Analysis of The Potential Utilization of Solar Energy for Residential-Scale Photovoltaic (PLTS) Power Generation in Tarutung District

Dody Lauren Bakkara, Siti Anisah, Pristisal Wibowo

Abstract

Electricity demand in Indonesia continues to increase, while dependence on fossil fuels remains dominant and vulnerable to global energy price fluctuations. Tarutung Subdistrict, North Tapanuli Regency, as a tropical highland area at an altitude of 900-1,200 meters above sea level, has solar radiation potential that has not been optimally utilized for household-scale Solar Power Plants (PLTS). This study aims to analyze solar energy potential, design an on-grid PLTS system, and assess the economic feasibility of investment for three household power categories (900 VA, 1,300 VA, and 2,200 VA). The research method uses a descriptive-analytical quantitative approach based on secondary solar radiation data for the 2023-2025 period from NASA POWER and BMKG. The results show an average annual Global Horizontal Irradiance (GHI) of 4.29 kWh/m²/day (PSH = 4.29 hours/day) with a coefficient of variation of only 4.2%, indicating radiation stability throughout the year. The three PLTS scenarios (1.2 kWp, 2.0 kWp, and 3.5 kWp) are able to meet 104-117% of daily electricity needs. Economic analysis shows a Payback Period of 4.8-6.8 years, a positive NPV of IDR 22.75-67.39 million, an IRR of 17.8-22.7%, and an LCOE of IDR 412-525/kWh, only 24-36% of the PLN tariff. PLTS implementation also has the potential to reduce CO_2 emissions by 1.19-3.48 tons per year per system. These results indicate that rooftop on-grid PLTS investment in Tarutung is feasible to highly feasible technically, economically, and environmentally.

Keywords*: *On-Grid PLTS, Solar Energy, Net-Metering, Economic Feasibility, Tarutung

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Introduction

Electricity demand in Indonesia continues to increase due to population growth, urbanization, and improvements in living standards, with national electricity consumption growing at an average annual rate of 6–8%. Meanwhile, Indonesia remains highly dependent on fossil fuels, which account for more than 80% of the national energy mix. This dependency increases the country's vulnerability to fluctuations in global energy prices and poses significant challenges to long-term national energy security.

As a tropical country located along the equator, Indonesia possesses abundant solar energy resources, with an estimated technical potential of 207.8 GWp according to the Ministry of Energy and Mineral Resources (MEMR) [1]. However, only a small fraction of this potential has been utilized for electricity generation. The adoption of photovoltaic (PV) technology represents one of the most promising renewable energy solutions, particularly for decentralized residential-scale electricity generation [12].

Tarutung District, the administrative capital of North Tapanuli Regency, North Sumatra Province, is situated in a highland area at an elevation of approximately 900–1,200 m above sea level and receives an average daily solar irradiation of 4.0–4.6 kWh/m²/day [2]. The highland environment offers favorable operating conditions for PV systems because the relatively lower ambient temperature improves photovoltaic conversion efficiency. It is well established that the output power of PV modules decreases by approximately 0.4–0.5% for every 1°C increase in cell temperature above the Standard Test Condition (STC) temperature of 25°C [9]. Despite these favorable climatic conditions, the utilization of solar energy in the region remains limited.

Residential-scale rooftop photovoltaic (PV) systems have emerged as a promising solution by utilizing existing rooftop space, reducing the loading on the utility distribution network, lowering household electricity expenses, and contributing to greenhouse gas emission reduction [3]. Furthermore, Indonesia's net-metering policy, established under the Minister of Energy and Mineral Resources Regulation No. 26 of 2021, has enhanced the economic attractiveness of residential rooftop PV systems. Under this regulation, every 1 kWh of electricity exported to the utility grid is credited as 0.65 kWh toward the customer's electricity bill [4].

Numerous previous studies have investigated the technical and economic feasibility of residential grid-connected rooftop PV systems in various regions of Indonesia, including Semarang City [6], Medan City [2], and residential customers with a contracted capacity of 2,200 VA [5]. Nevertheless, studies specifically addressing the solar energy potential and feasibility of residential PV systems in tropical highland regions, such as Tarutung District, where lower operating temperatures may improve PV performance, remain limited.

Based on these considerations, this study aims to analyze the solar energy potential, design a residential grid-connected photovoltaic (PV) system, and evaluate the economic feasibility of PV investment for three categories of residential electricity customers in Tarutung District, North Tapanuli Regency. The analysis utilizes the latest solar irradiation data for the 2023–2025 period obtained from the Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG) and the NASA POWER database.

Literature Review

2.1 Solar Energy and Solar Radiation Components

The Sun emits electromagnetic radiation with an average intensity of approximately 1,367 W/m² at the outer boundary of the Earth's atmosphere, commonly referred to as the solar constant [7]. Solar radiation reaching the Earth's surface consists of three primary components: Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance (DHI), and Global Horizontal

Irradiance (GHI), where GHI represents the sum of the direct and diffuse radiation components and is expressed as follows:

$$GHI = DNI \times \cos(\theta z) + DHI \quad (1)$$

where GHI is the primary parameter used in the design and performance assessment of photovoltaic (PV) systems [8]. Indonesia receives an average daily solar irradiation of 4.5–5.5 kWh/m²/day, corresponding to an estimated national solar energy potential of 207.8 GWp [1]. Medan City, the nearest major urban area to the study location, receives an average solar irradiation of 4.2–4.8 kWh/m²/day [2].

2.2 Grid-Connected Photovoltaic (PV) Systems

A photovoltaic (PV) system converts solar energy into electrical energy through the photovoltaic effect, a phenomenon first discovered by Edmond Becquerel in 1839 and later developed into practical silicon solar cells by Bell Laboratories in 1954 [3]. In a grid-connected (on-grid) PV system, the generated electricity is supplied directly to the utility grid. Excess electrical energy can be exported to the grid through a net-metering mechanism, eliminating the need for battery storage and thereby reducing the overall investment cost compared with stand-alone PV systems [13]. The main components of a grid-connected PV system are presented in Table 1.

Table 1. Main Components of a Grid-Connected Photovoltaic (PV) System

No.	Komponen	Fungsi
1	Panel Surya (PV Module)	Mengkonversi energi cahaya matahari menjadi listrik DC melalui efek fotovoltaik
2	Inverter Grid-Tie	Mengkonversi listrik DC menjadi AC dan mensinkronkan dengan frekuensi jaringan PLN
3	Mounting Structure	Struktur penyangga panel surya pada atap bangunan dengan sudut kemiringan optimal
4	Sistem Pengkabelan	Kabel DC, AC, dan konektor MC4 yang menghubungkan seluruh komponen sistem
5	Sistem Proteksi	MCB, MCCB, surge protector, dan grounding untuk keamanan sistem
6	kWh Meter Bidirectional	Mengukur energi yang diproduksi dan diekspor ke jaringan PLN (net-metering)

2.3 Photovoltaic (PV) Modules and Performance Characteristics

Based on their semiconductor materials, photovoltaic (PV) modules are generally classified into monocrystalline, polycrystalline, thin-film, and bifacial technologies. Monocrystalline PV modules typically achieve conversion efficiencies of 17–22%, polycrystalline modules 14–18%, and thin-film modules 7–13%, while bifacial modules can further improve energy yield by harvesting solar radiation from both the front and rear surfaces. Comparative studies have shown that monocrystalline PV modules provide the highest overall performance, achieving an average operational efficiency of approximately 18.5% under tropical climatic conditions [10].

The operating temperature significantly influences PV module performance. For every 1°C increase in cell temperature above the Standard Test Condition (STC) temperature of 25°C, the output power decreases by approximately 0.4–0.5% [9]. The relationship between module output power and operating temperature is expressed as:

$$P(T) = Pstc \times [1 + \alpha P \times (T - Tstc)] \quad (2)$$

2.4 Photovoltaic (PV) System Design Calculations

Peak Sun Hours (PSH) represent the equivalent number of hours per day during which solar irradiance equals 1,000 W/m². The daily energy production and the required PV system capacity can be estimated using the following equations [8]:

$$PSH = H / G_{stc} \quad (3)$$
$$E\_hari = P\_STC \times PSH \times PR \quad (4)$$
$$P\_STC = E\_kebutuhan / (PSH \times PR) \quad (5)$$

where Performance Ratio (PR) represents the overall system efficiency by accounting for inverter losses, cable losses, shading, temperature effects, and soiling losses. Typical PR values for grid-connected PV systems range from 0.75 to 0.85 [17].

2.5 Economic Feasibility Analysis of PV Systems

The economic feasibility of residential PV system investment was evaluated using the Payback Period (PBP), Net Present Value (NPV), Internal Rate of Return (IRR), and Levelized Cost of Energy (LCOE). A positive NPV and an IRR exceeding the selected discount rate indicate that the investment is financially feasible [5], [6].

$$PBP = C0 / Penghematan\_Tahunan \quad (6)$$
$$NPV = -C0 + \Sigma [CFt / (1+r)t] \quad (7)$$
$$LCOE = (C0 + \Sigma[Om\_t/(1+r)t]) / \Sigma[Et/(1+r)t] \quad (8)$$

where (C_0) is the initial investment cost, (CF_t) is the net cash flow in year (t), (OM_t) represents the annual operation and maintenance cost, (E_t) is the annual electricity generation, and (r) is the discount rate.

2.6 Net Metering Policy for Residential Rooftop PV Systems in Indonesia

Net metering is a policy mechanism that allows residential PV system owners to export surplus electricity to the utility grid in exchange for bill credits. In Indonesia, this mechanism is regulated under the Minister of Energy and Mineral Resources (MEMR) Regulation No. 26 of 2021 concerning Rooftop Photovoltaic Systems, which specifies an export–import credit ratio of 1:0.65 with electricity credits that can be accumulated for up to three months [4]. This regulation supersedes the earlier MEMR Regulation No. 49 of 2018 [18] and supports the implementation of Presidential Regulation No. 112 of 2022 on the Acceleration of Renewable Energy Development for Electricity Supply [19].

Research Methodology

3.1 Research Design and Study Area

This study employed a quantitative research approach with a descriptive-analytical design based on secondary data. The study was conducted in Tarutung District, North Tapanuli Regency, North Sumatra Province, Indonesia, located at approximately 2°01′ N latitude and 98°58′ E longitude, with an elevation ranging from 900 to 1,200 m above sea level. The research was carried out over a six-month period, from January to June 2026.

3.2 Data Collection and Sources

The data used in this study consisted of:

1. Solar radiation data, including Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI), and Diffuse Horizontal Irradiance (DHI), for the period 2023–2025, obtained from the NASA POWER Database and the BMKG Deli Serdang Climatological Station;
2. Residential electricity consumption data for three customer categories (900 VA, 1,300 VA, and 2,200 VA) obtained from PLN Tarutung Service Unit;

3. Technical specifications of photovoltaic (PV) modules and grid-tied inverters collected from the manufacturers' datasheets of at least three different brands for comparative analysis; and
4. Market prices of PV system components obtained from authorized distributors, together with the applicable residential electricity tariffs issued by PLN.

3.3 Data Analysis Method

The data analysis was conducted in three sequential stages.

First, the solar energy potential was evaluated through the processing and cross-validation of GHI data obtained from NASA POWER and BMKG using the Pearson correlation coefficient and the Root Mean Square Error (RMSE). The validated data were subsequently used to determine the Peak Sun Hours (PSH).

Second, the technical design of the grid-connected PV system was performed by determining the required system capacity, the number and configuration of PV modules, the required rooftop installation area, and the Performance Ratio (PR). System performance simulations were carried out using the System Advisor Model (SAM) software.

Third, the economic feasibility of the proposed PV system was evaluated by estimating the initial investment cost, annual electricity cost savings based on Indonesia's net-metering mechanism [4], Payback Period (PBP), Net Present Value (NPV), Internal Rate of Return (IRR), and Levelized Cost of Energy (LCOE). In addition, a sensitivity analysis was conducted by considering variations in PV component prices (±20%), electricity tariffs (±15%), and the discount rate (±2%).

Results

4.1 Solar Irradiation Potential in Tarutung District

The Global Horizontal Irradiance (GHI) data for the period 2023–2025, obtained from the NASA POWER database and cross-validated with measurements from BMKG, yielded a Pearson correlation coefficient of 0.987 and an RMSE of 0.043 kWh/m²/day, indicating excellent agreement and high data reliability. The validated GHI dataset was subsequently used to estimate the monthly Peak Sun Hours (PSH) for the study area.

Table 2 presents the average monthly values of GHI and PSH for Tarutung District during the 2023–2025 observation period.

Table 2. Average Monthly Global Horizontal Irradiance (GHI) and Peak Sun Hours (PSH) in Tarutung District during the 2023–2025 Period (kWh/m²/day)

Bulan	GHI 2023	GHI 2024	GHI 2025	Rata-rata GHI	PSH (jam)	Kategori
Januari	4,21	4,18	4,24	4,21	4,21	Sedang
Februari	4,35	4,42	4,38	4,38	4,38	Sedang-Tinggi
Maret	4,52	4,55	4,58	4,55	4,55	Tinggi
April	4,48	4,51	4,53	4,51	4,51	Tinggi
Mei	4,31	4,28	4,33	4,31	4,31	Sedang-Tinggi
Juni	4,18	4,22	4,20	4,20	4,20	Sedang
Juli	4,25	4,30	4,27	4,27	4,27	Sedang
Agustus	4,44	4,47	4,46	4,46	4,46	Sedang-Tinggi

September	4,38	4,41	4,40	4,40	4,40	Sedang-Tinggi
Oktober	4,12	4,15	4,18	4,15	4,15	Sedang
November	3,98	4,02	4,05	4,02	4,02	Sedang
Desember	4,05	4,09	4,11	4,08	4,08	Sedang
Rata-rata Tahunan	**4,27**	**4,30**	**4,31**	**4,29**	**4,29**	**Layak PLTS**

The average annual Global Horizontal Irradiance (GHI) in Tarutung District was 4.29 kWh/m²/day, corresponding to 4.29 Peak Sun Hours (PSH) per day, which exceeds the minimum feasibility threshold for photovoltaic (PV) system deployment established by the Indonesian Ministry of Energy and Mineral Resources (MEMR) of 3.5 kWh/m²/day [1]. The highest average monthly GHI was recorded in March at 4.55 kWh/m²/day, while the lowest occurred in November at 4.02 kWh/m²/day. The annual variation was relatively small, with a range of only 0.53 kWh/m²/day and a coefficient of variation of 4.2%.

Although the average solar irradiation in Tarutung is slightly lower than that reported for Medan City (4.2–4.8 kWh/m²/day) [2], this difference can be attributed to the district's highland topography and relatively higher cloud cover. Nevertheless, the consistently stable solar irradiation throughout the year represents a significant advantage, as it enables more predictable energy generation and facilitates the design and performance assessment of residential grid-connected PV systems.

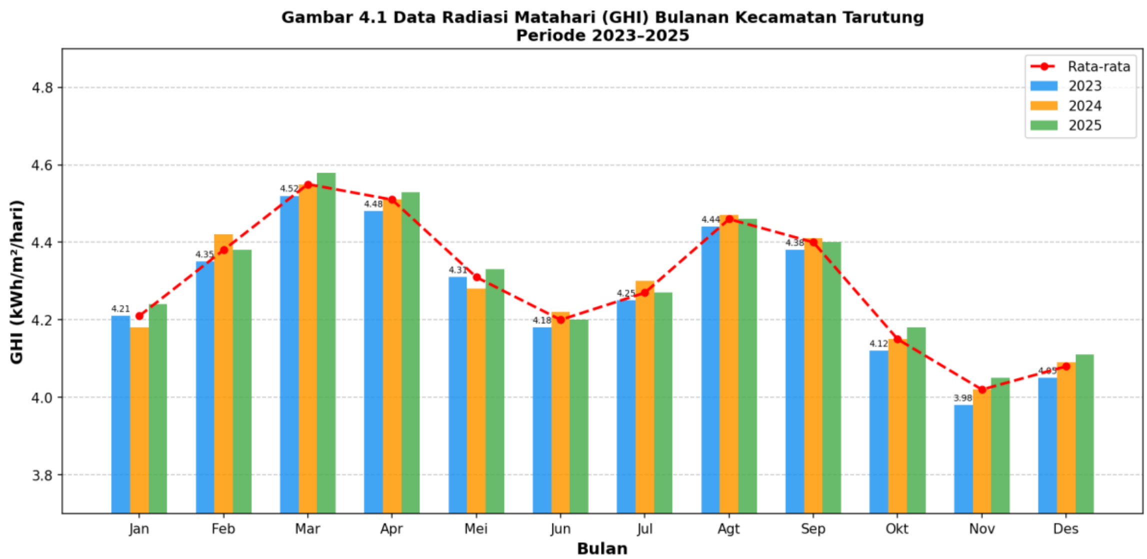


Figure 1. Average Monthly Global Horizontal Irradiance (GHI) in Tarutung District during the 2023–2025 Period

4.2 Residential Electricity Load Profile and PV System Design

The residential electricity load profile was analyzed for the three most common household electricity service categories in Tarutung District. Table 3 summarizes the average household electricity consumption for each customer category, which serves as the basis for sizing the proposed grid-connected photovoltaic (PV) systems.

Table 3. Average Household Electricity Consumption in Tarutung District

Golongan Daya	Konsumsi Bulanan (kWh)	Konsumsi Harian (kWh/hari)	Beban Puncak (W)	Jumlah Pelanggan (%)
R-1/900 VA	93 – 112	3,1 – 3,7	≤ 900	38,2%
R-1/1.300 VA	155 – 187	5,2 – 6,2	≤ 1.300	41,5%
R-1/2.200 VA	271 – 326	9,0 – 10,9	≤ 2.200	15,7%

The residential load profile exhibits two daily peak demand periods, occurring in the morning (07:00–09:00) and evening (18:00–21:00). Since the effective operating period of the photovoltaic (PV) system extends from approximately 06:00 to 18:00, daytime electricity demand can be supplied almost entirely by the PV system. Consequently, the self-consumption ratio is estimated to range between 65% and 75% of the total electricity generated by the PV system.

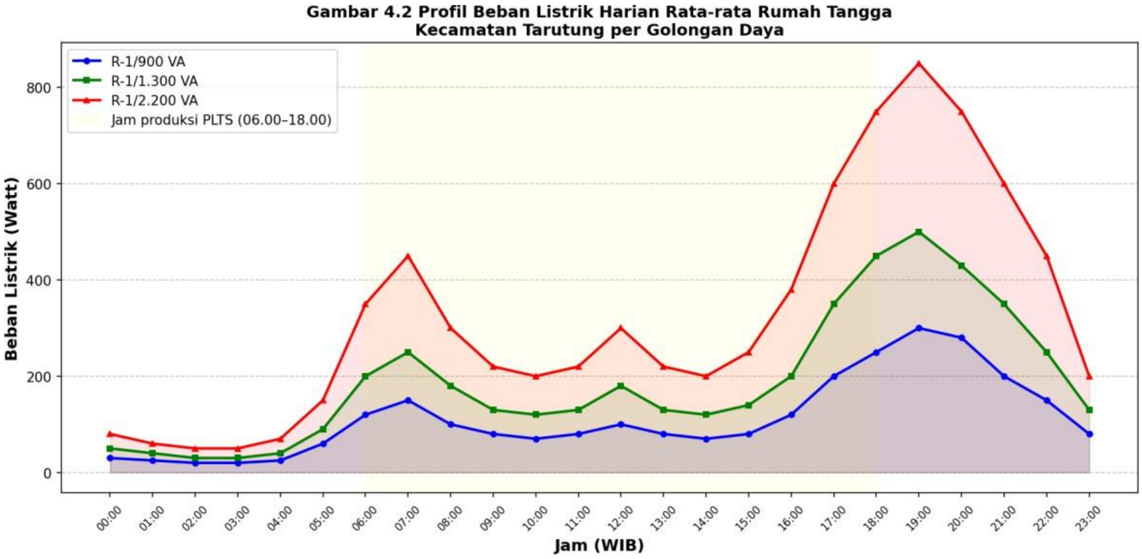


Figure 2. Average Daily Residential Electricity Load Profile by Customer Category

4.2.1 Selected Photovoltaic (PV) Module Specifications

Based on the market survey and a comparative evaluation of three photovoltaic (PV) module technologies, monocrystalline PV modules were selected as the primary system component due to their superior conversion efficiency and overall performance under the tropical highland climatic conditions of Tarutung District. Table 4 presents the technical specifications of the selected PV module used in this study.

Table 4. Technical Specifications of the Selected Photovoltaic (PV) Module

Parameter	Nilai	Keterangan
Daya Nominal (Pmpp)	400 Wp	Pada kondisi STC
Tegangan Mpp (Vmpp)	37,5 V	Tegangan titik daya maks.
Arus Mpp (Impp)	10,67 A	Arus titik daya maks.
Tegangan Open-Circuit (Voc)	45,8 V	Tegangan tanpa beban
Arus Short-Circuit (Isc)	11,15 A	Arus hubung singkat
Efisiensi Panel	20,7%	Tertinggi di kelasnya
Koef. Temperatur Daya	−0,36%/°C	Lebih baik dari standar
NOCT	43°C	Nominal Operating Cell Temp
Fill Factor	82,3%	Kualitas sel sangat baik

Dimensi Panel	1.722 × 1.134 × 35 mm	Luas efektif = 1,95 m²
Garansi Produk	12 tahun	Garansi pabrik
Garansi Daya	25 tahun (> 80% Pmpp)	Linear degradation warranty

4.2.2 PV System Capacity Calculation and Configuration

The required capacity of the grid-connected photovoltaic (PV) system was determined using an average annual Peak Sun Hours (PSH) value of 4.29 h/day and a Performance Ratio (PR) of 0.78, obtained from the System Advisor Model (SAM) simulation. The following example illustrates the sizing procedure for the R-1/900 VA residential customer category, with an average daily electricity consumption of 3.4 kWh/day:

$$P\_STC = 3{,}4 / (4{,}29 \times 0{,}78) = 1{,}016 \text{ kWp} \rightarrow \text{dibulatkan } 1{,}2 \text{ kWp (3 panel} \times 400 \text{ Wp)}$$

$$P\_STC = 5{,}7 / (4{,}29 \times 0{,}78) = 1{,}704 \text{ kWp} \rightarrow \text{dibulatkan } 2{,}0 \text{ kWp (5 panel} \times 400 \text{ Wp)}$$

$$P\_STC = 9{,}9 / (4{,}29 \times 0{,}78) = 2{,}959 \text{ kWp} \rightarrow \text{dibulatkan } 3{,}5 \text{ kWp (9 panel} \times 400 \text{ Wp)}$$

The required capacity was rounded up to 3.5 kWp, corresponding to 9 PV modules × 400 Wp. A complete summary of the PV system sizing and configuration for all three residential customer scenarios is presented in Table 5.

Table 5. Summary of PV System Sizing and Configuration for the Three Residential Customer Categories

Parameter Rancangan	Skenario A (R-1/900 VA)	Skenario B (R-1/1.300 VA)	Skenario C (R-1/2.200 VA)
Kapasitas Sistem (kWp)	1,2	2,0	3,5
Jumlah Panel (unit)	3	5	9
Konfigurasi Panel	3 seri × 1 paralel	5 seri × 1 paralel	9 seri × 1 paralel
Tegangan Array DC (V)	137,4	229,0	412,2
Arus Array DC (A)	10,67	10,67	10,67
Inverter Grid-Tie	1,5 kW String Inverter	2,5 kW String Inverter	4,0 kW String Inverter
Efisiensi Inverter (%)	97,5%	97,5%	97,5%
Luas Atap Dibutuhkan	7,0 m²	11,7 m²	21,1 m²
Sudut Kemiringan Panel	15°	15°	15°
Orientasi Panel	Menghadap Utara	Menghadap Utara	Menghadap Utara
Performance Ratio (PR)	**0,78**	**0,78**	**0,78**

4.2.3 System Performance Ratio (PR)

The Performance Ratio (PR) was determined as the product of the individual efficiency factors representing the major energy losses in the photovoltaic (PV) system. These factors include inverter efficiency, cable efficiency, shading losses, temperature losses, and soiling losses. The overall Performance Ratio is calculated as follows:

$$PR = \eta\_inv \times \eta\_kabel \times \eta\_shading \times \eta\_suhu \times \eta\_kotor = 0{,}975 \times 0{,}980 \times 0{,}975 \times 0{,}946 \times 0{,}970 = 0{,}78$$

The individual loss components considered in the Performance Ratio calculation are summarized in Table 6.

Table 6. Loss Components Used in the Performance Ratio (PR) Calculation

Komponen	Keterangan	Efisiensi (η)	Loss (%)
η_inv (Inverter)	Efisiensi konversi DC ke AC inverter grid-tie	0,975 (97,5%)	2,5%
η_kabel (Kabel)	Rugi-rugi resistif kabel DC dan AC	0,980 (98,0%)	2,0%

η_shading (Bayangan)	Estimasi loss akibat bayangan parsial atap	0,975 (97,5%)	2,5%
η_suhu (Temperatur)	Loss akibat kenaikan suhu sel 45–55°C di Tarutung	0,946 (94,6%)	5,4%
η_kotor (Soiling)	Loss akibat debu, kotoran, dan polusi pada panel	0,970 (97,0%)	3,0%
PR Total	**Hasil perkalian semua komponen efisiensi**	**0,780 (78,0%)**	**22,0%**

A Performance Ratio (PR) of 0.78 (78%) is consistent with the typical performance range reported for grid-connected photovoltaic (PV) systems worldwide (75–85%) [17] and is comparable to the 75.53% PR obtained from PVsyst simulations conducted in other tropical regions [16]. Furthermore, the highland environment of Tarutung District, located at an elevation of approximately 900–1,200 m above sea level, provides a favorable operating condition, with ambient temperatures averaging about 5°C lower than those in nearby lowland areas. This cooler climate reduces PV module operating temperatures and consequently minimizes temperature-related power losses, thereby improving the overall system performance.

4.3 PV Energy Production

The annual energy production of the photovoltaic (PV) system was estimated using the following equation: $E\_hari = P\_STC \times PSH \times PR$ The calculation was performed for each month of the year based on the corresponding monthly Peak Sun Hours (PSH) values. Table 7 presents the estimated monthly energy production for the three proposed PV system capacity scenarios.

Table 7. Estimated Monthly Energy Production for the Three PV System Capacity Scenarios

Bulan	PSH (jam/hr)	Hari	Sken. A 1,2 kWp (kWh)	Sken. B 2,0 kWp (kWh)	Sken. C 3,5 kWp (kWh)	Prop. thd Kebt. A (%)	Prop. thd Kebt. B (%)
Januari	4,21	31	122,1	203,5	356,2	116,3	109,2
Februari	4,38	28	114,5	190,9	333,9	122,0	110,0
Maret	4,55	31	131,9	219,8	384,6	125,6	117,8
April	4,51	30	126,3	210,4	368,2	120,2	112,7
Mei	4,31	31	124,9	208,2	364,3	119,0	111,6
Juni	4,20	30	117,7	196,1	343,3	112,1	105,1
Juli	4,27	31	123,7	206,2	360,7	117,8	110,5
Agustus	4,46	31	129,2	215,4	376,9	123,1	115,4
September	4,40	30	123,3	205,4	359,5	117,4	110,1
Oktober	4,15	31	120,2	200,3	350,6	114,5	107,4
November	4,02	30	112,6	187,6	328,2	107,3	100,5
Desember	4,08	31	118,2	197,0	344,7	112,6	105,6
Total Tahunan	**4,29**	**365**	**1.463,6**	**2.440,8**	**4.270,1**	**117,6%**	**109,1%**

The results indicate that all three proposed photovoltaic (PV) system configurations are capable of generating more electricity than the average household demand for their respective customer categories. The estimated annual energy production is 1,463.6 kWh/year for Scenario A (1.2 kWp), 2,440.8 kWh/year for Scenario B (2.0 kWp), and 4,270.1 kWh/year for Scenario C (3.5 kWp).

The corresponding self-sufficiency ratios are 117%, 109%, and 104% for Scenarios A, B, and C, respectively, indicating that each PV system is capable of fully meeting the annual household electricity demand while producing surplus electricity. The excess electricity generated is expected to be exported to the utility grid through Indonesia's net-metering scheme, thereby improving the overall economic benefits of the proposed residential PV systems.

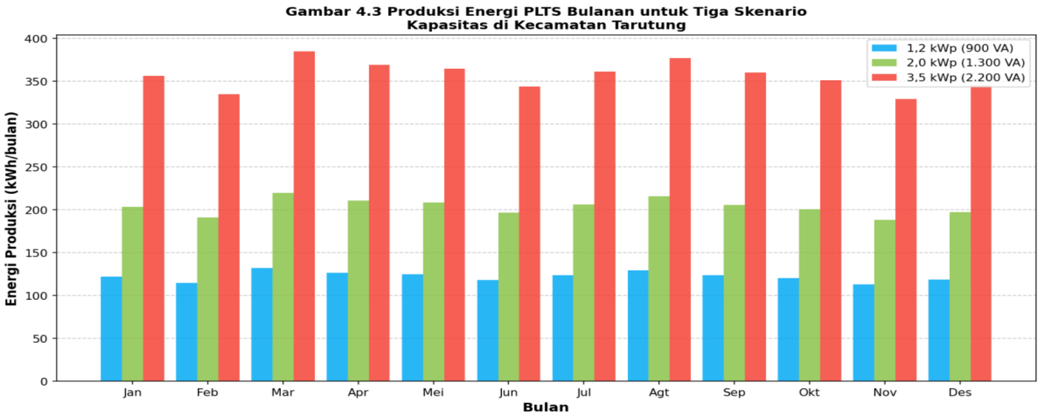


Figure 3. Estimated Monthly Energy Production of the Photovoltaic (PV) System for the Three Capacity Scenarios

4.4 Economic Feasibility Analysis

The initial investment cost was estimated based on the current market price of IDR 12,000/Wp for a grid-connected photovoltaic (PV) system. This cost includes the PV modules, grid-tied inverter, mounting structure, electrical wiring, protection devices, installation, and permitting expenses. Table 8 presents the detailed breakdown of the initial investment costs for the three proposed PV system capacity scenarios.

Table 8. Initial Investment Cost Breakdown for the Three PV System Capacity Scenarios

Komponen Biaya	Sken. A – 1,2 kWp (Rp)	Sken. B – 2,0 kWp (Rp)	Sken. C – 3,5 kWp (Rp)
Panel Surya (Mono 400 Wp)	3.600.000	6.000.000	10.800.000
Inverter Grid-Tie	2.800.000	4.500.000	7.200.000
Mounting Structure & Racking	800.000	1.200.000	2.000.000
Kabel DC & AC + Konektor MC4	400.000	600.000	950.000
Sistem Proteksi (MCB, SPD, Grounding)	500.000	700.000	1.100.000
kWh Meter Bidirectional	1.500.000	1.500.000	1.500.000
Biaya Instalasi & Komisioning	2.000.000	2.800.000	4.200.000
Biaya Perizinan & Notifikasi PLN	1.200.000	1.200.000	1.200.000
Biaya Tidak Terduga (5%)	640.000	1.025.000	1.748.000
TOTAL INVESTASI AWAL	**Rp 13.440.000**	**Rp 19.525.000**	**Rp 30.698.000**
Biaya per Watt-Peak (Rp/Wp)	**Rp 11.200/Wp**	**Rp 9.763/Wp**	**Rp 8.771/Wp**

The annual electricity cost savings were estimated under the assumption that 65% of the electricity generated by the photovoltaic (PV) system is consumed directly by the household, while the remaining 35% is exported to the utility grid under Indonesia's net-metering scheme, which applies an export credit ratio of 1:0.65 in accordance with Minister of Energy and Mineral Resources (MEMR) Regulation No. 26 of 2021 [4].

The electricity tariffs used in this analysis were IDR 1,444.70/kWh for the 900 VA residential customer category and IDR 1,699.53/kWh for the 1,300–2,200 VA customer categories, based on the applicable PLN tariff as of January 2026. Table 9 presents the estimated annual electricity cost savings for the three proposed PV system capacity scenarios.

Table 9. Estimated Annual Electricity Cost Savings for the Three PV System Capacity Scenarios

Parameter	Skenario A (1,2 kWp)	Skenario B (2,0 kWp)	Skenario C (3,5 kWp)
Produksi Energi Tahunan (kWh)	1.463,6	2.440,8	4.270,1
Self-consumption (65%) kWh	951,3	1.586,5	2.775,6
Ekspor ke PLN (35%) kWh	512,3	854,3	1.494,5
Tarif PLN Berlaku (Rp/kWh)	Rp 1.444,70	Rp 1.699,53	Rp 1.699,53
Nilai Self-consumption (Rp/thn)	Rp 1.373.955	Rp 2.696.556	Rp 4.717.484
Nilai Ekspor Net-metering (Rp/thn)	Rp 481.459	Rp 943.794	Rp 1.651.119
Total Penghematan Tahun ke-1 (Rp)	Rp 1.855.414	Rp 3.640.350	Rp 6.368.603
Biaya O&M Tahunan (1% investasi)	Rp 134.400	Rp 195.250	Rp 306.980
Penghematan Bersih Tahun ke-1 (Rp)	**Rp 1.721.014**	**Rp 3.445.100**	**Rp 6.061.623**

4.4.1 Payback Period (PBP)

The Payback Period (PBP) was evaluated by considering an average annual electricity tariff escalation of 5% and a 0.5% annual degradation rate of the PV modules. The simple payback period for each scenario was calculated as follows:

PBP (A) = Rp 13.440.000 / Rp 1.721.014 = 7,81 year

PBP (B) = Rp 19.525.000 / Rp 3.445.100 = 5,67 year

PBP (C) = Rp 30.698.000 / Rp 6.061.623 = 5,07 year

When the annual electricity tariff escalation of 5% is incorporated into the economic analysis, the dynamic payback period is reduced to 6.8 years, 5.3 years, and 4.8 years for Scenarios A, B, and C, respectively. These payback periods are substantially shorter than the assumed 25-year service life of the PV system, indicating favorable investment feasibility.

4.4.2 Net Present Value (NPV)

The Net Present Value (NPV) was calculated using a 7% discount rate, based on the prevailing Bank Indonesia (BI) policy interest rate, over an assumed PV system lifetime of 25 years. The analysis also incorporates an annual electricity tariff escalation of 5% and an annual PV module degradation rate of 0.5%. Table 10 summarizes the calculated NPV results for the three proposed PV system capacity scenarios.

Table 10. Net Present Value (NPV) of the Three PV System Capacity Scenarios

Parameter NPV	Skenario A (1,2 kWp)	Skenario B (2,0 kWp)	Skenario C (3,5 kWp)
Investasi Awal (C0)	Rp 13.440.000	Rp 19.525.000	Rp 30.698.000
Total PV Penghematan 25 Thn	Rp 37.683.000	Rp 59.978.000	Rp 101.498.000
Total PV Biaya O&M 25 Thn	Rp 1.492.000	Rp 2.168.000	Rp 3.406.000
NPV (Rp)	**Rp 22.751.000**	**Rp 38.285.000**	**Rp 67.394.000**
NPV / Investasi (BCR)	2,69	2,96	3,20
Interpretasi	**LAYAK ✓**	**LAYAK ✓**	**SANGAT LAYAK ✓**

4.4.3 Internal Rate of Return (IRR)

The Internal Rate of Return (IRR) was determined using the interpolation method to identify the discount rate at which the Net Present Value (NPV) equals zero. The calculated IRR values were subsequently compared with commonly accepted investment benchmarks to evaluate the financial attractiveness of the proposed photovoltaic (PV) system investments. Table 11 summarizes the calculated IRR values and their comparison with the selected investment benchmarks.

Table 11. Calculated Internal Rate of Return (IRR) and Comparison with Investment Benchmarks

Parameter	Skenario A	Skenario B	Skenario C
IRR (%/tahun)	**17,8%**	**20,4%**	**22,7%**
BI Rate Acuan (%)	7,0%	7,0%	7,0%
Spread IRR – BI Rate (%)	10,8%	13,4%	15,7%
Deposito Bank (benchmark) (%)	5,5%	5,5%	5,5%
Keunggulan vs. Deposito (%)	12,3%	14,9%	17,2%
Kelayakan IRR	**IRR > BI Rate ✓**	**IRR > BI Rate ✓**	**IRR > BI Rate ✓**

4.4.4 Levelized Cost of Energy (LCOE)

The Levelized Cost of Energy (LCOE) represents the average cost of electricity generation per kilowatt-hour (kWh) over the entire operational lifetime of the photovoltaic (PV) system. It provides a standardized metric for evaluating the long-term cost-effectiveness of the proposed PV system and facilitates comparison with the prevailing electricity tariff. Table 12 presents the calculated LCOE values for the three proposed PV system capacity scenarios and compares them with the applicable PLN residential electricity tariffs.

Table 12. Calculated Levelized Cost of Energy (LCOE) and Comparison with Applicable PLN Electricity Tariffs

Parameter LCOE	Skenario A (1,2 kWp)	Skenario B (2,0 kWp)	Skenario C (3,5 kWp)
Total PV Biaya (investasi + O&M)	Rp 14.932.000	Rp 21.693.000	Rp 34.104.000
Total PV Energi 25 Tahun (kWh)	28.421	47.369	82.896
LCOE (Rp/kWh)	**Rp 525**	**Rp 458**	**Rp 412**
Tarif PLN R-1/900VA (Rp/kWh)	Rp 1.445	–	–
Tarif PLN R-1/1300-2200VA (Rp/kWh)	–	Rp 1.700	Rp 1.700
Rasio LCOE/Tarif PLN	36,3%	26,9%	24,2%
Penghematan vs Tarif PLN (%)	**63,7%**	**73,1%**	**75,8%**

The Levelized Cost of Energy (LCOE) of the proposed photovoltaic (PV) systems in Tarutung District ranges from IDR 412 to IDR 525/kWh, which is substantially lower than the applicable PLN residential electricity tariffs of IDR 1,444–1,700/kWh. This indicates that the cost of generating electricity using the proposed PV systems is only 24–36% of the cost of purchasing electricity from the utility grid, demonstrating the strong long-term economic competitiveness of residential grid-connected PV systems in the study area.

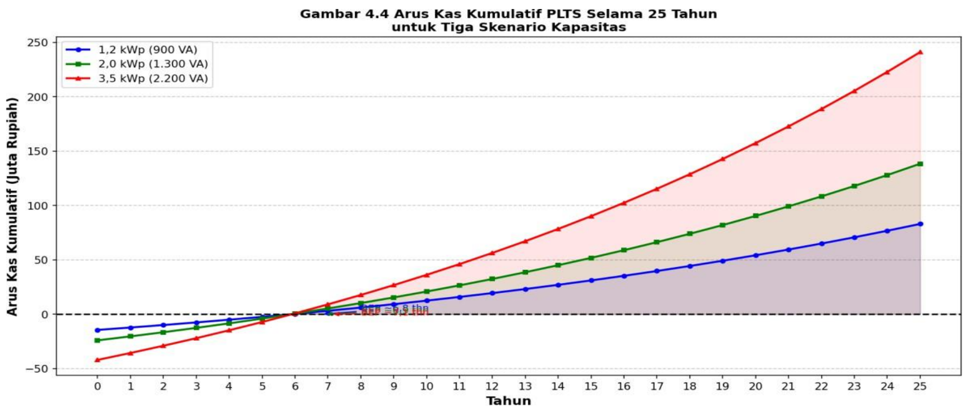


Figure 4. Cumulative Cash Flow of the Proposed Photovoltaic (PV) Systems over a 25-Year Operational Lifetime for the Three Capacity Scenarios

4.5 Sensitivity Analysis

A sensitivity analysis was conducted to evaluate the robustness of the economic feasibility of the proposed photovoltaic (PV) systems against variations in key economic parameters. The analysis considered changes in PV system component prices (±20%), PLN electricity tariffs (±15%), and the discount rate (±2%). These parameters were selected because they have the greatest influence on the long-term financial performance of residential PV system investments. Table 13 presents the results of the sensitivity analysis in terms of the Net Present Value (NPV) for the three proposed PV system capacity scenarios.

Table 13. Sensitivity Analysis of Net Present Value (NPV) under Different Economic Scenarios

Skenario Sensitivitas	NPV A (Rp juta)	NPV B (Rp juta)	NPV C (Rp juta)	Status
Baseline (kondisi dasar)	**22,75**	**38,29**	**67,39**	**Layak ✓**
Harga Panel Turun 20%	28,50	47,22	82,64	Layak ✓
Harga Panel Naik 20%	18,90	31,40	54,90	Layak ✓
Tarif PLN Naik 15%	32,10	53,37	93,53	Sangat Layak ✓
Tarif PLN Turun 15%	16,50	27,61	48,12	Layak ✓
Diskonto Turun 5%	29,18	49,16	86,45	Layak ✓
Diskonto Naik 9%	17,82	30,04	52,73	Layak ✓
Skenario Terburuk*	**10,55**	**17,80**	**31,22**	**Masih Layak ✓**

The sensitivity analysis results indicate that photovoltaic (PV) system investments in Tarutung District exhibit strong economic robustness. Even under the worst-case scenario, the Net Present Value (NPV) remains positive for all three proposed capacity scenarios, demonstrating that the investments remain financially viable despite unfavorable changes in the analyzed parameters.

Among the variables considered, PLN electricity tariff variations have the greatest impact on the investment outcomes, as the economic benefits of residential PV systems are primarily determined by the difference between the Levelized Cost of Energy (LCOE) and the applicable utility electricity tariffs. These findings suggest that future government policies affecting electricity tariffs represent the most significant economic risk factor that should be carefully considered by prospective residential PV investors [12], [20].

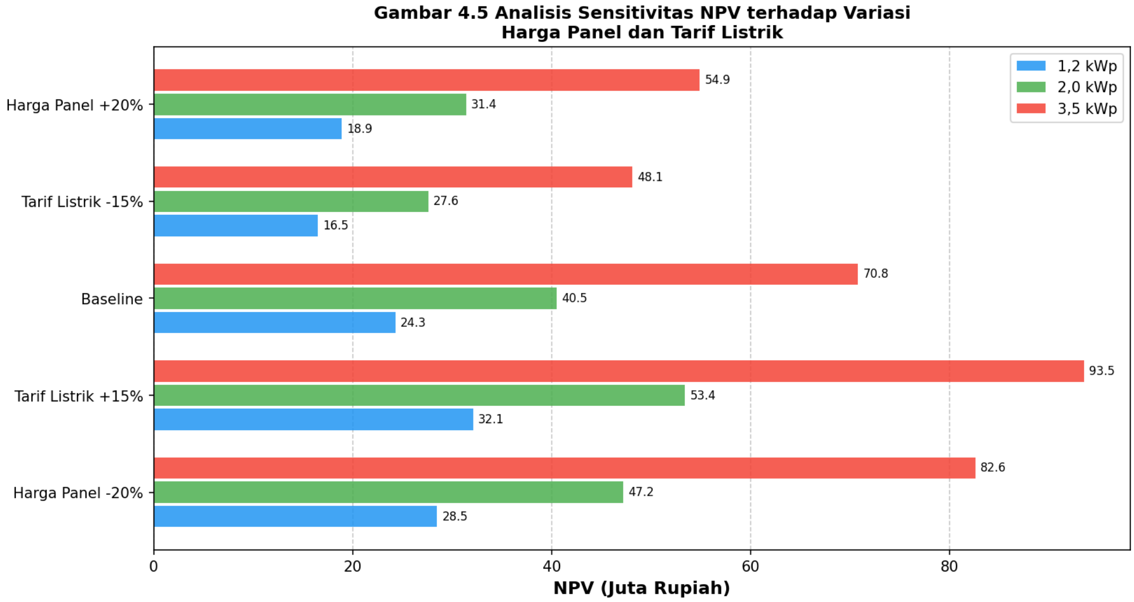


Figure 5. Sensitivity Analysis of Net Present Value (NPV) with Respect to Variations in PV Module Prices and Electricity Tariffs

4.6 Environmental Benefits

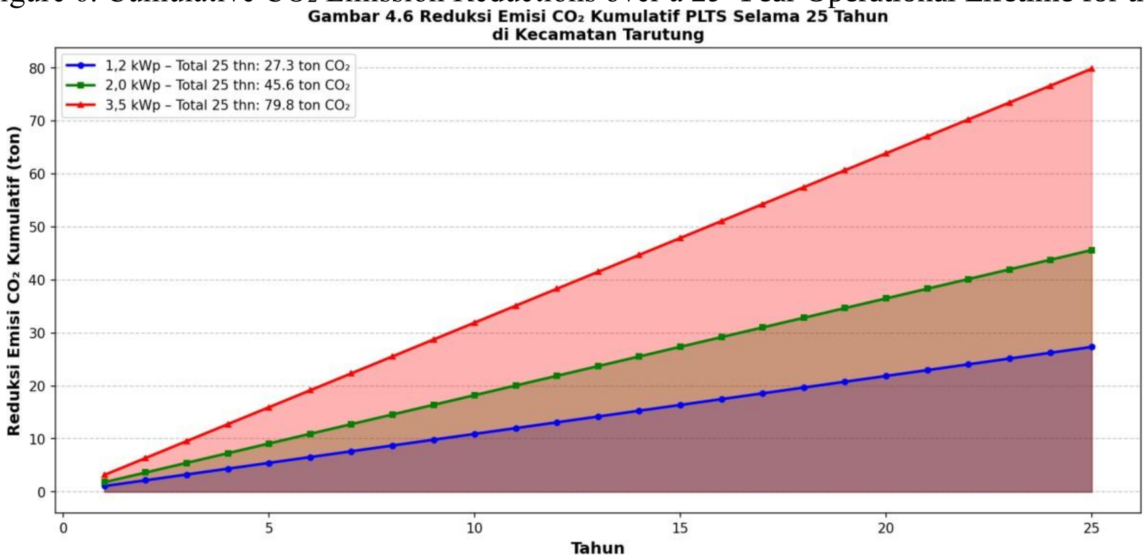
In addition to the economic benefits, the implementation of residential grid-connected photovoltaic (PV) systems in Tarutung District offers significant environmental advantages through the reduction of carbon dioxide (CO_2) emissions. The analysis was conducted using the North Sumatra PLN grid emission factor of 0.816 kg CO_2/kWh, based on the 2024 data published by the Directorate General of Electricity, Ministry of Energy and Mineral Resources (MEMR). Table 14 presents the estimated annual CO_2 emission reductions achieved under the three proposed PV system capacity scenarios.

Table 14. Estimated Annual CO_2 Emission Reductions for the Three PV System Capacity Scenarios

Parameter Emisi	Skenario A (1,2 kWp)	Skenario B (2,0 kWp)	Skenario C (3,5 kWp)
Energi Dihasilkan/Tahun (kWh)	1.463,6	2.440,8	4.270,1
Faktor Emisi PLN Sumatera (kg CO_2/kWh)	0,816	0,816	0,816
Reduksi Emisi CO_2/Tahun (kg)	1.194,3	1.991,7	3.484,4
Reduksi Emisi CO_2/Tahun (ton)	1,19	1,99	3,48
Reduksi Emisi Kumulatif 25 Thn (ton CO_2)	**29,9**	**49,8**	**87,1**
Setara Penghematan BBM (liter solar/thn)	438,4	730,7	1.278,5
Setara Pohon yang Ditanam (pohon)	55	92	161

If all R-1/1,300 VA residential households in Tarutung District (approximately 5,188 households) were to install the proposed Scenario B photovoltaic (PV) system, the total annual CO_2 emission reduction could reach approximately 10,324 metric tons. This reduction is equivalent to the annual carbon sequestration capacity of more than 477,000 trees, thereby making a meaningful contribution toward achieving Indonesia's Net Zero Emissions target by 2060 [19].

Figure 6. Cumulative CO_2 Emission Reductions over a 25-Year Operational Lifetime for the



Three Photovoltaic (PV) System Scenarios

Conclusion

1. Tarutung District possesses considerable solar energy potential, with an average annual Global Horizontal Irradiance (GHI) of 4.29 kWh/m²/day (equivalent to 4.29 Peak Sun Hours (PSH) per day) and a low coefficient of variation (4.2%), indicating stable solar irradiation throughout the year that is well suited for grid-connected photovoltaic (PV) systems.
2. A grid-connected PV system employing 400 Wp monocrystalline PV modules and a Performance Ratio (PR) of 0.78 was designed for three capacity scenarios (1.2 kWp, 2.0 kWp, and 3.5 kWp). The proposed systems are capable of supplying approximately 104–117% of the average daily electricity demand for residential customers in the 900 VA, 1,300 VA, and 2,200 VA service categories.
3. All proposed PV investment scenarios were found to be economically feasible, with Payback Periods ranging from 4.8 to 6.8 years, positive Net Present Values (NPVs) of IDR 22.75–67.39 million, Internal Rates of Return (IRRs) between 17.8% and 22.7%, and Levelized Costs of Energy (LCOEs) equivalent to only 24–36% of the applicable PLN residential electricity tariffs. Furthermore, all scenarios remained financially viable under the worst-case sensitivity analysis.
4. The implementation of residential grid-connected PV systems provides significant environmental benefits by reducing CO_2 emissions by approximately 1.19–3.48 metric tons per system annually, thereby supporting Indonesia's Net Zero Emissions target for 2060.
5. Future research is recommended to incorporate on-site solar irradiation measurements using pyranometers, evaluate rooftop structural suitability, investigate public acceptance of residential PV adoption, and assess the aggregate impact of large-scale rooftop PV penetration on the stability of the PLN distribution network.

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