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Application of Electric Energy Storage Technologies for Small and Medium Prosumers in Smart Grids

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Abstract

As the energy transition advances toward a low-carbon economy, small- and medium-sized consumers are increasingly becoming active prosumers, capable of generating, storing, and managing their own electricity. However, the intermittent nature of renewable sources poses significant challenges in matching generation with consumption, making energy storage a key element for prosumer participation in smart grids. This work assesses the performance of various energy storage technologies suitable for prosumer applications, focusing on parameters such as efficiency, lifecycle behavior, and system integration. Lithium-ion batteries, supercapacitors, and hydrogen-based technologies were tested under real-world operating conditions within residential, commercial, and industrial scenarios. The results confirm that hybrid configurations deliver the most balanced performance, with supercapacitors improving short-term stability in commercial contexts and hydrogen storage enabling long-duration autonomy in industrial settings. In terms of battery state of charge, the experimental tests showed clear differences across prosumer types: in the residential case, it dropped to about 20–25% in the morning, but recovered to nearly full capacity by midday and stabilized at around 70–75% by the end of the day; in the commercial case, it fluctuated more widely, between roughly 18% and 100%, evidencing the highest stress on batteries; while in the industrial case, it reached 25–30% at peak demand, with hydrogen sustaining autonomy under extended load and ensuring greater long-term reliability. Overall, the findings reinforce the importance of tailored storage strategies to unlock the full potential of prosumers in smart grids.

Keywords: prosumer; smart grid; energy storage system; hybrid storage; photovoltaic; supercapacitors; hydrogen

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1. Introduction

The growing penetration of renewable energy sources and the progressive decentralization of electricity generation are reshaping traditional power systems into more adaptive and resilient networks [1–3]. Within this changing framework, consumers are no longer limited to a passive role. Instead, an increasing number are evolving into prosumers, who both generate and consume energy [4–6]. This evolution is especially significant for small- and medium-scale prosumers, who, by adopting local generation technologies in residential and commercial contexts, applying demand response measures and utilizing storage systems, can actively enhance the flexibility and reliability of smart grids.

A major obstacle for prosumers lies in the intermittency and unpredictability associated with renewable generation. Photovoltaic (PV) and wind energy, which are the most commonly deployed technologies at the prosumer level, inherently depend on variable environmental factors. These fluctuations can lead to mismatches between production and consumption patterns [7,8]. To address these mismatches, energy storage systems (ESSs) have become a key element of smart grid strategies, enabling excess electricity to be retained during periods of high generation and to be utilized during times of deficit [9,10].

Among the available ESS options, electrochemical batteries, especially lithium-ion, have been the most widely adopted due to their favorable energy efficiency and capacity for short to medium term storage [11,12]. Nevertheless, technological progress in alternative storage methods such as supercapacitors and hydrogen-based systems has expanded the range of possibilities. Each technology offers specific benefits in terms of power density, cycle life, charge/discharge dynamics, and scalability [13–16]. When used in combination, these systems can form hybrid architectures that capitalize on their complementary features and mitigate individual drawbacks [17–20]. Lithium-ion batteries are favored in distributed energy storage applications due to their high energy density and efficiency, as well as their relatively long operational lifespan. However, alternatives like lead-acid batteries continue to be employed depending on cost and availability, despite offering lower durability. Over time, all batteries experience degradation that reduces their usable capacity and necessitates replacements, which may challenge the long-term economic sustainability for prosumers. In contrast, supercapacitors store energy through electrostatic mechanisms rather than chemical reactions, allowing for extremely rapid charge and discharge cycles. Although their total energy capacity is smaller, their efficiency and longevity make them ideal for short-duration applications, particularly when deployed in tandem with slower but larger-capacity storage technologies. Hydrogen storage provides a distinct value proposition by enabling long-term storage through the conversion of surplus electricity via electrolysis. The resulting hydrogen can later be transformed back into electricity using fuel cells. While promising for large-scale and industrial scenarios, hydrogen systems still face technical and economic barriers including low round-trip efficiency and significant infrastructure requirements.

Each storage option brings its own strengths and weaknesses, and no single solution can be universally applied to all prosumer scenarios. The optimal configuration is highly dependent on variables such as consumption profile, scale of energy use, economic factors, and grid interconnection conditions. This work examines the suitability of various storage technologies, both individually and as hybrid systems, with the goal of identifying the most effective configurations for small and medium prosumers integrated into smart grids.

In recent years, the development of distributed energy systems has shifted toward architectures that allow for real-time energy balancing, bidirectional power flows, and intelligent control systems capable of responding to changing demand and supply conditions [21–23]. Within this context, energy storage is no longer seen as a passive buffer but as an active component of grid management and market participation. The ability to deploy hybrid energy storage systems tailored to specific demand profiles opens the scenario to more granular optimization strategies, particularly when integrated with control algorithms, demand-side management techniques, and economic forecasting tools [24,25]. This increasing complexity has spurred the integration of advanced modeling and simulation techniques to predict the behavior of energy storage components under variable conditions. Particularly in hybrid systems, the control logic governing the interaction between fast-response devices like supercapacitors and long-duration units such as hydrogen storage requires sophisticated coordination schemes to avoid performance degradation or energy losses [26–29]. In this sense, the proper modeling of response times, degradation patterns,

and operational constraints is essential not only for sizing and design, but also for the long-term reliability of prosumer-centric architectures.

Moreover, energy storage systems are increasingly expected to support not just self-consumption but also ancillary services such as frequency regulation, peak shaving, and participation in local energy markets [30,31]. These extended functionalities demand a new layer of control flexibility that goes beyond simple charge–discharge cycles. Particularly for small and medium prosumers, this implies a dual optimization challenge: maximizing local energy use while optimizing system lifespan and operational cost. Hybrid systems offer a promising pathway to achieve this balance, yet their real-world behavior under dynamic conditions remains insufficiently explored, especially from the perspective of different user scales. Energy storage strategies that have been recently proposed in the literature address challenges that are highly relevant to prosumer integration. Robust planning of shared rental storage in industrial parks demonstrates that flexible business models can effectively address PV uncertainty and demand variability in small- and medium-scale communities, which closely resemble commercial and collective prosumer contexts [32]. Likewise, hybrid microgrid configurations with coordinated storage control have been proven to enhance operational stability and cost-effectiveness, supporting the integration of heterogeneous resources such as batteries, supercapacitors, and hydrogen in prosumer environments [33]. Furthermore, relay-assisted demand response strategies highlight that the effectiveness of prosumer-based storage depends on reliable bidirectional communications to coordinate flexibility and implement control signals [34].

The AGERAR PLUS project aims to harness the potential of cooperation to consolidate the innovative and scientific framework of Spain and Portugal in the energy sector. The project focuses on improving energy efficiency by promoting small- and medium-sized prosumers and energy communities through the use of information and communication technologies. Within these aims, in this paper, a practical evaluation of energy storage configurations is proposed for small and medium prosumers based on experimental setups that emulate residential, commercial, and industrial use cases. The experimental platform and datasets used in this study were developed within this project, specifically to test prosumer-oriented hybrid storage under real PV-driven operation. All results reported were obtained on the project hybrid microgrid, which mainly integrates PV arrays, lithium-ion and lead-acid batteries, a supercapacitor bank, and an electrolyzer–hydrogen storage–fuel cell loop. The present paper focuses on the application-level assessment of storage technologies for small and medium prosumers.

Unlike most of the existing literature, which focuses primarily on theoretical modeling or isolated technologies, this work emphasizes real operating conditions and comparative testing. For instance, previous studies [35] demonstrated through simulations how integrating hydrogen storage with batteries and supercapacitors can optimize system performance, but did not include experimental verification. Similarly, other studies [36] provided an in-depth review of hydrogen microgrid technologies, yet without hands-on evaluation or real-world validation. Furthermore, a lab-scale hybrid system has been presented, including experimental data on fast-response performance [34]. Other authors reviewed hybrid storage technologies in industrial parks and emphasized the need for real-world applicability of hybrid systems across service life and response time dimensions [37]. A hybrid supercapacitor–lithium-ion architecture within a DC microgrid was proposed at simulation level to enhance what is typically lacking in theoretical-only studies [38]. One of the novel aspects of this study lies in the simultaneous consideration of technical and operational parameters (such as storage efficiency, response time, and system integration potential) under dynamic solar PV generation. Furthermore, the article explores hybridization strategies, not only as performance enhancers but as ways to extend system lifespan

and reduce operational stress on individual components. This hybrid approach is framed as a realistic solution to the limitations found in single-technology systems, particularly for commercial and industrial-scale prosumers. In addition, the experimental platform provides direct validation of system behavior under fluctuating renewable inputs, offering insights into reliability and lifespan extension that extend beyond theoretical estimations. The work also integrates short-term dynamics with long-term operational horizons, bridging an often-missing link between daily variability and project-scale performance. This combination of experimental data, hybrid strategies, and long-term perspective constitutes the distinctive contribution of the study.

2. Materials and Methods

In order to validate the optimal energy storage configurations for prosumers in smart grids, a series of experimental tests were conducted. The analysis focuses on the performance of different energy storage technologies considering efficiency, response time, storage capacity, and economic feasibility.

A unified experimental platform was designed around a direct current (DC) bus architecture to ensure consistency and comparability across different test scenarios. This choice responds to the need for a flexible, modular, and technology-neutral infrastructure capable of accommodating various energy storage systems and load profiles. The adoption of a DC bus is especially suitable in environments dominated by PV generation and electrochemical storage, as it minimizes conversion losses, simplifies system integration, and improves overall efficiency. In all tested configurations, the DC bus is stabilized using lead-acid batteries. These function as a voltage buffer to mitigate transients, maintain bus stability during switching operations, and provide auxiliary support that prevents undervoltage events. The use of a common infrastructure ensures that the performance of each configuration can be assessed under equivalent boundary conditions, isolating the effects of component selection rather than platform-specific variables. The systems are based on an experimental microgrid located in the "El Arenosillo" Experimentation Center (CEDEA), based in the Spanish province of Huelva, belonging to the National Institute for Aerospace Technology (INTA). The microgrid, Figure 1, is a hybrid system that joins renewable sources like PV and wind, with energy storage systems like batteries or supercapacitors and a hydrogen loop (production, storage and use) by means of a high-voltage DC bus. This DC bus can supply/be provided by energy to/from a 3-phase and 1-phase AC bus through bidirectional AC/DC converters. The DC bus voltage is fixed by the lead-acid battery bank. DC generators include three PV fields, one of them mounted on an inclined surface (5.2 kWp), a BIPV vertical field (2.3 kWp), a flexible panel field (2.4 kWp), a small wind turbine (5 kWp), and a DC power supply (15 kW). The ESS (Energy Storage System) is based on lead-acid batteries (36 kWh), lithium-ion batteries (43.2 kWh and 33.2 kWh), and the use of hydrogen as an energy vector through an alkaline electrolyzer, high-pressure compressed tanks and metal hydrides to store hydrogen and two fuel cells for mobile and stationary applications. Regarding consumption loads, a bidirectional DC/AC converter injects power from the DC bus to the grid, and vice versa. A DC programmable load can be used to emulate DC load profiles as well. The entire platform is supervised and managed by a SCADA system, which autonomously executes the operating setpoints. These setpoints can be adjusted according to both operational requirements and atmospheric parameters. The SCADA also handles real-time monitoring and data logging, ensuring that performance indicators and system states are consistently recorded throughout the tests.

The main specifications of the operational devices are included in Table 1.

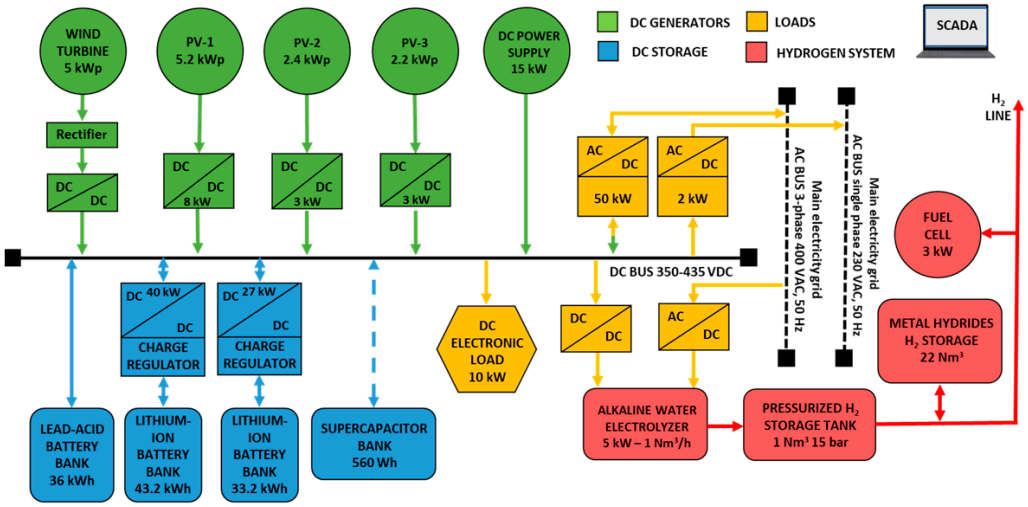

Figure 1. Experimental renewable microgrid for validation of hybrid ESS in prosumer-oriented systems, integrating photovoltaic generation, hydrogen storage, batteries, and supercapacitors.

The study defines three types of prosumer profiles based on energy demand scale, variability, and operational constraints: residential, commercial, and industrial. Each configuration is implemented and tested using real-time solar PV energy input and monitored for energy performance, control response, and storage behavior.

To validate the suitability of the three prosumer configurations proposed in this study, Multi-Criteria Decision Analysis (MCDA) was performed. The analysis was based on the technologies available in the experimental microgrid (Figure 1) and aimed to ensure that the selected system architectures respond to the operational priorities of residential, commercial, and industrial users. Five criteria were considered: response time, storage autonomy, reliability, scalability, and system complexity. Each technology (lithium-ion batteries, supercapacitors, and hydrogen storage) was scored on a scale from 1 to 3 according to experimental evidence and technical specifications, while weights were assigned to each criterion to reflect the specific requirements of each prosumer profile. The weighted results are summarized in Table 2, showing that lithium-ion batteries are most suitable for residential applications. Their commercial configuration requires the inclusion of supercapacitors to address short-term fluctuations, and the industrial configuration is strengthened by the integration of hydrogen to secure long-duration autonomy. The results of the weighted sums indicate that lithium-ion batteries obtain the highest overall score across all three prosumer types. However, the analysis also reveals that highly weighted criteria can justify the inclusion of complementary technologies when a single option dominates a specific dimension. In the commercial case, although lithium-ion achieves the highest aggregate score (2.45), the response time criterion carries a weight of 0.25 and is uniquely dominated by supercapacitors (score = 3), which leads to their inclusion in the configuration to ensure a fast transient response. Similarly, for industrial prosumers, lithium-ion again ranks first (2.45), but autonomy has the highest weight (0.30) and is uniquely dominated by hydrogen storage (score = 3), justifying its integration to guarantee long-duration operation. In contrast, the residential profile does not present such a dominant trade-off, and lithium-ion alone remains the most suitable option. This decision logic demonstrates how the MCDA not only ranks technologies, but also explains the hybridization paths required for different prosumer contexts.

Table 1. Specifications summary of the operational devices of the experimental renewable microgrid at INTA.

Equipment	Manufacturer	Model	Power (kW)	Range	Specifications
PV 1	BP	BP60 1991	5.2	P_{panel}: 38.25 Wp $Voltage_{oc}$: 365.5 V $Current_{sc}$: 26.8 A	136 panels Boost converter (200–400 V) (8 kW) Ethernet
PV 2	Solar Innova	ESF-M-BIPV-GG-P156-40-161W	2.4	P_{panel}: 161 Wp	15 series panels
PV 3	ENECOM	HF135	2.2	P_{panel}: 135 Wp	16 series panels Flexible panels
Wind turbine	AERO	AERO5000 W	5	Voltage: 230 Vac	Horizontal axis Electromagnetic brake
DC power supply	AMETEK	SORENSEN SGI 500X30D-1CAAR	15	Voltage: 500 V Current: 30 A	Input voltage: 380/400 V_{AC} Ethernet + RS-2326
Lead-acid	Upower	UP-100	36	$Voltage_{battery}$: 12 V $Current_{battery}$: 100 Ah	VRLA-AGM 30 batteries
Lithium-ion	CEGASA	ROOK3	43.2	$Voltage_{module}$ 48 V $Current_{module}$: 180 Ah $Energy_{module}$: 8.64 kWh	LiFePo4 5 Rokk E48 modules 15 cells/module Cegasa GBMS Zekalabs bidirectional boost-buck converter DC/DC LB-1091-01-01 (40 kWp) Ethernet
Lithium-ion	Pylontech	H32148	33.2	$Voltage_{module}$ 48 V $Current_{module}$: 148 Ah $Energy_{module}$: 8.64 kWh	LiFePo4 7 modules SC1000-200J-C
Super capacitors	Maxwell	BMOD0141 P064 B04	0.56	$Voltage_{module}$ 64 V $Current_{module}$: 100 A $Energy_{module}$: 80 Wh	7 series modules: $Capacity_{module}$: 141 F $Cells_{module}$: 4 Max. $voltage_{module}$: 68.4 V Max. $current_{module}$: 1900 A short current: 9000 A Temperature: −40 °C/65 °C
DC/AC converter	ZIGOR	Storage BG3	50	Voltage: 300–720 V_{DC} Current (DC): 173 A	Bidirectional Current (AC): 73 A Ethernet and RS-485 Efficiency: 96% <3% THD
Electronic load	APS	5VP10-32	10	Voltage: 600 V Current: 32 A/320 A	Programmable DC loads

The residential setup, Figure 2, is designed to emulate the behavior of a typical household integrating solar generation and aiming to reduce its reliance on the grid. In this case, the energy storage architecture is based on a bank of lithium-ion batteries, supported by lead-acid batteries that stabilize the DC bus. It should be noted that in residential applications, it is not common to use lead-acid batteries to stabilize the bus voltage. Power converter devices normally perform this function. This configuration, consistent with the experimental microgrid, is equally representative of the test results. The primary motivation for selecting lithium-ion technology in this context lies in its favorable characteristics for daily cycling: high round-trip efficiency, relatively long cycle life, and good energy density. These attributes make it ideal for scenarios where generation and consumption are strongly linked to daily solar cycles. The experimental configuration consists of a PV array, coupled through a bidirectional DC/DC converter to the lithium-

ion battery bank. This converter regulates both the charging process from PV surplus and the discharging operation when solar production is insufficient to meet demand. Lead-acid batteries are placed in parallel with the DC bus and are not intended for deep discharge. Instead, they serve as passive stabilizers, absorbing rapid transients caused by load switching or PV fluctuations. Residential demand profiles are typically characterized by low but continuous base loads during the day, followed by increased consumption in the evening hours. Under these circumstances, lithium-ion batteries are able to store the excess solar energy generated during the middle of the day and release it progressively in the afternoon and evening. Performance assessment includes monitoring the state of charge (SOC), energy autonomy (percentage of demand covered without grid input), charge–discharge efficiency, and the system's capacity to reduce peak demand from the grid. The combination of fast response, scalability, and energy density makes lithium-ion batteries particularly suitable for this segment, while the lead-acid element ensures robustness in maintaining system equilibrium.

Table 2. Multi-Criteria Decision Analysis (MCDA) applied to prosumer storage configurations from the technologies in the experimental microgrid.

Criterion	Weights (0–1)			Scores (1–3)		
	Residential	Commercial	Industrial	Li-Ion	Supercap	Hydrogen
Response time	0.15	0.25	0.15	2	3	1
Autonomy (duration)	0.25	0.20	0.30	2	1	3
Reliability (operational)	0.30	0.25	0.20	3	3	2
Scalability/integration	0.20	0.20	0.25	3	2	2
System complexity (lower is better)	0.10	0.10	0.10	2	2	3

Weighted sums Σ(w·s)	Li-ion	Supercap	Hydrogen
Residential	2.50	2.20	2.20
Commercial	2.45	2.30	2.05
Industrial	2.45	2.05	2.25

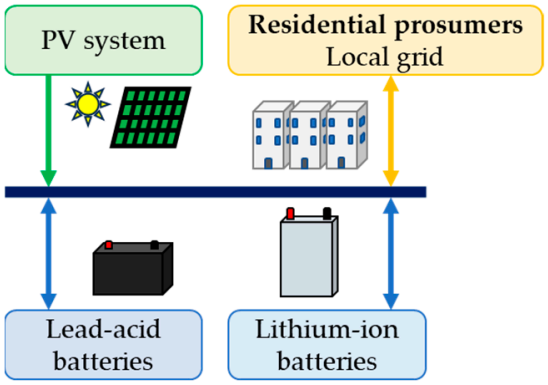

Figure 2. Schematic diagram of the residential prosumer energy storage system, combining lithium-ion and lead-acid batteries to provide daily load coverage and short-term stabilization with PV.

Commercial buildings, such as offices, retail spaces, or service providers, exhibit more complex energy demand profiles compared to residential users. These include both predictable base loads and unpredictable demand peaks linked to operational hours, climate control systems, or equipment use. To address these dynamic needs, the configuration developed for commercial prosumers, Figure 3, integrates three ESS components: lithium-ion batteries for energy storage, supercapacitors for fast power response, and lead-acid

batteries for DC bus stabilization. The lithium-ion batteries serve as the main energy reservoir, storing solar generation during periods of excess and supplying the base load during periods of deficit. This ensures that the system can sustain operation during extended hours of low generation, particularly at the start and end of the day. However, lithium-ion cells alone are not ideal for repeated high-intensity power fluctuations, as deep discharge and rapid cycling reduce their lifespan. To solve this issue, supercapacitors are incorporated into the system. These devices are capable of supplying or absorbing power nearly instantaneously, which makes them ideal for mitigating short-term load spikes such as the startup of HVAC compressors or lighting surges. The commercial PV installation feeds both the lithium-ion and supercapacitor modules. The lead-acid batteries again act as a voltage buffer to ensure smooth operation of the DC bus under all operating regimes. Key performance indicators for this configuration include the extent to which supercapacitors absorb fast fluctuations, the depth of discharge reductions in lithium-ion batteries, and the effect on total battery lifespan. Additionally, improvements in power quality are evaluated, including voltage ripple reduction and response times under load transients. This configuration has been selected to reflect a realistic commercial energy ecosystem that requires both long-duration energy management and fast-response stability mechanisms, combining reliability with dynamic capability.

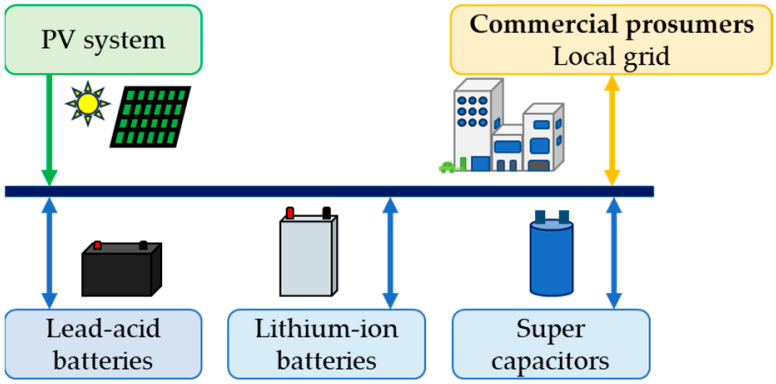

Figure 3. Schematic diagram of the commercial prosumer energy storage system, integrating lithium-ion batteries with supercapacitors to manage variable demand and short-duration peaks.

Industrial prosumers present the most demanding scenario in terms of both energy quantity and quality, Figure 4. Their consumption profiles are often continuous, high-powered, and sometimes highly variable depending on production cycles. To accommodate this, a hybrid configuration combining lithium-ion batteries for short-term storage and a hydrogen-based energy system for long-term surplus retention has been developed and tested. While a single battery solution could be a solution given the state and accessibility of current technology, especially in terms of cost and infrastructure, a progressive inclusion of hydrogen technologies is expected, as these provide sustainability and storage advantages over current electrochemical alternatives. Lithium-ion batteries cover immediate energy needs and absorb rapid variations in generation or consumption. However, due to their limited capacity and degradation under deep cycling, they are not ideal for storing prolonged surplus energy that may result from periods of sustained high PV output and low demand. To address this, a hydrogen energy subsystem is analyzed for its suitability for inclusion. This subsystem consists of an electrolyzer, a pressurized hydrogen storage tank, and a fuel cell. When excess electricity is available, it is used to power the electrolyzer and produce hydrogen from water. This hydrogen is stored and later converted back to electricity via the fuel cell when generation is insufficient and lithium-ion capacity is exhausted. In this setup, the fuel cell is essential for reconverting stored hydrogen into electricity, ensuring

that surplus energy becomes usable during periods of low PV generation. The motivation for integrating hydrogen storage in this case is twofold. First, it provides a scalable solution for long-term energy storage that can be adjusted to meet industrial demands. Second, it decouples generation from consumption over a longer time horizon than batteries allow, enabling the facility to operate during prolonged cloudy periods or production shifts without external energy input. The experimental system includes a PV array, a lithium-ion bank to absorb short-term imbalances, and a full hydrogen loop for long-duration storage. System performance is analyzed based on each subsystem (lithium-ion, electrolyzer, and fuel cell), overall efficiency of the hydrogen cycle, energy autonomy achieved, and load coverage under varying scenarios. This configuration reflects the strategic direction of many industrial energy systems, which aim not only for renewable integration but also energy independence and operational resilience.

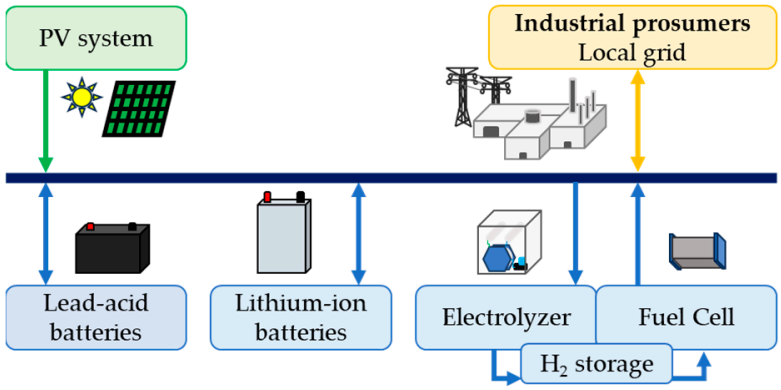

Figure 4. Schematic diagram of the industrial prosumer energy storage system, combining lithium-ion batteries with hydrogen storage to ensure long-term autonomy and surplus energy management.

3. Results

To evaluate the performance of different energy storage configurations for prosumers, the experimental evaluation of the proposed storage configurations was carried out with the aim of assessing their suitability for different types of prosumers—including residential, commercial, and industrial—operating within smart grids powered by solar PV generation. Each setup was tested independently under realistic operating conditions, provided by experimental profiles from the microgrid, allowing for the comparison of energy behavior, component performance, and the overall capacity of each configuration to manage generation variability and ensure supply continuity. This practical approach enables the validation of the hybrid system design presented in the previous section and supports the identification of optimal solutions tailored to specific user profiles.

For each prosumer type, the system's dynamic response was monitored in real time, focusing on energy flows, state of charge (SOC) of the batteries, and the interaction between storage components. Particular attention was paid to how effectively the system could absorb PV surplus, deliver energy when needed, and mitigate the impact of short-term or long-duration imbalances between generation and demand. The following subsections summarize the key findings for each use case, based on the data collected from the experimental platform.

In the case of the residential prosumer, the system incorporated lithium-ion batteries as the main storage device, complemented by lead-acid batteries used to stabilize the DC bus. During daytime hours with high solar irradiance, the energy generated was used first to satisfy the immediate load, and any surplus was directed to charge the lithium-ion battery bank. Once solar production declined in the evening, the stored energy was discharged

to cover demand. The time evolution of generation, consumption, and SOC is shown in Figure 5.

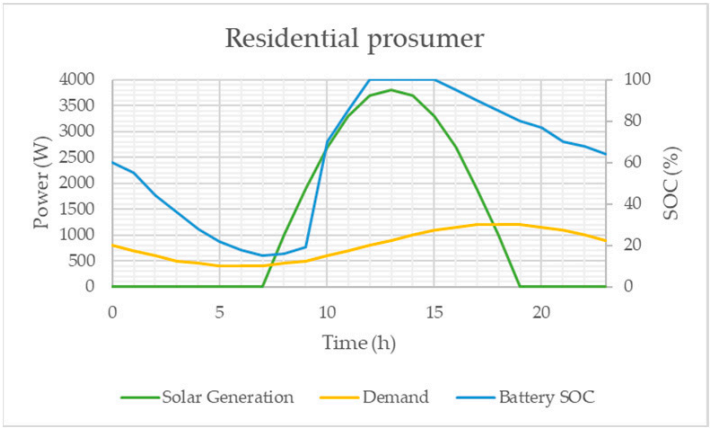

Figure 5. Results from the residential prosumer system, showing SOC dynamics of the battery storage system under daily demand and PV generation.

The results reveal a sharp increase in SOC coinciding with the midday solar peak, with batteries typically reaching full charge before noon. SOC levels remained elevated throughout the afternoon, and the battery progressively discharged during the evening consumption hours. This gradual decline in SOC overnight indicates that the system effectively supports residential loads beyond sunlight hours. Nonetheless, in some cases, the battery reached low SOC levels by early morning, suggesting that a larger storage capacity or improved demand-side control strategies could further increase energy self-sufficiency.

For the commercial prosumer configuration, lithium-ion batteries were combined with supercapacitors to enhance the system's responsiveness and reduce stress on the main battery unit. This setup aimed to address the highly variable and intermittent nature of commercial energy consumption. Supercapacitors were dimensioned to respond quickly to short-duration power peaks, while lithium-ion batteries covered the base load. The performance of the hybrid system is illustrated in Figure 6, which includes SOC trends, load profiles, and supercapacitor intervention periods.

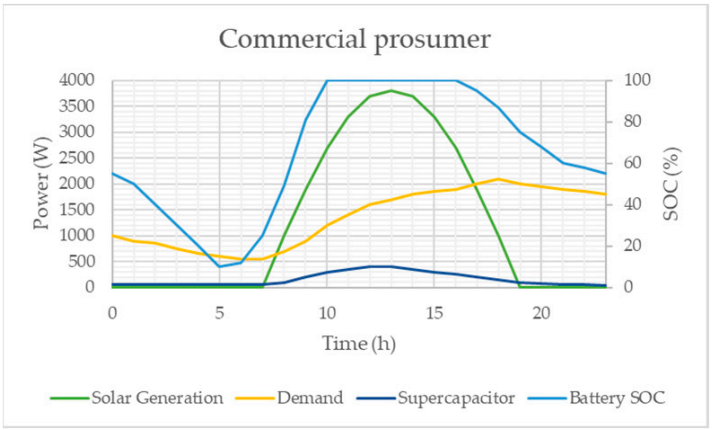

Figure 6. Results from the commercial prosumer system, showing the combined role of lithium-ion batteries and supercapacitors in handling short-term fluctuations and demand peaks.

The results indicate that the presence of supercapacitors significantly smoothed the SOC profile of the lithium-ion battery. Fewer deep discharge events were observed compared to the residential case. During rapid demand surges, the supercapacitors delivered

immediate energy, alleviating the load on the battery and effectively acting as a power buffer. This dynamic reduced the number of high-stress cycles in the lithium-ion system, which is expected to extend its lifespan and improve long-term system efficiency. However, given the limited energy capacity of supercapacitors, their role remains supportive and cannot substitute main storage in longer-duration events.

In the industrial prosumer scenario, a hybrid storage solution was implemented, combining lithium-ion batteries for short-term energy needs and hydrogen conversion for managing extended surplus periods. When the PV generation surpassed both the instantaneous demand and the lithium-ion battery's storage capacity, the excess electricity was automatically routed by the microgrid controller, according to predefined setpoints, to an electrolyzer to produce hydrogen. This hydrogen was then stored and later converted back into electricity using a fuel cell when energy demand exceeded available battery power. The system's performance over time, including energy distribution and conversion dynamics, is presented in Figure 7.

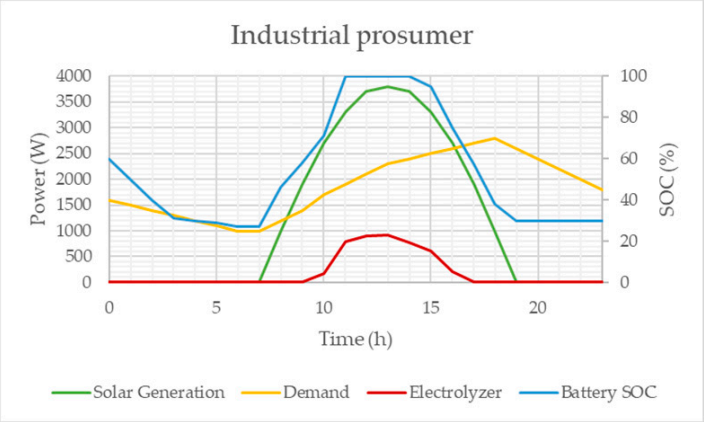

Figure 7. Results from the industrial prosumer system, highlighting hydrogen storage contribution to extended autonomy during high-demand periods and renewable variability.

The results demonstrate that hydrogen production was triggered during phases of high PV generation and full battery SOC, thereby avoiding energy curtailment. Later, during periods of insufficient generation or high load, the stored hydrogen was used to supply electricity via the fuel cell. This long-duration storage pathway provided an effective mechanism for extending energy autonomy. However, it was also observed that the overall round-trip efficiency of the hydrogen cycle was lower than that of battery-based systems, mainly due to losses in electrolysis and fuel cell conversion. This trade-off must be considered when designing systems for industrial prosumers, where reliability and energy security are key priorities.

In Figures 5–7, the state of charge (SOC) at 0 h reflects the specific demand conditions of each prosumer profile at the start of the test. Since residential, commercial, and industrial configurations begin with progressively higher initial loads, the SOC is observed at different levels.

4. Discussion

The experimental results presented in the previous section offer a practical basis for analyzing the suitability of different energy storage configurations in real-world prosumer systems. While the laboratory tests focused on controlled conditions, the insights obtained are directly translatable to operational environments where prosumers seek to improve self-sufficiency, reduce grid dependency, and manage energy costs.

For residential users, the experimental setup confirmed that lithium-ion batteries alone are generally sufficient to ensure continuity of supply during periods without solar generation. The system was able to cover evening demand effectively and maintain stable operation throughout the night under typical consumption levels. In real applications, this confirms the feasibility of deploying lithium-ion-based storage systems as standalone solutions for single-family homes or small apartment buildings, especially when combined with rooftop PV generation. However, several practical considerations arise when moving from the experimental platform to actual residential installations. One of the most critical aspects is storage sizing. While the test platform emulated realistic load profiles, actual household consumption can vary significantly depending on climate, occupancy, and appliance usage. Oversizing the battery bank increases system cost, while undersizing reduces autonomy. Demand-side management strategies such as smart appliance scheduling and peak-shaving algorithms can further enhance system performance without increasing battery size. Lead-acid batteries, although not suitable for deep cycling, have shown value as stabilizing elements for DC-based residential prosumers. In off-grid applications or hybrid AC/DC systems, they can improve converter performance and buffer transient events, enhancing the resilience of the power supply.

In commercial settings, the inclusion of supercapacitors alongside lithium-ion batteries significantly improved system stability and is particularly well-suited to businesses with variable loads. Supercapacitors provided immediate response to short-duration load peaks, effectively reducing the depth and frequency of lithium-ion battery discharge. This has important implications for real-world applications, where commercial prosumers often face sharp fluctuations in demand due to HVAC systems, office equipment, or refrigeration units. The hybrid configuration tested offers a viable architecture for office buildings, small retail centers, or service-sector facilities aiming to maximize self-consumption and minimize battery wear. In such scenarios, battery health is critical due to the economic impact of replacements. By limiting deep discharge cycles, supercapacitor integration can significantly extend battery lifespan and reduce total cost over time. For grid-connected commercial installations, the system could also contribute to ancillary services such as frequency support or local peak shaving. This opens the door to new revenue streams for prosumers participating in flexibility markets, provided the control systems are appropriately configured.

Industrial users often require both high power and long-duration storage to ensure operational continuity during production cycles. The tested configuration, combining lithium-ion batteries for short-term needs and hydrogen storage for long-term operation, proved effective in shifting excess solar energy across time. In real-world scenarios, this architecture is applicable to mid-scale manufacturing facilities, manufacturing-industrial plants or logistics centers aiming for high levels of energy independence. One of the main benefits of hydrogen integration is its ability to decouple energy generation and use over days or even weeks. This becomes especially relevant in cases where solar production significantly exceeds demand during certain periods, such as weekends or non-operational hours. The conversion of surplus energy into hydrogen avoids curtailment and makes the excess generation usable at a later time. Nonetheless, the lower round-trip efficiency of hydrogen storage compared to batteries remains a limiting factor, added to the additional cost and energy losses compared to battery storage, which continue to be challenges faced by this technology. In order be economically viable, hydrogen systems must be deployed at scale and benefit from synergies with other industrial processes, such as thermal needs or the use of hydrogen as a feedstock. In this sense, multi-vector energy hubs that combine electricity, heat, and gas could offer an ideal environment for this hybrid architecture. In the experimental results, the hydrogen pathway has been mainly illustrated through the

electrolyzer stage, since it provides a direct balance of electricity by showing how surplus PV is converted into hydrogen. However, for the system to be reliable over extended periods, the fuel cell is essential to reconvert this stored hydrogen back into electricity. Without the fuel cell, the hydrogen loop would not contribute to prosumer autonomy, while its integration enables long-term operation and ensures that the storage system remains consistent with the objective of reliable prosumer participation in smart grids.

Table 3 summarizes the key features, benefits, and limitations of each configuration tested, offering a practical reference for system designers, energy consultants, and decision-makers. As detailed, the residential configuration based on lithium-ion batteries complemented by lead-acid units for stabilization offers high efficiency and a reliable degree of autonomy for users with predictable daily consumption. However, its main limitation lies in the relatively short storage duration, which may not be sufficient during extended low-generation periods. In commercial environments, the integration of supercapacitors with lithium-ion and lead-acid batteries provides a notable advantage by reducing battery stress and smoothing power delivery during demand peaks. This hybrid setup, although more complex and costly, is particularly effective in scenarios with variable or impulsive loads. For industrial applications, the combination of lithium-ion batteries and hydrogen storage enables long-term energy operation and full use of surplus generation. This configuration addresses the need for supply continuity over extended periods but is constrained by low round-trip efficiency and higher infrastructure requirements. Lithium-ion batteries achieve high efficiencies of 90–95% and can typically operate for 8–12 years, making them well suited for short-term applications. In commercial systems, the addition of supercapacitors does not alter the intrinsic lifespan of the batteries, but their buffering effect reduces stress and favors operation closer to the upper end of this range. Hydrogen-based solutions, although less efficient (30–45%), offer the advantage of multi-day autonomy, with fuel cell stacks rated for 5000–10000 operating hours, which is particularly relevant in industrial contexts. The table thus illustrates a clear progression in system complexity and storage duration across the three use cases, reflecting the increasing demands and autonomy expectations of each prosumer type.

Table 3. Comparative summary of tested energy storage configurations for residential, commercial, and industrial prosumers.

Prosumer Type	Configuration	Main Advantage	Limitation	Recommended Context	Efficiency (%)	Storage	Lifespan/Cycles
Residential	Lithium-ion + Lead-acid (stabilization)	High efficiency and autonomy	Limited capacity for extended operation	Homes with rooftop PV and predictable daily load	90–95	Short-term (hours to 1 day)	8–12 years (~4000–6000 cycles)
Commercial	Lithium-ion + Supercapacitors + Lead-acid	Smoother operation and extended battery lifespan	Higher system complexity and cost	Smart offices and shops operating in variable demand with short-duration peaks	85–92	Short-medium-term (hours to 2 days)	8–12 years (~4000–6000 cycles)
Industrial	Lithium-ion + Hydrogen + Lead-acid	Long-term storage and surplus management	Low round-trip efficiency and infrastructure cost	Factories, manufacturing industries, off-grid or semi-autonomous sites	30–45 (H2) 90 (Li-ion)	Medium-long-term (days to weeks)	5000–10,000 h (fuel cell stack)

A comparative reading of Figures 5–7 shows distinctive battery SOC dynamics. In the residential case, the SOC starts around 80–85%, falls to a morning minimum of 20–25% (around hour 9–10), then rises rapidly with PV input to near 100%, finishing the day at ≈70–75%. The depth of discharge thus reaches around 60–65%, with SOC < 40% for

roughly 2–3 h. The commercial configuration exhibits the largest variability: SOC begins near 70–75%, drops to ≈18–20% at its lowest point, climbs to 100% around midday, and ends at 55–60%. This implies a discharge of 55–60%, but with a longer residence below 40% (4–5 h), evidencing higher cycling stress under variable loads and underscoring the value of supercapacitors to buffer short-term peaks. The industrial profile starts at 65–70%, reaches a minimum of 25–30%, recovers to 85–90% with PV, and closes the cycle at 50–55%; time < 40% is shorter (2–3 h), as the hydrogen loop provides the buffer needed for extended autonomy despite its lower round-trip efficiency. Overall, residential operation maintains a comparatively safer SOC margin over the day, commercial operation faces the most severe fluctuations and deeper discharges, and industrial operation leverages hydrogen to meet long-duration reliability targets while accepting efficiency trade-offs.

While the results are limited to 24 h layouts, the reliability of the storage configurations must also be considered in the long-term perspective of prosumer operation. Lithium-ion batteries, typically providing 8–12 years of lifespan under daily cycling, ensure robust short-term coverage but require proper sizing to avoid accelerated degradation. In commercial systems, the integration of supercapacitors not only smooths fast load fluctuations but also extends battery lifespan by reducing deep discharge cycles, thereby enhancing reliability over years of operation. In industrial contexts, the inclusion of hydrogen storage explicitly addresses multi-day or even seasonal imbalances, providing autonomy during consecutive cloudy periods when solar energy cannot be harvested. In adverse climates, where there is no stable solar availability, solar energy must be considered for replacement with another energy supply alternative that guarantees prosumer resilience. The ability to decouple generation and demand across weeks directly supports the project lifespan and legal/contractual obligations of prosumer facilities. In this sense, while the experimental validation covered daily cycles, the configurations proposed are inherently aligned with prosumer activity horizons that span equipment lifespan, project duration, and regulatory frameworks, which are essential for real-life application in smart grids. The configurations analyzed can be reasonably extrapolated to more demanding and realistic operating conditions, which prosumers are likely to face in practice. In residential systems, consecutive days of low solar input would not only test the sizing and cycling limits of the lithium-ion batteries but could also result in deeper discharges and accelerated degradation if storage is undersized. This highlights the importance of combining appropriate storage capacity with demand-side management measures, such as load shifting or flexible appliance scheduling, to maintain reliability during prolonged cloudy periods. In commercial systems, where load variability is typically higher and influenced by HVAC, refrigeration, or intermittent equipment use, the stabilizing role of supercapacitors becomes even more critical. Under these circumstances, supercapacitors absorb sharp transients and reduce the frequency of deep cycling events in the lithium-ion batteries, which is expected to extend their operational life and improve the cost-effectiveness of the overall system. In industrial contexts, which often involve continuous high-power consumption, the challenges of long-term operation are even greater. Industries with predominantly daytime power consumption could also be considered, where storage requirements would be less critical and system design could be simplified to prioritize short-term buffering rather than long-term autonomy. Extended cloudy periods or seasonal gaps in PV availability would shift the operational balance almost entirely to the hydrogen loop. In such cases, the electrolyzer–storage–fuel cell chain enables multi-day autonomy, providing a buffer that cannot be achieved with batteries alone. However, the lower round-trip efficiency of the hydrogen pathway compared to batteries underscores the need to consider trade-offs between reliability and energy losses. It should also be noted that the ratio between fast-response storage (supercapacitors) and long-term storage (lithium-ion batteries or hydrogen) is a critical design parameter.

Although no formal sensitivity analysis was conducted in this work, the commercial case showed that even a relatively small supercapacitor capacity significantly reduced cycling stress on the lithium-ion batteries. This highlights the importance of properly dimensioning the capacity ratio, which will be addressed in future research through dedicated parametric analyses and modeling studies to complement the experimental findings presented here.

From an economic perspective, the comparative analysis also highlights that the suitability of each hybrid storage setup depends not only on efficiency and reliability but also on cost optimization. While residential systems benefit from relatively low investment with lithium-ion systems, commercial configurations justify higher upfront costs through extended battery lifetime and reduced operational stress. In industrial contexts, although hydrogen pathways involve higher infrastructure expenses, they can become cost-effective when synergies with existing processes are leveraged.

To complement the experimental findings, Table 4 provides key techno-economic parameters for residential, commercial, and industrial prosumers. These values allow for situating experimental configurations within a broader feasibility framework. In residential contexts, the typical storage requirement lies between 8 and 12 kWh; this is consistent with a single lithium-ion pack, which is able to achieve a round-trip efficiency of 90–95% and a lifespan of 8–12 years. The associated investment ranges from 400 to 700 €/kWh, leading to a total NPC of EUR 8000–15,000 over the project lifespan, with a levelized cost of stored electricity (LCOE) between 0.15 and 0.25 €/kWh. For commercial prosumers, the required capacity scales up to 80–150 kWh, where hybrid systems combining lithium-ion batteries and supercapacitors can deliver efficiencies of 85–92%, with supercapacitors extending the effective battery life by mitigating high-stress cycling. In these cases, CAPEX values decrease in relative terms (300–600 €/kWh) due to economies of scale, but system complexity increases, resulting in NPC values of EUR 80,000–150,000 and LCOE between 0.12 and 0.20 €/kWh. Industrial prosumers face the largest storage requirements, typically ranging from 0.8 to 2.0 MWh or more, which justifies the integration of hydrogen-based solutions despite their lower efficiency (30–45%). Lithium-ion batteries are still used for short-term balancing, but the hydrogen loop provides multi-day autonomy and energy independence, with CAPEX ranging from 800 to 1500 €/kWh and NPC values between 0.8 and 2.5 M€. While these systems remain costly, they are particularly valuable in manufacturing environments where hydrogen can also be exploited as a feedstock or for combined heat and power applications, reducing the effective LCOE to 0.10–0.18 €/kWh under favorable synergies. Overall, this analysis reinforces that the suitability of each hybrid storage setup depends not only on technical performance but also on the balance between efficiency, cost, and reliability. Moreover, it highlights that the transition from residential to industrial contexts implies a clear progression in scale, complexity, and cost structure, which must be accounted for in prosumer-oriented smart grid planning.

Table 4. Techno-economic parameter for residential, commercial, and industrial prosumer storage systems [39–42].

Prosumer Type	Electricity Capacity Target Range	Required Capacity (kWh/Project)	Efficiency/Lifespan	CAPEX (€/kWh Installed)	OPEX (% CAPEX/year)	LCOE (€/kWh)	NPC (€/Project, Lifespan)
Residential	5–15 kWh	8–12 kWh	90–95% eff.; 8–12 years	400–700	1–2%	0.15–0.25	8000–15,000
Commercial	50–200 kWh	80–150 kWh	85–92% eff.; 8–12 years (Li-ion) + >15 years (supercaps)	300–600	1.5–2.5%	0.12–0.20	80,000–150,000
Industrial	500 kWh–several MWh	0.8–2.0 MWh	90% (Li-ion); 30–45% (H_2 loop); lifespan 10–12 y (batteries), 5000–10,000 h (fuel cell)	200–500 (Li-ion); 800–1500 (H_2 system)	2–4%	0.10–0.18	0.8–2.5 M€

5. Conclusions

The diversification of storage technologies is emerging as a key enabler in the deployment of decentralized renewable energy systems, particularly in scenarios where prosumers aim to increase self-sufficiency and reduce their reliance on the conventional grid. Based on the experimental evaluation of three hybrid configurations, this work highlights the relevance of selecting storage architectures according to the scale, profile, and operational needs of each prosumer type. The key findings can be summarized as follows:

- Residential prosumers: Lithium-ion batteries provide reliable short-term storage for capturing PV generation and covering evening demand, while lead-acid units contribute to voltage stabilization and dynamic response in DC-coupled systems.
- Commercial prosumers: Integrating supercapacitors with lithium-ion systems improves power quality and operational stability by absorbing instantaneous peaks, reducing stress on the battery bank, and extending its lifespan with direct economic benefits.
- Industrial prosumers: A dual solution combining lithium-ion batteries with hydrogen storage offers extended autonomy and surplus management. Despite lower round-trip efficiency, this pathway is particularly valuable in manufacturing contexts where hydrogen can be integrated with existing infrastructure and processes.

These conclusions are supported by the experimental evidence and comparative values previously analyzed. Residential lithium-ion systems achieved round-trip efficiencies of 90–95% with 8–12 years of expected lifespan, covering daily cycles with SOC variations between 20 and 100%. Commercial hybrid systems operated at 85–92% efficiency, with supercapacitors effectively mitigating SOC fluctuations down to 18–20%, thereby extending battery lifespan. Industrial configurations combining lithium-ion and hydrogen reached efficiencies of 90% and 30–45%, respectively, enabling multi-day autonomy, with fuel cell stacks rated for 5000–10,000 h of operation. These values confirm the practical feasibility of the proposed configurations for different prosumer types.

Overall, this research confirms that no single technology can fully address the broad spectrum of energy needs in prosumer environments. Instead, hybrid storage configurations tailored to specific load behaviors and operational goals represent a more effective and scalable approach. In future implementations, the role of advanced control strategies will be decisive. Energy management systems capable of dynamically orchestrating power flows between multiple storage layers based on forecast data and system constraints will be necessary to exploit the full potential of hybrid architectures. Moreover, the integration of techniques such as fuzzy logic, model predictive control, or reinforcement learning can further optimize energy allocation, component lifespan, and responsiveness to external conditions. These developments will be essential in the move from static configurations toward intelligent, adaptive systems that contribute to the evolution of active, resilient, and interconnected energy networks.

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Abbreviations

The following abbreviations are used in this manuscript:

DC	Direct Current
ESS	Energy Storage System
PV	Photovoltaic
SOC	State of Charge

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