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High-Resolution Analysis of Solar and Storage Integration in Residential Buildings with Reversible Heat Pumps

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Abstract

This study proposes a novel and replicable method to evaluate the cost-effectiveness of residential photovoltaic (PV) systems with battery storage (ESS) based on actual electricity consumption data from Italian households. The method integrates one year of real 15 min-interval household electricity consumption data, downloaded from the Italian national consumption portal (ARERA), with simulated PV generation and storage operation. Unlike most existing studies that rely on fully simulated demand profiles, this approach integrates real consumption data to more accurately capture daily and seasonal demand variability and the temporal mismatch with PV generation. The methodology has been validated through a case study of a residential dwelling in a Mediterranean area, with reversible heat pump loads and no existing PV or ESS, assuming the installation of a 3 kW_p PV system and a 5.76 kWh ESS. Results show that adding ESS nearly doubles self-consumption (from 32.0% to 68.7%) and self-sufficiency (from 24.9% to 53.5%), while reducing grid imports by 38.0% and energy exports by 59.5%. Annual savings rise by 112%, but the payback period lengthens from 10.5 to 14.4 years, reflecting the trade-off between higher self-consumption and battery cost. Beyond these specific results, the main contribution of this work lies in demonstrating how publicly available real consumption data can be combined with energy simulation to support transparent and replicable evaluations of PV and ESS systems. Implemented through a calculation tool, this method can support designers, households, and policy-makers in assessing optimal ESS sizing, evaluating economic feasibility without the need for complex modelling or proprietary data. This methodology contributes to sustainability goals by reducing dependence on fossil fuels, improving the energy autonomy of buildings, and supporting decarbonization policies.

Keywords: domestic energy consumption; photovoltaic self-consumption; sub-hourly energy matching; energy storage optimisation; smart home energy management; real-world operational data; solar energy; solar-ready

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1. Introduction

The European Directive (EU) 2024/1275 [1] highlights the need to reduce fossil fuel dependence and accelerate the decarbonisation of energy consumption in buildings. It requires new buildings to be "solar-ready," optimising solar generation potential to facilitate cost-effective installations.

Photovoltaic (PV) systems, which generate emission-free electricity, play an important role in this transition to achieve climate neutrality by 2050 [2]. With the growing relevance of self-consumption in household energy planning, it has become increasingly important to install PV systems not only in newly built homes but also in existing buildings. These systems help reduce dependency on the grid by generating clean energy on-site, especially when their output is consumed directly within the household. This optimisation not only enhances the economic and environmental benefits for the individual domestic consumer, who is protected from the volatility of fossil fuel prices, but also aligns with the Directive's goals [1] of achieving a zero-emission building stock by 2050.

Rooftop PV systems are estimated to be capable of meeting between 25% and 49% of electricity demand around the world [3], offering a viable solution to reduce land-use pressures and limit environmental impacts.

The Italian Integrated National Energy and Climate Plan [4] foresees, by 2030, significant growth in the use of heat pumps for heating and cooling, as well as greater electrification of residential energy consumption. In this context, Palladino and Calabrese [5] assessed Italy's rooftop PV potential, excluding additional land consumption. They estimated that approximately 450 km^2 of suitable rooftop area could accommodate over 72 GW of capacity, potentially generating more than 79,000 GWh annually.

However, their scenario analysis reveals significant challenges. Under the most probable projections, installed rooftop capacity would reach only 6 GW by 2030, just 11.5% of the Italian target, covering merely 10% of residential demand (≈6200 GWh). By 2050, this share could rise to 38%, still below national and European goals. Only under optimistic scenarios, supported by long-term incentives, rooftop PV could approach 50% of residential electricity consumption by mid-century.

While these figures describe the maximum technical potential based on available rooftop area, actual adoption depends on socio-economic factors and consumer behaviour. Simulation results presented by Danielis et al. [6] suggest that by 2030, around 44% of homeowners in Italy will have installed PV systems or PV systems combined with ESS. Among these adopters, approximately 75% are expected to include an ESS. By contrast, 56% of homeowners are projected to remain entirely dependent on grid electricity. Taking into account the stochastic nature of adoption, the share of households installing both PV and ESS by 2030 is estimated to range between 34.3% and 38.1%, with an average around 35.8%.

On this point, Alshareef and Maghrabie [7] provided a comprehensive analysis of Building-Integrated Photovoltaics combined with multiple ESS technologies, including electrochemical, mechanical, thermal, and hydrogen-based solutions, highlighting their respective advantages, limitations, and economic implications. This broader perspective confirms that while batteries remain the most common option for residential applications, alternative or hybrid storage strategies can play a critical role in enhancing flexibility, reducing grid dependency, and supporting the transition toward zero-energy buildings.

Ref. [8] emphasises the importance of flexible buildings that integrate solar PV systems with ESS, heat pumps, electric vehicles, and smart energy management systems in strengthening the electricity system. Such building-based solutions could cover over half of the EU's daily flexibility needs (52%), as well as approximately one-third of its weekly (35%) and annual (29%) requirements.

However, a fundamental challenge remains: the structural mismatch between PV generation timing and household demand. Beyond rooftop availability, the critical issue in residential contexts is that peak consumption often occurs in the evening, when solar production is minimal or absent. Zhang et al. [9] and Li et al. [10] highlighted the importance of ESS in shifting loads to improve self-consumption, although they noted that the influence of charging rates on cost savings diminishes with larger battery capacities. This observation aligns with the findings of Orioli and Di Gangi [11] who observed that the temporal mismatch between generation and consumption significantly affects both the energy and economic performance of PV installations, particularly in urban contexts, where the theoretical benefits of large-scale deployment may not translate into practical advantages. Current residential PV systems typically achieve baseline self-consumption rates ranging from 30% to 40% [12], with substantial variations depending on household characteristics and occupancy patterns. Self-Sufficiency Rates rarely exceed 80% unless PV systems and/or ESS are significantly oversized, pointing to fundamental limitations in current approaches as the challenge of balancing existing technological capabilities with economic constraints and the inherent variability of household-level energy supply and demand [13].

Luthander et al. [14] reported that integrating an ESS sized between 0.5 and 1 kWh per kilowatt of installed PV capacity can enhance relative self-consumption by approximately 13% to 24%. Additionally, implementing demand-side management strategies can contribute to a further increase of 2–15% compared to baseline self-consumption levels.

Furthermore, Wamalwa and Ishimwe [15] investigated optimal control in grid-tied PV-ESS under a price-based demand response program. In the case study, the integration of PV and ESS led to a 49% decrease in energy costs.

Zhang et al. [16] showed that, although ESS integration increases self-consumption and self-sufficiency, it often extends simple payback periods and raises concerns over long-term financial viability. Chen et al. [17] further pointed out that high upfront costs and relatively short operational lifespans limit the widespread adoption of ESS, while their usable capacity may still fall short of fully covering ESS needs for renewable generation and peak demand.

Acknowledging these limitations, other studies have focused on demand-side management strategies aimed at optimising existing consumption patterns without requiring additional investments in ESS units. These approaches also help to ease the pressure on the power grid resulting from the widespread integration of renewable energy sources. Some specialised applications have shown exceptional promise. Bandera et al. [18] achieved remarkable self-consumption rates of 70% in winter and 50% in summer through optimised inverter heat pump management, demonstrating that thermal load optimisation can rival the performance of ESS units while offering greater simplicity and computational efficiency. Their methodology achieves self-consumption levels comparable to those attained through chemical battery-based strategies.

Recent research increasingly emphasises that accurate optimisation of residential PV systems requires analysis at much finer temporal scales than traditionally employed [19–21]. Mistretta et al. [19] highlighted the importance of high-resolution data for building electricity optimisation, noting that variations in electricity generation mixes can range from +20% to −38% compared to annual averages, with significant implications for both energy performance and environmental impact assessment. This trend is further supported by the publication of real-world operational datasets, such as the 10 s-resolution PV generation and consumption data from an Estonian residential dwelling [20], which provide precise insights into energy usage dynamics under high climate variability. Similarly, De Masi et al. [21] adopted a combined experimental and numerical approach to evaluate PV system performance in a Nearly Zero Energy Building in a Mediterranean climate, demonstrating that the Performance Ratio is highly sensitive to external conditions and cell temperature, and that high-resolution data are essential for accurately estimating the system degradation rate and forecasting the long-term energy and environmental performance of the building.

To maximize electricity production and self-consumption, some researchers, such as Meng et al. [22], focused on improving the efficiency of PV energy generation at the panel level. They aimed to enhance Maximum Power Point Tracking algorithms. These methods seek to extract the highest possible power from PV panels under varying sunlight and temperature conditions, while reducing power fluctuations and speeding up response times. Innovations include a two-phase power forecasting model and an adaptive resistance factor based on the panel's voltage-to-current ratio.

While existing studies provide insights into various approaches for improving PV self-consumption, several gaps remain. Most employ annual or hourly data intervals, potentially missing optimisation opportunities at finer temporal scales, and often rely on simulated consumption profiles rather than real operational data, particularly in northern European contexts. Mediterranean climates present distinct challenges due to pronounced temporal misalignment between solar generation and demand, yet comprehensive empirical studies in these settings remain limited.

This study addresses these gaps through a high-resolution, data approach using real 15 min interval data from an Italian household, obtained through ARERA's national Consumption Portal, publicly accessible to all Italian citizens, enabling widespread replicability without additional monitoring infrastructure. The analysis integrates technical and economic dimensions: (1) assessing temporal alignment between PV production and consumption; (2) examining ESS role in improving self-consumption; (3) integrating time-of-use (TOU) tariffs in the economic assessment; (4) estimating payback periods under current market conditions. This comprehensive approach provides practical insights for optimising residential PV systems where demand peaks and solar availability are characteristically misaligned.

The novelty of this work lies in the development of a calculation tool for evaluating the self-consumption share of electricity generated by a photovoltaic (PV) system. The tool integrates actual consumption data, freely accessible to all Italian citizens, with the producibility of a simulated PV-EES system. The performance and economic feasibility of PV-ESS systems cannot be reliably assessed using only annual electricity demand values, as is still commonly done in practice. Accurate evaluation requires sub-hourly load data, since investment payback and self-consumption rates depend strongly on the real temporal structure of demand. By combining 15 min monitored consumption profiles from the national ARERA database with standardised PV–ESS calculations, this study provides a realistic and fully replicable methodology compliant with Directive 2024/1275/EU for assessing PV systems under actual operating conditions.

2. Methodology

2.1. Overview

Figure 1 provides an overview of the methodological approach adopted in this study, structured according to the following points:

- Data Collection: This phase involves gathering all the necessary input data, including household energy consumption profiles, local climatic information, technical specifications of PV systems and ESS, and electricity pricing structures.
- Calculation tool setup: A computational model is developed to perform sub-hourly energy simulations. It calculates tilted solar irradiance, estimates PV energy output, compares it with energy demand (based on actual consumption data), quantifies energy drawn from or fed into the grid, and incorporates the dynamics of the ESS.
- Results analysis: Energy performance indicators are evaluated, including monthly and annual energy balances, self-consumption rates, grid dependency, and exported energy quantities.
- Economic analysis: The final step assesses the financial aspects of the system through the calculation of energy savings, potential revenues from energy exports, and the estimation of the investment's payback period.

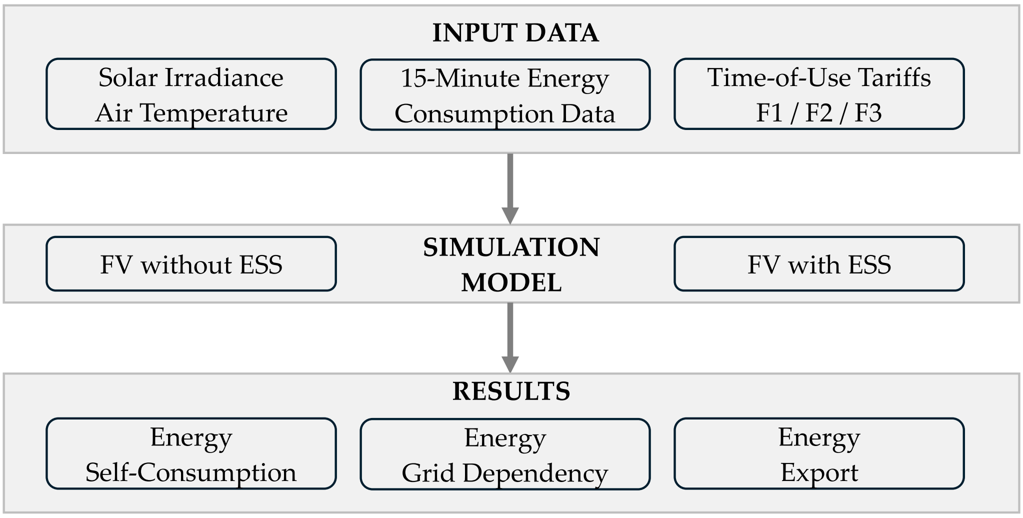

Figure 1. Overview of the workflow adopted in the study.

2.2. Input Data

The input dataset comprises: high-resolution profiles of the household's actual energy consumption, obtained from the Italian regulatory authority for energy (ARERA); electricity tariff structures for both purchased and exported energy; detailed local climatic data collected from meteorological stations; technical specifications of the photovoltaic (PV) and energy storage systems (ESSs) to be installed, provided by manufacturers; site-specific characteristics including roof slope, orientation, and available installation surface area.

2.3. Calculation Methods

As shown in Figure 2, the study implements Italy's standardized calculation methods for PV performance assessment, enhanced for high-temporal-resolution analysis.

The plane-of-array solar irradiance was estimated according to UNI 10349-1:2016 [23]. The UNI 10349-1:2016 standard provides reference climatic data and outlines methods for assessing the thermal-energy performance of buildings in the Italian context. Among its provisions, it includes a procedure to separate global solar irradiance into its direct and diffuse components. The algorithm presented in Annex A (Isotropic sky model) operates on an hourly basis and takes as input the global horizontal irradiance, enabling the calculation of direct and diffuse irradiance components on surfaces with any given tilt and orientation. In particular, it estimates the beam component incident on a tilted surface by using the direct horizontal irradiance and the solar incidence angle, through a dedicated formula. In this study, the standard methodology has been implemented with enhancements suggested by Summa et al. [24] for evaluating the solar incidence angle during sunrise and sunset conditions.

The EN 15316-4-3 standard [25] provides guidelines for calculating the energy performance of PV systems. In particular, Method 6 focuses on the hourly evaluation of electricity generation. Its main output is the amount of electricity produced and delivered on-site by the PV system, i.e., the net power production.

Finally, the modelling of the on-site electrical ESS system's behaviour has been developed using a dynamic hourly calculation method, as described in a normative document currently under development by the national standardization body [26], within the framework of building energy performance assessment. This draft standard is applicable to all types of ESS systems, including lead-acid and lithium-ion batteries. The model simulates the storage of energy exclusively from on-site generation systems, such as PV systems, excluding energy from the external grid. For the hourly calculation, the method requires as input the energy production of a generation system (e.g., photovoltaic), the building's total electricity demand, as well as the performance data specific to the ESS system.

Following the calculation flow illustrated in Figure 2, the entire hourly procedure was adapted to a 15 min resolution.

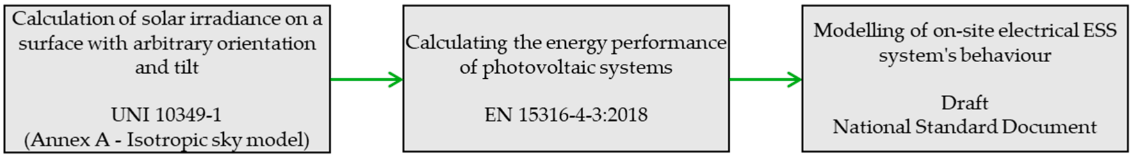

Figure 2. Workflow for PV and ESS modelling, based on UNI 10349-1, EN 15316-4-3:2018, and the Draft National Standard Document [23,25,26].

2.4. Specifications for EES System Modelling

This section outlines the calculation methodology for estimating energy flows in buildings equipped with Electrical Energy Storage (ESS) systems, as defined in reference [26] and adapted to sub-hourly time steps.

The modelling is performed over discrete time intervals (time steps, Δt). Although the reference technical specification is primarily developed and detailed for an hourly interval (Δt = 1 h), its algorithmic structure can be generalized for sub-hourly time steps (e.g., 15 min, 30 min). For such generalization, the power terms in the formulas (expressed in kW) must be explicitly multiplied by the duration of the time step Δt (expressed in hours) to obtain the corresponding energy flows (kWh).

The model incorporates the following key parameters related to the ESS system:

The model includes the following parameters:

- Effective usable ESS capacity ($W_{ESS,max}$) [kWh]: Represents the actual amount of energy that can be used from the storage battery, calculated to ensure performance is maintained over time (e.g., over 10,000 cycles).
- Initial ESS energy $E_{ESS,start}(t)$ [kWh]: Represent the electrical energy available in the storage system at the beginning of the considered time interval t.
- Maximum charging power ($\Phi_{ESS,max,load}$) [kW]: Indicates the maximum power at which the storage system can be charged during a given time interval.
- Maximum discharging power ($\Phi_{ESS,max,discharge}$) [kW]: Indicates the maximum power at which the storage system can deliver energy to meet demand.
- Charging efficiency (η_{charge}) [-]: Defines the ratio between the energy actually stored and the energy drawn for charging.
- Discharging efficiency ($\eta_{discharge}$) [-]: Defines the ratio between the energy actually delivered and the energy extracted from the storage system.
- Power loss due to self-discharge ($\Phi_{ESS,ls}$) [kW]: Quantifies the power dissipated by the storage system due to internal self-discharge, which reduces the available energy over time.

These parameters control how energy is stored, released, or lost during each time interval. Time step is the fixed period over which energy balances and system dynamics are calculated. All energy flows and capacities are calculated over this time step.

2.5. Mathematical Modelling

The steps of the calculation process and the mathematical formulas used are presented below.

2.5.1. PV Energy Used to Cover Electrical Demand

The first step in the hourly/sub-hourly calculation is to determine the share of the building's electrical demand that is immediately met by the output of the on-site generation system, without passing through the storage system. This quantity is important for determining the remaining energy, which can then be managed by the storage system or the grid. Equation (1) calculates the portion of electrical energy produced by the on-site system that is consumed directly by the building within the same time interval t.

$$E_{el,pv,used}(t) = \min\left(E_{el,pv,out}(t), C_{el}(t)\right) \quad (1)$$

where $E_{el,pv,out}(t)$ is the output of the on-site generation PV system for the time interval t (in kWh) and $C_{el}(t)$ is the building's electrical energy demand (sum of the demands of all electrical loads) for the time interval t (in kWh).

2.5.2. Energy Available from the ESS to Cover Electrical Demand

The amount of energy that the storage system can deliver to meet the building's remaining demand is assessed. This depends on the battery's current state of charge, its maximum discharging power, and its discharging efficiency.

$$E_{el,ESS,avail}(t) = \min\left(E_{ESS,start}(t), \Phi_{ESS,max,discharge} \cdot \Delta t\right) \cdot \eta_{discharge} \quad (2)$$

2.5.3. Electrical Demand Covered from the ESS

Once the energy available from the storage system has been calculated, it is determined how much of this energy is actually used to meet the portion of the building's demand that was not covered by direct generation.

$$E_{el,ESS,used}(t) = \min\left(C_{el}(t) - E_{el,pv,used}(t), E_{el,ESS,avail}(t)\right) \quad (3)$$

2.5.4. Electrical Demand Supplied by the Electrical Grid

After using on-site generation and energy from the storage system, if the building's demand is still not fully met, the remaining portion must be imported from the external electricity grid.

$$E_{el,grid,in}(t) = C_{el}(t) - E_{el,pv,used}(t) - E_{el,ESS,used}(t) \quad (4)$$

2.5.5. Excess PV Energy Production

Any excess production from the on-site system that was not directly consumed by the building is calculated. This surplus energy can then be directed to the storage system or exported.

$$E_{el,pv,exceed}(t) = E_{el,pv,out}(t) - E_{el,pv,used}(t) \quad (5)$$

2.5.6. PV Energy Used to Charge the ESS

After determining the excess energy produced by the on-site system (Equation (5)), the amount of this energy that can actually be used to charge the storage system is calculated. This step is necessary for managing the energy flow and optimizing the use of the storage system.

$$E_{el,ESS,charge}(t) = min(E_{el,pv,exceed}(t), \frac{W_{ESS,max} \cdot \Delta t - E_{ESS,start}(t)}{\eta_{charge}}, \frac{\Phi_{ESS,max,load} \cdot \Delta t}{\eta_{charge}}) \quad (6)$$

2.5.7. ESS State at the End of Time Step

This step allows determining the final state of charge of the storage system at the end of the interval, which will then become the initial state of charge for the next interval. The equation accounts for the initial energy, the energy used, the energy charged, and self-discharge losses.

$$W_{ESS,end}(t) = \max\Big(0,\ \mathrm{E}_{ESS,start}(t) - E_{el,ESS,used}(t) + E_{el,ESS,charge}(t) - \Phi_{ESS,ls} \cdot \Delta t\Big) \tag{7}$$

2.5.8. Energy Exported to the Grid

Finally, it is determined how much of the excess electrical energy produced by the on-site system was not used to charge the storage system and is therefore fed into the external electricity grid.

$$E_{el,grid,out}(t) = E_{el,pv,exceed}(t) - E_{el,ESS,charge}(t) \tag{8}$$

The computational flow representing the energy balance of the PV system integrated with an ESS is shown in Figure 3.

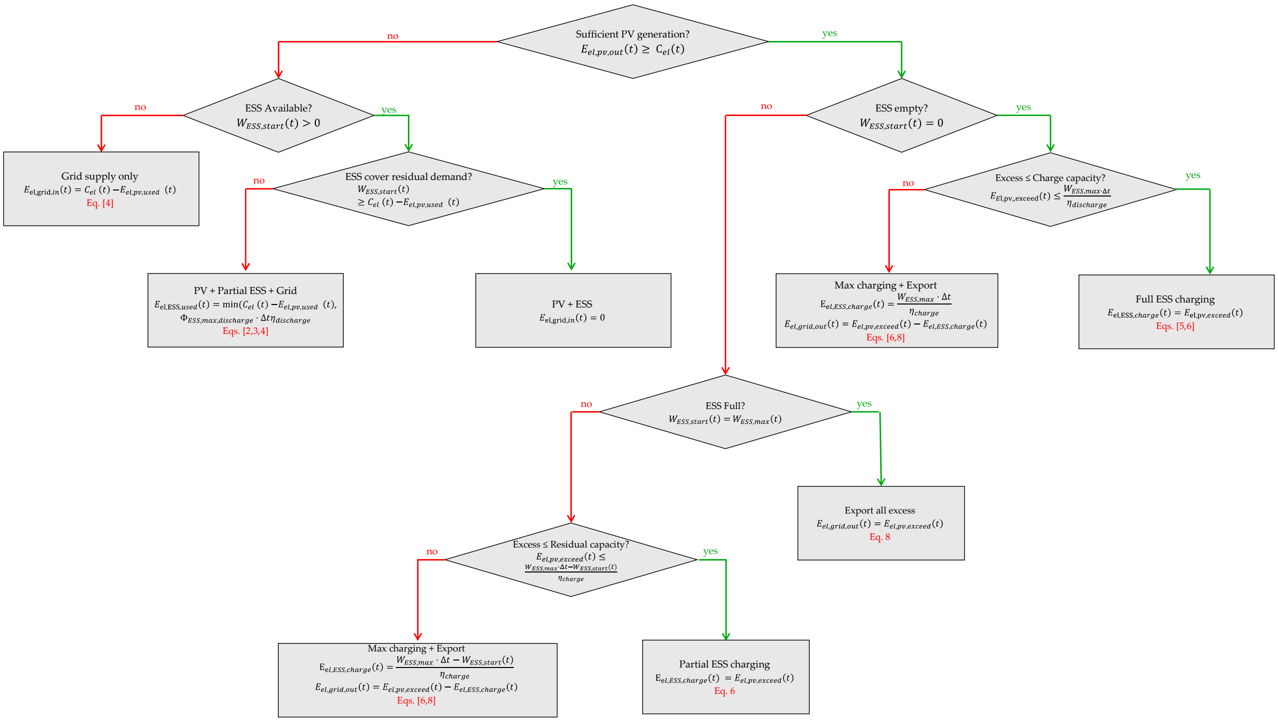

Figure 3. Flowchart of the real-time energy management system for a PV system with ESS.

2.6. *Calculation Tool*

The simulations of PV energy production and ESS behaviour were carried out using a custom-developed Excel tool in which the formulas from references [23–26] were directly implemented. The electricity consumption data, covering all electrical equipment and technical building systems that use electrical energy, were obtained from the ARERA platform, providing actual measured demand at 15 min intervals rather than simulated values.

The computational model was designed to conduct a detailed and dynamic analysis of energy flows. The energy simulation logic operates on 15 min intervals, ensuring high resolution to capture sub-hourly fluctuations between energy supply and demand.

3. Case Study

3.1. Energy Consumption Data

The energy consumption data have been obtained from the ARERA Consumption Portal [27]. The Consumption Portal is the official Italian website where consumers can access information about their electricity and natural gas supply accounts. This includes historical consumption data, key technical details, and contract information, all provided straightforwardly, securely, and freely.

Since 1 July 2019, customers have been able to view their consumption data and meter readings in an intuitive format, presented in tables and graphs. Data can be accessed with up to 36 months of historical depth and with detailed granularity, especially in the electricity sector, where quarter-hourly consumption data can be displayed.

These features enable consumers to understand better and monitor their energy usage, supporting a shift in consumption habits and helping guide their behaviour within the evolving energy market. Customers can also review their current and past contract details. Access to the Consumption Portal's energy and gas supply information requires logging into the private area via SPID (Public Digital Identity System). An example of the ARERA portal screen is shown in Figure 4.

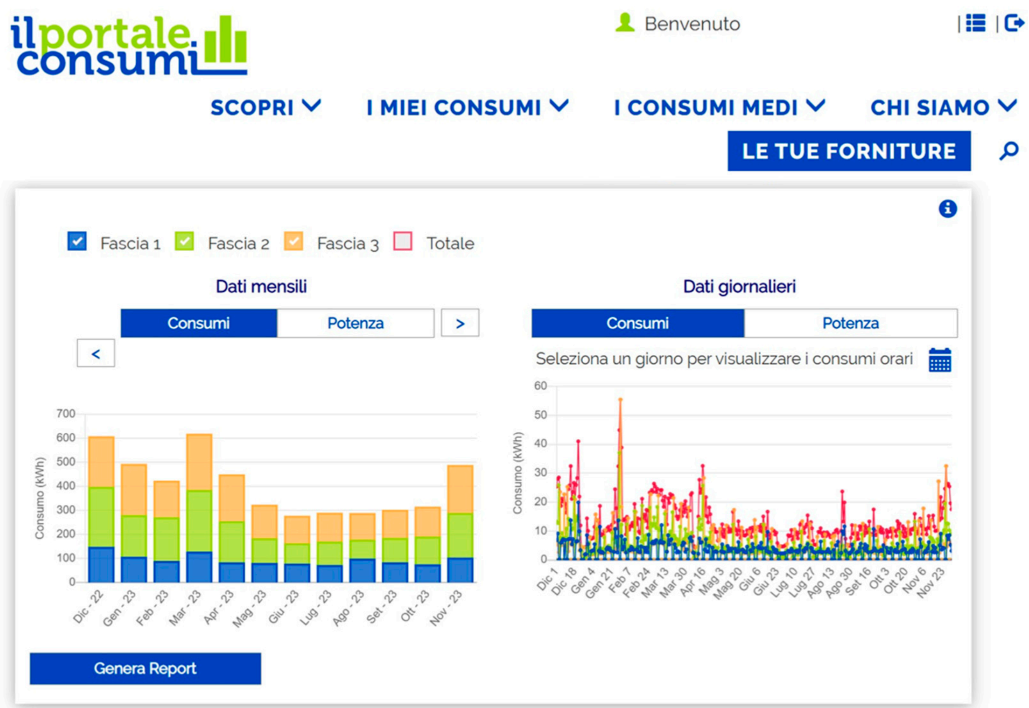

Figure 4. ARERA Consumption Portal (In Italian) [27].

The data acquired for the case study refer to the electricity consumption of a residential dwelling of approximately 100 m^2, located in the province of Rome. The building is occupied by three people: two adults employed in office-based jobs and one teenager. The dwelling is primarily occupied during the morning and evening hours, when both the adults and the teenager return from work or school. The house has about 20 m^2 of usable roof surface oriented south-east, which is relevant for potential photovoltaic integration. A reversible heat pump system is used for both heating and cooling; during winter and transitional seasons, it operates in heating mode in combination with a boiler, while during summer, it provides cooling. The technical specifications of the heat pump are provided in Appendix A, Tables A1 and A2. Figure 5 shows some photos of the monitored heat pump (a), the heat pump control and management panel (b), the outdoor temperature sensor for weather-compensated control (c), and the room control unit (d). No synthetic profiles or simulated loads are used. The resulting time series reflects the actual occupancy pattern and switching behaviour of the heat pump (typically 06:30–08:30 and 18:30–22:30 from Monday to Friday, and extended operation during weekends). The consumption data are shown in Figure 6. The blue graph represents the hourly electricity consumption, while the red lines mark the total consumption for each month.

(a) (b) (c) (d)

Figure 5. Photos of the monitored reversible heat pump: (**a**) outdoor unit; (**b**) heat pump control and management panel; (**c**) outdoor temperature sensor used for weather-compensated control; (**d**) room control unit.

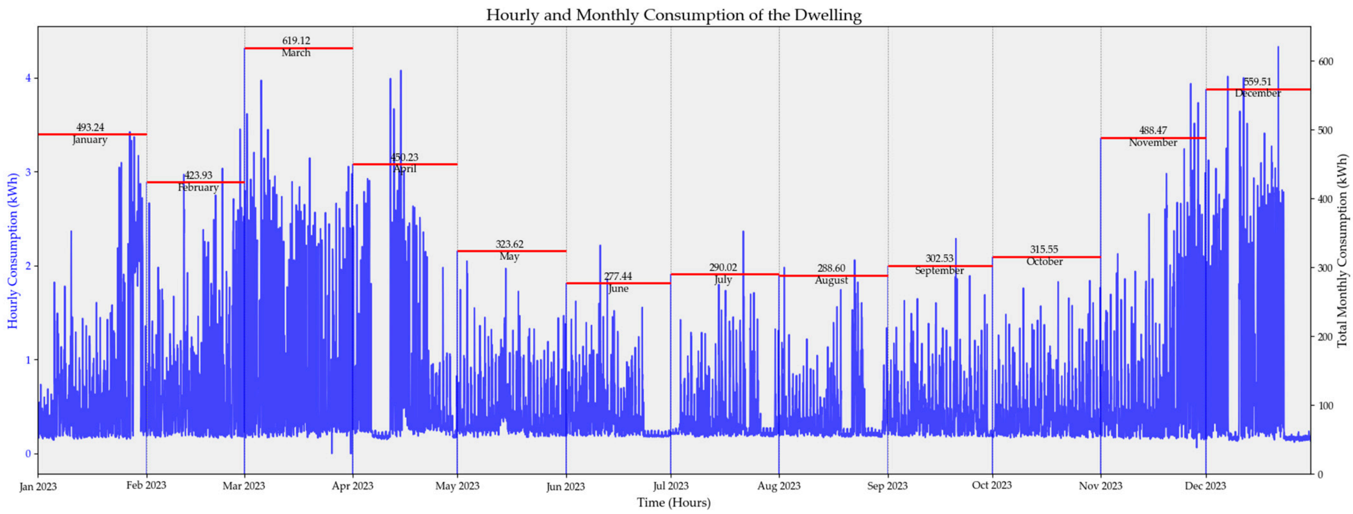

Figure 6. Hourly and monthly electricity consumption of a dwelling over the course of the year 2023.

3.2. Climatic Data

The climatic data utilised in this case study (air temperature and solar irradiance) were recorded by a weather station managed by ENEA, situated in Anguillara Sabazia, a municipality in central Italy near Rome. The dataset covers the entire year 2023, with measurements recorded at a one-minute time step. These data were recorded during the same period for which electrical consumption data are available, ensuring a coherent analysis of the interaction between climatic variables, PV production, and energy usage.

Eurostat [28] classifies Rome, based on heating and cooling degree days (HDDs/CDDs), as follows for the period 2010–2019: Cooling Degree Days (CDDs): 282.05, classified as warm; Heating Degree Days (HDDs): 1374.29, also classified as warm. These indicators provide a standardized reference for assessing seasonal energy demands for heating and cooling, and for comparing the climatic conditions of this site with those of other similar European locations.

Figure 7 presents the average monthly solar irradiance on a horizontal plane (ordinate) and the monthly average temperature (abscissa) for the year 2023.

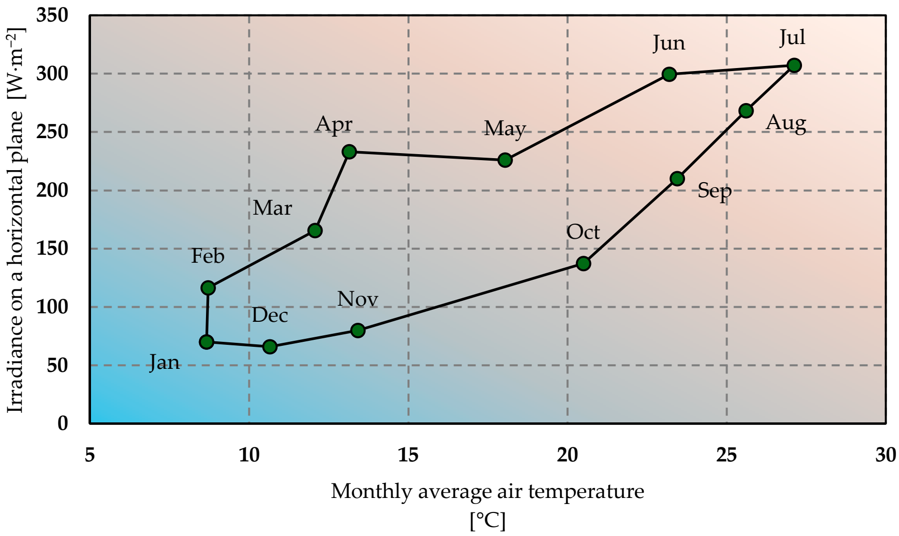

Figure 7. Average monthly solar irradiance on a horizontal plane [W·m^{-2}] measured by the meteorological station in Anguillara Sabazia (year 2023).

3.3. Electricity Prices

Figure 8 presents the regulated electricity service rates in Italy, expressed in euros per kilowatt-hour (€/kWh). It distinguishes between a single-rate tariff and differentiated tariffs for three time-of-use (TOU) bands defined by AEEG Resolution 181/06 [29]:

- F1: from Monday to Friday, from 8:00 AM to 7:00 PM, excluding national holidays.
- F2: from Monday to Friday, from 7:00 AM to 8:00 AM and from 7:00 PM to 11:00 PM; Saturday from 7:00 AM to 11:00 PM, excluding holidays.
- F3: from Monday to Saturday, from 11:00 PM to 7:00 AM; Sundays and national holidays all day.

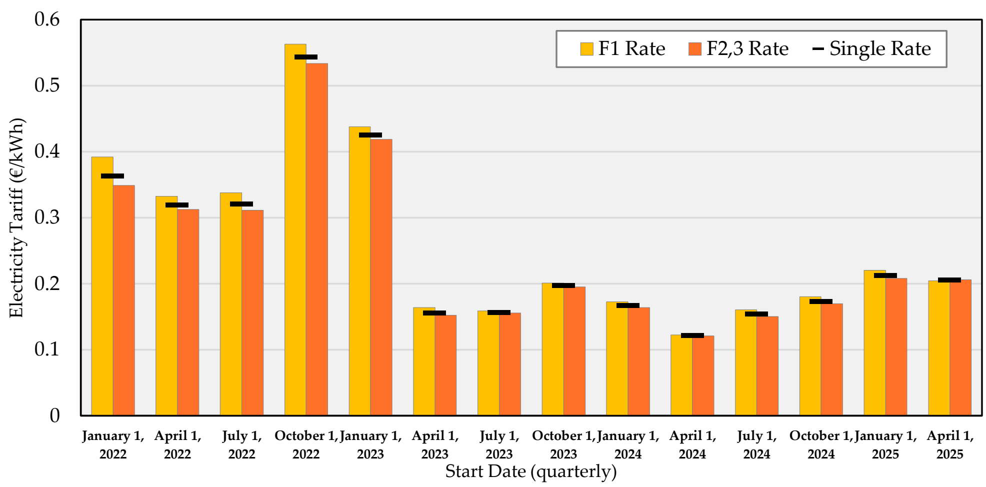

Figure 8. Economic conditions of the regulated electricity service in €/kWh. Net of taxes values (Source [29]). F1: Peak hours, F2: Intermediate hours, F3: Off-peak hours.

Energy costs are highest during peak hours (F1), while intermediate (F2) and off-peak (F3) periods offer lower rates, encouraging energy consumption during less demanding hours. Figure 8 illustrates the significant fluctuations in regulated electricity rates between 1 January 2022 and 1 April 2025.

The shown costs only take into account the "energy quota", while they do not include the fixed quota, the power quota, or the electronic bill discount.

Figure 9 presents the average monthly electricity purchase prices by TOU bands (F1, F2, F3) and market area [30]. The value of the energy fed into the grid corresponds to the total revenue obtained by the GSE through the sale of electricity on the energy market, sourced from plants operating under the dispatching contract known as "Ritiro Dedicato" [31]. The data are provided for the years 2023 and 2024. The prices are expressed in €/kWh. The TOU bands for electricity consumption in Italy are defined by [29], which regulates daily and weekly time slots.

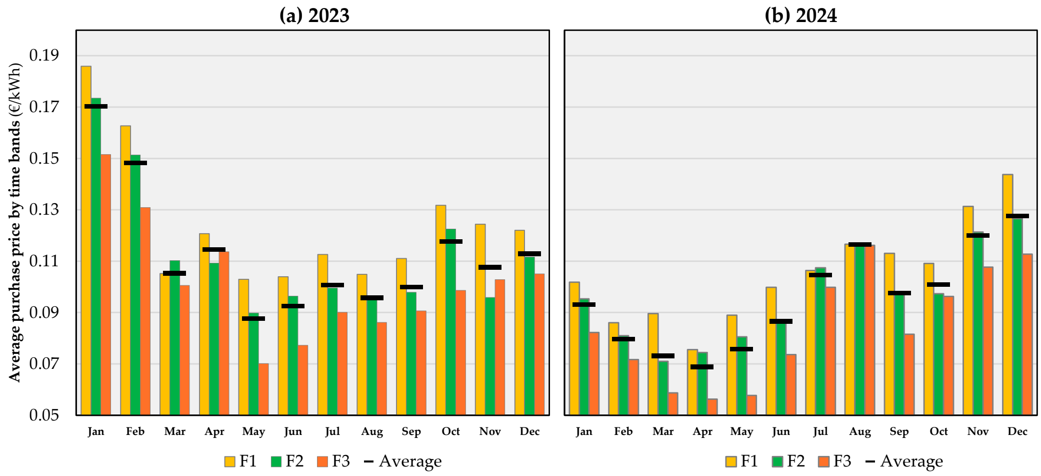

Figure 9. Average purchase price by TOU bands (Average monthly prices by time slot and market area (Article 13.4, "Annex A", AEEG Resolution 280/07, Source: [30]).

3.4. Technical Characteristics of the Simulated PV System

The performance evaluation of a PV system requires a detailed analysis of its key parameters. Table 1 provides an overview of the main characteristics considered in the simulation of a PV installation. These parameters include efficiency factors, module specifications, orientation, and environmental considerations, which together influence the energy output and overall system performance. Table 2 reports the main technical parameters of the $LiFePO_4$-based Energy Storage System (ESS) simulated in this study.

Table 1. Characteristics of PV System.

Parameter	Symbol	Value	Unit
Peak power of the system	W_{pv}	3.00	kW_p
Photovoltaic cell technology	-	Monocrystalline silicon	-
Azimuth angle of PV modules	-	135° (South-East)	degrees
Tilt angle of the PV modules	-	24.22	degrees
Albedo	-	0.20	-

As shown in Figure 10, the system is configured as a grid-connected photovoltaic installation with integrated battery storage. The functional diagram illustrates the main components and their interactions: (1) household lighting load; (2) energy meter for local consumption; (3) battery storage unit; (4) hybrid inverter; (5) PV array; (6) distribution board; (7) bidirectional energy meter; (8) grid connection point; (9) HVAC unit. The diagram provides a representation of the system architecture, highlighting the power flows among PV generation, storage, household loads, and the grid.

Table 2. Characteristics of the simulated ESS ($LiFePO_4$ ESS module).

Parameter	Symbol	Value	Unit
Maximum electrical storage capacity (1)	$W_{ESS\ max}$	5.76	kWh
Maximum peak charging power (1)	$\Phi_{ESS,max,load}$	5.76	kW
Maximum peak discharging power (usage) (1)	$\Phi_{ESS,max,use}$	5.76	kW
Efficiency (losses) associated with charging (1)	η_{charge}	0.97	-
Efficiency (losses) associated with discharging (1)	$\eta_{discharge}$	0.97	-
Auxiliary power	$\Phi_{ESS,aux}$	0.01	kW
Self-discharge rate (2)	$\Phi_{ESS,ls}$	0.003	kW/h
Characterisation of the battery state			
Available electrical energy in storage at time $t = 1$ (initialisation of the algorithm)	$W_{ESS,start}$	0	kWh

(1) Value taken from the technical datasheet of a commercial product. (2) For design or standard evaluations, in the absence of manufacturer-declared data, a self-discharge power loss of 0.003 kW/h is assumed, as indicated in a national draft standard document currently under development [26].

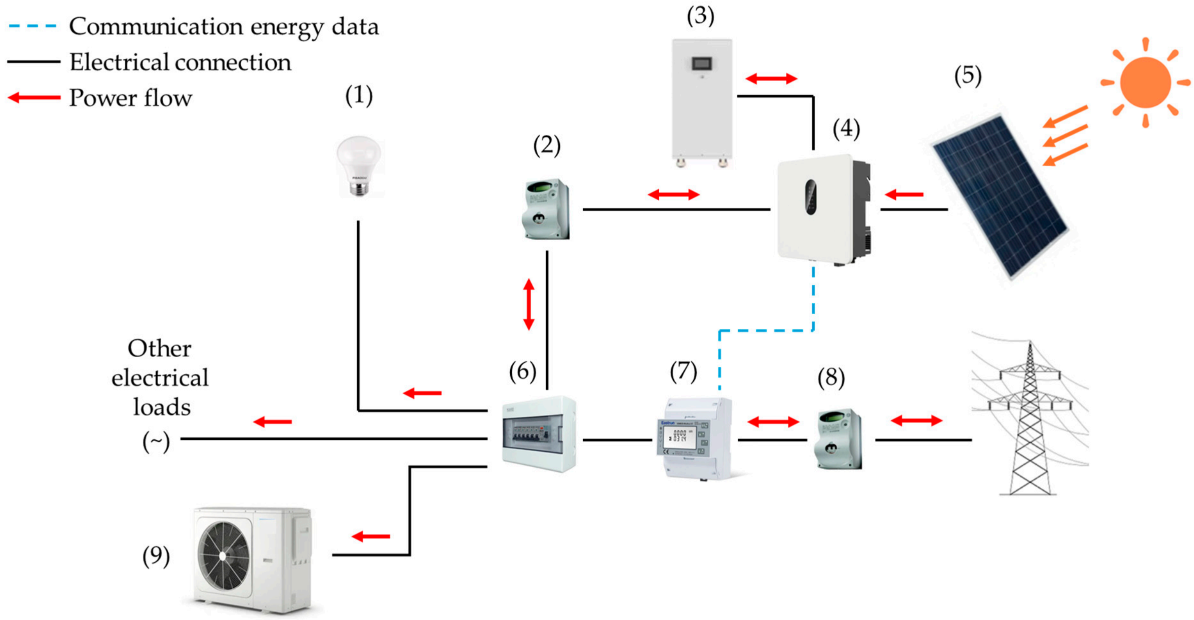

Figure 10. Functional diagram of a grid-connected PV system with battery storage (including PV array, inverter, storage unit, meters, and loads).

3.5. Price of PV Systems

The IRENA data [32] reveals that between December 2009 and December 2022, the cost of crystalline silicon solar modules decreased by 88% to 94%, with an average reduction of 91%. By December 2022, conventional modules were priced at USD 0.33/W, with low-cost modules at USD 0.22/W and high-efficiency ones at USD 0.43–0.44/W. Thin-film modules were priced at USD 0.23/W, with an 11% decrease from the previous year. Meanwhile, bifacial crystalline modules experienced a 5% cost increase, yet their market share rose to 30% in 2022. Figure 11 reports the price of residential grid-connected, roof-mounted, distributed solar photovoltaic systems in Italy from 2011 to 2023 [33].

Battery storage system costs depend on capacity (€500–1000/kWh) [35], technology (lithium-ion, especially $LiFePO_4$, being more expensive but more efficient than lead-acid), and installation complexity, particularly for retrofit configurations requiring inverter upgrades or component integration.

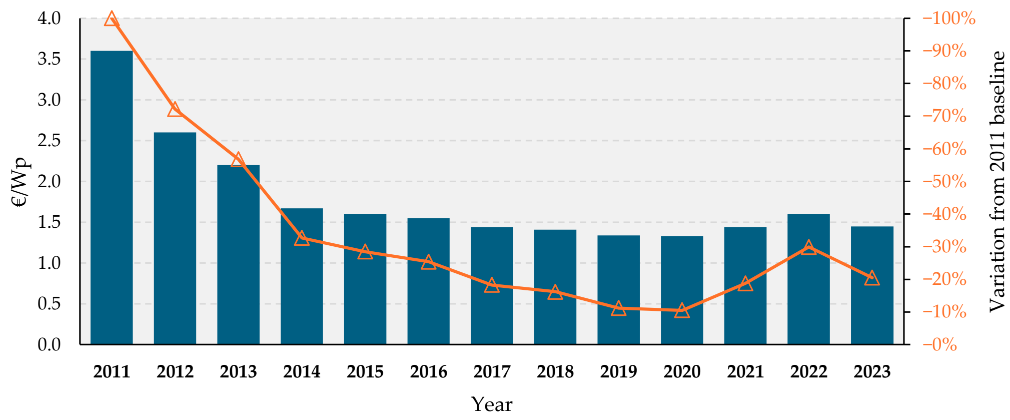

Figure 11. Price of residential grid-connected, roof-mounted, distributed PV systems in Italy from 2011 to 2023 (Source: [33,34]).

The economic analysis considers a turnkey cost of €5820 for the 3 kW_p monocrystalline PV system, and €9890 for the same PV system integrated with a 5.76 kWh battery storage system.

4. Results

4.1. Electricity Consumption and PV Energy Production (PV Without ESS)

Figure 12 summarises the monthly distribution of electricity consumption and PV energy production, disaggregated by TOU pricing bands (F1, F2, F3), in the absence of an ESS. The data show a seasonal asymmetry between production and electric needs. During the colder months (e.g., January and December), total monthly PV production remains markedly low, 141.8 kWh and 141.2 kWh, respectively, while the corresponding energy demand exceeds 493.2 kWh (January).

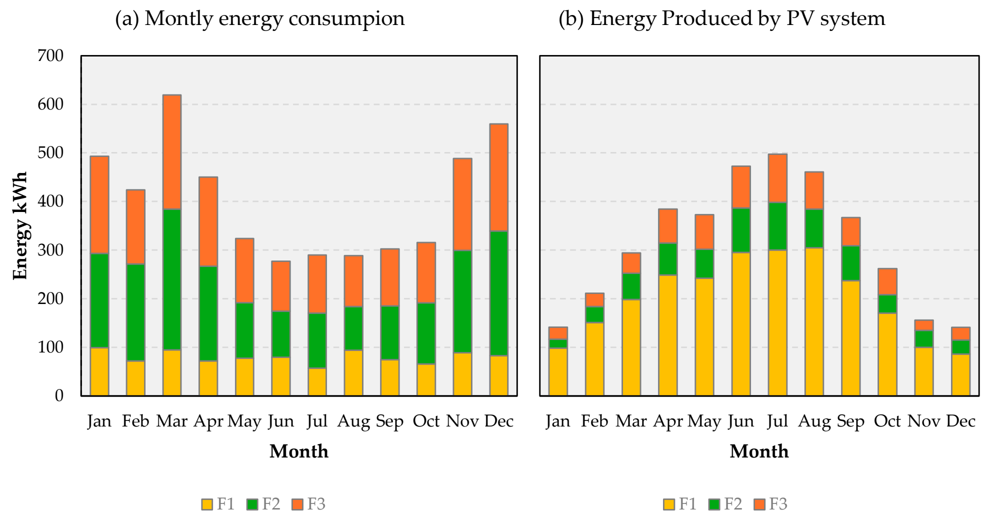

Figure 12. Total energy consumption and energy produced by the PV system without electrical storage by TOU (F1, F2, F3).

This imbalance is most evident in TOU slots with limited or no solar irradiance, like F3. In this band, the PV system contributes very little to meeting household demand. Although F3 accounts for a large share of annual consumption (2077.1 kWh/year), PV generation during these hours is only 44.0 kWh/year. This highlights a structural misalignment between renewable energy availability and actual load profiles.

Conversely, the hotter months (May to August) are characterised by elevated PV output, with monthly production exceeding 370 kWh. In July, for instance, generation peaks at 497.2 kWh against a relatively modest energy consumption of 290.0 kWh. This seasonal surplus, largely unutilised in the absence of an ESS, results in increased grid injection, reducing the share of energy that can be directly self-consumed.

The PV system generates 3762.0 kWh/year against an annual building consumption of 4832.3 kWh, resulting in a production-to-consumption ratio of 77.9%. Due to the temporal mismatch between production and consumption, only a part of this energy is effectively used on-site. The sub-hourly analysis confirms the well-known mismatch between PV generation and evening demand peaks, which limits self-consumption without ESS.

4.2. Self-Sufficiency (PV Without ESS)

Figure 13 presents the monthly amounts of PV energy that were effectively self-consumed by the building, disaggregated by TOU tariff bands (F1, F2, F3), along with the corresponding self-sufficiency percentages. The data reveal significant seasonal and temporal variability in the building's capacity to utilise locally generated energy, driven by both the variation in solar resource availability and the temporal distribution of electrical demand. By jointly analysing Figure 12, it becomes evident that there is an evident monthly and seasonal mismatch between consumption and PV production, particularly during the winter months, when energy demand exceeds the PV output.

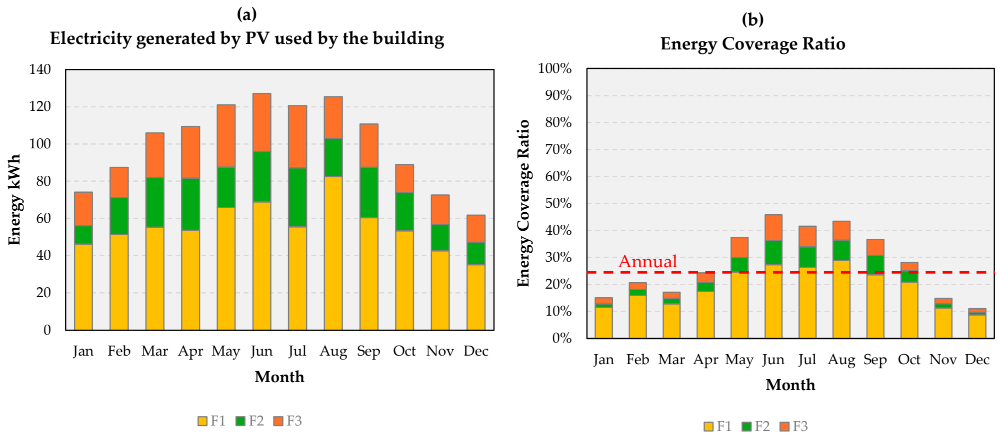

Figure 13. Electricity generated by the PV system without ESS used by the building and the percentage of self-consumption.

During the winter months, self-sufficiency values are notably low. For instance, in December, only 11.0% of the PV energy produced was directly used by the building. This limited utilisation is attributed to reduced solar irradiance during the winter season and to a mismatch between the timing of energy production and household demand-factors that, in the absence of an ESS, restrict the exploitation of the generated renewable energy. In contrast, the summer period shows a marked improvement in self-sufficiency efficiency. In June, self-sufficiency peaks at 45.8%, largely due to the overlap between daytime solar production and increased household energy use, associated with cooling systems. Nevertheless, even in months characterised by high PV output, such as July, a substantial portion of the generated energy, around 58.4%, remains unused on-site and is exported to the grid. Of particular interest is the behaviour observed in tariff band F3, which includes not only nighttime hours but also the entire duration of Sundays and national holidays. Although this band accounts for a substantial portion of annual energy consumption 1878.6 kWh, the share of PV energy self-consumed in F3 remains relatively low. On an annual basis, only 14.6% of the PV electricity produced is utilised during this time frame. This is due to the fact that, during off-peak hours (F3), electricity demand persists while PV availability drops to nearly zero. Overall, the annual self-sufficiency rate is 24.9%. While this confirms the partial effectiveness of distributed PV in reducing grid dependence, it also underscores the need for complementary measures to improve the temporal alignment between supply and demand. These could involve incorporating ESS units, implementing demand-side management measures, and scheduling household appliances to operate during periods of highest solar production.

4.3. Electricity Drawn from the Grid (PV Without ESS)

Figure 14 illustrates the amount of electricity drawn from the grid in the presence of a PV system without ESS, broken down by tariff TOU bands (F1, F2, F3) and for the monthly total. Additionally, it presents, for each TOU band and month, the share of monthly energy consumption that is covered by electricity purchased from the grid.

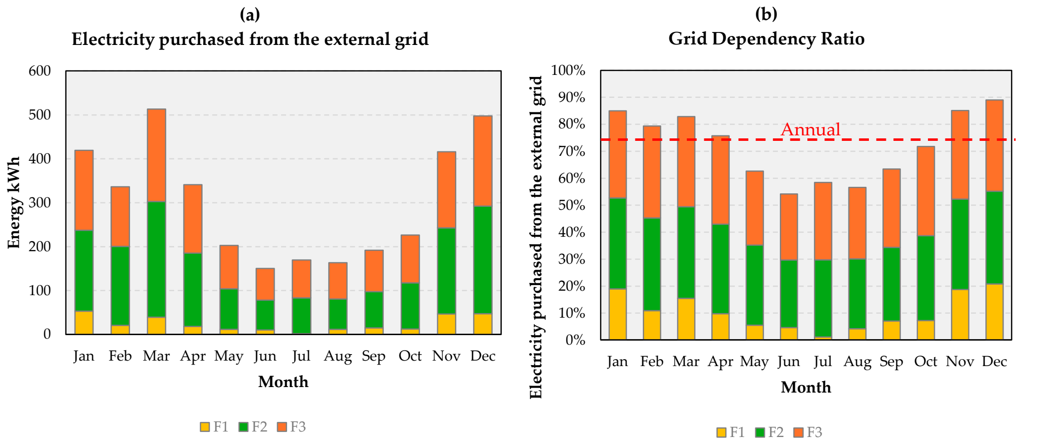

Figure 14. Purchased electricity from the external grid in the presence of a PV system without ESS.

4.4. Energy Produced by the PV System with ESS and Directly Consumed (PV with ESS)

Figure 15 presents data on the energy produced by the PV system with ESS and directly consumed by the building, distinguishing between the energy consumed instantaneously and that derived from the ESS. On an annual basis, the energy consumed with ESS reaches 2583.9 kWh/year, with a self-sufficiency percentage of 53.5%. This represents a substantial increase compared to the 24.9% recorded without ESS (Figure 13). The ESS enables the excess energy produced during periods of higher solar radiation (F1 and F2) to be stored and subsequently used during times of low or no PV energy production. The ESS contributes 1204.8 kWh/year of stored energy. In TOU band F3, the ESS supplies about 274.6 kWh/year. This extra energy mainly helps cover evening and nighttime demand, which would otherwise be fully met by the grid. In F1, annual self-sufficiency goes up from 70.0% to 87.6% when using the ESS, so more solar energy produced during the day ends up being used locally. In F2, the gain is similar, with annual self-consumption rising from 13.0% to 50.2%. The most notable improvement is seen in F3, where annual self-consumption increases markedly from 14.6% to 39.6%, emphasising the role of ESS in addressing the temporal gap between production and consumption, especially during periods with no solar availability.

Regarding seasonal performance, summer months (e.g., June to August) show particularly high levels of self-sufficiency, with values exceeding 85%, as high as 92.0% in August, due to abundant PV production and the capacity to store and deploy that energy efficiently (Figure 16). Winter months also show notable improvements. In December, self-sufficiency increases from 11.0% (without ESS) to 23.7%, demonstrating how ESS enhances the utilisation of limited solar energy even during low-production periods.

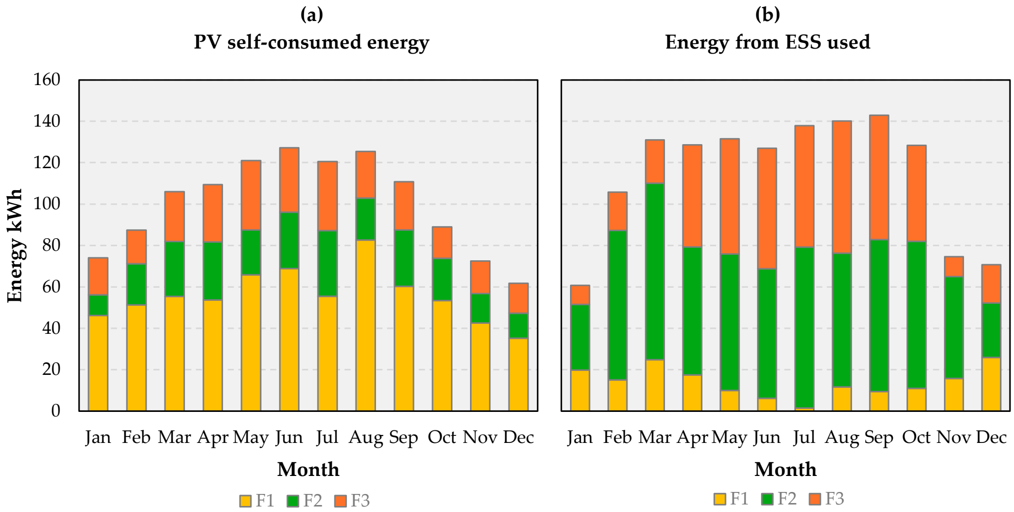

Figure 15. Instantaneous energy usage: (**a**) shows energy directly used from PV generation, (**b**) shows energy supplied by ESS.

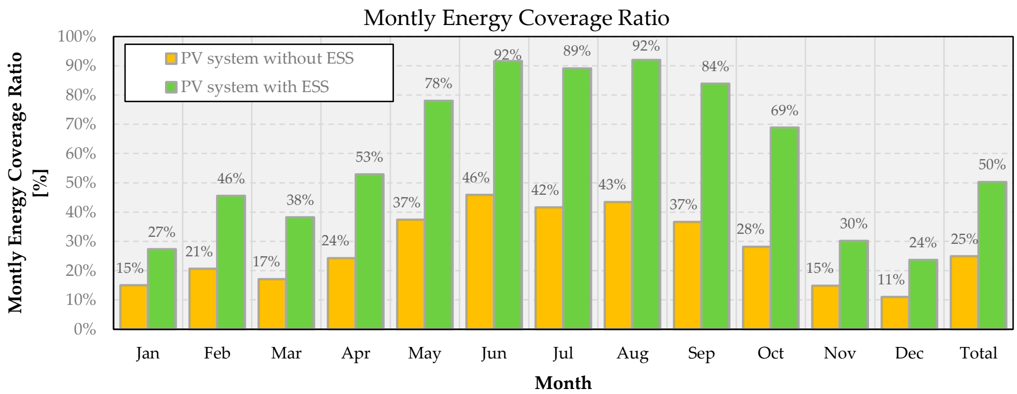

Figure 16. Monthly and annual self-sufficiency percentage.

The results underscore the effectiveness of the ESS in reducing grid dependence by better synchronising renewable generation with household electricity needs. The increased self-consumption facilitated by the ESS supports both economic savings and a reduction in the environmental footprint of energy use.

Figure 16 summarises the seasonal effect of ESS integration: despite limited PV production in winter months, the ESS still ensures a self-sufficiency increase exceeding 12% during critical months (November–February), thereby optimising the utilisation of available renewable generation.

4.5. Electricity Drawn from the External Grid (PV with ESS)

Figure 17 presents the quantification of electricity drawn from the external grid in the presence of a PV system with ESS, broken down by tariff TOU bands and for each month. Additionally, it includes the percentage of electricity purchased from the grid relative to the total consumption for each time band and for the overall monthly consumption. A direct comparison with Figure 14 (related to the scenario without ESS) highlights the substantial reduction in dependence on the external grid enabled by the integration of the ESS. On an annual basis, the total electricity purchased from the grid with ESS amounts to 2248.4 kWh/year, representing 46.5% of total consumption, significantly lower than the 3627.5 kWh/year (75.1%) recorded without ESS.

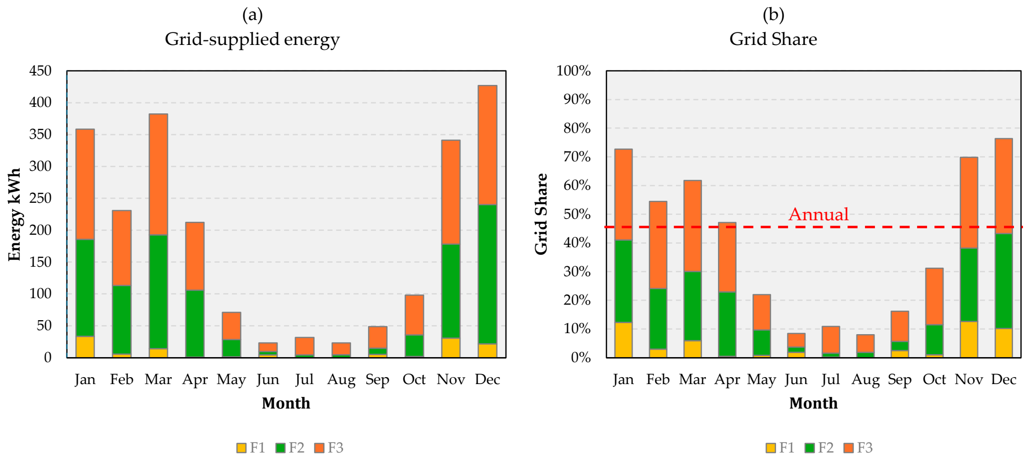

Figure 17. Drawn electricity from the external grid in the presence of a PV with ESS system.

In TOU band F3, a marked reduction is observed, with grid purchases falling from 1604.0 kWh/year to 1135.3 kWh/year (−29.4%). This shows that the ESS effectively stores daytime solar production, making it available later, especially at night and on weekends. Despite this improvement, complete independence from the grid is not achieved, due to the limited ESS capacity (5.76 kWh) and the persistence of residual nighttime energy consumption. Grid reliance in F1 is also notably reduced, from 287.8 kWh/year without ESS to 119.0 kWh/year with ESS (−58.6%), indicating a more efficient use of peak-hour PV generation through immediate consumption and energy shifting. Similarly, in F2, the electricity drawn from the grid decreases from 1735.7 kWh/year to 994.1 kWh/year (−42.7%), demonstrating the system's improved ability to rely on solar energy when it is most needed. As shown in Figure 18, the ESS implementation drives a consistent reduction in grid dependence across all months, with particularly intense improvements during high-production periods. In June, total electricity purchased drops to only 23.3 kWh (8.4%), while in August it reaches a minimum of 23.1 kWh (8.0%). Even in winter, the ESS delivers meaningful reductions. For example, in December, the grid contribution falls by 14.2%, from 497.8 kWh (without ESS) to 427.1 kWh.

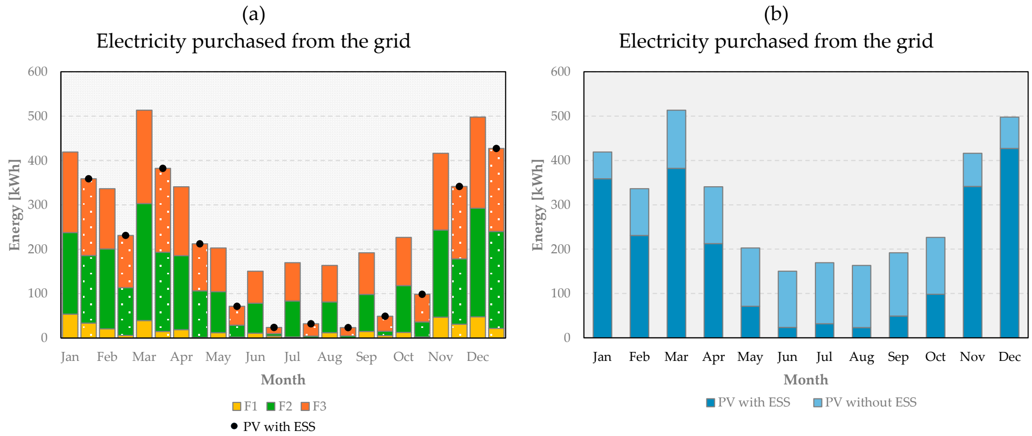

Figure 18. Monthly electricity purchased from the grid with and without ESS.

4.6. Surplus Energy Exported to the Grid (PV with ESS)

Figure 19 reports the monthly surplus energy exported to the grid under two scenarios: PV generation without ESS and with a 5.76 kWh ESS. The values are disaggregated by TOU tariff bands and presented as monthly and total annual figures. The data illustrate the reduction in exported surplus when ESS is integrated. In the absence of ESS, the system exports 2557.4 kWh/year, equivalent to approximately 68% of the total PV generation

(3762.0 kWh/year). This is a consequence of energy production exceeding demand during periods of low or no consumption, especially in high-production months such as June and July. By contrast, when ESS is deployed, the amount of exported energy drops to 1034.8 kWh/year, corresponding to 27.5% of annual generation. The most notable reductions are observed in the summer months, particularly July, where exported energy falls from 376.7 kWh to 227.2 kWh (−39.7%). Similar patterns are evident in other peak months such as June and August. Even in months with relatively low production, such as March and April, the integration of ESS more than halves the amount of energy exported.

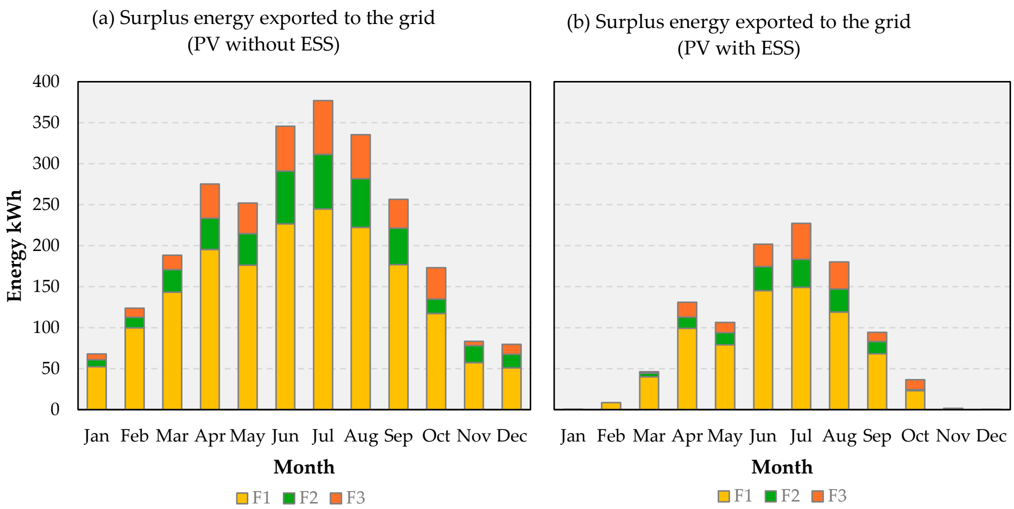

Figure 19. Monthly surplus energy exported to the grid (with and without ESS). The bars show absolute values in kWh, disaggregated by TOU tariff bands and month.

TOU-band analysis further underscores the benefits of storage integration. Without ESS, energy is exported even during peak periods (F1), whereas with ESS, exports during F1 are significantly reduced. This suggests that the ESS is not only capturing surplus generation but also reallocating it to meet peak-period demand internally. In winter months like December and January, the effect is more pronounced: exported energy nearly vanishes with ESS as virtually all generated energy is either consumed or stored to meet the building's needs.

The ESS improves energy autonomy, reduces grid draw, and minimizes grid injections, contributing to issues such as voltage regulation and network balancing on the distribution level. The reduction in surplus export also implies reduced dependence on feed-in tariffs or net metering schemes, further enhancing the economic resilience of PV systems [8].

4.7. PV Energy Utilisation Analysis (PV with ESS)

In addition to the information presented in the previous paragraphs, Figure 20 illustrates the breakdown of the energy produced by the PV system into the following components: instantaneous energy consumed by the properties, energy drawn from the ESS and used, and energy exported. The share of energy consumed instantaneously by the properties ranges from a minimum of 24.2% in July to a maximum of 52.2% in January. Energy supplied by the ESS varies between 27.9% in June and 53.3% in December. Exported energy exhibits the greatest seasonal fluctuation, ranging from 0.2% in December to a peak of 46.8% in July, a period characterised by PV generation significantly exceeding both immediate consumption and ESS capacity. During the winter months (January, November, and December), nearly all the generated energy is consumed locally, whereas between March and October, a substantial amount of energy is exported to the grid, benefiting the wider community.

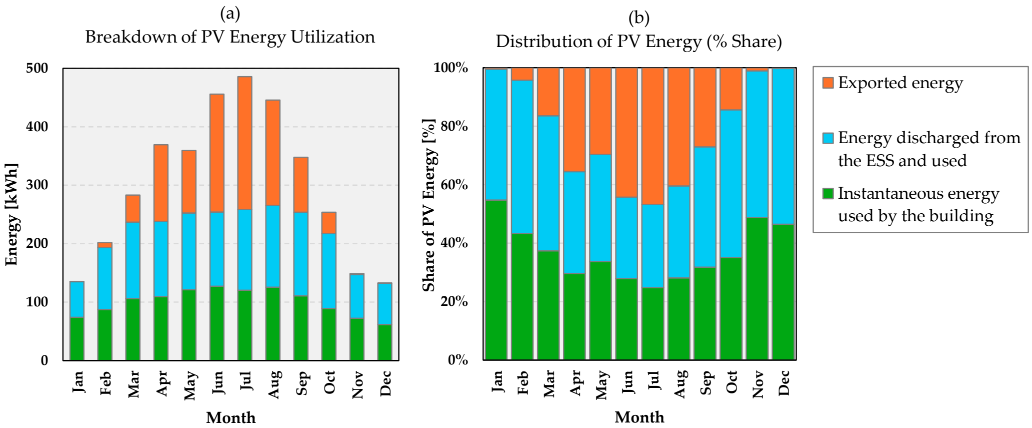

Figure 20. Monthly distribution of PV energy utilisation, shown as (**a**) absolute values in kWh and (**b**) percentages of total PV generation. The energy is categorised into instantaneous self-consumption, energy discharged from the ESS and used, and energy exported to the grid.

4.8. Daily Breakdown (PV with ESS)

Seasonal changes not only impact PV output due to solar availability but also reshape daily consumption patterns as household routines and thermal needs evolve throughout the year, introducing additional variability into the system's energy dynamics. Figures 21–24 illustrate that during summer (June), production levels are high and often exceed immediate consumption, leading to energy surplus and ESS saturation, which results in increased grid export. Conversely, in winter (December), the minimal energy production makes the system highly dependent on the grid, with limited ESS recharging. Transitional seasons (April and September) show intermediate patterns, with production following seasonal trends and a more dynamic ESS operation. The temporal mismatch between generation and consumption remains a major challenge for maximising self-consumption.

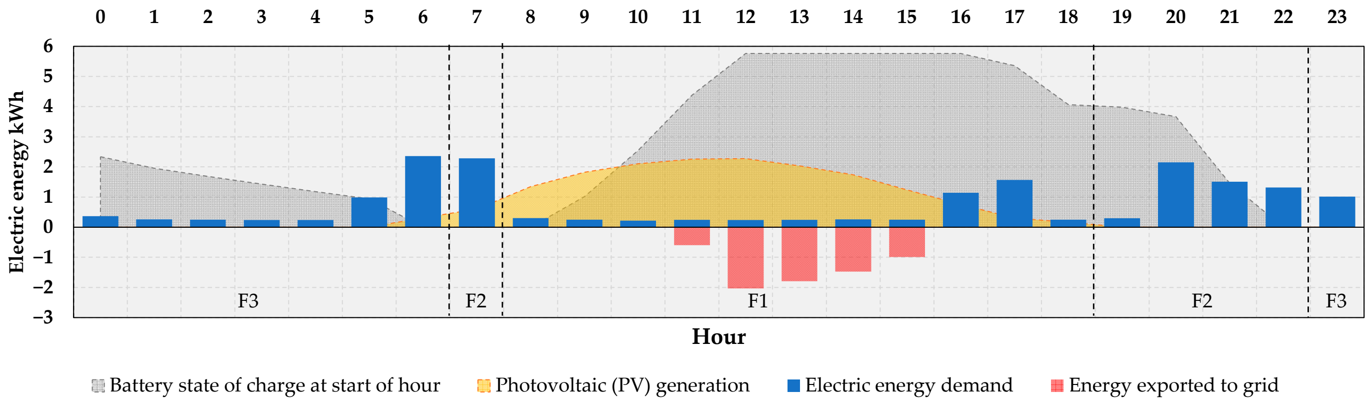

Figure 21. Hourly trend on 21 April: ESS state of charge, PV generation, electricity demand, and energy exported to the grid.

Self-consumption performance can be enhanced through demand-side management strategies, such as shifting loads to periods of peak generation. The analysis emphasizes the importance of considering not only the amount of energy generated, but also its immediate and deferred use via ESS, to reduce grid dependency and maximise both the economic and environmental benefits. The use of high-resolution data can be essential to understand the interaction between generation and consumption and to develop more precise seasonal optimisation strategies.

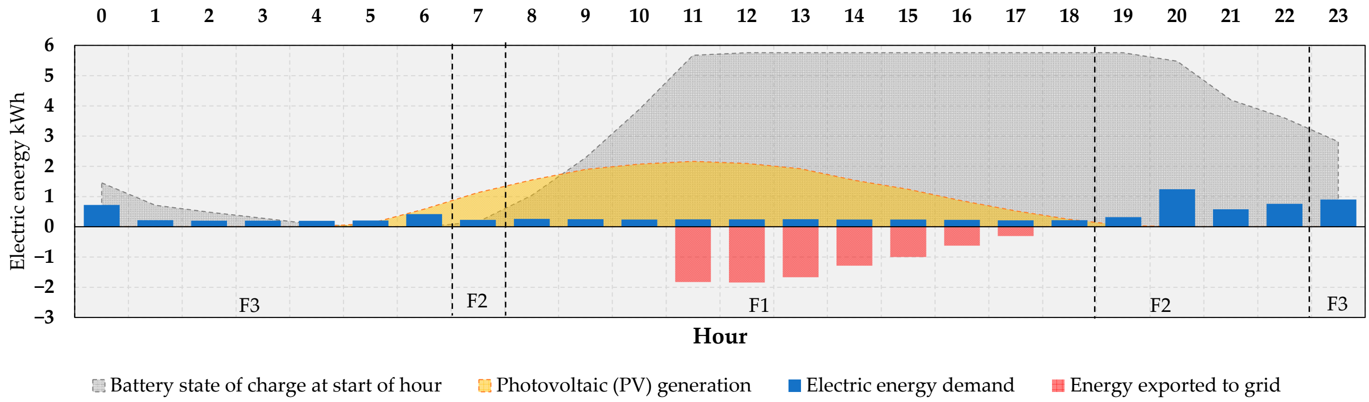

Figure 22. Hourly trend on 21 June: ESS state of charge, PV generation, electricity demand, and energy exported to the grid.

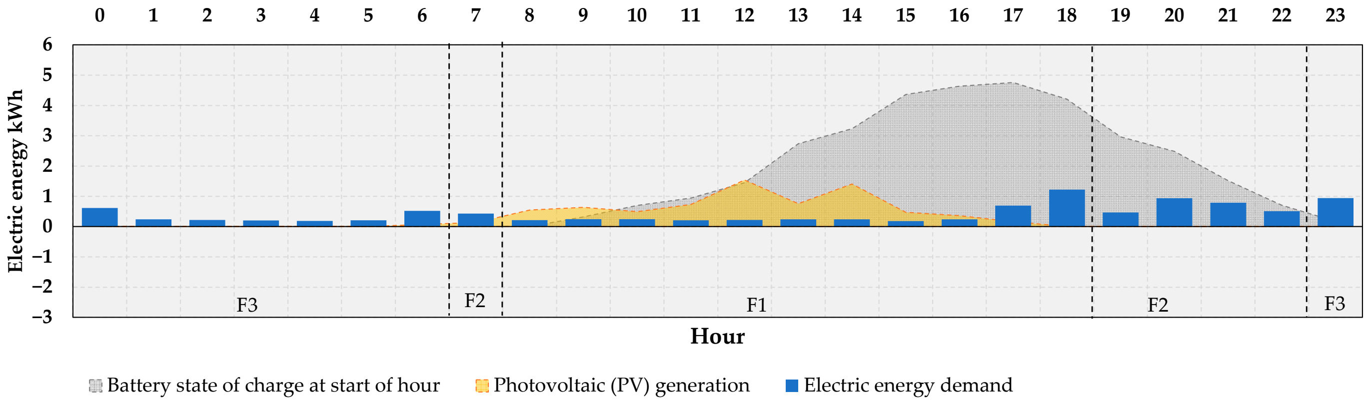

Figure 23. Hourly trend on 21 September: ESS state of charge, PV generation, electricity demand.

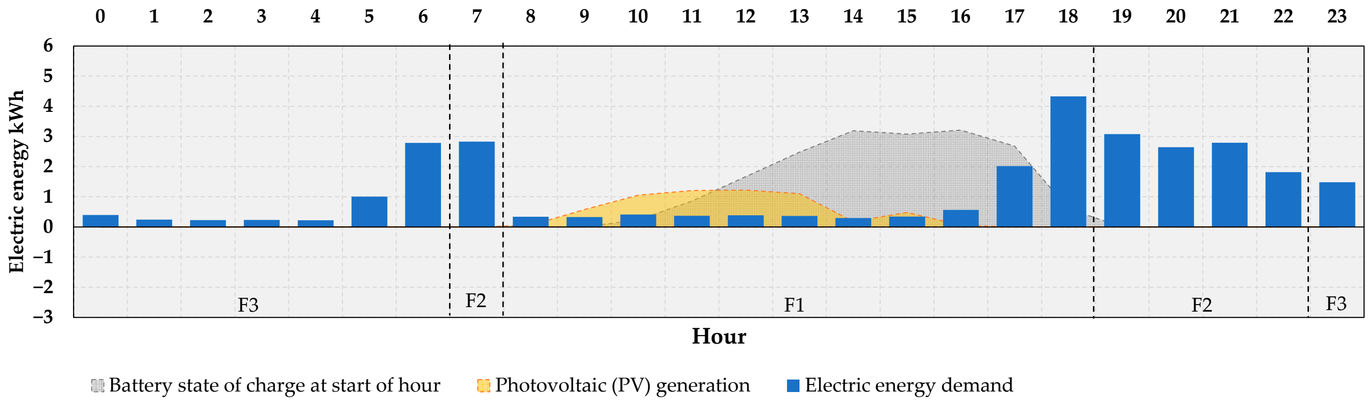

Figure 24. Hourly trend on 21 December: ESS state of charge, PV generation, electricity demand.

4.9. Economic Analysis

Table 3 presents the simple payback period results for the 3 kW_p PV system, both with and without ESS integration (5.76 kWh). The analysis is based on current market costs for turnkey solutions, including site inspection, design, installation, administrative procedures, insurance, and VAT [36]. The total costs considered were €5820 for the standalone PV system and €9890 for the PV with ESS configuration.

The results, calculated assuming no tax incentives, show a payback period of 10.5 years without ESS and 14.4 years with ESS ($LiFePO_4$ module). These findings align with Beltran et al. [37], whose annual simulations of residential PV with ESS systems demonstrate that state-of-the-art $LiFePO_4$ batteries have sufficient longevity to recover initial investments under real operating conditions, with useful lifespans exceeding 17.8 years (at 60% remaining capacity end-of-life threshold). While typical economic break-even points range between 8–12 years depending on country and tariffs, the 14.4-year payback period remains within the operational lifespan of modern $LiFePO_4$ systems.

Table 3. Simple Payback Time.

	Annual Savings from Avoided Grid Purchases	Revenue from Energy Sold to the Grid	Total Energy Savings	Payback Period
	€/Year	€/Year	€/Year	Year
3 kW_p solar system without ESS	271.8	283.7	555.5	10.5
3 kW_p PV system with ESS (5.76 kWh)	576.0	109.2	685.2	14.4

The economic trade-off between self-consumption benefits and reduced grid revenues explains the longer payback period for ESS-integrated systems. Table 3 quantifies this balance: ESS integration increases annual savings from €271.8 to €576.0 (+112%) through higher self-consumption rates but simultaneously reduces grid feed-in revenues from €283.7 to €109.2 (−61%), as stored energy is consumed on-site rather than exported. This dual effect results in a net annual benefit that, while positive, is insufficient to offset the higher initial investment in the short term. Cucchiella et al. [38] confirm this pattern, finding that although PV with ESS systems can be economically viable, their Net Present Value typically remains lower than standalone PV configurations due to the substantial upfront cost of ESS.

However, several dynamic factors suggest that future payback periods will improve substantially. First, projected lithium-ion battery price reductions of 40–60% by 2030 [32] will directly reduce the initial investment gap between PV and PV with ESS systems. Figure 11 supports this trend, illustrating the historical decline in residential PV system costs in Italy, which has followed a similar trajectory. Second, electricity market conditions are evolving in ways that favor ESS adoption. Since mid-2024, Italy's fully liberalized residential electricity market has introduced greater price volatility (Figures 8 and 9), making grid electricity costs less predictable while feed-in tariffs remain relatively stable or declining. This volatility increases the value proposition of self-consumption enabled by ESS, as consumers gain protection from peak pricing periods, a strategic benefit explicitly recognized by Directive (EU) 2024/1275 [1] in its emphasis on shielding consumers from fossil fuel price fluctuations. Third, emerging policy incentives for ESS installation and favorable self-consumption tariffs could further accelerate economic viability.

Beyond market dynamics, system optimization strategies can significantly reduce payback periods in practice. Proper PV sizing relative to household load profiles is critical for maximizing self-consumption and economic returns [39,40]. Furthermore, Demand Side Management practices that strategically shift consumption to align with PV generation periods can enhance both self-consumption rates and overall profitability [14,41]. These operational optimizations, combined with declining ESS costs and supportive policy frameworks, suggest that the current 14.4-year payback period represents a conservative baseline that is likely to improve considerably in the near future.

The economic analysis does not take into account the performance degradation of the solar thermal panels and the solar storage system.

To assess the robustness of the economic results, a sensitivity analysis was carried out by repeating the calculations using the updated 2024 electricity prices. Compared to 2023, the average cost of imported electricity decreased by approximately 34%, while the remuneration for electricity exported to the grid increased by 17.9% in F1, 17.2% in F2, and

20% in F3. The investment costs of both configurations (PV-only and PV with ESS) were kept constant, and the same 15 min load profile and climatic conditions used in the 2023 baseline scenario were maintained. This ensures that the sensitivity analysis isolates only the effect of energy price variations on the economic indicators.

Under the 2024 price scenario, the PV system without storage yields an annual revenue of €251.6 from exported surplus electricity and generates €183.3 of annual savings through avoided electricity purchases, resulting in a simple payback period of 13.4 years. When the 5.76 kWh battery storage unit is included, the annual revenue from exported energy decreases to €101.4, while the savings associated with increased self-consumption rise to €389.7. However, despite the higher self-consumption rates, the larger investment cost leads to a longer simple payback period of 20.1 years for the PV with ESS configuration.

These findings indicate that the economic performance of both configurations is highly sensitive to variations in energy prices. In particular, the significant reduction in the cost of imported electricity in 2024 reduces the economic value of self-consumed PV energy, leading to a more pronounced increase in the payback period of the PV with ESS system compared to the PV-only option.

5. Discussion

While this research presents the analysis of a single case study, the main contribution lies not in the specific numerical results but, rather, in the methodological approach used to develop the calculation tool. By combining publicly available high-resolution consumption data from the ARERA national Consumption Portal with sub-hourly PV production and ESS simulations, the proposed method is both replicable in the Italian context and adaptable to different contexts. This approach enables households, designers, and policymakers to realistically assess self-consumption potential, ESS sizing, and economic feasibility based on real consumption profiles, rather than relying solely on synthetic or simulated data.

In general, the results of this research confirm the structural misalignment between PV generation and household electricity demand, a challenge consistently observed in the literature [11,16,19,42,43]. Specifically, in the absence of an ESS, the simulated PV system directly covers 24.9% of the household's annual electricity demand (self-sufficiency), while the self-consumption rate amounts to 32.0% of the total energy generated.

These values should be interpreted within the broader context of existing literature, as results can vary significantly depending on factors such as climate, building characteristics, building's function, load profiles, prosumer's consumption habits, and PV system sizing [14,44]. The values fall within the typical baseline self-consumption rates for residential PV systems, generally ranging from 30% to 40% [12].

As an example of contextual variation, studies focusing on detached houses in Spain [44] show that a favourable alignment between hourly consumption and PV production curves, without ESS, can yield a self-consumption rate up to 21.05% and self-sufficiency up to 29.6%.

Integrating an ESS system significantly enhances on-site energy usage [6,14,43,45,46]. In our case study, the PV system achieved an annual self-consumption rate of 32.0%, rising to 68.7% when coupled with a 5.76 kWh ESS. Similarly, annual self-sufficiency increased from 24.9% without ESS to 53.5% with ESS. This increase is consistent with similar findings where the integration of an ESS in a residential building increased the self-consumption rate from 31% to approximately 60% [45]. The impact of the ESS is particularly pronounced during the F3 Time-of-Use (TOU) band, where the annual coverage of electricity demand increases markedly from 14.6% to 39.6%, thereby addressing the temporal gap between PV generation and evening/nighttime consumption.

Despite the notable technical gains, the economic analysis confirms that integrating an ESS often results in longer payback periods due to higher investment costs [16,17,38,47]. In our study, the simple payback period extended from 10.5 years (PV-only) to 14.4 years (PV with ESS). This result falls within the typical range reported in the literature for residential ESS systems, which is generally between 6 and 15 years [47]. High upfront costs and the relatively limited operational lifespan of ESS units continue to pose significant limitations to immediate financial viability [17].

Nevertheless, this economic outlook is projected to improve substantially in the near future. Investment costs for "behind-the-meter" ESS systems in the EU are expected to decline by around 20% by 2030 [48,49], while total installed costs for PV systems are projected to decrease by over 40% by 2029 [49,50]. These anticipated reductions will alleviate current financial barriers. Furthermore, dynamic factors such as the growing adoption of electric vehicles (EVs), which allows for load synchronization with PV production, and the increased price volatility in Italy's liberalized electricity market enhance the financial value of ESS-enabled self-consumption. This increased self-sufficiency offers consumers critical protection from fossil fuel price fluctuations, a strategic benefit recognized by Directive (EU) 2024/1275 [1].

Refs. [19,43] highlighted the importance of high-resolution data in accurately capturing the temporal dynamics between PV generation and household demand. Simulations based on coarser temporal resolutions (e.g., annual, seasonal, or hourly averages) may overestimate the potential for self-sufficiency, as they fail to fully reflect the real-time discrepancies between generated and consumed electricity. Conversely, the use of sub-hourly data (15 min) enables more realistic assessments of these mismatch effects and provides a clearer picture of the actual system performance under real operating conditions.

The contribution of this study is twofold: (1) It introduces a replicable method that combines real 15 min-interval consumption data, which in Italy can be collected through the national ARERA portal, with simulated PV generation and ESS operation. (2) Through a case study, it integrates a comprehensive technical and economic analysis, assessing the effect of ESS on self-consumption and grid dependence, as well as the payback period under current market conditions and hourly tariffs.

We acknowledge practical limitations: in the case study, full grid independence was not achieved due to seasonal and nighttime residual demand. Moreover, the calculation model was applied to a single household profile and specific PV/ESS dimensions primarily to validate the methodology. Future research should expand this framework to include diverse consumption profiles, the integration of Demand-Side Management (DSM) strategies, and the application of this methodology to energy communities comprising multiple buildings (residential, commercial, public), as encouraged by Directive (EU) 2024/1275 [1].

6. Conclusions

This study presents and applies a replicable methodology for evaluating the self-consumption potential and cost-effectiveness of PV systems by combining real 15 min-interval consumption data with sub-hourly production and ESS simulations. A calculation tool has been developed based on methods recognized by national standards, making it fully replicable using the provided formulas. Unlike many existing studies that rely on synthetic or simulated demand profiles, often at hourly or coarser resolutions, our approach uses publicly available data from the ARERA national Consumption Portal, providing a realistic view of the temporal mismatch between PV generation and household demand in a Mediterranean context.

The case study, used to validate the methodology, illustrates a concrete example of the importance of a sub-hourly assessment when heat pump systems are powered by a PV system with battery storage.

The integration of the ESS nearly doubles on-site energy utilization performance. The self-consumption rate increases from 32.0% to 68.7%, while the self-sufficiency rate rises from 24.9% to 53.5%. Dependence on the external grid is significantly reduced from 75.1% to 46.5% on an annual basis, with grid imports dropping by 38.0% and energy exports by 59.5%. The ESS has a particularly pronounced impact during nighttime hours and weekends (F3 tariff period), where demand coverage increases substantially from 14.6% to 39.6%, demonstrating its capability to bridge temporal gaps in the absence of solar irradiation.

A preliminary economic analysis, considering a turnkey cost of €5820 for PV-only and €9890 for the PV with ESS configuration, reveals the associated financial trade-offs. While the ESS increases annual savings due to higher self-consumption (from €271.8 to €576.0, a 112% increase), revenues from surplus energy sales decrease markedly (from €283.7 to €109.2, a 61% reduction). This combined effect results in an extended payback period, from 10.5 years for PV-only to 14.4 years for PV with ESS.

To evaluate economic robustness, a sensitivity analysis was conducted using 2024 energy prices. In this scenario, characterized by a 34% reduction in the average cost of imported energy, the payback period for PV-only increases to 13.4 years, while that for the PV with ESS system extends to 20.1 years. These findings underscore the high sensitivity of PV with ESS system profitability to fluctuations in grid electricity prices, which diminishes the economic value of self-consumption in the absence of fiscal incentives. Beyond the specific numerical results, the main contribution of this work lies in demonstrating that realistic assessments of PV systems can be performed using real sub-hourly consumption data, which better capture daily and seasonal demand dynamics compared to simulated or averaged profiles. This transparent and replicable method can support designers, households, and policymakers in evaluating ESS sizing, economic feasibility, and potential policy incentives, without requiring complex modelling or proprietary data.

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Abbreviations

ESS	Energy Storage System
PV	Photovoltaic System
TOU	Time-of-use

Appendix A

Table A1. Characteristics of the electrical storage system (ESS) used in the case study.

Electrical Characteristics	
Battery type	LiFePO4 Prismatic cell
Nominal capacity [Wh]	5760
Nominal voltage [V]	115.2
Operating voltage [V]	97.2~131.4
Recommended discharge current [A]	25
Maximum charge/discharge current [A]	50
Peak discharge current [A]	65@30se
Battery pack round-trip efficiency [%]	>95
Depth of discharge [%]	90
Life cycle	>6000
Operating conditions	
Installation location	Outdoor/Indoor
Operating temperature [°C]	Charging: 0~55 Discharging: −10~55
Storage temperature [°C]	−20~55
Cooling method	Natural ventilation
Humidity [%]	5~95
Altitude [m]	Max. 2000

Table A2. Characteristics of the reversible heat pump used in the case study.

General Technical Data	
Rated heating capacity [kW] (1)	5.85
Total power consumption [kW] (1)	1.46
COP EN14511 (1)	4.01
Cooling capacity [kW] (2)	4.40
Total power consumption [kW] (2)	1.06
EER EN14511 (2)	4.15
Heating capacity [kW] (3)	5.30
Total power consumption (3)	1.74
COP EN14511 (3)	3.05
Cooling capacity [kW] (4)	3.70
Total power consumption [kW] (4)	1.28
EER EN14511 (4)	2.89
ESEER (4)	4.00

(1) System water temperature 30/35 °C, outside air temperature 7 °C DB/6 °C WB; (2) System water temperature 23/18 °C, outside air temperature 35 °C DB; (3) System water temperature 40/45 °C, outside air temperature 7 °C DB/6 °C WB; (4) System water temperature 12/7 °C, outside air temperature 35 °C DB

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