Solar Energy 238 (2022) 150–161

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Self-consumption possibilities by rooftop PV and building retrofit requirements for a regional building stock: The case of Catalonia

Alba Torres-Rivas [a,b], Mariana Palumbo [b], Laureano Jiménez [c], Dieter Boer [a,*]

[a] Departament d'Enginyeria Mecànica, Universitat Rovira i Virgili, Av. Paisos Catalans 26, Tarragona, Spain
[b] GICITED Research Group, Departament de Tecnologia de l'Arquitectura, Universitat Politècnica de Catalunya, Barcelona, Spain
[c] Departament d'Enginyeria Química, Universitat Rovira i Virgili, Av. Paisos Catalans 26, Tarragona, Spain

ARTICLE INFO

Keywords:
Rooftop photovoltaic
Distributed generation
Renewable energy
Building retrofit

ABSTRACT

European Union policies are encouraging the implementation of renewable energies to reduce fossil fuels dependency. This is further motivated by the effects of global warming and the relevant temperature rise in large cities. Thus, it is increasingly important to analyze the large-scale potential of solar energy, making use of the roof availability for renewable energy generation in cities. Furthermore, it is important to couple this analysis with the energy demand of the buildings analyzing the self-consumption possibilities and help in the decision-making process in regional investments. The proposed methodology estimates and matches the roof potential for electricity generation by PV and the building's energy demand, including the building characteristics as a novelty. As a result, we calculate the self-consumption possibilities and the retrofit requirements of a selected housing stock. Our methodology starts with the quantification and classification of the residential stock. This includes the characterization of the types of dwellings in the regional residential stock, taking into account the size of the municipalities. Then the energy demand of the dwellings, depending on the characteristics of the buildings and the roof generation potential, is compared. Catalonia region (Spain), including the city of Barcelona is studied to show the contributions of this methodology to the energy transition. Results indicate that between 8 and 30% of the residential electricity demand of the municipalities can be covered by rooftop PV. Important energy retrofits (reductions of 80% of the energy demand) are required to approach the feasibility of self-consumption. Nevertheless, there is a limited potential impact in larger cities due to the reduced available roof area per habitant.

1. Introduction

It is estimated that 50% of the total energy consumption in the EU is used in heating and cooling buildings, while less than 10% of such energy is produced using renewable sources (EUR-Lex). There is evident potential for the development of distributed renewable energy production. European Union policies encourage the implementation of renewable energies to reduce fossil fuel dependency (Eurostat) to reach the goals of greenhouse gas emissions for 2050 (International Energy Agency, 2050; Union). This change has become a necessity due to global warming effects as the increase of temperatures, especially in the cities. Those top-level regulations also impact local policies (ICAEN), cities strategies (EUCF), and consumers' perceptions. The decentralized electricity generation can contribute to the new paradigm, where consumers have a central role, reducing their energy demand and providing electricity generated with rooftop PV installations. This change also provides the benefits of electrifying heating demand combining the use of PV and heat pumps, which improves the sector's efficiency (Larson et al., 2020). In this work, we propose a novel methodology that analyses the effect of building retrofit and coverage of top-roof with PV to evaluate the self-consumption possibilities at the municipality and regional levels.

The extensive implementation of solar energy networks for the heating and cooling of buildings has several advantages. On the one hand, it contributes to the diversification of energy generation sources, increasing renewable energy generation, and the possibility of self-consumption of the generated electricity in the same building reduces the demand during peak hours. On the other hand, it enhances the efficiency of the grid, as energy losses due to transport are reduced. To carry out this implementation, Nault et al. (Nault et al., 2015) identified simple metrics that can perform as indicators to evaluate energy aspects

* Corresponding author.
E-mail address: dieter.boer@urv.cat (D. Boer).

https://doi.org/10.1016/j.solener.2022.04.036
Received 30 June 2021; Received in revised form 11 April 2022; Accepted 13 April 2022
Available online 21 April 2022

Nomenclature

A	Municipalities with less than 101 inhabitants
Aa	Available roof area
Ar	Total roof area
B	Municipalities between 101 and 500 inhabitants
BSk	Cold semi-arid climate
Building Surface	Building surface for a cluster (m^2)
C	Municipalities between 501 and 1000 inhabitants
Cf	Facility coefficient
Cfa	Humid subtropical climate
Cfb	Temperate oceanic climate
Cs	Shadowing coefficient
Csa	Hot-summer Mediterranean climate
D	Municipalities between 1001 and 2000 inhabitants
Dfb	Warm-summer humid continental climate
E	Municipalities between 2001 and 5000 inhabitants
Energy Demand	Energy demand for the different building's cluster (kWh/m^2)
F	Municipalities between 5001 and 10,000 inhabitants
G	Municipalities between 10,001 and 20,000 inhabitants
GIS	Geographical information system
H	Municipalities between 20,001 and 50,000 inhabitants
DHW	Domestic hot water
I	Municipalities between 50,001 and 100,000 inhabitants
j	Set of clusters
J	Municipalities between 100,001 and 500,000 inhabitants
K	Municipalities with more than 500,000 inhabitants
N. Buildings	Number of buildings for cluster
L	Low
m	Set of municipalities
È	PV module efficiency
PR	Performance ratio
PV	Solar photovoltaic
RBT	Representative building typologies
Rad	Annual solar radiation (kWh/m^2)
RC	Roof coefficient
Roof Coef.	Building roof coefficient for the different buildings' cluster
Total Demand	Municipality total energy demand (kWh)
TotalElectricityproduction	Municipality total electricity generation (kWh)
Total Roof	Municipality total roof (m^2)
Total Surface	Municipality total building surface (m^2)

for neighborhoods. They classified solar potential methods into three categories: (1) geometry-based metrics, (2) external solar and geometry-based metrics, and (3) full climate and geometry-based metrics. For each metric, two kinds of performance criteria are identified: passive solar and active solar. Then, these metrics are applied to two case studies: an area with different urban planning options and a planning with different parameter options, showing the necessity to revise during the early design phase and integrate simple metrics with the aim to reduce the computational demand in early stages.

Most of the attempts made to evaluate the available roof area (and the consequent solar potential) follow a bottom-up strategy. This approach consists of analyzing in detail a comprehensive urban area to determine the ratio of the total roof area available and then extrapolate the results to a larger territory. Following this approach, Izquierdo et al. (2008) used cartographic maps to sample areas of 450 m × 450 m to estimate the available roof area (Aa) of urban areas in Spain. They defined the Aa as the total roof area (Ar) modified by two coefficients ranging from 0 to 1 (Cs and Cf) that accounted for the effect of shadows from other buildings and for the areas occupied by competing uses, respectively. Then, they classified urban areas into Representative Building Typologies (RBT). RBT were a function of population density and building density, which were both divided into quartiles (low, medium, high and very high). Ar per area unit, Cs and Cf were extrapolated from the sampling, assuming that they were characteristic to each RBT. Their results showed that Spain's total available roof area is 517 ± 183 km^2 and 14.0 ± 4.5 m^2/habitant (confidence level of 95%). Results agree with the values previously published by the IEA (393.7 km^2) (Kjellsson, 2002) and Greenpeace (595 km^2) (Greenpeace, 2005). The authors also reported that Catalonia is the region in Spain with the highest potential, with about 100 km^2 of available roof area.

Hofierka and Kanuk (Hofierka and Kaňuk, 2009) proposed a three-step methodology to assess the photovoltaic potential in a neighbor or mid-sized town. Their methodology includes (1) the creation of a 3D model of the city and its implementation in a geographical information systems (GIS) database; (2) the modeling of solar radiation; and (3) the calculation of potential energy production. They applied their methodology to a town in Slovakia. To extrapolate the results obtained, the authors divided the urban area into four zones according to the predominant building typologies: residential houses (767.5 buildings/km^2), blocks of apartments (230.2 buildings/km^2), industrial areas (258.2 buildings/km^2) and other facilities (212.0 buildings/km^2). Their results show that the ratio of the available roof area concerning the total and roof area (Aa/Ar) varies from 0.35 to 0.75 among the zones. The authors point out that higher photovoltaic potential and lower connection and maintenance costs should be expected in zones with higher buildings, such as blocks of flats or facilities.

Li et al. (2015) evaluated the effect of building aspect ratio, orientation and density (dependent on building height and floor occupation) on solar potential. Their analysis was not restricted to roofs but also included buildings' façades. They considered the "exploitable solar radiation", that is, the radiation above the minimum threshold from which solar technologies are feasible. The authors modeled an urban arrangement of nine pavilion dwellings to estimate the total building surface with "exploitable solar radiation" and then applied a corrective factor (0.75) that accounted for any other aspect restricting the available area (such as areas occupied by competing uses). Their results show that solar potential in roofs can be reduced by 60% at high-density configurations. The concept of "exploitable solar radiation" is also used by Santos et al. (2014), who exclude surfaces with solar irradiation lower than 800 kWh/(m^2y). Moreover, the authors also consider the size of the roof area and exclude those roofs of less than 24 m^2, as solar technologies will not be economically viable.

More recently, Mainzer et al. (Mainzer et al., 2014) proposed a methodology that combines the solar potential evaluation with the energy demand of the residential sector. They combine a standard load profile for the domestic demand with the roof building's surface and solar technical potential with GIS, enabling them to evaluate self-consumption possibilities for municipalities or regions.

On the other hand, there is a wide literature on building retrofit, including building case studies or building simulation models, and evaluating different technologies, measures or the implementation of new materials to a wide range of different buildings profiles. Those studies have proved to be an efficient tool for building retrofit. Examples include insulation materials (Carreras et al., 2015), the use of biobased materials (Torres-Rivas et al., 2018), the applicability of thermal energy storage (Tulus et al., 2016) or models with multiple combinations (Krarti et al., 2020). Furthermore, building stock analysis has been carried out in different investigations, analyzing mainly the energy

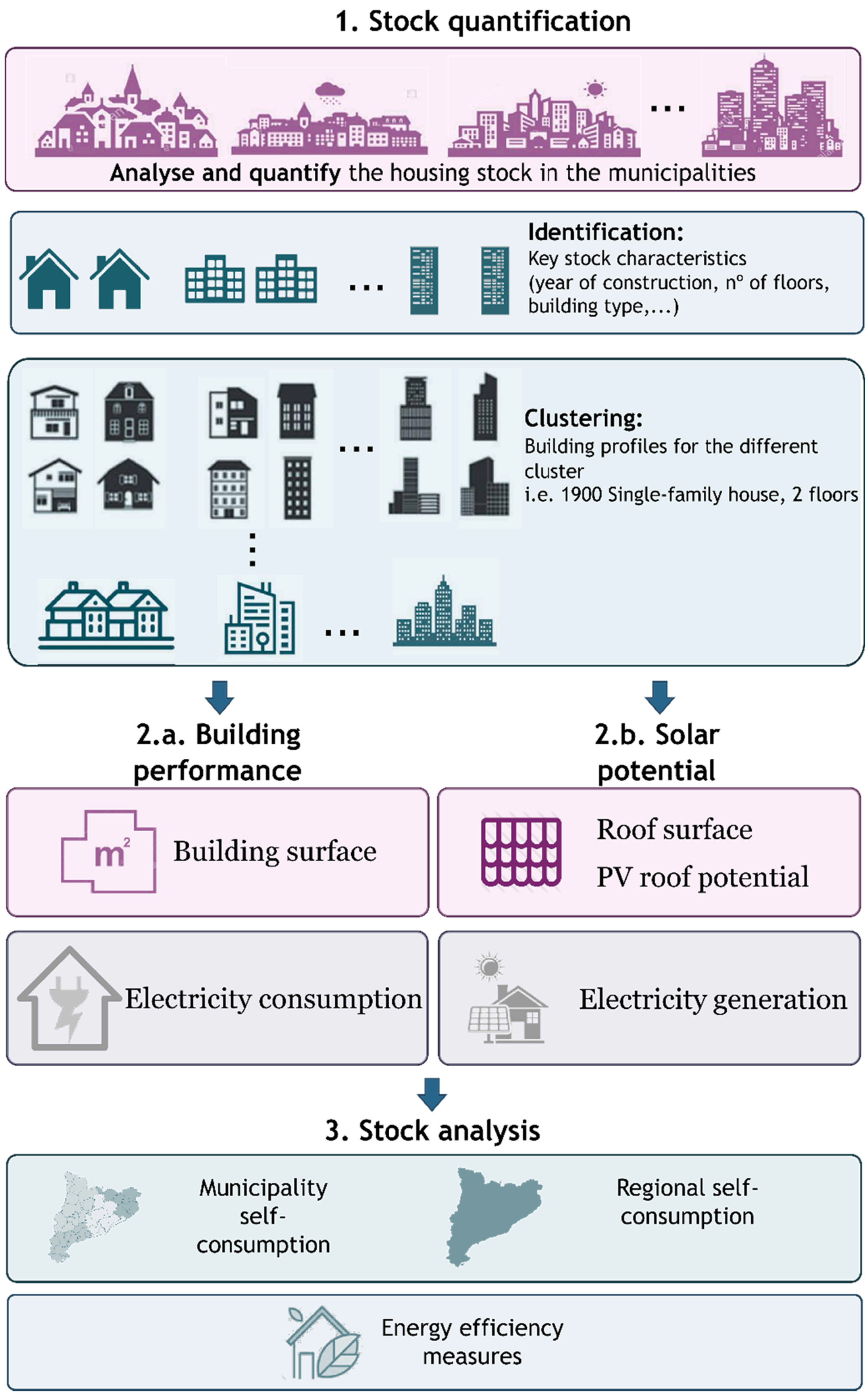

Fig. 1. Methodological scheme. 1 building stock quantification and distribution in the different municipalities; (2) Energy consumption and demand calculations by building typology. The energy generation includes the PV rooftop potential and the solar radiation; (3) Stock analysis, including building retrofit analysis and roof surface evaluation.

consumption but also the economic cost or the CO_2 emissions. Aksoezen et al. (2015) analyze the city of Basel, Switzerland, identifying that morphology of buildings and measured energy performance are key factors in the renovation of the building stock. Mastrucci et al. (2014) proposed a methodology that combines GIS with energy consumption and energy savings for heating in Rotterdam, Netherlands, applying different retrofit measures (insulation, windows and the renovation of the heating and ventilation system). They suggest that a wide range of savings (ranging from 4% to 70%) can be obtained for heating demand, depending on dwelling type and age. Furthermore, Krarti et al. (2020) followed a bottom-up approach to build a stock from three different simulated buildings. They analyzed the effect of building retrofit in a household, analyzing the energy consumption but also the peak demand, achieving 61% and 56% reduction, respectively.

According to the bibliography, a wide range of computational models have been developed for PV building integration, but they do not consider the energy performance of the envelope or with building constructive characteristics. On the other hand, housing stock models that implement building typology and the construction system do not include roof surface availability and PV integration.

This research aims to provide a methodology that analyzes the feasibility of self-consumption in the residential sector and the building retrofit possibilities, filling the actual gap. We propose a novel methodology to simultaneously estimate the roof potential and the energy demand, including the building profile and the construction characteristics. This allows the calculation of the covering potential of the buildings to any technology, in this case, PV. The methodology consists of quantifying the residential building stock and its characterization to classify the types and fractions of those dwellings among all the buildings. This enables the evaluation of the dwellings' energy demand, depending on the buildings' characteristics, and quantifies the PV roof potential. Furthermore, this model provides the possibility to analyze the effect of energy efficiency measures applied to the whole housing stock as it maintains the building information. This can provide guidelines for policymakers to justify future actions, such as specific subsidies.

The structure of the paper is divided into the following sections. The methodology for developing a regional residential building stock and roof potential in Section 2. The paper's case study for the evaluation of self-consumption and building retrofit is given in Section 3. The paper's results regarding the selected case study are presented and discussed in Section 4. Finally, the main conclusions are given in Section 5, which provide guidelines that can be useful for new policies regarding renewable energies and building retrofit.

2. Methodology

The following methodology quantifies the solar potential of the residential building stock and its energy demand. This enables the evaluation of potential energy production and quantifying the improvement required to achieve a regional balance between the potential of generation and the demand of the building stock. With this objective in mind, the current housing stock of a region has been quantified and characterized. This allowed us to analyze the different types of municipalities, the effect of the local climate conditions, and building retrofit possibilities.

This methodology is divided into three steps (Fig. 1). The first one corresponds to the quantification of the building stock. The second one analyzes the building performance and the solar potential. The last step is the self-consumption analysis and the improvement targets for the residential sector. Fig. 1 summarizes the key steps and the necessary data.

This methodology can be applied to different solar potential studies but mainly focuses on wide areas, decreasing the computational demand thanks to the clustering of the building stock. This can be coupled with building modeling, bibliographic data or GIS.

3. Building stock

This methodology is based on the statistical analysis of the housing stock, considering basic building features, the photovoltaic potential, the residential demand, and the retrofit potential. A review of the existing studies is carried out to properly quantify and characterize the housing stock, reducing the computational demand without compromising the results. Several reports characterize the building stock in the European Union globally (EPISCOPE; ODYSSEE-MURE) or specific countries (Cuchí and Sweatman, 2011; Cuchí and Sweatman, 2011; IDAE). Based on their conclusions, the most important characteristics defining the housing stock are (1) year of construction, (2) number of floors and (3) number of dwellings per building. Due to regulatory changes, old buildings have less or no insulation and worse enclosure than newer buildings. This affects the thermal conductivity of the roof and walls and the infiltration rate, which are two key parameters impacting the energy demand of any building (Carreras et al., 2015). The number of dwellings per building is important because it decreases the share of roof and external walls for each dwelling, which reduces the effect of outdoor climate conditions on energy demand. Finally, the number of dwellings per building is important to properly quantify the energy demand of the building and the roof surface (e.g., single-family houses tend to have fewer floors and an enclosure to surface ratio higher than multi-family houses which results in higher exposure to any climatic condition, especially roof solar radiation in Mediterranean climates) (ICAEN). Considering these three key factors (year of construction, building typology and numbers of floors), the regional area selected was analyzed and clustered.

The area's total housing stock was grouped according to the selected criteria, achieving the number of buildings that correspond to each group of buildings and the total building surface per group for each municipality. Once each municipality's housing stock is analyzed, the total built area and the total roof area (Ar) are quantified. The energy demand at the municipality scale is calculated for each cluster following equations (1) to (3) and based on the parameters proposed by Cuchí et al. (ODYSSEE-MURE).

$$Total\ \ Surface_m = \sum_j \left(N.Buildings_j \hat{A}\cdot Building\ \ Surface_j\right) \tag{1}$$

$$Total\ \ Demand_m = \sum_j \left(N.Buildings_j \hat{A}\cdot Building\ \ Surface_j \hat{A}\cdot Energy\ \ Demand_j\right) \tag{2}$$

$$Ar = \sum_j \left(N.Buildings_j \hat{A}\cdot Building\ \ Surface_j \hat{A}\cdot Roof\ \ Coef._j\right) \tag{3}$$

4. Solar potential

Solar potential is quantified for each municipality, applying the specific radiation conditions to the total roof area. To calculate the total roof area, different techniques can be applied. This study uses a ratio between the building surface and the roof surface, which reduces the computational demand. To quantify the total roof area, the stock of each municipality was divided into the different clusters of buildings, a specific ratio between the building surface and the total roof for each profile, which is influenced by the number of dwellings and the type of roof (e.g., flat or pitched). We ensure that all the roofs analyzed correspond to the residential sector and PV panel installation is feasible with this approach.

This total roof area does not correspond to the available roof area, as it is affected by orientation, architectonical effects, and shadings, among others. The whole area must be reduced to ensure a profitable installation of solar panels. A vectorial GIS map methodology can be used to discriminate the profitable roof surface from the non-profitable one to quantify those effects. However, for this study, we used the modifying coefficients (Cs and Cf) proposed by Izquierdo et al. (2008), and we analyzed the sensitivity of the roof profitability in the energy generation.

The solar potential of each municipality can be evaluated with simulation software, mathematical calculation or coupling the calculation of the roof surface and the bibliographic data of the energy generated. In addition, it can be linked with the energy generation in each time step to match the energy generation and demand. This match is an important parameter when the grid cannot absorb the energy or consider the use of, for example, batteries. Finally, the potential for self-consumption was calculated based on energy demand and energy generation in each municipality. In this study, we have coupled bibliographic data and mathematical calculations with an annual time step

Table 1
Municipalities sizes according to the number of inhabitants.

Municipality group	Size of the municipalities (number of inhabitants)
A	<101
B	101–500
C	501–1000
D	1001–2000
E	2001–5000
F	5001–10,000
G	10,001–20,000
H	20,001–50,000
I	50,001–100,000
J	100,001–500,000
K	>500,000

and assuming that the grid absorbs the electricity that is not consumed in buildings.

5. Study of catalan housing stock

The geographical area of the study was Catalonia, a region in the North-East of Spain. The area includes 947 municipalities, more than 7.5 million inhabitants, and 31.895 km^2, corresponding to approximately 3.8 million dwellings in 1.1 million buildings (Idescat). In this area, the regional government plans to achieve the so-called Energetic Transition Act (ICAEN), creating small decentralized suppliers of energy that provide electricity in local areas. The proposed model should help analyze the transition possibilities or identify the requirements to achieve this model in the residential sector: building retrofit, small electricity generators (e.g., solar farms), electricity grid improvements, etc.

The municipalities were clustered according to their population in eleven groups (from A to K, see Table 1) due to the high-density variation (Fig. 7) using statistical data (National Statistics Institute of Spain) (INE). In turn, as we are going to detail later, the housing buildings of each municipality were classified according to the year of construction, the number of floors, and the number of dwellings (single-family house or multi-family house).

Fig. 2 shows the distribution of municipalities by size in the provinces of Catalonia (Barcelona, Girona, Lleida and Tarragona,). It is important to remark the high number of small municipalities (less than 1000 inhabitants) and that only one city (Barcelona) has over 500,000 inhabitants. We can see that Girona (North-East) and Tarragona (South) have a similar distribution of municipalities, while Barcelona (Middle East) and Lleida (West) have different profiles. Despite these differences, it can be noticed that all the regions have a relevant share of municipalities between 101 and 2000 habitants (B, C and D).

Existing buildings were classified into 16 groups according to the number of dwellings (single-family and multi-family blocks), the number of floors (less or more than 3) and the year of construction (before 1960, from 1960 to 1980, from 1981 to 2001 and from 2002 to 2011). We updated the parameters assuming the worst scenario possible for the buildings from 2002 to 2011. New buildings have the same envelope as buildings from 2001, thus not considering energy efficiency improvements due to new regulation since 2006. The total roof area (Ar) of the buildings was calculated from the total built area and the number of buildings in each municipality, using a different ratio for each group.

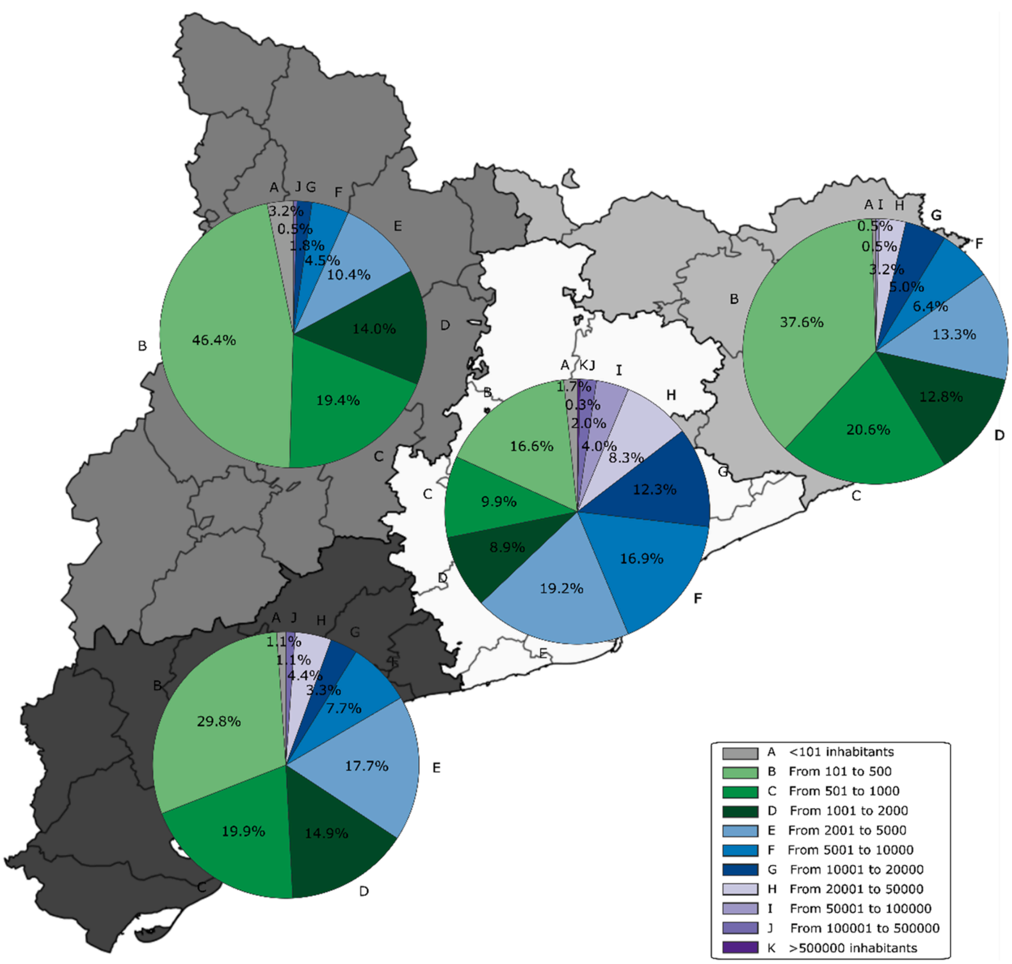

Fig. 2. Municipalities distribution in the different provinces of the area per municipalities' sizes, being the top-left corner the more rural area and the white one the one with bigger municipalities.

Table 2
Building profiles are taken from Cuchí et al. (EPISCOPE).[1]

	Year of construction	<1960		1961–1980		1981–2001		2002–2011[1]	
	Floors	≤3	≥4	≤3	≥4	≤3	≥4	≤3	≥4
Single family	kWh/ m^2 year	180.5	100.1	175.7	99.5	142.7	85.3	142.7	85.3
	m^2 roof/ m^2 dwelling	0.69	0.5	0.69	0.5	0.69	0.5	0.69	0.5
Multi family	kWh/ m^2 year	180.5	100.1	175.7	99.5	142.7	85.3	142.7	85.3
	m^2 roof/ m^2 dwelling	0.69	0.18	0.69	0.18	0.69	0.18	0.69	0.18

[1] Extrapolated by the authors from the original figures (Cuchí and Sweatman, 2011).

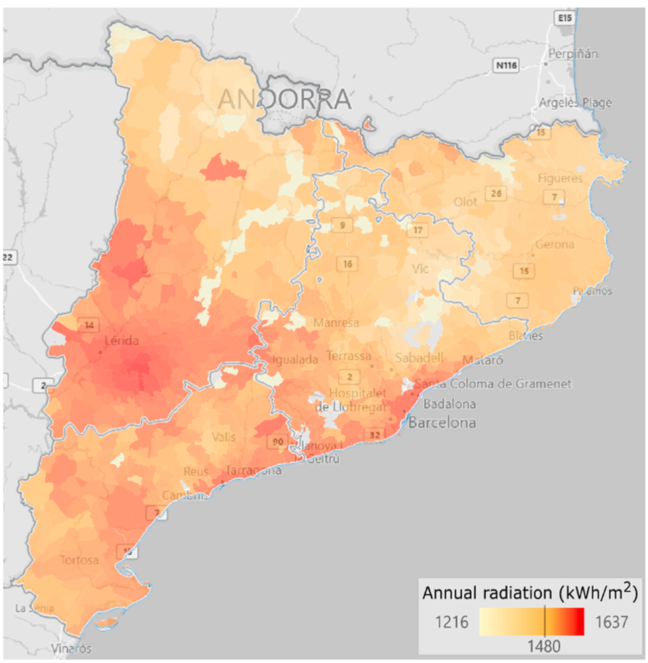

Fig. 3. Color map of the municipalities' annual solar radiation, red represents the higher and yellow the lower radiation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Finally, the estimations on the energy demand for each group were implemented and are shown in Table 2.

On the other hand, data provided by INE (Instituto Nacional de Estadística) (INE) was used to determine the total built area and the number of buildings corresponding to each category in each municipality.

According to Table 2, we can identify that the main difference in the energy demand is achieved in buildings built before 1980 and those built after this period. Identifying the reason for this change is important to analyze the building directives of Spain, which are also applied to the selected case study. This sector started to be regulated by 1957, with several technical standards, mainly based on constructive requirements. In 1977, the different technical standards were transformed to "Homologated solutions for the building sector", which implement the thermic requirements in buildings and the fire protection requirements. This changed the standards, generating the necessity to implement building insulation in the whole building envelope, an inflection point in the sector. More recently, in 1999, Building ordination law was presented to regulate the sector to achieve more fulfillment of the directives and proposed the necessity to actualize the building regulations. In 2006 the Technical Building Code entered into force, which provides new guidelines and further restrictions in the sector's energy demand. However, this research adopted the worst scenario applying the same energy demand as buildings built between 1981 and 2001. Due to the reduced number of buildings built since the economic crisis in 2008, this assumption is not considered to significantly affect the results obtained.

Once the total roof (Ar) and energy demand are quantified for the different municipalities, the available roof area (Aa) is calculated according to the roof coefficients (RC) suggested by Izquierdo et al. (Izquierdo et al., 2008). This article uses the maximum range of coefficients and the mean value to analyze the sensitivity to the coefficients at the municipality level. The corresponding value is 0.19 ± 0.06. Note that 0.19 is the suggested value for Spain, and the range used covers the worst and best cases.

Finally, the Ar is used to work out the PV potential, including the climate conditions of the municipality. These climate conditions determine the available annual solar radiation for the solar generation of each municipality, which is shown in Fig. 3(ICAEN). The figure shows that the south part of Lleida and Barcelona and the whole area of Tarragona have a higher potential of PV according to the solar radiation. We can also identify some municipalities in the area of Barcelona, Girona and Lleida that have low radiation. Those areas correspond to narrow mountain passes such as the area of Montseny, the reservoir of Rialp and Oliana or the natural park of Sant Joan de Toran, among others.

This paper uses the annual radiation to quantify the energy produced by the roofs following equation (4), with a PV module efficiency of 0.16 and performance ratio of 0.75 (Defaix et al., 2012). We assume that the grid can absorb the energy produced and supply the same amount when the building demand is required.

$$Total\ electricity\ production_m = TotalRoof_m \hat{A}\cdot RC\hat{A}\cdot \eta\hat{A}\cdot Rad_m\hat{A}\cdot PR \quad (4)$$

Regarding the self-consumption coefficient, it is supposed that the energy required for heating and cooling is obtained from heat pumps with a COP of 3 and other technologies with an efficiency of 0.85. The distributions have been carried out according to Spain's heating and cooling energy distribution (IDAE).

6. Results and discussion

We next discuss the results obtained from the methodology to the case study, first analyzing the characteristics of the municipalities. Fig. 4 summarizes the housing stock of the municipalities based on the year of construction and the size of the municipality. Furthermore, also the total constructed area, the total and available roof surface is considered. Fig. 4 is divided into ten subplots, one for each size of the municipality. In turn, each subplot contains eleven boxplots, one for each range of construction years. In each boxplot, the box represents the first and third quartiles (top and bottom of the box) and the mean value in the middle, the lines or whiskers represent the limit of outliers and the diamonds represent all the values.

The number of old dwellings in Catalunya is high, with the corresponding high heating and cooling requirements, especially relevant in buildings built before 1900. Those old dwellings are more common in small municipalities (less than 10,000 inhabitants). They represent a total of 86.8% of the municipalities but only 16.7% of the inhabitants, and these buildings correspond to 4.4% of the entire stock. If we analyze all the buildings previous to the first Spanish regulation, including energy efficiency measures (that is, before the '80s) (EPISCOPE), these are especially numerous in municipalities larger than 20,000 inhabitants. These correspond to 6.8% of the municipalities but include 72% of the

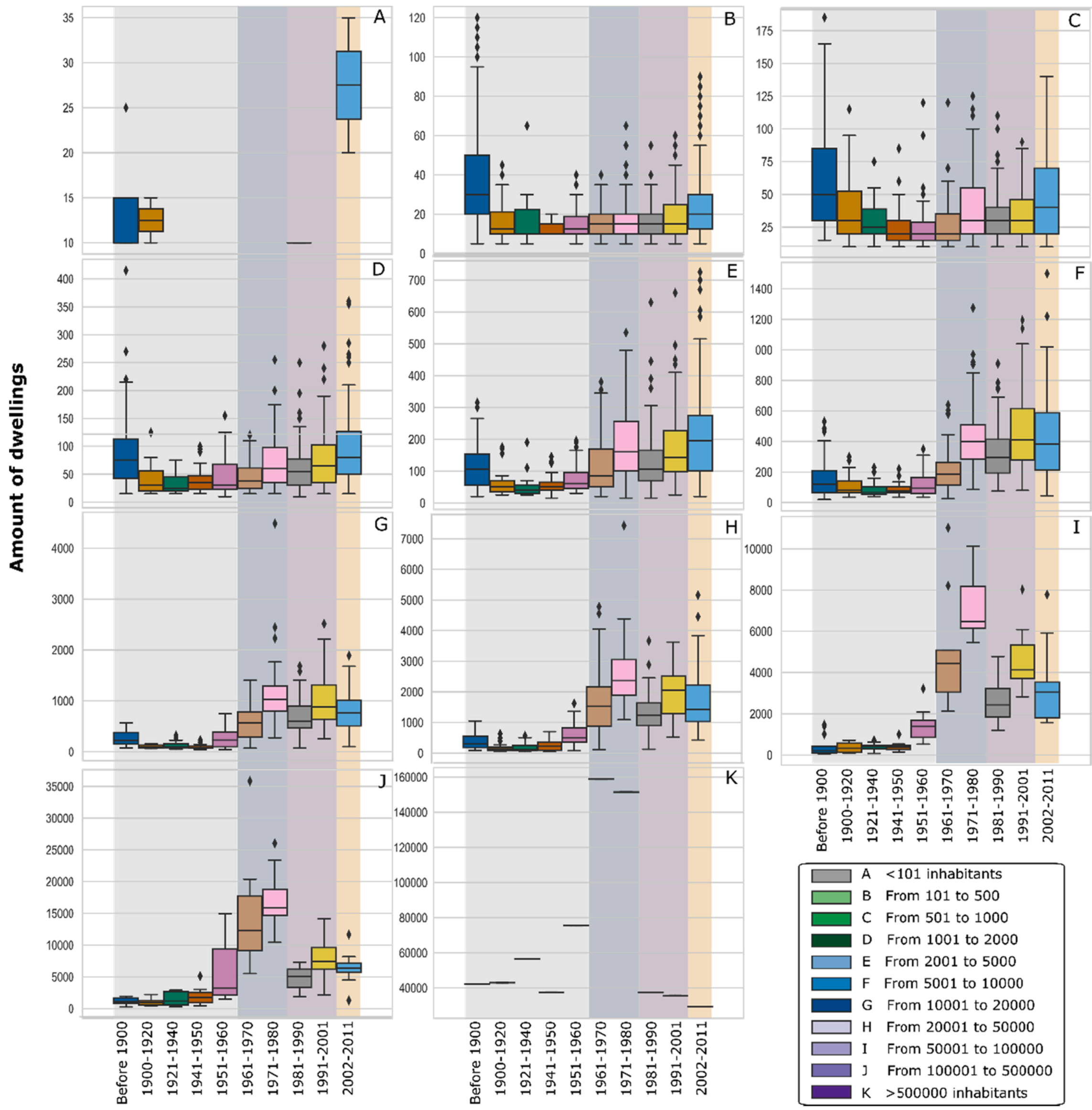

Fig. 4. Boxplot of the distribution of the number of dwellings according to the municipality size and the year of construction. Starting with the smallest municipalities (less than 101 inhabitants) until more than 500,000 inhabitants, increasing the size from top to bottom and left to right. The different building profiles (Table 2) are represented with different background colors, corresponding to the different building standards in Spain, with homogeneous distributions for small municipalities' sizes (B, C and D), with a higher share of buildings after '60s (green and purple backgrounds) for the municipalities' sizes E, F and G and an important increase of buildings after '60s (green background) and a decrease after '80s (purple background) for H, I and J. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

inhabitants. This is explained by the strong internal immigration from rural to urban areas and the high population growth during the '60s & '70s in the region. Those buildings correspond to 63.5% of the whole stock. The buildings constructed after that period -were restricted by law regarding thermal transmittance and overall energy demand, which improves their energy efficiency.

From Fig. 4, we identify three different groups of municipalities, A, B, C and D are the first group, with buildings of all ages and with an important number of old ones, built before 1900. The second group includes E, F, G: They have a lower amount of old buildings (built before 1960) and a higher share of buildings built after the '60s. Finally, the last group corresponds to H, I, J and K, with few old buildings, an important increase between '50s/'60s and '80s with a decrease of buildings after 1981.

Another important reduction in energy consumption is provided by the construction typology, comparing multi-family houses with single-family houses. This trend benefits big cities compared to small villages, as shown in Fig. 5. Data indicate that municipalities with less than 20,000 inhabitants have more single-family houses than multi-family houses. This analysis confirms the groups already identified in Fig. 3. The first group has an important amount of single-family houses, the second group has a moderate amount of each type, and the third one includes mainly multi-family houses.

Fig. 6 indicates the roof surface by habitant for all the municipalities' sizes with a violin plot representation. The white dot corresponds to the mean value, the black rectangular correspond to the first and third quartiles and the lateral shape wide correspond to the distribution of the municipalities of the different sizes. From the plot, it is noticeable that in municipalities up to 10,000 inhabitants (groups B to F, A is the exception), the roof surface per inhabitant is similar, between 3.6 and 3.9 m^2/inhab. As the size of the municipality increases, this figure decreases, reaching values of 2.9, 2.2, 1.9, 1.65 and 1.3, for the rest of the categories, respectively. These results concluded that the (total or available) roof surface per inhabitant is practically the same for small and medium

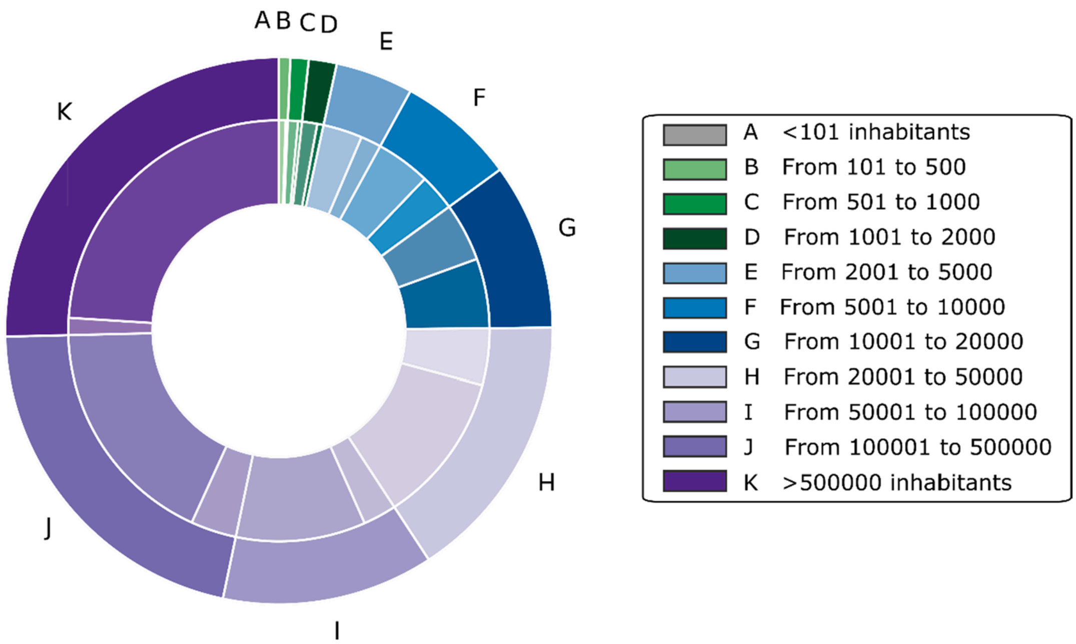

Fig. 5. The number of dwellings for each municipalities' size group (outer circle) is divided into single and multi-family houses (the inner circle). Light color corresponds to single-family houses and the darker one to multi-family houses.

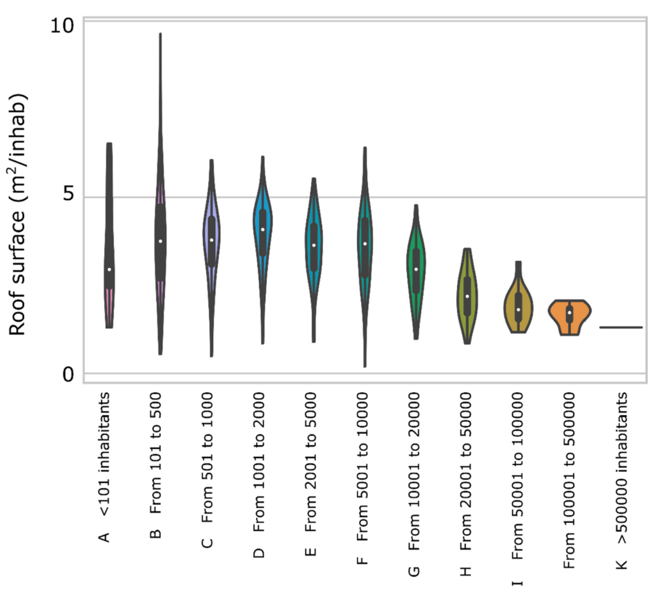

Fig. 6. Violin diagram of the total roof surface per habitant for the different municipalities' sizes, starting with the smallest municipalities and increasing the size from left to right.

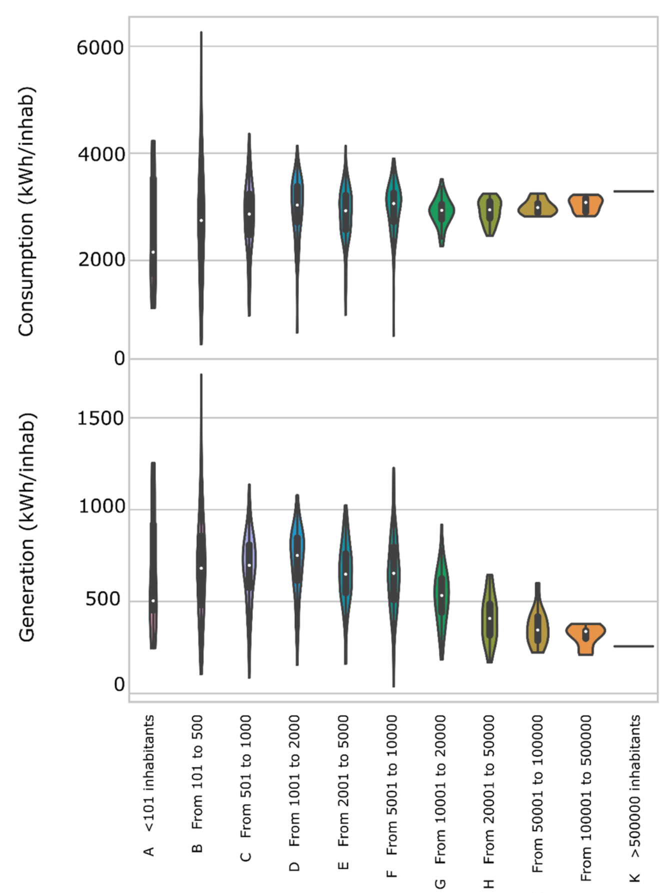

Fig. 7. Violin diagram of the electricity consumption and generation per habitant for the different municipalities size.

municipalities but is significantly reduced in big municipalities.

Finally, it is important to analyze the potential of self-consumption of the different municipalities to analyze if the residential sector is able to cover their energy consumption. Previous works by the Spanish Institute of Energy Diversification and Efficiency (IDAE) (IDAE) suggest an average national annual electricity consumption of 9922 kWh/dwelling. In this study, we obtained 10,815 kWh/dwelling. The energy consumption (Sánchez) is estimated as 106 kWh/m2, whereas our results are 95 kWh/m^2, extracted from the whole energy consumption, thus validating our methodology.

Figs. 6–8 quantify the energy that can potentially be provided by PV installed on the available roofs areas, the residential buildings' energy consumption, and the self-consumption factor. Fig. 6 has two subplots,

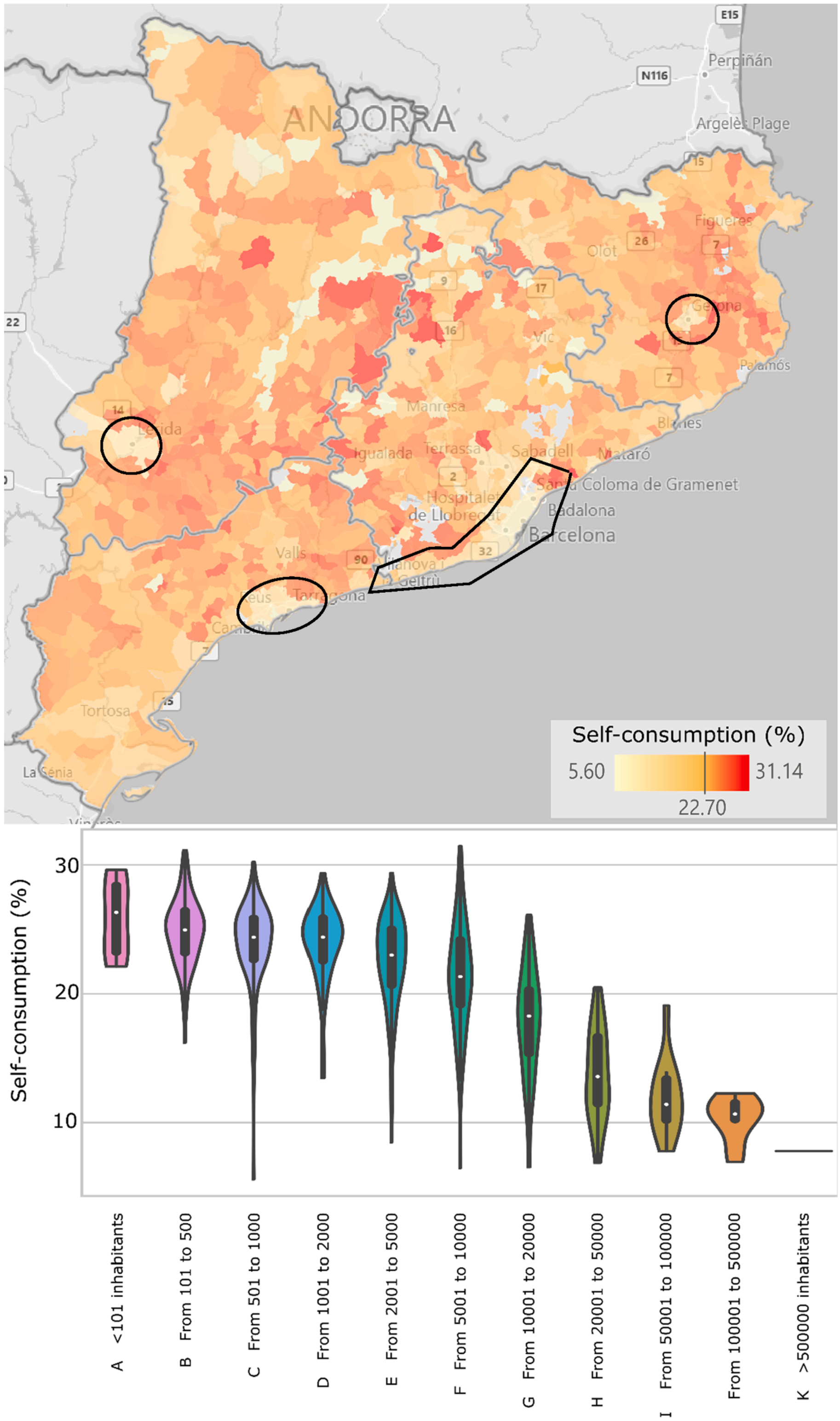

Fig. 8. Self-consumption subplots, the first one corresponds to a color map of the self-consumption, while the second one corresponds to a violin diagram with the distribution of the self-consumption for the different municipalities' sizes.

one with the consumption per inhabitant and one with the energy that can potentially be generated per inhabitant, which provides an initial overview of the possibilities of self-consumption.

The difference of magnitude between Fig. 7a and 7b suggests that there is only a limited possibility for self-consumption for the selected case study under the given conditions. We can see a similar consumption per habitant but an important decrease in the generation per habitant when comparing smaller with larger municipalities.

In Fig. 7a and Fig. 7b, we can see that municipality size A performs differently than the other small municipalities. This is mainly due to the small amount of buildings and municipalities included in this group, with only 11 municipalities and a total of 185 dwellings.

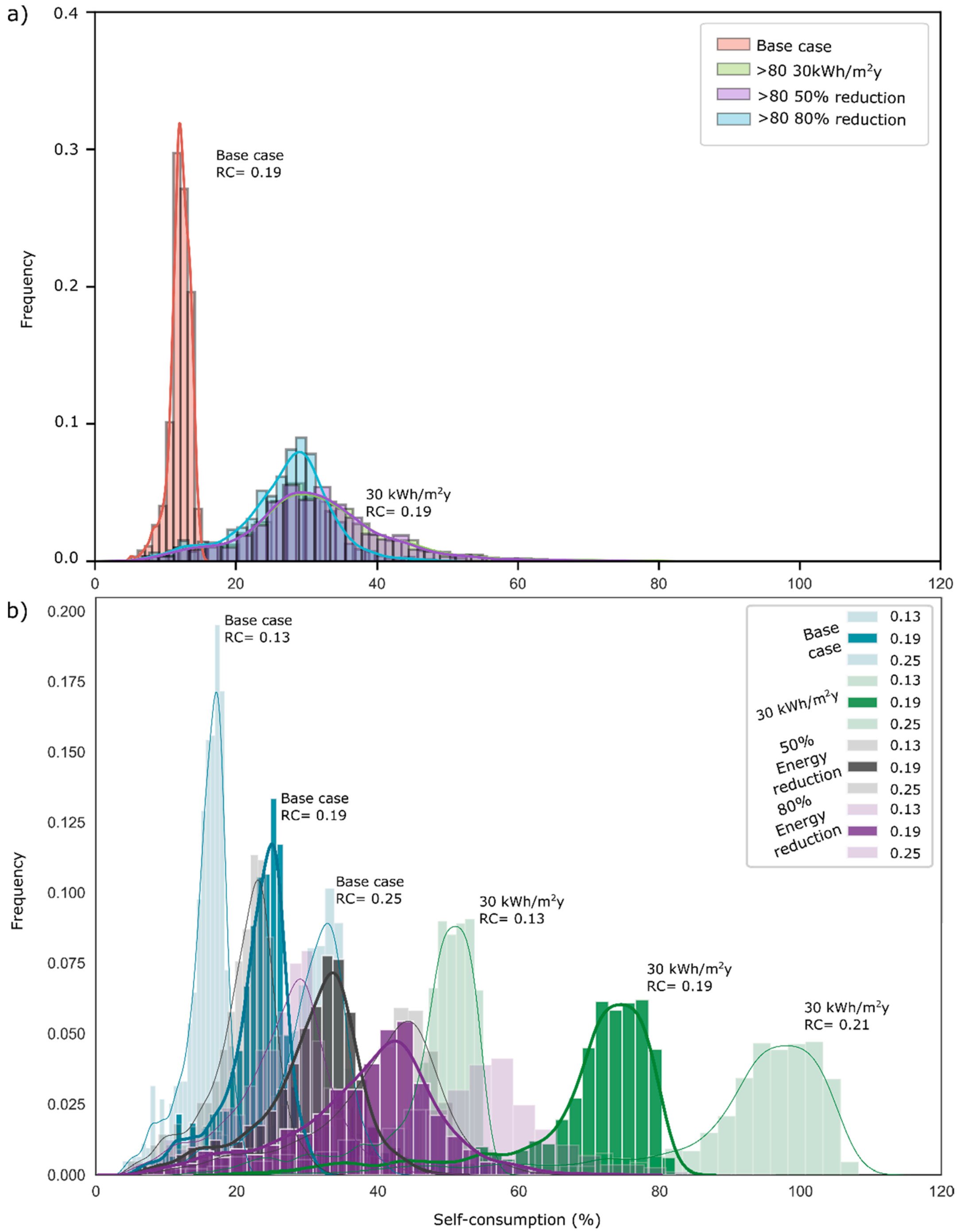

Fig. 9. Scenarios to evaluate the effect of the roof surface and building retrofit in self-consumption with PV, in part a) the buildings elder than 1980 are retrofitted, whereas in part b) the whole housing stock is retrofitted. The different colors represent the improvements in the energy demand of the buildings compared with the base case. In contrast, the different scenarios of the profitable roof coefficient are represented with the same color with a transparency effect. For clarification, the base case and the case study of 30 kWh/m^{2}y are labeled.

Fig. 8 shows that, as expected, municipalities with low solar radiation also provide low self-consumption, despite the size of the municipality. On the other hand, the municipalities with high radiation do not provide high self-consumption in most situations, as shown in the south area of Lleida and the coast of Barcelona. The capitals of the different regions and the big municipalities around Barcelona are also identified in the map due to their low self-consumption. In other words, for the selected case study, population density has a higher effect on the self-consumption possibilities than solar radiation.

In turn, the violin plot shows that all the municipalities achieve a self-consumption below 32%, with lower values for big municipalities. The average factor in cities of more than 20,000 inhabitants is 12%. In the case of Barcelona (the only municipality with more than 500,000 inhabitants), the self-consumption factor is 8%, three times lower than the value for small municipalities. This conclusion can be extrapolated to other regions, showing the importance of analyzing the effect of the building retrofit and the roof profitability in order to provide different scenarios that can provide guidelines to the policymakers. For that reason, we developed different scenarios for roof coefficient and building retrofit. For the first one, the different burdens of the profitable roof

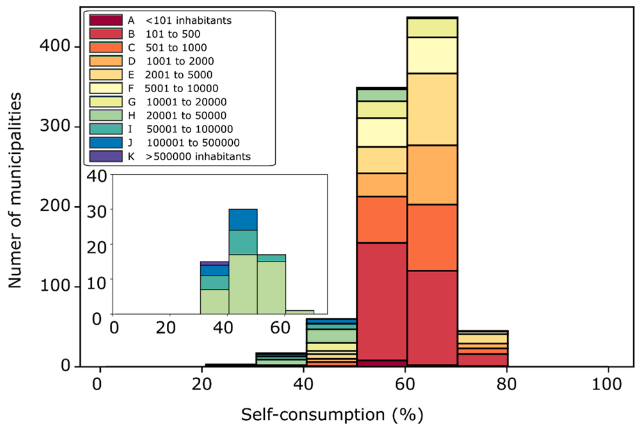

Fig. 10. Distribution of municipalities' self-consumption factor according to their size for the case of 80% of improvements in the climatization and roof coefficient of 0.19. The figure contains two stacked histograms, the first one with all the municipalities' sizes and a specific one for only the four biggest municipalities' sizes (H to K).

surface coefficient suggested by Izquierdo et al. (Izquierdo et al., 2008) are selected (varying from 0.13 to 0.25).

On the other hand, medium and deep retrofit scenarios, with savings of 50% and 80% in the energy demand for heating and cooling, are supposed for the whole stock and old buildings (before 1980). The baseline demand of 5349 kWh/y was maintained, as it is supposed that the lighting, DHW and appliances are the same before and after the building retrofit. Finally, the last scenario where the whole housing stock has a fixed demand of 30 kWh/(m^2·y), including heating, cooling, lighting and appliances. All those combinations provide 17 different scenarios with the different combinations of energy demand and roof coefficient. The six scenarios of building retrofit only in old buildings do not provide important self-consumption possibilities.

In Fig. 9, we combine two density plots with the different scenarios of building retrofit and profitable roof surface. In both plots, the y axis provides de frequency or fraction of municipalities with the corresponding self-consumption, we can see that the base case has more homogeneous performance in municipalities self-consumption, and as we implement retrofit measures, we increase the diversity in this factor. The results suggest that the retrofit should be carried out in the majority of the stock to arrive at values closer to total self-consumption, as improvements reducing the energy demand more than 80% are required to achieve values closer to 100%. Only in the case that the whole stock scenario approaches Passive Houses self-consumption can be provided by the residential stock. Despite that, improvements in the elder buildings, those without insulation (built before '80s), provide an important improvement in self-consumption with reductions in the energy demand since 50% reduction in heating and cooling. The effect of this retrofit increases the self-consumption possibilities more than double compared with the base case (12% base case, 27% 50% reduction, and 31% 80% reduction and 30 kWh/m^2y). Apart from building retrofit, this measure should be coupled with improvements in the electricity consumption provided by the different appliances or the combination with other heating sources like district heating. Massive retrofit is complex, and further evaluation of the environmental impact and cost should analyze the global effectiveness of the measures. On the other hand, if we study the effect of the profitable roof coefficient, we can see that it provides important effects in self-consumption possibilities, varying between ±3% in the base case until ±20% for the more restrictive scenario. This suggests that big municipalities with higher buildings could benefit from evaluating the effect of a PV installation on walls, increasing their generation capacity.

In order to analyze the municipality self-consumption possibilities of this scenario, a stacked histogram of the scenario of 80% of improvement in the energy required for heating and cooling in the whole stock and roof coefficient of 0.19 is shown in Fig. 10.

In Fig. 10, we can see that those small municipalities can achieve higher self-consumption, being especially remarkable for municipalities smaller than 20,000 inhabitants, where the majority achieve values higher than 50%. We also identified that municipalities with more than 50,000 have a lower potential for self-consumption with values lower than 50%, suggesting that only an important increment on roof surface availability could achieve self-consumption. It is also important to analyze the case of Barcelona with a self-consumption coefficient of 25.9, which shows the necessity to couple this generation with other alternatives.

All the studied scenarios suggest that bigger municipalities should be coupled with additional centralized renewable energy plants in order to cover all the extra electricity demand required. Those municipalities can also benefit from other roof generation, such as tertiary buildings or municipality pieces of equipment. As the effect of those municipalities is significant for the feasibility of self-consumption, we suggest that a more detailed analysis should be carried out in those municipalities, emphasizing the case of Barcelona due to the important effect on the overall energy demand of the region. On the other hand, we have also identified small municipalities' self-consumption possibilities, which suggests that combining building retrofit and multiple self-generation scenarios could provide small generation-consumption grids. Further analysis, which combines agricultural industry, biomass production, PV generation and building retrofit, could provide more insights into this area.

7. Conclusions

A methodology is presented to analyze the self-generation potential associated with the housing stock coupled with PV generation and the building energy demand. This methodology can provide insights on the self-consumption possibilities of the residential sector evaluating the rooftop PV generation on the buildings. Furthermore, this methodology provides an alternative to evaluate the effect of building retrofit for a region.

After analyzing the housing stock of the selected area (Catalonia), three different types of municipalities are identified based on the size and the distribution of the construction years of the housing stock. Small municipalities have mainly old buildings, medium municipalities have most of the housing stock built after 1960 and big municipalities have a large amount of the housing stock constructed between 1950/60 and 1980.

For the territory analyzed (7.5 million inhabitants and 31.895 km^2), the maximum self-consumption is around 30% and decreases drastically in larger municipalities (>20,000 inhabitants). The building typology also affects this tendency. Larger municipalities have many higher-rise multi-family houses, resulting in a lower roof surface per inhabitant.

From the scenarios considered, we can conclude that, in order to achieve a significant self-consumption, the housing building stock requires important retrofit measures, with reductions in the heating and cooling energy demand around 80%. This should also be coupled with improvements in the appliances' efficiency to further reduce the electricity demand, as only building retrofit would not be enough to approach self-consumption with rooftop PV generation (e.g., district heating, appliance renovation).

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.

Acknowledgments

The work has been funded by the Spanish government RTI2018-

093849-B-C33 (MINECO/FEDER) and by the European Union EFA353/19 SAVASCO (Interreg POCTEFA). The authors would like to thank the Catalan Government (2017SGR1409) and the Tarragona's council (2021PGR-DIPTA-URV01). This work is also partially funded by the Ministerio de Ciencia, Innovación y Universidades–Agencia Estatal de Investigación (AEI) (RED2018-102431-T).

References

Aksoezen, M., Daniel, M., Hassler, U., Kohler, N., 2015. Building Age as an Indicator for Energy Consumption. Energy Build. 87, 74–86.

Carreras, J., Boer, D., Guillén-Gosálbez, G., Cabeza, L.F., Medrano, M., Jiménez, L., 2015. Multi-Objective Optimization of Thermal Modelled Cubicles Considering the Total Cost and Life Cycle Environmental Impact. Energy Build. 88 (June), 335–346.

Cuchí, A., Sweatman, P., 2011. Una Visión-País Para El Sector de La Edificación En España, GBCe, CONAMA, pp. 70.

Cuchí, A., Sweatman, P., 2011. A National Perspective of Spain's Buildings Sector: A Roadmap for a New Housing Sector, Green Building Council España and Fundación Conama.

Defaix, P.R., van Sark, W.G.J.H.M., Worrell, E., de Visser, E., 2012. Technical Potential for Photovoltaics on Buildings in the EU-27. Sol. Energy 86 (9), 2644–2653.

EPISCOPE. TABULA/EPISCOPE [Online]. Available: https://episcope.eu/welcome/.

EUCF. EUCF - What [Online]. Available: https://www.eucityfacility.eu/what.html.

EUR-Lex. EUR-Lex - Comunicación de La Comisión Al Consejo y Al Parlamento Europeo - Programa de Trabajo de La Energía Renovable - Las Energías Renovables En El Siglo XXI: Construcción de Un Futuro Más Sostenible [Online]. Available: https://eur-lex.europa.eu/legal-content/HR/TXT/?uri=CELEX:52006DC0848.

Eurostat. What Is the Share of Renewable Energy in the EU? [Online]. Available: https://ec.europa.eu/eurostat/cache/infographs/energy/bloc-4c.html.

Greenpeace, 2005. Un Informe Sobre El Potencial de Las Energías Renovables En La España Peninsular Equipo de Trabajo, pp. 258.

Hofierka, J., Kaňuk, J., 2009. Assessment of Photovoltaic Potential in Urban Areas Using Open-Source Solar Radiation Tools. Renew. Energy 34 (10), 2206–2214.

ICAEN. I. C. d'Energia, Atlas de Radiacio Solar a Catalunya. Instituto Catalán de Energía [Online]. Available: http://icaen.gencat.cat/es/detalls/publicacio/Atlas-de-radiacio-solar-a-Catalunya-00003.

ICAEN. I. C. d'Energia, Pacte Nacional per a La Transició Energètica de Catalunya. Institut Català d'Energia [Online]. Available: http://icaen.gencat.cat/ca/plans_programes/transicio_energetica/.

IDAE. I. para la D. y A. de la E. PROYECTO SECH-SPAHOUSEC.

IDAE. I. para la D. y A. de la E. Consumos Del Sector Residencial En España.

Idescat. Idescat. Tema. Viviendas y Edificios [Online]. Available: https://www.idescat.cat/tema/habit?lang=es.

INE. I. N. de E. Censos de Población y Viviendas 2011 [Online]. Available: https://www.ine.es/censos2011/tablas/Wizard.do?WIZARD=4&reqCode=paso2.

International Energy Agency, Net Zero by 2050 – Analysis - IEA [Online]. Available: https://www.iea.org/reports/net-zero-by-2050.

Izquierdo, S., Rodrigues, M., Fueyo, N., 2008. A Method for Estimating the Geographical Distribution of the Available Roof Surface Area for Large-Scale Photovoltaic Energy-Potential Evaluations. Sol. Energy 82 (10), 929–939.

Kjellsson, E., 2002. Potential for Building Integrated Photovoltaics. IEA-PVPS Task 2002, 4.

Krarti, M., Aldubyan, M., Williams, E., 2020. Residential Building Stock Model for Evaluating Energy Retrofit Programs in Saudi Arabia. Energy 195, 116980.

Larson, E., Greig, C., Jenkins, J., Mayfield, E., Pascale, A., and Zhang, Chuan, et. al., 2020. Net-Zero America: Potential Pathways, Infrastructure, and Impacts Interim Report, pp. 1–345.

Li, D., Liu, G., Liao, S., 2015. Solar Potential in Urban Residential Buildings. Sol. Energy 111, 225–235.

Mainzer, K., Fath, K., Mckenna, R., Stengel, J., Fichtner, W., Schultmann, F., 2014. A High-Resolution Determination of the Technical Potential for Residential-Roof-Mounted Photovoltaic Systems in Germany. Sol. Energy 105, 715–731.

Mastrucci, A., Baume, O., Stazi, F., Leopold, U., 2014. Estimating Energy Savings for the Residential Building Stock of an Entire City: A GIS-Based Statistical Downscaling Approach Applied to Rotterdam. Energy Build. 75, 358–367.

Nault, E., Peronato, G., Rey, E., Andersen, M., 2015. Review and Critical Analysis of Early-Design Phase Evaluation Metrics for the Solar Potential of Neighborhood Designs. Build. Environ. 92, 679–691.

ODYSSEE-MURE. Energy Efficiency Trends & Policies | ODYSSEE-MURE [Online]. Available: https://www.odyssee-mure.eu/.

Manuel Hernández Sánchez, J. Energy Consumption and Associated Emissions of Residential Sector Consumo Energético y Emisiones Asociadas Del Sector Residencial.

Santos, T., Gomes, N., Freire, S., Brito, M.C., Santos, L., Tenedório, J.A., 2014. Applications of Solar Mapping in the Urban Environment. Appl. Geogr. 51, 48–57.

Torres-Rivas, A., Palumbo, M., Haddad, A., Cabeza, L.F., Jiménez, L., Boer, D., 2018. Multi-Objective Optimization of Bio-Based Thermal Insulation Materials in Building Envelopes Considering Condensation Risk. Appl. Energy 224, 602–614.

Tulus, V., Boer, D., Cabeza, L.F., Jiménez, L., Guillén-Gosálbez, G., 2016. Enhanced Thermal Energy Supply via Central Solar Heating Plants with Seasonal Storage: A Multi-Objective Optimization Approach. Appl. Energy 181, 549–561.

Union, E. 2050 Long-Term Strategy | Climate Action [Online]. Available: https://ec.europa.eu/clima/policies/strategies/2050_en.