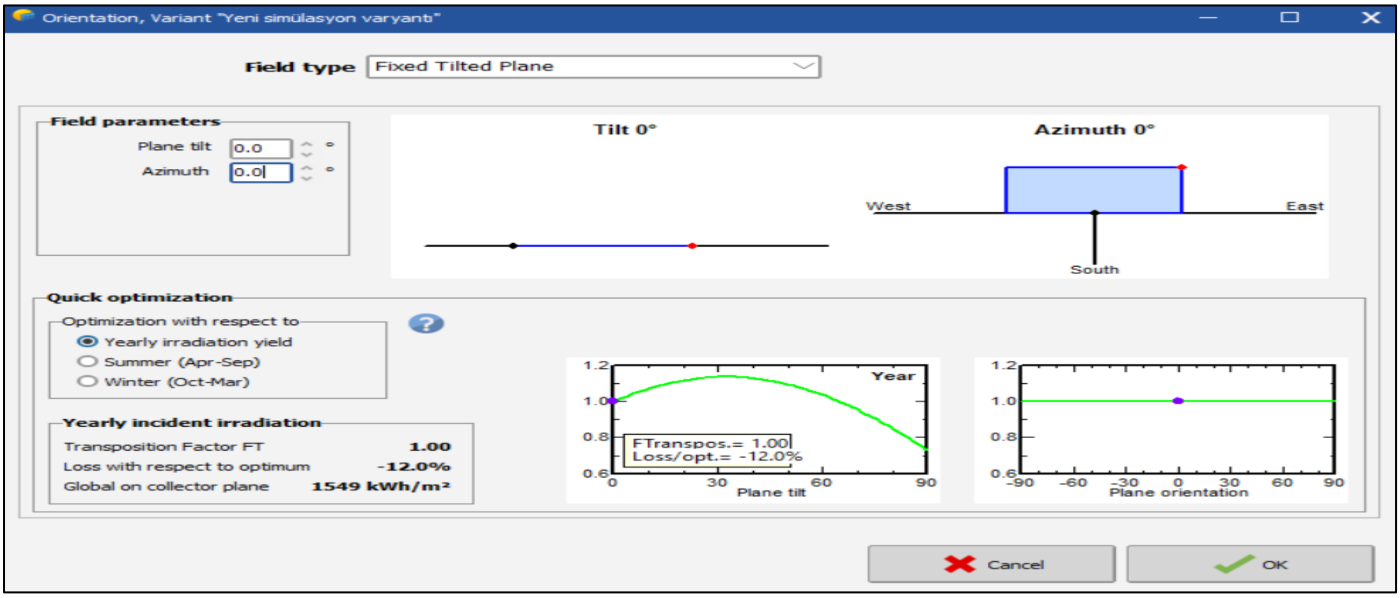

Fig 11 PV Panel Tilt Data

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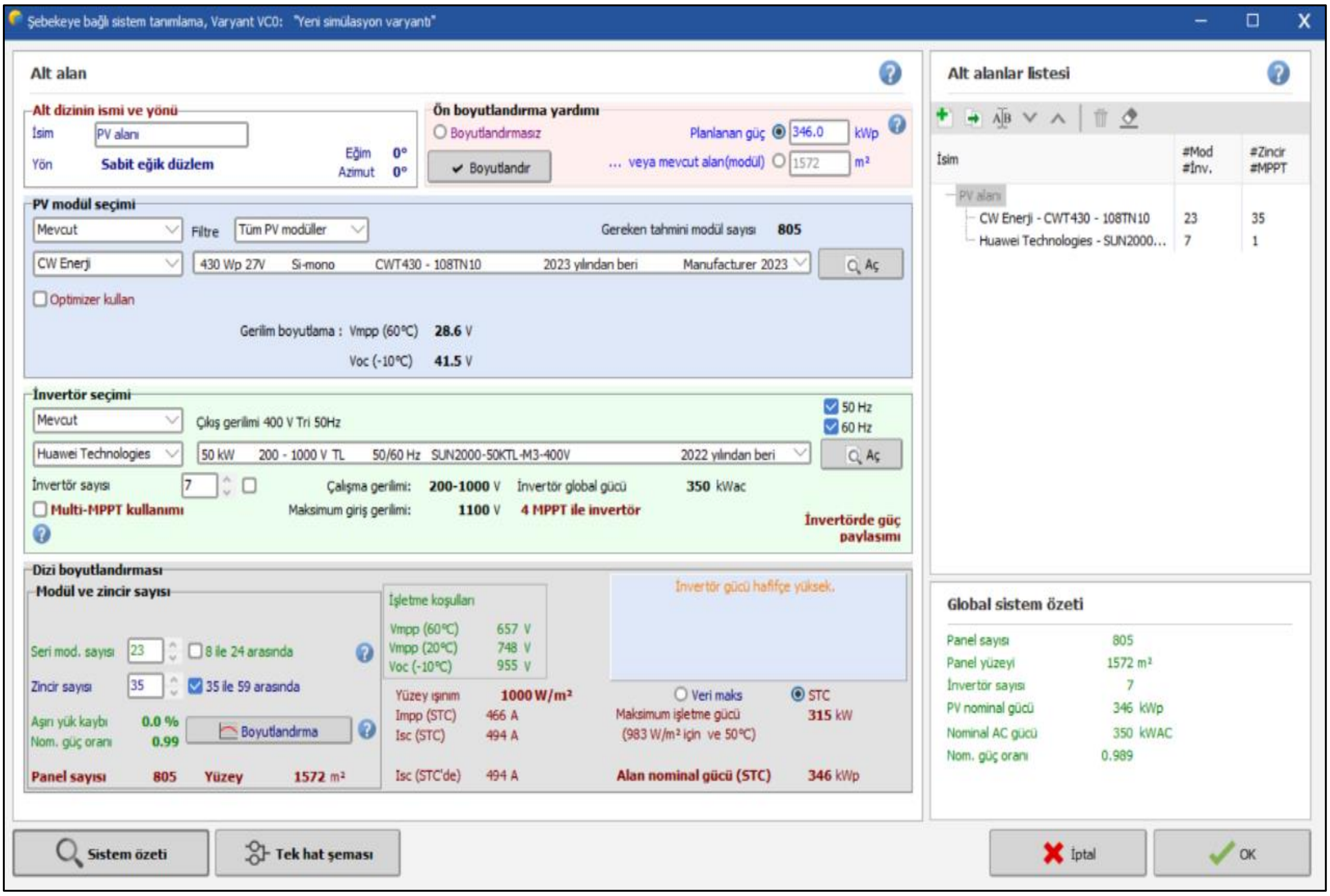

Fig 12 System Menu

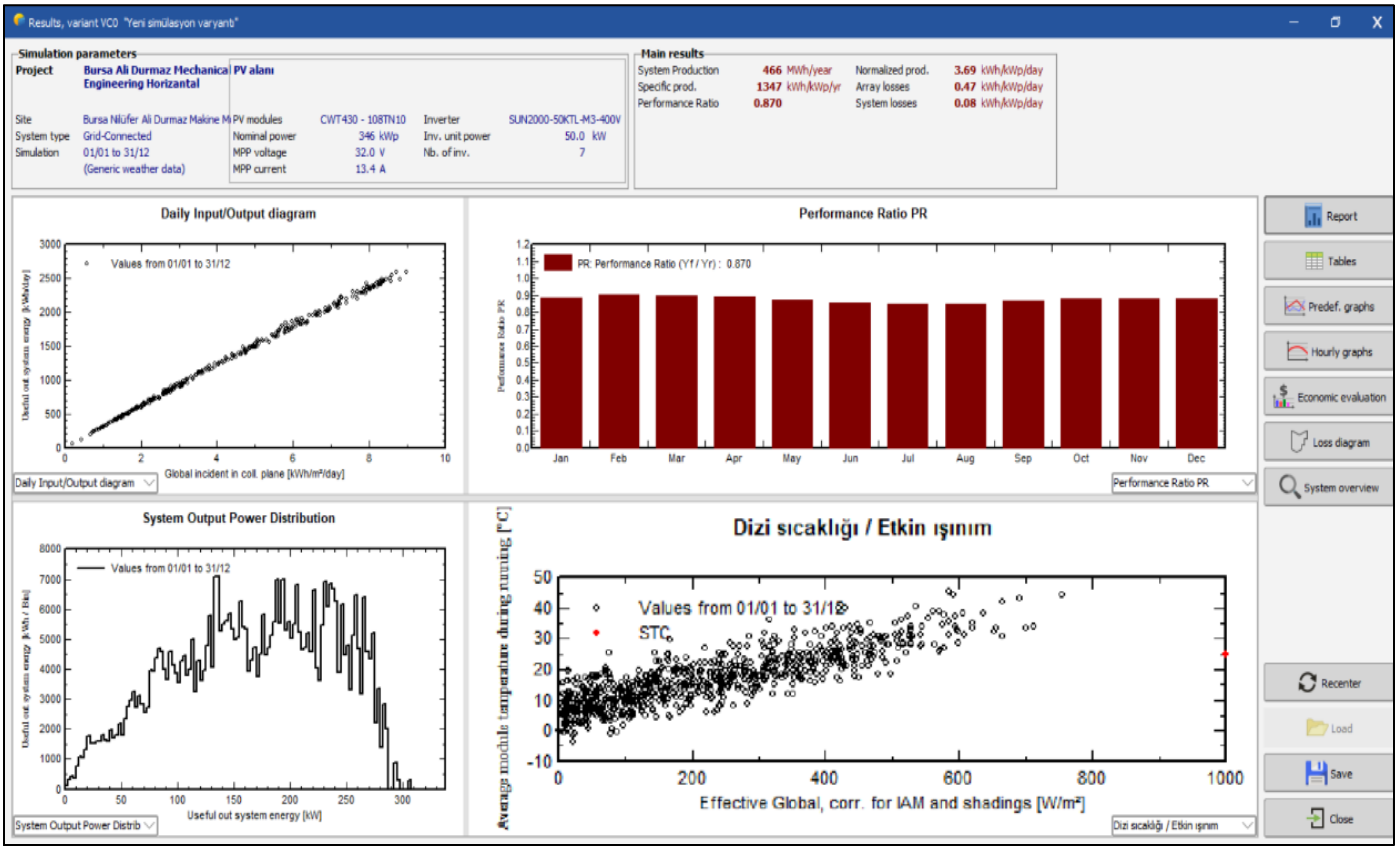

Fig 13 System Simulation

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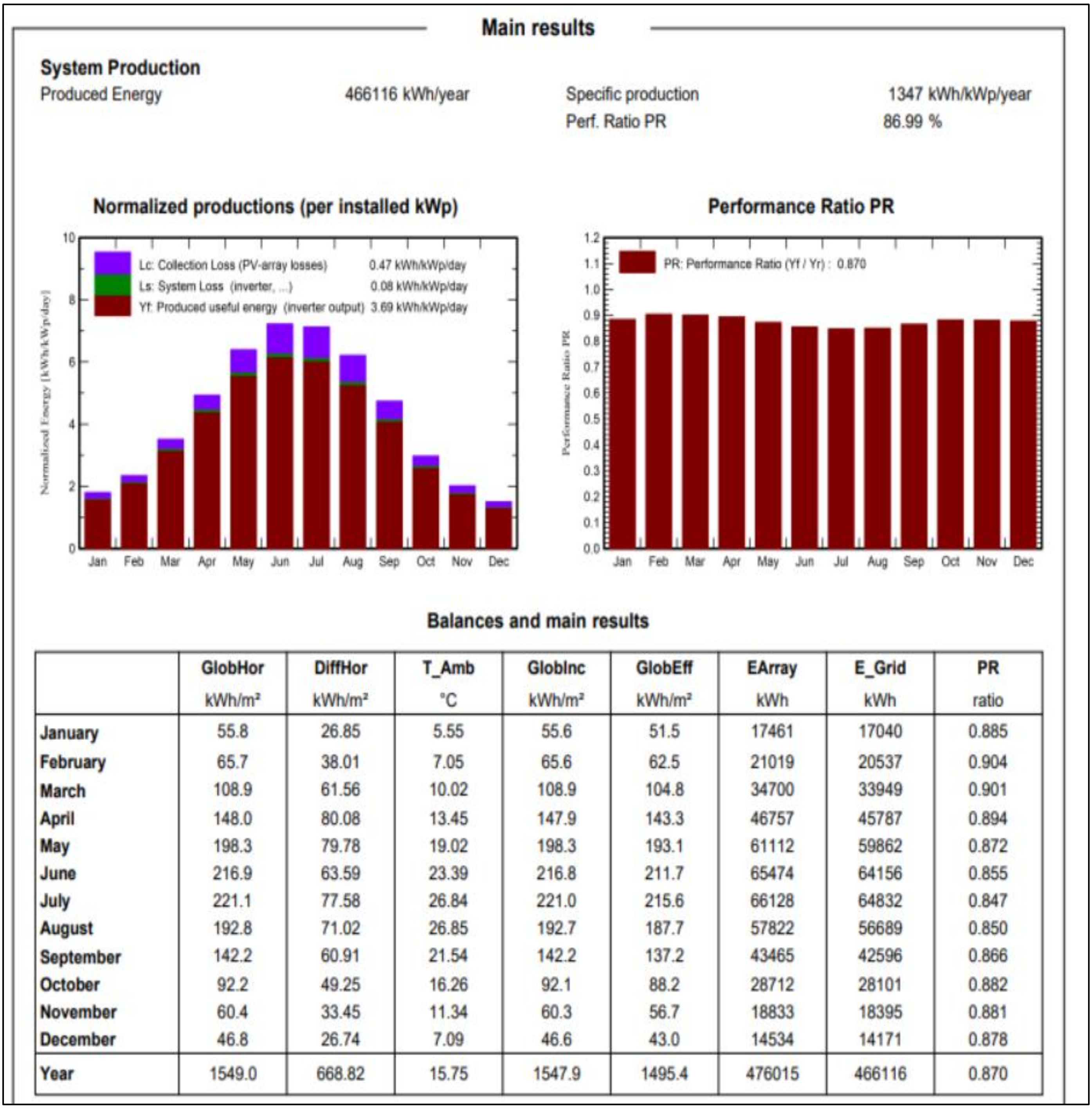

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_Grid kWh	PR ratio
January	55.8	26.85	5.55	55.6	51.5	17461	17040	0.885
February	65.7	38.01	7.05	65.6	62.5	21019	20537	0.904
March	108.9	61.56	10.02	108.9	104.8	34700	33949	0.901
April	148.0	80.08	13.45	147.9	143.3	46757	45787	0.894
May	198.3	79.78	19.02	198.3	193.1	61112	59862	0.872
June	216.9	63.59	23.39	216.8	211.7	65474	64156	0.855
July	221.1	77.58	26.84	221.0	215.6	66128	64832	0.847
August	192.8	71.02	26.85	192.7	187.7	57822	56689	0.850
September	142.2	60.91	21.54	142.2	137.2	43465	42596	0.866
October	92.2	49.25	16.26	92.1	88.2	28712	28101	0.882
November	60.4	33.45	11.34	60.3	56.7	18833	18395	0.881
December	46.8	26.74	7.09	46.6	43.0	14534	14171	0.878
Year	1549.0	668.82	15.75	1547.9	1495.4	476015	466116	0.870

Fig 14 General Results for Horizontally Oriented PV Panel

➢ *Optimum Tilting of PV Panels*

- Initially, the grid type is selected. In this study, the grid connected system was chosen.
- The geographical coordinates of the area where the PV panels will be installed were entered, and meteorological data were obtained via Meteonorm.
- In Figure 15, the field type option was set to a fixed tilted plane. The tilt angle of the panel plane was positioned at 34°, which is the optimum inclination angle for Bursa province, while the azimuth angle was assumed to be 0°.
- In Figure 16, the panel and inverter selection is presented. As in the horizontal layout, CWT430 108TN10 model PV panels were chosen. In this configuration, the number of panels is set to 567, and five HUAWEI SUN2000-50KTL-M3.
- The simulation of the proposed PV system installation is performed. Figure 17, a daily input/output diagram, performance ratio, system output power distribution, and string temperature graphs are included.
- In Figure 18, the energy balance and overall performance results of the planned system are presented monthly.

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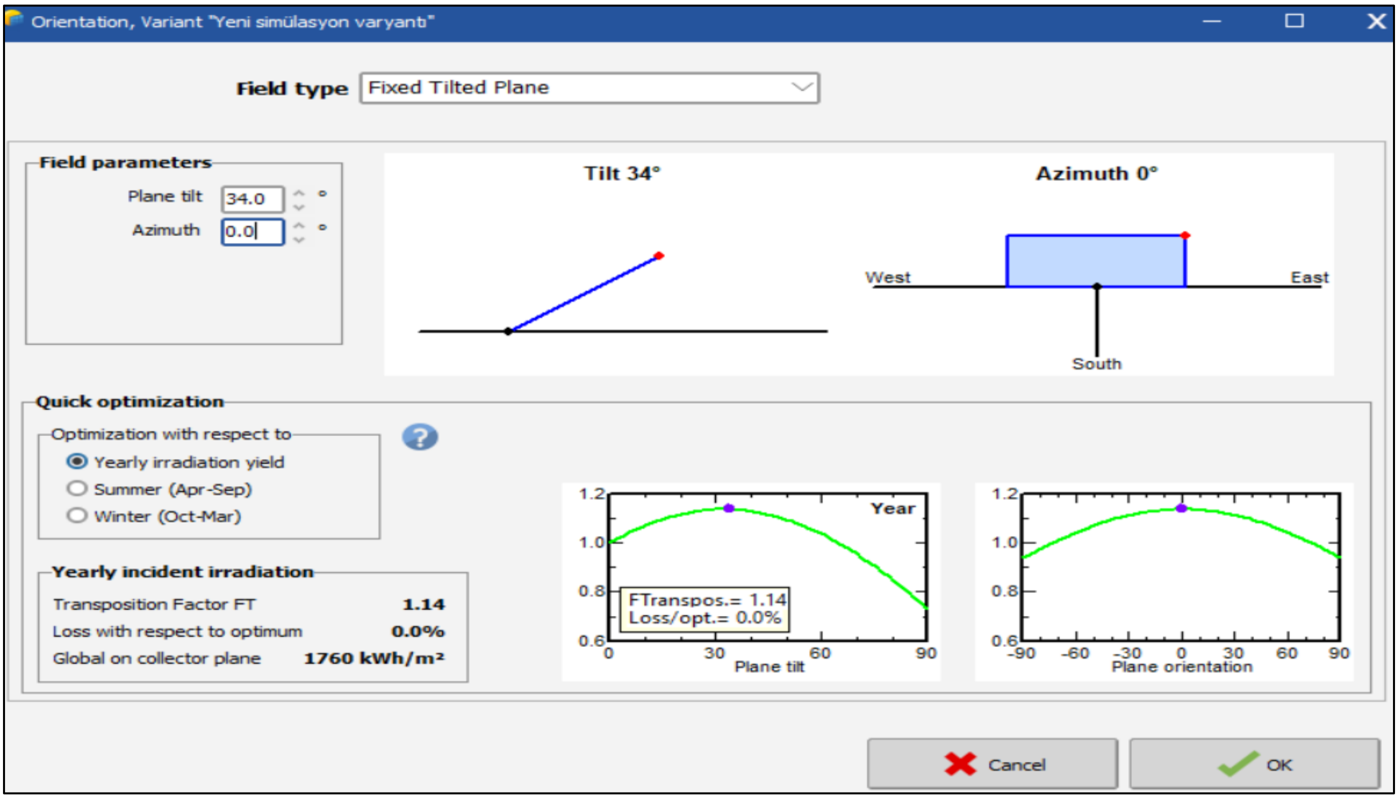

Fig 15 Orientation Data for the System with an Optimum Tilt Angle

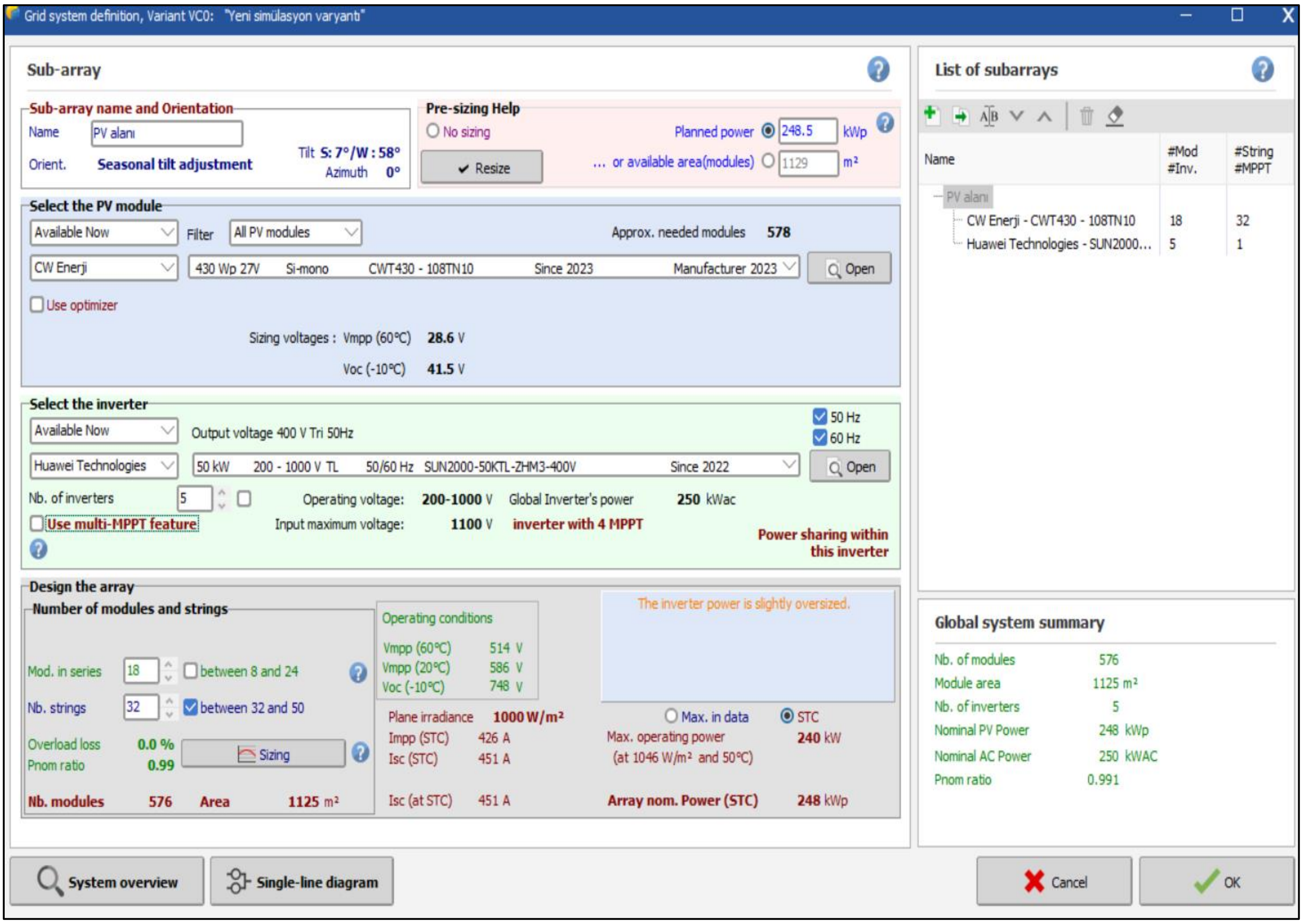

Fig 16 System Parameters with Optimum Tilt Angle

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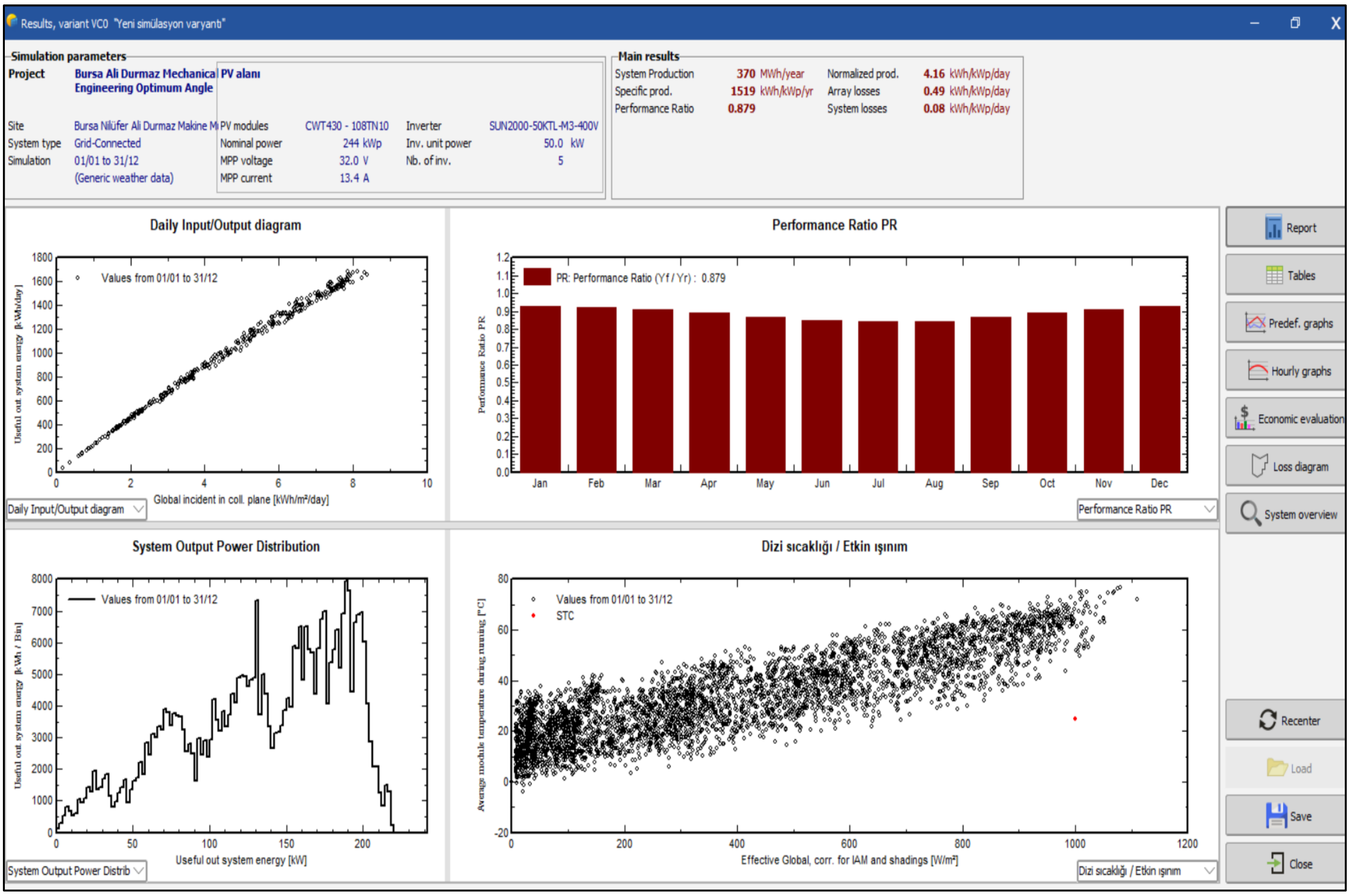
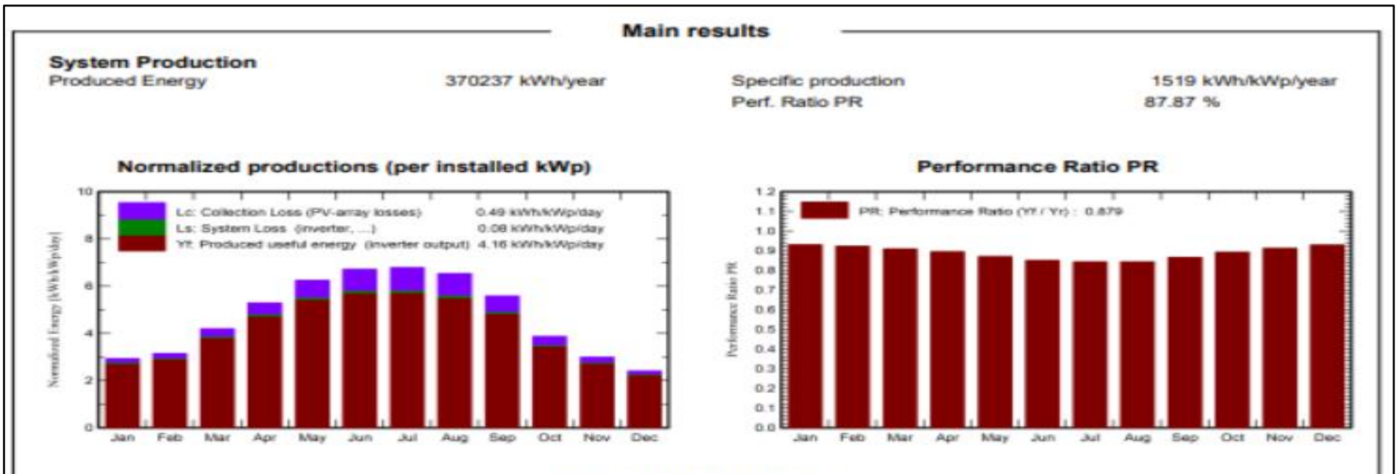


Fig 17 Simulation of the System with the Optimum Tilt Angle



Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_Grid kWh	PR ratio
January	55.8	26.85	5.55	90.8	89.4	21021	20594	0.930
February	65.7	38.01	7.05	88.2	86.7	20260	19852	0.924
March	108.9	61.56	10.02	130.1	127.5	29402	28833	0.909
April	148.0	80.08	13.45	158.7	155.1	35289	34622	0.895
May	198.3	79.78	19.02	193.8	189.0	41897	41107	0.870
June	216.9	63.59	23.39	201.4	196.3	42605	41787	0.851
July	221.1	77.58	26.84	210.3	205.1	44110	43270	0.844
August	192.8	71.02	26.85	202.7	198.1	42510	41695	0.844
September	142.2	60.91	21.54	167.6	164.0	36069	35398	0.866
October	92.2	49.25	16.26	120.1	118.0	26645	26139	0.893
November	60.4	33.45	11.34	89.9	88.5	20390	19988	0.912
December	46.8	26.74	7.09	74.8	73.6	17304	16953	0.930
Year	1549.0	668.82	15.75	1728.2	1691.3	377503	370237	0.879

Fig 18 General Results for Panels with Optimum Tilt Angle

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➢ *Financial Analysis*

Figure 19 illustrates the arrangement of PV panels in a horizontal plane. In this configuration, a total of 805 CWT430-108TN10 model panels and 7 Huawei Technologies SUN2000-50KTL-M3-40 inverters were utilized. Table 1 presents the cost analysis of the solar power plant installation

Fig 19 CWT430-108TN10 Model Panel [20]

Figure 20 shows an image of the inverter used in the study, while Table 2 contains its technical specifications.

Fig 20 HUAWEİ SUN2000-50KTL-M3 İnverter [21]

Table 1 contains the technical specifications of the PV panel used in the study. Figure 21. illustrates the horizontal installation of PV panels on the building's roof, with the modeling created using the SketchUp program. The cost analysis for the horizontal PV panel placement is detailed in Table 3, covering expenses for equipment, installation, labor, and maintenance. The performance and efficiency of PV systems are of paramount importance to modern energy grids. This PV system is automated using a supervisory control and data acquisition(scada) system. Scada systems facilitate remote monitoring, control, and comprehensive data acquisition of solar power plants, enabling continuous analysis of the plant's overall performance. This capability enhances operational efficiency, accelerates fault detection and diagnosis, and ultimately maximizes system reliability.

Table 1 Technical Specifications of the PV Module [20]

Specification	**Value**
Peak Power (P_{max})	430 W_p (STC)
Module Efficiency	22.02 %
Voltage at Maximum Power (V_{mpp})	32.34 V
Current at Maximum Power (I_{mpp})	13.30 A
Open-Circuit Voltage	38.51 V
Short-Circuit Current	14.10 A
Power Tolerance	0 ~ +5 W
Maximum System Voltage	1500 V DC
Operating Temperature Range	–40 °C to 85 °C
Dimensions	1722 × 1134 × 30 mm
Weight	21.45 kg
Cell Size	182.2 × 91.8 mm
Number of Cells	108 (6 × 18 configuration)
Glass Type	Anti-reflection coating

Table 2 Technical Specifications of the Inverter [21]

Specification	**Value**
Nominal AC Power Output	50 kW
Maximum AC Output Power	55 kW
Nominal AC Voltage	400 V
AC Voltage Range	320 V – 480 V
Nominal AC Frequency	50/60 Hz
Maximum Efficiency	98.7%
European Weighted Efficiency	98.4%
Protection Degree	IP66
Operating Temperature Range	-25°C to +60°C
Cooling Method	Natural Convection
Dimensions (W × H × D)	1035 × 700 × 365 mm
Weight	58 kg

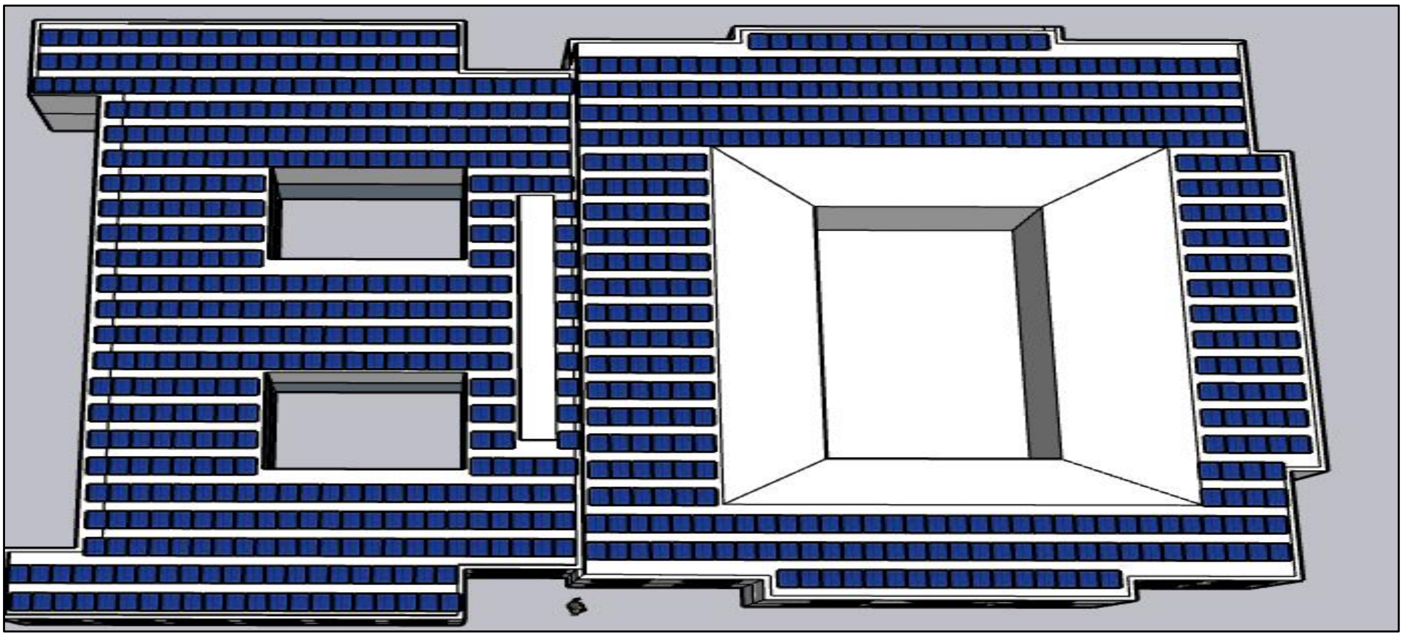

Fig 21 Horizontal Configuration of PV Panels

Table 3 Cost Analysis of Horizontal Configuration

PV panel	$93,498
Inverter	$16,833
Solar cable	$2,545
Connector	$1,111
Electrical panel	$3,847
Circuit breaker	$833
Solar mounting systems	$9,872
Labor costs	$32,909
Operation and maintenance costs:	$2,500/year
Solar panel installation	$1,953
PV automation	$1,764/ year
Total investment cost	$150,848.84

Figure 22 illustrates the positioning of PV panels at the optimum tilt angle, a configuration that is significant for achieving maximum efficiency. The PV system, configured at the optimum tilt angle, comprises 567 PV modules and 5 inverters.

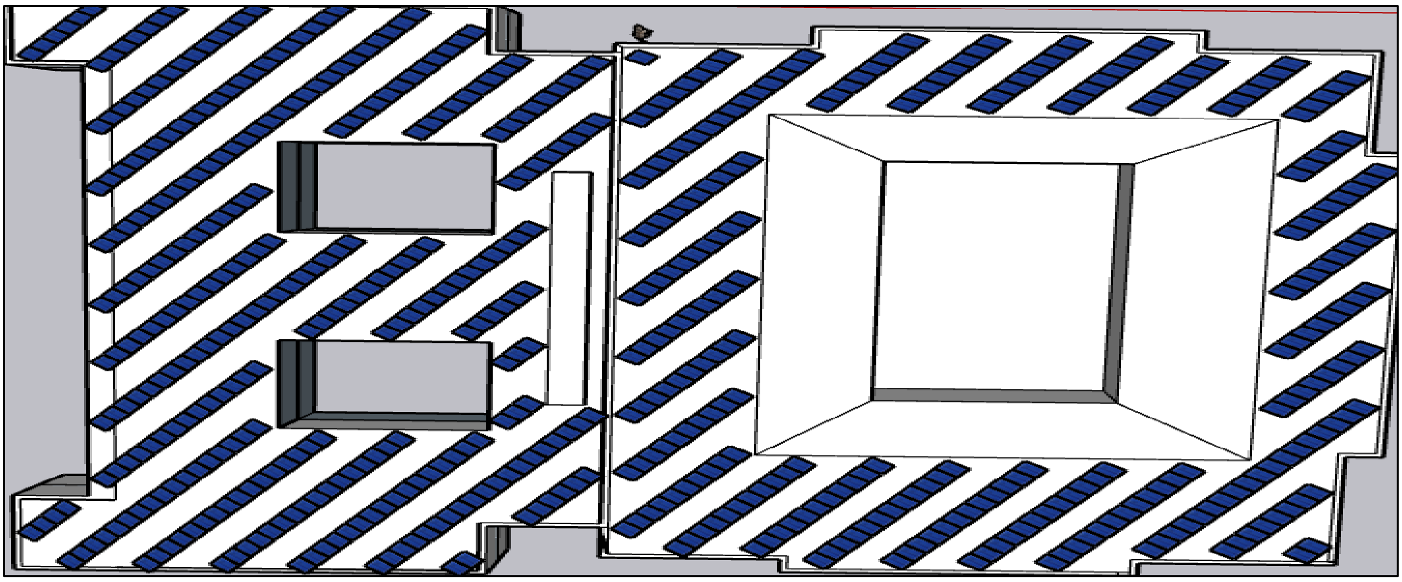

Fig 22 Top View of the PV Array Configured at the Optimum Tilt Angle

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Table 4 presents the cost analysis for the PV system installed at the optimum tilt angle. Table 5 presents the approximate annual electricity consumption of equipment used in the Bursa Ali Durmaz Mechanical Engineering Department, including laptop and desktop computers, projectors, lighting, air conditioners, a boiler, and kitchen appliances.

Table 4 Cost Analysis of the PV System Configured at the Optimum Tilt Angle

PV panel	$65,855
Inverter	$12,024
Solar cable	$2,240
Connector	$786
Electrical panel	$2,405
Circuit breaker	$670
Solar mounting systems	$17,740
Labor costs	$30,520
Operation and maintenance costs:	$2,500/year
Solar panel installation	$1,953
PV automation	$1,245/ year
Total investment cost	$137 938

Table 5 Annual Consumption of Device

Electrical Device	Annual Consumption(kWh)
Air conditioning	72 000
Tea boiler	11 680
Computer	8 468
Laboratory	7 834
Workstation	7 300
Lighting	3 103
Projector	2 920
3D printer	2 336
Dishwasher	730
Heating boiler	700
Refrigerator	360
Printer	146

Table 6 illustrates the energy outputs of the configurations under two different scenarios and the corresponding investment costs of the PV system.

Table 6 PV System Investment Costs

PV System	Generated Energy (kWh)	Total Investment Cost
Horizontal Configuration	466 116 kWh/year	$150,848.84
PV System with an Optimum Tilt Angle	370 237 kWh/year	$137,938

The annual energy yield of PV modules can be calculated using Equation 1. For the horizontal configuration, the total generated energy is 466 116 kWh, and the number of PV modules used is 805. Accordingly, the annual yield per panel is calculated as 579.03 kWh/panel. When positioned at the optimum tilt angle, the annual yield per panel increases to 652.98 kWh/panel.

$$\text{Annual Yield per PV Module} = \frac{\text{Generated Energy}}{\text{Number of PV modules}} \quad (1)$$

Efficieny improvement can be calculated using Equation 2. Therefore, fficieny improvement is calculated as 12,771%.

$$\text{Efficiency Imp.} = \frac{\text{Annual Energy Per Module}}{\text{Annual Energy of Horizontal System}} \quad (2)$$

$$\text{Efficiency Improvement (\%)} = \frac{652{,}98-579{,}03}{579{,}03} \times 100 = 12{,}771$$

The annual energy production per panel of the system with the optimum tilt is approximately 12,771% higher compared to the horizontal configuration. In other words, optimizing the tilt angle resulted in a 12,771% increase in panel-level efficiency. The comparative analysis of annual electricity generation for the two scenarios reveals that the horizontal configuration produced 466,116 kWh/year with an associated investment cost of $150,848.84. Conversely, under the optimum tilt angle configuration, the system yielded 370,237 kWh/year, corresponding to a total investment cost of $137,938. The annual difference in electricity generation between the two scenarios was calculated as 95,879 kWh/year. According to the EMRA-approved electricity tariff for medium voltage, dual-term

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public institutions, the daytime energy price is 3.37725 TL/kWh [22]. Based on these findings, it can be concluded that the panels installed at the optimum tilt angle provide higher efficiency and lower overall cost compared to the horizontal configuration.

The simple payback period is given in Equation 3.

$$\text{Simple Payback Period (SPP)} = \frac{\text{Total Investment Cost}}{\text{Total Annual Gain}} \tag{3}$$

The US Dollar was assumed to be 40,8 TL on August 15, 2025, according to the Central Bank of the Republic of Turkey (CBRT) [23].

The investment cost of the photovoltaic system positioned at the optimum tilt angle is $137,938, and the annual energy production is 370,237 kWh/year. The simple payback period was calculated as 4,501 years using Equation (3).

V. DISCUSSION AND CONCLUSION

In this study, the PVsyst 7.4 software was employed to model two different PV panel layouts on the roof of the Ali Durmaz Mechanical Engineering Building at the Uludağ University campus in Bursa, Turkey. The production data of the systems were compared, and different approaches to PV system design were evaluated. In the first configuration, the panels were installed in a horizontal arrangement. For this fixed-axis system, the tilt angle was set to 0° and the azimuth angle to 0°. This layout consisted of 805 monocrystalline panels and 7 inverters. In the second configuration, the tilt angle was set to the optimum value for Bursa, which is 34°, while the azimuth angle remained at 0°. This arrangement included 567 monocrystalline panels and 5 inverters. The defined parameters were entered into the software, and the results were generated. According to the simulation results, the horizontal layout produced 466 116 kWh/year, with an installation cost of $150,848.84. In comparison, the optimum tilt layout generated 370 237 kWh/year, with an installation cost of $137,938. When the two systems were compared in terms of annual production and investment cost, the optimum-tilt configuration demonstrated superior performance, exhibiting an approximately 12.77% higher efficiency. For the building, when panels were installed at a tilt angle of 34° and azimuth of 0°, and the annual electricity consumption was considered, the simple payback period was calculated to be 4.501 years. The findings of this study aim to provide university students with practical knowledge on renewable energy resources and to serve as a reference for investors intending to establish solar power plants.

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