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Technical Design Report for a Photovoltaic Self-Consumption Installation with Surplus Injection

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Abstract. This technical report documents a photovoltaic (PV) installation with self-consumption and surplus injection installed in Spain, which was designed for residential consumption and started up in an isolated single-family home with connection to the electricity distribution grid. Photovoltaic solar panels, inverter, lithium-ion batteries and a bidirectional meter have been integrated by this system. The report details the system's technical requirements, energy flow, electrical calculations, economic analysis and compliance with Spanish regulations.

Key words. Solar, battery, two-way, metering, self-consumption.

1. Introduction

Renewable energies play a crucial role in the transition towards a decarbonized energy system, with solar technology at the forefront. This project aims to generate electricity for self-consumption by exporting the surplus energy to the distribution network, in compliance with Royal Decree 244/2019 [1], which regulates self-consumption facilities in Spain.

The main design requirement is to have enough free area for solar panels installation, this condition is accomplished by detached or semi-detached single-family homes. Spain at 2020 had more than 6 million of this kind of homes [2], which means 32% of Spanish homes. In order to address European decarbonisation policies, the implementation of renewable energies in most of these homes could be beneficial for the energy transition.

There are several objectives to be reached, for instance, to reduce household electricity costs through optimized self-consumption, inject surplus power into the grid for financial compensation, enhance energy resilience with battery storage, minimize environmental impact through clean energy production and analyse economic feasibility and Return On Investment (ROI) [11] [3].

2. Literature review

Nonnenmacher, Tom & Nelson, Jenny & Winchester, Benedict. (2023) [3] explores strategies to maximize the return on investment for domestic photovoltaic systems. It emphasizes the importance of load management and proposes an incremental approach to align energy consumption with PV production. The research highlights that real-time energy use decisions can lead to significant savings and demonstrates that advanced device management strategies can result in over 17% cost savings compared to standard approaches.

Galilea, Carlos & Pascual, Julio & Berrueta, Alberto & Ursua, Alfredo & Marroyo, Luis. (2019) [4]. In this paper, an economic analysis for four houses with a PV self-consumption system with and without Li-ion batteries is carried out. In particular three different ways of sizing PV and batteries are analysed under three different billing scenarios for the compensation of surplus energy injected into the grid. The results show how the battery cost and lifespan affects the final profitability of the system and what future evolution in these factors is needed for making these systems profitable under different billing methods.

Roldan-Fernandez, Juan & Burgos-Payán, Manuel & Santos, Jesús.[5] consider to assess the profitability of residential PV self-consumption in Spain. To achieve that goal the hourly profiles of demand and PV self-production for an average dwelling have been elaborated based on one-year data from the System Operator. Our findings highlight that a 1.5-2 kW-peak PV commercial self-consumption kit yields to an optimum net billing situation for an average dwelling, which means an effective saving of the previous electricity bill.

López Prol, Javier & Steininger, Karl. [6]. PV self-consumption will play a key role in the transition to a low-carbon energy system. Spain, whilst among the EU countries with highest solar irradiation, has recently passed one of the most restrictive self-consumption regulations. The study of implications of this regulation in comparison with alternatives (net metering, net billing) on the profitability (internal rate of return) of potential residential, commercial and industrial investors, as well as the impact of PV self-consumption on government revenues and the electricity system shows this regulation hinders the diffusion of PV self-consumption applications by making them economically infeasible. It also creates inefficient disincentives for demand-side adjustment. To raise compliance with the relevant European Commission guidelines and to promote the diffusion of PV systems at minimum cost to the electricity system, a dynamic net billing scheme is recommended.

3. System overview

This report presents a study case as reference to analyse the self-consumption solar installation taking a real case implemented in Colmenar Viejo, Madrid, that operates as a grid-connected system with surplus injection, located at Latitude: 40°39' N, Longitude: 3°36' W, Altitude: 630 m. The home has an area of 308 m², with 220 m² of floor heating installed. It adheres to technical and regulatory standards (UNE, IEC, CE certifications) [7] to ensure electrical safety and efficiency. A residential PV installation involves several key steps to ensure optimal energy production, cost efficiency, and compliance with regulations. The process includes assessing energy needs, site conditions, components selection, system sizing, and installation.

To define an installation based on the needs of the property in question, a detailed analysis of its electrical consumption must be carried out, and thus define the amount of electricity that the Photovoltaic Installation must be able to generate, and be able to determine what useful surface will be necessary for the assembly of the photovoltaic modules (useful generation surface). Taking into account that a solar photovoltaic installation generates electricity during radiation hours (daytime), depending on how electrical consumption is distributed throughout the day, it should be necessary to have an electrical storage system which allows to accumulate the electricity generated by the photovoltaic installation that is not consumed instantly, and has able to consume when it is really necessary. The surface of the roof available for photovoltaic panels is 200 m2 with two slopes, the first one of 18º and the second one of 25º, both slopes with inclination towards the south. The main front of the building is South North.

The estimated annual electricity consumption of the home (according to the data provided) is around 9.600 kWh/year, spread over the 12 months of the year as shown in the following graph:

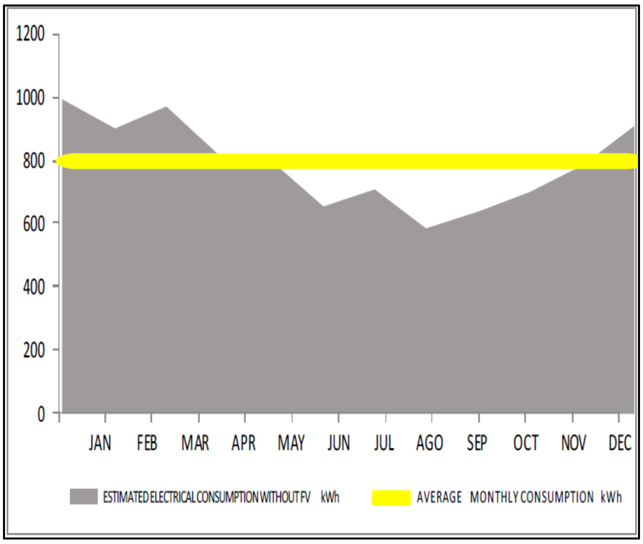

Fig. 1. Schematic representation of annual electrical consumption

4. Design methodology

In order to maximize savings in electricity consumption without oversizing the PV system, the installation of an electricity storage system is proposed, which will allow the electricity generated to be used to the maximum and used to supply the consumption at home, made up of batteries, where the electricity that is not consumed instantly is stored. With the installation of an accumulation system, the following is achieved: manage the electricity generated by the installation and reduce electricity consumption when the electricity generated throughout a day is greater than the electricity consumed. Use 100% of the electricity generated to supply consumption when it is less than the electricity consumed.

For sizing the system calculate the required PV capacity based on daily and annual electricity needs, considering the solar irradiance (kWh/m²/day) from PVGIS [8] in the location.

To calculate PV power is used the equation:

$$\text{PV Capacity (kW)} = \frac{\text{Daily Energy Consumption (kWh/day)}}{\text{Peak Sun Hours (hours/day)}}$$

Including system losses (typically 10–20%) due to inverter inefficiencies, wiring, and dust.

To calculate the electricity generated by the Proposed PV system, the following formula has been used (recommended in the "Technical Specifications for Grid-Connected PV Installations" of the IDAE) [9]:

$$E_p = \frac{G_{dm}(\alpha, \beta) \times P_{mp} \times PR}{G_{CEM}} \, kWh$$

Where:

E_p is the energy generated per day (kWh/day).
G_{dm} (α, ß) is the average daily solar radiation (kWh/(m²·day).
P_{mp} (kW) is the Power of the Installation (kW).

PR (%) is the efficiency of the PV system, determined by:

The dependence of the efficiency on the temperature (efficiency of the modules).
The efficiency of the wiring.
The losses due to orientation/azimuth and dirt.
Losses due to shadows.
The energy efficiency of the inverter.
Others.

G_{CEM} = 1 kW/m²

According to the calculations, the power generation system will use 36.4 m², ≈ 40 m², composed of 14 PV modules, each with a unit power of 575 W, 7 of them with a slope of 25º and the other 7 with a slope of 18º, producing a total installed power (Pp) of 8,05 kWp.

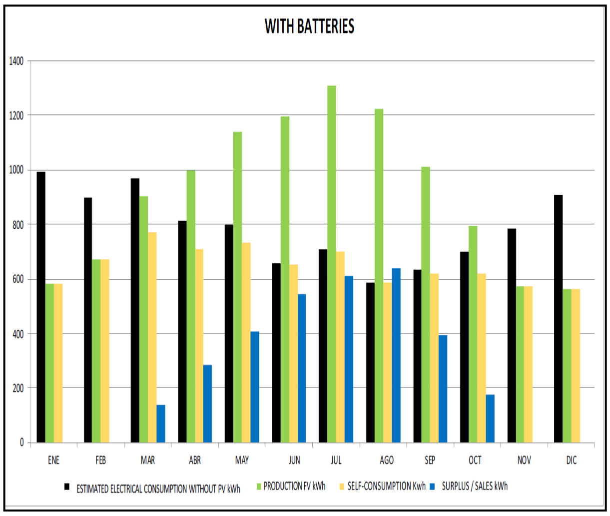

Fig. 2. Schematic representation of electrical consumption

4.1. Storage system and inverter device

A comparative study of the electrical consumption and generation of the Photovoltaic Installation has been carried out, with the aim of sizing the accumulation system, since approximately 60% of the electricity is consumed outside the hours of solar radiation, taking this fact into account, a Lithium-Ion Technology Storage System (Lithium batteries) is proposed, composed of a control module and a set of battery modules with a minimum storage capacity of 12,5 kWh.

The transformation and management system consists of a Monophase Hybrid Photovoltaic Inverter (battery charger), with a nominal power consumption of 6 kWn, capable of absorbing, for short periods of time, power peaks higher than the nominal power, which will operate automatically (using an integrated control system) according to the following scenarios [4]:

Scenario 1: If there is sufficient sunlight, the inverter covers the electrical demand, the surplus is used to recharge the storage system. If the batteries are charged, the surplus is injected into the grid.

Scenario 2: If there is not sufficient sunlight, the inverter covers the electrical demand by combining the electricity generated by the modules and the electricity stored in the batteries.

Scenario 3: If there is not sufficient sunlight and the battery is depleted or inhibited, the load is supplied by the grid through the inverter.

By implementing the described scenarios, efficiency and financial benefits can be further maximized.

4.2. System Overview Diagram

The graph, Fig. 3, shows a diagram of the distribution and orientation of the solar panel strings on the roof of the house, as well as their polarity towards the inverter.

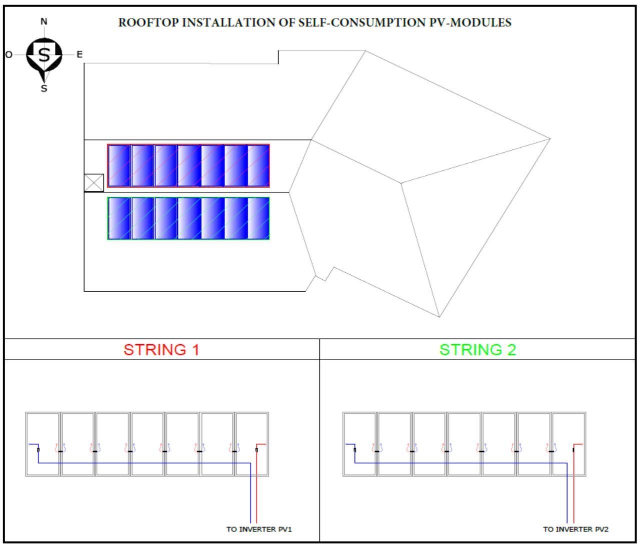

Fig. 3. Schematic representation of the rooftop PV system

4.3. Safety and Protection Devices

Overcurrent protection is managed by 32A fuses and miniature circuit breakers (MCBs); the grounding system is a single earth electrode with a calculated resistance of 25 Ω. Olso has an anti-reverse power flow system enabled to meet grid standards. The maximum power point tracker (MPPT) has an efficiency of 99,9% and the protection functions are anti-islanding, grid monitoring and insulation resistance monitoring.

5. Energy production and consumption analysis

Energy production is highest in summer due to higher solar irradiation, the battery storage ensures stable self-consumption throughout the year, and the surplus energy injection peaks in summer due to maximum solar output

The expected annual energy production and consumption are detailed in Table I below.

Table I: - Expected annual energy generation and usage

Parameter	Estimated Value (kWh)
Annual Energy Generation	12.074,09 kWh
Annual Self-Consumption	8.797,20 kWh
Surplus Energy Injected to Grid	3.099,43 kWh

The maximum production peak occurs in June and July, corresponding to increased solar irradiation, and the Self-consumption remains steady, optimizing battery usage. The Grid exports peak is in summer, aligning with maximum solar availability.

The following graph, Fig. 4 illustrates the monthly system's energy generation, self-consumption, and grid exports.

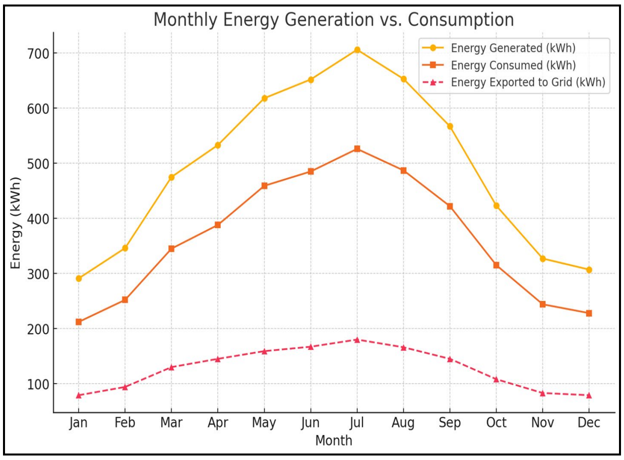

Fig. 4. Energy generation, self-consumption and grid export

6. Electrical circuit design and voltage drop analysis

The Single-Line Diagram (SLD) in Fig. 5 illustrates the system's electrical wiring, protection devices, and interconnections.

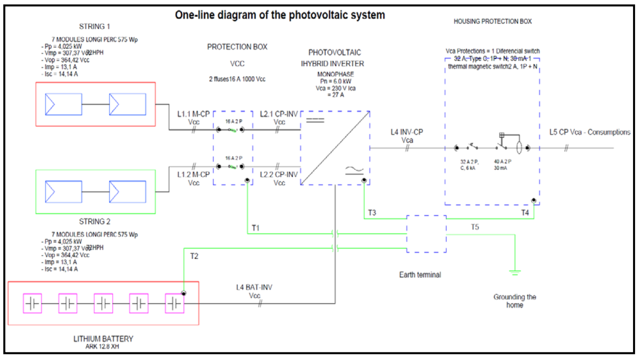

Fig. 5. System's Electrical Wiring and Protection Components

The string cables have 4 mm² of diameter for DC transmission; the AC distribution cables have 6 mm² of diameter for grid and household loads. Voltage drops is maintained below 1,5% for efficiency.

Voltage drop calculations were performed to verify efficiency. Results are summarized in Table II below.

Table II: - Summary of voltage drop calculations

Circuit	Power (kW)	Length (m)	Cable Section (mm²)	Current (A)	Voltage Drop (V)	Voltage Drop (%)
L1.1	4,03	25	4	17,68	1,9051	0,8283
L2.1	4,03	25	4	17,68	1,9051	0,8283
L1.2	4,03	5	4	17,68	3,8103	0,1657
L2.2	4,03	5	4	17,68	3,8103	0,1657
L3	6,25	3	6	25,00	2,1551	0,0937
L4	6,25	5	6	30,19	0,4338	0,1886
L5	6,25	15	6	30,19	1,3013	0,5658

These values confirm compliance with voltage drop standards (< 2%), ensuring minimal energy losses.

7. Economic analysis and ROI calculations

The table III below presents the initial investment and economic parameters used for ROI calculations.

Table III: - Economic Parameters for ROI Calculations

Investment Costs	
Component	**Cost (€)**
Solar Panels (14 units)	5.600,00
Inverter (Hybrid, 6 kW)	1.800,00
Battery Storage (12,8 kWh)	11.277,00
Installation & Labor	2.000,00
Miscellaneous Equipment	1.100,00
Total Initial Investment	19.735,00
Annual Savings and Revenue	
Parameter	**Estimated Value (€)**
Annual Self-Consumption Savings	1.320,00
Revenue from Grid Injection	465,00
Maintenance & Operational Costs	-150,00
Net Annual Savings	1.635,00

The ROI and simple payback period (SPP) calculations help determine the financial feasibility of the photovoltaic system. ROI measures the system's profitability over its lifetime, while SPP indicates the number of years required to recover the initial investment through savings and revenue. The ROI and SPP are calculated as:

$$ROI = \frac{\text{Net Annual Savings} \times \text{Lifetime (Years)}}{\text{Total Investment}}$$

$$SPP = \frac{\text{Total Investment}}{\text{Net Annual Savings}}$$

Conducting a sensitivity analysis on photovoltaic (PV) system's, the economic performance provides insight into how variations in electricity prices and maintenance costs can impact the system's the ROI and SPP.

The Table IV shows a summary of calculations assuming a 20-year system lifetime and the baseline scenario for performing a sensitivity between 5% y -5%

Table IV: - ROI Scenarios for 20-year lifetime

Scenario	ROI (%)	Payback Period (Years)
Baseline	165,70%	11,8
5% Increase in Electricity Prices	171,20%	11,5
5% Increase in Maintenance Costs	164,60%	12,0
-5% decrease in Electricity Prices	160,10%	12,3
- 5% decrease in Maintenance Costs	166,90%	11,7

This analysis indicates that moderate fluctuations in electricity prices and maintenance costs have a relatively small impact on the system's economic performance. The

PV system remains a sound investment under these scenarios.

For an in deep assessment would be necessary analysing additional variables such as system degradation rates, and potential changes in government incentives or policies. [6]

8. Conclusions and recommendations

The main result, after the implementation of the PV generation system reported here, has been a great reduction in the cost billed for the electrical consumption of the home due to self-consumption, as can be seen in Fig. 6.

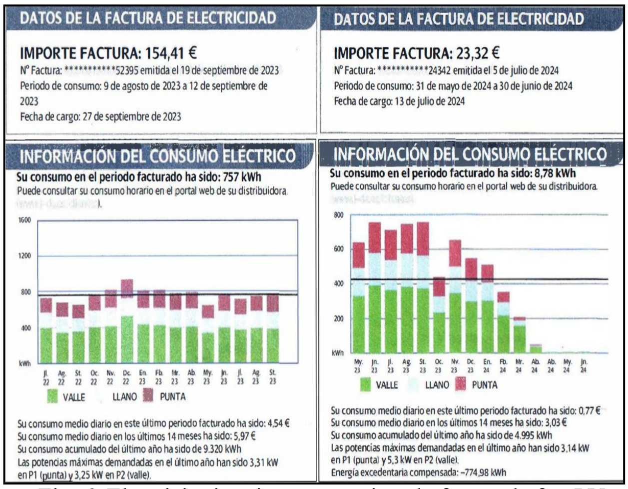

Fig. 6. Electricity invoices comparison before and after PV system installation

8.1. PV system conclusions

This study demonstrates the feasibility of a self-consumption PV system with surplus injection, achieving an optimal balance between energy independence and grid interaction.

With battery storage integration, self-consumption efficiency is enhanced, reducing grid dependency. The economic analysis confirms long-term profitability.

A well-designed residential PV system enhances energy independence, reduces electricity bills, and minimizes environmental impact.

Following a systematic approach ensures safety, efficiency, and regulatory compliance, ultimately leading to a successful solar energy installation.

8.2. PV system recommendations

Installation of smart energy management systems for enhancing battery charging efficiency.

Load profile optimization for reducing peak-hour consumption.

Perform expansion feasibility study for adding additional PV modules.

Acknowledgement

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