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ANALYSIS OF THE CONTRIBUTION OF SMALL SOLAR POWER PLANTS IN REDUCING CARBON FOOTPRINT AND PROTECTING FOREST WEALTH

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Abstract

This paper analyzes the potential for energy management using a solar system composed of a 14.4 kWp photovoltaic installation, a 10 kW Growatt inverter, and a 15 kWh battery, operating in zero export mode with the goal of meeting an average daily consumption of approximately 30 kWh. The research aims to assess the system's capacity to provide sufficient energy throughout the year, considering seasonal variations and system limitations. Methodology includes analyzing solar irradiation data for Serbia, modeling energy production, and simulating energy flows between generation, consumption, and storage. Results indicate that during summer months, the system can fully meet daily energy needs through direct consumption and battery storage, reducing dependence on fossil fuels and lowering greenhouse gas emissions. In winter, decreased solar production presents challenges for maintaining the same level of self-sufficiency, highlighting the importance of renewable energy sources. This study underscores the ecological significance of solar systems in reducing the need for forest exploitation for energy resources, there by contributing directly to forest conservation, biodiversity preservation, and overall ecosystem health. Utilizing renewable energy sources not only promotes sustainable development but also helps protect forests and the planet by decreasing carbon footprints and mitigating climate change.

Key words: *Solar energy, carbon footprint, photovoltaic system, battery storage, forest conservation, renewable energy.*

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Introduction

As global energy demands continue to rise and fossil fuel reserves steadily decline, nations are increasingly compelled to seek sustainable alternatives that can ensure long-term energy security and environmental protection [1, 2]. Solar energy stands out as one of the most promising options due to its global availability, scalability, and rapidly decreasing implementation costs [1]. In countries such as Serbia, which benefits from moderate to high annual solar irradiation, the deployment of distributed photovoltaic (PV) systems is both technically feasible and economically viable [3]. Nevertheless, their adoption remains limited by factors including high initial investment costs, policy constraints, and insufficient awareness of their broader environmental and societal benefits [4].

This paper presents a case study of a residential solar power plant operating in zero-export mode. By analyzing detailed operational data, the study evaluates the system's effectiveness in reducing grid dependency, contributing to environmental goals, and supporting forest conservation efforts [3, 6]. The results are expected to encourage wider adoption of similar systems and provide insights for shaping future energy policies. Solar PV has already been proven to significantly reduce carbon emissions [1, 5].

Climate change, deforestation, and pollution caused by fossil fuel combustion represent critical threats to global environmental stability [2, 7]. In Serbia, a significant share of rural households still relies on firewood for heating, which contributes both to forest degradation and air pollution [6]. The integration of decentralized renewable energy systems—particularly photovoltaic installations—offers a sustainable pathway to address these challenges [7, 8].

This study focuses on the technical performance and ecological impact of a residential-scale PV system designed to operate in zero-export mode. In addition to enhancing household energy independence, this approach reduces the reliance on firewood, thereby lowering associated emissions and easing pressure on natural ecosystems [6, 7].

Methodology

The PV-battery configuration used in this study follows established practice [3]. The analyzed system consists of a 14.4 kWp photovoltaic array paired with a 10 kW Growatt hybrid inverter and a 15 kWh lithium-ion battery. It operates in zero-export mode, meaning that all generated electricity is either consumed directly or stored in the battery. Data was collected through the Growatt monitoring platform, which provides daily and cumulative statistics on generation, consumption, battery usage, and system status [3]. Simulations were conducted to evaluate seasonal performance based on historical solar irradiation data for central Serbia [1, 3].

The research methodology included the collection of real-time operational data over a full calendar year (July 2024 to July 2025). Parameters such as daily energy generation, battery state of charge, direct consumption, and grid usage were analyzed.

The simulation model incorporated regional solar radiation data, panel efficiency factors, inverter conversion losses, and battery charge/discharge efficiency. Seasonal performance and system autonomy levels were compared to assess the system's reliability across different periods of the year [3, 5].

Energy modeling was supported by the PVsyst simulation tool, which provided yield forecasts based on geographic location and tilt angle. To estimate carbon footprint reductions, emission factors were applied: 0.998 kg CO_2/kWh for grid electricity in Serbia and 1.8 tons of CO_2 per ton of burned firewood [6]. For evaluating biodiversity and ecological impacts, tree equivalence metrics recommended by IRENA and Growatt were employed [1, 3, 7].

Results

The Growatt system interface (Fig. 1) displays real-time generation data along with historical performance statistics. On July 21, 2025, the system generated 27.5 kWh, closely matching the household's average daily load, while monthly production for that period reached 405.6 kWh [3].

Over the 12-month observation period, the solar system produced approximately 6.5 MWh of electricity [3]. During May to September, daily generation often exceeded 40 kWh, allowing surplus to be stored in the battery [3, 5]. In winter (November to February), generation dropped to 10–15 kWh/day, resulting in greater reliance on grid energy [5]. Battery autonomy was highest from June to August, where grid import was nearly zero. These seasonal contrasts emphasize the importance of storage capacity and load management [3, 8].

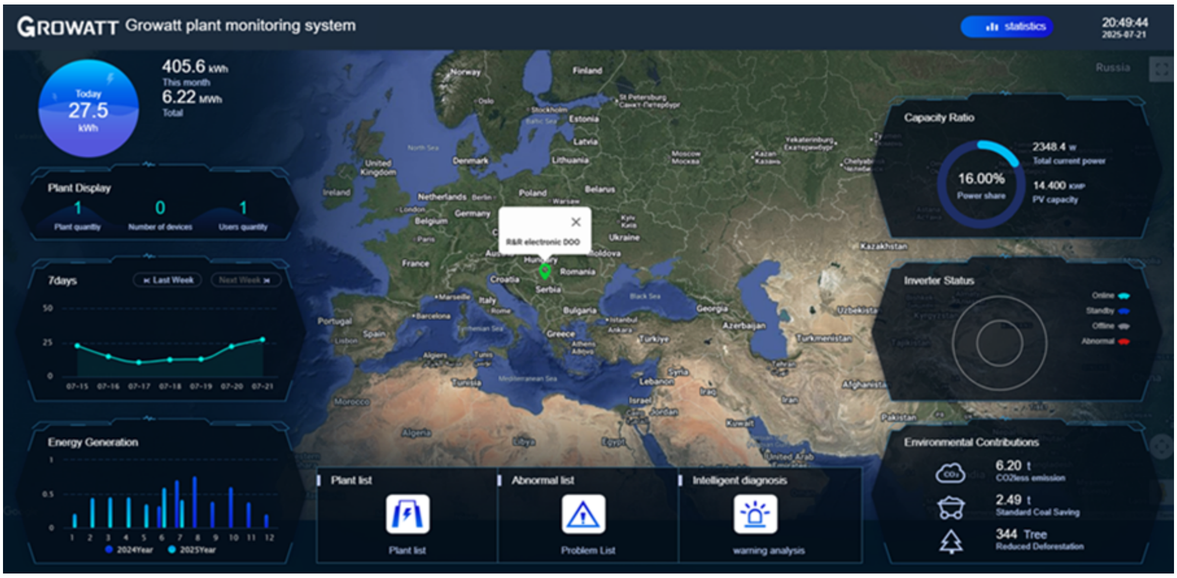

Figure 1: System interface & annual production [3].

A clear correlation was observed between system performance and environmental impact metrics. Each kWh generated by the system directly displaced fossil-fueled electricity, preventing CO_2 emissions [1], [2]. The battery contributed to load shifting and reduced peak-time grid demand [3]. When extrapolated nationally, even a modest deployment of such systems (e.g., 100,000 households) could offset over 600,000 tons of CO_2 annually and preserve up to 34 million trees over a decade [6, 7].

The system's interface in the "galactic" visual mode (Fig. 2) highlights the ecological contributions of the PV installation. Reported benefits include a reduction of 6,200.94 kg of CO_2 emissions, a saving of 2,487.84 kg of standard coal, and an equivalent conservation impact of approximately 344 trees [3, 6].

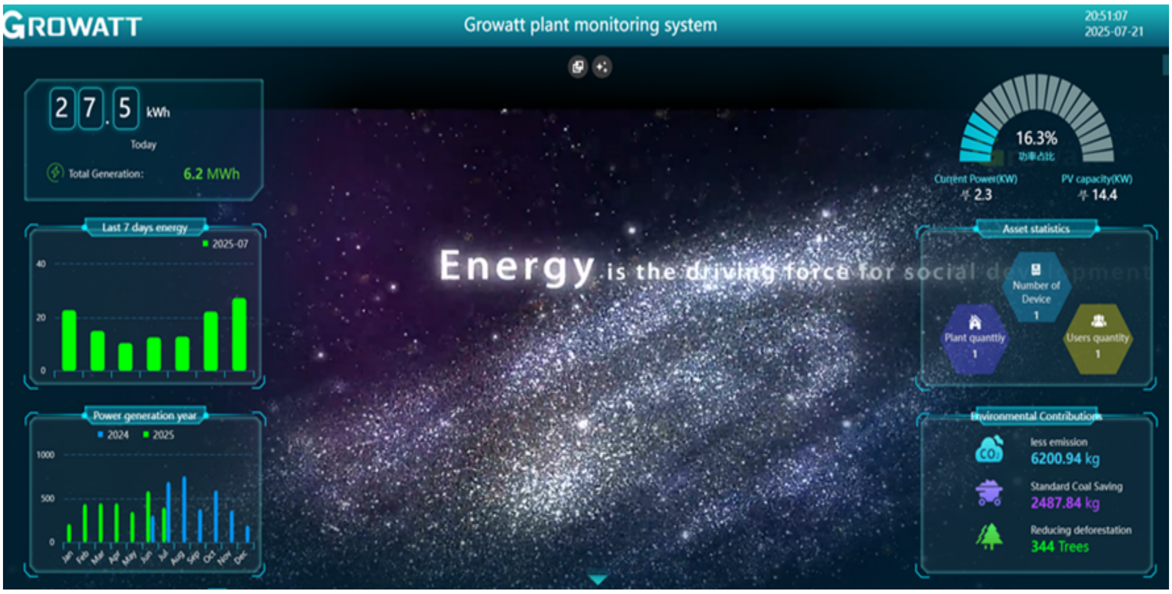

Figure 2: Environmental impact (Galactic mode) [3].

These results illustrate the system's ability to combine technical efficiency with measurable environmental gains [2]. By reducing fossil fuel dependency and mitigating greenhouse gas emissions, the system reinforces its role in supporting forest preservation and biodiversity protection [2, 7].

The comparative overview of energy flows between 2024 and 2025 (Fig. 3) illustrates photovoltaic generation, battery contribution, grid imports, and total household consumption. Most of the energy demand was satisfied by solar production and battery storage, while reliance on the grid remained minimal [3, 5].

The findings of this study support broader trends in decentralized energy solutions. As energy costs rise and environmental concerns grow, household-level solar systems provide an avenue for self-sufficiency and emission mitigation [1, 2].

In Serbia, where energy poverty and rural dependence on firewood remain high, these systems also alleviate the socioeconomic burden on vulnerable populations [6, 7].

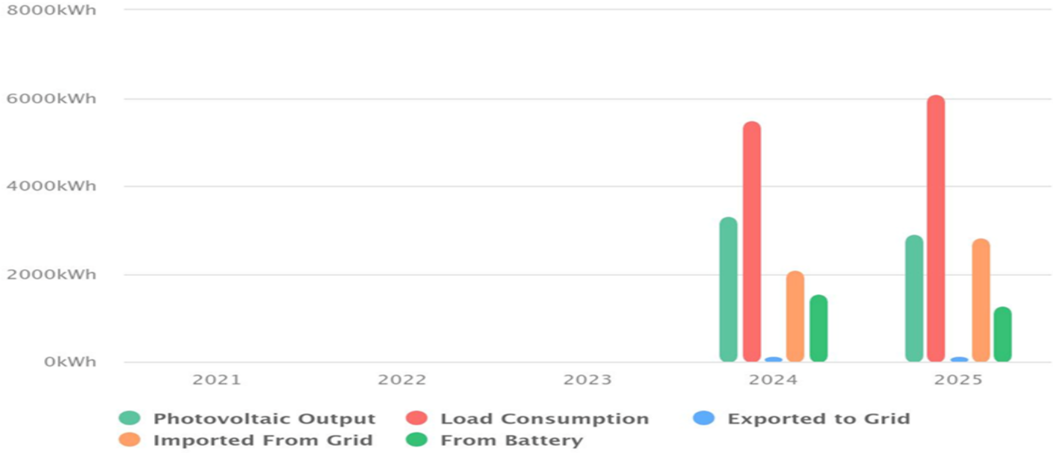

Figure 3: Comparative energy flows (2024–2025) [3].

From a policy perspective, the case study demonstrates the viability of grid-independent or hybrid solar systems. Subsidies for batteries, net metering policies, and educational campaigns could significantly accelerate deployment [4], [8]. The contribution of such systems to national carbon targets and forest conservation strategies is underutilized and deserves more strategic integration into energy and environmental planning [2, 7].

The seasonal production profile in winter (Fig. 4) reveals PV output averaging only 10–15 kWh/day, increasing reliance on the grid [3].

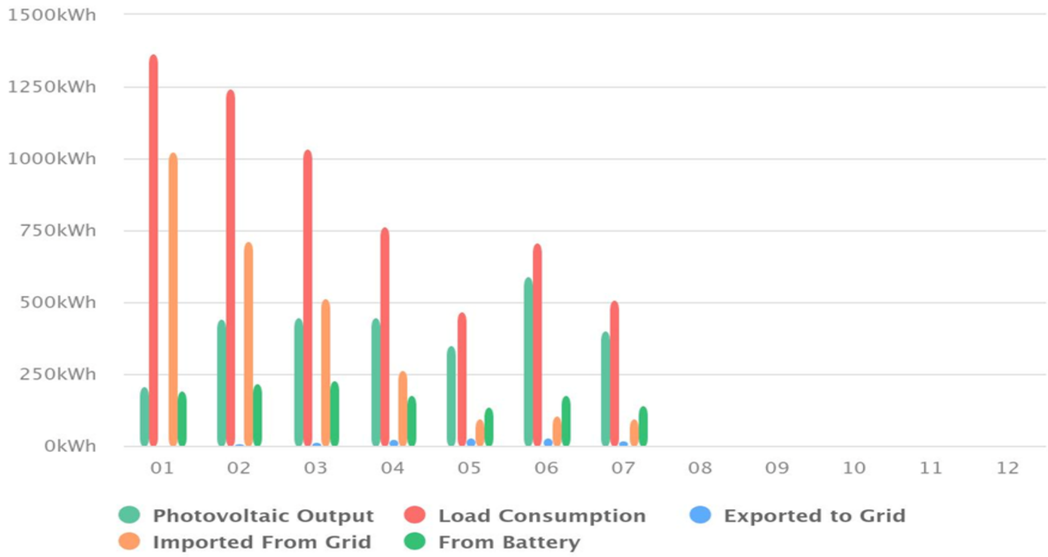

Figure 4: Winter performance profile [3].

Despite limitations, the system still supported household demand, with the battery optimizing available energy [3]. These results underline the need for hybrid renewable strategies to ensure autonomy during low irradiation periods [5, 8].

The comparison between direct consumption and battery storage (Fig.5) demonstrates how efficient energy use reduces grid imports [3].

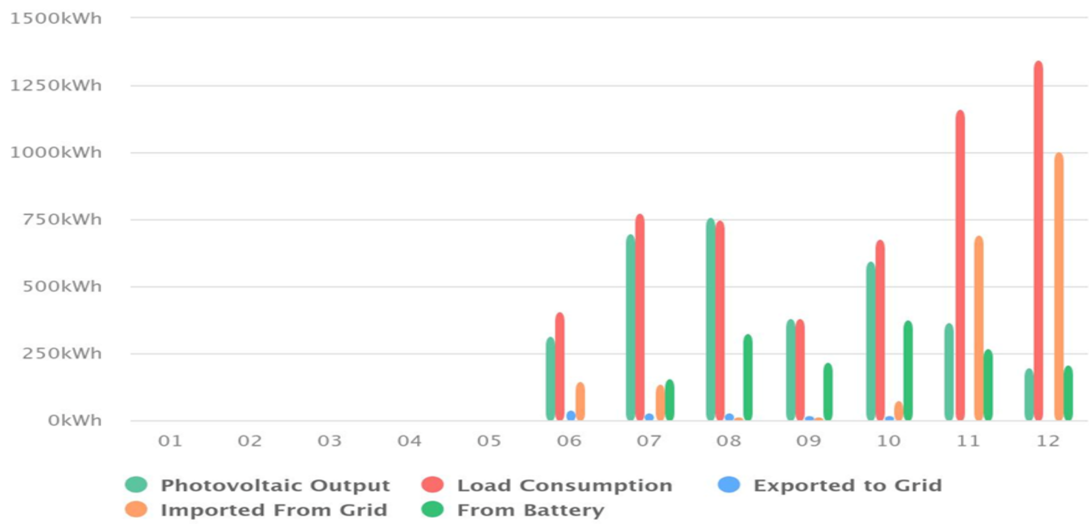

Figure 5: Direct use vs battery storage [3].

The inverter-battery system provided stable load coverage, highlighting the value of storage in maximizing self-consumption [3, 8].
Ecologically, effective storage minimizes grid reliance and lowers CO_2 emissions equivalent to conserving dozens of trees annually [6, 7].
The annual energy balance (Fig. 6) confirms the seasonal contrast between summer surpluses and winter deficits. During high-insolation months, the system not only covered daily household demand but also generated excess electricity for storage, while in winter, reduced production increased reliance on the grid [3, 5].

Figure 6: Annual energy balance [3].

Overall, the PV system supplied the majority of annual consumption, significantly reducing fossil-fuel dependency [1, 2].
These findings are consistent with international studies highlighting the role of distributed solar systems in achieving long-term sustainability [5, 8].

The annual savings and avoided emissions (Fig. 7) highlight the ecological and economic benefits of the PV system. By reducing grid imports, the installation prevented more than 6 tons of CO_2 emissions per year, contributing directly to climate change mitigation [2, 6]. The reduction in fossil-fuel dependency also lowered firewood consumption, easing pressure on forest resources and supporting biodiversity protection [6, 7].

Figure 7: Energy savings and CO_2 reduction [3].

These results align with national and international findings that underscore the importance of small-scale renewable systems in achieving sustainability targets [1], [8]. The zero-export operational mode (Fig. 8) ensured that all generated electricity was either consumed directly or stored in the battery, with no excess fed into the grid [3]. This strategy maximized household self-consumption and reduced peak-time grid demand, contributing to overall system stability [3, 8].

Figure 8: Zero-export operation [3].

From a regulatory perspective, zero-export systems comply with grid integration policies, making them particularly relevant in European contexts where distributed energy must align with sustainability goals [4]. Ecologically, this approach reduces fossil fuel reliance and helps safeguard forest ecosystems by lowering demand for firewood [6, 7].
The summary of carbon footprint reduction (Fig. 9) illustrates the long-term ecological contribution of the PV system. Annual operation avoided thousands of kilograms of CO_2 emissions, directly supporting national and international climate goals [1, 2].

Figure 9: Carbon footprint reduction [3].

Beyond emission reductions, the system indirectly preserved forest biomass, prevented soil degradation, and contributed to biodiversity protection [6], [7]. When projected at scale, widespread adoption of similar residential installations in Serbia and other regions could provide a substantial contribution to the EU Forest Strategy and global renewable energy transition targets [4, 8].

Discussion

The results demonstrate that during high-insolation months the system is capable of meeting the household's daily consumption while simultaneously charging the battery, thereby achieving near-complete energy independence [3]. In contrast, reduced solar input during winter months lowers self-sufficiency and necessitates reliance on supplemental energy sources [5]. The environmental benefits remain substantial, including an annual reduction of more than 6 tons of CO_2 emissions, decreased coal and firewood consumption, and reduced pressure on forest resources [2, 6]. If replicated at scale across rural and urban households, such systems could deliver significant cumulative impacts on climate mitigation and ecosystem preservation [1, 7].
This study confirms that even a single small-scale photovoltaic installation can provide meaningful contributions to both energy transition and ecological protection [2], [6]. With appropriately designed configurations and adequate storage capacity,

household solar systems can supply up to 80% of annual energy demand [3, 8]. By reducing reliance on firewood, these systems also contribute to the conservation of forest biomass, prevention of soil erosion, and preservation of habitats [6, 7].
Future research should investigate hybrid renewable configurations—such as solar combined with micro wind or biomass—that could further enhance off-grid autonomy [5, 8]. Moreover, large-scale adoption requires supportive policy frameworks, financial incentives, and public awareness initiatives to demonstrate feasibility and long-term benefits [4]. Seasonal performance and ecological impacts observed in this study are consistent with prior international findings [5, 8].

Conclusion

This study has demonstrated the technical performance and ecological benefits of a small-scale residential photovoltaic system operating in zero-export mode. During high-insolation periods, the system achieved near-complete energy autonomy, while in winter months reduced solar input highlighted the need for complementary renewable sources [3, 5]. Over the course of one year, the installation generated approximately 6.5 MWh of electricity, avoiding more than 6 tons of CO_2 emissions and significantly lowering reliance on coal and firewood [2, 6].
Beyond direct energy benefits, the system contributes to broader environmental and societal goals. By reducing demand for firewood, it alleviates pressure on forest ecosystems, supports biodiversity conservation, prevents soil degradation, and enhances ecosystem resilience [6, 7]. At scale, widespread adoption of similar systems across Serbia and comparable regions could meaningfully contribute to national climate targets, EU forest conservation strategies, and global sustainability commitments [1, 4, 8].
The findings confirm that decentralized solar power systems are not only technically viable but also essential for ensuring long-term energy security, reducing carbon footprints, and protecting natural resources [2], [7]. With appropriately sized storage solutions, these systems can cover up to 80% of household annual energy demand, providing both energy independence and ecological protection [3, 8].
Future policy development should prioritize supportive regulatory frameworks, financial incentives, and awareness campaigns to accelerate adoption [4]. Investments in hybrid systems that combine solar with wind or biomass could further strengthen system reliability, particularly in regions with pronounced seasonal variations [5, 8]. Thus, small solar power plants can serve as a cornerstone of sustainable development, contributing simultaneously to decarbonization, forest conservation, and climate change mitigation [1, 2, 7].

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