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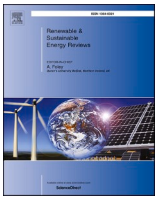

Techno-economic analysis of residential rooftop photovoltaics in Spain

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ABSTRACT

In response to the European Commission's renewable energy targets for 2030, this study presents a comprehensive, data-driven evaluation of the potential for electricity self-consumption in the Spanish residential sector based on rooftop PV systems. Utilizing real-time hourly electricity demand data and various surplus compensation policies, the research highlights the significance of data granularity, indicating that annual data-based PV estimations can lead to rooftop PV self-consumption capacity overestimations when compared to hourly data assessments. Furthermore, geographical variations reveal distinct rooftop PV self-consumption capacities between urban and rural areas, driven mainly by the prevalent building typologies. This discrepancy suggests that while rural regions, with their predominance of single-family dwellings, offer higher PV generation potential due to more available rooftop space, urban areas, dominated by multi-story buildings, face significant constraints in rooftop surface availability. Economically, the current surplus compensation policy in Spain reduces the profitability of PV installations, underscoring the necessity for enhanced policies to fully utilize all the available rooftop areas in the residential sector. The study's findings, particularly the revelation that residential rooftops in Spain may not be enough to meet the current electricity demand, emphasize the need for adaptive, region-specific policies and the potential role of energy communities. Policymakers and industry stakeholders are urged to prioritize rooftop utilization, ensuring the deployment of PV systems is both promoted and economically viable, steering Spain closer to its renewable energy and sustainability aspirations.

1. Introduction

The European Commission (EC) has set an ambitious plan, aiming for 45 % of its energy mix to come from renewable sources by 2030, as stipulated in the 2022 REPowerEU Plan [1]. A significant emphasis has been placed on solar photovoltaics (PV), with its rapid deployment capabilities being identified as a key driver for achieving this target. The aim is to escalate from 160 GW of PV installed in 2021 to over 320 GW by 2025, culminating in nearly 600 GW by 2030 [2].

While this directive reflects a forward-thinking approach to energy transition, the practicalities associated with its realization are complex. In the past few years, different EU Member States have launched varied initiatives to harness renewable energy, with a particular focus on PV. Evaluations of these policies have been carried out, suggesting that not all strategies are equally effective. Campoccia et al. analyses [3,4] revealed substantial differences in payback periods for PV investments across countries, highlighting the variability in policy effectiveness.

One of the prominent challenges in PV deployment is the delicate balance between regulations and profitability. While feed-in tariff (FIT) policies, for example, have been shown to significantly impact the volume of installed PV systems in a country, their effectiveness is not universal [5]. Garcia-Álvarez et al. [6] emphasized that such policies in some countries were more favourable to PV deployment than in others. This raises the question of whether a one-size-fits-all approach is truly applicable, given the diverse weather and socio-economic landscapes across the EU. Furthermore, comparing the hypothetical profitability of PV installations under other countries' regulations presents valuable insights in the analysis. Escobar et al.'s study [7], comparing the profitability of a PV installation in Spain under the regulations of other European nations, found several differences, suggesting that some policies were far more favourable than others. This disparity, if not addressed, could lead to unequal PV deployment across the EU, potentially hindering the collective achievement of the 2030 target. In conclusion, while the overarching goal of increasing renewable energy utilization in the EU is commendable, the journey is riddled with several socio-economic challenges [8,9]. The success of this endeavour relies on adaptive, effective, and region-specific policies that not only promote PV deployment but also make it economically viable [10]. As current research suggests, there's ample room for policy refinement to truly

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Nomenclature

Abbreviations

PV	Photovoltaics
EC	European Commission
EU	European Union
FIT	Feed-in tariffs
LDSMR	Spanish Law of Rural Sustainable Development
INE	Instituto Nacional de Estadística
TMY	Typical Meteorological Year
PVGIS	Photovoltaic Geographical Information System
CNIG	Centro Nacional de Información Geográfica
O&M	Operation and Maintenance
REE	Red Eléctrica de España
PVPC	Voluntary price for the small consumer

Notations

TAC	Total annual cost
NPV	Net present value
LF	Rooftop load factor
Edw	Hourly electricity demand per dwelling
Et	Hourly electricity consumption in a municipality
C	Number of electricity contracts in a municipality
S_{PV}	Rooftop surface available per dwelling
G(i)	Hourly global irradiation
E_{PV}	PV potential generation per dwelling
η	PV efficiency
SF	Solar fraction
SFa	Solar fraction based on annual data
SFh	Solar fraction based on hourly data
i	Observed hour
j	Total number of observed hours in a year
C_h	Hourly money flow
E_h	Net hourly energy balance
C_M	Monthly money flow
P_p	Electricity purchase price
P_s	Electricity sell price
IAC	Investment annual cost
C_{ope}	Operational annual cost
TIC	Total investment cost
CRF	Capital Recovery Factor
ir	Discount rate
n	Lifetime of the project
C_{fix}	Monthly fixed costs
VAT	Value-added tax
C_Y	Net Money Flow for one year
PV_{out}	Output power of the PV system

Units

GW	Gigawatt
kWh	Kilowatt-hour
m^2	Square meters
Wp	Watt-peak
EUR	Currency in Euros

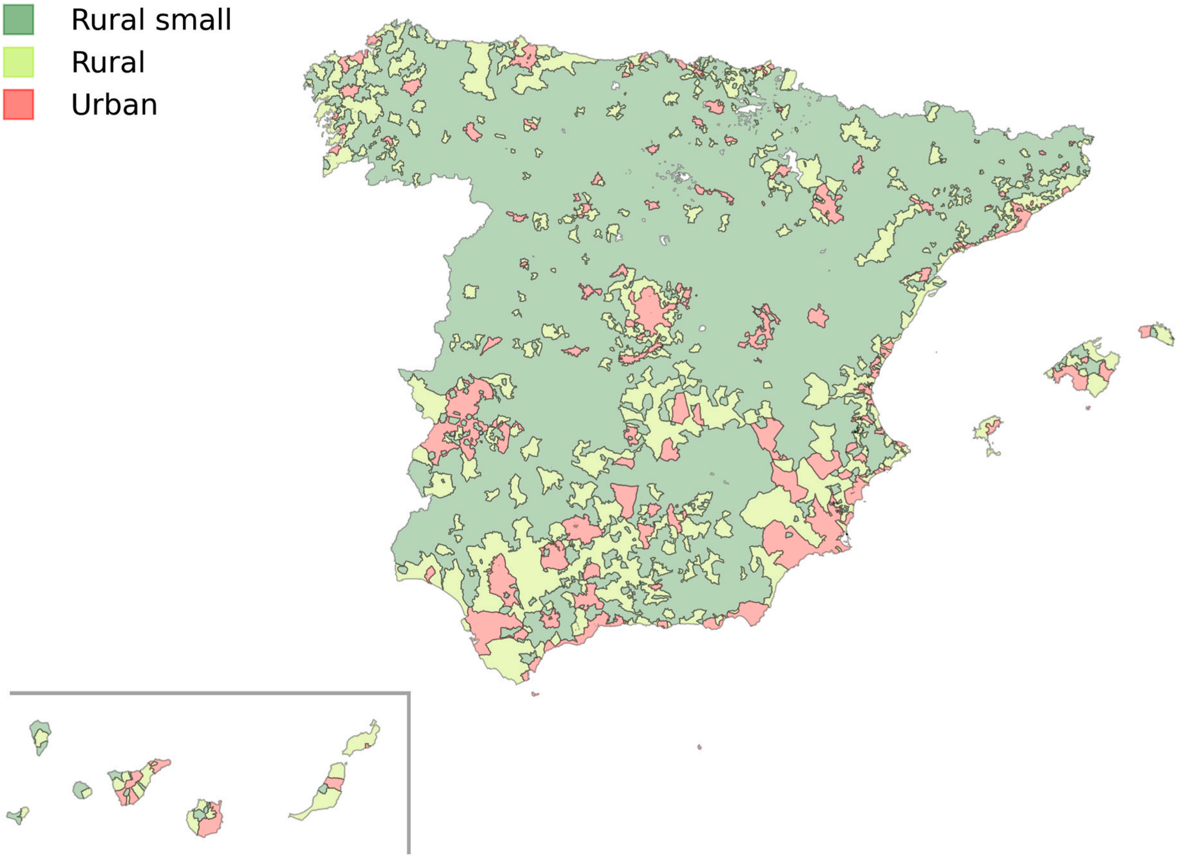

Fig. 1. Municipality distribution in Spain according to the Spanish Law of Rural Sustainable Development.

harness the EU's estimated PV potential [11] and guarantee a sustainable energy transition in the EU, and beyond.

As previous studies have underscored, the challenges associated with PV deployment extend beyond regulatory aspects, encompassing both geographic and demographic factors. For instance, a comprehensive study in the U.K. illuminated the nature of PV deployment across large territories, identifying the role of accurate local mapping and spatial analyses [12]. Such findings spotlight the need of understanding the local landscape for successful renewable energy interventions. In relation to this aspect, the urban-rural dichotomy presents another layer of complexity in PV adoption. Within identical regulatory frameworks, rural areas often demonstrate a more robust inclination towards PV system adoption compared to their urban counterparts [13]. This disparity is not merely coincidental but rooted in tangible differences like electricity demand patterns, population density, educational levels, and predominant housing typologies [14]. Such contrasts exemplify the need for policies that are not just generalized but contextually relevant, recognizing the unique needs and challenges of both urban and rural contexts [15].

As for Spain's energy transition targets, presented in the national plan "PNIEC 2021–2030″, a more than fourfold increase in PV power capacity is planned for 2030, reaching 39 GW from 9 GW in 2020 [16, 17]. This goal is supported by a series of legal changes and fiscal measures aimed at self-production of energy through PV systems. In 2019, a new law was passed to economically regulate surplus energy fed into the grid from self-generation infrastructure [18]. And more recently in 2021, a set of subsidies were announced by the government to cover a percentage of the cost of new PV and storage installations [19]. Yet, Spain's demographic landscape, characterized by a significant urban-rural dichotomy, adds its own layer of complexity to this roadmap. Fig. 1 shows the population distribution in Spain according to the rurality level by the Spanish Law of Rural Sustainable Development (LDSMR) [21]. The population distribution [22], with 68 % residing in urban areas but occupying only a 16 % of the land, contrasted with the rural areas (84 % of the land) inhabited by a 38 %, pose unique challenges for PV deployment. Previous studies corroborate that such population distribution will inevitably affect the PV deployment in a region [12–15]. Therefore, decision-makers face a series of challenges to enhance the deployment of PV systems in the Spanish residential sector: What can residential PV systems contribute to addressing the proposed energy transition? How should solutions differ between rural and urban areas? What regulations bode well for increased deployment of PV for self-consumption?

Recent studies on the potential of solar energy in Spain provide insights to answer these questions. The region of Canary Islands, for instance, can theoretically produce 150 % of its current energy demand from solar PV systems, making it economically viable even without surplus electricity compensation policies [23]. Interestingly, a focus on Gran Canary suggests that as electricity demand grows, the reliance on solar PV decreases compared to wind turbines [24]. Urban analyses, however, offer a different perspective. While Sevilla can barely meet its electricity needs through rooftop PV systems [25], Irun can only meet 59 %, mainly due to its prevailing weather conditions [26]. A detailed economic evaluation indicates that the profitability of these systems varies with the surplus compensation policy in place. Valencia's study emphasizes on shadow losses and PV investment cost as major factors affecting payback periods, which typically range between 7 and 15 years [27]. At a national level, Gomez-Exposito et al. [28] offer an optimistic perspective, underscoring Spain's capability to transition to a sustainable, emission-free energy paradigm, where self-consumption PV play a key role. However, the study highlights the model limitations posed by the lack of hourly data use when calculating the energy balances, thus affecting the conclusions.

In short, the potential of PV self-consumption in Spain and beyond, is primarily influenced by demographic, climatic, and economic considerations. Nevertheless, certain aspects that might lead to unmet the energy transition goals remain unexplored in existing literature.

With a careful review of the previous works on self-generation of electricity through PV systems, this study aims to investigate the following hypotheses.

- Calculating rooftop PV self-consumption capacity using annual production and consumption data might lead to notable overestimation when compared to calculations based on hourly data.
- The potential capacity for rooftop PV self-consumption in the residential sector varies significantly between urban and rural regions.
- The existing surplus compensation policy in Spain constrains the economic viability of self-consumption rooftop PV systems, thereby underutilizing the available rooftop surface.

This research introduces a data-driven approach to evaluate electricity self-consumption capacity and its economic viability using residential rooftop PV systems, while considering various surplus compensation policies and electricity prices. By utilizing a database of real-time hourly electricity consumption from individual smart meters across Spain, an emphasis is placed on detailed hourly data analysis, contrasting with the annual averages predominantly present in prior studies. With the integration of real demand data and the consideration of Spain's diverse demography and climate, a comprehensive regional assessment is presented. This allows for a detailed exploration of the distinctions and parallels in the capacity and profitability of rooftop PV systems between rural and urban environments, aiming to contribute robust insights to the energy transition discourse. Furthermore, economic evaluations, considering different surplus compensation policies, elucidate the influence of the current regulations on the profitability of rooftop PV installations and the resulting underutilization of the total available rooftop surface area. To prove the value of the proposed method, it is applied to the case study of the Tarragona province of Spain, and it involves the evaluation of its 184 municipalities, assessing both rural and urban areas. This analysis insights into potential energy self-consumption and the economic feasibility of rooftop PV systems in the residential sector in Spain and other regions.

2. Material and methods

Fig. 2 illustrates the methodological workflow of the study, consisting of four primary sequential phases: (1) Data acquisition, (2) Data preprocessing, (3) Model formulation, and (4) Optimization.

In the initial stage, different data are acquired from various publicly accessible online repositories, encompassing diverse domains such as residential electricity consumption, housing stock characteristics, meteorological records, demographic spatial data, PV systems' performance parameters, and diverse related economic indices.

Subsequent to data acquisition, the ensuing phase involves a systematic data refinement process, or preprocessing. This encompasses data cleansing, filtration, and normalization procedures, for each municipality considered in the analysis. Such processing entails the normalization of hourly electricity consumption data at the dwelling scale, segmentation of the buildings based on their rooftop availability to integrate PV systems, and the computation of hourly solar global irradiation in horizontal planes per square meter.

In the model formulation phase, the normalized datasets are harnessed to build the energy and economic models for each municipality. The energy model comprises the useful rooftop surface available per dwelling to install PV systems, the prospective electricity produced from the rooftop PV installations dependent on the degree of the available rooftop occupied (expressed as the rooftop load factor), and the inherent capacity for on-site electricity self-consumption, also named solar fraction. Concurrently, the economic model is formulated, scrutinizing an array of surplus compensation policies and likely electricity market scenarios. This model comprises the hourly economic balance between potential revenue generation via surplus electricity sales and

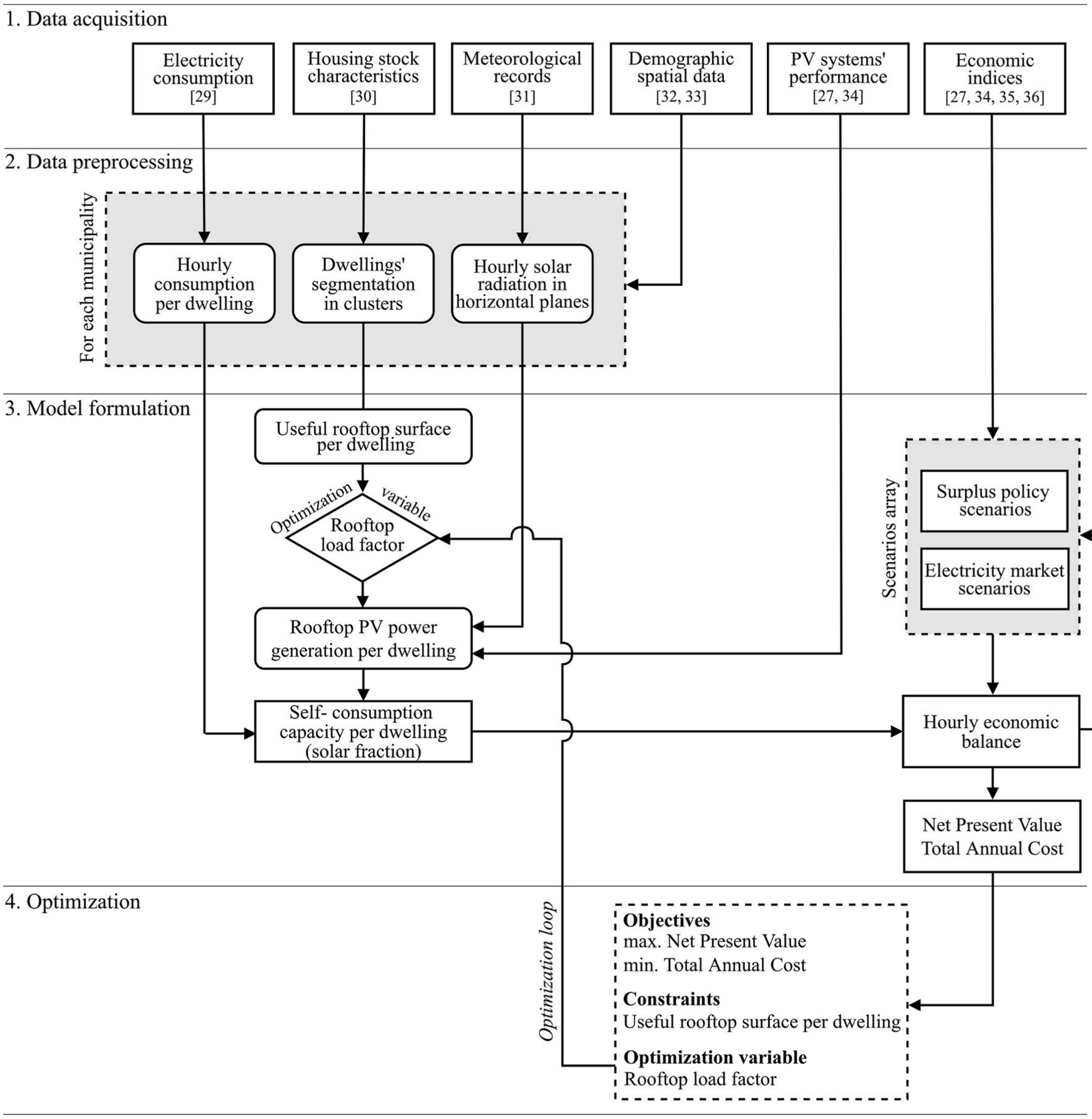

Fig. 2. Workflow of the proposed method.

expenditure incurred due to procurement of electricity during periods of solar production deficit.

In the final optimization phase, the energy and economic models are iteratively computed under different rooftop load factors, ranging from 0 % to 100 % of the available rooftop surface. This process aims to determine the optimal rooftop occupancy that maximizes the economic metric Net Present Value (NPV) and minimizes the Total Annual Cost (TAC) for each municipality over a 20-year span. By utilizing this approach, it can be determined what percentage of the rooftop area should be occupied by self-consumption PV installations to optimize economic benefits, considering different surplus compensation policies and various electricity markets trends.

For this purpose, a scalable software is developed in Python language to automatically extract data from various databases, process them, and carry out the techno-economic analyses proposed for each region in Spain. The outputs of the software are in the form of tabular and graphic files in order to facilitate further analyses.

2.1. Data acquisition

Electricity consumption: The hourly electricity consumption per municipality E_T in kWh and the corresponding number of electricity consumer contracts in the Spanish residential sector C are obtained from the recently available platform Datadis [29]. This platform gives access to extensive hourly electricity consumption data in Spain, facilitating the characterization of energy demand across municipalities and districts [30,31]. Regarding the data's representativeness, a report [32] from the Spanish National Commission of Markets and Competition indicates that Datadis covers 88 % of the electrical service points within the Spanish residential sector. This representativeness has been considered robust enough to validate the hourly electricity consumption at the municipal level in the region, mitigating concerns of potential data bias in the study.

Housing stock characteristics: The estimation of the availability of rooftop surface to install PV systems is based on the analysis of the following residential building's characteristics at the municipal level: year of construction; number of floors; and number of dwellings. These data are published periodically by the Spanish Statistics National Institute (INE) [33].

Meteorological records: The estimation of the PV potential generation is based on the local solar irradiation data in $W{\cdot}m^{-2}$ and according to the Typical Meteorological Year (TMY). These data are obtained from the database: Photovoltaic Geographical Information System (PVGIS), which is developed by the European Commission Joint Research Centre in Ispra, Italy, since 2001 [34].

Demographic spatial data: The geographical data, in the form of GIS-shape files (*.shp), are obtained from the Centro Nacional de Información Geográfica (CNIG) in Spain [35] and are used to define the administrative borders of each municipality. In parallel, the relationships across regions, municipalities, postal codes, and electoral censuses in Spain are obtained in form of spreadsheets from INE [36].

PV systems' performance: The parameters required to model the PV systems are the electric power per square meter of installed modules in $Wp \cdot m^{-2}$; the efficiency in %; and the lifetime of the whole PV system in years. The data have been obtained from General Cost Benchmarks records and from other similar studies in Spain [27,37]. It should be noted that no energy storage has been considered in the model.

Economic indices: The cost of installing PV systems (initial investment, O&M costs, and discount rate) has been obtained from the economic data provided by Refs. [27,37]; and the electricity prices in the Spanish wholesale market for both the purchase of electricity and for the sale of electricity surpluses have been obtained from the Red Eléctrica de España (REE) website, in Refs. [38,39] respectively. REE is the Spanish corporation which operates the national electricity grid in Spain.

2.2. Data preprocessing

Typical hourly electricity demand per dwelling: E_T corresponds to the real hourly electricity consumption in a municipality, and it depends to a large extent on the number of consumers in that municipality. Therefore, the Typical Electricity Consumption per Dwelling, E_{dw}, can be obtained by using equation (1) with the assumption that each dwelling has only one electricity consumer contract.

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

where C is the number of electricity consumer contracts in the municipality.

Dwellings within a municipality show typically diverse consumption patterns, but in the study, average hourly profiles for each municipality are used to simplify the model. This method highlights broader trends and aids in contrasting rural and urban areas. Due to data acquisition challenges and as supported by Rivera-Martin et al. [31], averages ensure consistent and realistic patterns for an entire municipality. It's important to note, however, that relying on these average hourly profiles might mask specific consumption fluctuations or peak demand periods within certain areas of a municipality. Even though, this simplification has less impact as the size of the analyzed sample increases, like when comparing behaviours of entire municipalities, or simulating Energy Communities that encompass a diverse range of building types.

As of the analysis date, only the 2019 hourly electric consumption data was complete. Years 2020 and 2021 were intentionally excluded due to potential demand changes caused by the SARS-CoV-2 events. Consequently, the energy balance was based on 2019 data for both electricity demand and solar irradiation.

Dwellings' segmentation in clusters: To calculate the availability of rooftop space in the average dwelling for each municipality, it is first essential to determine the total useable rooftop area in every municipality. This is achieved using the method proposed by Ref. [40]. This approach involves segmenting the housing stock of each municipality into 10 distinct groups based on their construction characteristics.

Hourly solar irradiation in horizontal planes: Hourly solar irradiation in the horizontal planes (G(i)) in $kWh \cdot m^{-2}$ is collected directly from the PVGIS platform [34]. For data retrieval, each studied region is represented by a single point based on latitude and longitude.

In residential contexts, irregular rooftops introduce significant challenges. While expansive areas, such as large commercial buildings or open fields, permit the optimization of PV panel orientation, residential rooftops with irregular shapes and limited area necessitate a broader approach. Maximizing the utilization of available rooftop space becomes crucial, often overshadowing the optimization of individual panels. Modelling PV installations horizontally is informed by these challenges. A study by Barbón et al. [41] concludes that for irregular random-shaped rooftops, common in Spanish residential contexts, the optimal PV panel tilt is 7°, and the conservative adoption of a lower angle is found to be effective in capturing significant amounts of the total energy received from the PV system.

2.3. Model formulation

Useful rooftop surface per dwelling: Upon segmenting the dwellings into 10 clusters for each municipality, the total surface area available for each group is calculated [40]. By summing these, the average surface area for the municipality is determined, yielding a single average surface value for a dwelling, termed S_{PV}.

Rooftop PV power generation per dwelling: The PV potential per dwelling, E_{PV}, is the energy in kWh that could be generated by a dwelling through PV installation as a function of the percentage (load factor) of the rooftop surface (S_{PV}) occupied by solar modules. This PV potential function also depends on the hourly solar radiation (G(i)) in horizontal planes in $kWh \cdot m^{-2}$ as well as the PV system performance factor (η). In the model developed, the rooftop load factor (α) is restricted to values between 0 % (no PV module installed) and 100 % (all the available roof surface (S_{PV}) is occupied by PV modules). Consequently, the PV potential per dwelling in kWh can be calculated, for each hour i observed, as:

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

Self-consumption capacity per dwelling (solar fraction): The solar fraction is defined as the percentage of the energy demand that can be met by the solar energy on an annual basis. Typically, this annual balance is obtained from using annual average data of demand and PV production. However, as previous studies had pointed out, the analysis of the balance based on hourly average data rather than annual would make valuable contributions to the study of self-consumption potential in a region [28]. Accordingly, in this study both methods are included, the one based on annual averages, SF_a (Equation (3)), and the one based on hourly averages, SF_h (Equation (4)).

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

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

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

Hourly economic balance: The hourly economic balance (C_h) in EUR depends on the corresponding prices of electricity and the net hourly energy balance (E_h) which can be obtained from equation (5): the difference between electricity consumed (E_d) and produced (E_{PV}) in an hour.

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

Thus, the net hourly economic balance for any observed hour i is calculated as:

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

When the net hourly energy balance (E_h) is positive, the purchase price (P_p) is used in equation (6); but when the balance is negative, selling price (P_s).

Accordingly, the monthly economic balance flow (C_M) in EUR is an aggregate of all the hourly economic balances for the month as in equation (7):

$$C_M = \sum_{i=1}^{I} C_{h,i} \tag{7}$$

where I indicates the number of hours observed in that month.

Total Annual Cost: The Total Annual Cost (TAC) for one PV system, in EUR, is the sum of annualized costs of owning, operating, and maintaining the PV system. TAC is composed of the Investment Annual Cost (IAC) in EUR and the operational cost (C_{ope}) in EUR as given by equation (8):

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

The IAC, as given by equation (9), is the result of the TIC after applying the Capital Recovery Factor (CRF) which is given by equation (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 discount rate in %; and n is the lifetime of the project in years.

The C_{ope} is the cost related with the electricity consumption, i.e., the electricity bill,

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

where C_{fix} is the Monthly fixed costs (EUR).

It is worth mentioning that each state, region, etc., has its own policies and laws on surpluses that may affect equation (11). For instance, in the current Spanish scenario, the monthly money flow (C_M) is restricted to be a positive value [18].

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

$$NPV = -TIC + \sum_{y=1}^{n} \frac{C_Y}{(1 + ir)^y} \tag{12}$$

where TIC is the Total Investment cost, and C_Y is the net economic balance for one year in EUR.

2.4. Optimization

Optimal Load Factor: This metric represents the optimal fraction of a dwelling's useable rooftop surface that should be covered with solar PV panels to maximize the economic profitability of the PV system. This assessment considers both the upfront installation costs and the economic advantages of consuming self-generated electricity over procuring it from the grid. Thus, the objectives are to simultaneously maximize the NPV and minimize the TAC. This is achieved by employing a linear programming approach for each of the objective functions. The optimization variable is the rooftop load factor, S_{PV}, as presented in equation (2), ranging from 0 % (indicating maximum economic efficiency without panel installation) to 100 % (signifying full utilization of the rooftop for maximum efficiency). The governing constraint is the available useable rooftop area per dwelling. Using this framework, the influence of varied surplus policy scenarios and electricity market dynamics on the optimal load factor can be comparatively analyzed across municipalities in the same jurisdiction.

Optimal PV Power Installed: This metric is a direct conversion of the optimal load factor into installed power values (Wp), facilitating an analysis of the issue from a direct power perspective. The formula for the Optimal PV power installed in Wp is defined by equation (13) as the product of the Optimal Load Factor (LF) in %, the rooftop surface availability per dwelling (S_{PV}) in m^2, and the output power of the PV systems considered (PV_{out}) in $Wp \cdot m^{-2}$.

$$PV\ power\ installed = LF \cdot S_{PV} \cdot PV_{out} \tag{13}$$

3. Case study

The methodology earlier described has been used to analyse the optimal photovoltaic potential in the Tarragona province, which is a region in the north-east of Spain, as a demonstration of the tools' capacity to generate results regionally. The region is constituted by 184 municipalities, including both rural and urban areas. The net energy balance was estimated for a period of one calendar year, and the economic profitability of installing PV systems was evaluated for a twenty-year projection. The hourly electricity demand corresponds to the 2019 data as obtained from Datadis database [29]. The solar radiation data was obtained from meteorological data series between 2006 and 2015 [34]. The local availability of rooftop surface was estimated using the most updated data in the INE database, dated 2011 [33]. The electricity prices have been defined based on the Spanish wholesale electricity market data trends between 2015 and 2021 [20]. Finally, the PV system's performance and investment costs have been defined based on the most up-to-date global benchmarking reports available and similar works [27,37].

3.1. The demographics of the region under study

The method presented was applied individually to the 184

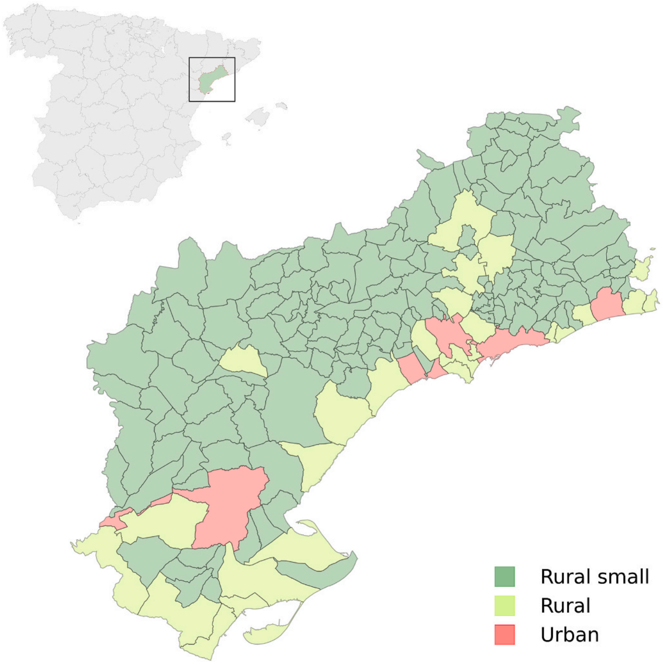

Fig. 3. Location of the Tarragona province within Spain and its municipalities classified according to the Spanish Law of Rural Sustainable Development.

municipalities in the Province of Tarragona in Spain, with about 800,000 inhabitants. This region, due to its heterogenous nature of its population distribution, affords the possibility of comparing the potentials of PV integration in the densely populated urban areas and the sparsely populated rural areas. Fig. 3 depicts the population distribution of the Tarragona province. According to the LDSMR, municipalities are classified according to their population size as urban areas (>30,000 inhabitants), rural areas (5000–30,000 inhabitants), and rural areas of small size (<5000 inhabitants). The population distribution of the province is such that 42 % of its population reside in urban areas, which represent only 6 % of the total surface area. Another 37 % of the population resides in rural areas corresponding to 22 % of the surface area. While the remaining 21 % reside in rural areas of small size, which corresponds to 71 % of the total surface area.

All the municipalities were grouped into 11 different hotspots according to their population size (Table 1), following the sizing clustering proposed by Torres-Rivas et al. [15] for the Catalan region in Spain.

3.2. PV systems' parameters

The PV system performance parameters utilized in the techno-economic analyses are presented in Table 2: the peak power per square meter, the efficiency of the PV system, and the lifetime.

Table 3 presents the economic parameters considered, that is, the cost in Euro per watt peak installed (EUR/Wp), the operation and the maintenance costs in EUR per watt per year, and the corresponding VAT in Spain.

3.3. Electricity market scenarios

The hybrid electricity tariffs proposed in this research, detailed in Table 4, are defined based on REE's Active Energy Billing Term of the Voluntary Price for the Small Consumer (PVPC) 2.0 TD tariff [38], the mean prices spanning 2015–2021 in Spain [20], and similar studies [27,31,42,43]. These prices are divided into three hourly segments during weekdays (P1, P2 and P3), maintaining uniformity over weekends (P1). To assess the effects on the profitability of PV systems, three pricing scenarios are analyzed: a descending price trend, an average trend, and an ascending trend. Surplus energy is compensated at 3/4 of the P1 rate for each scenario, resulting in 0.04, 0.09, and 0.12 EUR/kWh, respectively. Note that, while REE formally defines these surplus compensation rates [39], distribution companies often compensate at reduced rates. This discrepancy results in a lack of consensus within the reviewed literature regarding the appropriate surplus remuneration to consider. These variations are illustrated in Table 5, which contrasts the different rates adopted in recent studies focused on Spain.

Table 1
The population distribution of the municipalities in the province of Tarragona (Spain).

Number of municipalities	Size of the municipality (population)
4	<100
57	101 to 500
35	501 to 1000
26	1001 to 2000
32	2001 to 5000
14	5001 to 10,000
6	10,001 to 20,000
8	20,001 to 50,000
0	50,001 to 100,000
2	100,001 to 500,000
0	>500,000

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

PV performance parameters	Value
PV system output peak power	200 Wp/m^2 [34]
PV system efficiency	20% [34]
PV system lifetime	30 years [34]

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

PV economic parameters	Value
Residential PV system cost (VAT excl.)	1.8 EUR/Wp [27]
O&M cost (VAT excl.)	0.02 EUR/Wp·year [34]
VAT	21 % [27]

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

Period of the day (hours)	Scenario 1 (EUR/kWh)	Scenario 2 (EUR/kWh)	Scenario 3 (EUR/kWh)
P1: 0-8	0.06	0.12	0.17
P2: 8–10; 14–18; 22-24	0.10	0.18	0.26
P3: 10–14; 18-22	0.14	0.24	0.34
P1: Weekends	0.06	0.12	0.17

Table 5
Electricity market scenarios considered in related works.

	Fuster-Palop et al. (2021) [27]	A. Ordóñez et al. (2022) [31]		A. Rivera-Marín et al. (2023) [42]	Fuster-Palop et al. (2023) [43]
Period	2018	2019	2021	2020–2021	2021–2022
Tariff	Not specified	2.0TD	2.0TD	2.0TD	2.0TD
Buying price (EUR/kWh)	0.12	0.11	0.18	0.24/0.29/0.36	0.22/0.26/0.32
Selling Price (EUR/kWh)	0.05	0.05	0.11	0.11	0.18

3.4. Surplus compensation policy scenarios

In Spain, the current self-production surplus policy restricts potential profits from the sale of the excess production. Specifically, it is said that the monthly money flow (C_M) cannot be negative [18], which means that compensation for the sale of surpluses can never bring any economic benefits to the consumers. Mathematically, this implies that equation (11) must be redefined to satisfy this constraint as:

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

To study the implications this policy has on the economic profitability of PV systems, a hypothetical policy without this restriction (Equation (11)) is included in the analyses too.

4. Results and discussion

4.1. Typical hourly electricity demand

The first outcome of the procedure described in Section 2.3 corresponds to the typical hourly electricity demand per dwelling (E_{dw}) in each of the 184 municipalities within the province of Tarragona for one year. As noted in Section 2.2, the energy balances were based on 2019 data, being the only available complete dataset unaffected by SARS-CoV-2 to date. According to Spanish Weather Agency AEMET, Spain experienced above-average temperatures in 2019, consistent with the trend over the last 8–10 years [44]. This could mean a reduced energy demand for heating that year, potentially influencing the analysis results slightly.

Fig. 4 shows a reduced representation for 3 municipalities for a randomly selected week in both warm (summer) and cold (winter) seasons. Each municipality chosen respectively belongs to a different rurality group as defined by LDSMR: Porrera (pop. 441), rural small; Alcanar (pop. 9579), rural; and Reus (pop. 103,477), urban [21].

The typical daily electricity consumption patterns can be identified from the plots in Fig. 4. Three peaks are distinguished daily in both seasons and in Alcanar and Reus municipalities: two tiny peaks in the morning hours and a higher peak in the afternoon. Additionally, the decrease in electricity demand during the night hours is observed every day in these municipalities, right after the highest peak occur. However, the demand curves in Porrera show that the early morning peak is as significant as the late afternoon peak. Seasonal patterns can be distinguished too in the three municipalities by comparing the cold and warm week demand curves. In the three municipalities, hourly consumption in the cold season is higher than in the warm season, as are demand peaks.

The analyses of the electricity consumption data for all the municipalities reveal different seasonal local consumption patterns based on the situation of the municipalities. As Fig. 4 suggests, the electricity demand is typically higher during the cold season than in warm season. But with the classification of the municipalities according to being coastal or inland, Fig. 5 indicates that dwellings located in inland municipalities consume 20 % more electricity during the cold season as compared to the warm season while the ones located in coastal municipalities see their average consumption increased during the warm season by 10 % as compared with the cold one. A possible explanation for the higher demand during summer in coastal municipalities may be the increased use of electrical cooling equipment due to the high values of temperature and humidity during the season, which compensates for the lower demand for heating in colder season compared to inland areas [45]. Another complementary explanation is related with the fact that the population increases considerably in the coastal municipalities during the summer. This causes total consumption to increase, and since the number of total dwellings accounted in the model is the same in cold and warm seasons, the average consumption per dwelling will increase.

Fig. 6 provides an overall view of the province's average daily demand per dwelling in kWh. The 184 municipalities have been classified into 9 different population size groups according to Table 1 in Section 3.1.

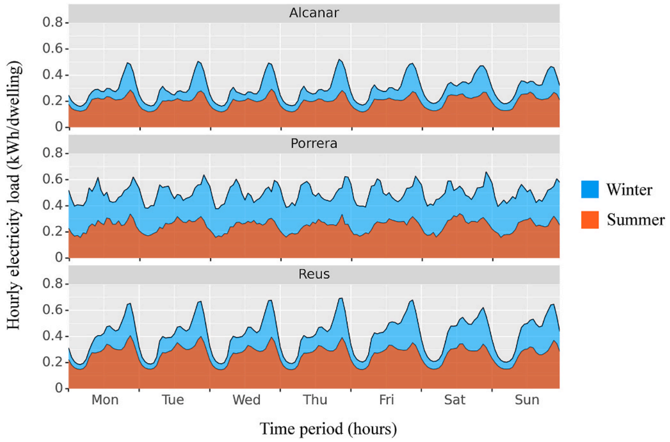

Fig. 4. Hourly electricity demand per dwelling during one-week period in 3 different municipalities in the Tarragona Province. In blue, typical demand during winter season (2 nd week of February 2019); in red, typical demand during the summer season (3rd week of June 2019).

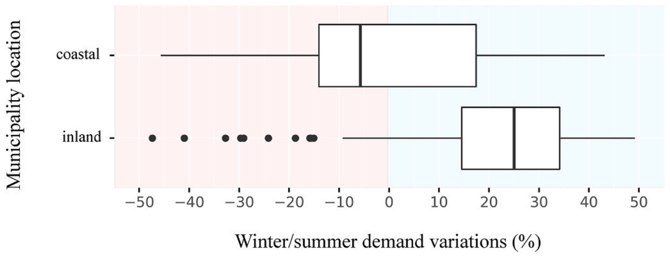

Fig. 5. Electricity demand excess per dwelling between winter (blue) and summer (red) seasons for the 184 municipalities grouped by their inland or coastal location.

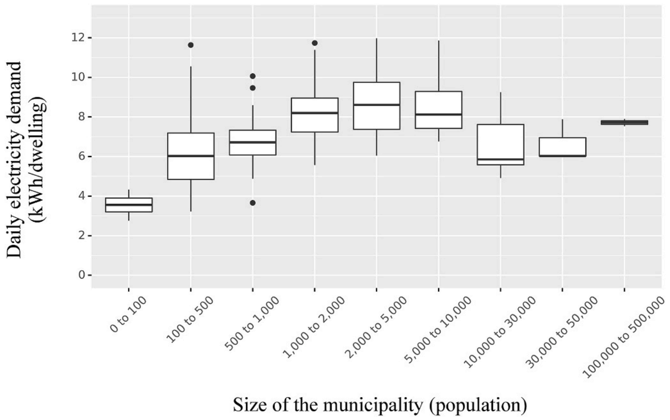

Fig. 6. Average electricity demand per dwelling per day, in kWh, in the 184 municipalities of the province of Tarragona grouped by size (population).

The average electricity demand of the province is about 8.09 kWh per dwelling per day. Generally, municipalities with less than 1000 inhabitants have a lower electricity consumption of less than 7 kWh per dwelling per day, with small villages with population less than 100 averagely consuming even lower than 4 kWh per dwelling per day. However, municipalities with over 1000 inhabitants (accounting for about 95 % of the province's population) averagely consume between 6 and 9 kWh per dwelling per day. Note that the low dispersion in the results for municipalities between 100,000 and 500,000 inhabitants is since the only 2 municipalities in the province of this size have a very similar urban layout. Note also that there is not a clear correlation between the number of inhabitants in a municipality and the average electricity demand per dwelling in that municipality as many factors may be responsible (e.g., electrification level, local availability of alternative energy resources, etc.).

4.2. PV rooftop potential

Fig. 7 presents the estimated rooftop availability per dwelling (S_{PV}) in square meters across the 184 municipalities, as determined by the method developed by Izquierdo et al. [40] in Section 2.2 and Section 2.3.

As outlined in Section 2.3, the model employs an average rooftop surface area per dwelling for each municipality. The logic behind using averages per dwelling is to juxtapose them with the average demand per dwelling available for each municipality. It's crucial to underscore that relying on average rooftop availability per dwelling might not capture the nuanced variations within a municipality. For instance, certain neighborhoods could predominantly consist of single-family dwellings, while others might be dominated by multi-story buildings. However,

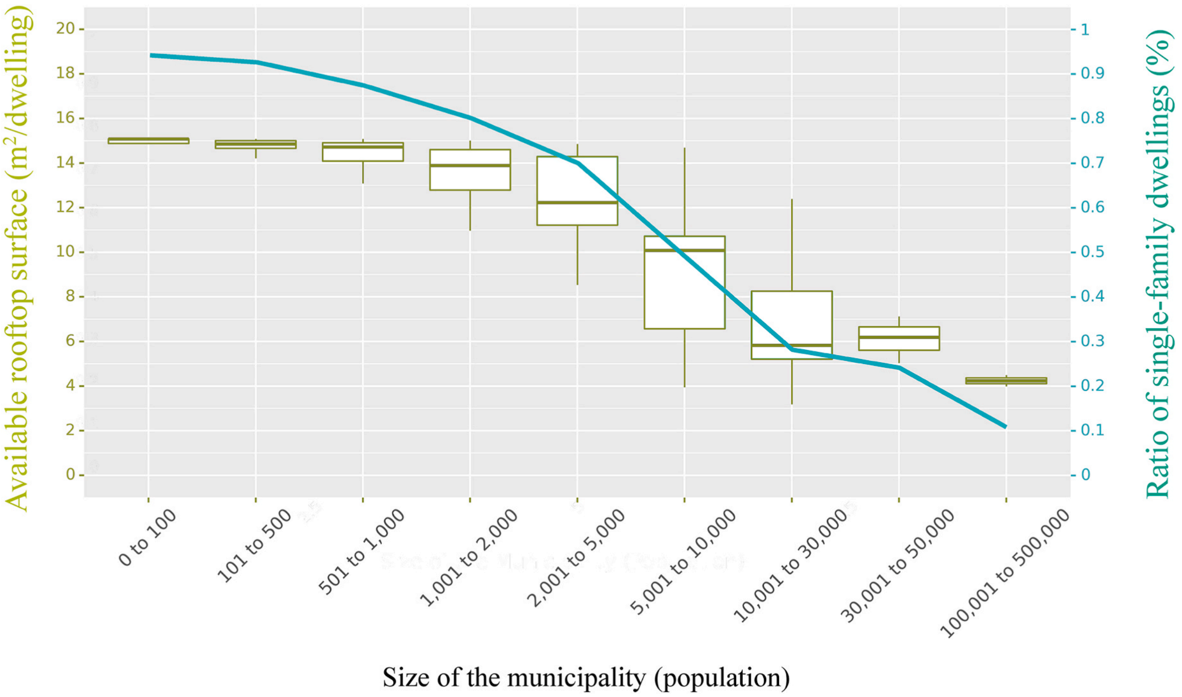

Fig. 7. Rooftop surface availability per dwelling for PV installations and proportion of single-family dwellings across the 184 municipalities of the Tarragona Province, segmented by population size.

this simplification has less impact as the size of the analyzed sample increases, like when comparing behaviours of entire municipalities, or simulating Energy Communities that encompass a diverse range of building types.

The analysis reveals that rural, smaller municipalities typically possess two to three times more average rooftop space per dwelling for solar panel installations than the urban, larger municipalities. This disparity can be attributed to the dominance of single-family dwellings in rural areas, as opposed to the prevalence of multi-story apartment buildings in urban areas [33]. This distinction is further illustrated in the chart via the secondary Y-axis. While residents of single-family houses have the luxury of leveraging the entirety of their rooftops for PV, those residing in multi-story buildings must share this space among multiple units. Specifically, as the municipality population escalates, the proportion of multi-story buildings increases, leading to a consequent reduction in rooftop availability per dwelling, a trend corroborated by Ref. [15].

The data underscores a robust linear correlation of 0.95 between the average rooftop space per dwelling and the proportion of single-family homes within a municipality. Parallelly, a log-linear correlation of 0.78 between the log-transformed municipality population and available rooftop space further emphasizes the intertwined relationship between housing type, population, and PV potential in a region.

Diving deeper into specifics: villages with fewer than 1000 residents, where single-family dwellings constitute over 85 % of residences, consistently offer 14–15 m^2 of rooftop per dwelling on average. On the other end of the spectrum, larger urban areas with populations surpassing 30,000 (and a single-family dwelling ratio hovering around 20 %) provide a mere average of 4–6 m^2 per dwelling for PV installations. When translated into PV capacity, this means rural dwellings can accommodate approximately eight solar panels, equivalent to 2.8 to 3.2 kWp. In contrast, urban dwellings might only support two panels to three panels, between 0.8 and 1.2 kWp.

It's important to note that, according to Eurostat, the proportion of single-family homes in rural and urban areas of the region analyzed closely mirrors the European average, at 83 % and 28 % respectively [46]. While architectural features can vary significantly across different parts of Europe, the findings of this study provide insight into residential rooftop availability trends that might be observed in other regions of the continent.

The subsequent section will compare these findings with household electricity demands and further explore the implications.

4.3. PV self-consumption potential

Equation (2) is used to estimate the hourly PV potential generation per dwelling for each municipality. The results of the three municipalities considered in Fig. 4 are presented in Fig. 8. The plot for each municipality shows the hourly PV potential generation per dwelling (E_{PV}) in kWh superimposed on the electricity demand curves for the municipalities. It should be noted that the E_{PV} here corresponds to the maximum potential as 100 % of the available rooftop per dwelling (S_{PV}) has been set to be occupied by solar panels. The comparison between municipalities shows that the PV potential generation is significantly higher in smaller municipalities than in larger municipalities. For example, the potential PV generation in Porrera during the warm season is approximately 66 % higher than that in Alcanar, and about 333 % higher than that in Reus. This is as a consequence of the negative correlation between municipality population and the rooftop availability per dwelling. The potential PV generation in the warm season is greater than in the cold season for the three municipalities. This is explained by the greater solar irradiation as well as the longer number of daily sunlight hours during the warm season as compared with the cold one. These findings on the hourly electricity demand and the hourly PV potential generation provide valuable information regarding the potential self-consumption capacity of a region at municipal scale. For instance, for the case of Reus, which is urban, the peaks of the electricity consumption are barely covered by PV generation during the cold season. Although surpluses (excess of PV production) can be generated when irradiation is higher during the warm season. Whereas in the rural areas, the peaks of electricity consumption are covered by potential PV generation both in the cold and warm seasons with potential surplus generation under favourable weather conditions. In general, similar results can be generated for the other municipalities within the province.

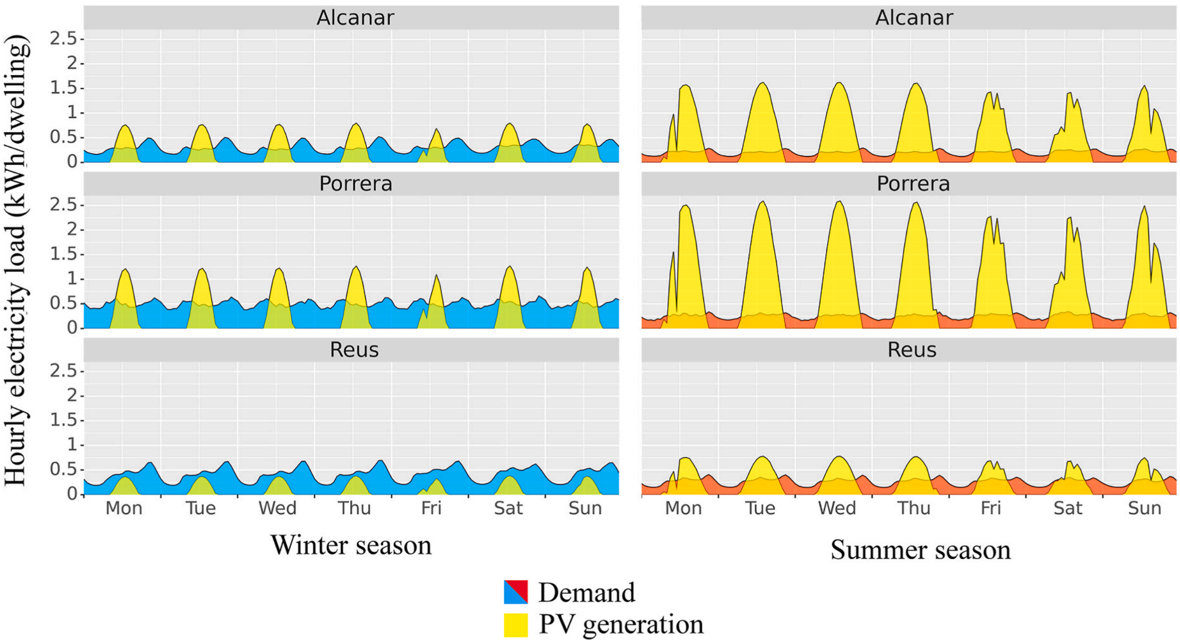

Fig. 8. Average electricity demand and potential PV generation per dwelling for two weeks (left column corresponds to 2 nd week of February 2019, right column corresponds to 3rd week of June 2019) at 3 different municipalities in the province of Tarragona. The electricity consumption per dwelling in kWh during cold season and warm seasons represented in blue and red respectively; in yellow the electricity that could be generated using 100 % of the rooftop PV potential per dwelling in kWh.

4.4. *Solar fraction (annual balance)*

Fig. 9 presents the results of the Solar Fraction based on yearly averages as described in Section 2.3. This annual net balance between electricity demand and PV potential production was carried out for the 184 municipalities in the province of Tarragona considering a hypothetical 100 % rooftop occupancy with solar panels. As previously explained, all the municipalities were classified by population groups according to Table 1.

The results show that almost all dwellings in municipalities with less than 20,000 inhabitants (43 % of the population and 44 % of the buildings) have an average Solar Fraction higher than 100 %, meaning that they could generate more electricity than they consume in a year by using all the available rooftop surface. This, however, does not translate to the self-sufficiency of these municipalities in terms of electricity generation from rooftop PV as not all the electricity produced will always be consumed at the time of production. The surpluses generated, especially during the solar radiation peak hours when the PV production is much higher than the demand, can either be stored to be used later (e. g., in batteries), injected into the grid, or directly lost. Following the analyses, municipalities with between 20,000 and 50,000 inhabitants (28 % of the population and 34 % of the buildings) each achieve a Solar Fraction per dwelling of approximately 75 %. This means that more energy is consumed than could be potentially generated in a year in a dwelling in average if all the available rooftops are occupied by PV panels. The situation is even more restrictive in self-consumption terms for the cases of municipalities with more than 50,000 inhabitants (30 % of the population and 22 % of the dwellings), where the solar fraction per dwelling is about 50 %. This implies that in average, municipalities representing the 58 % of the total population and the 56 % of the dwellings could not achieve a Solar Fraction equal or above 100 % if all their available rooftops surfaces were occupied by solar panels.

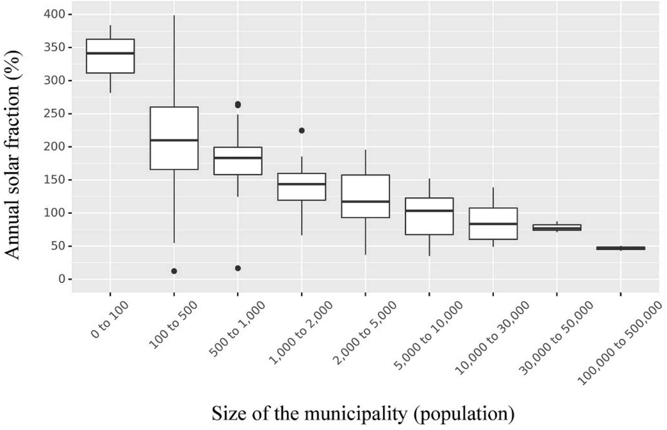

Fig. 9. Annual solar fraction (%) for the 184 municipalities of the Tarragona province grouped by size (population), calculated using the yearly basis balance.

4.5. *Solar fraction (hourly balance)*

When estimating the Solar Fraction using yearly averages as before, a non-trivial assumption is made, that is, the energy system has the capacity to store all surpluses generated allowing them to be used on-demand at any time. Unfortunately, this is not even close to reality. In a real-life approach scenario, not all the surplus electricity can be stored at the municipality level (and not even at the dwelling level) with the current batteries' technology and deployment level. Consequently, a lot of the surpluses are either re-injected into the grid when produced or directly lost. Therefore, a more realistic approach to the calculation of the net balance between the electricity consumed and the electricity produced by PV is the one based on hourly averages. This does away with the idea of storage, just the immediate consumption is catered for. Fig. 10 shows the results of the Solar Fractions for the whole province using this method. As can be observed, the self-production capacity in all municipalities decreases remarkedly compared to what was obtained in Fig. 9 based on the yearly average balance. With this second method, surpluses do not make the rural areas being self-sufficient anymore, and in general, all municipalities will remain between 30 and 55 % regarding their self-consumption capacity. Specifically, the Solar

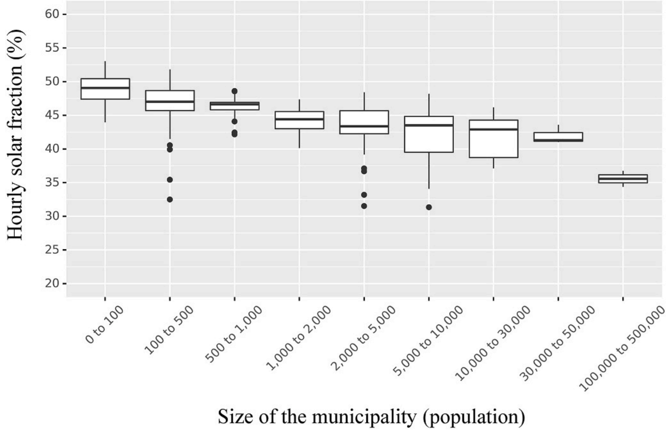

Fig. 10. Solar fraction per dwelling (%) for the 184 municipalities of the Tarragona province grouped by population using the hourly average method.

Fraction drop is about 20 % in urban areas and about 75 % in rural areas in average.

4.6. *Economic analysis*

The economic analysis by means of TAC and NPV have been carried out for the 184 municipalities in the province. Figs. 11 and 12 show the results for three specific municipalities, Porrera, Alcanar and Reus, each representing rural small, rural, and urban respectively. Three different electricity price scenarios were evaluated according to Table 4, one per column. Moreover, two different surplus compensation policies have been considered as defined in Section 3.4. In the analyses, the percentage of rooftop occupancy or load factor (X axis) ranges from 0, meaning that no PV system is installed; to 100 %, meaning that all the available rooftop is occupied by PV panels. A discount rate of 3 % was considered in all cases. Regarding the surplus compensation price per kWh, Section 3.3 and Table 5 underscore a notable variability in Spain's compensation rates. This variability is pivotal in shaping the profitability of PV installations: increased rates boost profitability, while decreased rates hinder it. A thorough exploration of the specific effects of surplus compensation prices is not covered in this research. The study instead relies on the average value derived from existing literature. In the first column in Fig. 11 a cheaper electricity prices scenario is considered. On the one side, in rural small and rural municipalities (Porrera and Alcanar, respectively), the TAC decreases up to certain point and then increases again. Hence, reaching a minimum between 30 and 40 % of the rooftop load factor (around 2–3 PV panels per dwelling), which would mean a saving of approximately EUR 50 per year compared to not installing PV. Thus, in these municipalities, when electricity is cheap and there is no electricity storage, independently of what surplus compensation policy scenario is considered, the economic optimum implies not deploying all the rooftops' PV potential. On the other side, in Reus, an urban municipality with a much lower useful rooftop surface, the TAC does not reach the optimal point (minimum) even with 100 % of the load factor (around 2 PV panels per dwelling). Hence, the economic optimum implies a deployment of 100 % of the rooftops' PV potential capacity. In this case, the optimum savings is also about EUR 50 per year. Complementarily, Fig. 12 shows equivalent results in terms of NPV.

The second column in Figs. 11 and 12 show the scenario of an average electricity price market. In Fig. 11, in the rural small and rural municipalities, the optimal TAC values occur at different load factor values depending on the surplus compensation policy applied. While under current policies the maximum occurs between 40 and 60 % (around 3–5 PV modules and EUR 150–180 savings per year), under more beneficial hypothetical policies without constraints, the optimum occurs at 100 % of the load factor (around 8 PV panels per dwelling and EUR 200–300 savings per year). Complementarily, the NPV results in Fig. 12 give desirable investment values under any level of load factor. As for the urban municipality, Reus, the optimal values are still 100 % (around 2 PV panels per dwelling and EUR 150 savings per year) under both surplus compensation scenarios and for both TAC and NPV.

The third column presents the scenario with the electricity prices being more expensive than the average. The results indicate also strong influence of the policies applied on the amount of surplus electricity that can be sold to the grid in rural small and rural municipalities. On one hand, if the current limited surplus compensation policy is considered (dashed orange line), the optimal load factor is between 60 and 75 % in both cases (i.e., 5–6 PV panels per dwelling). In this case, the total annual savings are EUR 250 in Alcanar and EUR 300 in Porrera, 50 % and 40 % respectively. On the other hand, without any limits on the amount of surplus electricity that could be sold (grey line), the load factors are 100 % in both cases (i.e., 8 PV panels per dwelling) and savings are EUR 350 in Alcanar and EUR 500 in Porrera which translate to 70 % and 71 % less the cost of not having PV systems. On the contrary, Reus is not affected by the policies regarding the sale of surplus electricity rather, the limited rooftop availability. The optimal load factor is 100 % (i.e., 2 PV panels per dwelling). The savings are EUR 250 which is 38 % less than less the cost of not having PV system. The NPV values in this third scenario shows that, for all municipalities, it is the most profitable scenario in economic investment terms.

In conclusion, rural areas, which have a high proportion of single-family dwellings (85 %), show more sensitivity to changes in electricity prices and compensation policies, suggesting a nuanced approach for PV installations. In contrast, urban areas, characterized by a higher proportion of multi-story blocks (80 %), consistently benefit from maximizing their limited rooftop space for PV installations, regardless of external economic factors. As highlighted in Section 4.2, these findings offer insight into potential trends across the rest of Europe, where the housing ratio in both rural and urban areas closely aligns with that of the analyzed region.

4.7. *Optimal rooftop load factor*

Fig. 13 visualizes the optimal load factor per dwelling, which is the economically most favourable proportion of rooftop covered by PV across the 184 municipalities in Tarragona (refer to Section 2.4 for methodology). The analysis juxtaposes two surplus policy scenarios, illustrating how policy changes could shift the economic attractiveness of rooftop PV installations. For this assessment, the third electricity price scenario from Table 4 has been considered.

As explained in Section 2.2, the model utilizes an average consumption and rooftop surface for each dwelling in a municipality. This means variations in consumption in specific dwellings can alter TAC and NPV outcomes, thereby affecting the optimal load factor. A priori, dwellings with higher consumption will benefit from a higher load factor, in contrast to those with lower consumption, which will obtain a lower return on their PV system. In parallel, dwellings with higher availability of rooftop than the average, particularly in urban areas, will obtain better results for TAC and NPV. However, this assumption should be taken with caution, since the final result also depends on the hourly demand curve in each case.

A central observation emerges when comparing the two policy frameworks. Under less restricted feed-in-tariff policies (as shown in the right figure) compared to the current ones (left figure), the economic viability of PV systems increases notably in rural municipalities. These rural areas, due to their prevalent single-family dwellings proportion, often have rooftop availabilities ranging from 4-5 square meters to 14–15 square meters per dwelling. Conversely, in the urban regions, where the average rooftop availability per dwelling is limited to 4–5 square meters, with a higher ratio of multi-story buildings, the economic return remains unchanged between both scenarios, since the primary

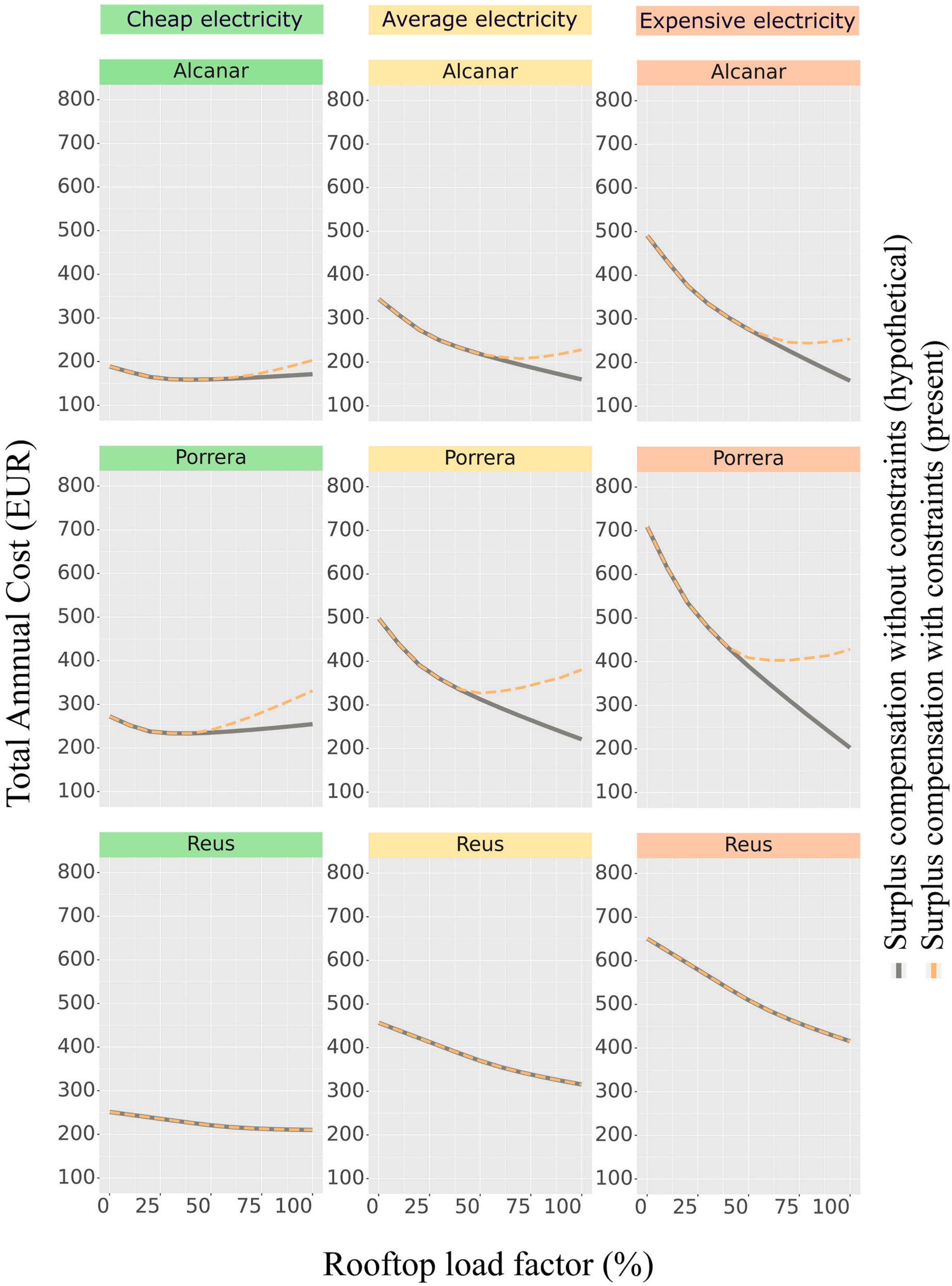

Fig. 11. Total Annual Cost (EUR) per dwelling based on the percentage of the rooftop occupied with PV panels at three municipalities in Tarragona province. Two surplus selling electricity policies have been considered: (orange dashed) current scenario with limits on the selling of surplus electricity, and (grey) a hypothetical scenario without limits on the selling surplus electricity. Three electricity price scenarios have been considered: (left column) downward electricity price scenario; (central column) average electricity price scenario; (right column) upward electricity price scenario. A 3 % discount rate has been considered in all cases.

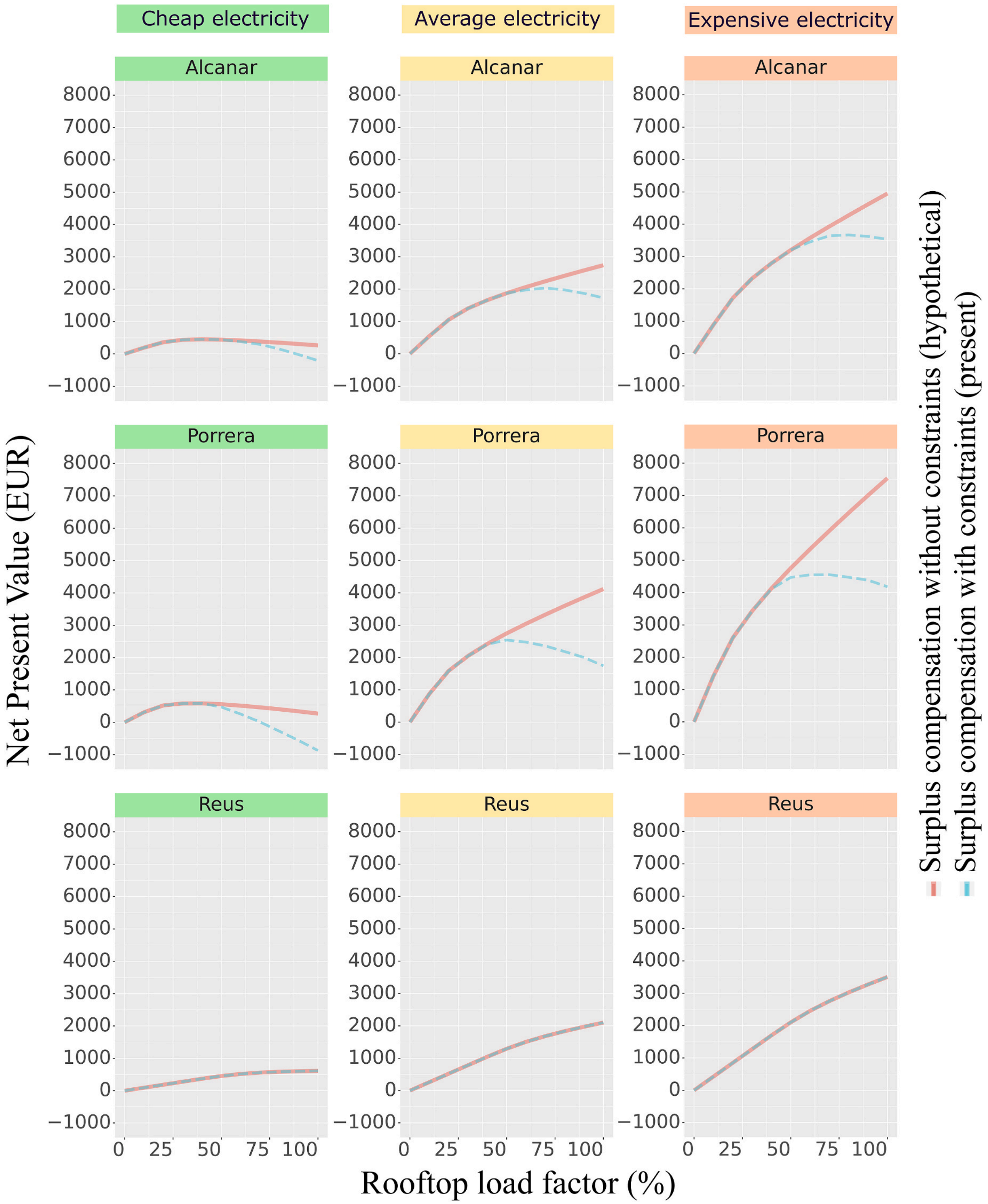

Fig. 12. Net Present Value (EUR) per dwelling based on the percentage of rooftop occupied with PV panels at 3 municipalities in Tarragona province. Two surplus selling electricity policies have been considered: (blue dashed) current limited scenario and (red) hypothetical unlimited scenario. Three electricity price scenarios have been considered: (left column) downward electricity price scenario; (central column) average electricity price scenario; (right column) upward electricity price scenario. A discount rate of 3 % has been considered in all cases.

constraint is the limited rooftop capacity. In terms of the load factor, while urban municipalities consistently achieve a 100 % optimal load factor under the present policy scenario with constraints, rural areas vary, with factors ranging from 40 % to 75 % based on electricity market prices (as depicted in Figs. 11 and 12). Yet, with a more accommodating compensation approach, all municipalities could attain a 100 % optimal load factor.

In essence, while maximizing rooftop PV installation under current Spanish policies doesn't always yield optimal economic benefits, a more accommodating compensation framework would make full rooftop utilization economically advantageous throughout all municipalities.

4.8. Optimal PV power to be installed

Section 4.2 highlighted the difference in rooftop space availability between rural and urban municipalities. This distinction is further

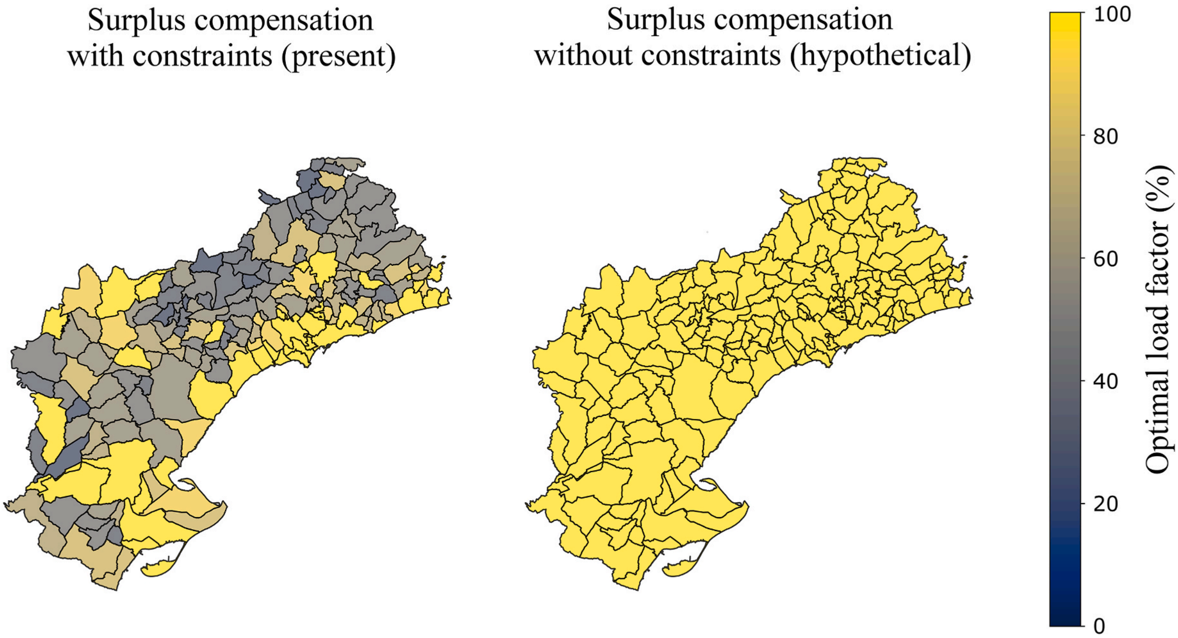

Fig. 13. Optimal Rooftop Load Factor per dwelling in % under 2 different surplus compensation policies in the province of Tarragona at the municipal scale.

reflected in Fig. 14, which depicts the optimal rooftop PV power installed per dwelling in each municipality, determined by the optimal load factor as described in Equation (13).

Diving deeper into the data, multi-story buildings dominate urban areas, making up 80 % of the dwellings and accommodating 42 % of the province's population. Such homes typically have the capacity to install between 0.8 and 1.2 kWp of PV power, translating to an annual savings of 33 % on the variable component of the electricity bill. In this setting, the purchase price of grid electricity, rather than the surplus compensation policy, primarily drives profitability. As electricity prices escalate, so does the economic appeal of the PV systems. Conversely, single-family dwellings, representing 85 % in rural areas, can potentially install up to 2.6 kWp, yielding a 40 % savings under present policies. However, with more lenient regulations, these savings could surge to 70 %.

5. Conclusion

The research presented provides a comprehensive, data-driven approach to assess the potential of electricity self-consumption in residential sector through rooftop PV systems. It innovatively integrates real-time hourly electricity demand data, various surplus compensation policies and fluctuating electricity prices, offering significant implications for industry stakeholders, policymakers, and regions alike.

The study underscores that data resolution matters. Rooftop PV self-

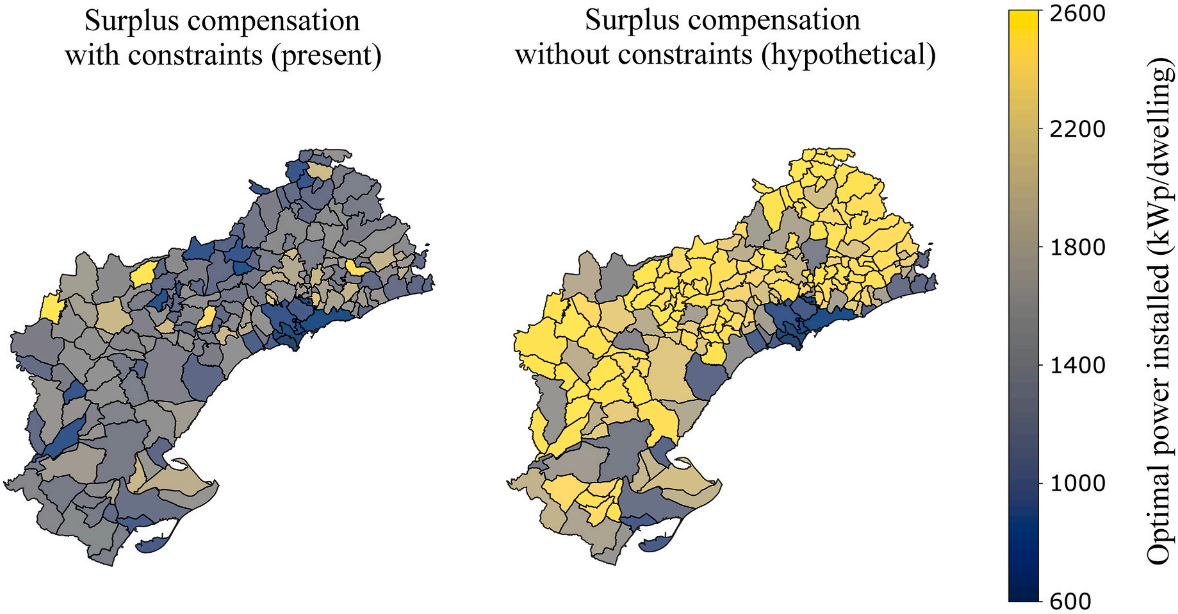

Fig. 14. Optimal PV power installed per dwelling in kWp/dwelling under 2 different surplus compensation policies in the province of Tarragona at the municipal scale. Supporting the findings from Section 4.7, it's clear that municipalities with ample rooftop space per dwelling, predominantly rural areas with a higher proportion of single-family homes, are significantly impacted by compensation policies when it comes to optimal PV power installations. In contrast, urban regions, characterized by multi-story buildings, exhibit limited variation under both policies due to rooftop space constraints.

consumption estimations based on annual data can lead to overestimations of capacity compared to those grounded in hourly data. When relying on annual data, the studied regions with predominantly single-family dwellings appear to achieve 100 % self-sufficiency. However, when estimated with hourly data, their self-sufficiency drops to approximately 50 %. Meanwhile, regions characterized by multi-story buildings experience a decrease in self-sufficiency from 50 % to 35 %. This has profound implications for energy planners, researchers, and potential rooftop PV users. Hourly-resolution data offers more precise insights, making it crucial for accurate forecasting and planning.

The varied geography considered in the analyses reveal another layer of insights. There is a discrepancy in rooftop PV self-consumption capacity between urban and rural areas. This distinction is largely driven by the relationship between a municipality's population and the dominant architectural style of its buildings. Urban areas, predominantly consisting of multi-story blocks, contrast with rural areas that have a larger proportion of single-family dwellings. Notably, the proportion of these prevailing buildings' typologies in rural and urban contexts aligns closely with the EU average. This differentiation means that rural areas have more available rooftop space per dwelling in average, thus, a higher potential for PV generation. Conversely, urban areas face significant constraints in terms of rooftop surface availability. However, it's important to note that these findings, based on the local building typologies, can be extrapolated to other regions, irrespective of their urban or rural classification. For regions with similar architectural trends, these insights remain relevant. For industry stakeholders and energy planners this suggests an opportunity to target areas with favourable building typologies for expansive PV installations. Additionally, it accentuates the role energy communities can play in harnessing and optimizing this potential. From a policy perspective, it underscores the importance of crafting policies and incentive structures tailored to specific architectural and regional contexts.

On the economic front, ensuring fair compensation rates is critical for motivating homeowners and industry players to invest in PV systems. However, the current surplus compensation policy in Spain limits the economic feasibility of PV installations, leading to an underutilization of available rooftop space. This repercussion is especially pronounced in regions with a high concentration of single-family homes, which typically corresponds to rural areas in Europe. This is a clear call to action for regulators and policymakers, as the use of roofs should be a priority to promote PV deployment. Implementing more favourable compensation policies can significantly boost the country's installation rates, leading to job creation in the renewable energy sector, boosting local economies, and driving it closer to renewable energy targets and sustainability goals.

Pivoting to the study's boundaries and future prospects, it's evident that analyses at a higher geographical resolution can refine the outcomes and reveal more understandings around PV self-consumption. Employing average consumption profiles for each municipality, while practical, may not capture specific consumption patterns in specific districts. An in-depth examination might provide a clearer view of self-consumption dynamics across various dwellings. Likewise, adopting one average rooftop area per dwelling might miss out on variances within municipalities, suggesting that individualized assessments could reveal higher PV opportunities in selected areas. Moreover, the choice to model PV installations horizontally, while justified, may not be universally optimal, and adjusting orientations, despite the potential loss of surface, could increase self-consumption potential in particular dwellings. Additionally, exploring the contributions of energy communities and integrating the service and industrial sectors could offer a more comprehensive perspective on the country's energy landscape.

Author contribution

Raul Saez: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft. Dieter Boer: Conceptualization, Validation, Writing – review & editing, Supervision, Project administration, Funding acquisition. Adedamola B. Shobo: Writing – review & editing. Manel Vallès: Conceptualization, Validation, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used openAI's chatGPT in order to improve language and readability, with caution. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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