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Energy Storage as a Tool to Increase the Security and Energy Efficiency of Household Electricity in North-Western Poland in the Sustainable Management of Micro-Installation Potential

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Abstract

Small-scale prosumer installations are playing an increasingly important role in the Polish electricity sector. These primarily include photovoltaic systems and heat pumps installed for internal use. Noticeable losses for individual investors, generated by the power flow mechanism during peak production hours (connection to the grid) and peak demand (drawback from the grid), as well as the issue of fluctuating grid capacity and the observed redispatch procedures for photovoltaic installations, are driving increased interest in equipping home energy installations with energy storage systems, strengthening the aspect of sustainable energy development in this dimension. The impact of energy storage on investment motivation and the actual effects of incorporating it into home energy installations have not yet been sufficiently researched, particularly in Poland. Therefore, the aim of the study was to assess the use of energy storage in home installations as a socio-technical direction of power development at the micro level, in light of the constantly increasing energy demand observed worldwide in line with the challenges of sustainable development. The results of a survey of 206 individual users of power installations equipped with energy storage systems in Poland were used for this study. The research was qualitative and quantitative in nature, with descriptive statistics and a logistic regression model used in the in-depth section, and the findings were supported by PQStat software. The research revealed that the selection of energy storage systems in home power grids is related to the potential for prosumer optimization. On the other hand, they are seen as a path towards increasing energy security at the household level. Supporting this direction of installation development at the micro level is a justified concept for the development of green energy in Poland, socially and environmentally beneficial as well as economically justified, i.e., in line with the trend of sustainable development. The information campaign, combined with financial support for this type of investment, should be continued and strengthened in Poland.

Keywords: energy storage; energy security; energy efficiency; household electricity in Poland; sustainable management of micro-installation; generation capacity management; electricity consumption management

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Academic Editors: Zhi Li and Yonghong Xu

Received: 18 January 2026
Revised: 16 March 2026
Accepted: 18 March 2026
Published: 19 March 2026

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https://doi.org/10.3390/su18063033

1. Introduction

Poland's electricity sector is undergoing a rapid "pressurization" driven by the diffusion of residential photovoltaic (PV) micro-installations. By the end of 2024, 1,544,574 renewable micro-installations were connected to the grid with a total installed capacity of 12,749.891 MW, and in 2024, micro-installations injected more than 8.5 TWh of electricity into the distribution system [1]. Moreover, prosumers accounted for almost the entire segment, with 1,522,655 prosumer-operated micro-installations recorded at the end of 2024 [2]. This scale changes operational realities in low-voltage (LV) grids: midday surplus generation, reverse power flows, and local voltage rise become more frequent, and households may experience export limitations, inverter disconnections, and uncertainty about the economic value of exported energy [3,4]. The system-level dimension of flexibility scarcity has also become visible in Poland through non-market redispatch communications concerning PV installations, including procedures for compensation [5]. In this context, the potential of home energy storage systems (BESS) for flexible energy management at the household level is increasingly emphasized. This can be a source of prosumer optimization and can determine increased energy security at the micro level. This is particularly important in the context of the rapid increase in household electrification. Furthermore, the use of energy banks, by eliminating partial energy fluctuations, can contribute to improved control of installation capacity and improve the quality of electricity use in tailored time periods at optimal consumption costs. Furthermore, economic and political signals, as well as programs supporting the development of renewable energy sources, along with integration with BESS, are influencing the increased adoption of energy storage in households.

Despite the practical importance of BESS at the household edge, gaps remain in how PV and energy storage are analyzed in low-voltage, high-prosumer-density contexts. First, many studies focus on techno-economic optimization, while household-level outcomes can be influenced by voltage-related "mild disruptions" of inverter operation and export constraints, which affect perceived value even without complete outages. Second, household decisions can be influenced not only by objective outcomes (kWh shifted or PLN saved) but also by behavioral constructs such as perceived benefits, perceived barriers, and energy knowledge, as noted by Kowalska et al. [6]. Therefore, this article focuses on the issue of energy storage in households, treating it as a socio-technical solution to examine how BESS addresses two key aspects of this concept: perceived energy security of households (resilience) and perceived energy efficiency of prosumers (prosumer optimization—energy management and electricity price optimization) in Polish conditions, which was the aim of the work. The study was conducted in the Lubusz, West Pomeranian, and Greater Poland voivodeships in Poland, courtesy of a service company that performs mandatory inspections of installations one year after commissioning. The voluntary and anonymous survey was directed to users with residential renewable energy installations with energy storage, which was a key aspect of the sample selection. The selection of the voivodeships included in the study determined the service company's area of operation and also the territorial reference of the authors' alternative research, enabling a multifaceted benchmarking of the findings.

The research issues determined the further structure of the work. Subsequent sections review the literature and develop a theoretical framework and hypotheses (Section 2). Next, materials and methods (empirical design, sample, measurements, and statistical procedures) are described in Section 3. Section 4 presents the results. Section 5 focuses on discussion and conclusions.

https://doi.org/10.3390/su18063033

2. Literature Review and Theoretical Framework

Poland has experienced one of the fastest expansions of residential photovoltaic (PV) micro-installations in Europe, which has shifted parts of system balancing and network-management challenges from the transmission level toward low-voltage (LV) distribution grids and prosumer households [3,7]. According to the national energy regulator, by the end of 2024 Poland had 1,544,574 renewable micro-installations connected to the grid with total installed capacity of 12,749.891 MW. In 2024, micro-installations injected more than 8.5 TWh of electricity into the grid [1]. Importantly, almost 99% of micro-installations were operated by prosumers, with 1,522,655 prosumer-owned units recorded at the end of 2024 [1,2]. Such scale increases the frequency and visibility of LV phenomena associated with high PV penetration (e.g., midday surplus generation, reverse power flows, and local voltage rise), which are widely reported as typical constraints for PV hosting capacity in LV grids [3,7], These system-level effects can be experienced at the household level as reduced ability to export surplus, inverter disconnections, and uncertainty about the economic value of exported energy—particularly under conditions of local overvoltage and voltage deviations [4,8,9]. Curtailment and non-market redispatch events also demonstrate that flexibility scarcity is not merely theoretical. In Poland, there are also redispatch procedures for photovoltaic installations—outside the market, on specific days, taking into account compensation procedures [5]. These changes strengthen the rationale for flexible solutions located close to the points of generation and consumption, including home energy storage systems (BESS), which are widely recognized as effective tools for increasing self-consumption and reducing low-voltage operational load through load shifting and peak shaving, as emphasized by, among others [10,11]. Beyond purely technical constraints in LV grids, Poland’s prosumer transition is increasingly shaped by regulatory and tariff incentives that reward temporal optimization of household generation and consumption. This is particularly important in the context of the constantly growing demand for energy from households, which highlights the need for prosumer optimization and provides a motivation for investing in energy storage. This relationship requires further investigation, particularly in the Polish market, highlighting a research gap for the purposes of the presented study (Research Thread No. 1).

Public support schemes further reinforce storage uptake and can be treated as an institutional signal that distributed flexibility is becoming a policy priority in Poland. Evidence from evaluations of the “Mój Prąd” program shows that subsidy architecture and its territorial allocation patterns were strongly associated with the pace of PV micro-installation deployment, and later editions increasingly emphasized on-site use of generation and complementary technologies [12,13]. In parallel, case-based and techno-economic analyses for Polish households confirm that residential batteries can measurably improve self-consumption outcomes and economic performance under variable tariffs, supporting the role of BESS as a practical flexibility asset close to the point of generation and consumption [14,15]. More broadly, European-scale modeling and review evidence underscores that rising shares of variable renewables increase the value of flexibility resources, with storage playing distinct roles across short- and long-duration timescales in net-zero pathways [16–18].

Beyond economics, residential BESS can contribute to household energy security [19], by providing short-duration backup capability when configured for islanding, as well as smoother operation of inverter-based resources in prosumer microgrid-like modes. This perspective is consistent with broader smart-grid and distributed-energy system principles, where local storage supports reliability and operational flexibility close to the point of consumption [20]. General knowledge among users of residential power grids with energy storage is crucial, enabling monitoring and managing consumption to improve the resulting economic efficiency. This requires deeper investigation, particularly in Poland, which justifies the adoption of further research themes identified for the presented study (research themes 2–4). It is worth noting that, from a technological and life-cycle cost perspective, the value of batteries in residential applications is strongly moderated by electrochemical aging mechanisms. Depth of discharge, temperature, and charge/discharge rate influence usable capacity, cycle efficiency, and life cycle, which in turn shapes realistic payback prospects and the total cost of ownership in prosumer photovoltaic battery systems [21].

The outlined background and identified gap in the literature justify the need for research to identify the actual drivers of energy storage in renewable energy installations at the household level. It is important to determine the motivations for investing in energy storage, as well as the expectations regarding them. It is particularly important to examine the need to reinforce renewable energy installations with energy storage in light of the increasing electrification of households, as well as to clarify the signaled role of batteries in shaping energy independence and security. This approach requires particular clarification in relation to Polish conditions, which was the aim of this work. In light of the above, the following research hypotheses were developed:

Hypothesis 1. *The development of household electrification implies the need for prosumer optimization, which motivates investments in energy storage.*

Hypothesis 2. *The source of the economic efficiency of home power systems is their equipment with energy storage systems.*

Hypothesis 2.1. *Users of home power systems are focused on using energy storage systems to increase their own energy consumption in the process of prosumer optimization.*

Hypothesis 2.2. *Users of home power systems are oriented towards the use of energy storage systems to reduce the level of peak import in the process of optimizing the cost of energy consumption.*

Hypothesis 3. *Energy storage systems are a key instrument for increasing the energy security of home power grid owners.*

Hypothesis 4. *The increase in economic efficiency resulting from the use of home power installations with integrated energy storage by households increases with the duration of their use.*

3. Materials and Methods

The objective of this paper was to define the research concept, which is reflected in the following steps:

1. Presentation of the research background
2. Analysis of the literature, identification of the research gap, and definition of hypotheses
3. Selection and explanation of the methodology
4. Presentation of the findings, in the following steps:
    - 4.1. Clarification of the definition of energy security and resilience of households in low-voltage networks based on an analysis of the literature findings
    - 4.2. Discussion of energy storage in households as a tool for improving the efficiency and flexibility of prosumers (self-consumption, reducing peak energy demand and electrical loads) based on an in-depth literature review
    - 4.3. Analysis of the author's own survey research regarding the motivations for investing in energy storage, with particular emphasis on aspects of energy security and economic efficiency arising from this background

5. Discussion and summary

A key role in the study is played by a literature review, which draws its sources from indexed open-access databases such as Scopus, Web of Science, and Google Scholar. Keywords specific to this paper were used to identify sources. The research was based on economic analysis techniques, along with descriptive statistics tools. A logit model was used for in-depth analysis, and the calculations were supported by the PQStat software tool. The choice of tools was dictated by the nature of the research and the specificity of the variables analyzed.

The research themes established through the literature review formed the basis for the development of the main (4) and auxiliary (2) hypotheses presented in the introduction.

The research encompasses the results of a survey of users of residential power installations. The study was conducted during the service activities of a company performing mandatory inspections of power installations one year after their commissioning and in subsequent years. The study period spanned September 2024–July 2025. The study included 362 customers of a service company located in northwestern Poland (the company's service area). The results of 206 surveys were included in the analysis, with the following criteria:

- Use of a renewable energy installation with an energy storage system,
- Correctly completed survey.

The research questions addressed the following:

- The purpose of investing in an energy storage system (investment motives) (energy security, energy efficiency, increased system efficiency),
- The level of satisfaction with investing in energy storage systems.

The survey consisted of 9 questions, each closed (6) and open (2).

The study was voluntary and anonymous (informed consent). The research material (surveys) analyzed did not contain any identifying information.

The territorial and quantitative limitations of the research sample mean that the results presented can only be analyzed within the adopted scope. This research limitation means that generalization of the obtained results to the studied country can only occur with certain reservations. These limitations create potential challenges for the authors' further research.

4. Results

4.1. Definition of Energy Security and Resilience of Households in Low Voltage Networks—Analysis of Literature Indications for Research Purposes

The term "security" encompasses a broad spectrum of meanings, including in relation to energy security [19,22]. Energy security is most often framed at the national or system level (adequacy of supply, import dependence, and price exposure), yet in prosumer-dense electricity systems it increasingly exhibits a household dimension: the capability of a household to maintain essential electricity services despite disturbances, price volatility, or local network constraints. In the resilience literature, this micro-level view is consistent with the broader distinction between reliability (performance under "credible/expected" contingencies) and resilience (performance under high-impact, low-probability events and complex disturbances, including the phases of degradation, degraded operation, and recovery). Quantitative frameworks emphasize that resilience should be assessed dynamically across these phases, rather than as a single-point reliability indicator [23–25].

In the household context, energy security and resilience can be conceptualized through three complementary components:

- Availability/continuity of supply, understood as the ability to power critical loads during outages or severe disturbances.

- Power quality, i.e., stable voltage and reduced disturbances affecting sensitive appliances,
- Autonomy and control, meaning the household's ability to manage supply and demand under uncertainty [26].

This framing is practically important because LV disturbances are not limited to complete blackouts: prosumer households can experience "partial insecurity" in the form of inverter tripping, voltage deviations, or export limitations that undermine perceived predictability and economic value of PV generation—especially when electrified end-uses (heat pumps, EV charging) increase dependence on continuous electricity services [27].

A key theoretical implication is that household resilience can be operationalized with metrics that are conceptually consistent with power-system resilience frameworks, yet tailored to micro-level service outcomes and user impacts. In addition to classical "performance-curve" approaches (e.g., resilience triangle/trapezoid and restoration trajectories), recent resilience literature stresses time-dependent, performance-based indicators that capture degradation and recovery phases rather than relying only on long-run averages such as interruption indices [23,24,28].

At the household/building level, these principles translate into a practical metric set that can be measured or estimated using inverter logs, smart-meter data, and BESS telemetry. Examples include:

- Critical-load coverage (kW supported or % of essential demand served),
- Autonomy duration (hours of supply for critical loads at a given state of charge and load profile),
- Service-quality continuity (frequency and duration of voltage-related disconnections, inverter trips, or equipment malfunctions),
- Recovery time (time to return to a "normal" operating regime after a disturbance). Importantly, recent work in building energy resilience recommends complementing purely electrical indicators with impact-oriented metrics that reflect consequences for occupants and operations—e.g., "occupant hours lost" (OHL) as an interpretable measure of service disruption severity and productivity loss, alongside "energy not served"–type measures for critical loads [29,30]. Moreover, it is important to diagnose the awareness and motivation of users of national power grids to develop solutions aimed at counteracting negative phenomena in the operation of installations by modernizing them with storage systems and, in the longer term, managing consumption, which emphasizes the importance of this study.

Residential storage can contribute to each component, depending on configuration and control. Backup-oriented architectures—typically requiring a compatible inverter, islanding/backup switching, and appropriate protection—can maintain critical loads during grid interruptions, which is consistent with microgrid conceptual design approaches that start from defining critical services, acceptable downtime, and operational modes during "grid-out" conditions [31]. Even without full islanding, BESS can still increase operational robustness at the household level by reducing the amplitude of net-load variations (smoothing), enabling planned load shifting, and supporting more predictable energy-management routines under local constraints. Reviews focused on resilience enhancement explicitly identify storage as a flexibility resource that can reduce outage impacts and improve restoration/operational performance when coordinated with control strategies [32].

From a socio-technical standpoint, household resilience is also shaped by the quality of control and the coordination between PV, storage, and flexible loads. Home energy management systems (HEMS) and rule-based or optimization-based control strategies can prioritize resilience objectives (e.g., maintaining a minimum state-of-charge reserve for backup) while still capturing economic value through self-consumption and peak-shaving. Such dual operation has been discussed in the literature on residential PV-storage scheduling, which highlights trade-offs between bill minimization and the preservation of resilience-oriented reserve margins [33]. In practical LV settings, the value of coordinated control is additionally strengthened when export constraints or curtailment risks exist, because local storage and HEMS can reduce forced disconnections and improve household predictability of PV utilization [27,33].

However, the resilience contribution of BESS is inherently conditional on availability of storage at the time of disturbance. This raises the importance of battery degradation mechanisms and operational settings (depth of discharge, temperature, cycling intensity), which influence usable capacity and round-trip efficiency over time and thus the real autonomy duration for critical loads. Battery science and engineering literature emphasizes that capacity fade is driven by both calendar aging and cycling-related degradation, with meaningful implications for long-term performance under frequent charge–discharge operation typical of prosumer optimization strategies [21]. Consequently, empirical household studies that interpret BESS as a resilience asset should acknowledge that resilience benefits are not static: they depend on state-of-health and control policies (e.g., reserve SOC) that determine whether backup capability is preserved across seasons and usage patterns.

An additional operational layer concerns inverter-based resource behavior during abnormal grid conditions. Modern interconnection standards increasingly require distributed energy resources (DER) to provide ride-through capabilities and grid-support functions (e.g., voltage regulation, frequency response), which may reduce cascading disconnections and enhance local stability under disturbances [34]. Although household prosumers rarely interact directly with standards, these requirements influence device settings implemented by manufacturers and DSOs, thereby indirectly affecting household resilience through fewer nuisance trips and improved power-quality performance. In LV grids with high PV penetration, such capabilities are particularly relevant because inverter tripping and voltage issues can translate into "partial insecurity" even when the wider grid remains energized [4,9].

Thirdly, security and trust are a necessary complement to technical resilience in households, creating a new dimension of value stemming from these conditions [35]. Stationary lithium battery standards specify requirements and tests for safe operation (e.g., thermal, electrical, and mechanical safety, and BMS-related protections), which becomes increasingly important as storage diffuses into residential buildings [36]. From a resilience perspective, safety is not merely a compliance topic: it conditions social acceptance and sustained utilization, and it shapes the willingness of households to rely on storage as a backup solution. Therefore, when modeling household-level energy security, it is theoretically justified to treat resilience as a multi-dimensional construct where continuity, controllability, power quality, and safety/trust jointly influence perceived security outcomes. Hence, the discussed dimension of innovative solutions at the household level seems to be a key direction in the process of strengthening this area [37].

A review of the literature findings defining energy security for individual users and its determinants at the household level indicates the crucial importance of energy storage in the outlined context. This aligns with Hypothesis 3, which states that energy storage is a key instrument for increasing energy security for home power grid owners. However, it is important to verify the user security aspect in practice—its understanding, as well as its shaping based on renewable energy installations with battery systems.

4.2. Household Storage as a Prosumer Efficiency and Flexibility Tool: Self-Consumption, Peak Shaving, and Electrified Loads—In-Depth Literature Research

In prosumer households, "energy efficiency" is increasingly interpreted not only as reducing total electricity consumption, but as improving the temporal match between PV generation and demand. Consequently, the literature typically operationalizes prosumer efficiency through indicators such as the self-consumption rate (share of PV generation used on-site) and self-sufficiency (share of household demand covered by PV and storage), complemented by grid-oriented measures such as peak import reduction and export limitation during high-generation hours [10].

Battery energy storage systems (BESS) affect these outcomes via three main mechanisms. First, load shifting stores midday PV surplus and discharges it during evening peaks, directly increasing self-consumption and reducing grid imports. Second, peak shaving smooths net-load profiles, which can mitigate household peak demand and reduce stress on LV feeders under high simultaneity. Third, BESS enables energy arbitrage under time-varying tariffs by charging during low-price periods and discharging when prices are high—often in a combined strategy with PV self-consumption [10,38].

A closely related stream of research shows that storage can be complemented—or partially substituted—by demand-side management (DSM) and controllable loads (e.g., domestic hot water preparation, space heating/cooling, HVAC pre-conditioning, and EV charging). The core idea is to exploit deferrable demand and thermal inertia as “virtual storage” so that surplus PV production is absorbed locally during midday hours, thereby improving self-consumption without necessarily increasing battery capacity [10,39]. Evidence also indicates that DSM is not limited to shifting a few appliances: hot-water tanks and heat pumps can serve as flexible sinks for PV, especially when operation is scheduled around PV output and comfort constraints; this is particularly relevant in Central-European climates and has been demonstrated in Polish household conditions for PV–ASHP systems oriented to domestic hot water [40].

In parallel, electrification of mobility expands DSM potential through smart EV charging, where charging profiles are aligned with PV generation and household load patterns, improving PV utilization and reducing peak imports. A dedicated review of PV-aware EV smart charging highlights objectives such as increasing PV self-consumption, lowering charging costs, and reducing peak-load stress, while noting trade-offs between algorithmic complexity and practical implement ability [41]. More recent modeling confirms that combining flexible EV charging and smart heating with household storage can produce wide ranges of PV self-sufficiency depending on demand patterns and technology combinations, reinforcing that DSM and storage should be analyzed as complements rather than isolated interventions [42]. Finally, DSM can also be interpreted as part of a broader peak-shaving toolkit (often coordinated through HEMS and demand-response logic), which is increasingly discussed as a flexibility pathway that improves both household economics and LV operability under high DER penetration [43,44]. Thermal storage solutions (e.g., dedicated TES coupled with PV for space heating) further broaden the DSM concept and show measurable self-consumption gains in real applications, underscoring that “storage” at household/building level can be electrical and thermal [45].

More recent evidence in the Polish context indicates that coupling PV with heat pumps can increase self-consumption, highlighting the role of electrified end-uses as “flexible sinks” for PV generation in households [40].

Importantly, the value of BESS for household efficiency depends on the grid and market environment, especially where export constraints or curtailment risks exist. Empirical data from high-DPV penetration LV networks show that PV-only sites can experience measurable curtailment losses, while coupling PV with batteries can substantially reduce average curtailed energy [33]. This aligns with the broader perspective that operational constraints in LV grids increasingly shift “efficiency” from a purely household concept toward a joint household–grid optimization problem, where behind-the-meter storage can reduce forced export limitations and improve the predictability of PV value streams [27,33].

The above findings are consistent with the adopted research strand, which posits that energy storage systems are a source of efficiency for home power systems, and that this efficiency can be achieved by increasing the use of one's own energy through prosumer optimization (Hypothesis 2 and Partial Hypothesis 2.2). These findings are important from the perspective of the study's adopted objective, and require comparison with the practical implications of the findings identified in a survey of users of power installations with energy storage modules. These findings will allow for the verification of a practical approach to the challenges of investing in energy storage systems and the motivations behind these choices.

4.3. Analysis of Own Survey Research in the Field of Determining the Motivation for Investing in Energy Storage

The utility of energy storage systems is increasingly emphasized in the literature. Their importance is considered crucial for the efficient operation of energy systems in economies. However, energy storage systems are particularly important in supporting the operation of home power installations, increasing prosumers' confidence in the ability to use generated electricity resources for their own benefit. This ensures the comfort of households and increases their confidence, considered from both a technical and economic perspective. Evidence in this regard is provided by survey results aimed at diagnosing and assessing the motives behind prosumers' choice of energy storage, along with an assessment of their importance in the areas of increasing the security and energy efficiency of home power grids in Poland, as outlined in the literature. The research was conducted for the period September 2024–July 2025, based on the responses of users of home power installations with integrated energy storage systems who have been using these installations for at least one year. The study area was defined as northwestern Poland (the area determined the service company's scope of operations), and specifically, the West Pomeranian, Lubusz, and Greater Poland voivodeships. The research sample comprised 206 surveys, selected from a population of 362 prosumers. In addition to survey completion, the sample classification criteria included the requirement to use a prosumer installation with an energy storage system as an integral part (Necessary condition). The sample classification process revealed that a significant percentage of power system users who are clients of the service company have renewable energy installations with integrated energy storage (56.9%). On the other hand, for 43.1% of the analyzed population, energy storage represents the future development potential of their home installations, which is an important observation. The survey sample was primarily composed of customers owning new homes with renewable energy solutions designed into them at the construction stage (61.65%), while the remainder were owners of renewable energy solutions installed as part of the modernization of heating systems in older buildings. The survey also considered the duration of ownership of renewable energy systems with energy storage systems as a differentiating factor among respondents. The share of respondents using systems with batteries for up to two years was found to be 59.70%, 28.64% for 2–4 years, and 11.65% for over 4 years. This indicates that investments in energy storage in the study area have gained popularity over the past 2–3 years.

Analysis of the structure of users of individual solutions revealed that the largest group of the population was formed by users of energy systems based on a photovoltaic system combined with an energy storage system. The second group consisted of users of systems based on a photovoltaic system combined with an air-source heat pump and an energy storage system. A detailed breakdown of the findings in this area is presented in Figure 1.

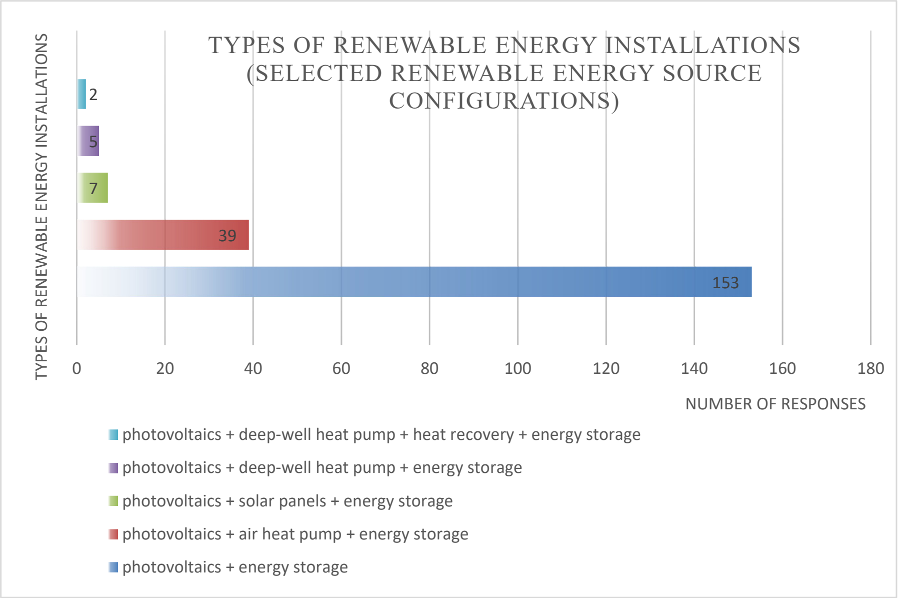

Figure 1. Types of Renewable energy installations (selected renewable energy source configurations).

The results of the presented research confirm that the primary solution chosen by households when investing in residential renewable energy systems in the studied region of Poland is a photovoltaic system combined with energy storage (74.27%). This aligns with the findings of the literature review, in which the majority of references focus on research, measurement, and analysis of the performance and efficiency of installations with this configuration, identifying it as a fundamental and justified solution.

The authors' study results confirmed that the primary goal of investing in renewable energy solutions with integrated energy storage is to increase prosumers' energy security. This study treats the issue of energy security in a broad sense, taking into account the aspect of security related to the physical accessibility of energy sources, as well as the aspect of financial availability of energy on the market (economic security). This motive was indicated by 95.14% of the surveyed population. On the other hand, respondents strongly indicated investing in renewable energy with energy storage as a source of energy efficiency for residential power installations (90.77%). Based on the obtained results, it can be concluded that for Polish prosumers (in the studied area of the country), energy security and energy efficiency are key objectives for investing in green energy sources equipped with energy storage systems; however, achieving the desired effects in this area is possible over time, as indicated by 72% of respondents.

This directly relates to the adopted hypotheses, providing a basis for their confirmation. The detailed study results revealed that:

- A total of 89.80% of respondents declared that investing in a storage facility was intended to increase their own consumption,
- A total of 37.37% of surveyed households indicated that reducing peak energy consumption was one of the factors in their decision to invest in an energy storage facility,
- A total of 27.27% of respondents cited the potential for improving the quality of the RES installation as one of the aspects of investing in an energy storage facility,
- A total of 18.44% of surveyed users of RES installations with integrated energy storage emphasized that the energy storage facility in a RES installation is currently a key element in justifying the investment in RES (economic efficiency).

Interestingly, 16.01% of respondents cited comfort (physical, psychological) associated with having a complete installation (energy security + source of economic efficiency) as their "other motives for investing in an energy storage system". In this case, mental and physical comfort means the emotional state of the user of a renewable energy installation, arising from the sense of energy security and the possibility of increasing economic efficiency in connection with the management of energy consumption and distribution.

The distribution of these results is presented in Figure 2.

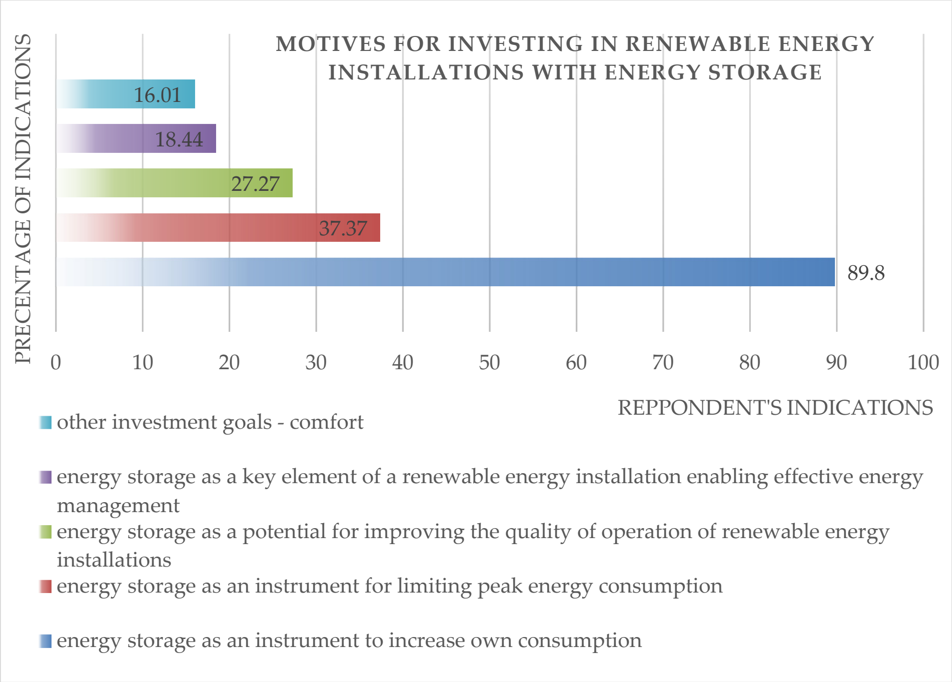

Figure 2. Motives for investing in renewable energy installations with energy storage—analysis of the indication results (multiple choice).

An in-depth survey of the technical aspects of renewable energy installations with energy storage systems revealed that 48.05% of surveyed users of such installations were unfamiliar with the details of their battery-based system's operation. However, as many as 54.36% monitored their power system's performance, including 17.96% who monitored the readings (at least once a week) using a dedicated app. This indicates that assessing the operational efficiency of a residential power system and analyzing its effectiveness is an important topic. Furthermore, the results indicate the potential for strengthening knowledge in this area, which should be further developed in areas useful for managing self-consumption and improving the efficiency of existing solutions. The process of increasing the efficiency of existing solutions in the field of managing the potential of micro-installations (managing production, consumption and distribution) can be described as prosumer efficiency.

An interesting aspect of the study is the satisfaction rating for investing in an energy storage system (either with the rest of the installation or as a retrofit option). In this regard, as many as 87.37% confirmed that purchasing an energy storage system was justified and expressed satisfaction with its use. Importantly, 86.40% of users of renewable energy installations with energy storage recommend investing in a storage system, which is the highest recommendation in assessing this investment direction.

The survey results provide arguments for the general verification of the adopted hypotheses, stating that the source of efficiency of home power systems is their installation with energy storage systems (Hypothesis 2), and that energy storage systems are a key instrument for increasing the energy security of home power grid owners (Hypothesis 3).

The indications exceeding 90% in both aspects absolutely confirm the above at the level of the surveyed population. One of the partial hypotheses was also positively verified, stating that home power system users are oriented towards using energy storage systems to increase their own energy consumption in the process of prosumer optimization (Hypothesis 2.1). In this respect, as many as 89.80% of respondents declared this as the goal of investing in an energy storage system. However, the second partial hypothesis—Hypothesis 2.2, which states that users of residential power systems are oriented towards using energy storage systems to reduce peak imports in the process of optimizing energy consumption costs—cannot be unequivocally verified positively, as indications that one aspect of the decision to invest in energy storage was the prospect of reducing peak energy consumption were reported by only 37.37% of surveyed households. This is important information, indicating the educational potential of a significant portion of the population of users of renewable energy installations with energy storage systems in this regard. It is reasonable to compare the above with the pattern of consumer attitudes [6].

4.4. In-Depth Research Results in the Area of Investment Goals in Energy Storage—Energy Security and Prosumer Efficiency

The detailed analysis of the survey results was enriched with statistical methods. This section focused on examining the aspect of economic efficiency. Descriptive statistics and a logistic regression model were used in this regard. In the case of the logistic regression method, it is necessary to define two dimensions of variables:

1. the explanatory variables, which for the purposes of the study were assumed to be:
   - The duration of use of the renewable energy installation with energy storage (Y)—a numerical variable (scale 0–1),
2. the explanatory variables, which in the presented study were assumed to be:
   - The use of energy storage systems to increase self-consumption in the prosumer optimization process, as a source of economic efficiency (X1),
   - The reduction in the level of imports in the process of optimizing the cost of energy consumption, as a source of economic efficiency (X2),
   - The use of energy storage systems to increase energy security, with the potential to enhance economic efficiency (X3).

The explanatory variables X1–X3 obtained from the survey were qualitative in nature. To facilitate their use in the regression model, they were transformed into dummy variables, giving them a quantitative, dichotomous character. Calculations of descriptive statistics for the adopted variables gave the following results (Table 1):

Table 1. Calculations of descriptive statistics.

	Mean	**SE**	**SD**	**SD^2**	**Min.**	**Max.**
Y	0.8752	0.0299	0.3438	0.1182	0	1
X1	0.8574	0.0867	0.9968	0.9935	0	1
X2	1.0766	0.0758	0.9062	0.8212	0	1
X3	0.3635	0.0767	0.8818	0.7776	0	1

In the step of the logistic regression study specifying the computational model [37]:

$$ln\frac{p_\mathrm{i}}{1-p_\mathrm{i}} = Z_\mathrm{i} = x^J\beta = \beta_0 + \beta^1 + \beta^2\mathrm{X}^1{}_\mathrm{i} + \beta^2\mathrm{X}^2{}_\mathrm{i} + \cdots + \beta_\mathrm{k}X_\mathrm{ki}$$

where

$$ln\frac{p_\mathrm{i}}{1-p_\mathrm{i}} = logit\ (p_\mathrm{i})$$

In the applied model, the factors subject to estimation are $\beta_0 \ldots \beta_\mathrm{k}$, influencing the result of vector β. In this model, the process of estimating variables is achieved using the odds ratio (OR). This approach illustrates the equivalence potential for the odds ratio for (X_{mi}) with a unit increment, or in the absence of such an increment, according to the notation [37]:

$$exp(\beta_m) = \frac{\Omega({x_\text{i}}^m, X_{mi}+1)}{\Omega({x_\text{i}}^m, X_{mi})}$$

whereby:

1. ${x_\text{i}}^m$—a vector of x_i is a vector without X_{mi}
2. estimated chance of acceptance of subscriptions:

$$ln\frac{p_\text{i}}{1-p_\text{i}} = exp\left({x_\text{i}}^J\beta\right) = exp(\beta_0 + \beta_1 X_{1\text{i}} + \beta_2 X_{2\text{i}} + \cdots + \beta_\text{k} X_{\text{ki}}) = \Omega(x_\text{i})$$

Considering the above, the change in X_{mi} (without changing the other parameters) is a derivative of the change in the odds ratio by $exp(\beta_m)$, expressing its multiplicity, where

for $exp(\beta_m) > 0$, the OR assumes an increasing trend,

for $exp(\beta_m) < 0$, the OR assumes a decreasing trend,

then:

X_m, $exp(\beta_m)$ maps the dimension of the fold change of OR in the interval Y = "1" for the outcome "1" and the variable x_m, relative to the OR for the outcome "0" and the variable x_m. The odds ratio (OR) $exp(\hat{\beta}_j)$ of the logistic function $\hat{\beta}_j$ determines the OR, in a situation where the average change is defined by the outcome changed by one unit [37].

The research concept was adapted to the type of variables and the specific nature of the study. Similar solutions have been successfully implemented in alternative studies [37].

According to the adopted concept, variable scores within the range <0.1> indicate that:

- a probability level of $\leq$0.5 indicates that the duration of use of the RES installation with energy storage with great probability does not affect the economic efficiency of the RES installation. (The specified classification threshold indicates a significant degree of independence of the process in assessing the predicted probability of its occurrence).
- a probability level of >0.5 indicates that the duration of use of the RES installation with an energy storage is highly likely to increase the economic efficiency of the RES installation.

Odds ratios > 1 allow for the identification of random mechanisms and the determination of the expected results in accordance with the adopted research concept [37].

PQstat software version 1.8.4.164 was used to determine the logistic regression results.

The results of correlations of the studied variables were as follows (Table 2):

Table 2. Results of correlations of the studied parameters.

Variable	Y1	X1	X2	X3
Y1	1			
X1	0.5235	1		
X2	0.3948	0.5925	1	
X3	0.4847	0.5315	0.5101	1

The interplay of the studied parameters is varied. The strongest correlation is found in the X1–X2 relationship, with a correlation level of 0.5925. The weakest correlation is found in the X2–X3 relationship, with a correlation level of 0.5101.

The correlation between the variables X–Y studied reached a maximum of 0.5285 for Y1:X1. The lowest correlation is found in the Y1–X3 relationship, with a correlation level of 0.4847.

The next step in the in-depth analysis involved determining the β vector, the b error, the confidence interval (CI), the Wald statistics, and the odds ratio (OR) results—Table 3.

Table 3. Statistical measurement results for the studied variables.

	OR Odds Ratio	Wald Stat.	−95% CI *	+95% CI	Error b	β
X1	0.5084	5.6637	−2.4356	0.2948	0.5461	−1.3652
X2	0.8020	0.2032	−0.3896	0.7118	0.2809	0.1610
X3	0.3246	0.1353	−0.7989	0.3719	0.2987	−0.2135
Pseudo R2:	0.3761					

* With regard to the sample used and the variability observed, the statistical software (PQ Stat) showed a negative lower limit for OR, which may be the result of an approximation error in the process of mathematically fitting the function to the data set to map the trend of the phenomenon. In view of the above results, they were considered close to zero in the statistical assessment of the significance of the result.

Statistical analysis enabled to understand the relationships between variables, providing knowledge for their assessment. Intraclass correlation measures are crucial for the reliability of the findings. The results of the Wald statistics indicate the significance of the explanatory parameters in the presented concept, which is crucial for robustness testing. The IT tool used (PAStat) ensured reliable measurement according to the established scales.

The logistic regression model for parameter Y is a key step in the findings.

The study results indicate that the process of improving energy efficiency related to the use of a renewable energy installation with energy storage is above the threshold value (>0.5) assuming a level of 0.5084, meaning that it is determined by its duration. With respect to general survey research, it can be concluded that knowledge about the operation of the installation, its functionality, and the potential for efficiency improvement is acquired by users over time. Experience with monitoring the yields of a prosumer installation is a crucial step in planning energy consumption and optimizing energy bills. This is an important observation, as consumption control is a key determinant of the actual management of electricity costs, a fact confirmed by an in-depth literature review.

The results with a probability of occurrence below the threshold (<0.5) indicate the use of energy storage systems to improve energy security, with the potential to enhance economic efficiency (X3, score 0.3246). Although the aspect of enhancing economic efficiency is complementary here, it is nevertheless articulated when selecting renewable energy solutions with integrated energy systems. This confirms the growing importance of this dimension in decision-making related to energy storage investments, which is an equally important observation.

Reliability tests performed for the study reveal the significance of the estimated variables adopted for the study. Based on the findings, the significance of the examined variables (X1–X3) can be determined, with the final value of the X2 function for variable Y indicating the highest potential for occurrence (OR = 0.8020), with a low error rate (b = 0.3761), relative to the specified collinearity limit. Therefore, variable X2 (reducing the level of peak imports in the process of energy consumption cost optimization as a source of economic efficiency) is the parameter with the highest probability of functioning in correlation with variable Y, related to the duration of use of the RES installation with energy storage.

5. Discussion

Residential BESS can be conceptualized as a distributed flexibility asset providing multiple household value [35] streams simultaneously [46]:

- Self-consumption increase and load shifting,
- Peak shaving (reducing maximum grid import and evening peaks),
- Backup capability for critical loads (system-dependent),
- Potential grid-support functions where rules and interoperability enable local services.

In practice, these value streams are frequently "stacked", meaning that a single battery is operated to achieve several objectives at once (e.g., daytime PV charging for self-consumption plus evening peak shaving plus maintaining a minimum reserve state of charge for backup). This combination forces operational trade-offs. Maximizing bill savings through aggressive cycling can reduce the reserve energy available for backup power during disruptions—reducing the expected energy security of households. While resilience-oriented backup policies can reduce the potential for arbitrage and self-consumption [32,33], which create potential for economic efficiency.

The literature on the subject indicates that the effectiveness of these functions depends largely on:

- System integration—the coupling architecture,
- The capacity of the installation,
- Quality of installation operation measurements (systematicity and detail),
- Control sphere (rule-based control vs. optimization-based scheduling).

It should be noted, that rule-based strategies are common and robust, but optimization-based HEMS can explicitly coordinate PV, BESS and flexible loads (EV charging, heat pumps, domestic hot water), improving PV utilization and peak management under time-varying tariffs and export constraints [42,47]. This is particularly relevant in prosumer-dense LV networks where "export limitations" may be imposed to increase hosting capacity and mitigate overvoltage risk; in such contexts, batteries and coordinated control can reduce forced export peaks and improve predictability of value streams [27,33].

In this regard, it is important to emphasize the technical context of creating energy security and the economic benefits derived from using renewable energy installations with energy storage systems. These are determined by:

- Usable energy capacity (kWh),
- Power rating (kW),
- Round-trip efficiency,
- Depth of discharge,
- Charge/discharge power limits,
- Cycle/calendar aging characteristics.

Moreover, given the diversity of household profiles, the same BESS system may generate substantially different results depending on daily load patterns or installation size. The level of household electrification (the scope of Hypothesis 1), as well as the seasonality of electricity demand, are also important factors in this paper. Therefore, it should be noted that the observed economic benefits arising from self-consumption or bill savings are not universal: they depend on the household demand schedule and the control strategy employed, as highlighted by, among others [10]. In this context, it is indicated that RES micro-installations at the household level are increasing their importance in the country's energy system as a result of actions aimed at increasing self-consumption of energy, as well as by adapting the operating mode to technical and economic conditions determined by the network capacity and the market price of electricity [48]. Energy security, related to both physical and economic access to energy, as well as consumption management options combined with the potential for real support for energy grids in terms of their energy efficiency and stability, are also important [49]. Integrated renewable energy systems are of interest in this area, as stand-alone photovoltaic installations, the most popular in Poland over the years, have already reached market maturity. Customers—both individual and institutional—are seeking more advanced solutions, which, with respect to individual installations [50], is confirmed by the customer preferences noted in this study. This trend is maintained by the promotion of high-efficiency solutions, aimed at improving the applicability and economic efficiency in the area of personalized energy reactions, which is increasingly emphasized in the literature [51]. This development trend on the Polish market is to be fulfilled by integrated renewable energy installation systems, which in turn will determine subsidy impulses for these purposes. This is linked to the idea of a new program to support the development of the renewable energy market in the 2026–2027 period—"Mój Prąd 7.0" (My Electricity 7.0), which is seen as a driving force for investments in renewable energy, highlighting the appropriateness of energy policy directions in line with the concept of sustainable development. This program is aimed at supporting investments in energy storage, heat storage, and HEMS/EMS systems [52].

Improving energy efficiency in Poland is driven not only by the energy transition, justified by the challenges of sustainable development. High energy prices and the prospect of continued government regulation are driving investment in renewable energy sources, as well as the exploration of economic models for managing energy production, consumption, and distribution. This research also confirms this, indicating, among other things, that the knowledge and skills of energy storage system users in this area increase with the duration of their use. This indicates significant potential for improving household energy efficiency over time, which is consistent with the next hypothesis adopted (Hypothesis 4).

The above leads to the conclusion that, at the household level, the control strategy is a key factor determining economic efficiency. Users focus on battery charging/discharging and flexible loads, often pursuing multiple goals, such as minimizing bills, reducing peak energy consumption, and directly contributing to environmental protection by reducing CO_2 emissions [47,53]. From an optimization perspective, the emphasis here is primarily on increasing self-consumption and local flexibility, while being sensitive to tariff burdens and distribution assumptions [54].

Household studies in real-world conditions highlight the seasonality of prosumer efficiency—self-sufficiency and self-consumption may be very high in summer, but drop significantly in winter due to the reduced efficiency of photovoltaic installations—which constitute the basic RES solution at the household level, which is also confirmed by the presented research—and higher demand, which has implications for the interpretation of the efficiency perception diagnosed in the studies and for modeling the impact of BESS systems on different household profiles. A recent Polish case study evaluated a PV + BESS systems under variable tariffs and documented substantial seasonal differences, highlighting the importance of tariff strategy, environmental conditions, and voltage-control considerations [14]. This study complements the above-mentioned aspect by establishing that time, considered in the context of installation use, also plays a significant role in users' approach to realizing the potential of RES installations with batteries, reinforcing sustainable development goals at the micro-installation user level. This includes acquired skills in analyzing performance and managing the installation's potential to increase economic, social, and environmental impacts (sustainable development).

This study contributes to a limited body of work that integrates technical, economic, and behavioral themes in the context of the Polish prosumer. In particular, studies rarely combine:

- Operational constraints at the LV level, which households increasingly experience as disruptions (export restrictions, voltage-related inverter shutdowns, and limited utilization of photovoltaic installations);
- The post-2022 net settlement environment, which links household profitability with market price signals and increases the value of time optimization;
- A dual-outcome perspective, in which BESS is analyzed simultaneously as a tool for household energy security/resilience and prosumer energy efficiency.

As a result, the literature offers limited empirical evidence on how Polish households perceive and evaluate storage under the combined influence of grid constraints and time-dependent settlement incentives. The present study addresses this gap by linking BESS ownership and household context (electrification, knowledge, and perceived barriers) to two outcome constructs—perceived household energy security and perceived prosumer efficiency, providing evidence that is directly relevant to prosumers and important from the perspective of shaping sustainable energy policy in Poland, in which renewable energy sources play an increasingly important role [55–61].

6. Conclusions and Implications

Survey results from users of RES installations equipped with home battery energy storage systems (BESS) indicate that the dominant investment motive is household energy security (95%). At the same time, a clear majority of respondents perceive BESS as a source of efficiency in home energy systems (91%). Regarding prosumer optimization, BESS is most strongly associated with increasing self-consumption (90%), whereas using BESS to reduce peak/critical-time imports is reported much less frequently (37%). This suggests that, in practice, "optimization" is primarily understood as retaining locally generated energy within the household rather than actively managing peak demand and costs. High levels of perceived purchase justification and satisfaction (87%) as well as willingness to recommend BESS (86%) point to substantial user-perceived value and support further diffusion of the technology. However, it is worth emphasizing the fact that investors in photovoltaic installations who intended to take advantage of funding for this activity under the 'My Electricity 6.0' program, which coincided with the time of the survey, were obliged to invest in energy storage facilities. This may have distorted the results of the voluntary choice and the recorded aspect of increasing security to some extent. Nevertheless, the study covered a range of different RES installation configurations and did not examine the issue of subsidization, so the above is only a side observation.

The presented results also reveal a competence and operational gap: 48% of respondents do not know the detailed operating principles of their battery-based system, and only 54% declare that they monitor system performance (including 18% who check at least weekly via an app). This implies that a considerable share of users treats the solution as a "black box," which may limit the realization of the full BESS potential—particularly in terms of peak import reduction strategies. From a market perspective, the results highlight the need for stronger user education, including in the areas of sustainability, standardized post-installation onboarding, and simplified monitoring/reporting tools (e.g., clear KPIs such as self-consumption, peak import, and cost savings). From the perspective of public policy and distribution system operators, the results support the positioning of BESS in communication and support systems, emphasizing energy security, while also justifying tariff and information incentives that promote more grid-friendly behavior, including peak demand reduction. These actions directly contribute to the sustainable development of the country's energy transition at the increasingly significant level of micro-installations in the national energy system.

Author Contributions: All authors have made significant contributions to this paper from the conception of the study through to the identification and selection of the research methodology and its conduct, the writing of the paper, and its editorial side. Conceptualization, E.C.-P., S.Z. and B.B.; methodology, E.C.-P., S.Z., J.S.-R. and B.B.; validation, J.S.-R., B.B. and S.D.; formal analysis, E.C.-P. and S.Z.; resources, S.Z., E.C.-P., J.S.-R., B.B. and S.D.; writing—original draft preparation, S.Z., E.C.-P., B.B. and S.D.; writing—review and editing, S.Z., E.C.-P., J.S.-R. and S.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: This study is waived for ethical review as it used the survey technique by Institution Committee.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The original contributions presented in this study are included in the article.

Conflicts of Interest: The authors declare no conflicts of interest.

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https://doi.org/10.3390/su18063033