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Research Article

Validating the Credibility of Photovoltaic Systems Simulation Tools with a Case Study

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ABSTRACT

In this study, a photovoltaic system with an installed power of 10 kWp, which was built on the roof of a school cafeteria in Gümüşhacıköy district of Amasya, was modeled using the PVsyst software and PVSOL software. The real-life data of the system and the production data calculated from the software used were compared. While the actual total electricity production data of this photovoltaic system for 2021 was determined as 12.473 MWh, this value was obtained as 12.912 MWh using PVsyst software and 13.556 MWh using PVSOL software. While there was a 3.40% difference between the estimated production value and the real-life data with the PVsyst software, it was determined that there was a 7.99% difference between the estimated production value and the actual production value of the system as a result of the simulation made with PVSOL. From the production estimates made with two different simulation software, it was seen that the PVsyst software gave results closer to the real-life data.

1. Introduction

In today's conditions, countries are turning to renewable energy sources in electricity generation due to the limited fossil resources, geographical reserves only in certain regions, economic cost, supply security, use as a means of sanction between countries, and negative effects on the environment [1].

As in the rest of the world, Türkiye's increasing energy demand along with its growing population increases the demand for renewable energy [2]. To reduce external dependence on energy and energy imports, studies on determining the potential of renewable energy resources and expanding their use continue to increase [3]. Türkiye has a significant amount of renewable energy resources (wind, solar, water, geothermal, etc.) and the optimum use of these resources is of great importance [4]. Aware of these natural resources, Türkiye's share of renewable energy-based electricity generation is continuously increasing [4]. While in 2009, the electricity generated from wind, solar, and geothermal energy was quite low, according to December 2022 data, the total electricity generated from these three energy sources increased to 22 512.9 MW. According to March 2024 Turkish Electricity Transmission Corporation (TEİAŞ) data, Türkiye's installed capacity reached 107 799 MW. While the installed wind capacity was 11 961 MW, the installed solar capacity increased to 12 639 MW [5].

In the study titled "Modeling and Simulation of 30 kW Grid Connected Photovoltaic System with

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PVsyst Software", modeling and simulation studies were carried out on a school roof in Batman province with PVsyst Software for a 30 kW grid-connected photovoltaic system using 300 Wp polycrystalline PV panels facing full south direction with 34^0 panel slope and 0^0 azimuth angle. What kind of results will be encountered in case of realization of this PV system was evaluated with the PVsyst simulation program. As a result of the simulation, it was planned that 35.31 MWh/year of electricity could be generated at the school and 35.31 MWh/year of energy generated could be sold to the grid to generate income for the school. Considering the energy needs of the places where the system is designed, it is concluded that the system can meet how much of this need and cost analyzes can be made [6].

In their study titled "Analysis of the Lebit Energy Solar Power Plant with Pvsyst Program", Demiryürek et al. [7] analyzed the data of Lebit Energy solar power plant in Siirt province, which has an installed capacity of 200 kWp, by comparing them with PVsyst software. They compared the actual production values for one year with the simulation values obtained with the PVsyst program and observed that the program reflects the reality with a very small error margin of 0.56 %. As a result of the analysis and investigations, they concluded that more energy production can be achieved if regular dust and snow cleaning is carried out.

In a study, the real-life data of 3 different solar power plants in Kilis province for the years 2018, 2019, and 2020 were compared with the system data designed with PVsyst 7.1. software using the same system features. As a result of the analysis, it was observed that the data obtained were close to each other, but the power plant energy production values were less [8].

Thailand is rapidly moving towards sustainable electricity generation using renewable energy systems, especially solar photovoltaic systems and wind turbines. Four renewable energy modeling tools (SAM, PVsyst, HOMER and RETScreen) were used to model solar photovoltaic systems (PVS), wind turbine systems (WTS) and solar photovoltaic-wind turbine hybrid systems (PVWHS) in different regions of Thailand. The results of the analysis using PVsyst software were reported to be close to the real data with an error rate of 6.9 % [9].

In the study conducted by Altınkök et al. [10], a 3D photovoltaic system design was carried out on the roofs of Giresun University Faculty of Engineering in Türkiye using the PVSol program. When the analysis of the simulation results was evaluated, it was stated that the Faculty would contribute to the production of approximately 138.054 MWh of electricity and in this case, approximately 52% of the annual consumption could be met.

Dirlik et al. [11] investigated the real data of 7 solar power plants (SPP) in different geographical regions in Türkiye are compared with the results of PVSyst, PVSOL and HOMER software. As a result of the study, it was stated that the most suitable software for these analyzed power plants was HOMER.

In this study, PVsyst V.7.1.0 DEMO and PVSOL Premium 2022 DEMO software were used to design an on-grid photovoltaic (PV) system with an installed capacity of 10 kWp on the roof of the cafeteria of a school in Gümüşhacıköy district of Amasya province.

2. Material and Methods

2.1. Solar energy potential of Amasya province

Amasya province is located in the inner part of the Central Black Sea region (34° 57' 06" - 36° 31' 53" East Longitude and 41° 04' 54" - 40° 16' 16" North Latitudes). According to the data of the General Directorate of Meteorology, the solar energy potential of Amasya is given in Figure 1 [12]. Compared to other regions, the solar energy potential of the Black Sea region is low. It is seen that the average solar radiation of the districts of Amasya province is between 1400-1550 KWh/m^2-year and this value is lower than Türkiye's average annual total irradiance of 1527.46 kWh/m^2 -year [13].

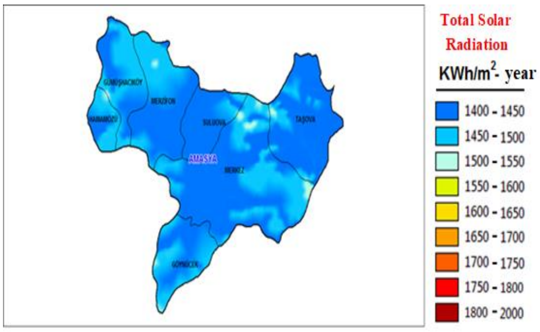

Figure 1. Solar energy potential atlas of Amasya province [12]

Gümüşhacıköy district is located in the northwest of Amasya. The average daily sunshine duration of the district is 6.63 hours, which is lower than Türkiye's average daily sunshine duration of 7.5 hours. When we look at the global radiation values of Gümüşhacıköy district given in Figure 2, it is seen that the highest radiation intensity is reached in July with 6.19 kWh/m^2-day. The lowest radiation intensity is observed in December with 1.34 kWh/m^2-day.

As seen in Figure 3, the highest efficiency per square meter is obtained from monocrystalline silicon PV panels. Monocrystalline panels are preferred in order to obtain more intense energy in a small area, especially where there is insufficient space to install panels.

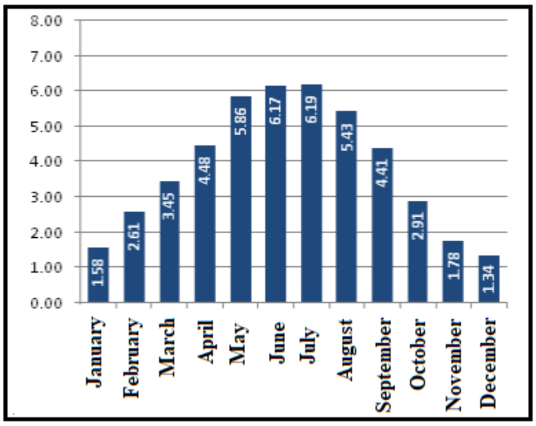

Figure 2. Gümüşhacıköy global radiation values (kWh/m^2-day) [12]

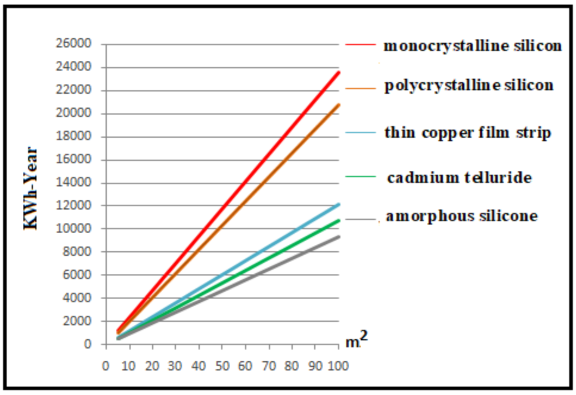

Figure 3. Comparison of energy densities of photovoltaic panel types (kWh/year) [12]

2.2. Rooftop photovoltaic system

In the photovoltaic system installed on the roof of the school cafeteria, 28 pieces of 395 Wp monocrystalline PV panels were placed according to the roof slope. Total installed power is 395 Wp x 28 = 11.060 kWp. Growatt 10000-TL3-S brand inverter with 3-phase 2 MPPT input and 10 kW power is used in the power plant. PV panels are arranged in 2 strings (chains) with 14 panels in each string (Figure 4). The roof slope is 11° vertically (N-S). The azimuth angle of the roof where the PV panels are located is 40° in the south-east direction, not exactly south. The system is grid-connected (on grid) and fully supplies the electricity it generates to the grid. The electricity generated by the system is mutually offset by the distributor company.

Figure 4. Installation of PV Panels on the roof in 2 chains

In this project, the orientation of the roof where the PV panels are located is deviated from south to east by 40°, so the azimuth angle is -40°. The azimuth angle can be easily found with various interactive maps and websites using satellite images.

2.3. PVsyst software

One of the most preferred programs for designing PV solar systems is PVsyst software. PVsyst program is a simulation program developed by the University of Geneva, Switzerland, where solar energy systems such as PV field irrigation systems, grid-connected, off-grid PV systems can be designed in 3D and the results can be obtained as reports and graphics. PVsyst program provides the opportunity to make calculations using detailed specifications for the system [14].

The program allows us to obtain the solar radiation data of the region where we will apply, by entering the coordinates of the region where the solar power plant (SPP) will be established, through various software, or by entering it manually. PVsyst accesses the solar radiation and meteorological data of the selected location using Meteonorm, NASA or PVGIS databases.

2.4. System design with PVsyst software

When designing the photovoltaic system, factors such as panel orientations, panel properties, inverter properties and shading effect are fully entered into the system. If desired, an economic evaluation is made. After marking the geographical coordinates of the roof where the PV panel is installed on the interactive map, the meteorological data of Gümüşhacıköy district in the PVsyst database is retrieved via Meteonorm 7.3. As a result, monthly global radiation, wind speed and temperature values falling on the horizontal plane of the location where the PV panels were installed were obtained. When Solar Energy Potential Atlas (SEPA) and Meteonorm 7.3. data are compared, it is seen that the data are close to each other and while Meteonorm annual average is 3.86 kWh/m^2/day, this value is 3.865 kWh/m^2/day according to SEPA [15].

Panel inclination and orientation directly affect the efficiency of the photovoltaic system. The roof on which the PV panels are installed does not face directly towards the south and faces 40^0 east from the south. This caused the azimuth angle to deviate 40^0 from the south direction and this caused a decrease in efficiency. Again, the angle of the panels with the vertical is 11^0, which is considerably smaller than the optimum angle of 33^0 according to the latitude of the building. This causes a decrease in efficiency compared to the optimum slope. According to the slope and azimuth angles where the system is installed, the total loss is around 7.9 %.

The values where the panel inclination is 33^o and the panel direction is exactly facing south, i.e. the azimuth angle is 0^o, give us the optimum situation. In this case, PVsyst shows 0 % losses. The surface radiation rate also increases from FT=1.06 to FT=1.15. If the panel slope was 33^o and the azimuth angle was 0^o in the photovoltaic system installed on the roof, the system would be operating at the highest efficiency. If the panel slope was 33^o and the panel direction was in the same direction as the roof as in the real situation, that is, if the azimuth angle was -40^0, the loss would be 3.8 % compared to the optimum situation. This shows us how important the panel tilt alone is in the performance of the system. If the panel tilt is 11^o as in the real photovoltaic system and we change the panel orientation and ignore the deviation of 40^0 and make the azimuth angle 0^0, the loss compared to the optimum case is 6.2 %.

In roof applications, in sloping roofs, PV panels are generally installed according to the slope of the roof and additional construction costs are avoided. This way is used because the installation construction is a little more difficult and costly on sloping roofs. Determining the panel inclination and azimuth angle that can achieve maximum efficiency before starting the project and assembling according to these values will significantly increase the amount of energy produced by photovoltaic systems that will operate with a constant inclination for many years.

In the real photovoltaic system, a total of 28 PV panels of 395 Wp were placed in 2 arrays and connected to several 14 panels per MPPT. The power of the system was selected as 11.06 kWp independently of the area since there is enough roof space (Table 1).

Since the 10 kW Growatt 10000-TL3-S inverter used in the system is available in the Pvsyst program, inverter selection is made here (Table 2).

Table 1. Characteristics of the PV panel used

ELNPLUS6612M-395	
Characteristics	**Value**
Voc	49.12 V
Vmpp	40.28 V
Isc	10.14 A
Impp	9.81 A
Maximum power at STC (Pmax)	395 Wp
Number of Panels Used	28

Since the PV panel used in our study is not readily available in the database of PVsyst software, PV panel specifications were found in the manufacturer's catalogs and added to the component library of PVsyst program.

Table 2. Specifications of the inverter used in the system

GROWATT 10000-TL3- S Inverter	
Characteristics	**Value**
Max. Recommended PV Power	12000W
Max. DC Voltage	1000V
Start Voltage	160V
Nominal Voltage	600V
Max. Input Current	13A/13A
Rated AC Output Power	10 kW
Max. AC apperent Power	11kVA
Max. Output Current	16.7A
AC Nominal Voltage	230V/400V; 320V/438V

2.5. PVSOL premium 2022 software

Valentin Software Simulation Software, based in Berlin, Germany, launched PVSOL Photovoltaic Systems Design Software in 1998. PVSOL is a dynamic software that enables professional design for photovoltaic systems. It allows the 3D design of many photovoltaic systems such as grid-connected, off-grid, DC pumping, rooftop systems, battery storage systems and field applications. Single and dual-axis solar tracking systems can be designed. With PVSOL, the shading effect of field applications, rooftop parallel and elevated mounting angle systems can be designed in 3D and shading effects can be calculated. The software provides the opportunity to include satellite maps in 3D design [16].

2.6. System design with PVSOL software

The system specifications installed on the roof were defined in the same way. Electrical parameters, temperature coefficient data and dimensions of 395 Wp panel specifications, which are not readily available in the PVSOL program, were entered into the panel data section in the system. The Growatt 10000TL3-S inverter used in the system was selected exactly as it is available in the software. In the system, a total of 28 panels were placed in 2 arrays. The building location was selected from the map and the azimuth angle was automatically output and the roof slope value was entered as 11°.

The main building and the tree near the power plant were placed in the field according to their exact location. Considering that the tree is a deciduous tree, solar transmittance values were selected. These choices are important in finding shading losses.

3. Results and Discussion

3.1.Design results with PVsyst software

The system installed on the roof of the school was designed with PVsyst software together with the actual panel, inverter, tilt, location, angle and shading effect, and it was calculated that the total annual electrical energy to be supplied to the grid would be 12.91 MWh. The system performance ratio was found to be 78.74%. When the economic data for the system is entered, it is seen that the system covers the installation cost after approximately 6.64 years due to the effects such as the ownership of the land, rent expenses and the absence of taxes.

As a result of the simulation made with PVsyst software without shading objects, it was calculated that the system would produce 13.650 MWh of electricity annually, and because of the simulation using shading objects, it could produce 12.912 MWh of electricity annually. This result shows that there is an annual loss of 738 kWh of electricity due to shading, causing a loss of 5.40 % in the system. Looking at the monthly estimated production results, it is seen that the highest production is reached in July and the lowest electricity production is realized in December (Figure 5).

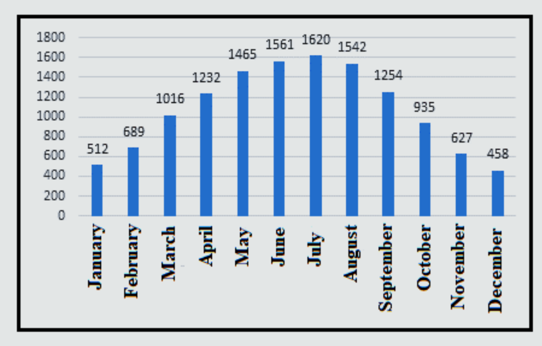

Figure 5. Estimated monthly production amounts (kWh) of the design made with the PVsyst

When the loss diagram obtained as a result of the simulation is examined, the annual global radiation amount coming to the horizontal plane in the area where the panels are installed is 1.408 MWh/m² (Figure 6). As a result of azimuth angle, panel inclination and shading objects, the effective radiation amount hitting the panels decreased to 1.346 MWh/m². The radiation loss due to close shading objects is 4.68 % and the loss due to reflection is 3.77 %.

When the contamination loss of the panels is accepted as 1%, the effective irradiation amount reaching the panels is 1.346 MWh/m² when the optical losses to the panels are subtracted. Since the area covered by the panels is 56 m^2, the energy that can be produced with the total incoming 1.346 MWh/m² radiation will be 1.346 $MWh/m^2 * 56\ m^2 = 75.376$ MWh. Since the STC (Standard Test Conditions) efficiency of the PV panels used in the solar power plant is 20.01 %, the amount of energy converted will be 14.95 MWh.

The PV loss due to irradiance level is 1.12 % as the panels receive less radiation than they should. The loss in the panels due to temperature is 7.95%, the main reason for this situation is that the panels are installed fully integrated on the roof without leaving enough air space. For the existing installed power plant, PVsyst calculated the estimated annual production result as 13.642 MWh when we selected the installation type as "Free modules with air circulation" in the calculations made under the thermal parameters tab in the detailed losses section while keeping all system features the same. When "Semi-integrated with rear air duct" is selected, the production value is calculated as 13.296 MWh. However, when the installation type of the photovoltaic system is selected as "Integrated with rear insulation", where the photovoltaic system is fully integrated on the roof, the estimated annual production is lower at 12.912 MWh. This result shows us to what extent the roof mounting type affects the thermal losses.

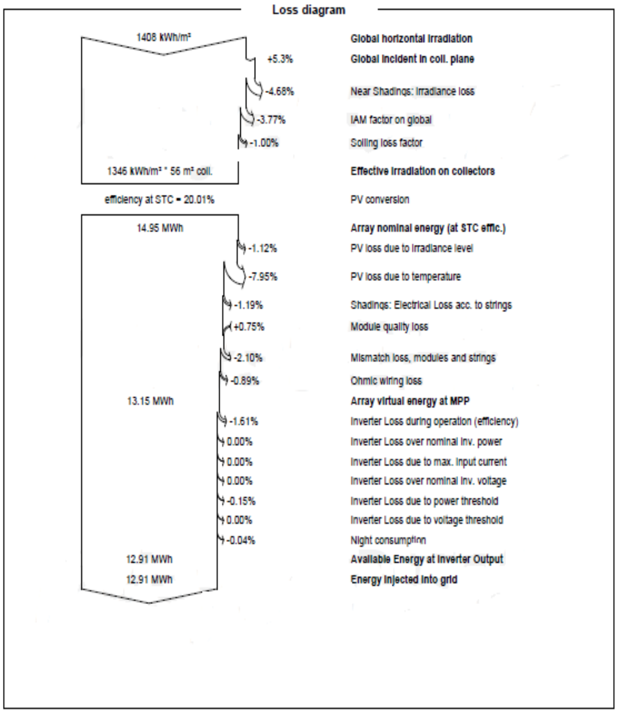

Figure 6. Loss diagram of the design with the PVsyst

According to the module chains, the electrical loss due to shadowing is 1.19 %. According to the power tolerance and quality of the modules determined during production, no loss was observed. Additionally, a gain of 0.75% was observed. Mismatch losses due to the connection type of panels and arrays were calculated as 2.10%. Mismatch losses also increase due to shadowing on the panels. The ohmic wiring loss was calculated as 0.89%. As a result of the array losses, the total energy at the panel outputs was 13.15 MWh.

The loss due to the inverter efficiency is 1.61%. The loss due to the inverter exceeding the required power limits is 0.15%. The loss due to the inverter's electricity consumption at night is calculated as 0.04%. In total, 1.80% loss is foreseen in the inverter. After the losses in the inverter, the energy generated by the photovoltaic system at the output of the inverter and supplied to the grid is calculated as 12.91 MWh.

3.2. Design results with PVSOL program

As a result of the calculations, while the PVSOL software finds the annual production amount to be 14.910 MWh without the shading effect of the main building and tree, it is seen that it decreases to 13.556 MWh when the shading effect is included. According to the PVSOL program, the shading effect causes an annual loss of approximately 9.08%.

With PVSOL software, it was concluded that the system can generate 13.556 MWh of electrical energy per year. The performance of the system was calculated as 78.66%. With the PVSOL software, it is estimated that the highest electricity production will occur in June and the lowest production will occur in December (Figure 7).

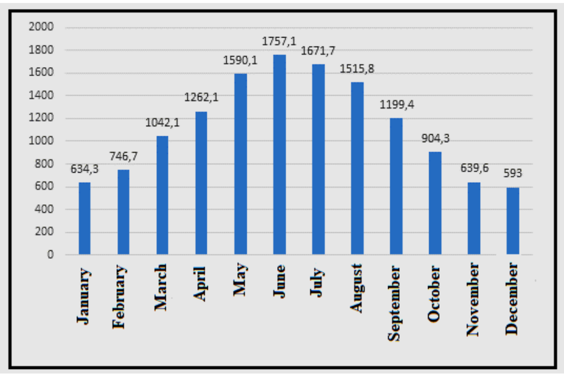

Figure 7. Monthly production amounts (kWh) found as a result of the PVSOL design

3.3. Economic analysis

The photovoltaic system installed on the roof of the school cafeteria was installed in November 2020 with an installation cost of approximately 85 000 TL ($10 193 - dollar exchange rate: 8.34 TL). A total of 28 panels cost $6 799.52, the inverter cost $1 798.56, and a total of $1595 was spent on project costs, metal rails, cabling, installation and labor costs. Since the system land belongs to the public, no rent or tax is paid. With PVsyst software, it was concluded that the system would operate for 25 years and generate 12.9 MWh of electricity per year, and since the Renewable Energy Resources Support Mechanism (YEKDEM) solar energy purchase price is determined as 13.3 cents/kWh with a 10-year purchase guarantee for Renewable Energy Resources (YEK) certified facilities that have entered into operation until 06.30.2021, when the sales tariff for the system installed in November 2020 is entered as 13.3 cents/kWh, the system will pay for itself after approximately 6.0 years. However, since the photovoltaic system installed on the roof cannot meet the self- consumption of the school, the offset is realized in kWh, not in money. When the amount of electricity produced by the system is read and deducted from the two-way meter, the remaining kWh amount is paid to the distributor company [17].

In November 2020, when the electricity bills received by the school are examined, the distributor company sells electricity to the institutional consumer with a tariff of 0.99154 TL/kWh, including consumption cost, taxes and funds [18]. Considering that the PVsyst software will generate 12.912 MWh of electricity per year, the amount of the invoice that the school will pay to the distributor company will decrease by 12 912*0.99154 TL= 12 802.76 TL per year. It is seen that the photovoltaic system will reduce the amount of electricity bills that the school will pay annually by 12 802.76 TL and will amortize the total installation cost of 85 000 TL in November 2020 within 6.64 years.

Due to the COVID-19 Pandemic, distance education was partially or completely switched to distance education in some months during the 2019-2020 and 2020-2021 academic years. Since there were no students in the school during these periods, electricity consumption data for 2018 was used to understand the full capacity of consumption. The school's electricity consumption in 2018 was 44. 072,73 MWh per year and the photovoltaic system produced a total of 12.473 MWh of electricity throughout 2021. This shows that the photovoltaic system alone cannot meet the electricity consumption.

As can be seen in Table 3, production covered consumption only in July. In July and August, it was seen that the system could meet the consumption as a result of the decrease in electricity consumption due to the school's summer vacation, the department workshops not working, and the heaters not burning.

Table 3. Electricity consumption of the school by month

Months	Electricity Consumption of the School in 2018 (MWh)	Production Values of Photovoltaic System in 2021 (MWh)
January	5.94159	0.460
February	3.44331	0.664
March	4.66566	0.924
April	4.35849	1.181
May	3.81063	1.451
June	2.82501	1.520
July	1.62702	1.633
August	1.51572	1.501
September	2.5617	1.252
October	5.78322	0.939
November	2.61693	0.559
December	4.92345	0.389
Total	**44.07273**	**12.473**

It was observed that the difference between the production and consumption amounts increased with the increase in electricity consumption especially in winter months and the decrease in sunshine duration and solar radiation values.

The photovoltaic system installed on the roof produced a total of 12.473 MWh of electrical energy during the 1-year in 2021. Table 4 shows the comparison of the amount of electricity generated by the system with the simulation results of the software.

For 2021, it is seen that the production forecast values of the PVSOL software are higher than the real-life data of the system. It is seen that the closest forecast of the PVSOL software to the real-life data was realized in August 2021. For 2021, the forecast values of PVSOL software deviated the most from the real-life data in June and December.

PVsyst software, on the other hand, made its closest prediction for 2021 in September and October, and showed the most deviation from the real-life data in March and December for 2021. For 2021, the estimated production value of the software is generally higher than the real-life data. In 2021, the real-life data was lower than the production results predicted by both software (Table 4).

Table 4. Monthly comparison of simulation results with the real-life data of the photovoltaic system

Months	PVsyst (MWh)	PVSOL (MWh)	The real-life data in 2021 (MWh)
January	0.512	0.6343	0.460
February	0.689	0.7467	0.664
March	1.016	1.0421	0.924
April	1.232	1.2621	1.181
May	1.465	1.5901	1.451
June	1.561	1.7571	1.520
July	1.620	1.6717	1.633
August	1.542	1.5158	1.501
September	1.254	1.1994	1.252
October	0.935	0.9043	0.939
November	0.627	0.6396	0.559
December	0.458	0.593	0.389
Total (MWh/year)	**12.912**	**13.556**	**12.473**

During 2021, the rooftop photovoltaic system produced a total of 12.473 MWh of electricity. PVsyst software estimated the total amount of energy that can be produced for 2021 as 12.912 MWh/year and PVSOL software estimated it as 13.556 MWh/year. There was a difference of 0.439 MWh with PVsyst software and 1.083 MWh with PVSOL software between simulation results and the real-life data for 2021. There is an annual difference of 3.40% with PVsyst software and 7.99 % with PVSOL software.

PVSOL software shows the annual average global solar radiation value of the region where the panels are installed as 1.504 MWh/m^2 and makes calculations according to this value, while PVsyst software shows the annual global solar radiation value of the same region as 1.408,4 MWh/m^2 and makes production calculations according to this value. According to the SEPA map, the global solar radiation value of most of Gümüşhacıköy district is between 1400-1450 kWh/m^2.

The photovoltaic system installed on the examined roof does not work with optimum efficiency due to the low roof slope and the roof not facing exactly south. According to the calculations made with PVsyst software, the most suitable panel inclination for the location where the panels are installed is 33° and the panel directions are oriented exactly to the south (azimuth angle = 0°). However, the panel slopes of the fully integrated (non-ventilated) panels on the roof are 11^o and the panel orientations are deviated from the south direction to 40^o east direction. This significantly reduced the amount of electricity generated by the system.

With the calculation made with PVsyst software, if the main building and the tree had remained in place and all photovoltaic features were used in the same way without changing the panels and inverters used in the system, if the azimuth direction had remained the same (azimuth =-40^o) and only the panel vertical slope had been placed at 33^0, the estimated annual production of PVsyt software would be 13.317 MWh/year. This would be 0.405 MWh/year more than the 12.912 MWh/year calculated by the PVsyst software with panel inclinations of 11^o. If the panels were installed in the most optimum situation with the panel orientations facing full south and the panel slope was 33^o, the PVsyt software estimated annual production would be 13.943 MWh/year.

4. Conclusion

In this study, the real electricity production data of the 10 kWp Photovoltaic Solar Energy System installed on the roof of the school cafeteria in Gümüşhacıköy district of Amasya province was compared with the results obtained using PVsyst and PVSOL software. Comparison of the real-life data with the computational results given by the software is important data for measuring the degree of accuracy and analyzing the extent to which shading losses affect the photovoltaic system. At the same time, these comparison results can also be characterized as a feasibility study to understand whether solar power plants can be invested in Gümüşhacıköy district and for future photovoltaic applications.

As a result of the evaluations made on the 10 kWp Photovoltaic solar energy system, it was determined that the software used gave approximate results to the real production data.

As a result of the calculations made by entering all the parameters of the system, it was concluded that a total of 12.912 MWh of electrical energy could be produced annually with the PVsyst software, and 13.556 MWh of energy could be produced annually with the PVSOL software. During 2021, the actual amount of energy produced by the photovoltaic system was determined as 12.473 MWh. The amount of electrical energy produced is lower than the simulation results with both software for 2021. It was observed that there was a total annual deviation of 3.40 % from the real-life data with the PVsyst software and 7.99 % annually with the PVSOL software.

According to the Turkish National Electricity Grid Emission Factor Information Form prepared by the Ministry of Energy and Natural Resources, the system prevented 12.473 MWh * 0.6482 tons = 8.085 tons of CO_2 emissions for 2021, considering that it prevented 0.6482 tons of CO_2 emissions for every 1 MWh of electricity generated from solar or wind energy [19]. Considering that the system will operate for 25 years, it is calculated that it will reduce a total of 202.125 tons of CO_2 emissions.

Article Information Form

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This study does not require ethics committee permission or any special permission.

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