

Analysis of the Effectiveness of Using Vehicle-To-Home (V2H) Technology as An Element of a Home Energy Management System*

Przemyslaw SZOPA

Cracow University of Economics, Rakowicka 27, 31-510 Kraków, Poland
Department : Metrology and Instrumental Analysis,

Correspondence should be addressed to: Przemyslaw SZOPA, szopap@uek.krakow.pl

*Presented at the 47th IBIMA International Conference, 29-30 June 2026, Madrid, Spain

Abstract

The dynamic development of photovoltaic (PV) micro-installations and the electromobility sector in Poland faces the National Power System with significant challenges in energy balancing. The introduction of a net-billing model based on hourly prices exposes prosumers to financial losses caused by price cannibalization of energy generated from renewable energy sources. This article aims to assess the techno-economic and operational efficiency of Vehicle-to-Home (V2H) technology as a functional substitute for stationary energy storage systems (BESS) in Polish market conditions of net-billing and dynamic tariffs. The paper presents a case study of an electrified residential building (160 m²) with a daily energy demand of 16 kWh, integrated with a PV installation producing 6200 kWh/year and an electric vehicle with a 60 kWh gross battery capacity. The results of empirical simulations for a summer sunny day (34 kWh PV generation) demonstrate that implementing HEMS V2H management algorithms can increase the total energy self-consumption rate to 66%, reducing daily energy purchase costs by up to 94.6%. Despite barriers related to vehicle location instability and the lack of clear procedures for connecting mobile storage facilities by power grid operators, V2H technology is a highly engineering-effective tool for economic optimization and energy management in a prosumer PV microgrid.

Keywords: Vehicle-to-Home (V2H), Net-billing, Self-consumption, Energy Storage, Prosumer Photovoltaics. Energy Management

Introduction

As a key pillar of economic development, the modern energy sector faces numerous challenges directly linked to environmental protection while simultaneously ensuring energy supplies through conscious resource management. In the face of the increasing energy demand of highly developed countries, the stability of national electricity distribution networks is becoming crucial (International Energy Agency, 2023; Tayri and Ma, 2025). As the fastest-growing country in Central and Eastern Europe, Poland faces a steadily rising annual demand for electricity. Consequently, securing a high share of clean energy for electric transport is crucial also to reducing air pollution. (Szopa, 2024; Sarnek and Szopa, 2022). Over the past decade (2015–2025), successive Polish governments have strongly promoted renewable energy, particularly that based on photovoltaic installations installed on buildings and private properties, creating an extensive energy system based on distributed energy.

Cite this Article as: Przemyslaw SZOPA Vol. 2026 (4) “Analysis of the Effectiveness of Using Vehicle-To-Home (V2H) Technology as An Element of a Home Energy Management System” Communications of International Proceedings, Vol. 2026 (4), Article ID 4732126, <https://doi.org/10.5171/2026.4732126>

Distributed energy has made a significant contribution to Poland's overall energy balance in recent years (Central Statistical Office, 2025; Kurtyka, 2022). With the growing number of photovoltaic installations, the Polish energy sector has faced the challenge of storing surplus energy during periods of low demand (Olczak et al., 2022; IEO Report, 2024). Addressing the storage challenge is crucial for managing renewable energy. This issue has become particularly acute with the development of electric vehicles, particularly BEVs (Battery Electric Vehicles – fully electric) and PHEVs (plug-in hybrids) (Tayri and Ma, 2025). These vehicles are most often charged in the evenings, during the peak energy consumption of the day. The load of the electricity grid is increasing year by year due to the growing demand for electric cars (International Energy Agency, 2024). Government programs promoting the purchase and use of electric cars on preferential terms are also important (Polish Act on Electromobility, 2018; My Electrician Program 2021; Priority Program "NaszEauto" 2025). The electric vehicle (EV) market in Poland is experiencing rapid expansion. According to data from the Polish Automotive Industry Association (PZPM) and the Polish Association of New Mobility (PSNM), approximately 252,000 electric cars were registered between 2016 and 2026 (E-mobility Index, 2026). There has been a particularly strong upward trend in new registrations over the last two years (2024-2025), as shown in Figure 1. The increasing number of registered electric cars significantly burdens the power grid, which has not been fully adapted to the rapidly changing energy consumption load during peak demand (Calearo et al., 2020). For this reason, real-time power balancing by the power grid is becoming crucial for the continuity of supply and the security of the grid itself. (Inci et al., 2024) Currently, two key areas directly impact power balancing in the power grid: power surpluses and power shortages. Every transmission network has a limited capacity to buffer excess energy if it is not consumed instantaneously by end-users (Kempton and Tomić, 2005).

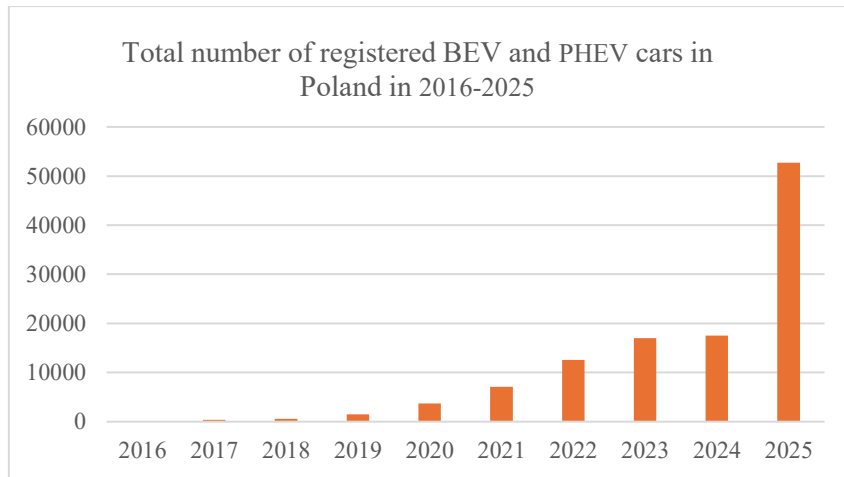


Fig. 1. Total number of registered BEVs and PHEVs in Poland in 2016-2025

Source: Own elaboration based on PZPM and PSNM

The ideal grid state occurs when instantaneous power generation matches power demand, resulting in the relationship $\Delta P(t)=0$, where $\Delta P(t)$ represents the instantaneous difference between power supply and demand within the network. Achieving fully stable grid parameters requires characterizing both the capacity of supply sources and the demand from grid consumers (Rubanenko et al., 2021). The instantaneous power grid imbalance indicator can be expressed by the following relationship:

$$\Delta P(t) = [P_G(t) + P_{0ZE}(t) \pm P_M(t) \pm P_I(t)] - [P_o(t) + P_s(t)],$$

where:

$P_G(t)$ – controllable power relating to energy production from non-renewable sources, scalable in a short time,

$P_{0ZE}(t)$ – uncontrollable power dependent on the conditions of a specific climate zone, derived from the conversion of solar, wind, and water energy,

$P_M(t)$ – power from energy storage,

$P_I(t)$ - imported and exported power,

$P_o(t)$ - the instantaneous grid load drawn by end-use devices,
 $P_s(t)$ - power losses in cables and transformers.

Managing peak grid loads during evening hours requires highly effective energy management, particularly when integrating volatile renewable sources. Consequently, there is a strong emphasis on promoting prosumer photovoltaic (PV) installations equipped with efficient energy storage systems (ESS). These storage assets enable the flexible shifting of power generated during peak solar irradiance periods (Mahmud et al., 2018). Figure 2 illustrates the dynamic profiles of PV power supply and grid load relative to prosumer consumption.

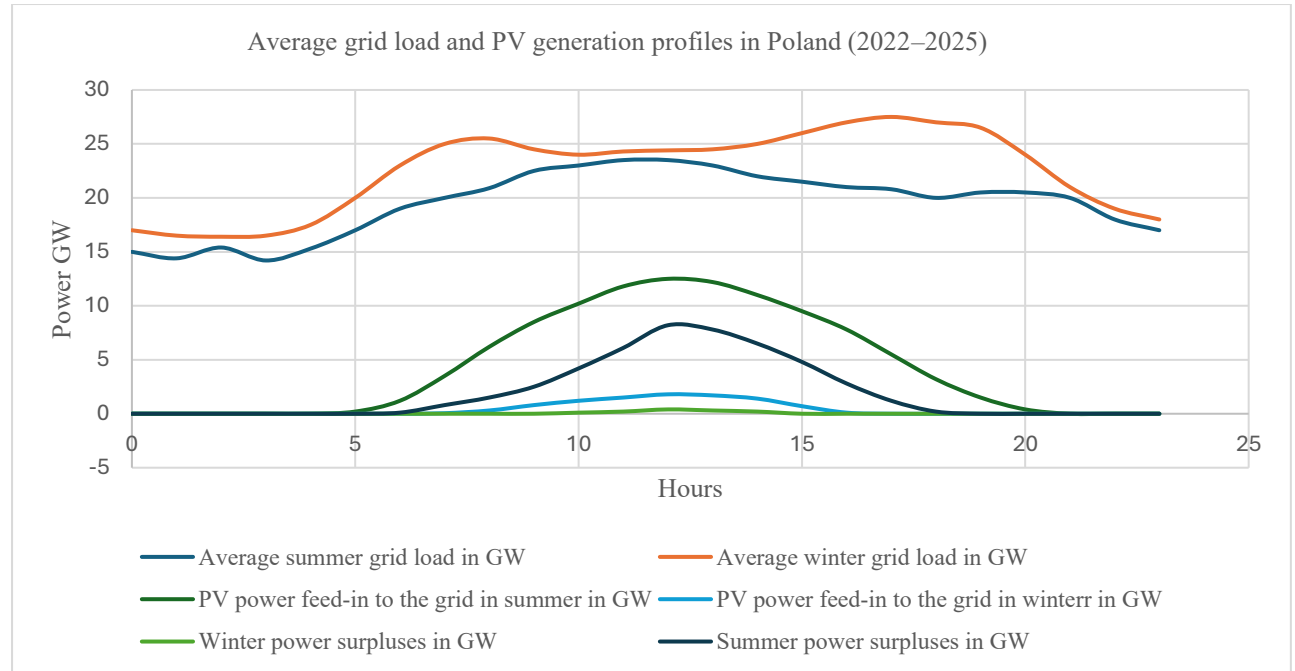


Fig. 2. Daily load profile of the National Power Grid and PV generation in Poland (averaged model 2022–2025).

Source: Own elaboration based on data from PSE (Polish Power Grids) and the Forum Energii portal.

The comparison indicates a significant mismatch between the profiles of commercial and residential photovoltaic (PV) generation and the actual grid load during midday hours. A high surplus of energy fed into the network, particularly during summer, is frequently wasted due to constraints in grid hosting capacity. In winter, however, peak electricity demand clearly shifts to the morning and evening hours, when renewable generation is at its lowest (O'Shaughnessy et al., 2019; Yang et al., 2026). The solution to this problem is effective energy storage in BESS (Battery Energy Storage) systems during periods of high energy supply, both at the micro- and macro-scale levels. The problem with storing electricity using battery storage has both advantages and disadvantages. The main disadvantage of these solutions is often the high purchase and operating costs relative to their capacity and the benefits obtained from energy storage, which significantly hinders their implementation in small-scale, residential photovoltaic systems. Analysing energy storage systems commonly used in households in relation to their actual energy capacity, it is important to consider the costs associated with their technology, which often significantly impacts the final economic calculation (Toosi, 2020; Markotić et al., 2025). Currently (2026), energy storage prices are declining on the global market; however, the cost per kilowatt-hour (kWh) remains high when accounting for the total capital expenditures and operational costs of the complete system. A significant limitation of these storage systems, relative to their unit cost, is their actual usable capacity, which is frequently lower than the nominal capacity declared by manufacturers. For safety and lifespan optimization, lithium-ion and lithium iron phosphate (LFP) batteries cannot be fully discharged. This operational constraint directly restricts the usable battery capacity to 80%–90% of its nominal value (Hu et al., 2024). Furthermore, the battery pack is not the standalone component of a storage installation; it requires an advanced Battery Management System (BMS), a dedicated bi-directional inverter for charging and discharging, and auxiliary protection infrastructure against short circuits and thermal events (such as fire). Due to their high initial cost, these balance of system (BOS) components significantly increase the net cost per kilowatt-hour (kWh) of usable storage capacity. Consequently, an energy

storage system is neither asset-free nor maintenance-free. Its operational expenditures relative to actual capacity are driven by three primary factors:

- Battery charging and discharging efficiencies: This process causes physical energy losses dissipated as heat due to the internal chemical reactions occurring within the cells.

- Capacity degradation: Cells experience capacity fade over time and with each operational cycle. Typical manufacturer warranties guarantee a retention of 70% to 80% of the initial capacity after one decade or approximately 6,000 full equivalent cycles. Consequently, after ten years, a 10 kWh battery pack will realistically store only 7–8 kWh of energy.

- Temperature sensitivity: Operating cells at low ambient temperatures prevents safe charging at high currents. Conversely, sustained operational temperatures above 35°C accelerate the thermochemical degradation of the cell structure (Ma et al., 2018).

Taking the aforementioned factors into account, residential energy storage systems deployed in small households should ideally feature a capacity ranging from 5 kWh to 20 kWh. On the Polish market (2026), the average wholesale (net) prices for standalone storage kits are structured as follows: PLN 5,000–9,000 for a 5 kWh system, PLN 10,000–18,000 for a 10 kWh system, and PLN 20,000–35,000 for a 20 kWh system. The total investment required for an energy storage system, including installation and VAT, ranges from PLN 13,000 to PLN 20,000 gross for a 5 kWh system, and approximately PLN 19,000 to PLN 35,000 gross for a 10 kWh system. For a larger capacity 20 kWh configuration, gross costs can escalate to PLN 55,000. Such high initial capital expenditures significantly diminish the overall profitability of the storage system. Consequently, the deployment of these technologies relies heavily on robust government subsidy mechanisms, such as the Polish 'Mój Prąd' (My Electricity) program. Without financial support, the payback period on an energy storage investment often substantially exceeds 10 years, closely approaching the limit of the cells' operational warranty life (Cieślak, 2024).

Integration of Vehicle-to-Home (V2H) technology as an alternative to stationary BESS: Analysis of capacity and charging topology

In today's distributed energy sector, replacing expensive stationary energy storage with mobile storage systems—enabled by modern bidirectional charging technologies integrated into electric vehicles (EVs)—emerges as a highly viable alternative. A fundamental question of the current study is to determine whether an EV equipped with Vehicle-to-Home (V2H) capabilities can effectively substitute for a dedicated, stationary Battery Energy Storage System (BESS). This substitution potential depends crucially on the power conversion topology and the communication protocols implemented for energy exchange between the vehicle and the home grid. In this context, two primary technological paradigms can be distinguished:

- Unidirectional, intelligent Vehicle-one-Grid (V1G) charging operates solely to charge an electric vehicle from the residential PV grid. The alternating current (AC) to direct current (DC) conversion occurs via an on-board charger (OBC) or an external DC charging station. Because these vehicles cannot feed stored energy back into the building's microgrid, they cannot substitute for traditional stationary storage. Instead, V1G technology enables demand-side peak-shaving by modulating the charging load to coincide with periods of maximum grid or PV surplus. Implementing intelligent Home Energy Management System (HEMS) algorithms (Junquera et al., 2017) optimizes this process, modulating charging timeframes to align with the PV generation curve or dynamic tariff price troughs. While this significantly minimizes grid stress, the stored energy remains locked within the vehicle for mobility purposes and cannot be repurposed for home appliances.

- Bidirectional Vehicle-to-Home (V2H) charging utilizes the electric vehicle (EV) battery to enable the direct substitution of traditional stationary energy storage systems in households. This bidirectional topology facilitates reverse power flow from the vehicle's battery back into the building's internal AC microgrid. Consequently, it requires advanced steering electronics capable of operating seamlessly in both charging and discharging modes (Mendes et al., 2023).

Implementing Vehicle-to-Home (V2H) systems as a substitute for stationary Battery Energy Storage Systems (BESS) requires a meticulous comparison between the energy potential of modern electric vehicles (EVs) and the actual daily load profiles of residential buildings. Due to the significant disparities between the capacity of a mobile electrochemical buffer and the real energy demand of an average household, selecting the optimal mobile storage configuration becomes crucial (Videgain Barranco, 2021). Modern electric vehicles (EVs) utilize high-energy-density battery packs whose nominal capacities far exceed those of residential energy storage systems, which typically range from 5 to 15 kWh. Manufacturer data indicate that the usable capacities of vehicles supporting bidirectional V2H power flow vary substantially across different automotive segments. Within the city car and compact crossover categories, the nominal capacities of batteries integrated into V2H frameworks range from 58 kWh to 77.4 kWh, as seen in models like the Kia EV6, VW ID.4, and Hyundai Ioniq 5. Conversely, in the premium and heavy vehicle segments, nominal battery capacities escalate to between 99 kWh and 123 kWh, as seen in the Kia EV9 and Tesla Cybertruck. To maintain an operational energy reserve for driving requirements—for instance, by enforcing a minimum 30% State of Charge (SoC) buffer—the net battery capacity available to the HEMS ranges from 40 kWh to as much as 85 kWh of usable energy per vehicle. When evaluated against the load profiles of Polish single-family buildings, the nominal capacities offered by these mobile e-mobility storage assets prove entirely sufficient. Notably, the energy consumption profile of a residential building is highly dependent on the heating technology used and the building's thermal insulation. Buildings utilizing conventional heat sources (such as gas, biomass, or solid fuels) exhibit an annual electricity demand for household appliances, electronics, and lighting ranging from 2,500 kWh to 3,500 kWh. This baseline requirement translates into an average daily demand of 6.8 kWh to 9.6 kWh. Conversely, modern all-electric buildings—equipped with heat pumps, energy recovery ventilators, and air conditioning systems—exhibit a substantial annual electricity demand of 10,000 kWh to 15,000 kWh, characterized by strong seasonality. During the summer and transitional seasons, the average daily energy consumption is approximately 10–15 kWh. However, during sub-zero winter temperatures and intensive heat pump compressor operation, daily electricity consumption escalates to 35–50 kWh (Central Statistical Office, 2026; Arinea, 2024). Given the large capacity of these connectable mobile storage assets, the energy autonomy of single-family buildings can be significantly extended. The power autonomy of a single-family home utilizing a mobile storage configuration with a usable capacity of 50 kWh is summarized in Table 1.

Table 1. Energy autonomy of a single-family residence supported by an EV battery

Energy autonomy of a single-family residence supported by an EV battery (50 kWh EV energy storage)		
Building Energy Profile	Daily energy consumption	Building autonomy time without PV generation
Standard (without heat pump)	6.8 – 9.6 kWh	5.2 – 7.3 days
Electrified (Summer)	10.0 – 15.0 kWh	3.3 – 5.0 days
Electrified (Winter - Peak)	35.0 – 50.0 kWh	1.0 – 1.4 days

Source: Own elaboration based on the ARINEA Portal and the RM Solar Portal

In a long-term analysis that accounts for synergies with a residential PV micro-installation, deploying V2H technology can increase the average photovoltaic self-consumption rate (SCR) by between 25% and 47%, compared to a maximum SCR of only 20% for a standalone PV system (Naworyta, 2025). Consequently, from

spring to autumn, a typical Polish single-family residence can achieve near-complete energy independence by utilizing the vehicle battery as a daily buffer for surplus PV generation. However, the limitations of V2H technology become apparent during the heating season (December to February). Due to minimal winter PV generation coupled with a high building energy load—primarily driven by heat pump operation for space heating—a 50 kWh vehicle battery can sustain safe backup power for only about 24 to 30 hours. Nevertheless, from a system perspective, this backup capacity still drastically outperforms conventional stationary home batteries, making V2H technology a highly effective mechanism for stabilizing a building's net load profile.

Economic optimization of microgeneration systems in the net-billing model by increasing the self-consumption rate via V2H technology

The prosumer net-billing system, introduced in Poland via the 2022 amendment to the Renewable Energy Sources Act, is based on value-based energy accounting. Surplus generation from photovoltaic (PV) micro-installations is introduced into the grid and compensated at the market energy price—specifically the hourly (RCE) or monthly (RCEm) market clearing price—whereas electricity consumption is billed at the full retail rate. Under these regulatory and economic conditions, the self-consumption rate (SCR) emerges as the dominant factor determining the investment's return on investment (ROI). Utilizing the capacity of an electric vehicle (EV) battery within a Vehicle-to-Home (V2H) framework fundamentally redefines the economic efficiency of this process. The resulting increase in PV self-consumption, achieved by shifting daily surpluses into mobile storage assets during periods of low market value compared to a standalone PV installation, is illustrated in Figures 3 and 4.

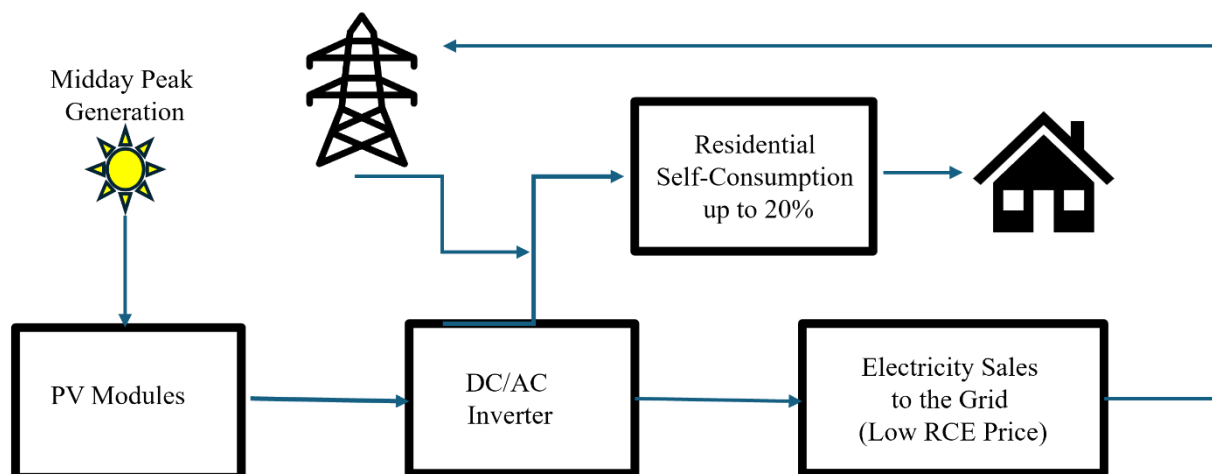


Fig. 3. Energy distribution and sales algorithm for a PV installation without energy storage
Source: Own elaboration

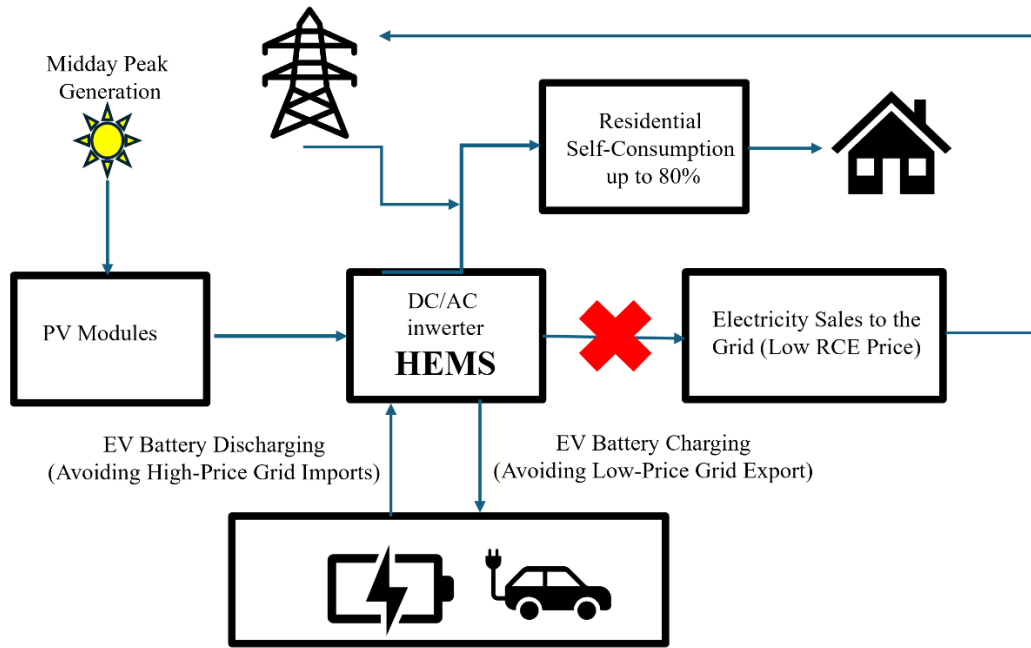


Fig. 4. Energy distribution and sales algorithm for a PV installation using a mobile energy storage system based on an electric vehicle using V2H technology.

Source: Own elaboration

To fully map the energy conversion and flow dynamics within the examined prosumer architectures, two comparative operational models were developed, as reflected in the accompanying block diagrams. These algorithms realize the millisecond-level decision-making sequence of the automated control logic, where the overarching optimization objective is minimizing energy imports from the external distribution grid. The block diagram in Figure 3 depicts the control architecture of a conventional photovoltaic micro-installation lacking local energy storage capabilities. Conversely, Figure 4 illustrates the algorithm governing dynamic energy management via an EV-based mobile storage system using V2H technology, via a master HEMS. The red indicator on the AC grid connection line symbolizes a temporary energy export curtailment enforced by the HEMS optimization algorithms.

In a market system driven by short-term price fluctuations, the daily profile of photovoltaic (PV) generation from both micro- and macro-scale installations induces severe price cannibalization, creating pronounced midday price drops. Between 11:00 AM and 3:00 PM, when distributed PV generation peaks, the market-clearing price of energy (RCE) on the Polish Power Exchange (TGE) drops dramatically during oversupply periods, frequently approaching zero or turning negative. Conversely, the afternoon and evening peak in residential demand (5:00 PM to 10:00 PM) coincides with a total absence of solar generation. Consequently, a prosumer without an energy storage system is compelled to purchase electricity from the grid at a fixed retail tariff—or elevated hourly rates under dynamic pricing—burdened by variable distribution fees, taxes, and a quality fee. Cumulatively, this results in an average gross cost of approximately PLN 1.04 per 1 kWh, based on data for the most prevalent G11 tariff in Poland (2026). In the absence of local energy storage, the average self-consumption rate (SCR) of a typical Polish single-family residence remains limited to 10%–20%. Consequently, the remaining 80%–90% of generated energy is introduced into the grid under economically disadvantageous net-billing pricing. Implementing Vehicle-to-Home (V2H) technology dynamically changes these proportions, primarily by utilizing the EV battery as a flexible buffer to absorb surplus generation. On a sunny day, the average surplus generation from a 10 kWp photovoltaic (PV) micro-installation reaches approximately 35–50 kWh. Conventional wall-mounted residential storage systems, often constrained by capital costs and subsidy limits to capacities of 5–20 kWh, typically saturate within 2–3 hours of peak solar irradiance. Conversely, a large-scale EV battery (e.g., 77 kWh) can fully accommodate the entire daily surplus. By deploying this expanded storage capacity, the SCR is substantially elevated. Storing energy electrochemically within the EV cells and subsequently inverting it to support household appliances enables the total self-consumption rate—both direct and time-shifted—to reach 60%–80%. Every kilowatt-hour of electricity that powers a household directly from the vehicle battery instead of the distribution grid generates a net financial benefit. This profit represents the spread between the retail electricity purchase cost (approximately PLN 1.04/kWh) and its midday market clearing price, which frequently drops below PLN 0.20–0.30/kWh. This operational strategy effectively protects prosumer clearing accounts from devaluation caused by extremely depressed buyback rates. In Poland, the mandatory introduction of dynamic tariffs linked to real-time wholesale

market prices has played a pivotal role in maximizing self-consumption profits since 2026. Managing this complex energy exchange process—in accordance with both the V2H protocol and dynamic tariff structures—is entrusted to a master Home Energy Management System (HEMS). The main optimization algorithm relies on the continuous monitoring of the system's operational expenditures, executing the specific HEMS operational scenarios detailed in Table 2.

Table 2. Decision matrix of the HEMS algorithm

HEMS V2H algorithm decision matrix		
PV generation status	Current RCE price level	HEMS algorithm decision
High (mid-day)	Low / Negative	Export Lock; EV Max Charging
None (Evening)	High (Peak Demand)	Starting protocol V2H; Covering home demand with EV
None (Night)	Low (Night Valley)	Charging the EV storage from the power grid

Source: Own elaboration

Implementing a mathematical V2H control model not only avoids wasting renewable energy during midday price drops but also ensures highly efficient energy management. If weather forecasts indicate insufficient solar irradiance for the following day, the predictive HEMS charges the EV battery overnight—leveraging the price valleys of dynamic market tariffs. Subsequently, the system discharges this low-cost stored energy during the morning to support energy-intensive household loads, such as the heat pump's morning heating cycle, thereby avoiding expensive peak-hour rates. Consequently, within a net-billing framework, V2H technology successfully transforms a passive prosumer into an active energy manager.

Case Study: Techno-Economic analysis of substituting stationary BESS with V2H technology under a Net-Billing framework

The following case study presents a techno-economic and operational simulation of Vehicle-to-Home (V2H) technology deployment within the Polish electricity market. The analysis is grounded in the scenario of a highly energy-intensive single-family residence, characterized by a substantial baseload driven by installed Heating, Ventilation, and Air Conditioning (HVAC) systems based on heat pump technologies. The simulation incorporates the following operational parameters: a well-insulated 160 m² residential building with an actual annual electricity consumption of 5,840 kWh, paired with a 6 kWp photovoltaic (PV) micro-installation. Based on empirical data from the real operational installation, the average daily energy consumption throughout the year was established at 16 kWh. The annual energy yield from the 6 kWp PV system reaches 6,200 kWh. An electric vehicle (EV) featuring a net battery capacity of 54 kWh is integrated into the system. The designated buffer, according to HEMS, allocated strictly for home demand, is configured at approximately 21.6 kWh (corresponding to 40% of the total battery capacity), which seamlessly covers the baseline daily electricity requirements of the building (16

kWh). The remaining 60% of the capacity (32.4 kWh) constitutes an inviolable driving reserve to ensure mobility. The retail electricity procurement costs from the grid (comprising the G11 dynamic tariff and variable distribution charges for 2026) are defined as follows: PLN 0.45/kWh during the night and midday price drops, and PLN 1.15/kWh during the evening peak hours (5:00 PM–10:00 PM). The buyback prices tariff for surplus PV generation (hourly RCE) averages PLN 0.20/kWh during peak solar irradiance. To model the system dynamics, the building's average daily load profile is divided into the following operational timeframes: 00:00–06:00 (night): 2.5 kWh; 06:00–16:00 (daytime): 3.5 kWh; 16:00–22:00 (evening residential peak): 8.5 kWh; and 22:00–24:00 (late evening): 1.5 kWh. This comparative analysis was conducted for a clear summer day, characterized by an empirical PV generation profile yielding 34 kWh. The techno-economic performance for the baseline scenario, where the PV system operates without any energy storage capacity, is summarized in Table 3. Conversely, Table 4 details the operational and financial outcomes for the configuration where a mobile EV-based energy storage system with a gross capacity of 60 kWh is integrated into the home electricity network.

Table 3. Techno-economic analysis of a standalone PV system without energy storage.

Balance of PV energy generation and building self-consumption (06:00–16:00)	During periods of highest PV generation, the average residential load accounts for 3.5 kWh of electricity consumption. The remaining surplus of 30.50 kWh is instantaneously introduced into the external distribution grid.
Prosumer energy deposit valuation	$30.50 \text{ kWh} \times \text{PLN } 0.20 = \text{PLN } 6.10$
Evening and night consumption (16:00–06:00)	8.5 kWh during the evening peak + 4.0 kWh during off-peak, night hours
The actual cost of energy imports from the grid	$(8.5 \text{ kWh} \times 1.15 \text{ PLN}) + (4.0 \text{ kWh} \times 0.45 \text{ PLN}) = 9.78 \text{ PLN} + 1.80 \text{ PLN} = 11.58 \text{ PLN}$
Calculated energy self-consumption	10.5% (including conversion efficiencies and system losses)

Source: Own elaboration

Table 4. Techno-economic analysis of a PV system integrated with a 54 kWh net mobile EV storage (utilizing a 40% operational buffer)

The dynamic EV charging phase	The PV generation surplus accounts for 30.50 kWh. However, the vehicle's storage capacity can accommodate a maximum of 21.60 kWh.
PV surplus energy export	Since the PV generation surplus (30.50 kWh) exceeded the operational buffer capacity (21.60 kWh), the remaining 8.90 kWh of electricity is instantaneously exported to the distribution grid
Prosumer deposit valuation under V2H	$9 \text{ kWh} \times 0.20 \text{ PLN} = 1.8 \text{ PLN}$
Evening V2H discharging phase	Between 17:00 and 22:00, the master HEMS completely isolates the building from the distribution grid. During this timeframe, the EV battery discharges to fully accommodate the evening residential demand of 8.50 kWh
Overnight consumption	An import of 4.0 kWh of electricity from the grid is executed during the low-cost overnight off-peak tariff, incurring a total cost of 1.80 PLN
Calculated energy self-consumption	66 % (including conversion efficiencies and system losses)

Source: Own elaboration

The empirical maximum daily summer PV yield of 34 kWh demonstrates that for a 6 kWp micro-installation, the 40% operational buffer programmed via the HEMS in a compact electric vehicle (60 kWh gross) becomes fully charged on days with extreme solar exposure. This capacity limit forces a partial energy export of approximately 8.90 kWh to the distribution grid, which, under the net-billing framework, still generates an additional clearing account revenue of PLN 1.80 per day. Notably, under lower solar irradiance levels, the percentage of solar energy self-consumption would naturally increase in both scenarios. However, given that daily electricity generation can reach up to 50 kWh for residential PV systems under Polish geographic conditions, determining the maximum self-consumption rate (SCR) for these parameters becomes particularly critical.

Summary and conclusions

The techno-economic analysis conducted in this paper, coupled with the empirical validation of actual generation and load profiles, demonstrates that integrating Vehicle-to-Home (V2H) technology with a Home Energy Management System (HEMS) provides a highly effective alternative to traditional stationary Battery Energy Storage Systems (BESS). Conventional stationary BESS units are characterized by an unfavorable ratio of capital expenditures to actual usable capacity. Within the net-billing framework, this economic mismatch drastically extends the investment payback period beyond a decade. Conversely, utilizing the integrated electrochemical buffer already available in an electric vehicle (60–100 kWh) successfully mitigates this financial barrier. This is important due to the fact that the implementation of hourly market-clearing pricing (RCE) for exported electricity exacerbates the risk of severely depressed buyback rates for prosumers. Based on empirical measurement data from the analyzed PV micro-installation (annual generation of 6,200 kWh; peak daily June production of 34 kWh), the baseline self-consumption rate (SCR) of the standalone building is merely 10.5%, resulting in substantial lost potential revenue despite energy overproduction. Implementing the predictive HEMS optimization algorithm for V2H technology—utilizing a programmable net EV battery buffer of 21.6 kWh—elevates the total SCR to 66%. Storing surplus energy within the mobile EV asset and its subsequent bidirectional discharging into the household microgrid (8.5 kWh) effectively shields the prosumer clearing account from devaluation, reducing daily electricity procurement costs by 94.6%. From spring to autumn, the V2H-integrated residential microgrid achieves near-total energy independence. Furthermore, the V2H framework introduces a unique 'strategic reserve' functionality: during grid outage events (blackouts), the HEMS can temporarily override the standard mobility buffer, unlocking additional stored energy to sustain critical household loads over an extended period. Despite clear economic advantages, the widespread adoption of Vehicle-to-Home (V2H) systems in Poland faces significant logistical and institutional barriers. The primary operational limitation stems from spatial-temporal constraints; the system's efficacy relies heavily on the physical presence of the vehicle in the residential garage during peak solar irradiance hours (between 11:00 and 15:00). Furthermore, at the institutional level, Poland still lacks unified procedures and

interconnection standards from Distribution System Operators (DSOs) regarding the certification of bidirectional inverters with islanding capabilities. A critical future research challenge remains the long-term assessment of how V2H cycling impacts the accelerated chemical degradation of lithium-ion cell structures, alongside the legal implications concerning the potential voiding of manufacturer warranties for EVs utilizing V2H and Vehicle-to-Grid (V2G) power transfer protocols.

References

- Act of 11 January 2018 on Electromobility and Alternative Fuels [Ustawa z dnia 11 stycznia 2018 r. o elektromobilności i paliwach alternatywnych], Journal of Laws [Dz.U.] 2018, item [poz.] 317 as amended [z późn. zm.], Poland, 2018.
- Calearo L., Marinelli M., Ried, S., Pfab X., Cabrera J.C.D, Spalthoff C., Braun M., Sæle H., Divshali H., Hänninen S., Ceraolo M., Barsali S., Larsson M, Magdowski A., Gimenez L., and Fernández G., (2020) "Electric vehicles demonstration projects—An overview across Europe," in *Proc. 55th Int. Universities Power Eng. Conf. (UPEC), Sep. 2020*.
- Central Statistical Office (GUS), "Renewable energy sources in 2024," Warsaw, 2025.
- Cieślak, K. J. (2024). Profitability Analysis of a Prosumer Photovoltaic Installation in Light of Changing Electricity Billing Regulations in Poland. *Energies*, 17(15), 3618.
- Electricity Grids and Secure Energy Transitions. (2023), International Energy Agency (IEA), Paris.
- E-mobility Index: BEV and PHEV Vehicle Registration Report in Poland," Polish Automotive Industry Association (PZPM) & Polish Association of New Mobility (PSNM), Warsaw, 2026.
- Grid Integration of Electric Vehicles. (2024): Executive summary, International Energy Agency (IEA), Paris.
- Hu, C., Geng, M., Yang, H., Fan, M., Sun, Z., Yu, R., & Wei, B. (2024). A Review of Capacity Fade Mechanism and Promotion Strategies for Lithium Iron Phosphate Batteries. *Coatings*, 14(7), 832.
- İnci, M., Çelik, Ö., Lashab, A., Bayındır, K. Ç., Vasquez, J. C., & Guerrero, J. M. (2024). Power System Integration of Electric Vehicles: A Review on Impacts and Contributions to the Smart Grid. *Applied Sciences*, 14(6), 2246.
- IEO Report: The Photovoltaic Market in Poland 2024," Institute for Renewable Energy, Warsaw, 2024.
- Junquera I., García-Villalobos J., Zamora I., Eguía P., San Martín J. I. (2017), Home energy management systems and electric vehicles: challenges and opportunities, *Renewable Energy and Power Quality Journal*, No. 15.
- Kempton, W. i Tomić, J. (2005) , Vehicle-to-grid power fundamentals: Calculating capacity and net revenue, *Journal of Power Sources*, 144(1).
- Kurtyka M. (2022), Energetyka rozproszona jako element uniezależniania Polski od zewnętrznych wstrząsów, *Energetyka Rozproszona, Zeszyt 8, s. 41-47*.
- Ma S., Jiang M., Tao P., Song C., Wu J., Wang J., Deng T., Shang W., (2018), Temperature effect and thermal impact in lithium-ion batteries: A review, *Progress in Natural Science: Materials International, Volume 28, Issue 6*.
- Mahmud K., Hossain M.J., and Town G.E., Peak-Load Reduction by Coordinated Response of Photovoltaics, Battery Storage, and Electric Vehicles (2018,), in *IEEE Access*, vol. 6.
- Markotić, T., Šljivac, D., Marić, P., & Žnidarec, M. (2025). Sustainable Integration of Prosumers' Battery Energy Storage Systems' Optimal Operation with Reduction in Grid Losses. *Sustainability*, 17(15), 7165.
- Mendes G., Tikka V., V2H Vahidinasab V., Aghaei J. (2023), Review of emerging advanced smart charging flexibility business models, *27th International Conference on Electricity Distribution (CIRED 2023), NTU Research Repository, Nottingham*.
- My Electrician" (Mój elektryk) Program, National Fund for Environmental Protection and Water Management, Warsaw, 2021.
- Naworyta W., (2025), Ocena możliwości podniesienia autokonsumpcji energii z instalacji PV w gospodarstwie domowym przez zastosowanie magazynu energii, *Zeszyty Naukowe Instytutu Gospodarki Surowcami Mineralnymi i Energią Polskiej Akademii Nauk 1(113)*.

- O'Shaughnessy E., Jesse Cruce J and Xu1 K., (2019), Solar PV Curtailment in Changing Grid and Technological Contexts, Presented at the *2019 CIGRE Grid of the Future Symposium Atlanta, Georgia November 3-6, 2019*.
- Olczak P., Matuszewska D., Lishchenko A., Zhydyk I., Koval V., Iermakova O. (2022), The economic efficiency of photovoltaic energy for energy prosumers,– *Energy Policy Journal, Vol. 25, Iss. 4*.
- Polish Priority Program "NaszEauto," National Fundusz for Environmental Protection and Water Management, Warsaw, 2025.
- Rubanenko O., Gundebommu S.L., Cosovic M. and V. Lesko V., (2021) Predicting the Power Generation from Renewable Energy Sources by using ANN, *2021 20th International Symposium INFOTEH-JAHORINA (INFOTEH)*, East Sarajevo, Bosnia and Herzegovina, 2021.
- Sarnek M. and Szopa P., (2022), The economic role of alternative fuels in the development of clean wheeled transport in terms of decarbonisation. *Proceedings of the 40th International Business Information Management Association (IBIMA)*, 23-24 November 2022 Virtual Conference.
- Szopa P., (2024), The development of electromobility in Poland and Europe as a contribution to improving air quality and the associated costs. *Proceedings of the 44th International Business Information Management Association (IBIMA)*,
27-28 November 2024 Granada, Spain.
- Tayri, A. and Ma, X. (2025), Grid Impacts of Electric Vehicle Charging: A Review of Challenges and Mitigation Strategies, *Energies*, 18(14).
- Toosi, A. H., (2020) Life Cycle Cost Optimization of Battery Energy Storage Systems for BIPV-Supported Smart Buildings, A Techno-Economic Analysis. *Sustainability*, 17(13), 5820.
- Videgain Barranco, P., Covrig, C.F., (2021), Vehicle-to-Grid and/or Vehicle-to-Home round-trip efficiency, *JRC Technical Report*, Luxembourg:Publications Office of the European Union.
- Yang Y., Son W., Woo J., (2026), Shifting behavior, shaping grids: Appliance-level insights for targeted residential demand response, *Utilities Policy, Volume 101*.