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FACULTY OF ELECTRICAL ENGINEERING

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PREFACE

The Third International Conference "Electrical Engineering, Technology, Informatics, Mechanical Engineering and Automation – Technical Sciences in the Service of the Economy, Education and Industry" (ETIMA'25), organized by the Faculty of Electrical Engineering at the "Goce Delchev" University – Shtip, represents a significant scientific event that enables interdisciplinary exchange of knowledge and experience among researchers, professors, and experts in the field of technical sciences. The conference was held in an online format and brought together 78 authors from five different countries.

The ETIMA conference aims to establish a forum for scientific communication, encouraging multidisciplinary collaboration and promoting technological innovations with direct impact on modern life. Through the presentation of scientific papers, participants shared the results of their research and development activities, contributing to the advancement of knowledge and practice in relevant fields.
The first ETIMA conference was organized four years ago, featuring 40 scientific papers. The second conference took place in 2023 and included over 30 papers. ETIMA'25 continued this scientific tradition, presenting more than 40 papers that reflect the latest achievements in electrical engineering, technology, informatics, mechanical engineering, and automation.

At ETIMA'25, papers were presented that addressed current topics in technical sciences, with particular emphasis on their application in industry, education, and the economy. The conference facilitated fruitful discussions among participants, encouraging new ideas and initiatives for future research and projects.

ETIMA'25 reaffirmed its role as an important platform for scientific exchange and international cooperation. The organizing committee extends sincere gratitude to all participants for their contribution to the successful realization of the conference and its scientific value.

We extend our sincerest gratitude to all colleagues who, through the presentation of their papers, ideas, and active engagement in discussions, contributed to the success and scientific significance of ETIMA'25.

The Organizing Committee of the Conference

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DESIGN, ANALYSIS AND IMPLEMENTATION OF PHOTOVOLTAIC SYSTEMS

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Abstract

This paper presents the technical design and simulation-based performance analysis of a photovoltaic system implemented on the rooftop of a small industrial facility located in the central region of North Macedonia. The system includes 136 monocrystalline solar panels with a rated power of 545 W each, connected through two 36 kW Sungrow inverters and configured to efficiently support industrial energy demands.
Simulations were performed using PVsyst software based on real meteorological data from METEONORM, with calculated energy yield, monthly generation profiles, system losses, and performance ratio. The PV system demonstrated high efficiency, with a projected annual generation of 98 MWh and an average performance ratio exceeding 87%.
The technical solution also considers optimal panel orientation, tilt angles, cable dimensioning, and protection measures, in accordance with engineering standards. The project highlights the viability of rooftop PV systems in industrial applications as a reliable and sustainable energy source.

Key words

Photovoltaic system, PVsyst, METEONORM, solar energy, renewable energy, energy performance.

Introduction

Solar photovoltaic (PV) technology is a key driver of the global shift to renewable energy, offering a sustainable, low-emission alternative to conventional power. Its scalability, low costs, and versatility make it suitable for both large-scale and distributed systems. North Macedonia has strong solar potential, with daily irradiation above 4.0 kWh/m² in many areas, supported by national and EU renewable energy policies. Rooftop PV in industrial facilities can cut grid use, reduce costs, and boost energy independence. This study designs, simulates, and evaluates a rooftop PV system for a small facility in Sveti Nikole using METEONORM data and PVsyst modeling, assessing layout, yield, performance ratio, and losses to confirm feasibility and long-term benefits.

1. Literature review

Photovoltaic (PV) systems have been extensively studied as a sustainable solution for electricity generation in residential, commercial, and industrial sectors. Numerous studies [6], [10] have shown that system performance strongly depends on local climatic conditions, optimal orientation and tilt angles, and the quality of installed components. Accurate design and simulation are essential for maximizing efficiency, with PVsyst being one of the most widely used tools for performance estimation and loss analysis [8].

In industrial applications, research demonstrates that large-scale rooftop PV systems can significantly reduce operational costs and improve energy self-sufficiency, particularly when integrated with the grid under net metering policies [2], [1]. For regions with high solar irradiation, such as the Mediterranean and Balkan areas, performance ratios (PR) between 80% and 88% are commonly reported, with variations influenced by shading, temperature effects, and maintenance practices [1], [6], [8].

Although several studies have investigated PV system optimization using meteorological databases such as METEONORM [5], there is limited literature focusing on small-to-medium industrial facilities in central North Macedonia. This paper addresses that gap by designing and evaluating a grid-connected PV system for an industrial site in Sveti Nikole. The research integrates real meteorological data, detailed technical specifications, and simulation-based analysis to validate the system's performance and assess its potential for wider deployment in similar climatic regions.

2. Methodology

2.1 Site Selection & Climatic Data

The photovoltaic system is located in Sveti Nikole, in the central region of North Macedonia (41.86°N, 21.94°E). This area benefits from high solar potential, with average daily global horizontal irradiation exceeding 4.2 kWh/m². Such conditions make it highly suitable for photovoltaic energy generation.

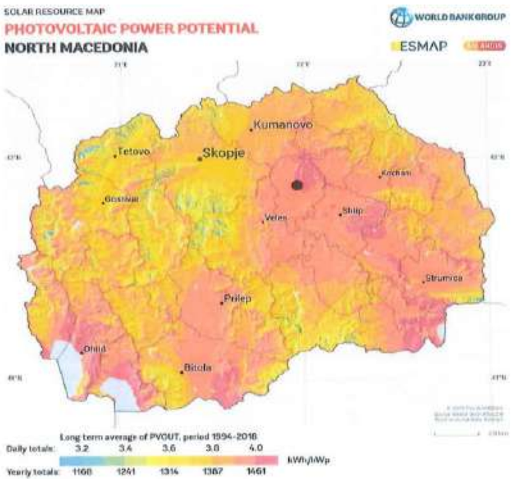

Fig. 1 Solar potential map of North Macedonia
Source: author based on [12]

Meteorological data for the site were obtained from the METEONORM 9.1.0.13 database for the period 1981–2000. The results indicate strong seasonal variation in solar radiation, with the highest values observed during the summer months.

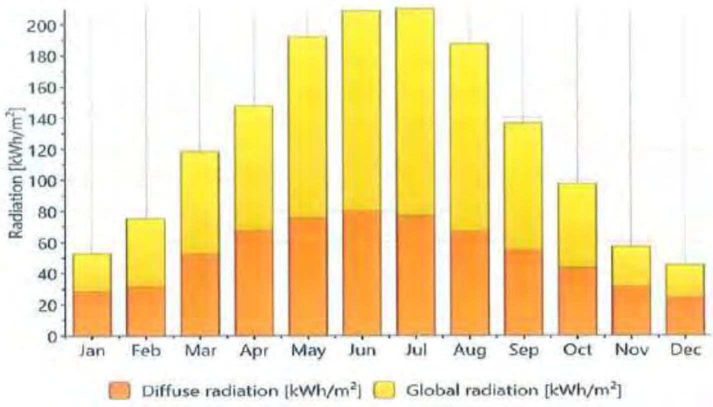

Fig. 2 Average solar radiation according to METEONORM
Source: author based on [5]

These favorable climatic conditions provide a strong foundation for achieving high energy yields from the PV system and ensure the economic viability of the project.

2.2 System Design Parameters

The photovoltaic system is mounted on the existing gable roof of the facility, with a total usable surface area of approximately 722 m². The roof has a tilt of 6% relative to the horizontal plane and is divided into two main fields with different orientations:

- Field 1: +34.0° (south-east facing)
- Field 2: –146.0° (south-west facing)

These orientations affect the angle of incidence of solar radiation and overall energy production.

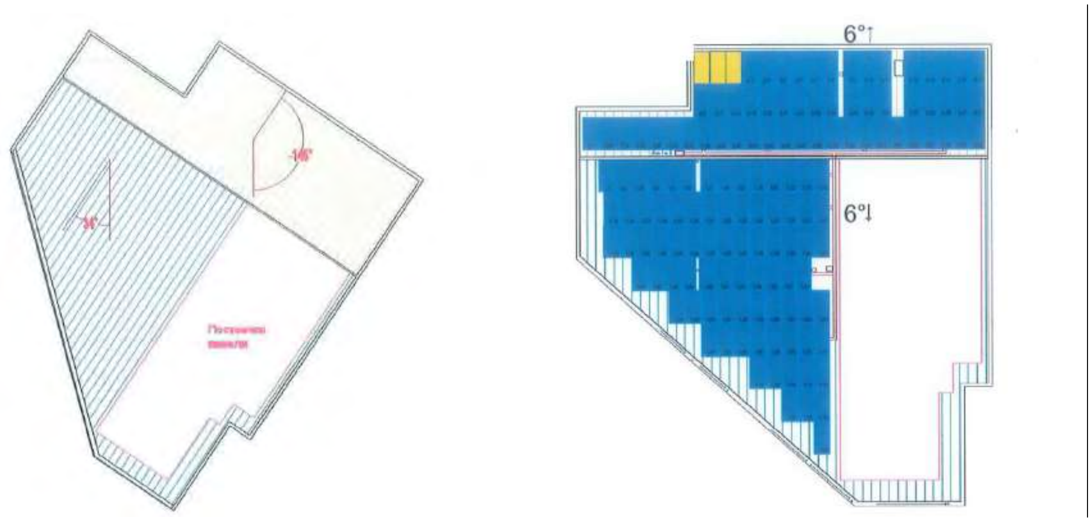

Fig. 3 Roof sketches showing orientation angles (left) and photovoltaic module layout (right)

The PV array consists of monocrystalline modules manufactured by JA Solar, model JAM72S30-545/MR, each with a rated power output of 545 W. The panels are arranged in two zones according to roof orientation. Detailed panel specifications are provided in Table 1.

Table 1: Technical specifications of the photovoltaic module

Parameter	Unit	Value
Maximum Power Pmax	[W]	545
Voltage at Maximum Power Umpp	[V]	41.8
Current at Maximum Power Impp	[A]	13.04
Open Circuit Voltage Uoc	[V]	49.75
Short Circuit Current Isc	[A]	13.86
Efficiency	[%]	21.5
Operating Temperature Range	[°C]	-40 ÷ +85
Maximum System Voltage	[V]	1500
Dimensions	[mm]	2278 × 1134 × 35
Weight	[kg]	28.6
Temperature Coefficient (Pmax)	[%/°C]	-0.45

Source: author based on [3]

The system uses two three-phase string inverters, model Sungrow SG36KTL-M, each with a nominal AC output power of 36 kW and equipped with 3 MPPT inputs and a maximum efficiency above 98%. These inverters ensure high conversion efficiency and flexibility in connecting multiple strings. Technical specifications are listed in Table 2.

Table 2: Technical specifications of the Sungrow SG36KTL-M inverter

Parameter	Unit	Value
Maximum input voltage	V	950
MPP voltage operating range	V	200–950
Nominal AC output power	W	36,000
Nominal voltage	V	400
Maximum output current	A	48
Number of inputs / MPP trackers	–	8 / 3
Efficiency (Max / Euro)	%	98.5 / 98.3
Protection rating	–	IP 65

Source: author based on [11]

2.3 Electrical Configuration

String layout: The PV array is divided into 8 strings, each with 17 modules in series. Strings are grouped 4+4 and connected to two three-phase string inverters (Sungrow SG36KTL-M, 36 kW each). This corresponds to ≈37 kW DC per inverter and 72 kW total AC at the point of common coupling.

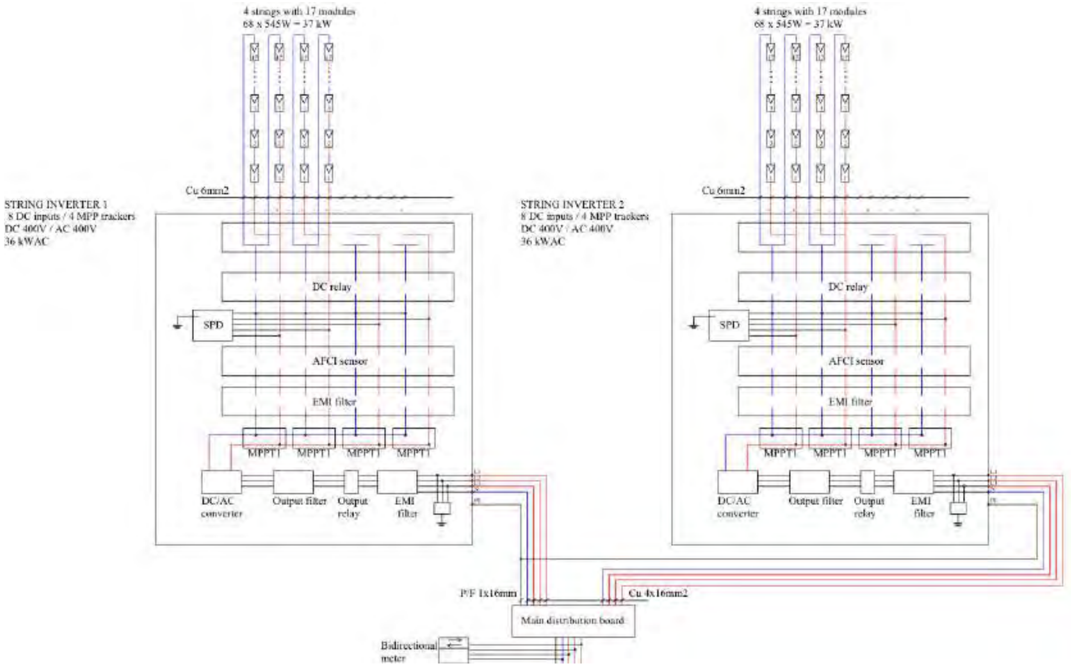

Fig.4 Electrical single-line diagram of the PV system

DC cabling: string home-runs use PV1-F Cu 6 mm² outdoor-rated solar cable with MC-type connectors. Cables are routed in roof trays to each inverter's DC terminals. Overcurrent protection and DC surge protection (SPD) are integrated in the inverters; no external DC combiner is required.

AC cabling and metering: each inverter's AC output is protected by breakers and routed with Cu 4×16 mm² cable to the main LV switchboard via the stairwell shaft. A bi-directional energy meter records import/export for grid settlement (net metering).

Grounding and bonding: all metallic parts (module frames, rails, inverters, AC panels) are bonded to the common PE. The mounting structure is tied to the earth grid at least every 10 m. If the resistance to earth exceeds 10 Ω, additional bonding/electrodes are installed. All grounding joints are anti-corrosion protected (bituminous coating).

Lightning and surge protection: the building's external LPS protects the roof area. Internal protection includes equipotential bonding, SPD coordination at inverter inputs/outputs, and cable routing that minimizes loop areas.

Electrical schematic: the single-line diagram summarizing strings, inverter DC/AC interfaces, protection, and grid interconnection should be inserted here as Figure 3.

3.4 Simulation Setup

The performance assessment of the photovoltaic system was carried out using PVsyst software, which enables detailed modeling of PV systems based on geographic location, system design parameters, and meteorological data. The simulation inputs were derived from METEONORM 9.1.0.13 climatic data for the project site in Sveti Nikole.

PVsyst modeling process. The model was configured with the exact roof geometry, module specifications (JA Solar JAM72S30-545/MR), inverter parameters (Sungrow SG36KTL-M), string layout, tilt, and azimuth angles for each zone. Separate sub-arrays were defined for the two roof orientations (+34° and –146° azimuth).

Shading analysis. The near-shading scene was constructed in PVsyst to evaluate possible shading losses from surrounding structures and the roof geometry. The iso-shading diagrams for both orientations are shown in Figure 5 and Figure 6.

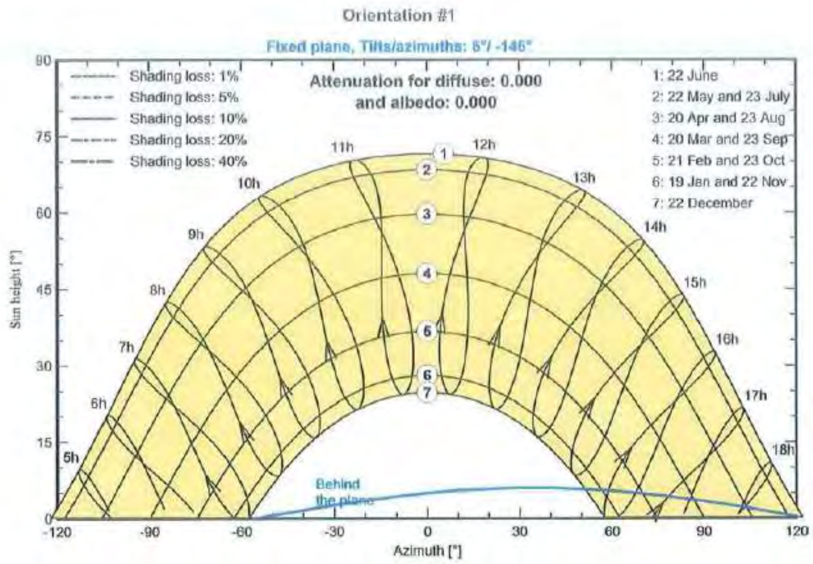

Fig. 5 Solar path and shading analysis – Orientation #1 (azimuth -146°)

Source: author based on PVsyst simulation results

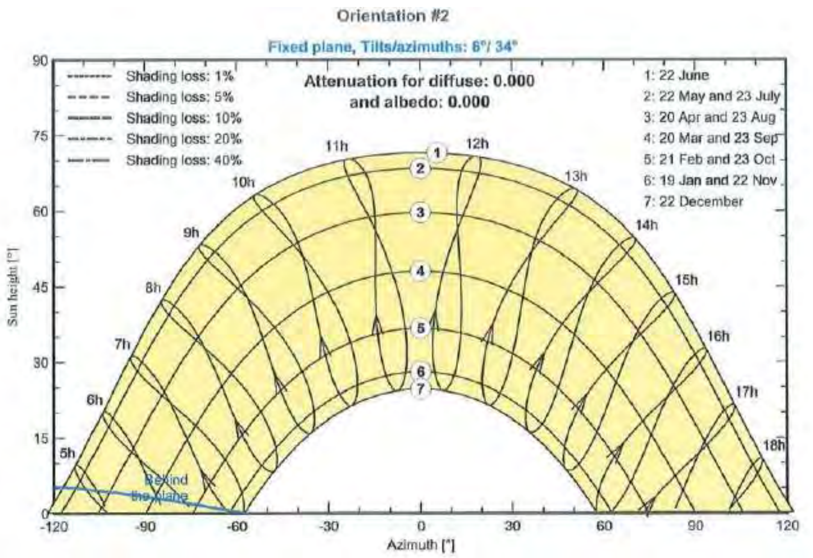

Fig. 6 Solar path and shading analysis – Orientation #2 (azimuth +34°)

Source: author based on PVsyst simulation results

Input assumptions.

- Loss factors: Mismatch losses (2.10%), ohmic wiring losses (0.87%), angular losses (0.02%), low-irradiance losses (1.50%), and module quality gain (+0.75%).

- Temperature effects: PV module temperature coefficient applied according to datasheet, resulting in ~5.32% annual loss due to high operating temperatures.
- Inverter efficiency: Maximum/Euro efficiency 98.5% / 98.3%.
- Performance ratio (PR): Calculated monthly and annually to quantify system efficiency excluding environmental factors.

These settings ensured that the simulation closely represented expected real-world conditions, providing reliable performance and loss estimations for the designed PV system.

3. Results and Discussion

3.1 Energy Yield Analysis

The PVsyst simulation results indicate that the photovoltaic system achieves high performance, with notable differences between the two roof orientations. Zone 1 (+36° azimuth) produced the highest specific yield due to its more favorable orientation, while Zone 2 (–146° azimuth) demonstrated slightly lower productivity. The annual energy production per zone is summarized in Table 3.

Table 3: PV zone parameters and calculated annual energy yield

Zone	Panel Orientation [°]	Panel Tilt α [°]	Shading Angle β [°]	Number of Panels	Installed Capacity [kW]	Annual Irradiation on Plane [kWh/m²]	Specific Production [kWh/kWp]	Annual Production [MWh]
1	+36	6	0	80	43.60	1505	1375	60,00
2	-146	6	0	56	30.52	1505	1259	38.40
Total	–	–	–	**136**	**126**	–	**1317**	**172.00**

Source: author based on PVsyst simulation results

Overall, the system's total installed DC capacity is 74.1 kWp, with an expected annual AC energy yield of approximately 98.7 MWh, corresponding to an average specific production of 1,317 kWh/kWp/year.

The monthly production trend is illustrated in Figure 7. Monthly energy production of the PV system, which shows peak generation in May, June, and July, and lower values during winter months due to reduced irradiance.

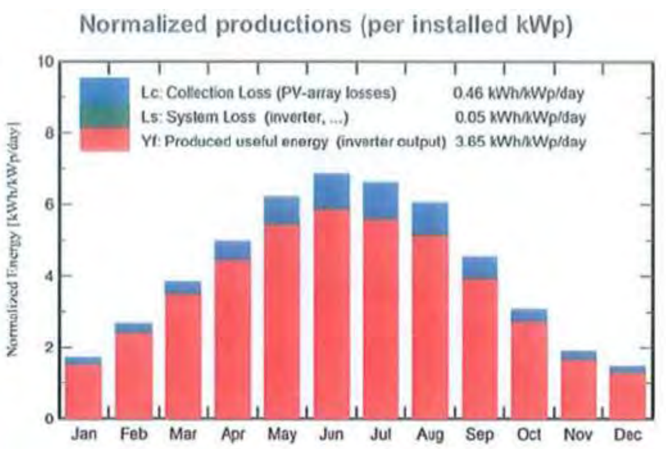

Fig. 7 Normalized daily production per installed kWp
Source: author based on PVsyst simulation results

The simulation data confirm that seasonal variability is strongly correlated with solar resource availability and roof orientation. The overall production profile aligns with regional climatic conditions, and the system design effectively maximizes yield within the site constraints.

3.2 Performance Ratio and Losses

The Performance Ratio (PR) is a key metric that reflects the overall efficiency of a PV system, excluding the influence of local solar resource availability. For the analyzed system, the PR remained consistently high throughout the year, ranging between 84% and 92%, with an annual average of 0.877.

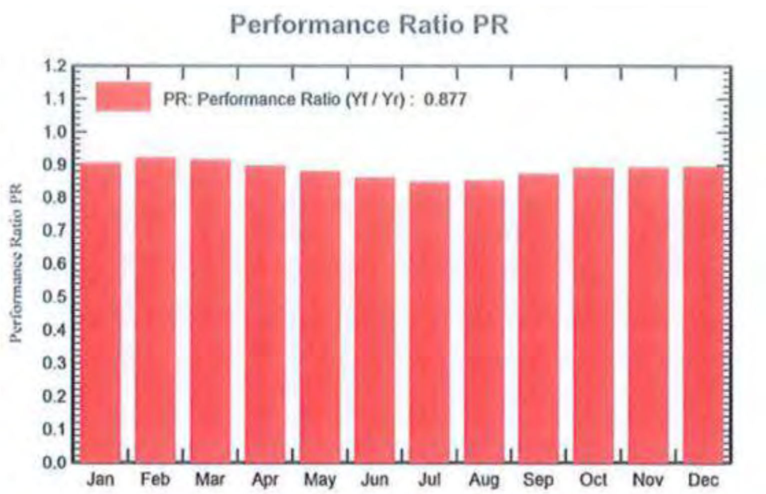

Fig. 8 Monthly Performance Ratio of the PV system
Source: author based on PVsyst simulation results

The detailed energy loss analysis from PVsyst is shown in Figure 9. Loss diagram of the PV system. The largest losses are associated with high operating temperatures (5.32%), mismatch between modules and strings (2.10%), and wiring losses (0.87%). Collection losses from the PV array amount to 0.46 kWh/kWp/day, and inverter/system losses are limited to 0.05 kWh/kWp/day.

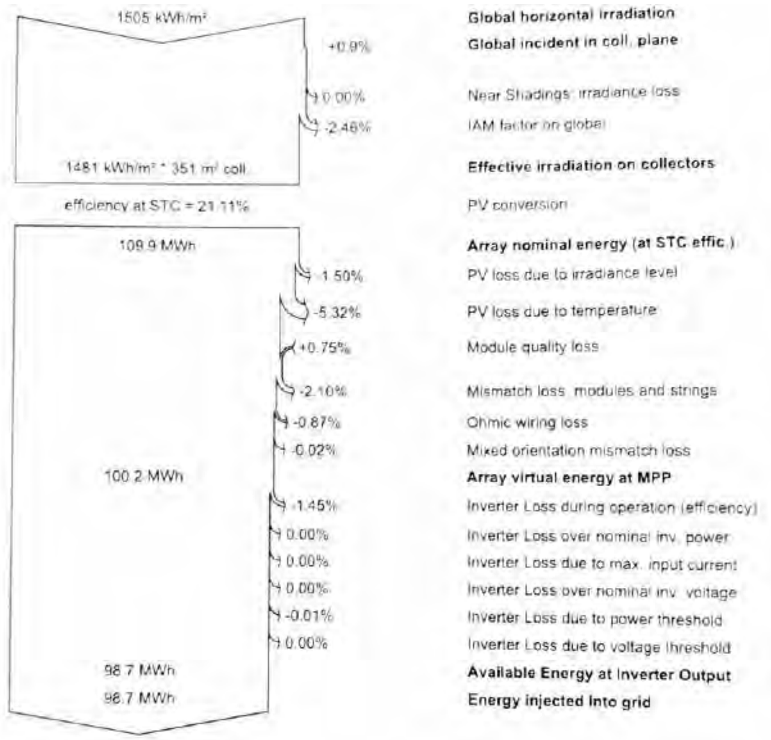

Fig. 9 Energy loss diagram of the PV system

Source: author based on PVsyst simulation results

These results indicate that the system has been designed with high-quality components and optimized configuration, resulting in minimal system losses and stable year-round performance.

3.3 Correlation and Output Distribution

The correlation between daily global irradiation and daily energy delivered to the grid is presented in Figure 10. Correlation between daily irradiation and delivered energy. The results show a strong and nearly linear relationship, confirming that increases in solar irradiation directly translate to higher energy yields. Minimal data scatter indicates consistent system operation and the absence of significant performance fluctuations under varying weather conditions.

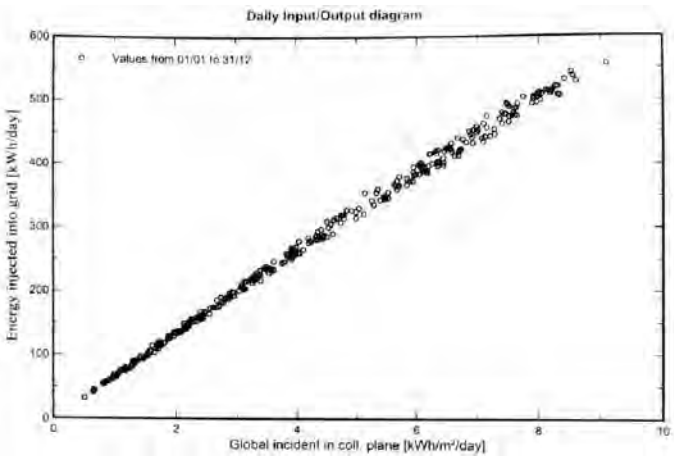

Fig. 10 Correlation between daily solar irradiation and energy injected into the grid

Source: author based on PVsyst simulation results

The distribution of daily output power over the year is illustrated in Figure 11. Histogram of daily delivered power to the grid. Most operating days fall within the 30–55 kW range, which corresponds well with the nominal AC capacity of the system (72 kW from two 36 kW inverters). Peak outputs around 40–50 kW dominate, with occasional maximum values approaching 60 kW during periods of high solar resource availability.

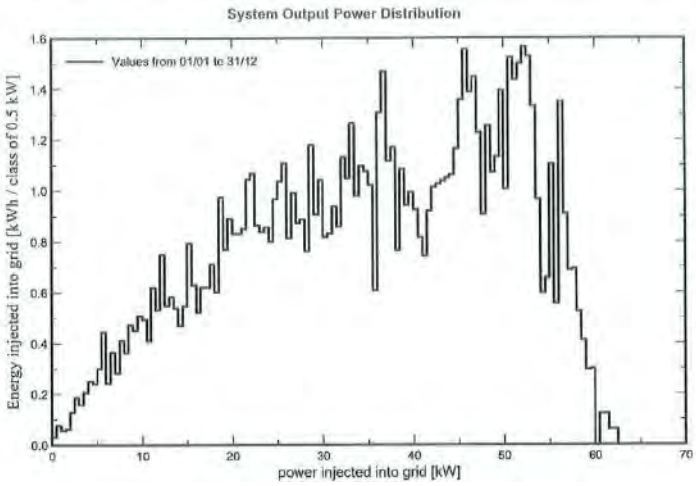

Fig. 11 Distribution of daily AC power injected into the grid

Source: author based on PVsyst simulation results

This analysis demonstrates that the system consistently operates in its optimal power range for a significant portion of the year, while seasonal and irradiance variations drive expected changes in daily production.

3.4 Technical Observations

The two roof orientations (+36° and –146° azimuth) with a fixed tilt of 6° resulted in measurable performance differences. Zone 1 (+36°) achieved a higher specific yield (1,375 kWh/kWp/year) compared to Zone 2 (1,259 kWh/kWp/year), highlighting the importance of azimuth alignment for maximizing energy capture.

High ambient temperatures during summer months had a moderate impact on performance, with an estimated 5.32% annual energy loss due to the negative temperature coefficient of the PV modules. Shading analysis confirmed minimal obstruction for both orientations, with negligible shading losses.

Electrical losses were also kept low through optimized design. Cable losses were limited to 0.87% by using adequately sized conductors (PV1-F Cu 6 mm² for DC, Cu 4×16 mm² for AC). Mismatch losses between modules and strings accounted for 2.10%, a typical value for systems with multiple orientations. The inverters achieved high conversion efficiency, with Max/Euro efficiencies of 98.5% / 98.3%, minimizing conversion losses to 1.45%.

Overall, the combination of favorable design choices, quality components, and minimal shading ensures stable, high-efficiency operation, supporting the projected annual yield and long-term reliability of the PV system.

4. Conclusions

The designed photovoltaic system for the industrial facility in Sveti Nikole demonstrates high technical performance and operational stability. Based on PVsyst simulations using site-specific meteorological data, the system is expected to deliver an annual yield of approximately 98 MWh with an average Performance Ratio (PR) of 87.7%.

Loss analysis confirmed that the system operates near optimal efficiency, with minimal losses attributed to temperature effects, mismatch, and cabling. The combination of favorable site conditions, optimized panel orientation, and high-efficiency inverters ensures reliable year-round operation.

From an industrial perspective, the system will significantly reduce grid electricity consumption and operational energy costs, while contributing to environmental sustainability through reduced greenhouse gas emissions.

Future developments could include the integration of battery energy storage to improve self-consumption rates and supply continuity, as well.

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