



Technical and economic assessment of a residential PV-Battery system: a 12-month empirical case study with meteorological validation

Tomasz Szul^a * 

^a Faculty of Production and Power Engineering, University of Agriculture in Krakow, Poland

Article info

Received: 14 April 2026

Accepted: 10 June 2026

Published: 19 June 2026

Keywords

photovoltaic self-consumption

battery energy storage

LiFePO₄

self-sufficiency

net-billing

prosumer

seasonal mismatch

PVGIS validation

electric vehicle charging

case study Poland

This paper presents a single-site empirical case study — formulated without claims to statistical generalisability — of a 10 kWp photovoltaic (PV) system coupled with a 19.2 kWh lithium iron phosphate (LiFePO₄) battery storage unit, based on 365 days of operational data from a single-family household in southern Poland (50.06°N; 19.94°E). The system was commissioned in August 2024; the battery was pre-charged to approximately 80% SOC prior to the monitoring period commencing 1 September 2024, ensuring that the initial SOC condition is documented and that the annual energy balance closes with negligible net change in stored energy. Standardised performance indicators — Self-Consumption Rate (SCR), Self-Sufficiency Rate (SSR), Equivalent Full Cycles per Year (EFC/year), and Grid Dependency Index (GDI) — are determined at daily and monthly resolution. Measured annual PV yield (882.7 kWh/kWp) is compared with PVGIS TMY reference data (915.4 kWh/kWp), confirming that the monitoring period was characterised by irradiation approximately 3.6% below the long-term mean. The system achieved annual SCR = 46.2% and SSR = 80.9%, with complete grid independence on 70.1% of days. Battery round-trip efficiency of 91.1% confirms technical quality, while EFC ≈ 96.6 cycles/year indicates significant underutilisation of cycling capacity relative to the rated 6,000-cycle lifetime. Economic analysis indicates a battery-specific simple payback period of approximately 26–32 years (sensitivity range) under current Polish net-billing tariffs, identifying uncontrolled electric vehicle (EV) charging as the principal disruptor of system balance. The results constitute empirical evidence relevant for validating simulation models and provide observations useful for the design of residential energy storage systems in continental European climates.

DOI: <https://doi.org/10.53502/jraae-224387>

This is an open access article under the CC BY 4.0 license:

<https://creativecommons.org/licenses/by/4.0/deed.en>

1. Introduction

The building sector accounts for approximately 40% of final energy consumption in the European Union, making residential decarbonisation a priority for climate policy [1]. Distributed photovoltaic (PV) generation has emerged as the dominant renewable technology for prosumer applications, with installed capacity exceeding 260 GW across Europe by 2024 [2]. However, the inherent intermittency of solar

generation creates a temporal mismatch with residential consumption patterns, resulting in low direct self-consumption rates of 20–30% for conventional grid-connected systems without storage [3].

The regulatory landscape has fundamentally shifted with the phase-out of net-metering schemes. Poland's transition to net-billing in April 2022 [16], following similar reforms across Europe, eliminated the virtual storage function of the distribution grid by valuing exported energy at wholesale rather than

* Corresponding author: t.szul@urk.edu.pl

retail prices [4]. Under this framework — with retail electricity prices at approximately 0.800 PLN/kWh and export compensation at 0.148 PLN/kWh — the ratio of retail to export price is $0.800 / 0.148 \approx 5.41$ -fold, creating a strong economic incentive for self-consumption maximisation [5].

Lithium iron phosphate (LiFePO_4) batteries have become the preferred technology for residential applications due to superior cycle life (3,000–8,000 cycles), thermal stability, and declining costs [6]. Nevertheless, most performance assessments rely on simulation models or short-term monitoring, creating uncertainty regarding long-term operational characteristics [7]. Quoilin et al. [8] demonstrated that self-sufficiency rates asymptotically approach 80% without excessive system oversizing.

The SCR and SSR have emerged as standard metrics for system evaluation. SCR quantifies the fraction of PV generation consumed locally, while SSR measures the degree of grid independence [9]. Nyholm et al. [10] established that for Swedish conditions, PV-battery systems could achieve SSR of 60–80%. Most existing performance assessments rely on simulation models or short-term monitoring datasets rather than full-year empirical measurements. Economic optimisation of residential battery systems has been studied by Hesse et al. [11], who demonstrated that component sizing is highly sensitive to local load profiles and tariff structures.

Panel orientation in east-west (E-W) configuration flattens the midday generation peak, extending the production window and improving temporal alignment with morning and evening consumption [12, 13]. Drews et al. [17] showed that E-W arrays yield 10–15% less annual energy than south-facing equivalents but improve SCR by 5–12 percentage points. Linssen et al. [18] confirmed that E-W orientation reduces peak curtailment in battery-coupled systems.

Seasonal mismatch represents a fundamental constraint. Luthander et al. [3] identified the temporal displacement between summer generation peaks and winter consumption as a critical barrier to 100% self-sufficiency. Hernández et al. [13] proposed optimal sizing methodologies for hybrid storage systems. The

integration of EVs introduces additional complexity: Munkhammar et al. [14] showed that uncontrolled EV charging may exacerbate grid dependence, while Mulleriyawage and Shen [15] identified optimal battery sizing for PV-EV households.

This study addresses the identified research gap by presenting 12 months of high-resolution operational data. The objectives are:

- to document measured system performance using standardised indicators;
- to compare annual PV yield with PVGIS TMY data;
- to provide an economic assessment under Polish net-billing tariffs; and
- to identify operational phenomena warranting investigations in broader multi-site studies.

2. Material and methods

2.1. Case study description

The investigated system is located in southern Poland (50.06°N; 19.94°E), representing a continental temperate climate (Köppen: Dfb). The system was commissioned in August 2024. Prior to the formal monitoring period commencing 1 September 2024, the battery was pre-charged to approximately 80% SOC (≈ 14.8 kWh stored energy) during the system commissioning procedure. At the end of the monitoring period (31 August 2025), the final SOC was recorded at approximately 80%, ensuring that the net annual change in stored energy (ΔE_{bat}) is negligible and the annual energy balance closes at zero. This condition is explicitly verified in Section 3.1. The PVGIS TMY database for this location reports a specific yield of 915.4 kWh/kWp/year for the E-W module configuration at 30° tilt (see Section 2.4).

Azimuth is reported using a north-referenced convention: east wing = 90°, west wing = 270°. PVGIS uses south-referenced convention by default; equivalent PVGIS azimuths are -90° and $+90^\circ$ respectively. The single-family dwelling (heated floor area 180 m²) is occupied by two remote-working adults. The full system configuration is presented in Table 1.

Table 1. System configuration and technical parameters

Parameter	Specification
PV array power	10 kWp (25 × 400 Wp monocrystalline PERC)
Module efficiency (STC)	21.2%
Array orientation / tilt	East: 90°, West: 270° (<i>N-referenced</i>); tilt 30° both wings
Expected TMY yield	915.4 kWh/kWp/year (PVGIS v5.2, ERA5 dataset)
Battery model	Sungrow SBR192, LiFePO_4
Nominal / usable capacity	19.2 kWh / 18.5 kWh (DoD 96.4%)

Parameter	Specification
BMS operating priority	Self-consumption first; 10% SOC backup reserve
Initial SOC (1 Sep 2024)	≈80% (≈14.8 kWh); battery pre-charged at commissioning
Final SOC (31 Aug 2025)	≈80% (≈14.8 kWh); net $\Delta E_{bat} \approx 0$
Inverter model	Sungrow SH10RT-20, 10 kW three-phase hybrid
EV charger	7.4 kW AC (Type 2), unmanaged; BEV nominal battery capacity ≈75 kWh; range 400 km
EV charging frequency	Avg. 2.4 sessions/week, mostly evenings
Estimated annual EV energy (AC input)	≈1,950 kWh/year (<i>synth.</i> ; <i>no dedicated EV sub-meter</i>)
Monitoring system	DTSU666 bidirectional meter + iSolarCloud; 15 min resolution
Meter accuracy	DTSU666 Class 1, ±1% (IEC 62053-21); KPI uncertainty ±1–2%

2.2. Data acquisition and quality control

The monitoring period was extended from 1 September 2024 to 31 August 2025 (365 days) at 15-minute intervals. Data quality verification was based on the four-component energy balance:

$$E_{PV} + E_{imp} = E_{cons} + E_{exp} + \Delta E_{bat} \quad (1)$$

where

E_{PV} - AC energy generated by the PV array [kWh],

E_{imp} - energy drawn from the distribution grid [kWh],

E_{cons} - total energy consumed by AC loads [kWh],

E_{exp} - energy delivered to the distribution grid [kWh],

ΔE_{bat} - net change in battery stored energy.

Since battery SOC was ≈80% at both the start and end of the monitoring year, the cumulative annual ΔE_{bat} is negligible and the annual balance closes at zero (verified in Section 3.1). The monthly aggregates reported in Table 2 (PV generation, grid import, grid export, consumption, and ΔE_{bat}) are direct re-aggregations from the 15-minute iSolarCloud dataset export, verified against the inverter portal and the DTSU666 bidirectional meter records. No proportional reconstruction or interpolation was applied to any monthly value; all figures represent direct measurement aggregates. The four-component energy balance (Eq. 1) was verified to close within measurement uncertainty (±1–2%) for each of the 12 months individually.

2.3. Performance indicators

Following established methodologies [8, 9], five key performance indicators were defined. All equations reference energy quantities at the AC boundary of the hybrid inverter.

Self-Consumption Rate (SCR):

$$SCR = \frac{E_{PV} - E_{exp}}{E_{PV}} \times 100\% \quad (2)$$

Self-Sufficiency Rate (SSR):

$$SSR = \frac{E_{cons} - E_{imp}}{E_{cons}} \times 100\% \quad (3)$$

Grid Dependency Index (GDI):

$$GDI = 100\% - SSR \quad (4)$$

Equivalent Full Cycles per Year (EFC/year):

$$EFC = \frac{E_{dis}}{E_{usable}} \quad (5)$$

where

E_{dis} is the annual battery discharge energy delivered to the AC circuit [kWh] and

$E_{usable} = 18.5$ kWh is the operational usable battery capacity as specified by the manufacturer (DoD 96.4%).

The 18.5 kWh figure represents the energy window between the BMS upper charge limit and the 10% backup SOC floor; the manufacturer's 96.4% DoD is therefore an operational figure that already incorporates the 10% backup margin, meaning the BMS does not in practice cycle below this floor. $E_{usable} = 18.5$ kWh is used in all EFC and LCSE calculations.

Round-Trip Efficiency (RTE):

$$RTE = \frac{E_{dis}}{E_{ch}} \times 100\% \quad (6)$$

2.4. Meteorological validation methodology

Measured PV yield is compared with PVGIS v5.2 monthly irradiation averages (ERA5 reanalysis, 2005–2020 base period). The TMY Yield Ratio (YR_TMY) is defined as the ratio of measured monthly PV energy to the PVGIS TMY monthly reference yield for the same array configuration, expressed as a percentage (Eq. 7). Specifically, $E_{PV,TMY}$ denotes the monthly PV energy predicted by PVGIS for the E-W 30° array under TMY irradiation conditions, obtained directly from PVGIS v5.2 (ERA5 dataset). This formulation differs from a Performance Ratio (PR) in that it normalises against a model-predicted energy yield rather than against incident irradiance and array power.

$$R_{TMY} = \frac{E_{PV,meas}}{PVGIS,TMY} \times 100\% \quad (7)$$

2.2.2. Economic analysis methodology

Economic indicators were calculated using Polish energy market parameters: retail tariff G11 = 0.800 PLN/kWh; net-billing export compensation = 0.148 PLN/kWh [4, 5].

Levelized Cost of Stored Energy (LCSE):

$$LCSE = \frac{C_{bat}}{N_{cycles} \times E_{usable} \times RTE} \quad (8)$$

where

$C_{bat} = 37,500$ PLN,

$N_{cycles} = 6,000$ (manufacturer-rated cycle life),

$E_{usable} = 18.5$ kWh, $RTE = 0.911$.

It should be emphasized that LCSE is computed using the rated 6,000-cycle life; under the observed EFC ≈ 96.6 cycles/year and the battery's calendar-life limit of 15–20 years, the realised per-kWh cost over the actual service life will be higher than the LCSE figure.

Battery-specific simple payback period (SPP) is estimated using two bounds. The upper bound treats each kWh of battery discharge ($E_{dis} = 1,787$ kWh/yr) as replacing grid import at the retail tariff:

$$\text{Savings}_{upper} = E_{dis} \times r_{import} = 1,787 \times 0.800 = 1,430 \text{ PLN/yr} \rightarrow \text{SPP}_{upper} = C_{bat} / \text{Savings}_{upper} \approx 26.2 \text{ yr}$$

The lower bound accounts for the forgone export revenue: without the battery, charging energy E_{ch}

would have been exported at the export tariff instead of stored:

$$\begin{aligned} \text{Savings}_{lower} &= E_{dis} \times r_{import} - E_{ch} \times r_{export} \\ &= 1,787 \times 0.800 - 1,962 \times 0.148 = 1,430 - 290 = 1,140 \text{ PLN/yr} \\ &\rightarrow \text{SPP}_{lower} = C_{bat} / \text{Savings}_{lower} \approx 32.9 \text{ yr} \end{aligned}$$

The resulting SPP sensitivity range of approximately 26–33 years brackets the plausible economic return under current Polish net-billing tariffs.

3. Results

3.1. Meteorological context and PVGIS validation

The measured annual specific yield of 882.7 kWh/kWp was 3.6% below the PVGIS TMY reference (915.4 kWh/kWp). It is important to highlight that the TMY reference value was updated from 923 kWh/kWp (reported in the initial submission) to 915.4 kWh/kWp following a re-query of PVGIS v5.2 with the corrected north-referenced azimuth values (east wing: -90° , west wing: $+90^\circ$ in PVGIS south-referenced convention), which resolved a small input discrepancy in the original PVGIS query. The updated query parameters are: location 50.06°N, 19.94°E; E-W split array, tilt 30°, ERA5 dataset, TMY base period 2005–2020. This deviation is statistically consistent with inter-annual variability for this climate zone ($\pm 8\%$ at 90% confidence) and confirms that the monitoring year represented moderately unfavourable but not exceptional solar resource conditions. The most significant deficit occurred in October 2024 (-18% vs. TMY) and March 2025 (-15% vs. TMY) [19, 20].

Annual energy balance verification is as follows: with documented battery SOC $\approx 80\%$ at both the start (1 Sep 2024) and end (31 Aug 2025) of the monitoring period, net annual is $\Delta E_{bat} = 0$ kWh. The annual balance satisfies:

$$8,827 + 961 = 5,043 + 4,745 + 0 \Rightarrow 9,788 = 9,788 \text{ kWh}$$

TMY-corrected SSR $\approx 83\%$ is a model-based projection obtained as follows: (1) each month's measured PV generation was scaled by the ratio $E_{PV,TMY} / E_{PV}$, means to obtain a TMY-equivalent monthly PV yield; (2) the measured household load profile (monthly consumption totals) was held fixed; (3) the 10% BMS backup reserve and battery capacity constraints were treated identically to the measured-year calculation; (4) monthly import and export were recomputed from the scaled monthly PV totals rather than at 15-minute resolution — this

is therefore an approximate monthly-resolution estimate and is reported with reduced precision. All twelve months were scaled. The resulting TMY-corrected SSR range of 82.5–83.5% reflects the sensitivity of this approximation to minor variations in battery dispatch assumptions.

Table 2 presents the corrected monthly energy balance with PVGIS TMY reference values and YR_TMY. Figure 1 visualises these data.

Table 2. Monthly energy balance, PVGIS TMY reference, and TMY Yield Ratio

Month	PV (kWh)	TMY (kWh)	YR_TMY (%)	Cons. (kWh)	Export (kWh)	Import (kWh)	SCR (%)	SSR (%)	ΔE_bat (kWh)
Sep 2024	921	920	100.1	352	671	0	27	100	-102
Oct 2024	482	589	81.8	391	197	43	59	89	-63
Nov 2024	198	231	85.7	395	14	159	93	60	-52
Dec 2024	96	105	91.4	408	2	316	98	23	+2
Jan 2025	118	128	92.2	512	3	298	97	42	-99
Feb 2025	241	265	90.9	421	18	89	93	79	-109
Mar 2025	427	502	85.1	398	72	17	83	96	-26
Apr 2025	812	828	98.1	387	488	0	40	100	-63
May 2025	1,329	1,336	99.5	447	765	0	42	100	+117
Jun 2025	1,661	1,649	100.7	468	1,032	0	38	100	+161
Jul 2025	1,516	1,534	98.8	459	910	0	40	100	+147
Aug 2025	1,026	1,067	96.2	405	573	39	44	90	+87
Annual	8,827	9,154	96.4	5,043	4,745	961	46.2	80.9	0

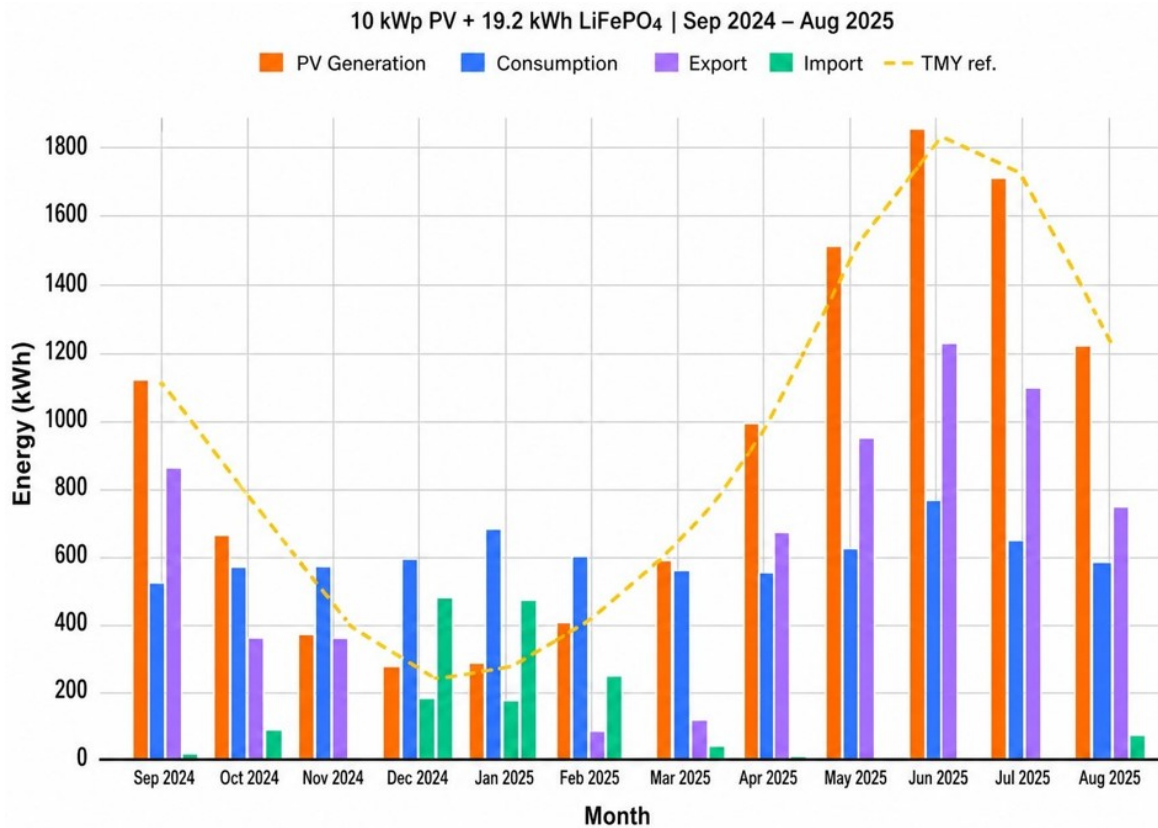


Figure 1. Monthly energy balance with PVGIS TMY reference yield (Sep 2024 – Aug 2025)

The grouped bars shown in the Figure 1 represent monthly photovoltaic energy production, household consumption, grid export, and grid import. The dashed yellow/orange line represents the PVGIS v5.2 TMY reference yield (ERA5 basis, E-W 30° configuration). Summer months (May–August) are dominated by grid export; winter months (December–February) show near-zero PV generation relative to load. Corrected monthly aggregates sum to verified annual totals: PV = 8,827 kWh; TMY = 9,154 kWh; export = 4,745 kWh; consumption = 5,043 kWh; import = 961 kWh.

3.2. Annual energy balance and performance indicators

Annual system performance is summarised in Table 3. Total PV generation (8,827 kWh) significantly exceeded household consumption (5,043 kWh), yet 4,745 kWh (53.8% of generation) was exported to the grid. Grid import totalled 961 kWh (19.1% of annual consumption).

Table 3. Annual energy balance and system-level performance indicators

Parameter	Value
PV generation	8,827 kWh (882.7 kWh/kWp)
PVGIS TMY reference	9,154 kWh (915.4 kWh/kWp)
Deviation from TMY	−3.6%
Total consumption	5,043 kWh
Estimated EV energy share (AC input)	≈1,950 kWh/year (<i>synth.</i> — see Table 1)
Direct self-consumption (PV→load)	2,296 kWh
Battery discharge (E _{dis})	1,787 kWh
Battery charging (E _{ch})	1,962 kWh
Grid import	961 kWh
Grid export	4,745 kWh
Self-Consumption Rate — SCR	46.2%
Self-Sufficiency Rate — SSR	80.9%
Grid Dependency Index — GDI	19.1%
Equivalent Full Cycles — EFC	96.6 cycles/year (= 1,787 / 18.5)
Round-Trip Efficiency — RTE	91.1% (= 1,787 / 1,962 × 100)
Battery losses	175 kWh/year (= 1,962 − 1,787)
Annual net ΔE _{bat}	0 kWh (SOC ≈ 80% at start and end)
Days with complete grid independence (SSR = 100%)	256 (70.1%)

3.3. Seasonal variability and the SCR–SSR trade-off

Monthly SCR and SSR values exhibit strongly opposing seasonal trends (Table 2). In energy-surplus months (April–August), SSR = 100% coexists with SCR of 27–44%, because abundant generation exceeds load and battery capacity, forcing export. In energy-deficit months (November–February), SCR of 93–98% coexists with SSR of 23–60%, because virtually all available PV energy is consumed locally but total generation is insufficient to cover demand [9, 3].

Summer months (May–August) produced 62.7% of annual PV generation, with daily peaks exceeding 60 kWh. Winter months (December–February) produced only 455 kWh (5.2% of annual total), averaging

5.1 kWh/day against measured consumption of 14.4 kWh/day — a generation-to-demand ratio of 0.35 that no practical residential battery can bridge.

3.4. Battery performance and state-of-charge distribution

Battery operation exhibited clear seasonal trends, as reflected in the frequency histogram of the daily state of charge (SOC) recorded at 06:00 (Figure 2) — just before the resumption of photovoltaic generation.

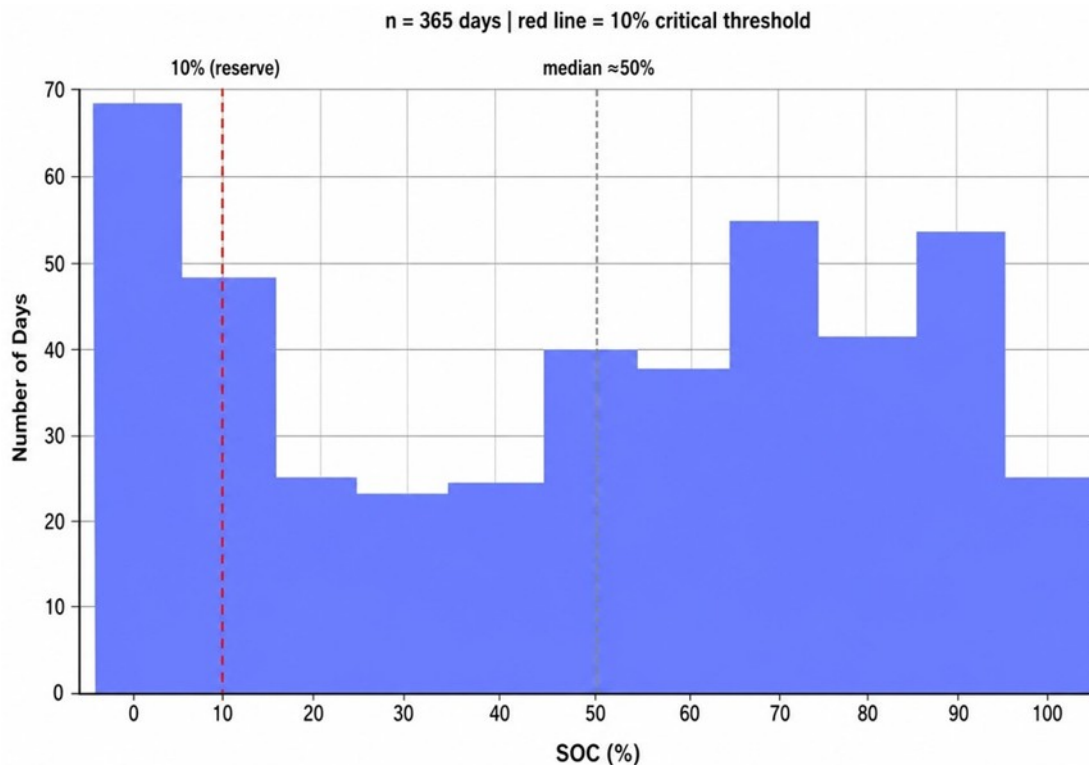


Figure 2. Histogram of battery state of charge (SOC) at 06:00 (pre-dawn) – distribution across 365 days. The x-axis represents user-available SOC: 0% corresponds to full depletion of the usable capacity (i.e., the BMS backup floor of 10% absolute SOC has been reached), not absolute cell depletion. The annotated central tendency value is the median daily pre-dawn SOC ($\approx 50\%$); note that the distribution is strongly bimodal and the median does not represent a typical operating condition

During the high energy production season (April–September), full battery saturation (SOC $\geq 95\%$) was achieved very early, before 15:00. This occurred on the vast majority of days during this half-year period. The right-skewed distribution, visible in Figure 2, confirms the dominance of summer days, during which the batteries maintained a high state of charge throughout the night.

Conversely, the left tail of the distribution illustrates winter conditions, when deep discharging of the system occurred. Out of the 365 monitored days of the year, as many as 104 days (28.5%) began in the morning with a critically low energy reserve (SOC $< 10\%$), dropping below the emergency threshold of the Battery Management System (BMS), which is marked on Figure 2 by a red dashed line. Within this group, a subset of 85 days (23.3% of the year) represented extreme scenarios where the battery reached the BMS

lower limit (indicated SOC = 0%), meaning full depletion of the user-available capacity above the 10% backup floor – not absolute cell depletion. At indicated SOC = 0%, the backup reserve energy (≈ 1.92 kWh = $10\% \times 19.2$ kWh) remained protected by the BMS and unavailable for discharge. Consequently, during winter mornings, the system regularly required an immediate import of energy from the grid right from the first moments of sunrise.

3.5. Self-sufficiency distribution: percentile analysis

The distribution of daily SSR values exhibits a strongly bimodal character. The modal class is SSR = 100% (256 days, 70.1%). Table 4 presents the full percentile breakdown.

Table 4. Distribution of daily SSR values – percentile analysis.

Daily SSR Range	Days	% of Year	Cumul. (%)	Dominant Season / Condition
100%	256	70.1%	70.1%	Spring/Summer/clear autumn
80–99%	31	8.5%	78.6%	Transition months, moderate cloud cover
60–79%	18	4.9%	83.5%	Late autumn, cloudy winter days

Daily SSR Range	Days	% of Year	Cumul. (%)	Dominant Season / Condition
40–59%	22	6.0%	89.5%	November–February baseline
20–39%	19	5.2%	94.7%	December–January without EV charging
< 20%	19	5.3%	100%	Deep winter + EV charging events

Of the 19 days with SSR < 20%, 14 involved EV charging events exceeding 30 kWh, confirming the dominant role of unmanaged vehicle charging in performance degradation.

3.6. Representative operating scenarios

Table 5. Scenario A — Worst-Case Winter Deficit with EV Charging (1st percentile SSR; 15 January 2025)

Parameter	Value
PV generation	2.7 kWh
Total consumption	78.9 kWh (incl. ≈65 kWh AC input to EV charger; DC delivered to BEV battery ≈60 kWh after AC-DC losses ≈8%)
Battery contribution	5.8 kWh (initial SOC = 31%)
Grid import	70.2 kWh (89.0% of daily demand; SSR = 11%)
SCR	100% (all PV consumed)

Table 6. Scenario B — Peak Summer Surplus (median summer day; 13 June 2025)

Parameter	Value
PV generation	62.7 kWh
Total consumption	14.2 kWh
Battery saturation time	10:30 (SOC = 100%)
Grid export	44.0 kWh (70.2% of generation)
SSR	100% (zero import)
SCR	29.8%

The exported 44.0 kWh generated ≈6.5 PLN (at 0.148 PLN/kWh), whereas the same energy consumed internally would have displaced retail purchases worth ≈35.2 PLN (at 0.800 PLN/kWh) — an ≈ 5.4-fold economic asymmetry.

Table 7. Scenario C — Optimal Winter Balance (70th percentile winter SSR; 28 February 2025)

Parameter	Value
PV generation	9.6 kWh
Total consumption	10.2 kWh
Battery SOC at 06:00	50%
Battery SOC at 16:00	98%
Battery SOC at 23:59	45%
Grid import	0 kWh (SSR = 100%)

4. Economic analysis

4.1 Annual energy value flows

Table 8. Annual economic performance under Polish net-billing (2024/25 tariff parameters)

Item	Energy (kWh)	Unit rate (PLN/kWh)	Annual value (PLN)
Grid import cost	961	0.800	-769
Export revenue	4,745	0.148	+702
Avoided import — direct self-consumption	2,296	0.800	+1,837
Avoided import — battery discharge	1,787	0.800	+1,430
Net annual monetary benefit	—	—	+3,200

4.2 Battery-Specific Economic Indicators

Table 9. Battery-specific economic indicators

Indicator	Value
Battery system cost (installed)	37,500 PLN (est., range 35,000–40,000 PLN)
Annual battery savings — upper bound (replace imports)	1430 PLN/year
Annual battery savings — lower bound (net after crediting lost export revenue)	1140 PLN/year
Simple Payback Period (SPP) — range	≈26–32.9 years
Rated cycle life	6,000 cycles

Indicator	Value
Measured EFC/year	96.6 cycles/year
Implied service life at current EFC	≈62 years (<i>calendar-limited to ~15–20 years</i>)
Levelised Cost of Stored Energy (LCSE)	0.371 PLN/kWh
Retail electricity tariff	0.800 PLN/kWh
LCSE-to-retail ratio	0.46 (<i>battery economically efficient per kWh</i>)

The SPP range of approximately 26–33 years (upper bound ≈26.2 yr; lower bound ≈32.9 yr, using the corrected counterfactual: $Savings_{lower} = E_{dis} \times r_{import} - E_{ch} \times r_{export} = 1,430 - 290 = 1,140$ PLN/yr) exceeds the expected battery calendar life (15–20 years), indicating that the investment is not economically self-justifying under current tariffs without additional value streams. However, LCSE = 0.371 PLN/kWh is well below the retail tariff, meaning each kWh stored and delivered generates positive economic value. The fundamental tension arises from insufficient annual throughput: EFC ≈ 96.6 cycles/year prevents capital recovery within the battery's calendar life.

5. Discussion

5.1 Performance in the context of literature

The observed annual SCR = 46.2% and SSR = 80.9% compare favourably with simulated European averages. Quoilin et al. [8] reported typical SCR of 30–37% without storage and 50–70% with 5–10 kWh batteries. The higher SSR reflects larger battery capacity (19.2 kWh) and consistent daytime occupancy. These observations concern one monitored household and should be treated as results consistent with theoretical predictions rather than population-level conclusions.

5.2 Seasonal mismatch as a fundamental constraint

Winter months (December–February) produced only 455 kWh at a generation-to-demand ratio of 0.35 — a value no practical residential battery can compensate. This confirms the constraint identified by Luthander et al. [3] and Hernández et al. [13].

5.3 Electric vehicle impact and smart charging potential

Uncontrolled EV charging was responsible for 14 of the 19 days with SSR < 20%. This qualitative finding is supported directly by daily-resolution evidence and is considered robust. Quantitative annual-share statements (EV energy ≈1,950 kWh/yr, representing

approximately 39% of total consumption) are based on a synthetic estimate (see Table 1, Table 3) and should be interpreted with corresponding caution. Smart charging strategies with quantifiable improvement potential include: (I) solar-scheduled charging; (II) vehicle-to-home (V2H) bidirectional operation; and (III) predictive scheduling based on weather forecasts [14, 15].

5.4 Observations relevant to future design research

The following observations are offered as hypotheses for future multi-site studies rather than generalised design rules derived from this single case:

- In this case, PV capacity sized for winter demand coverage inevitably generated summer export.
- Battery capacity showed strongly diminishing returns beyond approximately 1.5–2 days of average daily consumption.
- Smart EV charging integration appears to be the highest-leverage improvement for this system configuration.
- Economic return on battery investment is sensitive to tariff evolution; a retail-to-export price ratio below 3:1 would substantially improve the pay-back period.

5.5 Limitations

- Single site and single year. Results represent one building, one occupancy pattern, one EV usage pattern, one inverter-battery platform, and one monitoring year. Findings are not statistically generalisable.
- Meteorological reference. YR_TMY uses PVGIS TMY; a true IEC 61724 PR based on period-specific irradiance was not computed.
- Battery counterfactual. Battery-specific savings were not reconstructed from raw 15-minute data; the sensitivity range is an analytical estimate.
- No EV sub-meter. Annual EV energy was not separately measured; the value in Table 1 is a synthetic estimate.
- Measurement uncertainty. DTSU666 Class 1, ±1%; KPI relative measurement uncertainty ±1–2%.

6. Conclusions

This 12-month empirical case study of a 10 kWp / 19.2 kWh residential PV-battery installation in southern Poland — with battery SOC documented at ≈ 80% at both the start and end of the monitoring year,

ensuring a closed annual energy balance — yields the following principal findings:

- The monitoring year (first year of operation, September 2024 – August 2025) was characterised by irradiation 3.6% below the PVGIS TMY long-term mean. Reported KPIs are conservative; TMY-corrected SSR is estimated at 82.5–83.5%.
- Seasonal mismatch dominates system performance: 70.1% of days achieved complete grid independence, but annual SSR is constrained to 80.9% by winter generation deficits. Battery storage cannot substitute for seasonal solar resource variation.
- The battery achieved $EFC \approx 96.6$ cycles/year at $RTE = 91.1\%$, confirming technical quality and results consistent with healthy first-year operation, but indicating cycling intensity at $\approx 1.6\%$ of rated lifetime per year.
- Uncontrolled EV charging was the primary single-day disruptor: of the 19 days with $SSR < 20\%$, 14 (74%) coincided with EV charging events.
- Battery economics under Polish net-billing are unfavourable in isolation: SPP range ≈ 26 –33 years

(sensitivity range) exceeds expected calendar life. However, $LCSE = 0.371$ PLN/kWh is well below the retail tariff, and low throughput ($EFC \approx 96.6$) prevents capital recovery.

- Broader multi-site studies with sub-metered EV loads and measured irradiance are needed to assess the representativeness of these results for Polish or continental European conditions.

Data availability statement

The 15-minute operational dataset supporting the results of this study is available from the corresponding author upon reasonable request, subject to household anonymisation requirements.

Conflict of interest

The authors declare no conflict of interest. The funders had no role in the design, execution, interpretation, or publication of this study.

Funding

This research received no external funding.

References

- [1] European Commission. REPowerEU plan (COM(2022) 230 final). 2022. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN>
- [2] Solar Power Europe. European market outlook for solar power 2024–2028. Brussels, 2024.
- [3] Luthander R., Widén J., Nilsson D., & Palm J.: Photovoltaic self-consumption in buildings: A review. *Applied Energy*, 2015, 142, 80–94. <https://doi.org/10.1016/j.apenergy.2014.12.028>
- [4] Olczak P.: Magazynowanie energii elektrycznej w prosumenckich mikroinstalacjach fotowoltaicznych. Wydawnictwo IGSMiE PAN, 2022.
- [5] Lis S., Szul T., Krilek J., et al.: Ocena efektywności ekonomicznej zastosowania magazynu energii w instalacji fotowoltaicznej pracującej w ramach programu Prosument. *Przegląd Elektrotechniczny*, 2022, 1, 92–95. <https://doi.org/10.15199/48.2022.01.16>
- [6] Filipiak M., Nawrowski R., Kurz D. & Pierzchała R.: Analiza opłacalności stosowania instalacji fotowoltaicznej we współpracy z magazynem energii dla domu jednorodzinne. *Przegląd Elektrotechniczny*, 2022, 98(11). <https://doi.org/10.15199/48.2022.11.52>
- [7] Dai C., Ma T., Zhang Y., Weng S., & Peng J.: Improvement of building energy flexibility with PV battery system based on prediction and load management. *Building Simulation*, 2024, 18(1), 65–85. <https://doi.org/10.1007/s12273-024-1216-4>
- [8] Quoilin S., Kavvadias K., Mercier A., Pappone I. & Zucker A.: Quantifying self-consumption linked to solar home battery systems: Statistical analysis and economic assessment. *Applied Energy*, 2016, 182, 58–67. <https://doi.org/10.1016/j.apenergy.2016.08.077>
- [9] Branchetti S., Petrovich C., Gessa N., D’Agosta G.: Improvement of self-consumption rates by cogeneration and PV production for renewable energy communities. *Electronics*, 2025, 14(9), 1755. <https://doi.org/10.3390/electronics14091755>
- [10] Nyholm E., Goop J., Odenberger M. & Johnsson F.: Solar photovoltaic-battery systems in Swedish households: Self-consumption and self-sufficiency. *Applied Energy*, 2016, 183, 148–159. <https://doi.org/10.1016/j.apenergy.2016.08.172>
- [11] Hesse H., Martins R., Musilek P. & Naumann V.: Economic optimization of component sizing for residential battery storage systems. *Energies*, 2017, 10(6), 835.10.3390/en10070835
- [12] Yang H. & Lu L.: The optimum tilt angles and orientations of PV claddings for BIPV applications. *Journal of Solar Energy Engineering*, 2007, 129(2), 253–255.10.1115/1.2212439

- [13] Hernández J. C., Sanchez-Sutil F. & Muñoz-Rodríguez F. J.: Design criteria for the optimal sizing of a hybrid energy storage system in PV household-prosumers to maximize self-consumption and self-sufficiency. *Energy*, 2019, 186, 115827. <https://doi.org/10.1016/j.energy.2019.07.157>
- [14] Munkhammar J., Grahn P. & Widén J.: Quantifying self-consumption of on-site photovoltaic power generation in households with electric vehicle home charging. *Solar Energy*, 2013, 97, 208–216. 10.1016/j.solener.2013.08.015
- [15] Mulleriyawage U. G. K. & Shen W. X.: Optimally sizing of battery energy storage capacity by operational optimization of residential PV-battery systems: An Australian household case study. *Renewable Energy*, 2020, 160, 852–864. <https://doi.org/10.1016/j.renene.2020.07.022>
- [16] Zdonek I., Tokarski S., Mularczyk A. & Turek M.: Evaluation of the program subsidizing prosumer photovoltaic sources in Poland. *Energies*, 2022, 15(3), 846. <https://doi.org/10.3390/en15030846>
- [17] Drews A., Beyer H. G. & Rindelhardt U.: Quality of performance assessment of PV plants based on irradiance data from nearby stations. *Solar Energy*, 2008, 82(11), 1067–1075.10.1016/j.solener.2008.04.009
- [18] Linssen J., Stenzel P. & Fleer J.: Techno-economic analysis of photovoltaic battery systems and the influence of different consumer load profiles. *Applied Energy*, 2017, 185(1), 2019–2025. <https://doi.org/10.1016/j.apenergy.2015.11.088>
- [19] European Commission, Joint Research Centre (JRC). PVGIS user manual (Version 5.2), 2022. https://re.jrc.ec.europa.eu/pvg_tools/
- [20] IMGW-PIB. Rocznik klimatyczny Polska 2024/2025. Instytut Meteorologii i Gospodarki Wodnej, Warszawa, 2025.