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Empiric Results from the Successful Implementation of Data-Driven Innovative Energy Services in Buildings

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Abstract: The residential building sector is critical to the success of Europe's 2030 and 2050 decarbonization targets. To achieve that success, this paper demonstrates how advanced Pay-for-Performance (P4P) energy services for energy service companies (ESCOs) can address challenges by leveraging low-cost data collection systems in buildings to offer a combination of revenues stemming from informed decision-making, energy management optimization, and active participation in demand response schemes. Our methodology includes (i) preliminary assessments to identify each building's occupancy patterns, equipment, and smart readiness, (ii) the installation of sensors and data gateways, (iii) the deployment of data-driven energy efficiency and demand response measures, and (iv) the evaluation of non-energy services such as comfort and air quality monitoring. We conducted empirical tests in three distinct building typologies: a multi-apartment residential building in Spain, detached dwellings in Croatia, and a hotel bungalow in Greece, to measure self-consumption savings, occupant-driven energy use behaviour changes, and the potential for explicit demand response. The results indicate overall payback periods of less than 10 years, although effectiveness varies depending on occupant engagement, building suitability, and the local energy market context. These findings reinforce the technical and economic feasibility of enhanced ESCO smart services and provide practical insights for scaling up data-driven solutions to advance Europe's energy and climate objectives.

Keywords: smart energy services; energy efficiency (EE) in buildings; energy flexibility; energy service companies (ESCOs); demand response aggregators; energy performance contracts (EPC)

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1. Introduction

1.1. Background

Decarbonizing residential and commercial buildings by 2050 requires significant changes in energy service delivery and management. This urgency is driven by the increasing awareness of climate change and the need for sustainable energy solutions [1–3]. energy service companies (ESCOs) and energy aggregators can play pivotal roles by adapting their business models to incorporate advanced data-driven solutions. Unlike traditional energy services that often fail to optimize energy use and effectively engage building occupants, the introduction of Pay-for-Performance (P4P) energy service contracts enhances energy efficiency (EE) and sustainability through data-informed decision-making, optimized energy management, and active participation in demand response schemes [4–7]. In general, energy aggregators are involved in active demand response (DR) programmes, while ESCOs are involved in supplying cost-effective energy efficiency services.

Aggregators optimize energy use by consolidating demand flexibility from multiple buildings, enabling participation in DR schemes that adjust consumption based on grid needs and offering peak load reduction for congestion management and frequency regulation solutions for balancing services [8]. This approach enhances energy efficiency, supports renewable energy adoption, and provides cost-effective management, as pursued by the in-force European directives about the energy performance of buildings [9]. ESCOs offer comprehensive energy solutions, including audits, retrofitting, and performance contracting, ensuring the implementation of energy-efficient technologies. They invest in energy-saving measures, mitigate financial risks, and guarantee returns through reduced consumption costs. The collaboration between ESCOs and aggregators creates a flexible, dynamic energy management ecosystem, significantly reducing greenhouse gas emissions and fostering sustainable energy infrastructure [10–12].

Present energy performance contracts usually lack a fair and robust methodology to measure service performance, and just aim at setting fees that allow consumers to enjoy economic savings while ensuring a reasonable payback of the investments made. Pay-for-Performance contracts differ significantly from traditional ESCO models by aligning incentives with measurable performance outcomes through adequate Performance Measurement Verification (PMV) protocols based on the use of abundant energy and non-energy data flows [13]. Linking service performance with service payment is a fairer and more acceptable business approach for end users than the usual EPC practice. These P4P contracts not only focus on energy savings, but also integrate non-energy benefits such as improved indoor comfort and air quality. These additional benefits are pivotal in engaging building occupants and enhancing the overall acceptance and effectiveness of these services. As highlighted by studies, the inclusion of non-energy benefits can significantly increase the perceived value of energy efficiency measures, thereby boosting participation and satisfaction among building occupants [14]. By leveraging low-cost data collection systems and advanced analytics, ESCOs can offer a combination of revenue streams stemming from informed decision-making, energy management optimization, and participation in demand response schemes. For example, smart thermostats and automated HVAC systems can adjust energy use in real time based on occupancy patterns and external temperature forecasts, resulting in significant energy savings and enhanced occupant comfort [15,16]. Additionally, these technologies enable buildings to act as flexible resources in the energy grid, providing services such as peak load reduction and frequency regulation, which are increasingly valuable in a renewable energy-dominated grid [17].

In the pursuit of highlighting current state-of-the-art energy services for buildings, a comprehensive search was conducted using the Scopus database. All documents up to the end of 2023 were extracted, using the following query [18]: TITLE-ABS-KEY ("energy service*" AND "building*") AND (EXCLUDE (PUBYEAR, 2024)). This search yielded a total of 796 documents, which were then analyzed following the methodology described in [19], using VOSViewer version 1.6.20 software. From these documents, 5468 keywords were identified, and the 39 most frequently occurring keywords (those appearing at least 30 times) were mapped (see Figure 1).

The literature map reveals key areas in energy services for buildings, emphasizing the interconnectedness of energy efficiency, management, utilization, and conservation. At the core is energy efficiency, which is closely linked to energy management, conservation, and utilization. These elements are further supported by the integration of smart technologies and advanced building equipment, reflecting the roles of ESCOs (energy service companies) and aggregators. The map identifies three main clusters: ESCOs, aggregators, and environmental concerns.

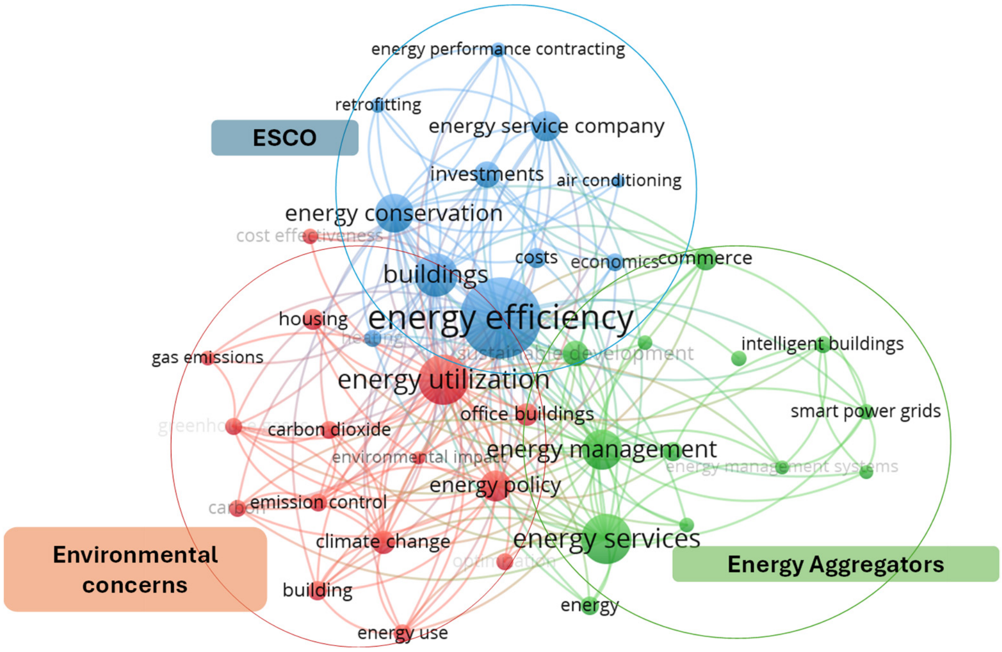


Figure 1. Most co-existing keywords on energy services and buildings.

Economic factors, costs, and investments are critical for the adoption of ESCO solutions and energy performance contracting in retrofitting and improving building energy efficiency. The blue cluster focuses on ESCOs, centring on keywords such as "energy efficiency", "buildings", "investment", "costs", and "retrofitting" and efficient systems like heating and air conditioning. The presence of "energy performance contracting" on the periphery indicates limited implementation in ESCO projects. In this regard, prominent studies that have demonstrated a high impact, especially by their high levels of citation, include surveys related to EPC that revealed the impact of policies to execute EPC, especially in public buildings [20], a simulation-based decision model for establishing a contracting period in building EPC [21], energy conservation opportunities through EPC [22], and partnership in building EPC [23]. However, these high-impact documents are not empirically and experimentally assessed.

In the open literature, in-depth reviews of ESCOs and buildings also exist that address various aspects such as financing instruments for residential energy renovations [24], energy flexibility readiness in buildings [25], the SWOT approach on ESCOs [26], challenges in and perspectives on upscaling energy control [27], institutional and financial barriers in developing countries through super ESCOs [28], sustainable models for fostering local economic development [29], and energy management tools for facility managers [30]. Notably, non-energy aspects such as comfort do not appear on the map, highlighting a clear knowledge gap in this area.

User engagement, decision-making, intelligent buildings, and smart power grids are crucial for optimizing energy use and integrating renewable energy sources [31]. The green cluster highlights the role of energy aggregators, showing connections between "energy services", "energy resources", "energy management", and "sustainable development". Keywords related to demand response activities, such as "smart grid", "electric utilities", and "decision-making", are also significant in this cluster.

In the literature, the study of the energy aggregator role has focused on business model analysis [32], cost–benefit structures, and the development of optimization models for distributed resource arbitrage, typically from prosumers [33,34]. These models often aim to maximize aggregator profits through participation in electricity markets and green energy certificate trading [35]. The current research focuses on integrating flexible assets that may exist in residential or service-oriented environments. Some authors have designed rescheduling strategies for appliances to provide flexibility to the distribution grid [36], while others propose consumer management models for the aggregator based on the buildings owner's level of commitment [37]. However, the actual behaviour of users in accepting these modifications or even increasing load shifts beyond those suggested by the aggregator in pursuit of economic incentives remains an area under investigation. Thus, consumer response in a real environment represents a clear knowledge gap in the literature.

Sustainable development and environmental impacts, including emission control and climate change mitigation, are integral to energy efficiency goals. The red cluster focuses on addressing environmental concerns, emphasizing "energy utilization", "energy policy", "environmental impact", and "emission control" through reduced carbon dioxide and other greenhouse gasses. However, the literature map predominantly features "office buildings", with a notable absence of residential buildings, indicating a gap in the literature that warrants further investigation.

Considering the above literature review, this paper focuses on five main knowledge gaps relevant to ESCO-based energy services. First, despite the recognized importance of energy performance contracting, there is limited real-world application, especially in low-input ESCO projects. Second, much of the existing work overlooks residential buildings, focusing predominantly on office buildings, an omission we address by implementing our approach across multiple building typologies, including residential sites. Third, Pay-for-Performance (P4P) models for ESCOs often remain at the theoretical level (e.g., simulation and survey-based studies) rather than being empirically and experimentally validated. Fourth, non-energy aspects like comfort and air quality, crucial for fostering user engagement and satisfaction, are rarely examined in the literature. Finally, by testing the feasibility of these advanced energy services in real-world demonstration sites, our study provides much-needed empirical evidence and insights, thereby helping to close these gaps and bolster practical understanding of how ESCO projects can succeed in diverse residential and commercial contexts.

1.2. Scope and Objectives

This paper evaluates the deployment of the abovementioned smart energy services for energy service companies/contracts (ESCOs) in buildings by analyzing a set of metrics evaluating user profiles, building type, and equipment. The design and proposal of the smart energy services and business models were previously developed and published [13]. We demonstrate the technical and economic performance of a set of data-driven energy efficiency, flexibility, and non-energy services through empirical testing in pilot buildings in Spain, Croatia, and Greece. The study contrasts the performance of those services in residential buildings in Spain (building block of apartments), Croatia (detached houses), and a commercial building in Greece (hotel bungalow). We assess self-consumption savings, behaviour change-driven savings, and remuneration from the delivery of explicit demand response (DR) coming from the automatic operation of electric heating and cooling for grid operators. Additionally, we examine non-energy service results like improved indoor comfort preservation and air quality monitoring for health and well-being.

2. Materials and Methods

To execute the project activities and structure of this study, we followed a step-by-step methodology, which is visually outlined in Figure 2. Initially, we conducted a comprehensive review of "smart energy services" in buildings, covering both market perspectives and practical applications. This was essential to set a contextual foundation. The next stage involved the critical "selection of demonstration sites", which was integral for hands-on application and data-driven insights. We selected three distinct sites characterized by variations in building type, user profile, location, and climate, enriching the research with diverse scenarios and meaningful contrasts. For evaluation, we proceeded with the "selection of metrics", focusing on both implicit savings derived from well-informed behavioural changes as well as energy and non-energy performance indicators. To facilitate accurate evaluation, we developed a tailored "system architecture" with a structured data collection protocol for effective assessment and interpretation. With the methodology established and executed, we synthesized key insights from empirical data, highlighting the lessons learned throughout the process.

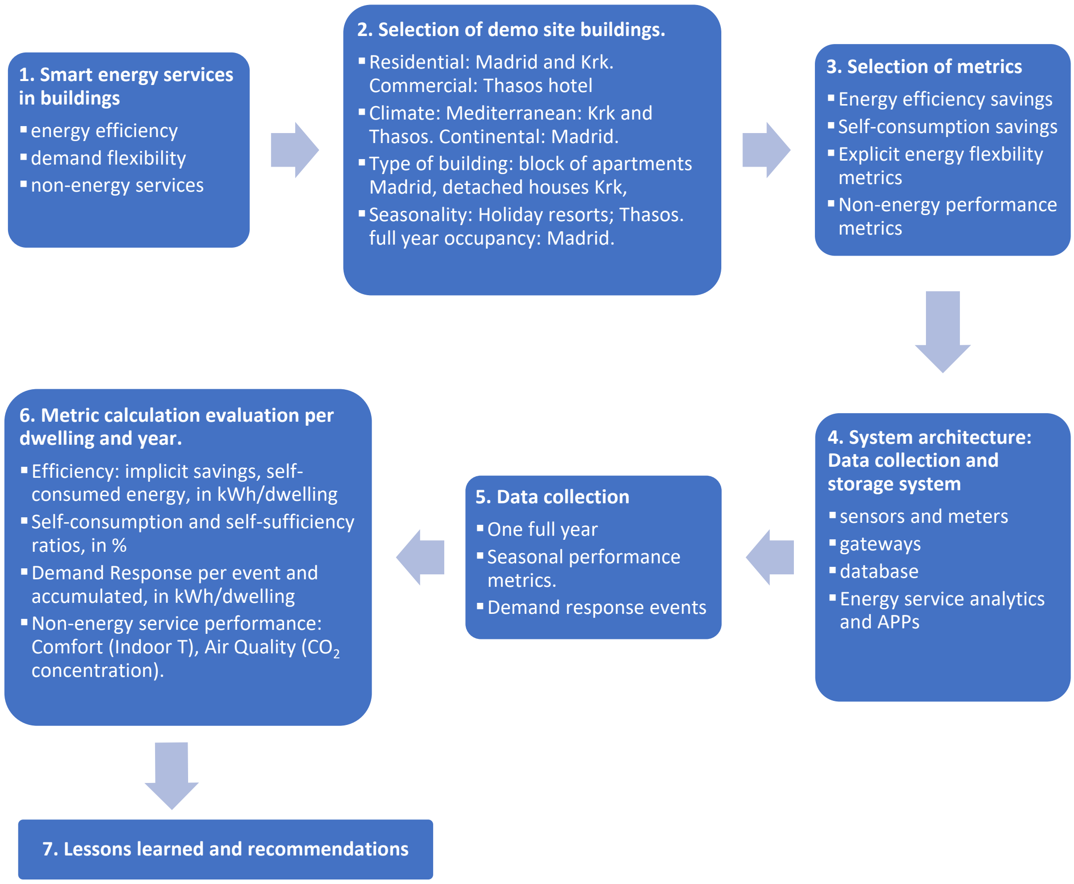


Figure 2. Flow chart methodology.

2.1. Type of Smart Energy Services and ESCO Business Models

In general terms, many residential buildings are not ready for deploying advanced digital services for energy management, nor do these buildings' occupants seem to be, either from an aptitude or an attitude standpoint [13]. Leading the energy efficiency battle should be put in the hands of qualified professional companies that can deliver solutions and energy management protocols to guide the joint effort of building residents as energy consumers. Energy Performance Contracting (EPC) has been extensively used by the private sector as a tool to improve energy performance [38]. However, many ESCOs do not find the residential sector attractive due to relatively low per-dwelling consumption and the difficulties inherent to managing energy demand in every energy-consuming unit (dwelling) [39,40]. Effective and low-cost energy management consists of using the metering and comfort data generated by the buildings to facilitate decision-making and provide useful analytics to energy managers and building occupants to improve energy performance [41]. Figure 3 shows the three main categories of energy services and the different data-driven energy services developed and tested in this study.

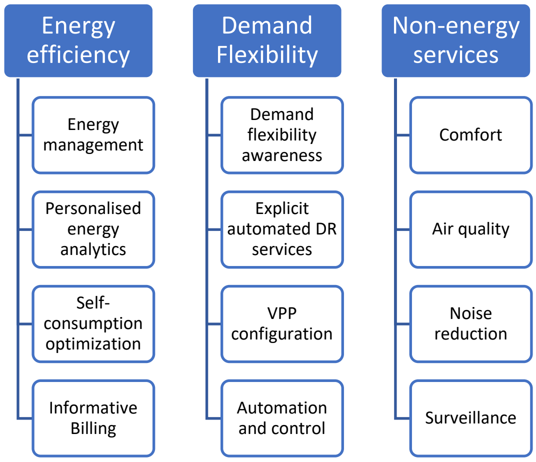


Figure 3. Smart energy services categorized in three innovative ESCO business models.

In order to create more attractive businesses models for ESCOs, several revenue streams may be claimed from a set of standard data-driven energy services deployed in a large number of dwellings and buildings [13]. These revenue streams encompass several types of services delivered simultaneously and using the same data sources (See Figure 4):

- Savings derived from smart energy efficiency services. This category includes historic and real-time energy consumption monitoring, informative billing, KPI calculations, personalized energy analytics, and self-consumption optimization;
- Revenues derived from the participation in demand response markets to deliver demand flexibility to grid operators. This category includes smart contract proposals and signing, Virtual Power Plan (VPP) configuration, automated triggering of flexibility events and flexibility measurement, and verification and settlement;
- Revenues derived from possible non-energy services. This category includes other value-perceived services such as comfort preservation, air quality monitoring, noise reduction, surveillance, and other non-energy services that users are willing to pay for.

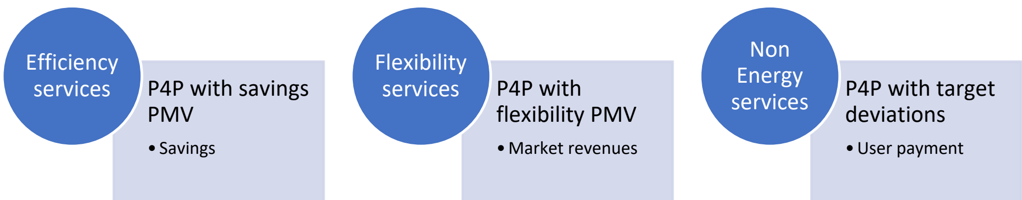


Figure 4. Revenues and economic benefits obtained from each category of energy services.

The addition and combination of as many smart services as possible increase the revenue streams and shorten the paybacks of the investment needed to put in place the data capturing, transfer, and storing infrastructure that is needed at each building dwelling. However, present Energy Performance Contracting (EPC) is widely implemented in industrial and commercial buildings with higher and more predictable energy demands, but it is hardly used in the residential building sector due to lower demand and higher market fragmentation leading to rising transaction costs [38]. The metering data and a specially tailored Protocol of Measurement and Verification (PMV) supported by the continuous real-time metering data flow would make it possible to measure performance for every one of the service offerings. The payment to the service provider should be made on the basis of the performance registered under a clear and comprehensive Pay-for-Performance (P4P) approach [13].

The proposed approach also considers the diverse profiles of users and the varying readiness of buildings to adopt such technologies. The success of these innovative business models for ESCOs in buildings depends significantly on user profiles, building equipment, and the smart readiness of buildings. Active participation of building residents is essential for realizing the full potential of these services [8]. Empirical testing in pilot buildings across different geographical locations can assess the technical and economic viability of these services and highlight the impact of citizen engagement and building suitability on the outcomes of smart energy services.

2.2. Selection of Demo Sites

For the evaluation of the energy services, three distinct pilot sites were selected, each varying significantly in context and approach (See Figure 5). The best-endowed buildings for the mentioned energy services should be fitted with PV facilities and large electric demands from HVAC and Domestic Hot Water (DHW). Heat pumps offer a unique chance to funnel and control HVAC and DHW dwelling demands in an efficient way [42], either by using dedicated submetering equipment or by using Non-Intrusive Load Monitoring (NILM) techniques [43]. The first pilot site, located in Madrid in Spain, is a high-efficiency apartment building with permanent residents. This building features individual dwelling demands and a centralized shared PV facility with comprehensive energy management and detailed data collection. The second pilot site, on Thasos Island in Greece, is a seasonal resort. Here, the focus is on energy management through PV systems and battery energy storage systems (BESS), employing centralized control with minimal guest involvement, due to the transient nature of the population. The third pilot site, situated on Krk island in Croatia, consists of detached holiday houses with occasional occupancy, leading to the implementation of simpler systems with lower data availability. Each site is tailored to its specific climate, occupancy patterns, and energy management requirements.

Figure 5. Location of the demonstration sites of this study.

2.3. System Architecture and Data Collection

To evaluate the feasibility of the smart energy services proposed for ESCOs, pilot data were collected and managed following the high-level approach presented in Figure 6.

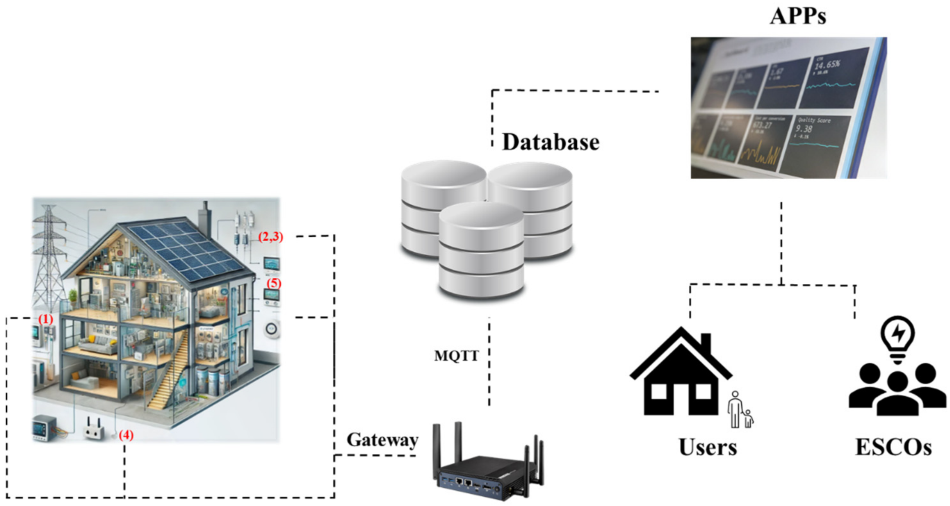


Figure 6. High-level approach for data collection and management for business model demonstration. (1) electricity meters, (2,3) actuators–smart relay, (4,5) sensors.

Energy-related equipment such as (1) electricity metering, (2,3) actuators–smart relay power control, (4), and (5) sensors such as indoor temperature and humidity and air quality, were installed in each pilot site and the data were collected via Wi-Fi through the gateways at every dwelling. Data transmission from the gateways was facilitated using Message Queuing Telemetry Transport (MQTT) communication protocols to an external database for data ingestion and storage. Data cybersecurity attacks were avoided using Secure Sockets Layer certificates and encryption. Finally, data retrieval from the databases was conducted through API requests, called by the different energy service applications (APPs) developed for this purpose. Two separate Graphic User Interfaces (GUIs) allowed data visualization for building users on one side and for energy service suppliers (ESCOs/aggregators) on the other.

2.4. Selection of Metrics and Evaluation

A comprehensive set of metrics was selected to evaluate the impacts of the smart energy services in the demo site buildings, encompassing energy efficiency (final and primary energy savings), self-consumption savings, energy flexibility, non-energy metrics (comfort, air quality), economic metrics (investment, payback periods), and environmental metrics (CO_2 savings), as described in Table 1.

National ratios are used to calculate CO_2 emissions [44] and primary energy [45] from the final energy balance. Bidirectional metering provides data for grid Import (energy shortfall) and Export (energy surplus), while energy generation (Gen) is also metered. Self-consumed energy is the difference between the energy generation and the energy surplus (exported). The self-consumption ratio (See Equation (1)) is the ratio of self-consumed energy to generated energy in the period. The self-sufficiency ratio (See Equation (2)) is calculated as the ratio of self-consumed energy to the total electricity demand in the period. Demand is the result of the grid balance (imports−exports) plus the energy generation.

$$Selfconsumption\ \% = \frac{(Gen - Export)}{Gen} \tag{1}$$

$$Selfsufficiency\ \% = \frac{(Gen - Export)}{(Import - Export + Gen)} \tag{2}$$

Both ratios are very dependent on seasonality. In the case of demand response services, a number of flexibility events were performed on the HVAC equipment of some

Madrid dwellings (reverse heat pumps with on−off smart control) and the results were extrapolated to a full year's time. At present, energy flexibility markets are not still open for aggregation and the economic assessment was estimated based on energy market prices and the literature review [46].

Table 1. Assessment metrics measured at each demonstration site.

Type	Variable	Measurement Equipment	Units
Energy efficiency	Final energy savings Primary energy savings	Energy metres per dwelling	kWh/dwelling/year kWh/dwelling/year
Self-consumption	RES generation Self-consumed energy	Energy metres per PV facility	kWh/dwelling/year kWh
	Self-consumption ratio Self-sufficiency ratio	Estimated	% %
Energy flexibility	Energy flexibility per event	Energy metres per flexible asset	kWh/dwelling/event
	Energy flexibility per year	Estimated	kWh/dwelling/year
Non-energy metrics	Indoor temperature	Indoor temperature sensor	Degrees Celsius
	CO_2 concentration	VOC sensor	ppm
Environmental metrics	CO_2 savings	Estimated	Kg CO_2/dwelling/year
Economic metrics	Investment	Real installation cost	€/dwelling
	Energy savings	Estimated	€/dwelling/year
	Flexibility remuneration	Estimated	€/dwelling/year
	Payback period	Estimated	years

2.5. Testing Methodology

Prior to the testing phase, a smart readiness assessment of the initial situation of the buildings was conducted to determine the gap between the data availability and the digital service technical requirements to ensure the successful deployment of the P4P energy services described above. This gap resulted in an inventory of data-capturing and metering devices that were installed at each dwelling, along with the data gateways and HVAC actuators. A full year of data collection was registered to capture seasonal variations. Demand response market signals were artificially sent to schedule short events in which to test the explicit energy demand flexibility of HVAC systems in winter and summer. Automatically triggered events were run to measure the energy shifts and verify the delivered flexibility during the event, following a well-structured Performance Measurement and Verification (PMV) protocol [13]. This hybrid protocol also establishes the energy baseline that is used to assess the performance of the energy efficiency services. The data were analyzed regularly and the annual lump sums and KPI per dwelling are reported in the following section. Building occupancy and equipment constrained the full testing of all the smart services. The seasonal occupancy of the hotel jeopardized testing in winter, but the presence of the Battery Energy Storage System (BESS) made this location the only place where it was suitable to test the smart battery charging management module. On the other hand, the continuous occupancy of the dwellings in Madrid enabled full-year testing of the demand response services, which was partially hindered in Thasos and not conducted in Krk.

3. Results

This section summarizes the overall results of the smart energy service deployment and testing on an annual basis, and the calculation of the selected performance metrics per dwelling and per year at each demonstration building.

3.1. Annual Verified Energy Savings

Figure 7 presents the evolution of energy savings in the period of testing obtained from the demo site building in Madrid. The baseline energy consumption (blue line) represents the building's estimated usage, derived from historical data and outdoor temperature as a main variable. In contrast, the actual consumption (orange line) reflects the values recorded through smart electricity metres during the testing period, showing close alignment with the baseline projections. The actual metering difference from the baseline reflects the effective energy-saving measures when the flexibility events were triggered using the HVAC systems. From the results, it is evident that during the period with low energy demand (heating/cooling), analytics events have less impact on energy savings (e.g., during March and April). In contrast, when there is high energy demand, applying the analytics events can lead to more significant energy saving, evident in cold winter and hot summer periods. From the demo site, verified energy savings of 6.9% were registered, with economic savings of 54.18 €/year/dwelling corresponding to the behavioural change in the energy analytics recommendations. It is worth noting that this low energy saving is due to the characteristics of the building (new building, well insulated, with a great energy management system), and that in buildings with poor thermal characteristics, more savings from flexibility events are expected. Nevertheless, when these savings are considered at building level, the total verified energy saving becomes more significant, reaching 3832 kWh/year.

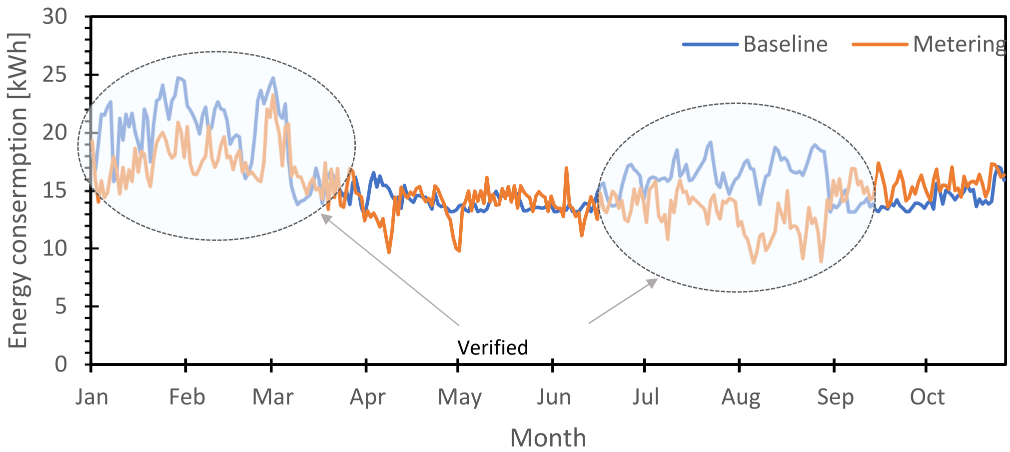


Figure 7. Energy performance verification for half the year in the Madrid demo site building.

3.2. Annual Self-Consumption Energy Savings

Figure 8 shows the monthly self-consumption and self-sufficiency ratios for Madrid from October 2022 to September 2023, the period during which the total energy demand was 3268 kWh/dwelling/year. The Madrid building features two PV-generation facilities of 15 kWp each, serving 17 dwellings and generating a total of 3312 kWh/dwelling/year. Self-consumption ranged from 27.2% to 71.1%, peaking in winter, indicating the higher use of the scarcer self-generated energy during winter, due to higher heating demands and lower generation. Self-sufficiency varied between 20.9% and 58.5%, with the highest levels in summer, reflecting the higher solar energy generation rate during summer. These results demonstrate the building's capacity to optimize energy use across different seasons, enhancing performance particularly in winter months. The self-consumption optimization service prompts users to shift consumption at high availability times and reduce them at low generation times. During the period of testing, self-consumed energy per dwelling was registered as 1344 kWh/dwelling/year, corresponding to 377 €/dwelling/year, which represents 41.1% of the total demand. However, adding these cost savings to the verified savings of the energy-personalized analytics service, the total energy savings from the grid in this demo site building amounted to 48% of the building's demand.

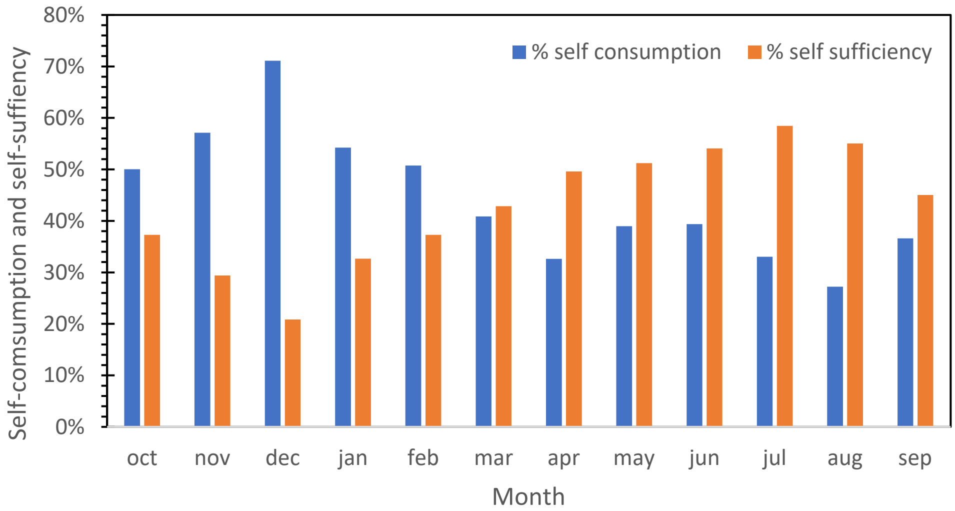


Figure 8. Energy self-consumption and self-sufficiency ratios (Madrid demo site residential building, 2022–2023).

The five-room bungalow on Thasos Island is supplied by a 17 kWp PV facility, which generates 2527 kWh/room/year, and an 8.3 kWh lithium-ion battery with a useable capacity of 7.8 kWh and a max charge/discharge power of 2.6 kW. Figures 9 and 10 illustrate the self-consumption and self-sufficiency ratios of the demo site from October 2022 to September 2023, the period during which the total energy demand was 1743 kWh/room/year, comparing scenarios with and without battery storage. It is worth noting that it is during the period that the bungalow is in service (from June to October) that the energy demand is significant. Focusing on performance without battery, Figure 9 showcases self-sufficiency ranging between 18% and 37%, while self-consumed energy ranges between 7% and 47%. It is evident that while self-sufficiency is more stable, self-consumed energy during the period is more dispersed. These results reflect the effective use of PV generation during the peak operational months (May to September) and highlight its strong seasonal influence on energy performance. The findings demonstrate the need for efficient energy management, especially in cases without battery support, indicating the importance of optimizing self-consumption during the resort's active season despite low winter demand.

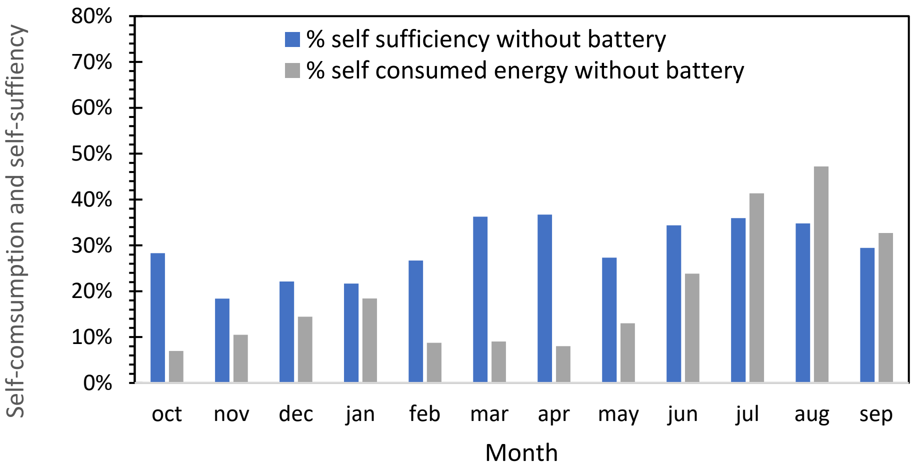


Figure 9. Self-sufficiency and self-consumed energy without battery (Thasos Island demo site bungalows, 2022–2023).

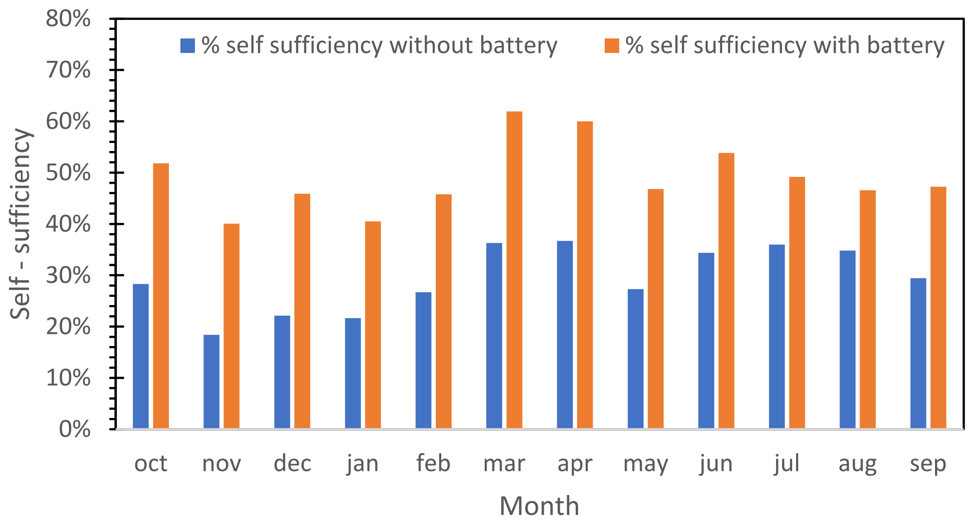


Figure 10. Self-sufficiency without battery and self-sufficiency with battery (Thasos Island demo site bungalows, 2022–2023).

Figure 10 compares the self-sufficiency ratios with and without battery storage, showing that integrating batteries significantly enhances self-sufficiency rates, particularly during high-solar-generation months. Without a battery, self-sufficiency ranged from 18% to 37%, whereas with a battery, self-sufficiency improved to between 40% and 62%, with peaks in March and April. The battery's role in storing excess solar energy generation reduces reliance (by up to 20%) on external energy sources and enhances overall energy independence, effectively aligning with the resort's seasonal operation. This combined approach addresses occupancy fluctuations and further stabilizes energy performance throughout the year.

Figure 11 presents the self-consumption and self-sufficiency ratios for dwelling 5 on Krk Island from October 2022 to September 2023, the period during which the total energy demand was 86,156 kWh/dwelling/year, with an 8 kWp facility shared among seven detached houses that generates 10,546 kWh/dwelling/year. Self-consumption reached its highest level at 70% in December, primarily due to increased heating demands during winter, combined with low generation rates. However, the annual self-consumption rate is only 13.9%, due to a weak demand from May to November as a result of the high seasonal usage of these buildings. Self-sufficiency is also low throughout the year (12%), varying between 8% and 20%, with peak values observed in the summer months, particularly in July and August. These results highlight several combined issues: a low self-consumption rate due to the regulated incentives of energy sales to the grid (86% of the energy is poured into the grid) and the seasonal mismatch between energy generation and demand on Krk Island, where winter conditions drive high consumption despite low solar generation, while summer periods feature abundant solar generation but lower energy demand. These seasonal dynamics underscore the need for improved flexibility and the adoption of storage solutions to better align the energy supply with demand throughout the year.

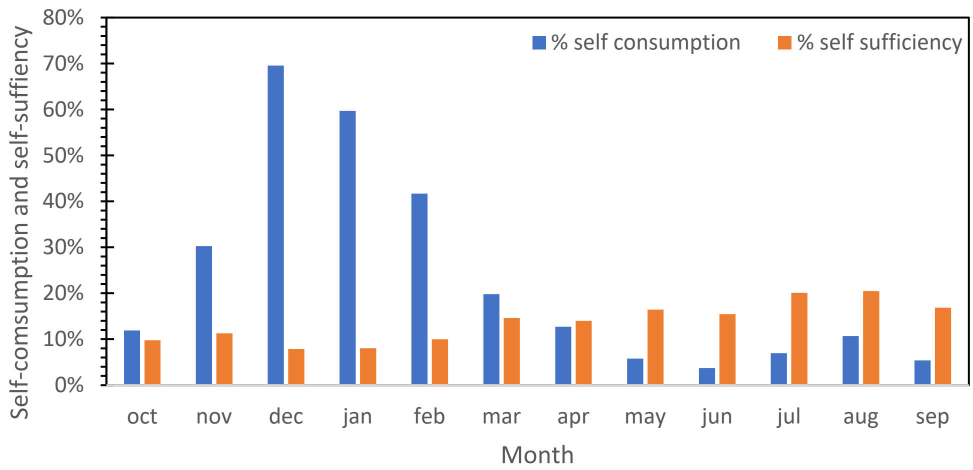


Figure 11. Self-consumption and self-sufficiency (Krk Island demo site detached houses, 2022–2023).

3.3. Demand Response Results

Several automatic demand response events were triggered in the dwellings of the Madrid demo site building, acting upon the on–off control of the reversible heat pumps of the dwellings (details in Table 2). Flexibility availability is thus subject to the use of this demand in the dwellings, estimated at 72 days in the summer period (cooling demand) and 96 days in the winter period (heating demand). Successful events delivered an average energy shift of 0.6 kWh per event in winter, with an average remuneration of 0.42 €/event and 0.3 kWh per event in summer, involving an average remuneration of 0.21 €/event. Flexibility is potentially available for 38% of the events in summer and 75% of those in winter. About 50% of the events fail to deliver the committed flexibility, resulting in a penalty of 0.15 €/event.

Table 2. Demand Response test parameters and test results for winter and summer seasons.

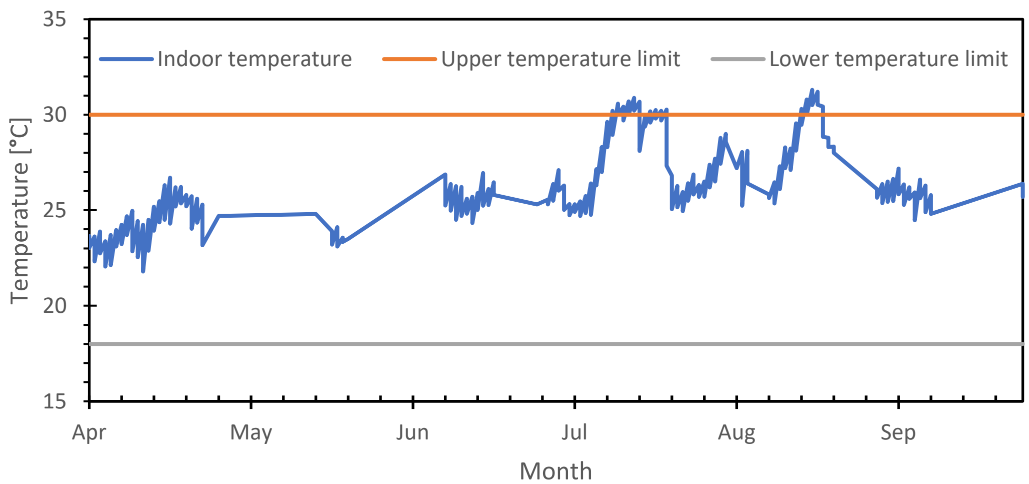
DR Test Parameters and Results	Units	Winter (Heating)	Summer (Cooling)
Average energy flexibility per successful event	kWh/event	0.6	0.3
Average energy flexibility per failed event	kWh/event	0.4	0.4
Average remuneration per successful event	€/event	0.42 €	0.21 €
Average penalty	€/event	0.15 €	0.15 €
Average cases with penalty	%	50%	50%
Flexibility days per season	days	96	72
Available dwellings with flexibility	%	75%	38%
Number of events per day	events/day	4	4
Number of events per year	events/year	288	108
Total time in events (15 min events)	hours/year	72	27
Annual energy flexibility per dwelling	kWh/year/dwelling	115.2	10.8
Annual flexibility retribution per dwelling	€/year/dwelling	99.4 €	14.6 €

With these empiric test results, a conservative extrapolation of results was performed to extend the results to a full year of continuous service, with an average of 4 short 15 min events per day (to avoid comfort issues and user dissatisfaction linked to long and frequent HVAC operations). This is close to 400 events/year and 100 h/year of external automatic operation of the HVAC system at each dwelling. Based on these assumptions, the total demand flexibility available from each dwelling's HVAC is 126 kWh/year, and the total remuneration deducting penalties is 114 €/year per dwelling. In Thasos, the bungalows are occupied only in summer, thus reducing the demand flexibility to the cooling system in the warmest months of summer. This reduces the annual energy flexibility to just 10.8 kWh/year per room, which results in a retribution of 15 €/year per room. The demand flexibility test hypothesis and test results are shown in the table below.

3.4. Non-Energy Service Performance

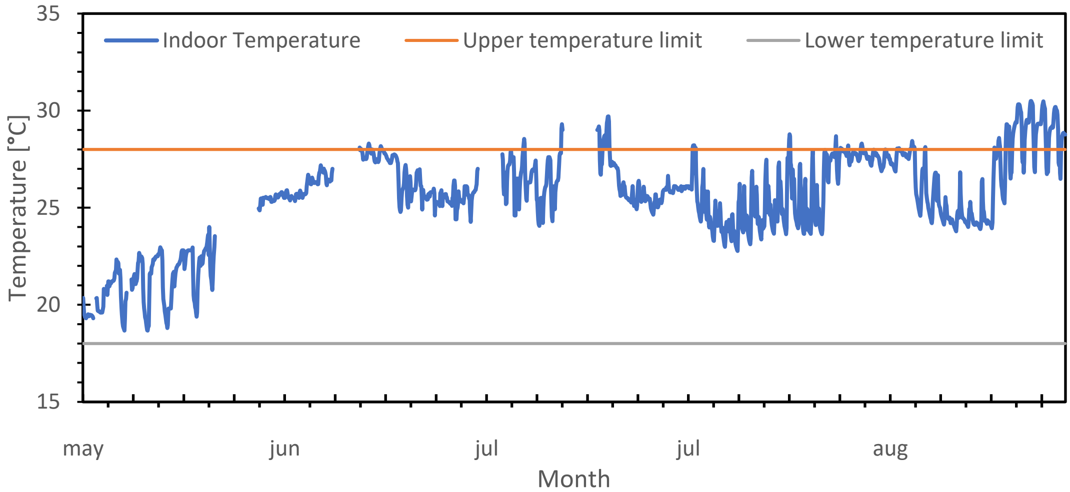
Although a variety of non-energy services can be offered with the installed hardware and software infrastructure (noise control, surveillance, flooding or fire prevention, and early warning), comfort (through indoor temperature monitoring) and air quality (through CO_2 concentration monitoring) were tested in Madrid and Thasos. Figure 12 shows indoor temperature monitoring in Madrid and Thasos as part of the Comfort Preservation Service. The service was not automatic and depended on users' reactions to the alarms and recommendations. In Madrid, indoor temperatures exceeded comfort limits for 4.5% to 11.7% of hours in different apartments, while in Thasos, the range was from 6% to 10% in the five rooms, mainly during the warmest months. In Thasos, higher temperatures coincided with room vacancy, indicating reduced control during unoccupied periods. Alongside temperature control, the service also improved health and well-being through air quality management. Despite occasional deviations, the service effectively balanced comfort and grid demand objectives.

CO_2 concentrations were recorded hourly and reported in Figure 13, with the worst daily values stored and analyzed against the following predefined air quality scale: excellent (<65 ppm), good (220 ppm), moderate (660 ppm), and poor–unhealthy (>2200 ppm). The results shown in Figure 14 highlight the distribution of days based on the maximum hourly CO_2 levels across the year in the Thasos bungalow. Significant hourly fluctuations were observed, particularly between late February and early May, with peak concentrations occurring in mid-March, mid-April, and early May. These surges, representing short-term episodes, contributed to 11.0% of days reaching the poor air quality category and 1.5% falling into the unhealthy range. However, the average daily CO_2 concentration was 187 ppm, with an average daily maximum of 496 ppm, indicating that these spikes were isolated and did not substantially impact the overall air quality. Throughout the year, most days recorded moderate (49.3%) or good (33.8%) air quality levels, while excellent air quality was noted on 4.4% of days. The data confirm that while occasional poor or unhealthy air quality events occurred, the overall air quality remained predominantly stable and within safe limits, as reflected in the daily averages.



(**a**)

Figure 12. *Cont.*



(**b**)

Figure 12. Comfort service; sample of indoor temperature control at pilots in (**a**) Madrid and (**b**) Thasos.

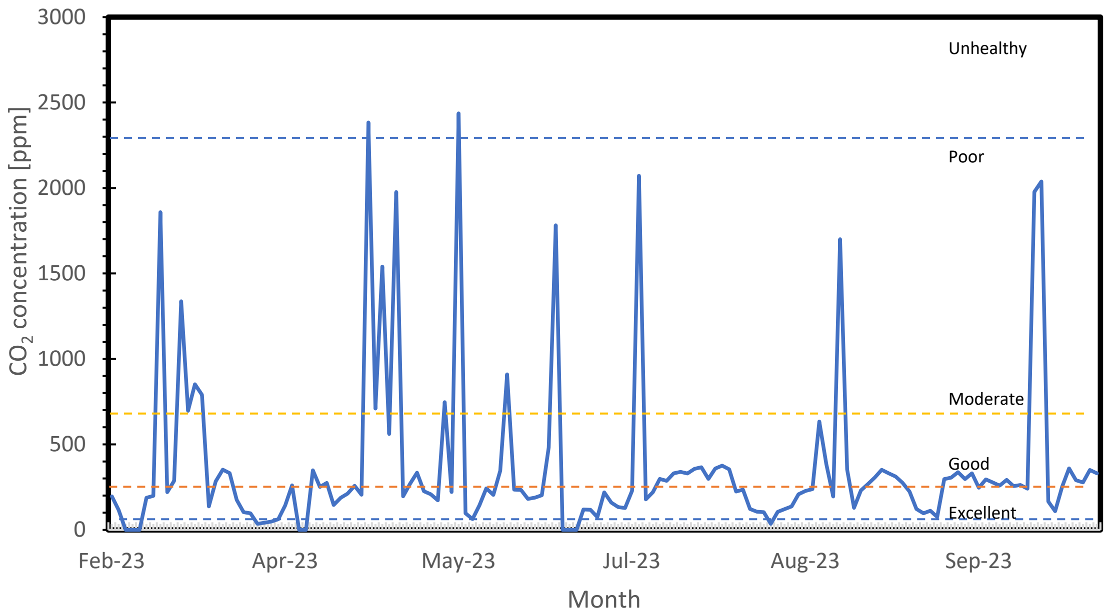


Figure 13. Comfort service; sample of CO_2 concentration records in Thasos bungalows.

3.5. Economic Assessment

The data capturing system at each dwelling includes the necessary sensors, metres, smart actuators, and data gateway described in the System Architecture and Data collection section, and the onsite installation by qualified personnel. All buildings had an initially low smart readiness index. Installation costs depend on site accessibility and the number of revisits due to the unavailability of the dwelling residents, technical difficulties, and post-installation maintenance visits. The average cost per dwelling was 723 € per dwelling, ranging from the 605 €/room in Thasos and the 886 €/dwelling in Krk. Thasos and Krk are remote locations with limited access. Installation at the hotel premises (Thasos) was efficiently carried out in one attempt by its own maintenance personnel, while the variety of houses in Krk required many visits per dwelling to successfully complete installation.

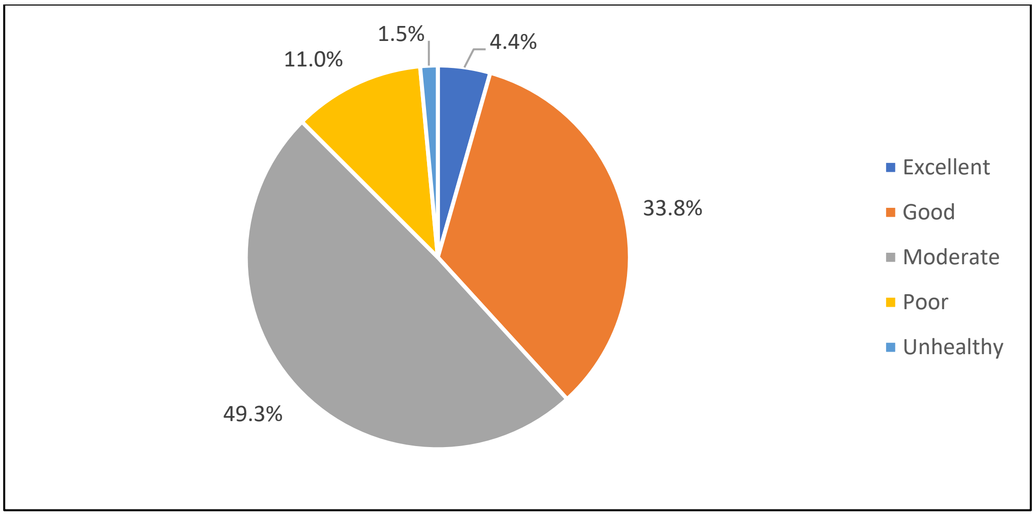


Figure 14. Distribution of indoor air quality days during the testing period in Thasos bungalow.

The seasonality of the hotel usage profile hinders the possibility of reaching high revenues, as all the energy savings are limited to the summer period, with low cooling demands in mild weather conditions. The total revenues of the advanced energy services are 476 €/year per room, of which 17% comes from the optimal use of the battery energy schedule and only 3% is derived from the potential participation of the cooling demand in explicit demand response schemes. The savings in Madrid amount to 960 €/year per dwelling and are the result of the aggregation of multiple services: self-consumed energy (48%), PV surplus sales (35%), behavioural change recommendations (6%), and demand flexibility (12%). The case of Krk might be misleading, as these buildings report the highest revenues (1294 €/y per house), but 76% of them come from the PV energy sales that are prioritized over self-consumption, due to regulation incentives. Self-consumption is only 15% of the revenues and the estimated potential participation in explicit demand response markets amounts to 9% of the incomes. These results highlight how energy incentives can shape the direction of energy-saving strategies, influencing whether efforts prioritize increasing self-consumption or optimizing on-site economic benefits through enhanced energy sales.

The payback periods for the necessary investment range from Madrid's low of 2.5 years to Thasos' high of 9.3 years. The calculation of this payback also takes into account the investment made in the generation and storage equipment for a fairer assessment. In any case, these payback periods are all below the 10-year period of the average ESCO contracts, usually signed in the residential sector. A summary of the economic metrics at each demo site building is shown in Table 3.

Table 3. Economic metrics at each demo site building in €/year per dwelling/room.

Metric	**Madrid Demo Site**	**Thassos Demo Site**	**Krk Demo Site**
Investment per dwelling (€)	677 €	605 €	886 €
Annual incomes for energy efficiency services and self-consumption (€/year)	960 €/y	476 €/y	198 €/y
Annual incomes for demand response services (€/year)	114 €/y	15 €/y	-
Payback time efficiency services (years)	3.1	9.6	7.5
Payback time efficiency + flexibility (years)	2.5	9.3	-

3.6. Comparative Overview of the Results in the Three Demonstration Buildings

Table 4 summarizes the key results obtained from the three project demonstration sites: Madrid, Thasos, and Krk. The table includes essential aspects such as annual final and primary energy savings, self-consumption and self-sufficiency ratios, and demand response services. This comparison provides a comprehensive overview of the performance of each site in relation to the established objectives. Although results are given per year and per dwelling (per room in the case of the Thasos bungalow), straight comparisons should consider that dwellings or rooms may differ in size, occupancy, seasonality, and climate. Dwellings are the smallest consuming unit and have an allocation of shared PV generation. Krk's dwellings are the largest (incentivized for selling to the grid), whereas Thasos' bungalow rooms obtain the highest energy savings due to a large PV facility supported with batteries, whose charge is optimized by a PV optimization algorithm. The application produces a daily battery charging strategy based on battery status, PV availability, demand forecast, and hourly energy prices to save energy and minimize supply costs. The service was only tested in Thasos, as it was the only demo site with PV and storage assets. From the last week of May to the middle of October (the whole holiday season), the service predicted additional energy savings of 2524 kWh/year, meaning an additional 29% of savings on top of the self-consumption savings (49%). The largest savings in absolute terms were recorded in the Madrid demo building dwellings, despite the small size and the good quality of the building envelope. The reason for this is the fairly high HVAC consumption of a continuous occupancy in a continental climate. Savings from self-consumption amounted to 41%, while savings from implicit energy management recommendations were estimated to be 7% of the annual demand. Krk's large PV production does not align in time with consumption, being inversely distributed with high consumption peaks in winter, matching low generation rates. In summer, the distribution is just the opposite. In this site, the low participation of dwellers in other efficiency recommendations and the lack of historic data to set up an adequate energy baseline to verify further savings limited the energy savings to those coming from the low self-sufficiency rate.

Table 4. Summary of the main energy performance indicators in the three demonstration buildings.

Metric	Units	Madrid	Thasos	Krk
Dwellings	Number	17	5	7
Final energy demand	kWh/y/dwelling	3268	1743	12,308
Final energy savings	kWh/y/dwelling	1569	1353	1468
Primary energy savings	kWh/y/dwelling	4864	2549	2483
Energy efficiency improvement	%	48%	78%	12%
RES production	kWh/y/dwelling	3312	2527	10,546
Demand flexibility delivered	kWh/y/dwelling	126	10.8	-
Self-consumption ratio	%	41%	34%	14%
Self-sufficiency ratio	%	41%	49%	12%
GHG emission reduction	kWh/y/dwelling	584	1204	208

4. Discussion

This section showcases the main key findings from testing smart energy services across three demonstration sites. These insights are categorized into five key categories, which are further elaborated upon in the subsequent subsections: building suitability, building equipment, flexibility, user interaction, and smart services.

4.1. Building Suitability for Smart Energy Services

A significant challenge encountered was the heterogeneity of building characteristics and equipment within the European Union's residential sector. This diversity hinders the implementation of a unique smart solution applicable to all residential buildings. Preliminary site visits are crucial to understand the specific characteristics and needs of each household before planning installations. The continuous occupancy of dwellings enhances both efficiency and flexibility potentials. Conversely, seasonal occupancy diminishes these potentials and substantially extends the payback periods for smart energy services. This suggests that targeting permanently occupied residences may yield more favourable outcomes for energy service implementations.

4.2. Building Equipment

The successful deployment of smart energy services requires buildings to be equipped with electric heating, ventilation, and air conditioning (HVAC) systems and domestic hot water (DHW) systems. Electric DHW systems with water tank thermal storage have high potential for energy flexibility, but the challenges in controlling legacy equipment deem them unfeasible. Buildings lacking photovoltaic (PV) installations exhibit limited potential for energy services, as a significant portion of revenues are derived from self-consumption savings and their optimization. An inadequate understanding of existing energy systems and the building's smart readiness often leads to multiple visits to install data-capturing systems, escalating installation costs. Despite the relatively low per-building cost of these systems, a low initial Smart Readiness Indicator (SRI) and modest service revenues, particularly from flexibility, may prolong the payback periods.

4.3. Flexibility

A noticeable lack of interest among residents in participating in flexibility tests was identified, partly due to the current closure of flexibility markets in the testing countries. Additionally, residents exhibited a strong aversion to external explicit control of their HVAC systems for flexibility activation, resulting in low collaboration in energy flexibility testing. Participation in implicit energy efficiency measures recommended by the system was also low. Implementing a centralized operation managed by a community energy manager could enhance adherence to behavioural recommendations.

Energy flexibility associated with heating demand is greater than that with cooling demand. However, the financial returns from energy flexibility are significantly lower than the savings achieved through smart energy efficiency. Attempts to perform precise HVAC power control via temperature setpoints were unsuccessful on legacy equipment like heat pumps. The alternative on–off control method was intrusive and offered limited flexibility.

4.4. User Interaction

A common challenge is users' unfamiliarity with energy metrics in order to understand the parameters displayed by the user interface. While user manuals offer partial assistance, personalized support is critical during the initial deployment phase of smart services. Guests in holiday resorts showed reluctance to participate in energy-saving or flexibility events, something that can jeopardize the successful implementation of the services in this type of buildings. However, centralized monitoring and automation conducted by qualified hotel staff yielded positive results, especially in unoccupied rooms where guest comfort and preferences were not affected. This case highlights the challenge of reluctance of user participation, especially in commercial buildings and demonstrates the need to assign a dedicated individual as a remedy.

4.5. Smart Services

Developing energy management applications should prioritize user-friendly design to simplify the use of smart ESCO services, with open communication channels for user feedback. Despite the low cost and availability of data-capturing devices like sensors and metres, incompatibilities between different manufacturers' equipment highlight the need for standardizing device choices and adopting standard solutions. Moreover, careful planning during installation can reduce costs by minimizing the need for on-site revisits.

Commercial gateways are often proprietary and offer limited or no access to the internal code modifications necessary for developing new solutions. While they are recommended for use with equipment from the same manufacturer, they may present compatibility issues with devices from other manufacturers. Standardizing and utilizing common data collection equipment and gateways across all demonstration sites significantly simplifies equipment installation, maintenance, and commissioning, as well as the development of service applications.

Other challenges include the lack of historical data and poor correlation of independent variables for baseline construction in efficiency savings verification. In locations like Krk, the absence of historical digital metering made long-term energy efficiency baseline construction challenging. Similarly, in well-insulated buildings under mild climates like Thasos' summer, the low correlation between energy use and weather complicated the verification of efficiency savings.

From the findings, summarised in Table 5, it is evident that energy savings from self-consumption typically surpass those achieved through behavioural change services, as demonstrated in the Madrid building tests. Significant savings from smart battery charging management could be estimated in the Thasos demo site. However, the large self-consumption savings in Krk are basically obtained from an over-dimensioned PV facility.

Table 5. Annual energy savings obtained from the different efficiency services tested, in kWh/y per dwelling/room.

Data in kWh/Year per Dwelling/Room	Madrid	Thassos	Krk
Implicit Energy Efficiency savings (verified)	225	(1)	(1)
Self-consumption savings	1344	848	1468
PV-battery Optimization savings	(2)	505	(2)
Total Energy savings	**1569**	**1353**	**1468**
PV Total Generation	**3312**	**2527**	**10,546**

(1) It is not reported because verification through the baseline could not be performed; (2) it is not reported due to the unavailability of a storage facility capable of supporting testing activities.

These findings indicate that outcomes are highly dependent on building types and, notably, on the residents' energy consumption patterns. Although the payback periods are reasonably below ten years, ESCOs planning to offer data-driven smart services should conduct preliminary analyses to assess the suitability of their services before making investments and entering binding Pay-for-Performance (P4P) long-term contracts.

Figure 15 summarizes the key insights gained during the implementation and evaluation of the energy services across the demonstration sites, highlighting the most common challenges, such as building heterogeneity, user resistance, technological incompatibilities, and limited historical data. It also identifies opportunities to address these challenges, including tailored energy services solutions, community energy management, the standardization of data management and the adoption of standardized and homogeneous energy equipment for future deployments. These findings emphasize the importance of balancing obstacles with strategic innovations to optimize the deployment of smart energy services.

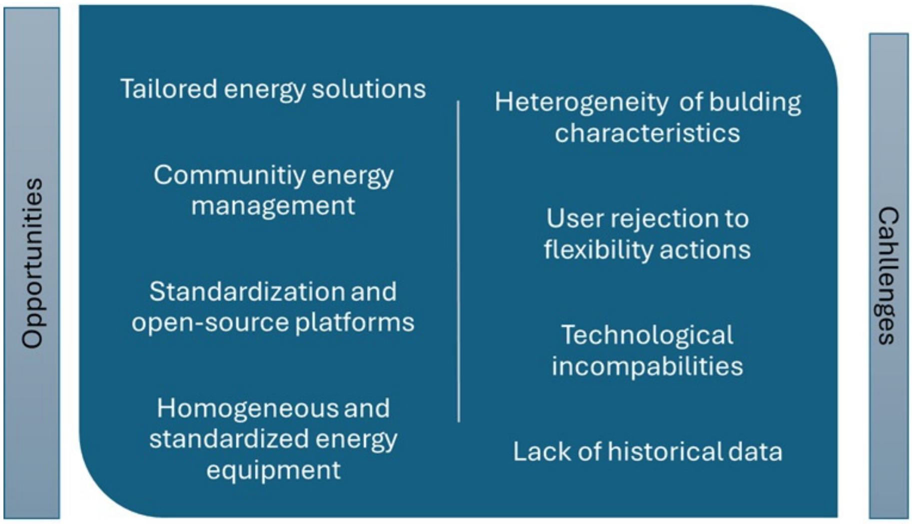


Figure 15. Challenges and opportunities identified in the implementation of data-driven innovative energy services.

5. Conclusions

This paper showcases the viability of new business models based on smart energy services for the building sector. The integration of electric HVAC systems with solar energy and storage solutions has been key to maximizing outcomes. Additionally, demand flexibility has shown potential to reduce payback periods, although real demand response market conditions could not be tested. The combination of several energy efficiency and flexibility services that use the same data-capturing system yields payback times of less than 10 years in a variety of residential and commercial buildings. The positive attitude of end users has also been crucial for the successful implementation of these services. The most complete case study tackled in this paper involves implicit energy efficiency through behavioural change, self-consumption, and demand flexibility from HVAC systems, tested for a full year in the Madrid residential building, where the total economic savings per dwelling were estimated to be 1569 €/year, with an additional 126 €/year from participation in potential demand response markets. The investment for the smart data-driven services and the PV facility shows a payback period of 2.5 years. This payback period increases to 9.3 years for seasonal occupancy profiles such as the Thasos bungalow rooms, or 7.5 years for the detached dwellings on Krk island with occasional occupancy (self-consumption savings only). Opportunistic value-added non-energy services can also help reduce the payback of the necessary investments on data-capturing and -handling infrastructure.

From the testing conducted in the three demo site buildings, it is observed that results vary largely depending on building type and the usage patterns of the building's residents. Therefore, ESCOs should carry out a preliminary analysis of the buildings, equipment, and energy consumption profiles to determine the suitability of the smart services to each building and end user.

The smart energy service providers should also work on standardizing solutions and integrating legacy equipment to become operable assets for implicit energy efficiency. Difficulties in engaging dwellers in personalized energy management can be partially overcome by additionally involving community energy managers and designing smart services to be deployed on the community level.

Further efforts should be made in several areas to enhance the performance of smart energy services in residential buildings. The lack of historical data for efficiency baselining may be tackled by the use of appropriate ex-ante energy performance models, whereas centralizing the smart service control and operation to dedicated community energy managers would contribute to making service performance less dependent on users' engagement and avoid intrusive automation. Finally, the opening of energy flexibility markets to aggregated demand response from buildings would enable a more realistic testing of the potential of this energy source for congestion and balance management in electricity grids.

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