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Data-driven techno-economic analysis of rooftop photovoltaic systems in the Spanish residential sector at municipal level

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Abstract

The current energy transition goals set by Spain in the PNIEC 2021-2030 anticipate a photovoltaic (PV) installed capacity of 39 GW by 2030, against the installed capacity of about 9 GW in 2020. The global improvement of PV systems' cost-effectiveness coupled with the current escalation in energy prices and the high annual solar energy potential of Spain are positive drivers. Thus, there has been an acceleration in the deployment of PV in the country, where the installed capacity has increased by 72% in the last two years, up to 15 GW. To study the potential contribution of residential rooftop PV systems in the future Spanish electricity mix, a data-driven multi-regional tool has been developed in Python. The hourly net electricity production-consumption balance is obtained for one year by using specific hourly solar irradiation data and real hourly electricity consumption data for each of the 8,131 municipalities in Spain. Furthermore, the economic potential of such installations is evaluated with the consideration of different electricity market scenarios as well as surplus electricity compensation policies. The analysis of the results shows a capacity for self-consumption which is 3 to 4 times higher in rural areas than in urban areas when energy storage is not considered. Furthermore, the current compensation policies may negatively affect the economic profitability of PV systems in the areas with the most significant PV potential.

Keywords

Data-driven tool; Regional analysis; Rooftop photovoltaic; Self-consumption potential; Techno-economical assessment.

1. Introduction

According to *PNIEC 2021-2030* national plan [1], Spain aims to deploy 39 GW of PV power by 2030 in the country, a significant increase from the 9 GW capacity in 2020. To encourage self-production of energy through PV systems in the residential sector, legal changes and fiscal measures have been implemented recently, including a law passed in 2019 to regulate surplus energy fed into the grid [2] and subsidies announced in 2021 to cover a percentage of the cost of new installations [3]. These measures, combined with the improving cost-effectiveness of PV systems and rising electricity prices [4], have led to an increase in PV system installations for self-consumption in Spain of 72% over the past two years [5].

Spain has a heterogeneous population distribution, with 16% residing in rural areas and occupying 84% of the land, while 84% live in urban areas and occupy 16% of the land [6]. According to [7-10], this distribution will affect the deployment of PV systems in the country, as some areas have low population densities but large surface areas to install PV while others have high population densities but small surface areas to install PV. Therefore, challenges remain in optimizing the deployment and integration of solar PV systems into different regional energy systems. Decision-makers in Spain need to address key questions, including the contribution of individual PV systems to the energy transition, promotion of larger-scale solutions such as energy communities, and how solutions should differ in rural and urban areas.

Previous studies have examined the potential of solar PV systems in specific regions of Spain, such as the Canary Islands. One study [11] found that the islands' potential solar fraction (i.e., percentage of the total energy demand satisfied by solar energy) is about 150%, meaning that there will be an overproduction of energy from PV compared to current demand. The same study concludes that PV systems would be economically profitable on the islands even without policies to compensate for electricity surpluses. Another recent study [12] focused on Gran Canary Island examined a theoretical hybrid energy system based on PV, offshore wind turbines, and energy storage to support local electricity self-consumption, with positive results. However, its analysis of future electrification scenarios showed that the optimal weight of solar PV generation systems decreases as electricity demand increases in contrast to wind turbines.

Moreover, other studies have focused on PV self-consumption capacity at the municipal scale in urban areas of Spain, such as the cases of Seville [13], Irun [14], and Valencia [15]. In Seville, PV systems installed on the roofs of buildings (residential, services, and industrial) could virtually meet the electricity demand of the city.

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However, in Irun, only 59% of the city's demand could be covered by PV on building rooftops due to the prevailing climatic conditions. The study presented a sensitivity analysis of PV systems' economic profitability under three different surplus compensation policies: sole self-consumption, net-metering, and electricity transactions between buildings. The results showed that to achieve an investment return rate below 12 years, 27% to 71% of the roof surface area would need to be used, depending on the compensation policy. Meanwhile, the study of Valencia developed a multiple linear regression model to determine the economic payback of PV installations on residential buildings. The model identified shadow losses and power unit cost as the main factors affecting the payback period, which ranged between 7 and 15 years in most cases. High electricity demand buildings with low surpluses were found to be more profitable than those with large surpluses, due to the low economic compensation when injecting surplus electricity to the grid. The study suggested the promotion of energy communities to improve the profitability of PV systems.

At the national level, Gomez-Exposito et al. [16] evaluated Spain's potential for sustainable energy systems based on rooftop PV systems. The study highlighted the model's limitations due to the lack of hourly resolution energy demand data although it showed promising possibilities regarding a greener future in Spain.

With a careful review of the previous works on self-generation of electricity through PV systems, no work is yet to assess the impact of current Spanish surplus compensation policies on economic profitability and adoption. Additionally, no regional-level study has been conducted on the self-consumption capacity of the residential sector using massive data of real electricity consumption with hourly resolution. To address this gap, this work proposes a novel data-driven method to analyze the economic profitability and electricity self-production capacity using PV modules on residential rooftops, considering different compensation policies and flexible electricity prices. The analysis uses real hourly electricity consumption data from individual smart meters for all municipalities in Spain, allowing for higher resolution energy balances and individual analyses for each municipality. This enables the assessment and comparison of the capacity and profitability of rooftop PV between rural and urban areas.

2. Material and methods

Data from online databases are used to estimate the average electricity demand, rooftop surface availability, PV generation capacity, and solar fraction at different scales and regions. An economic analysis is conducted to find the optimal PV investment, calculating Net Present Value, Total Annual Cost, and Payback Period at the dwelling scale. Sensitivity analyses are performed for different scenarios of electricity prices and surplus electricity compensation policies. A Python-based software is developed to extract and process data automatically and generate tabular and graphic outputs for ease of analysis.

2.1 Architecture of the solution

Figure 1 illustrates the four main steps of the workflow: 1) Data collection, 2) Pre-processing, 3) Modeling, and 4) Analysis and visualization. Input datasets such as electricity consumption data, cadastral data, weather data, PV performance data, and economic data are collected in step one. Step two involves cleaning, filtering, and normalizing the collected data. In step three, the normalized datasets are combined to build the energetic and economic models. Finally, the techno-economic indicators are computed for all regions in Spain at the municipality level at hourly resolution.

2.2 Data processing

__Hourly electricity demand per dwelling:__ Equation (1) can be used to obtain the Average Electricity Consumption per Dwelling, E_{dw}, by assuming one electricity contract per dwelling. E_{dw} is derived from the hourly electricity consumption in a municipality, E_T, and is influenced by the number of consumers in the area, C.

$$E_{dw} = \frac{E_T}{C}. \tag{1}$$

__Rooftop availability per dwelling__: The average amount of available rooftop surface per dwelling in square meters has been determined for each of the 15 typical housing clusters proposed by [17] in Spain. This calculation utilized the "void fraction coefficient," "shadowing fraction coefficient," and "facility coefficient" proposed by [18]. These coefficients consider factors such as empty space, shading, and obstacles in rooftops.

__Hourly solar irradiation per square meter:__ Hourly solar irradiation data G in kWh·m^{-2} is obtained from the PVGIS platform [19]. Municipalities are reduced to one point (latitude and longitude) for simplicity when retrieving data. Solar PV modules are assumed to be installed horizontally to simplify the model by discarding the dependency of irradiation on the panel's azimuth angle and considering the associated decrease in efficiency for this configuration.

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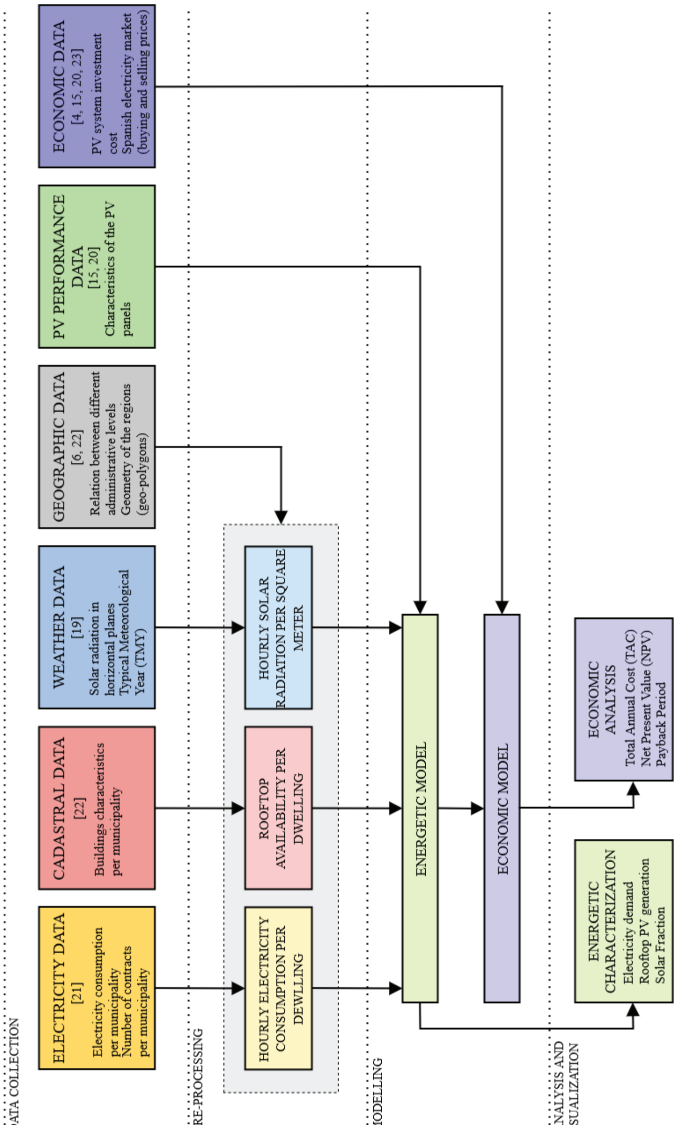

Figure 1. Workflow of the proposed method.

2.3 Techno-economic model

PV potential generation per dwelling. The PV potential per dwelling (in kWh) is determined by the percentage of rooftop surface (S_{PV}) covered by solar modules (load factor), hourly solar radiation (G) in kWh·m^{-2}, and the PV system performance factor (η). In the developed model, the rooftop load factor (α) ranges from 0% (no PV module) to 100% (full coverage of available roof surface). Equation (2) calculates the PV potential per dwelling (in kWh) for each observed hour *i*.

$$E_{PV,i} = G_i \cdot \alpha \cdot S_{PV} \cdot \eta. \tag{2}$$

Solar Fraction. The Solar Fraction represents the proportion of the annual energy demand that can be met by solar energy. Typically, this balance is calculated using annual average data of demand and PV production. However, studies have shown that analyzing the balance using hourly average data can provide valuable insights into the region's self-consumption estimation [16]. This study includes both methods: the one based on annual averages (SF_a, Eq. 3) and the one based on hourly averages (SF_h, Eq. 4).

$$SF_a = \frac{\sum_{i=1}^{j} E_{PV,i}}{\sum_{i=1}^{j} E_{d,i}} \cdot 100\%. \tag{3}$$

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$$SF_h = \frac{\sum_{i=1}^{j} \frac{E_{PV,i}}{E_{d,i}}}{j} \cdot 100\%. \tag{4}$$

where $E_{d,i}$ is the hourly electricity demand (in kWh) at each hour i, $E_{PV,i}$ is the hourly PV electricity production (in kWh) at each hour i, and j is the total number of hours in a year.

Net money flow. The hourly money flow (C_h) in EUR is determined in Eq. (6) at each hour i according to the price of electricity and the net hourly energy balance (E_h), calculated in Eq. (5) as the difference between electricity consumed (E_d) and produced (E_{PV}) in an hour. When the net hourly energy balance (E_h) is positive, the purchase price (P_p) is used in Eq. (6); but when the balance is negative, selling price is used (P_s).

$$E_{h,i} = E_{d,i} - E_{PV,i}. \tag{5}$$

$$C_{h,i} = \begin{cases} E_{h,i} \cdot P_p & if E_{h,i} > 0 \\ E_{h,i} \cdot P_s & if E_{h,i} < 0 \end{cases}. \tag{6}$$

Accordingly, the monthly money flow (C_M) in EUR is an aggregate of all the hourly money flows for the month for the number of hours I observed in that month:

$$C_M = \sum_{i=1}^{I} C_{h,i}.$$

(7)

Total Annual Cost TAC The Total Annual Cost (TAC) for a PV system in EUR includes the annualized costs of owning, operating, and maintaining the system. TAC is the sum of Investment Annual Cost (IAC) in EUR and operational cost (C_{ope}) in EUR, as shown in Eq. (8):

$$TAC = IAC + C_{ope}. \tag{8}$$

The IAC, as given by Eq. (9), is the result of the TIC after applying the Capital Recovery Factor (CRF) which is given by Eq. (10):

$$IAC = TIC \cdot CRF, \tag{9}$$

$$CRF = \frac{ir \cdot (1+ir)^n}{(1+ir)^n - 1}. \tag{10}$$

where IAC is the Investment Annual Cost in EUR; TIC is the Total Investment Cost in EUR; CRF is the Capital Recovery Factor; ir is the Interest Rate in %; and n is the lifetime of the project in years. In Eq. (8), C_{ope} refers the cost of electricity consumption, i.e., the electricity bill, where C_{fix} is the Monthly fixed costs in EUR by using Eq. (11):

$$C_{ope} = \sum_{y=1}^{12} \left[\left(C_{fix,y} + C_{M,y} \right) \cdot (1 + VAT) \right]. \tag{11}$$

It is worth mentioning that each state, region, etc., has its own policies and laws on surpluses that may affect Eq. (11). For instance, in the current Spanish scenario, the monthly money flow (C_M) is restricted to be a positive value [2].

Total Investment Cost TIC The total investment cost for one PV system includes the cost of all the hardware, the installation cost, and the maintenance cost, in Euro per peak watt (EUR/Wp) and it is obtained by using Eq. (12):

$$TIC = (1 + F_{ind}) \sum_{k=1}^{K} \left[C_c \cdot (1 + FNPV_k) \cdot \left(1 + F_{m,k}\right) \cdot (1 + VAT) \right]. \tag{12}$$

where:

- F_{ind} — Factor for the indirect costs of the project (e.g., engineering cost) and it is estimated as 0.2 [20].
- FNPV — Net Present Value Factor for the possible repositions of components during the lifetime of the project.
- F_m — Factor for installation and maintenance costs and it estimated as 0.01 [20].
- VAT — Value-added tax (specific for each country)
- K — the number of all the different components of in system

Net Present Value NPV. The Net Present Value for one PV system (in EUR) as determined by Eq. (13), gives the time value of money invested and the economic risk of the project.

$$NPV = -TIC + \sum_{y=1}^{n} \frac{C_Y}{(1+ir)^y} \tag{13}$$

where C_Y is the Net Money Flow for one year in EUR.

3. Case study

This methodology was applied to assess the PV potential and self-consumption capacity in all 8,131 municipalities in Spain, covering both rural and urban areas. The study estimated the net energy balance over one calendar year and evaluated the economic profitability of PV systems over a 20-year projection. Hourly electricity demand data for 2019 was obtained from the Datadis database [21] for each municipality, while solar radiation data was collected from meteorological data series from 2006 to 2015 [19]. The availability of rooftop surface was estimated using the latest data from the INE database (dated 2011) [22]. Electricity prices were based on trends in the Spanish wholesale electricity market from 2015 to 2021 [4], while the performance and investment costs of the PV system were based on up-to-date global benchmarking reports and other referential works [14,15,20].

It should be noted that complete data on electric demand and housing stock is not available for all 8,131 municipalities in Spain. 326 municipalities, mostly with populations under 500 and representing 0.79% of the country's population, lack complete electricity demand data for 2019 [21]. Meanwhile, 138 municipalities representing 0.09% of the population have no statistical data on the housing stock [22].

In order to facilitate the analysis, all municipalities have been classified into 11 hotspots based on their population size, as shown in Table 1.

Table 1. Population distribution of the municipalities in Spain.

Number of municipalities	Size of the municipality (Number of inhabitants)
1233	< 100
2521	101 to 500
968	501 to 1,000
848	1,001 to 2,000
931	2,001 to 5,000
548	5,001 to 10,000
499	10,001 to 20,000
110	20,001 to 50,000
84	50,001 to 100,000
57	100,001 to 500,000
6	> 500,000

3.1 PV systems' parameters

Table 2 presents the PV system performance parameters used in the techno-economic analyses, including peak power per square meter, system efficiency, and lifetime.

Table 2. Performance parameters of the PV systems considered for the analyses.

PV performance parameters	Value
PV system output peak power	200 W_p/m^2 [20]
PV system efficiency	20 % [20]
PV system lifetime	20 years [13,14,20]

Table 3 summarizes the economic parameters considered in the analysis, including the cost in EUR per peak watt installed, the operation and maintenance costs in EUR per watt per year, and the VAT rate.

Table *3*. Economic parameters of the PV systems considered in the analyses.

PV economic parameters	Value
Residential PV system cost (VAT excl.)	1.6 EUR/Wp [14,15,20]
O&M cost (VAT excl.)	0.02 EUR/W·year [20]
VAT	21%

3.2 Electricity market scenarios

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Table 4 outlines the proposed hybrid tariffs for electricity prices, which are based on REE's Active Energy Billing Term of the Voluntary Price for the Small Consumer (PVPC) [23] and the average prices in Spain from 2015-2021 [4]. The prices are divided into three hourly sections during the week with no differentiation on weekends. Three scenarios are considered: a downward trend, average trend, and an upward trend price.

Table 4. The three scenarios of hourly electricity prices considered in the analyses.

Period of the day (hours)	Downward trend (EUR/kWh)	Average trend (EUR/kWh)	Upward trend (EUR/kWh)
0-8	0.06	0.12	0.17
8-10; 14-18; 22-24	0.10	0.18	0.26
10-14; 18-22	0.14	0.24	0.34
Weekends	0.06	0.12	0.17

3.3 Surplus compensation policy scenarios

In Spain, the self-production surplus policy restricts profits from selling excess production as the monthly money flow (C_M) cannot be negative [2]. This means compensation for surplus sale cannot provide economic gains to consumers. To account for this constraint, Eq. (11) is redefined as Eq. (11b). However, to evaluate the impact of this policy on PV system profitability, both equations are computed, and their results compared.

$$C_{ope} = \begin{cases} \sum_{y=1}^{12}\left[(C_{fix,y} + C_{M,y}) \cdot (1 + VAT)\right] \; if \; C_{M,y} > 0 \\ \sum_{y=1}^{12}\left[(C_{fix,y} + 0) \cdot (1 + VAT)\right] \; if \; C_{M,y} < 0 \end{cases}. \tag{11b}$$

4. Results and discussion

4.1. Hourly electricity demand

Figure 2 displays the average electricity demand per dwelling per year (E_{dw}) in kWh for 7,828 municipalities in Spain. These municipalities were categorized into 11 population groups using Table 1 in Section 3.1. The average daily electricity demand in Spain is 7.6 kWh per dwelling per day, increasing to 8.5 kWh during winter and decreasing to 7.3 kWh during summer. Urban areas with over 30,000 inhabitants exhibit similar consumption patterns as the average. However, rural areas tend to have lower consumption, likely due to factors such as electrification levels and local alternative energy availability.

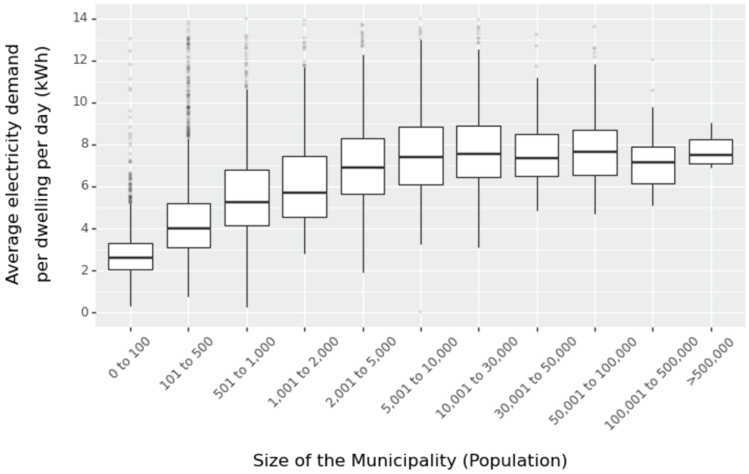

Figure 2. Average electricity demand per dwelling per day, in kWh, in the 7,828 municipalities in Spain with available data (>99% population representativity) grouped by population.

4.2 PV rooftop potential

Figure 3 displays the estimated useful rooftop surface to install PV per dwelling for the 7,828 municipalities with available data in Spain, calculated using the methodology described in Section 2.2. Small rural municipalities (less than 5,000 inhabitants and 12% of the total population) have a consistent 10 m^2 of surface per dwelling in average, while larger urban areas (over 100,000 inhabitants and 40% of the population) have only between 3 – 4 m^2. This is due to a higher concentration of single-family buildings in rural areas compared to urban areas, where the proportion of multi-story housing blocks is significantly higher. Expressed in PV power terms, smaller rural areas can accommodate up to 5 solar panels per dwelling in average, equivalent to around 1.5 – 2.0 kWp of installed power, while larger urban areas can only accommodate up to 2 solar panels per dwelling in average, approximately 0.8 – 1.2 kWp. These results will be further discussed in the next section in relation to electricity demand.

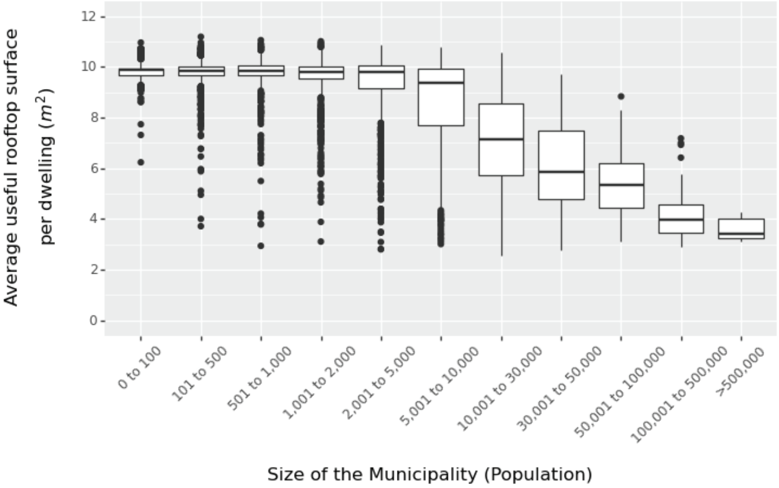

Figure 3. Available rooftop surface per dwelling, in square meters, for the installation of PV panels in the 7,828 municipalities in Spain with available data (>99% population representativity) grouped by population.

4.3 Solar Fraction

When estimating the solar fraction for municipalities in Spain, the annual balance method driven by Eq. (3) assume that surplus solar energy can be stored for on-demand use. However, this is not realistic due to current storage technology limitations. Therefore, a more practical approach is determined by using the hourly balance method driven by Eq. (4), which only considers immediate consumption. Figure 5 shows the results using this method, which demonstrate a decrease in self-production capacity for all municipalities compared to the annual balance method (Figure 4). With the hourly method, rural areas are no longer 100% self-sufficient, and all municipalities will remain between 30 and 55% solar fraction. Specifically, large urban areas experience a 30% drop, while rural areas see a 50 – 75% drop.

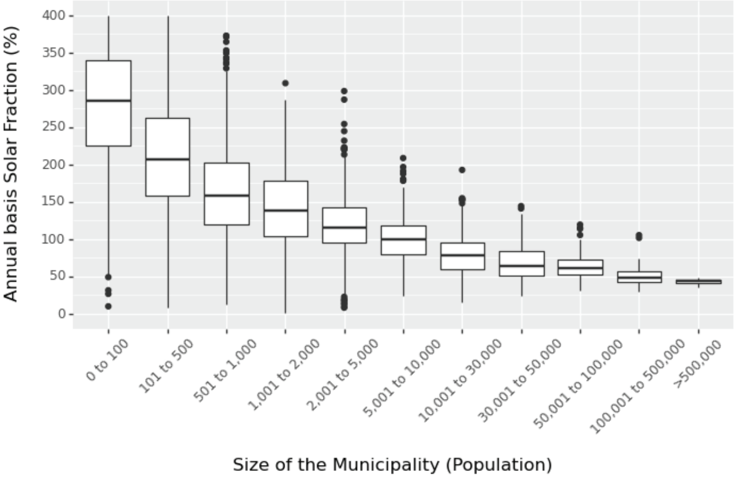

Figure 4. Solar fraction per dwelling (%) obtained with the annual balance method in the 7,828 municipalities in Spain with available data (>99% population representativity) grouped by population.

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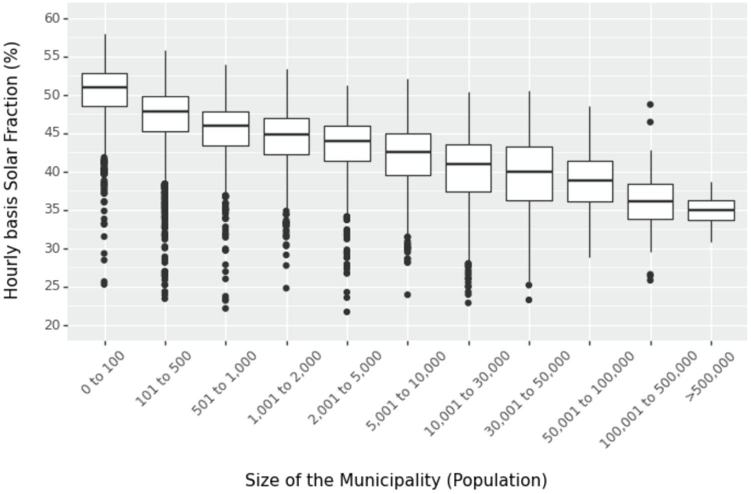

Figure 5. Solar fraction per dwelling (%) obtained with the hourly balance method in the 7,828 municipalities in Spain with available data (>99% population representativity) grouped by population.

4.4 Economic analysis

The economic optimization of 7,828 municipalities was conducted employing Total Annualized Cost (TAC), Net Present Value (NPV), and Payback Period (PBP) as key metrics. Figure 6 illustrates the outcomes for a selection of six municipalities distributed across various regions and diverse population sizes, thereby enabling a comparative study between urban and rural morphologies and also between different prevailing climate conditions. This selection encompasses Bilbao and Sopuerta in the north, Madrid and Ajalvir in the center, and Sevilla and Pruna in the south. Each pair of cities symbolizes urban and rural morphologies, respectively. Three distinct electricity price scenarios, as outlined in Table 4, were assessed, in conjunction with two surplus compensation policies, elucidated in section 3.3. The outcomes are portrayed for green (downward trend), orange (average trend), and red (upward trend) electricity price scenarios. The compensation policies considered include one that permits economic gains and another that aligns with the current Spanish regulations, devoid of economic incentives. The x-axis signifies the percentage of rooftop occupancy or load factor, which ranges from 0% (indicating no PV system installation) to 100% (indicating full occupancy). For this analysis, an interest rate of 3% and a projected lifespan of 20 years were presumed. Neither inflation nor owners' risk factor were considered in the study.

The TAC results, as shown in the first row, demonstrate that all six municipalities could obtain economic benefits from the installation of solar panels. However, the optimal rooftop load factor is subject to variations on the size of the municipality and the surplus compensation policy considered. Large urban municipalities such as Bilbao, Madrid, and Sevilla, generally have less rooftop surface availability compared to their rural counterparts, Sopuerta, Ajalvir, and Pruna. This constraint in urban areas diminishes the PV potential capacity, and consequently, the potential economic gains, as depicted by the marginal decrease of TAC with increasing load factor. Furthermore, the limited PV potential implies that surplus in urban municipalities are inadequate to reap the benefits of more generous compensation policies for PV system owners. Hence, both policy scenarios exhibit similar behavior. In contrast, rural municipalities, with generally larger rooftop surface availability per dwelling, yield superior economic performance and more significant surpluses. Consequently, they stand to gain the most from a hypothetical, more favorable surplus compensation policy.

The second row presents the NPV values, which supplement the TAC analysis by suggesting the optimal rooftop load factor for PV investment. The Payback period values also exhibit variability, dependent on the size of the municipality, electricity prices, and compensation policy. It is evident that current compensation policies could potentially hinder the complete deployment (100% load factor) of PV in rural areas. In an average market scenario, a dwelling in the rural areas could attain a PBP between 8 and 10 years under the current compensation policy. However, this could be reduced to between 6 and 8 years if a more favorable policy were implemented.

In summary, the analysis indicates that all municipalities could profit economically from the installation of solar panels. However, the optimal rooftop load factor and investment return timing are subject to multiple influencing factors. Moreover, current compensation policies negatively impact dwellings with more than 6 – 8m2 of available surface for installing PV.

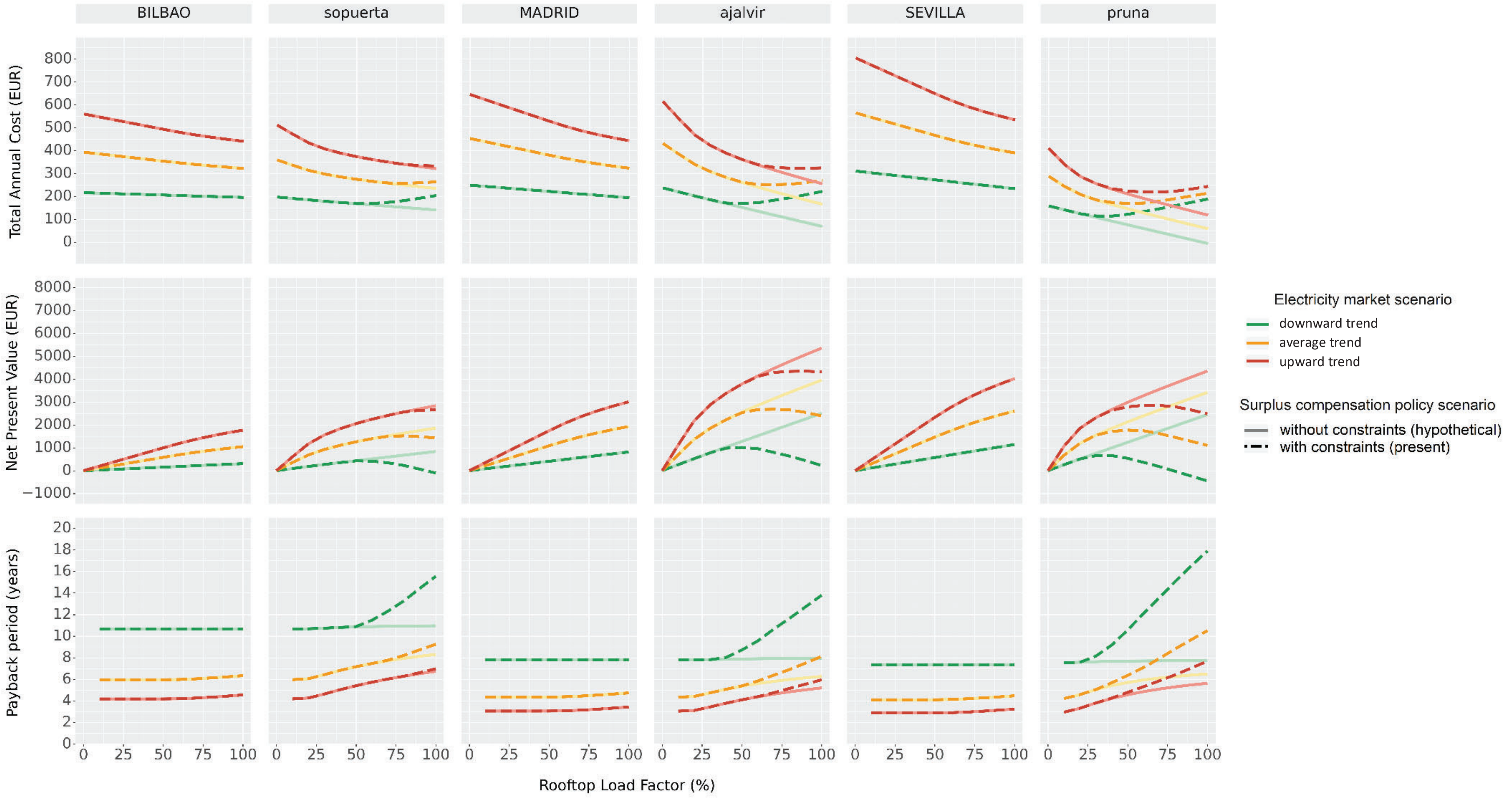

Figure 6. Total Annual Cost, Net Present Value, and Payback Period associated with installing solar panels on residential rooftops in different regions of Spain, under different electricity market and surplus compensation policy scenarios. Capitalized municipality names indicate urban morphology municipalities, while lowercase names indicate rural morphology municipalities.

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5. Conclusions

This study introduces a new hourly data-driven method to assess the feasibility of residential solar PV systems for electricity self-consumption in Spain. The method employs mathematical models to estimate the electricity demand, self-consumption capacity, and economic profitability of rooftop-based PV systems at the municipal level, considering different surplus compensation policies and flexible electricity prices. The most relevant conclusions of this work are presented below:

- Rural areas have up to three times more rooftop surface per dwelling than urban areas, resulting in higher rooftop PV generation capacity. This correlation is linked to population size and rooftop availability per dwelling in a municipality.
- High-resolution hourly data is crucial for estimating self-consumption capacity when planning PV deployment. Analyzing hourly data reduces the potential by up to 75% in rural and 30% in urban municipalities compared to yearly data analysis.
- Current policies do not fully compensate for surplus electricity generated by PV systems, limiting potential investments in residential PV systems by 40 – 60% of their maximum capacity and reducing economic profitability.

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