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Performance evaluation of rooftop photovoltaic integration using self-consumption and self-sufficiency indicators with IoT-based monitoring

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ABSTRACT

Indonesia's energy transition has increased the importance of rooftop photovoltaic (PV) systems, yet their integration with the PLN grid remains challenging because intermittent generation affects supply-demand balance and complicates the evaluation of local PV utilization. This study proposes and evaluates a low-cost internet of things (IoT)-based AC-side monitoring system for residential rooftop PV integration using an ESP32 microcontroller and PZEM-004T energy sensors. The proposed framework monitors three measurement points, namely PV output, grid line, and household load, and classifies the operating condition into export and import states. Based on measured historical field data, the operational performance of the system is assessed using the self-consumption ratio (SCR) and self-sufficiency ratio (SSR). The results show that PV generation dominates during daytime operation, whereas household demand becomes increasingly dependent on the PLN grid from late afternoon to night. Across the observation period, daily SCR ranges from 1.08% to 6.86%, while daily SSR ranges from 3.07% to 74.61%, indicating limited overall self-consumption but relatively strong daytime load support. These findings show that the proposed low-cost AC-side IoT monitoring framework can effectively quantify rooftop PV-grid interaction and provide a practical basis for evaluating local PV utilization and grid dependence under actual household operating conditions.

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1. INTRODUCTION

Indonesia's energy transition has positioned rooftop photovoltaic (PV) systems as an important component of distributed renewable energy deployment, with a national target of 3.61 GW of rooftop solar capacity by 2030 [1]. Rooftop PV offers an attractive pathway to reduce dependence on fossil-based electricity and support climate-change mitigation efforts [2]. In addition, its implementation can contribute to better daytime energy utilization and support building-level energy efficiency [3], [4]. However, integrating rooftop PV into the utility grid remains challenging because its intermittent output can introduce power variability, affect the supply–demand balance, and reduce the efficiency of on-site energy utilization [5], [6]. In practical grid-connected operation, rooftop PV can supply local demand during solar hours, whereas the utility grid remains necessary when PV output declines or becomes insufficient [7], [8]. Therefore, in addition to measuring PV generation, a monitoring system is required to quantify how much PV energy is directly utilized by local loads and how much is exchanged with the grid [9], [10].

Two commonly used indicators for evaluating grid-connected prosumer performance are the self-consumption ratio (SCR) and the self-sufficiency ratio (SSR) [11]-[13]. SCR expresses the proportion of locally generated PV energy that is consumed on-site, while SSR indicates the proportion of the total load demand that can be supplied by local PV generation [14]-[16]. These indicators are particularly useful for assessing rooftop PV operation under import–export conditions because they provide complementary information on local energy utilization and grid dependence [17], [18]. In addition, recent studies on prosumer performance evaluation continue to use SCR and SSR to interpret the effect of grid interaction and operating constraints in photovoltaic systems [19]. For a consistent evaluation of these indicators in practical on-grid operation, the energy flows should be measured on the AC side so that PV output, grid exchange, and load demand can be compared within the same electrical domain.

Previous studies have reported smart-metering and IoT-based platforms for electrical energy monitoring, including cloud-connected architectures, real-time data logging, monitoring analytics, and low-cost implementations using microcontrollers and AC energy sensors [20]-[24]. These studies demonstrate that IoT can provide practical and accessible solutions for real-time monitoring of electrical and PV system parameters. However, many existing monitoring studies mainly emphasize measurement, visualization, or remote supervision, while fewer studies extend the monitoring function toward direct evaluation of rooftop PV utilization under actual residential import–export operation.

At the same time, SCR- and SSR-oriented studies have widely discussed self-consumption behavior, energy autonomy, and the influence of storage or grid limitation on prosumer performance [11]-[13], [19]. Even so, those studies often focus on indicator interpretation and performance assessment without presenting a practical low-cost monitoring framework capable of capturing bidirectional AC-side power exchange at multiple points in a real residential rooftop PV-grid connection. Limited attention has therefore been given to combining low-cost IoT monitoring, export–import classification, and historical SCR/SSR evaluation within a single AC-side monitoring architecture under real household operating conditions.

Based on this gap, this study proposes and evaluates a low-cost IoT-based AC-side monitoring system for rooftop PV integration with the PLN grid. The proposed system uses an ESP32 microcontroller and PZEM-004T AC energy sensors to monitor three key measurement points, namely PV output, grid line, and household load, and to classify the operating state into export and import conditions. Using measured historical field data, the study applies SCR and SSR to assess how effectively rooftop PV energy is utilized locally and to what extent the household load can be supplied by PV generation. In this way, the work contributes a practical monitoring framework for assessing rooftop PV integration under actual household operating conditions. The rest of this paper is organized as follows. Section 2 presents the proposed method/procedure, Section 3 explains the method, Section 4 provides the results and discussion, and Section 5 concludes the paper.

2. THE PROPOSED METHOD/PROCEDURE

2.1. System configuration and study site

This study was conducted at the Department of Electrical Engineering, Faculty of Engineering, Universitas Andalas, using a grid-connected rooftop photovoltaic (PV) system. The monitored PV installation consisted of five PV modules rated at 250 Wp each, resulting in a total installed capacity of 1.25 kWp. The PV array was connected to the PLN grid through a 2K-SM grid-tie inverter rated at 2200 W, with a nominal AC output voltage of 230 Vac and a nominal frequency of 50 Hz. In this configuration, the inverter rating exceeded the installed PV capacity, indicating that inverter overloading was not expected during the measurements and that the observed operating performance was primarily limited by the available PV generation. The monitored demand represented typical residential electrical usage and consisted of a laptop charger (45 W), an electric iron (300 W), a hair dryer (350 W), an electric drill (1100 W), and a lamp (25 W). These appliances were selected to represent day-to-day variations in residential load demand during the observation period.

2.2. Monitoring architecture and measurement points

Figure 1 shows the proposed monitoring architecture for rooftop PV-grid integration. The monitoring system employed an ESP32 microcontroller as the main data-acquisition unit and three PZEM-004T AC energy sensors installed at the PV inverter output, the PLN grid line, and the household load bus. These three AC-side measurement points were selected to capture the main energy-flow paths in the system, namely PV-to-load, PV-to-grid (export), and grid-to-load (import).

The monitored electrical variables included voltage, current, active power, frequency, and cumulative energy. All measured data were transmitted via Wi-Fi to the Arduino IoT Cloud platform for real-time visualization and historical storage. This arrangement enabled continuous observation of the interaction between rooftop PV generation, household demand, and grid exchange under actual grid-connected operating conditions.

2.3. System workflow and export-import identification

The operational workflow of the proposed monitoring framework is shown in Figure 2. At the beginning of operation, the ESP32 initialized the sensors, established the Wi-Fi connection, and synchronized the system time to ensure accurate time-stamped measurements. The system then entered a continuous monitoring cycle in which electrical variables from the PV side, grid side, and load side were acquired and processed in real time. The operating condition was identified from the relationship between PV generation and load demand. When PV generation exceeded the instantaneous load requirement, the operating state was classified as export. Conversely, when PV generation was lower than the load demand, the operating state was classified as import, indicating that additional energy was supplied by the PLN grid. The measured data, together with the identified operating-state labels, were then uploaded to the cloud database for further analysis.

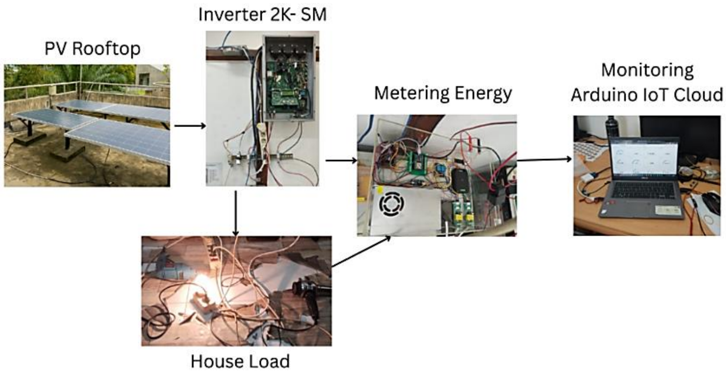

Figure 1. Experimental monitoring architecture of rooftop PV-grid integration

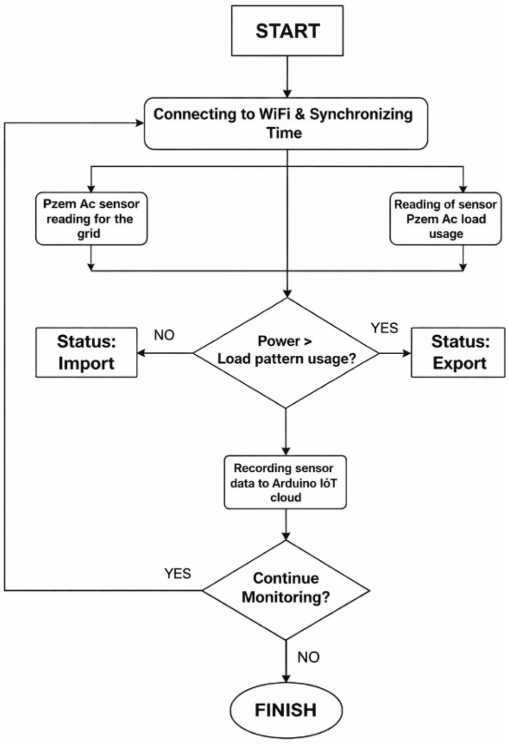

Figure 2. System operation flowchart of the proposed monitoring framework

3. METHOD
3.1. Data acquisition procedure
This study employed an experimental method to implement and evaluate the proposed IoT-based monitoring framework under actual operating conditions. Prior to installation, field observation was conducted at the rooftop PV system, the grid-tied inverter, and the point of common coupling to identify the sensing locations and the practical conditions of bidirectional power exchange. In parallel, a literature review was carried out to refine the communication scheme, system configuration, and performance indicators. After installation, the monitoring system recorded the AC-side electrical variables continuously and stored the measured data in the cloud platform as historical operating records.

Different combinations of household appliances were operated during the observation period to simulate day-to-day variations in residential electricity demand. On September 18, 2025, the active loads were a laptop charger and a lamp; on September 19, 2025, a hair dryer and a laptop charger; on September 20, 2025, an electric iron and a hair dryer; on September 21, 2025, an electric drill and an electric iron; on September 22, 2025, an electric iron and a lamp; and on September 23, 2025, a hair dryer, an electric iron, an electric drill, and a lamp. The practical implementation of the monitoring and measurement setup used in this study is shown in Figure 3. The figure presents the experimental arrangement used to observe the AC-side voltage of the rooftop PV system during operation.

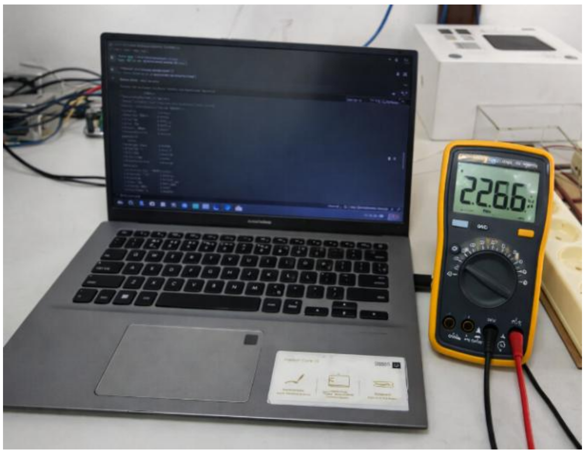

Figure 3. Experimental setup for AC-side voltage measurement of the rooftop PV system

3.2. Data processing and performance indices
The raw measurements were filtered, validated, and aggregated into fixed time intervals prior to performance analysis. One-minute interval data collected over six consecutive days, from September 18 to 23, 2025, between 10:00 and 20:00, were used for evaluation. The operational performance of the rooftop PV system was assessed using the SCR and the SSR, which are widely used indicators for evaluating local PV utilization and energy self-sufficiency in grid-connected prosumer systems. SCR expresses the fraction of renewable electrical energy that is utilized locally rather than exported to the grid and is defined as (1) [19].

$$SCR_x = \frac{E_{lgc,x}}{E_{gen,x}} \quad (1)$$

Where $E_{lgc,x}$is the locally generated and consumed energy, $E_{gen,x}$ is the total generated PV energy, and $x$denotes the observation interval, such as daily or the total study period. In the present study, because the measurements were performed on the AC side under grid-connected operation without battery storage, the locally generated and consumed energy corresponds to the portion of PV energy that is not exported to the grid, so that (2):

$$E_{lgc,x} = E_{gen,x} - E_{export,x} \quad (2)$$

where $E_{export,x}$ is the total exported PV energy during the same interval. Similarly, SSR is defined as the ratio between locally generated and consumed energy and the total load demand, expressed as [19]:

$$SSR_x = \frac{E_{lgc,x}}{E_{load,x}} \quad (3)$$

where $E_{load,x}$ is the total electricity demand during the same observation interval. This formulation represents the degree of energy independence from the PLN grid by comparing the portion of PV energy utilized locally with the total load demand.

3.3. Sensor consistency verification

Since the SCR and SSR values were derived directly from the PZEM-004T measurements, the consistency of the recorded electrical quantities was examined before the performance analysis. In this stage, the verification focused on the relationship between measured active power and cumulative energy. For each meter, incremental active energy was obtained by integrating the measured active power over time, and the result was then compared with the incremental energy reconstructed from two consecutive cumulative energy readings. This procedure was applied separately to the PV-side meter and the grid-side meter using one-minute operational data.

To reduce the influence of unstable relative-error values at very low power levels, only intervals with active power greater than 50 W were included in the evaluation. The relative error obtained for each valid interval was then summarized using the mean relative error and the maximum absolute relative error for each observation day. In addition, supporting field checks were carried out using a handheld digital multimeter and a clamp meter to observe the AC-side voltage and load current during system operation. These observations provided practical confirmation of the monitored electrical quantities under actual operating conditions. However, they were used only as supporting checks and were not intended as a formal calibration against a certified reference instrument.

3.4. Scope and limitations

The study focused on short-term operational monitoring of a residential rooftop PV system over a six-day observation period. Therefore, the reported results reflect system behavior under the observed household load combinations and operating conditions, and they do not yet represent longer-term seasonal variation. In addition, the evaluation of the sensing devices was limited to internal consistency between measured active power and cumulative energy. Although supporting observations were performed using a handheld digital multimeter and a clamp meter, no comparison with a calibrated reference meter was conducted. For this reason, the proposed monitoring system is more appropriately interpreted as a tool for operational performance assessment of rooftop PV integration rather than as a formally calibrated metrological instrument.

4. RESULTS AND DISCUSSION

4.1. Sensor characterization and performance verification

Because the SCR and SSR values were derived directly from the AC-side measurements, the consistency of the PZEM-004T readings was evaluated first. For each meter, the internal consistency between active power and cumulative energy was examined using one-minute interval data collected over six consecutive days. Only intervals with active power above 50 W were included in the calculation in order to avoid inflated relative error at very low load levels. The resulting mean relative error and maximum absolute relative error for each day are summarized in Table 1.

Table 1. Results of the sensor consistency check

Date	Channel	Valid 1-min interval (p > 50 W)	Mean relative error (%)	Max. absolute relative error (%)
September 18, 2025	PV	459	-0.0002	0.469
September 18, 2025	GRID	141	-0.0014	0.469
September 19, 2025	PV	465	0.0004	0.337
September 19, 2025	GRID	135	-0.0007	0.331
September 20, 2025	PV	462	-0.0001	0.109
September 20, 2025	GRID	138	-0.0002	0.104
September 21, 2025	PV	459	-0.0001	0.102
September 21, 2025	GRID	141	0.0006	0.101
September 22, 2025	PV	459	-0.0002	0.199
September 22, 2025	GRID	141	-0.0001	0.195
September 23, 2025	PV	459	0.0000	0.064
September 23, 2025	GRID	141	0.0002	0.067

Table 1 shows that the number of valid one-minute intervals on the PV side ranges from 459 to 465 samples per day, whereas the grid side ranges from 135 to 141 samples. In both channels, the mean relative error remains very close to zero, approximately within ±0.002%, while the maximum absolute relative error stays below 0.5% throughout the observation period. These results indicate that the incremental energy reconstructed from the power signal agrees closely with the cumulative energy reported by the meter. Consequently, the PZEM-004T sensors can be considered sufficiently consistent for operational monitoring and for the derivation of SCR and SSR in this rooftop PV-grid integration study.

When compared with previous low-cost monitoring studies, the error level obtained in this work remains within a practically acceptable range. Sousa *et al.* [25] reported voltage errors around 0.5% for a low-cost wireless smart meter, whereas Tsai *et al.* [26] reported mean absolute percentage errors below 2% for AC appliance monitoring. In the present study, the maximum absolute relative error remained below 0.5%, indicating that the consistency achieved here is within the same practical accuracy range and suitable for operational analysis.

4.2. Current dynamics and export-import transition

The current profiles were analyzed to identify the daily operating transition between rooftop PV supply and PLN support. Figure 4 compares the PV current and the grid current during the observation period from September 18 to 23, 2025. Figure 4 shows that from 10:00 until approximately 17:40 to 17:46, the PV current remains above the grid current. This condition indicates that rooftop PV serves as the main source for the household load and, when generation exceeds consumption, allows surplus energy to be exported to the PLN network. After the transition point, the pattern reverses, and the grid current becomes dominant, which means that PV output is no longer sufficient to support the load on its own. Although the magnitude of the current varies from day to day because the household load combinations are different, the same dominance pattern remains consistent across all observation days.

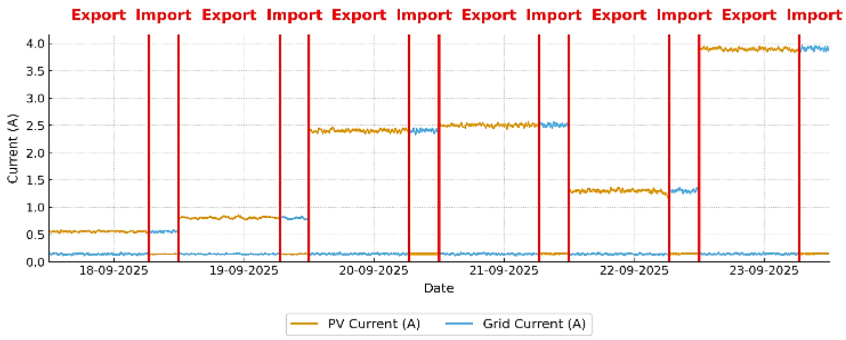

Figure 4. Comparison of PV and grid current dynamics under export–import conditions (September 18 to 23, 2025)

A similar daily shift is commonly reported in grid-connected rooftop PV systems, where local generation supports daytime demand while dependence on the utility grid increases once solar availability declines. In this study, however, the transition time and current values remain entirely based on the measured profiles of the monitored system, while the cited literature is used only as a comparison for interpreting the operating pattern. To clarify the export-import transition further, the difference between PV current and grid current was expressed as $I_{\Delta} = I_{PV} - I_{PLN}$. The result is shown in Figure 5.

Figure 5 shows that I_{Δ} remains positive during the daytime period, which confirms that PV generation dominates the supply side and corresponds to export conditions. Once the transition occurs, I_{Δ} becomes negative and remains so until the end of the observation period, indicating that PLN becomes the main support for the load and the system operates under import conditions. Thus, the delta-current profile does not only confirm the crossover seen in Figure 4, but also gives a clearer and more compact representation of the operating state of the PV-grid interaction.

4.3. Power and cumulative energy behavior

Figure 6 shows the variation of PV and grid power under export and import conditions during the observation period from September 18 to 23, 2025. Figure 6 shows that during the export period, approximately from 10:00 until 17:40–17:46, the average PV power reaches 421.35 W, whereas the average contribution from PLN is only 30.86 W. This means that most of the daytime load demand is supplied by rooftop PV, while the excess is directed to the grid. After the system enters the import period, the situation changes markedly. The average power supplied by PLN rises to 423.82 W, whereas the average PV power falls to 31.44 W as solar irradiance decreases. This result confirms that the operating mode is governed mainly by the availability of solar power, especially toward late afternoon and evening.

A similar pattern appears in the cumulative energy profile. Figure 7 compares the accumulated PV energy and grid energy over the same observation period. Figure 7 shows that during the productive solar period, PV energy accumulates much faster than grid energy. This indicates that local generation contributes most of the energy required by the household load during the day. However, after the productive solar window ends, cumulative grid energy becomes dominant. This means that although rooftop PV is effective in supporting daytime consumption, the system still depends strongly on PLN once solar output declines. The same qualitative trend is also described in grid-connected rooftop PV studies, where local generation is strongest during solar hours but continued supply outside that window remains dependent on the utility grid.

Figure 5. Delta current (I_delta) variation of PV and grid under export–import conditions (September 18 to 23, 2025)

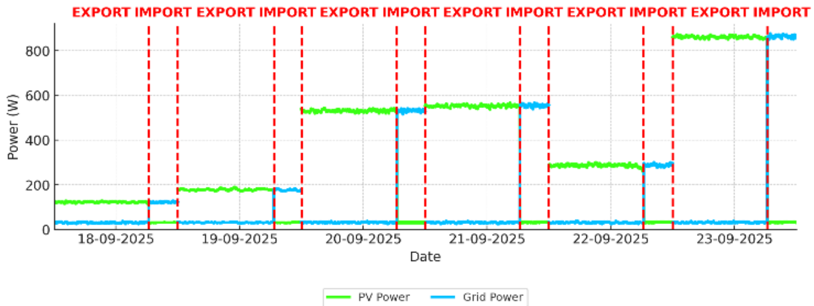

Figure 6. Variation of PV and grid power under export and import conditions (September 18 to 23, 2025)

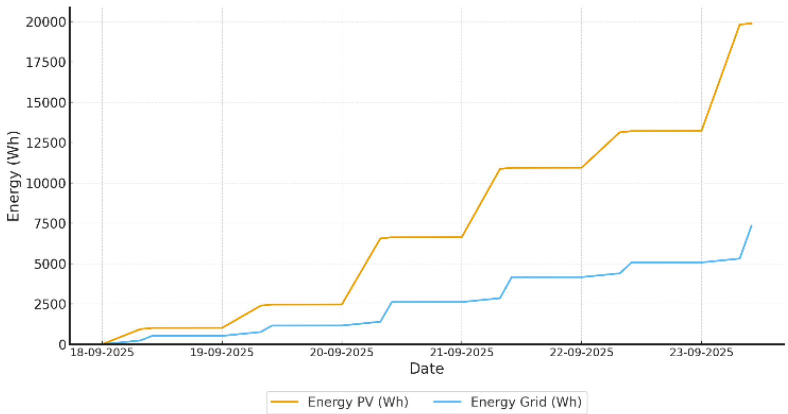

Figure 7. Comparison of cumulative PV and grid energy profiles (September 18 to 23, 2025)

4.4. SCR and SSR analysis

The current, power, and cumulative energy results can be summarized more clearly through the SCR and SSR indicators. These two indices were calculated from the AC-side energy data of the monitored system to evaluate how effectively PV generation supported local demand. Based on the observation data, the daily SCR remains low, ranging from 1.08% to 6.86%. This indicates that only a small portion of the total PV production is retained as direct local use across the evaluated operating window. By contrast, the daily SSR spans from 3.07% to 74.61%, which shows that the rooftop PV system can still supply a large fraction of the load during certain daytime periods. In other words, the monitored system performs well as a daytime support source, but its overall self-consumption remains limited when assessed across the full daily cycle.

This combination of low SCR and relatively high daytime SSR suggests that the main limitation lies in the mismatch between the timing of PV production and the timing of household demand. A direct numerical comparison with previous SCR/SSR studies should be made carefully because these indicators are strongly affected by PV capacity, load profile, storage installation, and grid-export limitation. Even so, Ciocia *et al.* [19] likewise showed that self-consumption and self-sufficiency change significantly depending on grid limitation and storage configuration. Therefore, the low SCR but relatively high daytime SSR observed here can reasonably be interpreted as evidence that the system supports the load effectively during solar hours, yet still exhibits limited daily self-consumption because the demand profile is not fully aligned with PV production. From an operational perspective, this result implies that improving local PV utilization would likely require better alignment between appliance use and PV generation, for example through daytime load shifting. In addition, if the objective is to improve energy independence beyond daylight hours, storage or more advanced demand management would be necessary. Without such measures, the system remains effective during the day but structurally dependent on the grid at night.

4.5. Discussion and implications

Taken together, the results show that the proposed low-cost AC-side monitoring framework is able to capture the essential operating behavior of rooftop PV integration, including the transition between export and import, the relative contribution of PV and grid power, and the resulting energy-performance implications expressed through SCR and SSR. In this sense, the system does not merely provide real-time electrical measurements, but also supports a more interpretable assessment of local PV utilization and grid dependence at the household level. All of these conclusions remain grounded in the present experimental observations.

From an application standpoint, the main opportunity for improving rooftop PV utilization appears to lie in demand-side adjustment rather than in additional PV generation alone. During the daytime, PV already dominates the supply profile, so increasing the operation of flexible household loads in that period would be expected to improve self-consumption directly. At the same time, the strong evening dependence on PLN shows that energy independence remains limited in the absence of storage. Therefore, the present results can serve as a practical basis for load scheduling, prosumer performance evaluation, and future planning of residential rooftop PV systems. In addition, these findings suggest that policy measures encouraging daytime energy use or prosumer-oriented incentives could improve the effective utilization of rooftop PV systems. Such approaches may help reduce excess energy export while increasing local self-consumption under grid-connected operation.

5. CONCLUSION

This study evaluated the operational performance of a grid-connected residential rooftop PV system using a low-cost IoT-based AC-side monitoring framework together with the SCR and SSR indicators. The results show that the monitored system operated under export conditions from 10:00 until approximately 17:40 to 17:46, when PV generation exceeded grid contribution, and then shifted to import operation as solar output declined and reliance on the PLN grid increased. This behavior was also reflected in the power profile, where the average PV power during the export period reached 421.35 W, while the average PLN contribution during the import period increased to 423.82 W. In terms of cumulative energy, PV contributed more strongly during the daytime, whereas grid energy became dominant again from late afternoon to night.

The calculated SCR and SSR values further indicate that the rooftop PV system was effective in supporting household demand during daytime operation, yet its overall daily self-consumption remained limited. Daily SCR ranged from 1.08% to 6.86%, while SSR ranged from 3.07% to 74.61%. These results suggest that the main limitation was not simply the availability of PV generation during solar hours, but the mismatch between the timing of PV production and the household load profile. As a result, although the proposed monitoring framework successfully captured the key operating behavior of rooftop PV-grid interaction under actual household conditions, the system still depended strongly on the grid outside the productive solar period. Overall, the study shows that low-cost AC-side IoT monitoring can provide a practical basis for assessing local PV utilization and grid dependence in residential prosumer systems. Future work may extend this research through longer monitoring periods, more diverse household load scenarios, and the integration of storage or load-shifting strategies to improve self-consumption and energy independence.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Syafii	✓		✓	✓		✓	✓			✓		✓	✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [S], upon reasonable request.

REFERENCES

[1] R. S. Sari, Sarjiya, and L. M. Putranto, "Realizing national targets through generation expansion planning: a transition energy case study of Java-Bali power system, Indonesia," in *Proceedings of the International Conference on Electrical Engineering and Informatics*, IEEE, Oct. 2024, pp. 130–135. doi: 10.1109/IConEEI64414.2024.10747999.

[2] A. H. Ikevuje, J. M. Kwakye, D. E. Ekechukwu, O. B. Ogundipe, and A. E. Esiri, "Optimizing the energy mix: strategies for reducing energy dependence," *Open Access Research Journal of Multidisciplinary Studies*, vol. 8, no. 1, pp. 094–104, Sep. 2024, doi: 10.53022/oarjms.2024.8.1.0051.

[3] D. E. H. J. Gernaat, H. S. de Boer, L. C. Dammeier, and D. P. van Vuuren, "The role of residential rooftop photovoltaic in long-term energy and climate scenarios," *Applied Energy*, vol. 279, p. 115705, Dec. 2020, doi: 10.1016/j.apenergy.2020.115705.

[4] Q. Yin, A. Li, and C. Han, "The role of solar photovoltaic roofs in energy-saving buildings: research progress and future development trends," *Buildings*, vol. 14, no. 10, p. 3091, Sep. 2024, doi: 10.3390/buildings14103091.

[5] N. Mansouri, A. Lashab, D. Sera, J. M. Guerrero, and A. Cherif, "Large photovoltaic power plants integration: a review of challenges and solutions," *Energies*, vol. 12, no. 19, p. 3798, Oct. 2019, doi: 10.3390/en12193798.

[6] Z. Sandi, "Examining power quality challenges in photovoltaic-grid integration: a critical review," *Journal of Power, Energy, and Control*, vol. 1, no. 1, pp. 12–23, Apr. 2024, doi: 10.62777/pec.v1i1.4.

[7] M. Morey, N. Gupta, M. M. Garg, and A. Kumar, "A comprehensive review of grid-connected solar photovoltaic system: architecture, control, and ancillary services," *Renewable Energy Focus*, vol. 45, pp. 307–330, 2023, doi: 10.1016/j.ref.2023.04.009.

[8] B. Uzum, A. Onen, H. M. Hasanien, and S. M. Muyeen, "Rooftop solar PV penetration impacts on distribution network and further growth factors—a comprehensive review," *Electronics (Switzerland)*, vol. 10, no. 1, pp. 1–31, Dec. 2021, doi: 10.3390/electronics10010055.

[9] J. Reed, S. Mahlen, L. Zhao, M. Lindemann, M. H. Kapourchali, and M. H. Kapourchali, "Industrial IoT-based monitoring application for grid-tied photovoltaic systems," in *Proceedings of the IEEE Power Engineering Society Transmission and Distribution Conference*, IEEE, May 2024, pp. 1–5. doi: 10.1109/TD47997.2024.10556219.

[10] L. Wibowo, R. Wahyusari, T. Yuwono, and A. Shofia, "IoT-based high-accuracy monitoring system for on-grid photovoltaic power system using nodemcu esp8266 and pzem004t," *Journal of Mechatronics, Electrical Power, and Vehicular Technology*, vol. 15, no. 2, pp. 230–241, Dec. 2024, doi: 10.55981/j.mev.2024.823.

[11] C. Petrovich, S. Branchetti, and G. D'Agosta, "Parametrization of self-consumption and self-sufficiency in renewable energy communities: a case study application," *Energy, Ecology and Environment*, vol. 10, no. 3, pp. 324–351, Jun. 2025, doi: 10.1007/s40974-025-00353-z.

[12] I. Sytnik and A. Stopochkin, "Methodology for assessing the level of electricity self-sufficiency in European Union countries," *Energies*, vol. 16, no. 18, p. 6597, Sep. 2023, doi: 10.3390/en16186597.

[13] J. Wiesenthal, "Self-consumption and self-sufficiency in energy sharing communities in Germany: what is the impact of wind energy?," *IOP Conference Series: Earth and Environmental Science*, vol. 1532, no. 1, p. 12002, Aug. 2025, doi: 10.1088/1755-1315/1532/1/012002.

[14] J. M. Zepter, J. Engelhardt, T. Gabderakhmanova, and M. Marinelli, "Re-thinking the definition of self-sufficiency in systems with energy storage," in *SEST 2022 - 5th International Conference on Smart Energy Systems and Technologies*, IEEE, Sep. 2022, pp. 1–6. doi: 10.1109/SEST53650.2022.9898436.

[15] F. Zhao, Z. Li, G. Xiao, Y. Li, S. Ahmed, and T. Ma, "Techno-economic comparison of p2p energy sharing and residential battery storage in the photovoltaic community," *International Journal of Green Energy*, vol. 21, no. 5, pp. 1107–1123, Apr. 2024, doi: 10.1080/15435075.2023.2234041.

[16] Y. Zheng, H. Shen, and J. Li, "A techno-economic sizing method for pv/battery/grid hybrid solar systems for residential buildings," *Journal of Mechanical Science and Technology*, vol. 35, no. 11, pp. 5245–5254, Nov. 2021, doi: 10.1007/s12206-021-1041-y.

[17] A. M. Ateş, "3-years energetic and economic analysis of a 30kwp rooftop PV power plant," *Mühendis ve Makina*, vol. 64, no. 710, pp. 175–194, Apr. 2023, doi: 10.46399/muhendismakina.1072368.

[18] S. I. Sun, M. Kiaee, S. Norman, and R. G. A. Wills, "Self-sufficiency ratio: an insufficient metric for domestic PV-battery systems?," *Energy Procedia*, vol. 151, pp. 150–157, Oct. 2018, doi: 10.1016/j.egypro.2018.09.040.

[19] A. Ciocia *et al.*, "Self-consumption and self-sufficiency in photovoltaic systems: effect of grid limitation and storage installation," *Energies*, vol. 14, no. 6, p. 1591, Mar. 2021, doi: 10.3390/en14061591.

[20] A. Asnil, K. Krismadinata, I. Husnaini, H. Hazman, and E. Astrid, "Real-time monitoring system using IoT for photovoltaic parameters," *TEM Journal*, vol. 12, no. 3, pp. 1316–1322, Aug. 2023, doi: 10.18421/TEM123-11.

[21] Y. Cheddadi, H. Cheddadi, F. Cheddadi, F. Errahimi, and N. Es-sbai, "Design and implementation of an intelligent low-cost IoT solution for energy monitoring of photovoltaic stations," *SN Applied Sciences*, vol. 2, no. 7, p. 1165, Jul. 2020, doi: 10.1007/s42452-020-2997-4.

[22] N. Iksan, P. Purwanto, and H. Sutanto, "Real-time monitoring of photovoltaic systems and control of electricity supply for smart micro grid-pv using iot," *TEM Journal*, vol. 13, no. 1, pp. 514–523, Feb. 2024, doi: 10.18421/TEM131-53.

[23] H. Satria, S. Syafii, R. Salam, M. Mungkin, and W. Yandi, "Design visual studio based gui applications on-grid connected rooftop photovoltaic measurement," *Telkomnika (Telecommunication Computing Electronics and Control)*, vol. 20, no. 4, pp. 914–921, Aug. 2022, doi: 10.12928/TELKOMNIKA.v20i4.23302.

[24] A. B. Dela Cruz and others, "Design and performance of a solar-powered single-phase smart energy monitoring system," *Asian Journal of Electrical Sciences*, vol. 13, no. 1, pp. 1–9, Mar. 2024, doi: 10.70112/ajes-2024.13.1.4228.

[25] E. L. de Sousa *et al*., "Development a low-cost wireless smart meter with power quality measurement for smart grid applications," *Sensors*, vol. 23, no. 16, p. 7210, Aug. 2023, doi: 10.3390/s23167210.

[26] H. L. Tsai, L. P. Truong, and W. H. Hsieh, "Design and evaluation of wireless power monitoring IoT system for AC appliances †," *Energies*, vol. 16, no. 1, p. 163, Dec. 2023, doi: 10.3390/en16010163.

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