

A Comparative Analysis of Estimated and Actual Energy Output in Residential Photovoltaic Systems in Craiova, Romania

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Abstract - Accurate estimation of photovoltaic (PV) energy production is essential for ensuring the optimal design, operation, and economic viability of solar installations. However, discrepancies often arise between predicted and actual energy yields, particularly in regions characterized by variable meteorological conditions. The paper presents a synthesis of methods for estimating energy production of photovoltaic systems. For two types of residential systems located in Craiova, a comparative analysis is presented between the estimated values obtained using the most efficient methods and the actual measured values. The research combines simulation-based predictions with real operational data collected over a defined monitoring period to evaluate the accuracy of commonly used estimation models. To estimate solar radiation and energy production, some of the most common specialized software for renewable energy sources were used. The findings reveal that estimation tools tend to overpredict energy output during periods of high temperature and unstable atmospheric conditions, while performing more accurately during stable seasonal intervals. These results highlight the importance of localized calibration of prediction models and the integration of detailed climatic data for improving accuracy. The study contributes valuable insights for system designers, operators, and policymakers seeking to enhance PV system reliability and advance renewable energy planning in Romania and similar climatic regions.

Cuvinte-cheie: *sisteme fotovoltaice rezidentiale, energie estimata, energie produsa, radiatie solara.*

Keywords: *residential photovoltaic systems, energy estimation energy production, solar irradiation.*

I. INTRODUCTION

The rapid global expansion of photovoltaic (PV) technologies has intensified the need for accurate methods of estimating energy production in order to ensure efficient system design, economic feasibility, and long-term operational reliability [1]. In this context, comparing estimated energy output with actual measured production is essential for evaluating both the performance of PV installations and the accuracy of the prediction models employed. Such assessments are particularly relevant in regions with variable climatic conditions, where meteorological fluctuations can significantly influence solar energy yields.

Craiova, located in the southwestern part of Romania, represents an area characterized by a temperate-

continental climate with distinct seasonal variations. These conditions can lead to notable discrepancies between predicted and real PV energy generation, making the region suitable for case studies aimed at performance evaluation and model validation. Understanding these discrepancies is crucial for improving forecasting methodologies, optimizing system configurations, and enhancing the overall reliability of renewable energy integration into the local grid.

Energy production estimation for PV systems can be conducted through various approaches, depending on the desired level of accuracy, the availability of input data, and the intended application (e.g., system design, performance monitoring, research). Existing literature [2], [3], [4] has addressed this topic extensively, with most studies focusing on the quantification of available solar radiation.

The present paper outlines several specific methods for evaluating the energy production of residential photovoltaic systems located in a specific area [5],[6],[7]. The chosen location is the city of Craiova, Romania. The photovoltaic energy production estimated using these methods is compared with the actual energy generated by residential photovoltaic systems.

A comparative case study is conducted on two residential PV configurations: an off-grid system with panels installed on a flat terrace and a grid-connected system with panels mounted on a pitched roof.

A preliminary version of this study was presented in [5].

II. A COMPARATIVE ANALYSIS OF THE METHODS USED TO ESTIMATE THE ENERGY PRODUCED BY PHOTOVOLTAIC SYSTEMS

In the specialized literature, numerous methods exist for estimating the energy output of photovoltaic (PV) systems. Essential factors that must be considered in any estimation method include [8], [9], [10]:

- local solar irradiation – the primary variable
- panel orientation and tilt
- effect of temperature
- losses: cables, inverter, shading, dust, mismatch
- annual panel degradation (0.3–0.8% per year)
- system availability (operating time without interruptions).

A synthesis of the main estimation methods is presented below:

1. First-approximation method

This approach is based on simple theoretical estimates using the equation [5]:

$$E = G \cdot A \cdot \eta \quad [\text{kWh}] \quad (1)$$

where:

E -energy produced [kWh]

G -average annual solar irradiation (irradiance) [kWh/m²]

A -PV panels area surface [m²]

η -overall efficiency (panels + inverter + losses).

This method is fast and easy to apply, but does not account for seasonal variations, detailed losses, or specific local conditions.

2. Method based on climatological data and correction factors

This method uses meteorological databases (e.g., Meteonorm, PVGIS) for radiation and temperature, applying specific loss factors such as those caused by temperature, shading, or soiling of the PV modules.

It offers greater accuracy by using real-world data, but requires access to climatic datasets and knowledge of the installation parameters [8], [9].

3. Computer simulation (dedicated software)

Examples of software include PVGIS, PVsyst, PV*SOL, Helio Scope, and SAM (NREL).

These tools model the PV system using actual parameters and hourly meteorological conditions, including 3D shading effects [9], [10].

Such methods are highly accurate and ideal for system sizing and economic analysis, but may require a license, as well as time for detailed modeling.

4. In-situ measurement method

This approach involves radiation and temperature sensors that measure actual production over a short period (e.g., several months), followed by long-term extrapolation [4].

It accurately reflects local conditions, but requires a longer time to obtain estimates and entails additional equipment costs.

5. Statistical method based on similar installations

Historical data from PV systems with comparable characteristics and location are used.

This method is quick and based on real performance results, but depends on the availability of relevant data and the exact similarity of operating conditions.

The above methods are summarized in Table I, and a complexity–accuracy analysis of these methods is illustrated in the chart shown in Figure 1.

The selection of an appropriate method for estimating the energy production of photovoltaic systems depends on the purpose of the analysis and the required level of accuracy. Software simulations are suitable for preliminary assessments and system sizing, whereas on-site measurements provide more precise data, essential for detailed feasibility studies and performance optimization.

A 2024 study [11] shows that PV system performance depends significantly on local climatic conditions (irradiance, temperature, humidity, and losses) and recommends incorporating all these factors into the modelling framework to obtain realistic predictions.

The comparative analysis [12] highlights that the choice of the irradiance database (satellite products, reanalysis data, or ground measurements) strongly influences production estimates — differences between datasets can lead to substantial variations in the predicted annual energy yield.

Recent research [13] emphasizes that software-based simulation methods — integrating irradiance, module temperature, losses, and degradation — provide the most robust production estimates, particularly when input parameters are well characterized.

For short-term forecasting (hours to days), hybrid approaches that combine physical models, automatically bias-corrected climatological data, and machine-learning/statistical techniques tend to reduce errors compared to simple baseline methods [14].

TABLE I.
COMPARATIVE TABLE OF METHODS FOR ESTIMATING THE ENERGY OUTPUT OF PHOTOVOLTAIC SYSTEMS

Method	Principle	Required Data	Deviation	Advantages	Disadvantages	Example Applications
Simple Theoretical Estimation	Calculates energy based on average solar radiation and overall efficiency	Average annual irradiation, panel surface area, overall efficiency	±20–30%	Fast, easy to apply, does not require software	Does not account for seasonal variations, detailed losses, or local conditions	Preliminary estimates, concept-stage projects
Climatological Data Correction Factors	Uses tilted-plane irradiation and associated loss factors	Monthly/hourly meteorological data, technical parameters of the system	±10–15%	Relatively accurate, accounts for real losses	Requires reliable local data	Technical and economic feasibility studies
Software Simulation	Models the system using actual parameters and hourly conditions	Detailed meteorological data, panel and inverter specifications, site geometry	±5–10%	Highly accurate, includes shading, orientation, and degradation	Requires software and modeling time	Professional projects, tenders, investment analysis

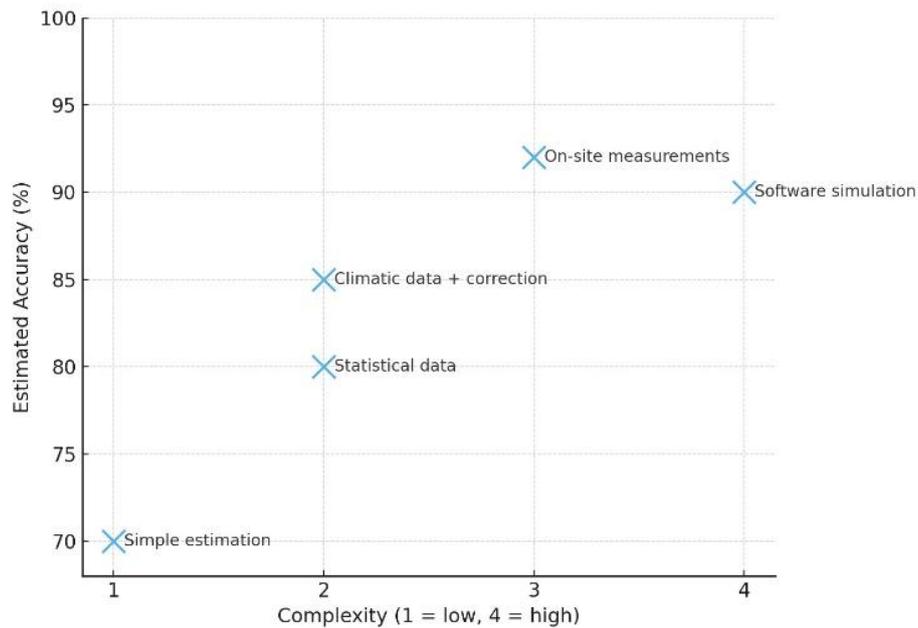


Fig. 1. PV energy production estimation methods. Complexity versus accuracy

The accuracy of PV energy yield estimation is most commonly determined by comparing the estimated output with the measured production and quantifying the deviation. For instance, in the case of a simple theoretical estimation method, a 30% deviation corresponds to an estimated accuracy of approximately 70%. According to the chart in Figure 1, it can be observed that, in terms of complexity and accuracy, methods based on dedicated simulation software and those employing on-site measurements are the most suitable.

Therefore, in the case study presented in this paper, these methods will be applied.

III. IMPLEMENTATION OF ENERGY YIELD ESTIMATION METHODS FOR PHOTOVOLTAIC SYSTEMS LOCATED IN CRAIOVA

The case study analyzes the energy production of two types of residential photovoltaic systems located in Craiova, Romania. The first photovoltaic system is an off-grid type with PV panels mounted on a terrace, while the second system is an on-grid type with PV panels mounted on a pitched roof.

A. Off Grid Photovoltaic System

The off-grid photovoltaic system (Figure 2) has the following characteristics:

- PV capacity: 3 kWp
- PV module type: 12 polycrystalline silicon PV modules, model Conergy 245P
- total module area: 20 m²
- PV module efficiency: 15.6%

Because solar radiation is the most important parameter for estimating the energy production of photovoltaic systems, in the first part a comparative analysis is made between the estimated and the real, measured solar radiation.

To estimate the solar irradiation and the energy production, the PVGIS24 software was used.

The PVGIS software, through the GIS component, provides information about the geolocation of the analyzed photovoltaic system as seen in Figure 2.

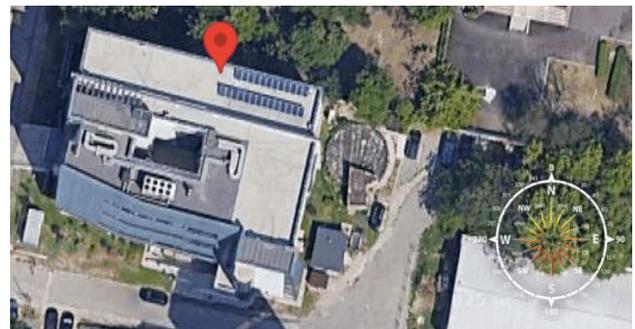


Fig. 2. Geolocation of photovoltaic system

PVGIS24 is a modernized version featuring an advanced interface, geolocation through Google Maps, and complex simulations with multiple inclinations and orientations. It includes intuitive charts, CSV/JSON export options, and an analysis of natural terrain shading; however, it does not account for artificial obstacles such as trees or buildings.

Key Features of the PVGIS24 Software:

- Estimation of annual energy production (kWh), equivalent full-load hours at nominal power (kWh/kWp), monthly distribution, and graphical tools to support optimization.
- Data export capabilities in CSV, JSON, or PDF formats.
- Integrated Financial Simulator that enables the assessment of self-consumption, cost savings, and return on investment (ROI) by incorporating information on energy consumption, costs, subsidies, and other parameters.

- High flexibility, making it suitable for both basic users and professionals (households, institutions, consultants, etc.).

- High accuracy, based on satellite-derived datasets and climate reanalysis.

- Terrain shading analysis, particularly relevant in mountainous regions or densely built urban areas.

The simulation results are presented in Figure 3. In estimating solar irradiation and energy production using the PVGIS software, in addition to the technical characteristics of the photovoltaic system, other real operating condi-

tions were also considered, such as the positioning of the PV panels, the tilt angle, and related parameters.

Measurement of solar irradiation was carried out with the monitoring equipment of a photovoltaic system located in Craiova (Figure 4 and Figure 5).

Weather parameters were monitored online and stored on an SD card.

Data is downloaded in * CSV format that can be easily imported into Excel and then processed in the desired form.

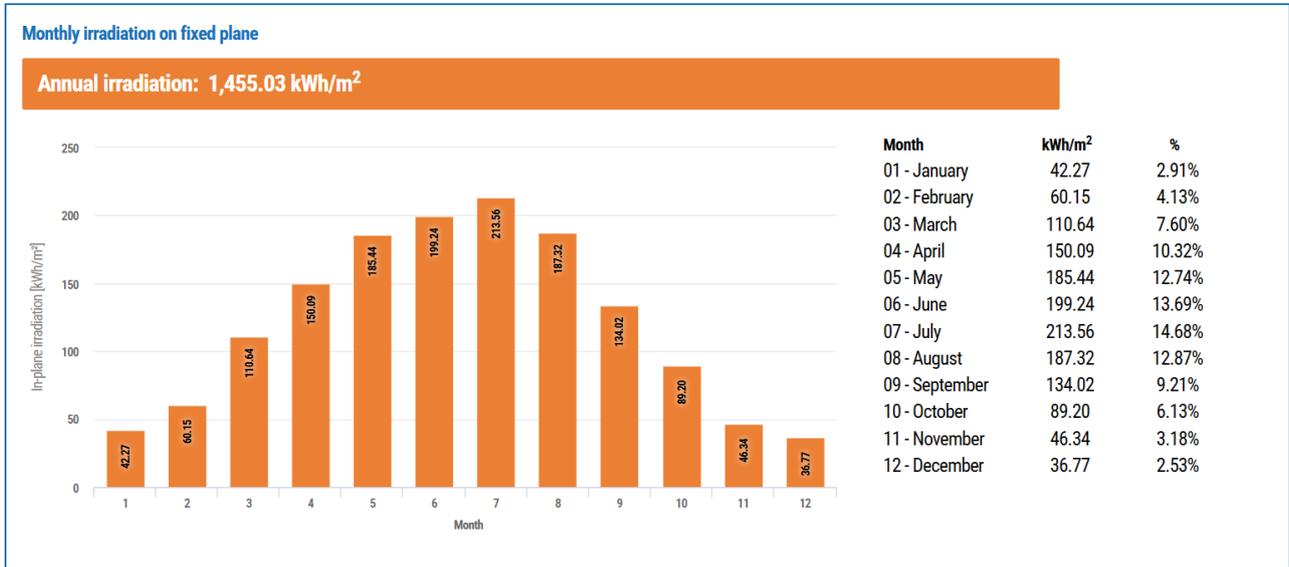


Fig. 3. Monthly irradiation on fixed PV plan – estimated values



Fig. 4. Equipment for measuring weather parameters: 1- pyranometer; 2- anemometer.



Fig. 5. Window of monitoring system

The resulting graph of solar radiation monitoring is presented in Figure 6 during the year 2025, up to the present.

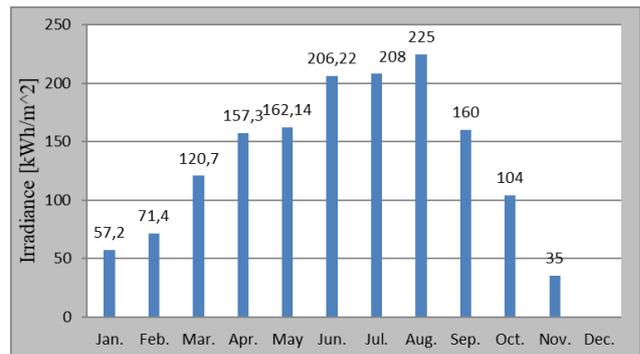


Fig. 6. Monthly irradiation on PV plan measured during the year 2025

To verify the accuracy and performance of the monitoring system's pyranometer, a Skylinx weather station containing a high-precision pyranometer was used.

The used pyranometer to measure the global solar irradiation was Li-200S, manufactured by Li-Cor Inc. Lincoln, Nebraska, US, (City, State if US, Country), with a measurement error $\pm 5\%$, and with a measurement accuracy comparable to pyranometers of class 1, according to [15]. This pyranometer transmits a current output signal with a sensitivity of $10 \mu A$ at $1000 W/m^2$.

For the comparative analysis, two days with different levels of solar radiation were taken into account, namely 2025.01.15 and 2025.06.15. The resulting graphs are presented in Figure 7 and Figure 8, respectively.

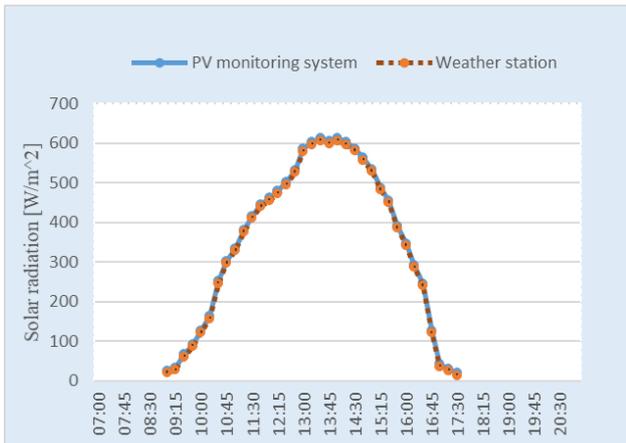


Fig. 7. Chart of global solar irradiation, measured on 2025.01.15

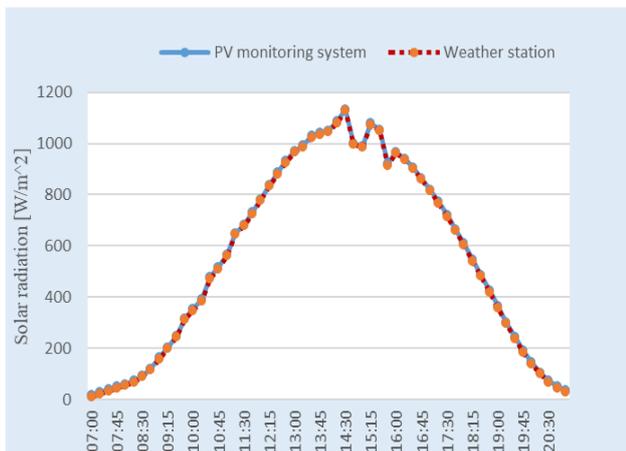


Fig. 8. Chart of global solar irradiation, measured on 2025.06.15

As seen in Figures 7 and 8 the measurements obtained from the two pyranometers show no significant differences

Based on the solar radiation graphs presented in Figures 3 and 6, a comparative analysis was made between the estimated and calculated solar radiation. The numerical values are presented in Table II.

TABLE II
ESTIMATED AND MEASURED SOLAR RADIATION VALUES DURING THE YEAR 2025

Month	Estimated solar radiation [kWh/m ²]	Measured solar radiation [kWh/m ²]	Relative deviation [%]
Jan.	42,27	57,2	26,10
Feb.	60,15	71,4	15,75
Mar.	110,64	120,7	8,33
Apr.	150,09	157,3	4,58
May	185,44	162,14	14,37
Jun.	199,24	206,22	3,38
Jul.	213,56	208	2,67
Aug.	187	225	16,88
Sep.	134	160	16,25
Oct.	89	104	14,42
Nov.	46	35	31,42
Average value	128,25	136,99	14,01

According to the values presented in the table II, there is an average relative deviation between the estimated and measured solar radiation of 14.01 %. It is mentioned that the comparative analysis was made until December 2025, the current moment when the article was elaborated.

Similarly, for the photovoltaic system analyzed using the PVGIS24 software, the estimated energy production graph was generated (Fig. 9).

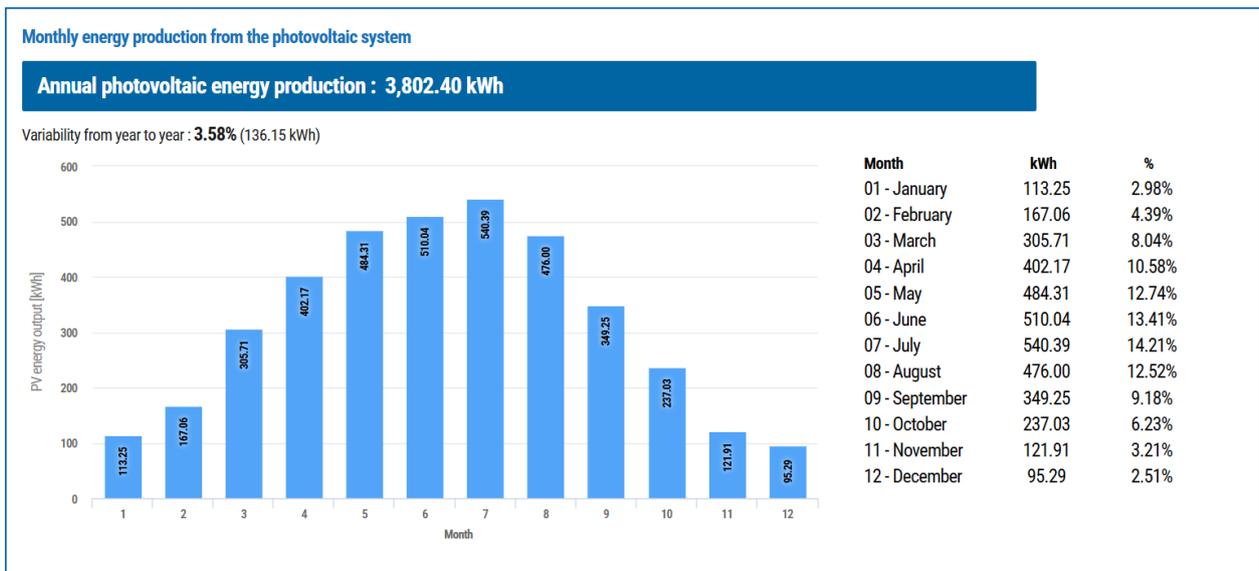


Fig. 9. Monthly energy production from the off-grid PV system – estimated values

Over the course of one year, the monthly solar irradiation reaches approximately 1445 kWh/m², whereas the annual energy output of the PV system amounts to 3802 kWh.

To perform a comparative analysis between the estimated photovoltaic energy production and the actual photovoltaic energy production, data provided by the PV system's own monitoring system were used.

The data regarding energy production were processed and presented in a graphical format suitable for comparative analysis (Fig. 10, 11).



Fig. 10. Monthly DC energy production from the PV system measured during the year 2025

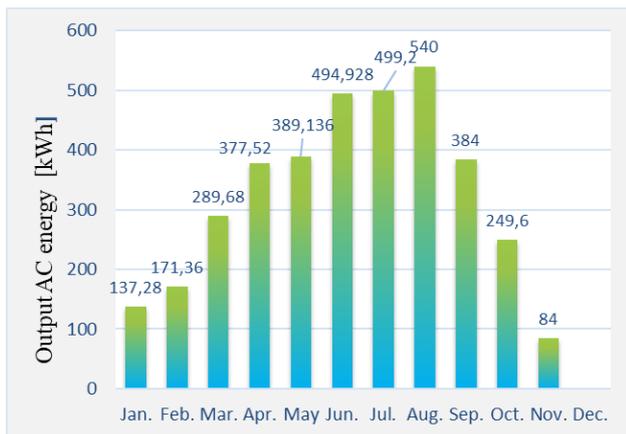


Fig. 11. Monthly AC energy production from the PV system measured during the year 2025

Based on the energy production graphs presented in Figures 9 and 11, a comparative analysis was made between the estimated and calculated output energy. The numerical values are presented in Table III.

TABLE III
ESTIMATED AND MEASURED OUTPUT ENERGY VALUES OF PV SYSTEM DURING THE YEAR 2025

Month	Estimated output energy [kWh]	Measured AC output energy [kWh]	Relative deviation [%]
Jan.	113,25	137,28	17,50
Feb.	167,06	171,36	2,50
Mar.	305,71	289,68	5,53
Apr.	402,17	377,52	6,52
May	484,31	389,136	24,45
Jun.	510,04	494,928	3,05
Jul.	540,3	499,2	8,23
Aug.	476	540	11,85
Sep.	349	384	9,11
Oct.	237	249,6	5,04
Nov.	121	84	44,04
Average value	336,89	328,79	12,53

According to the values presented in the Table III, there is an average relative deviation between the estimated and measured output energy of 12.53%.

In general, the differences between the estimated and measured energy are not significant. The exception is No-

vember, because in 2025 it was an atypical month, with few sunny days.

B. On grid photovoltaic system

The on-grid connected photovoltaic system (without storage) is installed at a residential house and mainly consists of:

- 16 photovoltaic panels grouped into two strings (PV1 and PV2), each with 8 panels;
- a single-phase HUAWEI SUN2000-6KTL-L1 inverter with a power rating of 6 kW.

The photovoltaic panels are mounted in a fixed position on the south-facing slope (PV1) and the west-facing slope (PV2) of the building's roof. The main technical characteristics of a photovoltaic panel are as follows:

- PV capacity: 7,4 kWp
- type of PV panels: monocrystalline - half-cell PV modules, model Huawei, MF0020, 465 W
- photovoltaic surface area: 35,34 m²
- PV panel efficiency: 21,05%



Fig. 12. Image of the PV panels mounted on the West facade of the roof (PV2 string)

The PV system contains a monitoring software application called Fusion Solar. This is Huawei's inverter software ecosystem for PV system monitoring and management. It includes a mobile application and a web platform/cloud-portal.

The web platform is often called SmartPVMS — Smart PV Management System — and enables the management, monitoring, and maintenance (O&M) of PV plants.

A screenshot of the main application screen is shown in Figure 13.

This image displays the energy produced by the PV system instantly.

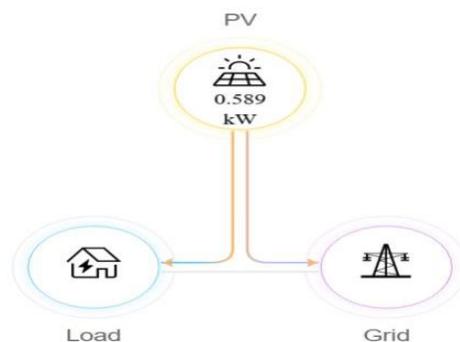


Fig. 13. The main screen of FusionSolar application

Similarly, to the previous example, the estimation of energy production was performed using the PVGIS24

software. The simulation result is illustrated in the graph shown in Figure 14.

By employing the FusionSolar monitoring software associated with the Huawei inverter, the actual energy output of the photovoltaic system was recorded.

The monthly graph of the energy produced throughout the year 2025, up to the present, is presented in Figure 15.

As in the previous case, to make a comparative analysis between the estimated and measured energy, the numerical values were represented in Table IV.

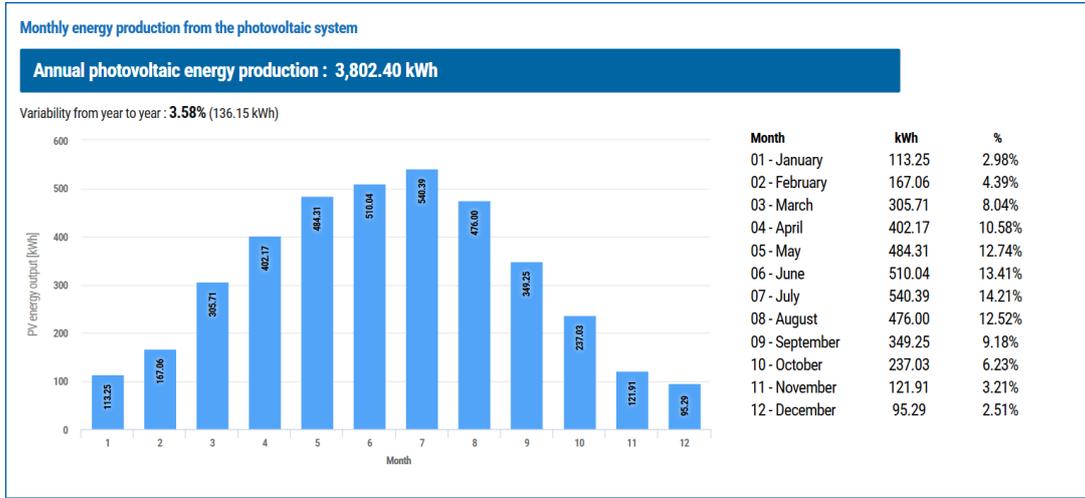


Fig. 14. Monthly energy production from the on-grid PV system - estimated values

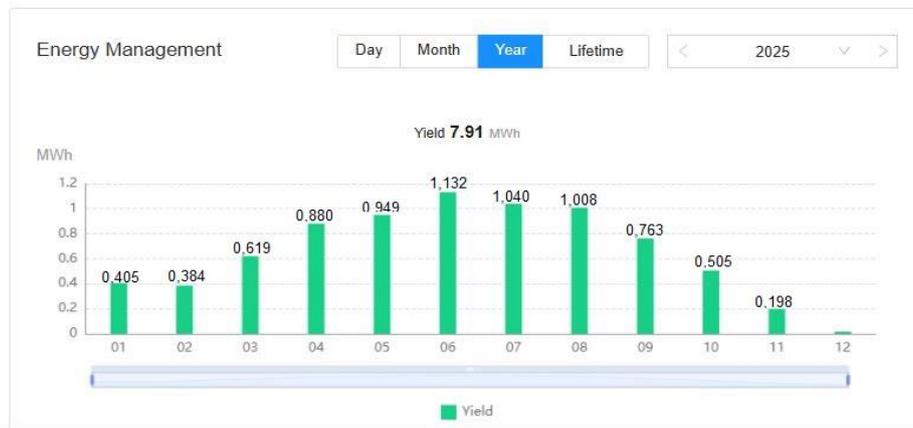


Fig. 15. Monthly energy production from the on-grid PV system measured during the year 2025

TABLE IV
ESTIMATED AND MEASURED OUTPUT ENERGY VALUES OF ON GRID PV SYSTEM DURING THE YEAR 2025

Month	Estimated output energy [kWh]	Measured output energy [kWh]	Relative deviation [%]
Jan.	334	405	17,53
Feb.	452	384	17,70
Mar.	758	619	22,45
Apr.	930	880	5,68
May	1059	949	11,59
Jun.	1090	1132	3,71
Jul.	1169	1040	12,40
Aug.	1087	1008	7,83
Sep.	839	763	9,96
Oct.	639	505	26,53
Nov.	358	198	80,80
Average value	792,27	716,63	19,65

According to the data in the table, it can be observed that the difference between the estimated energy and the measured energy is 19.65%, which is approximately 7%

higher compared to the previously analyzed off-grid PV system.

IV. DISCUSSIONS

The comparative analysis performed for the two photovoltaic systems highlights several important aspects regarding the accuracy of energy production estimation models under the climatic conditions specific to the Craiova region. In both case studies, the simulation results obtained with the PVGIS24 software show a tendency to overestimate the actual energy output. This effect is consistent with observations reported in the literature, especially for areas characterized by variable atmospheric transparency, periods with increased cloudiness and elevated temperatures during the summer months.

For the off-grid system, the average deviation between estimated and measured energy production is 12.53%. This value indicates a relatively good agreement between the prediction models and real-world operating conditions, with the exception of specific months in which irradiation variability was more pronounced. The November deviation corresponds to an atypical month in terms of solar

availability, which confirms the sensitivity of simulation tools to meteorological anomalies not fully captured in historical databases.

The on-grid system exhibits a higher average deviation of 19.65%, approximately 7% above the value obtained for the off-grid system. This difference can be attributed to several technical and environmental factors: 1) the presence of two roof orientations—south and west—which introduces non-uniform irradiation profiles; 2) higher operating temperatures on rooftop-mounted modules, which reduce electrical efficiency; and 3) potential partial shading or local obstacles not considered in the PVGIS terrain-based shading model. Additionally, inverter clipping during periods of high irradiance may contribute to reduced energy yield, especially for the 6 kW inverter operating with a 7.4 kWp installed capacity.

Solar radiation analysis further indicates an average deviation of 14.01% between estimated and measured irradiation. Since irradiation is the primary variable used in PV energy models, this discrepancy directly influences the accuracy of the estimated energy outputs. Therefore, improving the precision of local irradiation data—through the use of in-situ sensors, long-term monitoring, or refined satellite datasets—would significantly enhance predictive accuracy.

Overall, the study confirms that while PVGIS24 provides reliable preliminary estimations, localized calibration and real-time monitoring remain essential for accurate performance assessment, system optimization, and investment decision-making.

V. CONCLUSIONS

This research presents a comparative evaluation of estimated and measured energy production for two residential photovoltaic systems installed in Craiova, Romania. The results demonstrate that simulation tools such as PVGIS24 offer reasonably accurate predictions but tend to overestimate the real energy yield, with deviations ranging between 12% and 20% depending on system configuration and seasonal conditions.

For the off-grid system, the average deviation of 12.53% indicates that the estimation model performs well when the installation is less influenced by complex shading or thermal effects. In contrast, the on-grid rooftop system shows a higher deviation of 19.65%, emphasizing the influence of module orientation, roof mounting temperature effects, and other local factors not fully integrated into the simulation model.

The comparison of estimated and measured solar radiation further reveals an average deviation of 14.01%, suggesting that irradiation data is a major source of uncertainty in predictive simulations. This finding reinforces the importance of continuous on-site monitoring using calibrated pyranometers to improve long-term prediction accuracy.

In conclusion, the study shows that software-based estimation remains a valuable tool for preliminary design, feasibility studies, and performance assessment. However, for detailed analysis and optimization, real operational data and localized calibration are indispensable. Future work may focus on integrating machine-learning-based correction models, extending measurement campaigns, and developing hybrid datasets combining satellite and in-situ information to further enhance prediction accuracy for

photovoltaic systems in Romania's variable climatic conditions.

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Contribution of authors:

First author – 50%

First coauthor – 20%

Second coauthor – 20%

Third coauthor- 10%

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