# Diagnosis of the building stock using Energy Performance Certificates for urban energy planning in Mediterranean compact cities. Case of study
## The city of València in Spain.

Manso-Burgos; Ribó-Pérez, D.; As, J. Van; Montagud-Montalvá, C.; Royo-Pastor, R.

**DOI**
10.1016/j.ecmx.2023.100450

**Publication date**
2023

**Document Version**
Final published version

**Published in**
Energy Conversion and Management: X

**Citation (APA)**
Manso-Burgos, Ribó-Pérez, D., As, J. V., Montagud-Montalvá, C., & Royo-Pastor, R. (2023). Diagnosis of the building stock using Energy Performance Certificates for urban energy planning in Mediterranean compact cities. Case of study: The city of València in Spain. *Energy Conversion and Management: X*, *20*, Article 100450. https://doi.org/10.1016/j.ecmx.2023.100450

Energy Conversion and Management: X 20 (2023) 100450

Contents lists available at ScienceDirect

Energy Conversion and Management: X

journal homepage: www.sciencedirect.com/journal/energy-conversion-and-management-x

# Diagnosis of the building stock using Energy Performance Certificates for urban energy planning in Mediterranean compact cities. Case of study: The city of València in Spain.

Á. Manso-Burgos [a,*], D. Ribó-Pérez [c], J.Van As [b], C. Montagud-Montalvá [a], R. Royo-Pastor [a]

[a] IIE, Universitat Politècnica de València, Camino de Vera, s/n, 46022 València, Spain
[b] Eindhoven University of Technology, 5612 AZ Eindhoven, The Netherlands
[c] Delft University of Technology, Faculty of Technology, Policy, and Management, Delft, 2600 GA, The Netherlands

ARTICLE INFO

*Keywords:*
Energy Performance Certificates
Characterization of the building stock
City building diagnosis
Big data analysis

ABSTRACT

This research aims to diagnose the energy performance of buildings in València and identify areas where energy efficiency can be improved. The energy performance results of all 129,487 EPCs in the city were mapped and compared to socioeconomic variables to gain insights into the reasons behind the results. The study reveals that the city's building stock has poor energy performance, attributed to the lack of building standards during the city's expansion in the 1960s and 1970s. The worst energy performances are observed in the peripheral districts, particularly in the city's northern half, where low-income and low-renting rates are common, resulting in reduced investment capacity for individuals to retrofit their homes. To promote quick dissemination of measures to retrofit households, they must be adequate, economical, and replicable, avoiding social, administrative, and economic barriers. The study highlights the importance of EPCs as an objective tool to diagnose the energy efficiency of a city's building stock. Policymakers can use the findings to identify areas that require improvements and evaluate the appropriate actions to improve the building stock's energy performance. This study presents significant potential to reduce buildings' energy demand and achieve climate goals through EPCs.

## 1. Introduction

Making cities carbon–neutral is a major challenge due to their high energy consumption and significant emissions [1,2]. Over 75 % of the European population lives in urban areas, and the building stock is responsible for approximately 36% of all $CO_2$ emissions [3] and 40% of the final energy consumption in the European Union [4]. With these metrics, a huge energy-saving potential lies within the building environment in cities [5]. Nevertheless, construction and energy efficiency in the built environment actions are capital and human-intensive and require technical and administrative expertise. Therefore, cities must prioritise resources during transition to achieve a twofold objective. Improvements in energy efficiency in buildings can reduce the energy demand of cities while reducing the energy poverty situation of many urban areas.

According to a survey of the Buildings Performance Institute Europe, Energy Performance Certificates (EPCs) are currently one of the most important sources of information on the energy performance of buildings in the EU [6]. The EPC document describes how efficiently a building or building unit uses energy. The European Union introduced energy performance certification in 2002 with the first Energy Performance of Buildings Directive 2002/91/EC (EPBD). Consequently, all Member States had to introduce an effective certification scheme before 2009 [7]. EPCs can identify the energy situation of properties and, therefore, those locations with a more significant retrofitting potential according to their distribution over the city, the building usage, and the construction year. However, they do not provide an overall assessment of the city's building energy efficiency situation, its reasons, or a plan to improve it.

Compact Mediterranean cities are among the hardest to decarbonise mainly due to their miscellaneous built environment, which combines various types of districts (historical versus newly developed) and uses (industrial, residential or mixed-use), which usually require completely diverging approaches. Another complexity is the great variety of

* Corresponding author.
*E-mail addresses:* almanbur@etsii.upv.es (Á. Manso-Burgos), david.ribo@iie.upv.es (D. Ribó-Pérez), j.v.as@student.tue.nl (J.Van As), carmonmo@iie.upv.es (C. Montagud-Montalvá), rroyo@ter.upv.es (R. Royo-Pastor).

https://doi.org/10.1016/j.ecmx.2023.100450

Available online 22 September 2023

everyday routines and consumption practices. Therefore, contrary to the case of Northern and Central European cities where large-scale solutions could work, the diversity of Mediterranean cities runs contrary to one-size-fits-all. In the case of compact Mediterranean cities, solutions must be tailored for specific peculiarities, even at the district or neighbourhood level.

Following this approach, there is an opportunity to use the existing EPCs combined with other urban primary sources to characterise the building stock energy performance. This information will show the potential to provide policy recommendations to implement renovation policies. Therefore, this research aims to contribute to the following topics:

First, diagnose the current state of the building stock using EPCs according to the construction year, property use, and district. Then, analyse the built environment situation with a combination of other primary data sources, such as income and construction of the built environment, to better understand the reasons for their situation. Furthermore, identify the areas with higher retrofitting potential and potential solution actions.

To do so, we use almost 130,000 EPCs in València to assess the current situation. Then, we separate the data according to the administrative districts and correlate them with sociodemographic data such as the *per capita* income and the percentage of rented households per district. This procedure helps us to combine two primary data sources to provide more insightful results regarding the current situation and solutions.

The results of this work can help policymakers in cities to identify the most suitable areas and usages for retrofitting buildings in the city. The approach allows the use of valuable primary data and a quick analysis often unavailable or used at the decision-making level. In particular, diagnosing the city of València can help local planners frame and design concrete actions regarding climate action and inequality reductions. Policies will be necessary to achieve the signed objective of becoming one of the 100 European carbon–neutral cities by 2030.

The rest of the paper is organised as follows. Section 2 provides an overview of the current literature to validate the usage of EPCs. Then, we describe the methodology implemented in Section 3. Section 4 presents the case of the municipality of València with the primary indicator parameters at an aggregated level. Section 5 aims to detail all the EPC information and its correlation with other sociodemographic data; we also show this with the detailed study of three particular districts. We discuss and argue policy implications and actions derived from the building status results in Section 6. Finally, we conclude the work in Section 7.

## 2. Literature review

The challenge of decarbonising compact cities requires new approaches. Modern urban energy planning methodologies reject default one-size-fits-all approaches in favour of district-level strategies that use city diversity as a lever for optimised decarbonisation strategies. This point can be better understood with the help of three examples. First, modern urban energy planning takes an approach at the neighbourhood and district levels [8]. Second, current standards for creating positive energy districts regard regional variation [9,10]. Third, multicriteria urban energy planning assumes city diversity by balancing technical factors like rooftop accessibility and thermal insulation with non-technical ones like affordability, ties to the local community, or institutional density [11–13].

This section reviews the main approaches to characterising the building stock in urban areas by putting the neighbourhoods and types of buildings at the centre of the analysis. The section focuses on the methodologies to analyse the energy performances in the built environment, and then it describes Energy Performance Certificates (EPCs) to characterise buildings' energy consumption. The section ends with a review of other studies that use EPCs to evaluate the building stock.

### 2.1. Energy performance of the building stock

Developing an urban energy transition plan becomes crucial to respond to the needs of each city district. The starting point is the analysis of the building stock's energy efficiency, then identifying the urban areas that are more energy intensive and present greater potential for improvement-finally, identifying and proposing measures to reduce their energy consumption and the associated $CO_2$ emissions.

Several methodologies can be found in the literature to analyse and characterise the energy performance of the building stock in cities [14]. Among them, building and city energy simulation models are developed. T. Johansson et al. developed a city energy model, and results showed that it was possible to automatically create 3-dimensional city energy models using spatial and non-spatial data from national registers and databases [15]. C. Prades et al. developed a dynamic simulation model for estimating the thermal demand of cities or districts, considering building information collected from the cadastral and altimetric datasets using GIS-based technologies [16]. The model was used to prioritise the buildings retrofitted in València from a sample of 1,026 buildings. However, dynamic simulation models require high computational costs and experimental validation. It is also highly dependent on real data, which needs to be reliable and representative enough to be considered for validation.

Other approaches are based on big data analysis, where public data from buildings is available. This information may come in the form of EPCs, associated with the cadastral reference of the buildings, or European building databases such as TABULA [17]. When considering big data analysis at the urban scale, the methodologies can be split into bottom-up and top-down approaches, depending on the level of aggregation of the input data analysed. Namely, aggregated data is used in the bottom-up approach and disaggregated in the top-down one. R. Zhuravchak et al. developed a top-down probabilistic modelling recipe to enable geospatial energy mapping and analysis of building energy performance [18]. Data from the cadastral system and the EPCs registry was considered for Trondheim in Norway. Special attention was paid to eliminating the collected data's uncertainties while rationalising data collection efforts. L. Belussi et al. developed a methodological approach for implementing a bottom-up model to estimate the buildings' energy performance and to define an energy diagnosis process at an urban scale in an entire district in Bologna, Italy [19]. As a bottom-up approach, they analysed the EPCs and open data available at public authorities to characterise the different types of buildings in the district.

### 2.2. Energy Performance Certificates

According to the Spanish regulation [20], the energy performance of a building is determined by calculating or measuring the energy consumption required to meet the annual energy demand of the building under normal operating and occupancy conditions. The energy rating is expressed through several indicators that explain the reasons for the building's good or bad energy performance. These indicators are obtained from the energy demand for heating, cooling, ventilation, domestic hot water production and, where appropriate, lighting. The main indicators are the demand for non-renewable primary energy and emission of $CO_2$, expressed annually and referring to the unit of the usable floor area of the building. Thus, all buildings will be classified on a seven-letter scale for each energy performance indicator, ranging from A (most efficient building) to G (least efficient building), following Table 1a for residential properties and Table 1b for other uses. As regulations outline, specific formulas are applied to determine the C1, C2, and C indices. These formulas compare the evaluated property's parameter (i.e., energy demand or emissions) with the average parameter value of newly constructed buildings with the same index as a reference. These reference values depend on the different climatic zones.

Previous work has determined that dwellings with green certificates consume approximately 25% less total energy [21]. In addition, better

**Table 1**
Energy rating and indexes for buildings to determine buildings' class.

(a) For private residential use.

| Class | | | Index | | |
|---|---|---|---|---|---|
| A | | | C1 | < | 0.15 |
| B | 0.15 | ⩽ | C1 | < | 0.50 |
| C | 0.50 | ⩽ | C1 | < | 1.00 |
| D | 1.00 | ⩽ | C1 | < | 1.75 |
| E | 1.75 | ⩽ | C1 | | |
| | | | C2 | < | 1.00 |
| F | 1.75 | ⩽ | C1 | | |
| | 1.00 | ⩽ | C2 | < | 1.50 |
| G | 1.75 | ⩽ | C1 | | |
| | 1.50 | ⩽ | C2 | | |

(b) For use other than private residential.

| Class | | | Index | | |
|---|---|---|---|---|---|
| A | | | C | < | 0.40 |
| B | 0.40 | ⩽ | C | < | 0.65 |
| C | 0.65 | ⩽ | C | < | 1.00 |
| D | 1.00 | ⩽ | C | < | 1.30 |
| E | 1.30 | ⩽ | C | < | 1.60 |
| F | 1.60 | ⩽ | C | < | 2.00 |
| G | 2.00 | ⩽ | C | | |

EPCs increase the value of real estate by adding energy efficiency as a comparative criterion [22–25] and can motivate behaviour change in public buildings [26]. Thus, EPCs can have broader applications than initially intended, increasing their impact but requiring higher quality and content standards [27]. L. Wederhake et al. conducted a benchmarking study using data-driven EPC methods, using variables that even occupants could reliably collect [28]. The method was tested using real data from 25,000 German single-family houses. They concluded that data-driven methods achieve about 35% higher accuracy than currently used engineering methods. Table 2.

The construction year of a building contains indirect information about the construction standards employed since the buildings are constructed with materials and methods according to the technical building code in place at that time. A. M. Martínez-Llorens et al. [29] found that literature is in conflict about the building age as a factor of energy consumption because some old constructions present reduced energy consumption than newer construction [30,31] with air-conditioning devices outweighing energy-saving impact [32].

According to H. Estiri [33], socioeconomic characteristics impact dwellings' energy consumption. He showed that, in the USA, high socioeconomic factors are related to homes with higher energy consumption due to the number of appliances. However, their direct energy use behaviours are more efficient than those of households at lower socioeconomic levels.

**Table 2**
Data gathered for this work indicating the source.

| Source | Access | Data obtained | Units |
|---|---|---|---|
| IVACE's EPC database | Open data [45] | Cadastral Reference | - |
| | | EPC Register Number | - |
| | | Energy Rating | A to G |
| | | Energy Consumption | kWh/ $m^2$ yr. |
| | | Emissions Rate | A to G |
| | | CO2 Emissions | kg $CO_2$ / $m^2$ yr. |
| | | EPC Validity | date |
| | | Address | - |
| | | Construction year | yr. |
| Cadastre service | Inspire QGIS plugin [48] | District | - |
| | | Neighbour | - |
| | | Building condition | - |
| | | Building area | $m^2$ |
| | | Plot area | $m^2$ |
| València's yearbook | Open data [47] | Av. income per household in each neighbour | €/hh. |
| | | Renting rate in each neighbour | % |

### 2.3. Evaluation of the building stock through EPCs

Different studies analyse the building stock using actual publicly available data of EPCs (i.e., M. Örbring et al. with 433 references analysed in Gothenburg (Germany) [34]; C. Ahern et al. with 35 references building stock analysed in Ireland [35]; A. Galli et al. 100,000 EPCs references of flats located in Italy [36]; or M. Herrando et al. analyses 21 faculty buildings at the University of Zaragoza in Spain [37]). Ferrantelli et al. evaluate the Estonian building stock through a set of 35,000 EPCs regarding their performance during COVID-19 [38]. Similarly, Ferrantelli and Kurnitski also assess the suitability of EPC classes and labels to achieve the European Climate Target Plan regarding building energy savings in the Estonian context [39]. Droutsa et al. presented an overview of the energy performance of the residential building stock in Greece according to 650,000 EPCs available in 2015 [40]. Hjortling et al. assessed the Swedish building stock employing data from 186,021 EPC. F. Pagliaro et al. performed a massive analysis using a sample of over 2,000,000 EPCs extracted from Italy's national EPC register (SIAPE) [41].

Particularly in Spain, Las-Heras-Casas et al. considered the Spanish region of Aragón by building type, climate zone and construction period, determining that almost half of the EPCs need revision after the change of the climate zones in the region [42]. In Catalonia, Gangolells et al. have performed an analysis based on energy performance certificates [30]. They established that most residential buildings were rated E, single-family houses use more energy than individual dwellings, and the tertiary sector performs better. Also, modern buildings consume less energy than older ones, and homes in hotter climates use slightly less energy.

There is also research on buildings' energy consumption in the Valencian Community. E. Lorenzo-Sáez et al. developed a geographic information system (GIS) methodology to map energy consumption and CO2 emissions using energy performance certificates for the city of Quart de Poblet, very close to València [43]. A. M. Martínez-Llorens et al. studied the Castelló de la Plana and València regions finding clusters of low energy consumption in the metropolitan area of València and Castelló de la Plana cities and high emission and consumption clusters in coastal touristic towns [29]. A. Perez-Garcia et al. reviewed the characteristics of dwellings in building blocks in the district l'Eixample in València [44]. Energy performance is assessed based on energy usage in the dwellings compared to the code limitations and introduction of retrofitting measures in the buildings to limit energy consumption.

However, to our knowledge, none assessed a compact Mediterranean city in Spain, such as València. Hence, the study of the complete building stock of València still needed to be made. Our sample of 129,278 EPCS represents 19% of València's building stock. This assessment is performed at the city and district levels, considering variables like property age, district incomes, and rent rates. The district's innovative approach will help prioritise retrofitting strategies over the city. This same approach could be applied to even smaller areas such as neighbourhoods. Results will help public authorities with the best policy strategies to reduce buildings' energy demand.

## 3. Methodology

The methodology in Fig. 1 uses data cleaning, statistical analysis, and mapping to identify areas for retrofitting buildings with lower energy

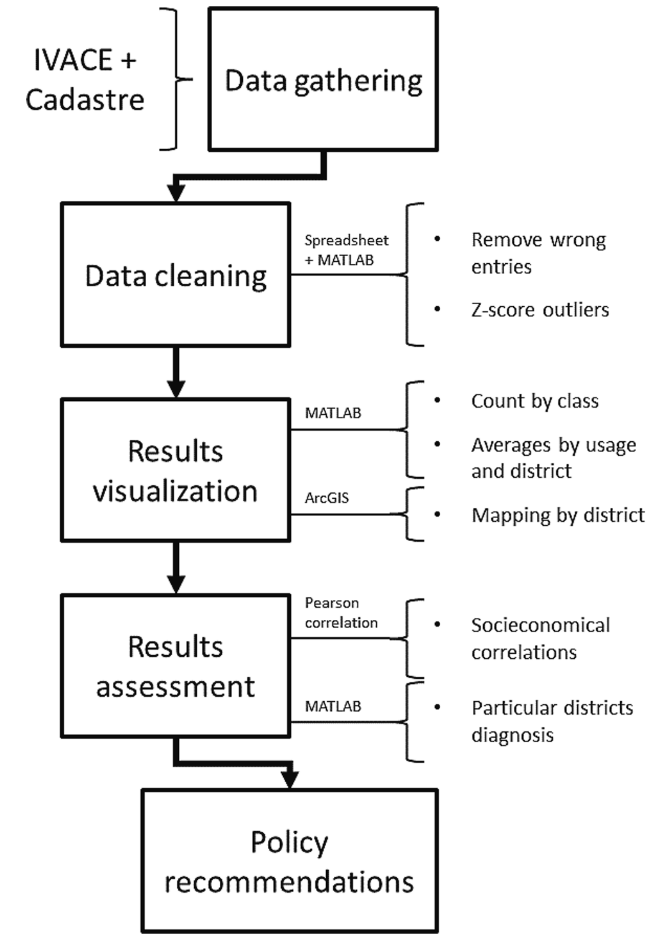



**Fig. 1.** Methodology outline.

efficiency.

Data gathered involves the EPC database and socioeconomic information of València, as summarised in Table 2. EPC data is gathered from the local institution monitoring the energy performance certificates that, in the case of the Valencian Community, are under the supervision of Instituto Valenciano de la Competitividad Empresarial (IVACE). In 2022, they made available the database for all the EPCs as open data [45]. For this work, we used EPC at the dwelling level and focused on the energy class instead of the emissions class. We also considered the energy performance of the buildings by their usage according to the Cadastre service [46]. From the Cadastre service, we obtained the district and neighbour of each property [46]. Furthermore, we have retrieved socioeconomic data from the city hall to correlate the energetic performance with those factors. From this information, we focused on the average income per dwelling and person and the renting rate in each district. We retrieved this data from the 2022 yearbook of the City Hall of València [47].

The collected data is cleaned by manually removing entries with missing information, outdated certificates and typos. We looked for duplicated EPCs, as each one has a unique identifier, but we found none. Next, we perform a Z-score analysis to detect and remove the data with exceptional values, whether high or low. The Z-score is the number of standard deviations from a specific data point's mean [49]. The Z-score analysis is applied to the final energy demand and $CO_2$ emission values. In our case, each point is compared to the values of its same class, as we consider that assessing the population as a whole could lead to retrieving more certificates of A or G as they are the classes in the extremes. Hence, Eq. 1 shows the calculation of the Z-score for each EPC. Outliers are identified and filtered from the data when the Z-score exceeds an absolute value of 3. Also, only positive values and entries were allowed with a building construction year after 1700.

$$z_i = \frac{(x_i - \overline{x}_{ci})}{\sigma_{ci}}. \tag{1}$$

in which $x_i$ is a specific value of an EPC, $\overline{x}_{ci}$ is the average value [50] and $\sigma_{ci}$ is the standard deviation of the certificate energy class. Also, the standard deviation is calculated using Matlab [51] as in Eq. 2:

$$\sigma_{ci} = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \overline{x}_{ci})^2}{n-1}}, \tag{2}$$

where $n$ is the sample size.

Once the dataset is prepared, we assess the data at the city and district levels. We identify the most prominent energy labels in the city and how they have evolved over the decades. For the time scope, we assessed the last century's evolution. We added all the certificates previous to 1930 because the sample is small; thus, their impact on the current building stock of the city is nonessential. This temporal evolution is superposed with the different building codes enforced to see their impact.

A spatial analysis of the worst energy ratings by the district is performed to identify areas with the most significant potential for improvement. District EPC data are mapped using a city shapefile in ArcGIS Pro [52]. The displayed rates were F and G for this work because the city's most prominent rate is E, which sets the baseline. This map helps identify the areas and trends over the city with worse performances.

Finally, we correlated the EPC and socioeconomic information to get significant insights into the city's building stock situation. Thus, we evaluated the concurrence of each district's good and bad labels, certification rates, average income per dwelling, and rental ratio. We used the sample Pearson correlation coefficient [53] to measure the linear correlation between two variables, Eq. 3.

$$r_{xy} = \frac{1}{n-1} \sum_{i=1}^{n} \left(\frac{x_i - \overline{x}}{\sigma_x}\right)\left(\frac{y_i - \overline{y}}{\sigma_y}\right) \tag{3}$$

## 4. Case study

Our case study is the city of València, the capital of the Valencian Community and the third-most populated municipality in Spain. It has a population of around 800,000 inhabitants and, including the metropolitan area, rises to more than 1,500,000. Thus, València constitutes one of the most significant urban areas on the European side of the Mediterranean Sea. The city's economy is currently centred on services, with about 84% of the working population employed in the service sector. However, the city maintains an industrial base, with an employed population of 5.5%. The Port of València is the fourth busiest port in Europe, the largest in Spain and the Mediterranean Sea basin.

València emitted 1.9 $MtCO_2eq$ in 2016, the last year with official data available [54]. In 2007, the figure was 2.7 $MtCO_2eq$; thus, the reduction is almost 30% in a decade. The residential sector is the second most polluting after transport, accounting for 16.10% of these emissions, as Fig. 2 indicates. Hence, this sector needs urgent actions to reduce its environmental impact to accomplish the city objectives regarding greenhouse gas emission reduction.

València has ambitious environmental objectives and has joined many missions like the EU Mission of Climate-Neutral and Smart Cities or the Covenant of Majors. The city has integrated these missions into its own València 2030 Urban Strategy to build a healthy, sustainable, shared, prosperous, entrepreneurial, creative, and Mediterranean city. In this context, València has been selected by the European Commission as one of the 100 cities to become carbon neutral in 2030 and will be the European Green Capital in 2024.

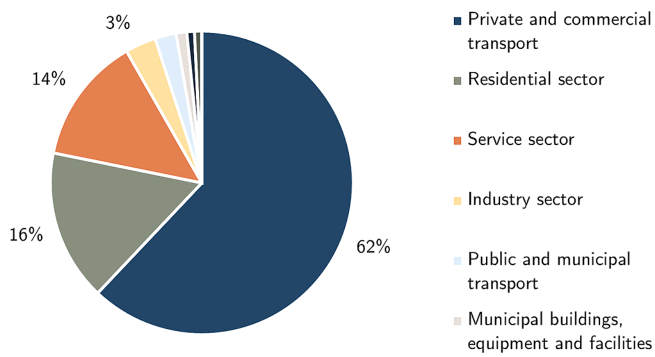



**Fig. 2.** Emissions of València in 2016, categorized by Activity Sector (Adapted from [54]).

In this work, the boundaries are the 19 administrative districts of the city. Not including other areas of the region or the metropolitan area is to make policy recommendations for city policymakers. Mixing autonomous administrations could complicate the process and make the recommended actions less feasible.

### 4.1. Historical development of the energy efficiency standards in Spain

Spanish regulation on buildings' energy efficiency has evolved over the years, starting in 1977 with the first building code in Spain: *Normas Básicas de la Edificación (NBE)* [55]. This building code set up minimal thermal requirements for envelopes by establishing maximum heat transmission coefficients [56].

In recent years, the European Union introduced Directives to compel Member States to improve the energy efficiency in buildings. In that sense, they approved the Energy Performance of Buildings Directive (EPBD) in 2002 (Directive 2002/91/EC [7]), requiring all EU countries, including Spain, to establish independent energy performance certification systems supported by independent mechanisms of control and verification. This Directive was revised in 2010 with Directive 2010/31/EU [57] and, more recently, in 2018 with Directive 2018/844, aiming to accelerate the building renovation rate towards more energy-efficient systems [3].

This successive revision of the EPBD led to the Spanish regulations adapting to the new requirements. The EPBD was first transposed in 2007 in Royal Decree RD/47/2007, which approved the Regulation of Thermal Installations in Buildings (RITE) [58]. The RITE constitutes the basic regulatory framework that regulates the requirements of energy efficiency and safety that thermal installations must meet in buildings to meet the demand for the well-being and hygiene of people. It approved a Basic Procedure for the energy efficiency certification in new buildings, setting the foundation for energy performance certification in Spain. RD/235/2013 consolidated and updated the previous RD/47/2007, incorporating the changes introduced by the revised EPBD 2010/31/EU [59]. It approved the basic procedure for certifying energy efficiency in both new and existing buildings, and it also requires EPCs to be updated every ten years. Besides, it required all new buildings to be nearly zero-energy by 2021. The legislation established that existing buildings or units of buildings occupied by a public authority must obtain an energy efficiency certificate and display their energy efficiency label if their total functional area exceeds 250 $m^2$ and are usually frequented by the public. Finally, RD/178/2021 updated the RITE to incorporate requirements derived from the publication of different European legislative texts, such as Directive 2018/844. This revision set more ambitious targets for energy efficiency in buildings, including requirements to justify installing conventional thermal systems instead of more efficient and sustainable ones, the obligation for buildings with high energy consumption to take the first step towards reducing greenhouse gas emissions and the promotion of the use of renewable sources in the heating and cooling sector, as well as to several European eco-design and energy-related product labelling regulations [60].

To expand the contents of this chapter, the TENECO Research Group conducted a comprehensive study of the evolution of the EPBD for residential and non-residential buildings in Spain from 2006 to 2020 [61]. They also analysed the implementation of Directive 2018/844 in Spain [62] and participated in the study of its implementation in Southern European countries [63]. They conclude that the EPBD has a positive effect, constricting the minimum energy efficiency requirements, limiting the consumption of non-renewable primary energy or designing modifications in the application of existing ones. However, they find it necessary that existing buildings become the main focus of the Directive as they represent the majority of buildings in the EU.

### 4.2. Data gathering and statistical assessment

In the Valencian Community, the certificates are under the supervision of IVACE [45], the Valencian Institute for Business Competitiveness, a public entity in charge of the management of the industrial policy of the regional government. In 2022, they made available the information for all energy certificates, and we retrieved the 129,487 energy certificates for València. After applying the Z-scores for outliers, we obtained a database of 128,312 energy certificates. Fig. 3 shows the reasons why 1,075 EPCs were excluded from the study. The main reason was that 69% of these certificates had a declared energy demand out of bounds when applying the Z-score method. The boundaries established by the Z-score method on each energy class can be found in the annexes in Section A.1.

The properties have multiple uses, but the certificates are primarily issued for individual dwellings and residential buildings, as shown in Fig. 4–residential usage accounts for almost 90% of the certificates, including single-family dwellings. Commercial usage follows with 7%.

Following this residential grouping, Table 3,4 show the main statistical parameters of the final energy consumption, $CO_2$ emission and construction year for residential and non-residential properties. Thus, residential properties are less energy-demanding and, therefore, are responsible for less greenhouse gas emissions per area. On top of that, the standard deviation is higher in the non-residential properties, implying that more diverse values are to be found. Significantly, the mean value is higher than the median in both cases. This discrepancy suggests that a relatively small part of the population is increasing the average energy demand and associated emissions for the whole population. Hence, identifying the suitable properties to act on would provide better results than unplanned interventions, supporting the nature of this study.

## 5. Results

We assess the city's building stock by evaluating the city's energy at its current status and the evolution over the decades in which the

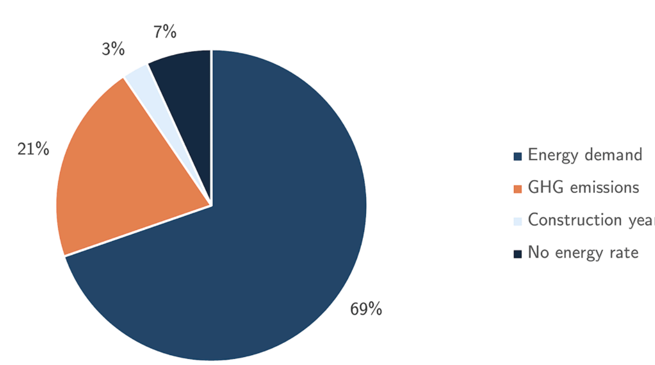



**Fig. 3.** Reasons for excluding EPCs from the population.

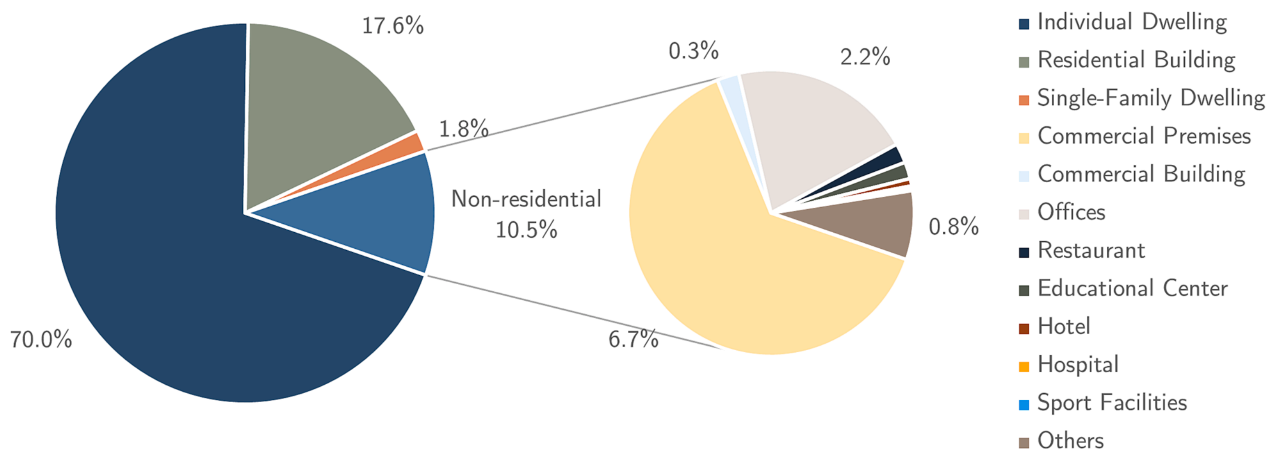



**Fig. 4.** Properties usages distribution in València.

**Table 3**
Statistical parameters of the assessed data for residential dwellings, i.e., Residential Building, Individual Dwellings, Single-Family Dwellings.

| Statistical parameter | Final energy demand [kWh/ $m^2$ yr.] | $CO_2$ emission [kg $CO_2$/ $m^2$ yr.] | Construction year |
|---|---|---|---|
| Average | 141.4 | 29.3 | 1968.9 |
| Median | 134 | 27 | 1969 |
| Maximum value | 882 | 178 | 2022 |
| Standard deviation | 58.4 | 13.6 | 24.2 |

**Table 4**
Statistical parameters of the assessed data for non-residential building types.

| Statistical parameter | Final energy demand [kWh/ $m^2$ yr.] | $CO_2$ emission [kg $CO_2$/ $m^2$ yr.] | Construction year |
|---|---|---|---|
| Average | 186.9 | 38.3 | 1970.7 |
| Median | 169 | 33 | 1972 |
| Maximum value | 961 | 179 | 2022 |
| Standard deviation | 95.1 | 22.0 | 27.0 |

buildings were constructed. This evaluation also considers the building use and how different variables correlate with each other to analyse the reasons behind the diagnosis. First, we consider the city as a whole and then study the differences among its districts.

### *5.1. City level results*

The first section of this chapter involves the considerations for the whole building stock of the city. Fig. 5 presents the distribution of energy ratings in València. Most dwellings (59.7%) are rated with a label of E, followed by a rating of G (16.1%). Meanwhile, label A represents only 0.18% of all EPCs.

The energy demand values for each class vary depending on the property type because the reference building changes. Hence, the same energy demand might be a Class-A for a commercial premise but a Class-D in an individual dwelling. Therefore, each use must be considered independently to understand the potential for improving a property's class in reducing energy demand and greenhouse gas emissions. Fig. 6 shows the energy demands for individual dwellings grouped by their real energy class, the most common property type in València (the energy demand for all uses is available in Section A.2). Better class implies less energy demand, and we see more dispersion in classes with larger populations of certificates (classes E and G). Outlier EPCs are detected and may need to be included in other classes, revealing the heterogeneity of the building stock and the possibility of measurement errors in the existing labels. A more reliable labelling methodology or better

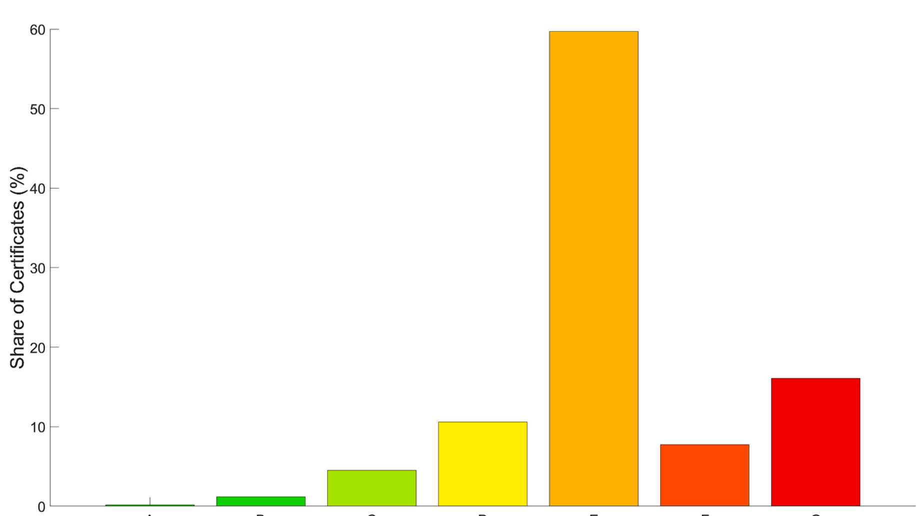



**Fig. 5.** EPCs distribution per label in València.

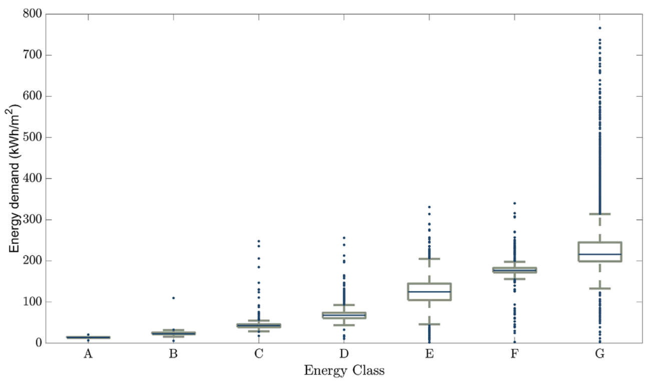



**Fig. 6.** Energy demands in each EPC class for individual dwellings.

controls are necessary for greater accuracy. Table 5 shows the average energy demands of each class and how improving the property class reduces it. Thus, on average, a Class-A dwelling demands 94% less energy than a Class-G house and 48% less than a Class-E. Just improving from the letter E to a D already represents a 25% demand reduction.

### 5.1.1. Energy rating over the construction year

Fig. 7a shows the share of EPCs over the construction year of the dwelling, grouped by decade, while Fig. 7b indicates the number of EPCs each decade. The overall trend shows an increase in share for energy ratings A and B, denoting that building codes of 1979 and 2006 improved newly constructed dwellings' energy performance. However, they only apply to a small share of EPCs (3.79% since 2008).

Most certified properties were constructed in the 1960s (26.5%) and 1970s (23.0%) and did not follow any energy building code. In the following decades, the building stock grew slower to the point that, in the 2010s, new construction almost halted due to the financial crisis Spain and the world were experiencing. Besides, construction barely improved from the 1980s to the 2000s. So, efficient construction only took place once the city expansion stopped. The result is an old building stock with lousy construction standards that needs renovations quickly.

### 5.1.2. Energy consumption per building use

Table 6 displays the different uses accredited on the EPCs. Most certified properties have residential usage (89.5%, as pointed out before), which are, at the same time, the less energy-intensive property uses even with high rates of F and G certificates. On the other hand, commercial uses, offices and restaurants have higher energy demands and still present a reasonably high share of deficient energy classes.

For a visual clue, Fig. 8 shows the share of EPCs, and Fig. 9 shows the energy demand distribution in each usage. Thus, we identify the residential uses as those with most certificates with classes F or G, followed closely by the commercial uses. On the other hand, services like sports facilities, hospitals, educational centres and hotels present excellent energy classes in their EPCs.

Considering those property uses that present more potential for improvement, we see in Fig. 9 that the residential ones demand less energy than commercial uses. The most outstanding usage here is restaurants, which present a substantial energy demand while their certificates can improve. Hospitals and hotels present an ideal combination of outstanding certificates and low energy demand.

## 5.2. District level results

The districts of València were characterised according to their EPCs to identify the areas with bigger room for improvement. The distribution of EPCs in each district changes significantly, and some districts have better energy performance than others. We used the map in Fig. 10 to visualise how the worst EPCs are spread across the city. According to their certificates, this map points to the districts with the worst energy performance.

In the case of València, the most affected districts by bad EPCs are the peripheral districts with a North–South asymmetry, as the northern half of the city core is in worse shape than the southern one. Those districts could be the starting point for a retrofitting campaign over the city; nonetheless, this decision should come after a more thorough assessment considering social impacts alongside energy efficiency.

Fig. 11a displays the distribution of EPCs by districts, and the worst individual districts are Pobles del Sud (District 19, 33.2% of certificates are F or G) and Poblats Marítims (District 11, 32.3%). On the other hand, districts El Pla del Real (District 6, 26.7%) and Ciutat Vella (District 1, 22.5%), in the city centre, and Patraix (District 8, 22.3%), in the southern half, contain the highest share of labels above E within its district. These differences already highlight where to focus the retrofitting actions.

Nonetheless, the quantity of EPCs in each district changes drastically, as Fig. 11b shows. The situation of Poblats del Nord (District 17, 638 certificates), Pobles de l'Oest (District 18, 2,156 certificates) and Pobles del Sud (District 19, 2,909 certificates) is remarkable for the low amount of certificates in comparison with the rest of the districts. However, these districts correspond to those with fewer properties in the city as they are situated on the city's outskirts and include rural and agricultural activities. Hence, the population is more scattered in fewer dwellings. It is best to consider the share of properties certified in the districts.

On average, the EPCs cover 18.9% of the properties in València. This share rises in Ciutat Vella (District 1, 24.1%), l'Olivereta (District 7, 22.8%), Extramurs (District 3, 22.7%) or Poblats Marítims (District 11, 20.2%), but it drops in Pobles del Sud (District 19, 13.2%) and Pobles del Nord (District 17, 13.4%). Thus, Pobles del Sud and Pobles del Nord are among the districts with fewer certificates and, simultaneously, those with lower certification rates. Promoting certification in those districts would help to understand their current status better.

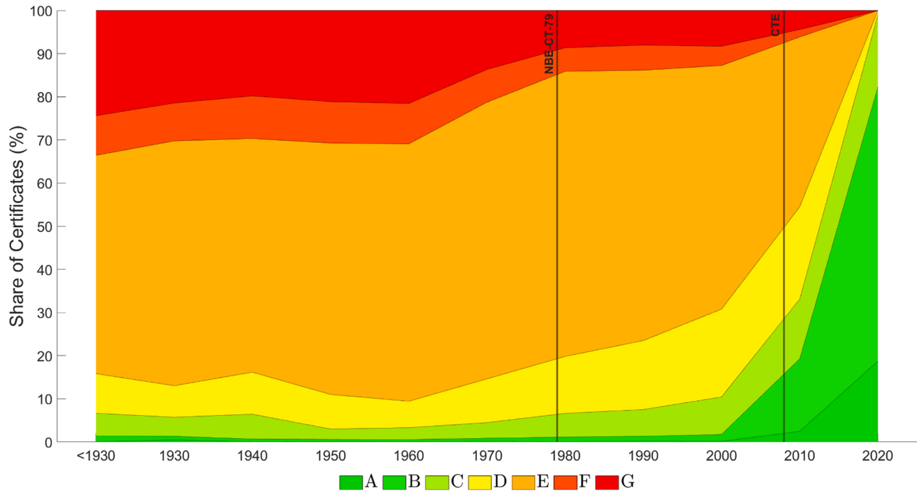
### 5.2.1. Correlations of districts EPCs with social characteristics

This section will expose an analysis to explain the situation of the building stock and why some buildings and areas perform better than others. The results exposed so far help identify the geographical areas in which the building stock of València can improve. However, we want to investigate if there are some socioeconomic bases behind that diagnosis. We hypothesise that better energy performances can correlate with people with higher incomes as they have access to dwellings with better building standards. We also expect new buildings to be more efficient thanks to the building codes enforced over time. In addition, property rental often involves some form of refurbishment to potentially increase the rent or decrease the problems tenants need to fix. So, we want to study if higher renting rates in a district improve the energy performance of the building stock.

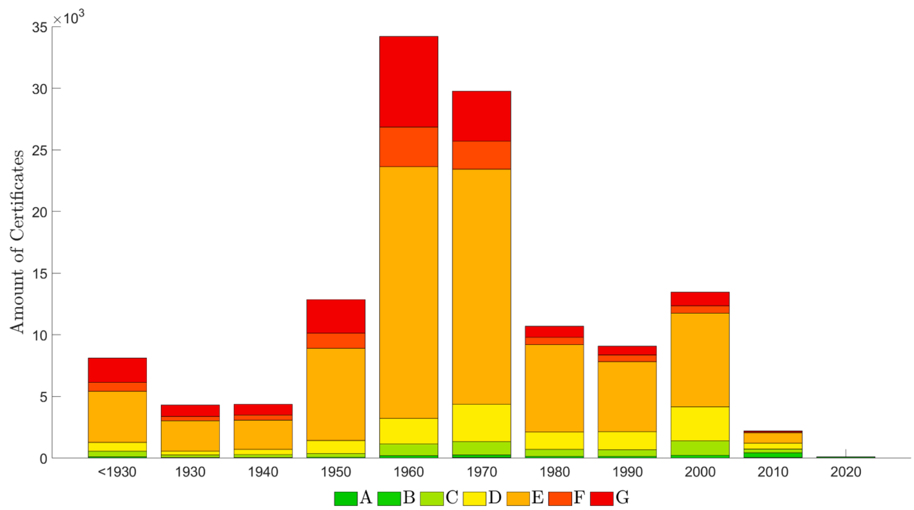
Another issue we need to address is the possible biases on certificating properties. We hypothesise that certain buildings are more prone

**Table 5**
Average annual energy demand per EPC class for individual dwellings and the increments in energy demand compared to Class-G and Class-E.

| Class | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| Energy demand (kWh/$m_2$) | 14.0 | 24.3 | 43.4 | 67.7 | 125.2 | 176.6 | 230.3 |
| Δ Class-G | −93.9% | −89.5% | −81.2% | −70.6% | −45.6% | −23.3% | 0.0% |
| Δ Class-E | −48.3% | −43.8% | −35.5% | −25.0% | 0.0% | 22.3% | 45.6% |




**(a)** Share of EPCs by construction decade.




**(b)** Count of EPCs by construction decade.

**Fig. 7.** Energy rating of buildings by construction decade in València.

to be certified than others, and these biases may affect the diagnosis. Since 2013, certifying newly built and existing properties has been mandatory before renting or selling them in Spain. Hence, properties newly built in 2013 may only be certified if their dwellers have changed; otherwise, they have never sold or rented the property and needed the certificate. Likewise, districts with higher renting rates may present higher certification rates.

Table 7 exposes the correlation coefficients among these variables to validate our hypothesis. Regarding the average income per district, we validate that higher incomes correlate with better certificates as top rates increase (with a + 72.5% correlation coefficient) and the poor ones decrease (-45.1%). On top of that, people with higher incomes live in older properties (likely the city centre), according to the correlation. The implications of these correlations may be that higher-income dwellings, which are old but present a good energy performance, have already been refurbished or were built following higher construction standards.

Concerning the impact of the property age, we do not confirm that new buildings improved their performance. There is a slight tendency towards reducing the number of certificates below the E rate, but the correlation towards decreasing the best labels is even higher. However, a strong correlation (-76.1%) indicates that newer properties are less certified than older ones. This correlation would verify our hypothesis that many properties still need certification because they have yet to be in the property market. Imposing the certification on all properties or other situations apart from the property market would increase the certification rates and improve the diagnosis.

Evaluating the effect of the renting rate, we confirm that it increases the certification rate (+36.9%) and improves the EPCs. It is especially acute in the case of reducing bad certificates (-49.1%) than in reaching top labels (+14.4%). This asymmetry may be explained by the owners not benefiting from the increase in comfort and energy billings reduction, thus refurbishing the dwellings with little ambition.

### 5.2.2. *Diagnosis of three particular districts*

EPCs can also help assess specific districts or areas, not just the whole city. We dedicate this section to three districts with exceptional circumstances: Ciutat Vella (District 1, in the city centre), Patraix (District 8, in the southern half) and Campanar (District 4, at the West side of the city).

**Table 6**
Statistics by Property Usage: number and share of certificates, average energy demand, standard deviation, and worst certificates share.

| Building use | EPCs | Share of EPCs | Av. Energy Demand (kWh/$m^2$/yr.) | Energy Demand Standard Deviation (kWh/$m^2$/yr.) | F and G labels share |
|---|---|---|---|---|---|
| Individual Dwelling | 89,810 | 70.0% | 143.3 | 57.2 | 26.5% |
| Residential Building | 22,639 | 17.6% | 132.1 | 59.7 | 16.9% |
| Single-Family Dwelling | 2,332 | 1.82% | 160.9 | 77.0 | 23.0% |
| Commercial Premises | 8,609 | 6.71% | 178.9 | 93.3 | 19.0% |
| Commercial Building | 335 | 0.26% | 210.9 | 95.7 | 17.6% |
| Offices | 2,795 | 2.18% | 203.7 | 93.1 | 13.6% |
| Restaurant | 300 | 0.23% | 244.5 | 121.7 | 15.0% |
| Educational Center | 255 | 0.20% | 176.1 | 66.2 | 3.1% |
| Hotel | 112 | 0.09% | 201.1 | 129.8 | 5.4% |
| Hospital | 47 | 0.04% | 153.8 | 105.7 | 0.0% |
| Sport Facilities | 26 | 0.02% | 214.0 | 81.3 | 0.0% |
| Others | 1,052 | 0.82% | 185.6 | 94.5 | 16.8% |

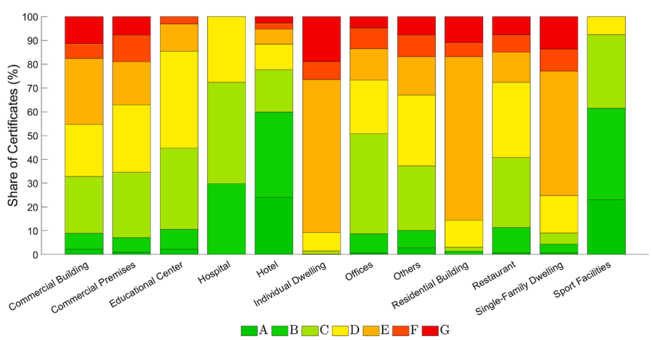



**Fig. 8.** Share of EPCs by usage in the city of València.

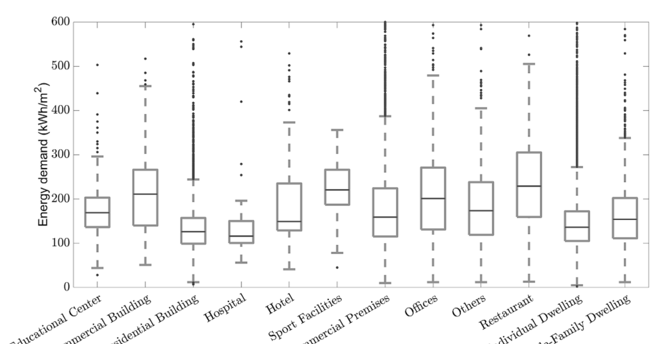



**Fig. 9.** Energy demand distribution of EPCs by usages in the city of València.

Ciutat Vella is the city center. Commerce and services comprise 73.03% of the district's economic activities, and it is one of the districts with a higher income per dwelling in the city [64]. This district is the sum of the Roman, Arab and Christian sites during the centuries, attracting many tourists. That could explain the low residential share of properties compared to the other districts, as shown in Fig. 13a. Also, it has the most antiquated building stock and, at the same time, one of the higher average incomes in València. Fig. 12a shows the district's distribution of EPCs over the decades. Alongside l'Eixample (the city centre

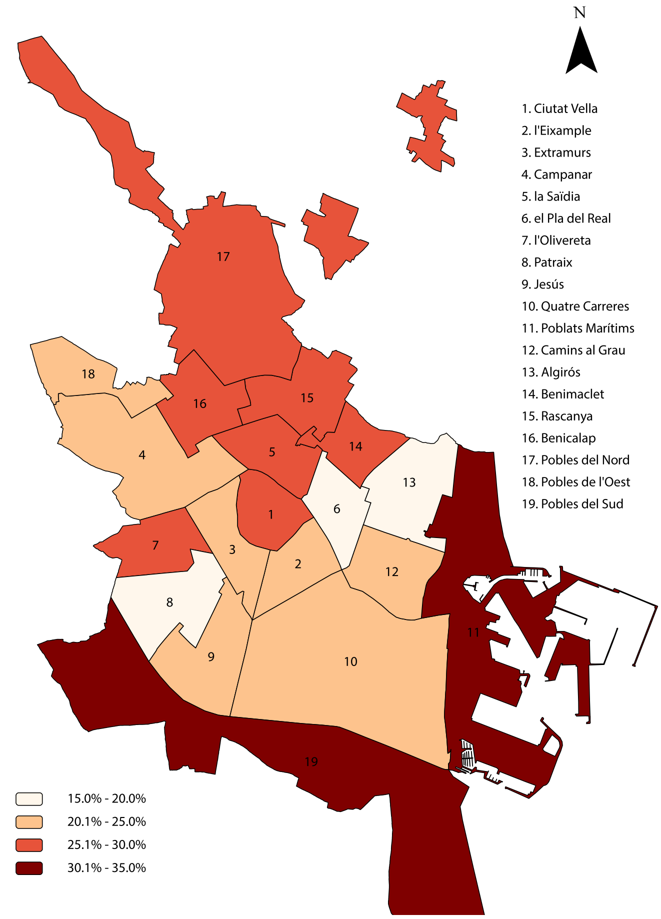
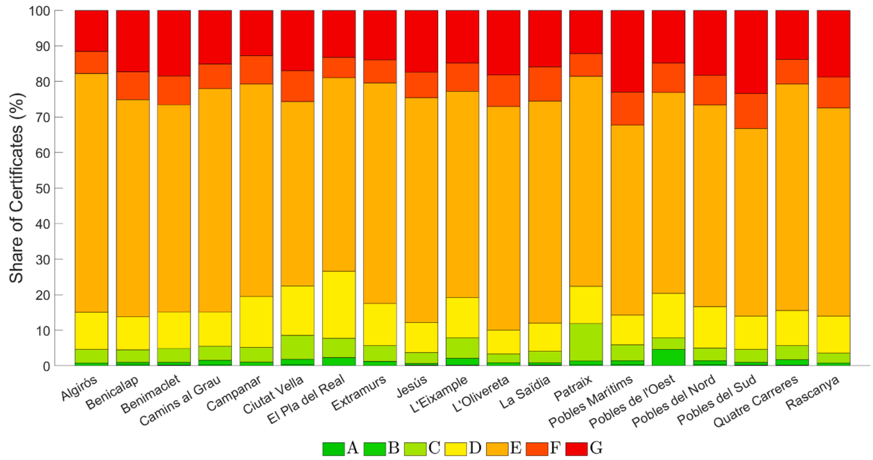


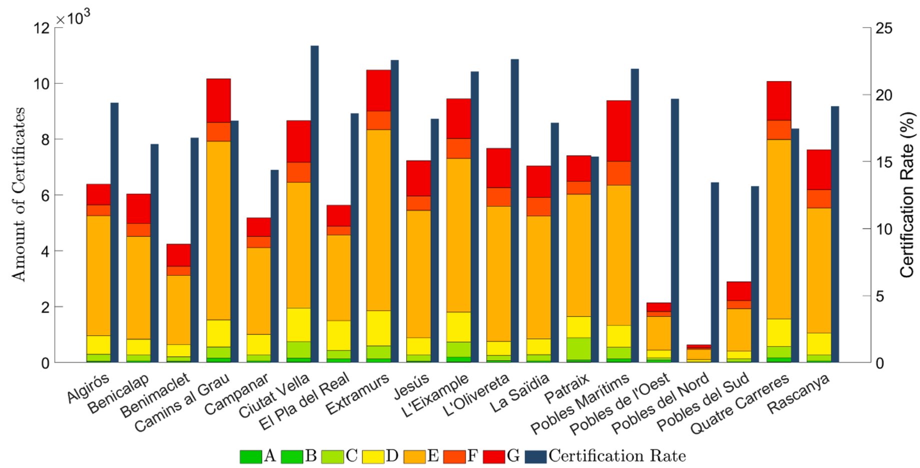

**Fig. 10.** Heat map of the city districts by their share of EPCs with labels F or G.

expansion of the 19th century), they are the only districts in which the most common construction period was before 1930. The 1960s followed the global building trend in the city, and it had another spike in the 2000s, concurrent with the Spanish property bubble. However, the district's energy efficiency is not among the poorest in València, and it is the second district with the most certificates above the E rate. The reasons are likely related to the higher investment capacity of its dwellers, either because they can afford properties with higher building standards or because they have renovated them. Hence, due to their economic background, it should be easier to implement retrofitting in this district than in others.

Patraix stands out on the map (Fig. 10) for its excellent performance compared to its surrounding districts in the city's southern half. This district is based on a residential population, and a recent actuation by the city hall made it more appealing for new families looking to settle. However, as Fig. 13b shows, the residential use of properties is low among the districts' certificates compared to the city average. Instead, there is a substantial presence of commerce and offices due to being next to one of the city's main urban dual carriageways, the V30, dominated by industries, offices and commercial areas. It is the third district of València in the share of certificates above E and second to last in the share of most poor certificates. Looking at Fig. 12b, the 2000s catches the eye for the 546 properties labelled C built in that decade. Assessing these certificates, we found that 498 correspond to new offices built in 2008 as an expansion of an industrial zone. Removing these certificates from the district, Patraix would pass from third to seventh among the districts with the best certificates. Hence, properties in Patraix need to improve their energy efficiency as the rest of the surrounding areas, even if a particular parcel increases the average of the entire district. This analysis shows how a limited assessment can lead to misleading




**(a)** Share of EPCs by district.




**(b)** Count of EPCs by district

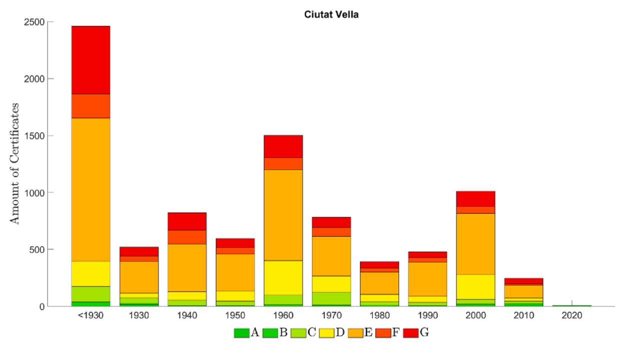
**Fig. 11.** EPCs share and count by districts in València.

**Table 7**
Correlation coefficient within the share of EPCs certified, EPCs above class E, EPCs below class E, average construction year, income per dwelling and share of properties rented in each district.

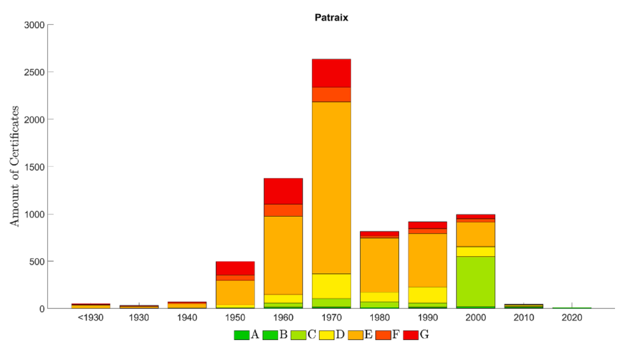
| | % EPCs certified | EPCs > Class-E | EPCs < Class-E | Year | Income per hh | % Rented |
|---|---|---|---|---|---|---|
| % EPCs certified | 1 | | | | | |
| EPCs > E | 0.047 | 1 | | | | |
| EPCs < E | −0.041 | −0.514 | 1 | | | |
| Year | −0.761 | −0.171 | −0.046 | 1 | | |
| Income per hh | 0.183 | 0.725 | −0.451 | −0.471 | 1 | |
| % Rented | 0.369 | 0.144 | −0.491 | −0.224 | 0.443 | 1 |

conclusions, finally affecting citizens who need access to help and subsidies to retrofit their properties.

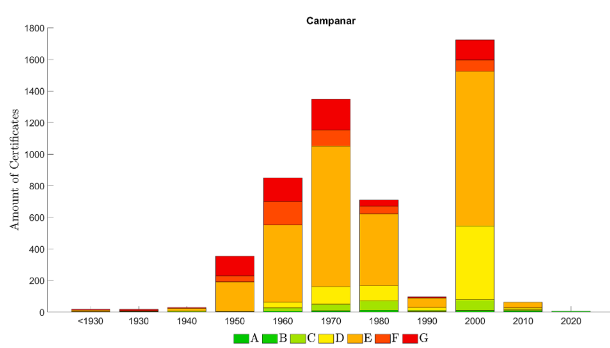
Campanar is one of the districts with a more considerable urban expansion within the context of the Spanish property bubble. Hence, property usage is predominantly residential housing, as seen in Fig. 13c. This expansion in the 2000s is perceptible in Fig. 12c, and we can diagnose the performance of the properties built in those years. The building standards are disappointing, considering that they do not improve what was done in the previous decades. Furthermore, the share of A, B and C rates halved from 8.8% in the 1990s to 4.4% in the 2000s. This decline has interrupted the upward trend in the most efficient certificates for the first time since the 1950s. This short-sighted expansion with poor standards left the district and the city with an energy issue to solve in the coming decades to accomplish the climate goals. Future city expansions, if any, should mandate the highest building standards of the promotors to avoid retrofitting newly constructed buildings with expense and discomfort for the citizens and the public administrations.




(a) District of Ciutat Vella.

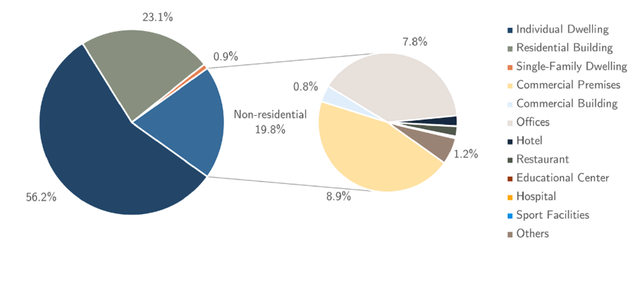



(b) District of Patraix.

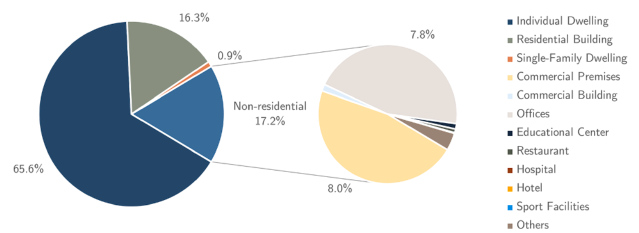



(c) District of Campanar.

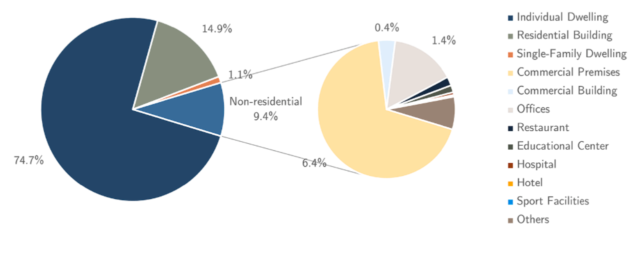
**Fig. 12.** Energy rating of buildings by construction decade in three districts of València.




(a) District of Ciutat Vella.




(b) District of Patraix.




(c) District of Campanar.

**Fig. 13.** Properties usages distribution in three different districts of València.

## 6. Discussion

The analysis of the results shows the poor situation of the properties in València. Residential dwellings are the most prominent property types and show poor energy performance after assessing almost 130,000 EPCs. These buildings will last for decades and pose a fundamental problem regarding energy consumption for thermal and cooling purposes; therefore, there is an urgency to refurbish and recondition them. This section discusses these results structured in city-specific analysis and recommendations for refurbishment actions to improve the current situation.

### *6.1. The situation of the stock of dwellings and properties*

The dwellings in València present a bad energy performance according to their energy labels, dominated by E and G rates. The antiquity of the building stock is among the main reasons, as 72.4% of the properties were built before 1980 with no building code in place. Labels A and B increased their share over the last decades, especially after introducing the new building code in 2008. EPCs with an A or B rate represented just 1.8% of labels in the 2000s and raised to 18.8% in the 2010s. This trend is still visible for the 2020s, as the share of A and B rates is 82.3%; however, the amount of certificates in properties built in the last decades is almost negligible. These figures add to the need to retrofit old buildings because the renovation rate for more efficient constructions needs to be faster to achieve the climate goals. Besides, retrofitting buildings has fewer emissions than constructing new efficient ones.

Retrofitting actions must focus on residential dwellings as they represent almost 90% of the building stock and are the property usage with the worst EPC rates. Besides, looking at the demands in each energy class in Table 5, improving the EPC on dwellings can significantly reduce the building stock demands. Specifically, improving the least-performing letters results in a more substantial decrease in demand. However, commerces are high-energy building uses and present improvement potential, as 37.4% of labels are E, F or G. In addition, these usages tend to form clusters in the city that would facilitate the scalability and efficiency of the retrofitting program.

The energy performance of the building stock varies from district to district. Peripheral districts such as Pobles del Sud and Poblats Marítims or the northern half of València contain high F and G rates. These discrepancies between districts already narrow the focus on retrofitting actions. It is essential to prioritise the buildings to start the actions because budget and time are finite to meet the climate goals.

However, these energy rates do not inform us about the reasons for these districts' worst performances. How to tackle these inefficiencies will change whether low-income citizens populate the districts or property owners dedicate them to tourist rental, for instance. Then, more than just the average energy rates are needed. We got some insights by correlating the energy rates with the district's average income, construction year, and rental ratio.

We found the worst EPC rates in low-income districts and lower renting rates. On the one side, this finding implies that the districts with more room for improvement have less capacity for investment. Hence, public actions to improve the building stock energy efficiency should include measures to facilitate the owners on the economic and bureaucratic sides of the retrofitting of their properties. Also, even if renting decreases the dwelling with lousy efficiency, increasing the renting rate does not favour efficient housing (the best certificates increase marginally) while generating investment potential for the owners. Therefore, public administrations could consider enforcing dwellings under renting to have a minimal EPC label greater than E. Administrations could implement this measure first in properties that generate high incomes for the owners, like tourist flats or those rented to more than one individual. However, the rise in apartment rents is a possible drawback that requires regulation to avoid price increases and the displacement of people living under rental contracts.

### 6.2. Efficiency actions to improve the stock

New stock will not replace old buildings at a sufficient rate. Moreover, the environmental impact of new buildings is larger than retrofitting and improving the energy efficiency of the existing stock. However, it is a challenge to widely promote the energy renovation of households due to economic, social, and administrative factors. Due to these barriers, public authorities must enhance and focus on effective, economical, and quick measures to retrofit households.

On a social and administrative side, these measures must be easily replicable and standardised to help facilitate their implementation by building communities and individual owners. Bureaucracy is not always easy to present, and companies with little experience in these actions face difficulties accessing subsidies and funding. Moreover, subsidising after the renovation can hinder households with lower initial financial capabilities. Also, individuals and communities see these actions as long and unpleasant, tending to delay investments until there is no alternative. Facilitating procedures and promoting an ecosystem of professionals with experience in these actions can trigger investments. As Rose et al. affirm, "policies and strategies should mainly aim for improving the financial and social acceptance of renovations" [65], aligning common values among stakeholders and developing a business perspective to achieve district-level building renovations [66].

Regarding the economic barriers, most properties with a low EPC are in neighbourhoods with lower investment capacity. Therefore, administrations can focus on quick and cheap measures that might only overcome the problem partially. Actions characterised by low investments but quick returns relate to installing weather stripes and sealing wall holes. Also, reducing humidities and waterproofing walls, rooftops, and window replacement on a superior scale. More comprehensive measures involve structural actions such as internal and external insulation. All these actions require low-interest loans, direct subsidies and fiscal measures alongside efforts to mitigate the gentrification of neighbourhoods.

### 6.3. Limitations of the results

Assessing the energy performance of buildings based on EPCs can provide valuable insights. However, it is vital to acknowledge the limitations of this approach. The most prominent of these limitations is the accuracy and reliability of the certificates. The EPCs are based on standardised data and assumptions, which may not accurately reflect buildings' energy usage and performance. Previous studies have studied this Energy Performance Gap (EPG) [67] and concluded that EPCs overestimate energy consumption for the least energy-efficient dwellings, and energy savings are often lower than predicted [21,22]. Thus, consequent actions from this kind of assessment must be planned carefully to not commit to misled schemes. Researchers have proposed many strategies to reduce this EPG that can be fit into two approaches [68]. The first approach is to improve the standard values or consider new approaches to make theoretical values more precise and accurate. In contrast, the second approach consists of closing the EPG by focusing only on actual consumption and getting it closer to theoretical consumption; for that, they propose to improve the actual building's energy systems and get it closer to theoretical consumption.

Another limitation of using EPC for assessing the building stock energy performance is the inconsistency in their implementation. Thus, a relevant bias in the certified properties may exist, distorting the results. We detect a lack of certification in new buildings, which may lead to a worse energy performance assessment than the current situation. Regardless, not enough new housing is built to distort the results seriously. Almost 20% of the properties are certified in València, and we believe it is big enough to capture the current state of the building stock.

The scope of EPCs is another limitation, as they typically focus on a limited set of metrics, such as energy consumption, $CO_2$ emissions, and energy efficiency ratings. While these metrics offer valuable insights, they do not grasp the full complexity of a building's energy performance. Factors like occupant behaviour [69], indoor air quality, natural lighting, comfort, use of renewable energy sources, and resilience to climate change are excluded despite their significant influence on real-life energy usage and the performance of buildings. Researchers have proposed including additional factors in the EPC to reduce this disparity [70].

Besides, energy performance certificates provide a static snapshot of a building's energy performance at a specific time. However, they are valid for a decade while a building's energy performance can evolve due to renovations, retrofits, changes in occupancy, or technological advancements. Thus, we can get an inaccurate representation of the building state by not considering the recent improvements in their energy efficiency. One solution could be to shorten the validity period of EPCs or expand the phenomenology in which a new EPC is required.

Finally, we are assessing the city and their districts using aggregated data. This approach may end in misleading conclusions if we do not consider the evaluation scale properly. This approach helps analyse the collective evolution of the energy performance in a city, identify areas with low energy efficiency ratings, estimate the scale of retrofit actions at economic, energetic and environmental scales and raise public awareness towards the buildings' energy performance where they live. However, it does not provide precise information regarding real energy consumption at any scale, as EPCs are based on theoretical calculations and assumptions. Also, it can overlook buildings with terrible performances masked by more efficient properties in their area, as could have happened in Patraix when considering the office buildings.

## 7. Conclusions

This work diagnoses the energy performance of the building stock in València. We used all the city's EPCs and mapped the results to visualise them. The research aims to identify where resides the potential to improve the city's energy efficiency to reduce the energy demand. Namely, we want to know which city areas are more affected by poor buildings and which constructive characteristics present the worst performances. We match the energy performance results with socioeconomic variables to get insights into the reasons behind them. This work's results should help policymakers understand the building stock energy situation, identify its reasons, and evaluate the appropriate actions to improve its performance.

The results indicate that the building stock presents a poor energy performance due to the city's expansion in the 1960s and 1970s under no building standards. New buildings present better energy performance, but the renovation rate is not fast enough to accomplish the climatic goals. The environmental impact of building new dwellings is greater than retrofitting the existing ones. Hence, retrofitting is mandatory to improve the energy performance of the building stock.

Retrofitting programs must prioritise some areas and buildings as resources and time are finite. Thus, we assess València by comparing the performance in each district. The worst energy performances are in peripheral districts, especially in the city's northern half. These poor performance districts present a sensible correlation with low-income and low-renting rates districts. Hence, the public authorities should consider that dwellings with more significant potential for improvement also have less investment capacity in retrofitting.

However, we acknowledge that using EPCs to evaluate building stock performance has limitations. The main one is the need for more reliability of the certificates, which are based on theoretical assumptions and reference values. Other limitations include the EPC's degree of implementation, the scope of their evaluation or the validity period. All of these cause the energy demand expressed in the EPCs and the actual energy consumption to vary significantly.

This work has shown the relevance of EPCs as an objective tool to diagnose the energy efficiency of a city's building stock. Two methods helped the diagnosis provide valuable insights: mapping visualisation and correlating variables from areas unrelated to the topic. This assessment allowed us to give some brief policy recommendations for the case of València; besides, this same assessment is possible in any city that certifies the energy efficiency of their properties, as it is mandatory in Europe. There is potential to be exploited using EPCs to evaluate measures for reducing buildings' energy demand and achieving climate goals.

## CRediT authorship contribution statement

**Á. Manso-Burgos:** Conceptualization, Software, Methodology, Data curation, Visualization, Writing - original draft. **D. Ribó-Pérez:** Conceptualization, Writing - original draft, Writing - review & editing. **C. Montagud-Montalvá:** Writing - review & editing, Supervision, Funding acquisition. **R. Royo-Pastor:** Writing - review & editing.

## Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Manso-Burgos, Alvaro reports financial support and article publishing charges were provided by C?tedra de Transici?n Energ?tica Urbana (Las Naves-VCiE-UPV). Montagud-Montalva, Carla reports financial support was provided by European Union s Horizon Europe under Grant Agreement No. 101075582. Montagud-Montalva, Carla reports financial support was provided by PURPOSED project (ref PID2021-128822OB-I00).

## Data availability

Data will be made available on request.

## Acknowledgements

This article is an extended and updated version of a paper originally presented at the 17th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES 2022) held in Paphos, Cyprus, over the period 6th to 10th November 2022 (denoted then as paper SDEWES2022.00306 Assessment of Buildings' Energy Efficiency over the Years at a City-wide Level: the Case of Valencia). This project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No. 101075582. The Spanish public administration partly supported this work under the grant PURPOSED project (ref: PID2021-128822OB-I00), financed by the Spanish State Investigation Agency. The Cátedra de Transición Energética Urbana (Las Naves-VCiE-UPV) also supported this work. Thanks to Mireia Roncero Tarazona for creating the maps in this article.

## Appendix A. Annexes

### A.1. Boundaries set for the Z-score by energy class

**Table 8**
Boundaries set for the Z-score by energy class.

| Energy class | Final energy demand [kWh/ $m^2$ yr.] | $CO_2$ emission [kg $CO_2$/ $m^2$ yr.] | Construction year |
|---|---|---|---|
| A | $0 < x_i < 387.8$ | $0 < x_i < 73.59$ | $x_i < 1700$ |
| B | $0 < x_i < 1,165$ | $0 < x_i < 74.37$ | $x_i < 1700$ |
| C | $0 < x_i < 704.8$ | $0 < x_i < 120.6$ | $x_i < 1700$ |
| D | $0 < x_i < 540.9$ | $0 < x_i < 109.9$ | $x_i < 1700$ |
| E | $0 < x_i < 352.1$ | $0 < x_i < 78.06$ | $x_i < 1700$ |
| F | $0 < x_i < 363.9$ | $0 < x_i < 81.37$ | $x_i < 1700$ |
| G | $0 < x_i < 976.2$ | $0 < x_i < 179.0$ | $x_i < 1700$ |

*A.2. Energy demand for each energy class by property use*

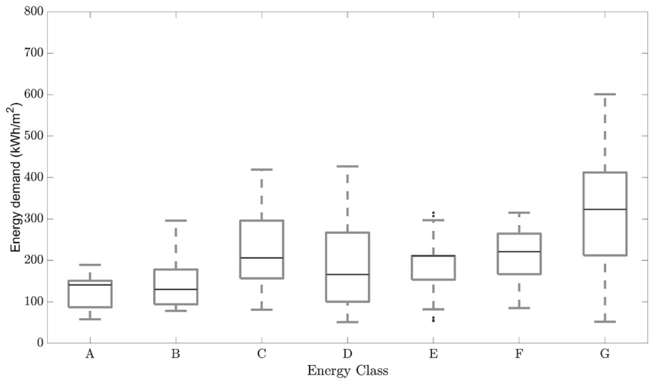



**Fig. 14.** Energy demands in each EPC class for commercial buildings.

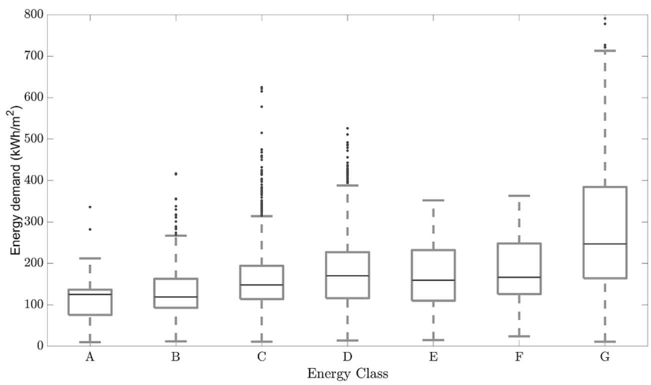



**Fig. 15.** Energy demands in each EPC class for commercial premises.

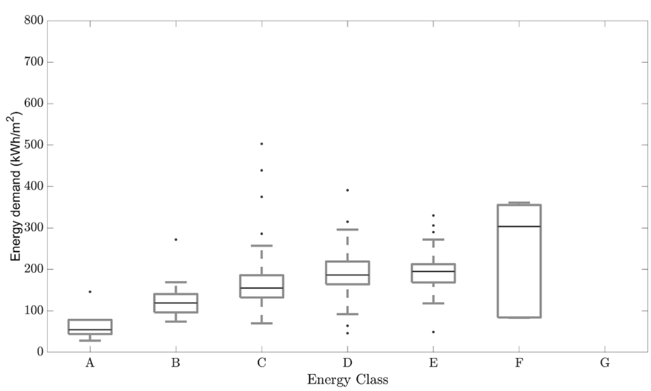



**Fig. 16.** Energy demands in each EPC class for educational centres.

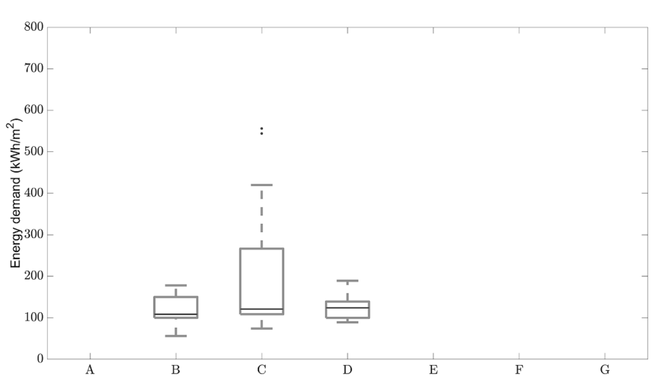



**Fig. 17.** Energy demands in each EPC class for hospitals.

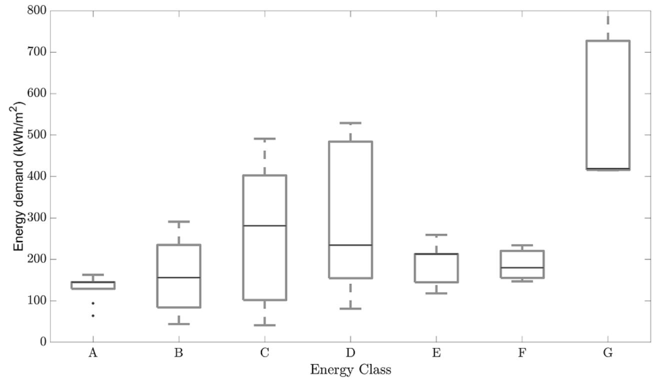



**Fig. 18.** Energy demands in each EPC class for hotels.

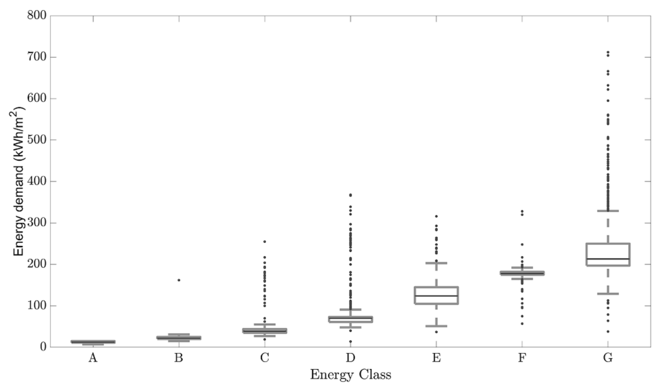



**Fig. 19.** Energy demands in each EPC class for individual dwellings (re-scaled for comparison).

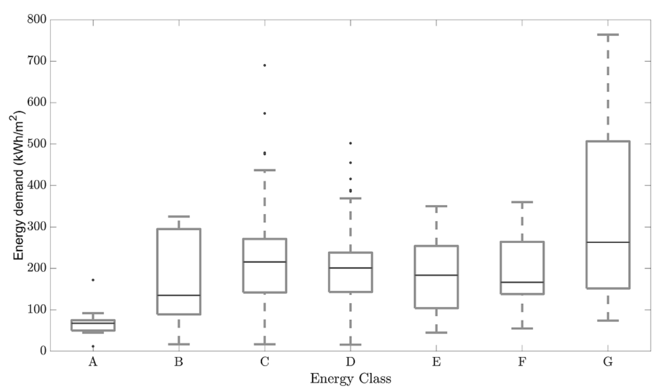



**Fig. 20.** Energy demands in each EPC class for offices.

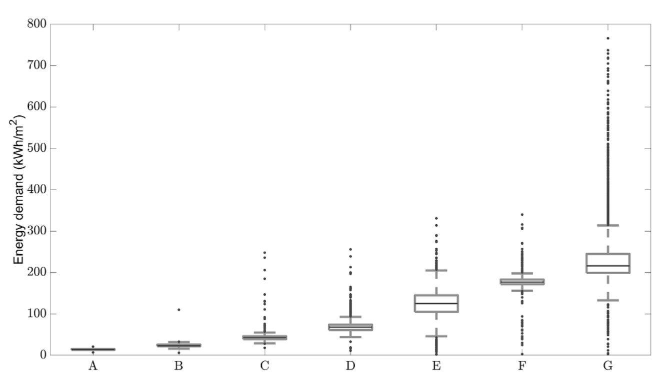



**Fig. 21.** Energy demands in each EPC class for residential buildings.

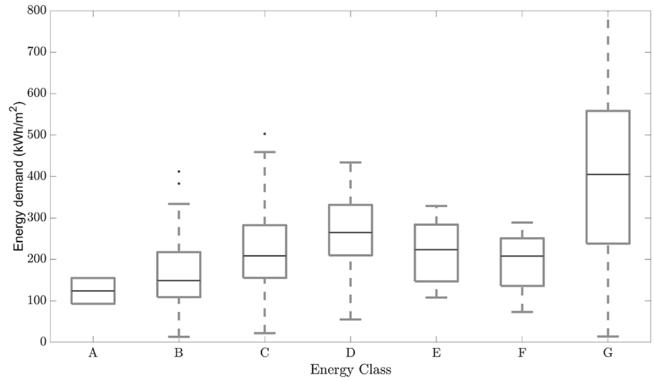



**Fig. 22.** Energy demands in each EPC class for restaurants.

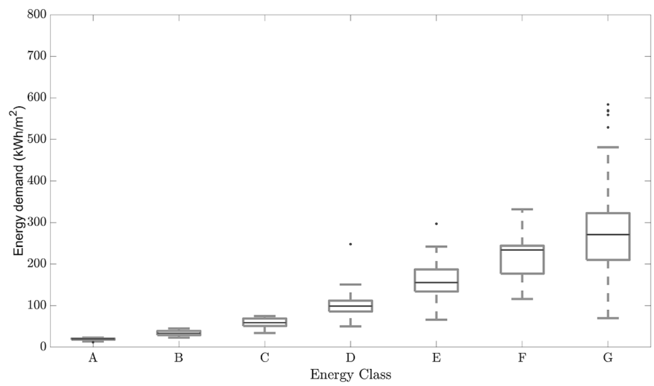



**Fig. 23.** Energy demands in each EPC class for single-family dwellings.

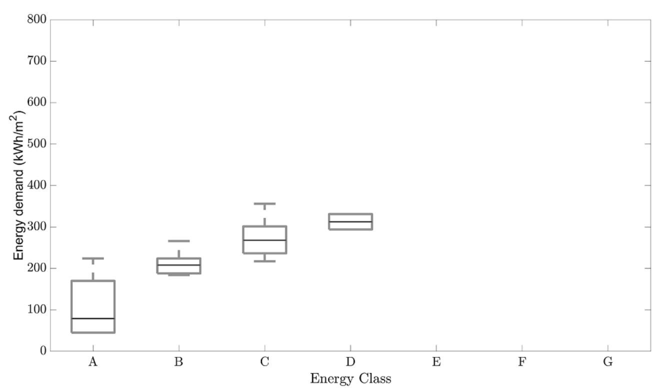



**Fig. 24.** Energy demands in each EPC class for sport facilities.

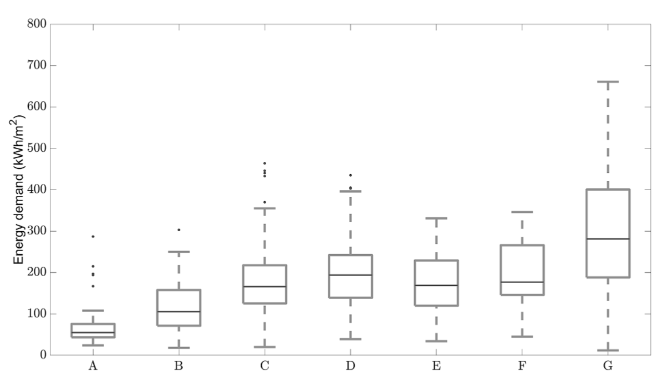



**Fig. 25.** Energy demands in each EPC class for other uses.

## References


[1] Droege P. Introduction - the great transformation: Cities and regions embracing renewable energy. In: Droege P, editor. Urban Energy Transition. second ed. Elsevier; 2018. p. 1–8. https://doi.org/10.1016/B978-0-08-102074-6.00001-2. URL:https://www.sciencedirect.com/science/article/pii/B9780081020746000012.

[2] Cajot S, Schüler N. Urban energy system planning: Overview and main challenges. Urban Energy Systems Low-carbon Cities 2019:19–49.

[3] EU, Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency, Official Journal of the European Union 156 (2018) 75–91. URL:https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2018.156.01.0075.01.ENG, available at URL: http://data.europa.eu/eli/dir/2018/844/oj.

[4] European Parliament and the council, Regulation (EU) 2017/1369 of the European Parliament and of the Council of 4 July 2017 setting a framework for energy labelling and repealing Directive 2010/30/EU, Official Journal of the European Union L 198 (2017) 1–22. arXiv:arXiv:1011.1669v3, available at URL:http://data.europa.eu/eli/reco/2019/786/oj.

[5] EU, Energy Efficiency Plan 2011 (2011). URL:https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex:52011DC0109.

[6] A. Arcipowska, F. Anagnostopoulos, F. Mariottini, S. Kunkel, Energy Performance Certificates (EPC) across the EU Mapping of national approaches, 2014. URL: http://bpie.eu/publication/energy-performance-certificates-across-the-eu/#.VDZi_vmSx9V.

[7] EU, Directive 2002/91/ec of the european parliament and of the council of 16 december 2002 on the energy performance of buildings, 2002. URL:https://eur-lex.europa.eu/legal-content/ES/ALL/?uri=CELEX%3A32002L0091.

[8] Yazdanie M, Orehounig K. Advancing urban energy system planning and modeling approaches: Gaps and solutions in perspective. Renew Sustain Energy Rev 2021;137:110607. https://doi.org/10.1016/j.rser.2020.110607. URL:https://www.sciencedirect.com/science/article/pii/S1364032120308911.

[9] Europe JU, Action SP. White paper on ped reference framework for positive energy districts and neighbourhoods. Online 2020;30:2021.

[10] Gabaldón Moreno A, Vélez F, Alpagut B, Hernández P, Sanz Montalvillo C. How to achieve positive energy districts for sustainable cities: A proposed calculation methodology. Sustainability 2021;13:710.

[11] Gómez-Navarro T, Brazzini T, Alfonso-Solar D, Vargas-Salgado C. Analysis of the potential for pv rooftop prosumer production: Technical, economic and environmental assessment for the city of valencia [spain]. Renew Energy 2021;174:372–81.

[12] Manso-Burgos A, Ribó-Pérez D, Alcázar-Ortega M, Gómez-Navarro T. Local energy communities in spain: Economic implications of the new tariff and variable coefficients. Sustainability 2021;13.

[13] Manso-Burgos A, Ribó-Pérez D, Gómez-Navarro T, Alcázar-Ortega M. Local energy communities modelling and optimisation considering storage, demand configuration and sharing strategies: A case study in valencia [spain]. Energy Rep 2022;8:10395–408.

[14] Geraldi MS, Ghisi E. Building-level and stock-level in contrast: A literature review of the energy performance of buildings during the operational stage. Energy Build 2020;211:109810. https://doi.org/10.1016/j.enbuild.2020.109810. URL:https://www.sciencedirect.com/science/article/pii/S0378778819330646.

[15] Johansson T, Vesterlund M, Olofsson T, Dahl J. Energy performance certificates and 3-dimensional city models as a means to reach national targets–a case study of the city of kiruna. Energy Convers Manage 2016;116:42–57.

[16] Prades-Gil C, Viana-Fons J, Masip X, Cazorla-Marín A, Gómez-Navarro T. An agile heating and cooling energy demand model for residential buildings. case study in a mediterranean city residential sector. Renew Sustain Energy Rev 2023;175:113166.

[17] Ballarini I, Corgnati SP, Corrado V. Use of reference buildings to assess the energy saving potentials of the residential building stock: The experience of tabula project. Energy Policy 2014;68:273–84.

[18] Zhuravchak R, Pedrero RA, del Granado PC, Nord N, Brattebø H. Top-down spatially-explicit probabilistic estimation of building energy performance at a scale. Energy Build 2021;238:110786.

[19] Belussi L, Danza L, Ghellere M, Guazzi G, Meroni I, Salamone F. Estimation of building energy performance for local energy policy at urban scale. Energy Procedia 2017;122:98–103.

[20] de España G, et al., Calificación de la eficiencia energética de los edificios, Madrid. https://energia. gob. es/desarrollo/EficienciaEnergetica/CertificacionEnergeti ca/DocumentosReconocidos/normativamodelosutilizacion/20151123-Calificacion-eficiencia-energetica-edificios. pdf (2015).

[21] Filippini M, Obrist A. Are households living in green certified buildings consuming less energy? evidence from switzerland. Energy Policy 2022;161:112724. https://doi.org/10.1016/j.enpol.2021.112724. URL:https://www.sciencedirect.com/science/article/pii/S0301421521005905.

[22] Monfils S, Hauglustaine J-M, The energy performance certification: A tool for smarter cities?, in: Systems Simulations in Buildings 2014, 2014.

[23] Dell'Anna F, Bravi M, Marmolejo-Duarte C, Bottero MC, Chen A. Epc green premium in two different european climate zones: A comparative study between barcelona and turin. Sustainability 2019;11:5605.

[24] Marmolejo-Duarte C, Chen A. La evolución del impacto de la eficiencia energética en los precios residenciales. un análisis para la barcelona metropolitana. Revista de la construcción 2019;18:145–55.

[25] Taruttis L, Weber C. Estimating the impact of energy efficiency on housing prices in germany: Does regional disparity matter? Energy Econ 2022;105:105750.

[26] Bull R, Chang N, Fleming P. The use of building energy certificates to reduce energy consumption in european public buildings. Energy Build 2012;50:103–10. https://doi.org/10.1016/j.enbuild.2012.03.032. URL:https://www.sciencedirect.com/science/article/pii/S0378778812001806.

[27] Pasichnyi O, Wallin J, Levihn F, Shahrokni H, Kordas O. Energy performance certificates – new opportunities for data-enabled urban energy policy instruments? Energy Policy 2019;127:486–99. https://doi.org/10.1016/j.enpol.2018.11.051. URL:https://www.sciencedirect.com/science/article/pii/S0301421518307894.

[28] Wederhake L, Wenninger S, Wiethe C, Fridgen G, Stirnweiß D. Benchmarking building energy performance: Accuracy by involving occupants in collecting data-a case study in germany. J Cleaner Prod 2022;379:134762.

[29] Martínez-Llorens AM, de La Paz PT, Mora-Garcia RT. Effect of the physical characteristics of a dwelling on energy consumption and emissions: The case of castellón and valencia (spain). Sustainability (Switzerland) 2020;12:1–20. https://doi.org/10.3390/su12229747.

[30] Gangolells M, Casals M, Forcada N, MacArulla M, Cuerva E. Energy mapping of existing building stock in Spain. J Cleaner Prod 2016;112:3895–904. https://doi.org/10.1016/j.jclepro.2015.05.105. URL:https://doi.org/10.1016/j.jclepro.2015.05.105.

[31] Karatasou S, Laskari M, Santamouris M. Determinants of high electricity use and high energy consumption for space and water heating in European social housing: Socio-demographic and building characteristics. Energy Build 2018;170:107–14. https://doi.org/10.1016/j.enbuild.2018.04.019.

[32] Chong H. Building vintage and electricity use: Old homes use less electricity in hot weather. Eur Econ Rev 2012;56:906–30. https://doi.org/10.1016/j.euroecorev.2012.02.009.

[33] Estiri H. A structural equation model of energy consumption in the United States: Untangling the complexity of per-capita residential energy use. Energy Res Social Sci 2015;6:109–20. https://doi.org/10.1016/j.erss.2015.01.002. URL:https://doi.org/10.1016/j.erss.2015.01.002.

[34] Österbring M, Mata É, Thuvander L, Mangold M, Johnsson F, Wallbaum H. A differentiated description of building-stocks for a georeferenced urban bottom-up building-stock model. Energy Build 2016;120:78–84.

[35] Ahern C, Norton B. A generalisable bottom-up methodology for deriving a residential stock model from large empirical databases. Energy Build 2020;215:109886.

[36] Galli A, Piscitelli MS, Moscato V, Capozzoli A. Bridging the gap between complexity and interpretability of a data analytics-based process for benchmarking energy performance of buildings. Expert Syst Appl 2022;206:117649.

[37] Herrando M, Cambra D, Navarro M, de la Cruz L, Millán G, Zabalza I. Energy performance certification of faculty buildings in spain: The gap between estimated and real energy consumption. Energy Convers Manage 2016;125:141–53.

[38] Ferrantelli A, Belikov J, Petlenkov E, Thalfeldt M, Kurnitski J. Evaluating the energy readiness of national building stocks through benchmarking. IEEE Access 2022;10:45430–43.

[39] Ferrantelli A, Kurnitski J. Energy performance certificate classes rating methods tested with data: How does the application of minimum energy performance standards to worst-performing buildings affect renovation rates, costs, emissions, energy consumption? Energies 2022;15.

[40] Droutsa KG, Kontoyiannidis S, Dascalaki EG, Balaras CA. Mapping the energy performance of hellenic residential buildings from epc (energy performance certificate) data. Energy 2016;98:284–95.

[41] Pagliaro F, Hugony F, Zanghirella F, Basili R, Misceo M, Colasuonno L, Del Fatto V. Assessing building energy performance and energy policy impact through the combined analysis of epc data–the italian case study of siape. Energy Policy 2021;159:112609.

[42] Las-Heras-Casas J, López-Ochoa LM, López-González LM, Paredes-Sánchez JP. A tool for verifying energy performance certificates and improving the knowledge of the residential sector: A case study of the autonomous community of aragón (spain). Sustainable Cities Soc 2018;41:62–72. https://doi.org/10.1016/j.scs.2018.05.016. URL:https://www.sciencedirect.com/science/article/pii/S2210670718302920.

[43] Lorenzo-Sáez E, Oliver-Villanueva JV, Coll-Aliaga E, Lemus-Zúñiga LG, Lerma-Arce V, Reig-Fabado A. Energy efficiency and GHG emissions mapping of buildings for decision-making processes against climate change at the local level. Sustainability (Switzerland) 2020;12:1–17. https://doi.org/10.3390/su12072982.

[44] Perez-Garcia A, Guardiola AP, Gómez-Martínez F, Guardiola-Víllora A. Energy-saving potential of large housing stocks of listed buildings, case study: l'Eixample of Valencia. Sustainable Cities and Society 2018;42:59–81. https://doi.org/10.1016/j.scs.2018.06.018.

[45] IVACE, Portal de datos abiertos del registro de los certificados de eficiencia energética en la comunitat valenciana, n.d. URL:https://gceedadesobertes.aven.es/dadesobertes/.

[46] Sedecatastro, Electronic Headquarters of the Cadastre - Home, 2022. URL:https://www.sedecatastro.gob.es/, available at URL:https://www.sedecatastro.gob.es/.

[47] A. de València, Yearbook by chapters - Valencia, 2022. URL:https://www.valencia.es/es/cas/estadistica/anuario-por-capitulos.

[48] INSPIRE, Services inspire of cadastral cartography, n.d. URL:https://www.catastro.minhap.es/webinspire/index_eng.html.

[49] Kreyszig E, Stroud K, Stephenson G. Advanced engineering mathematics. Integration 2008;9.

[50] Mathworks, mean, n.d.a. URL:https://es.mathworks.com/help/matlab/ref/timeseries.mean.html.

[51] Mathworks, std, n.d.b. URL:https://es.mathworks.com/help/matlab/ref/std.html.

[52] ESRI, 2D, 3D & 4D GIS Mapping Software — ArcGIS Pro, 2020. URL:https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview., available at URL:https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview.
[53] Mathworks, corrcoef, n.d. URL:https://es.mathworks.com/help/matlab/ref/corrcoef.html.
[54] A. de València, 2021. URL:https://www.valencia.es/es/-/planes-y-estrategias-plan-de-acci%C3%B3n-para-el-clima-y-la-energ%C3%ADa-sostenible-paces-.
[55] G. de España, Real Decreto 2429/1979 por el que se aprueba la norma básica de la edificación NBE-CT-79 sobre condiciones térmicas en los edificios., 1979. Available at URL:https://www.boe.es/buscar/doc.php?id=BOE-A-1979-24866.
[56] Gangolells M, Casals M. Resilience to increasing temperatures: Residential building stock adaptation through codes and standards. Build Res Inform 2012;40:645–64. https://doi.org/10.1080/09613218.2012.698069. URL:https://www.tandfonline.com/action/journalInformation?journalCode=rbri20.
[57] EU, Directive 2010/31/eu of the european parliament and of the council of 19 May 2010 on the energy performance of buildings (recast), 2010. URL:https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32010L0031.
[58] G. de España, Real Decreto 47/2007, de 19 de enero, por el que se aprueba el Procedimiento básico para la certificación de eficiencia energética de edificios de nueva construcción., 2007. Available at URL:https://www.boe.es/buscar/doc.php?id=BOE-A-2007-2007.
[59] España, Real Decreto 235/2013, 2013. Available at URL:https://www.boe.es/buscar/act.php?id=BOE-A-2013-3904.
[60] España, Real Decreto 178/2021, Boletin Oficial del Estado, 24 de marzo de 2021, núm. 71, 71 (2021) 33748–33793. Available at URL:https://www.boe.es/buscar/doc.php?id=BOE-A-2021-4572.
[61] Lopez-Ochoa LM, Las-Heras-Casas J, Olasolo-Alonso P, López-González LM. Towards nearly zero-energy buildings in mediterranean countries: Fifteen years of implementing the energy performance of buildings directive in spain (2006–2020). J Build Eng 2021;44:102962.
[62] López-Ochoa LM, Las-Heras-Casas J, González-Caballín JM, Carpio M. Towards nearly zero-energy residential buildings in mediterranean countries: The implementation of the energy performance of buildings directive 2018 in spain. Energy 2023;276:127539.
[63] Olasolo-Alonso P, López-Ochoa LM, Las-Heras-Casas J, López-González LM. Energy performance of buildings directive implementation in southern european countries: A review. Energy Build 2022;112751.
[64] S.O. València City Council, 2022. URL:https://www.valencia.es/cas/estadistica/mapa-distritos.
[65] Rose J, Thomsen KE, Domingo-Irigoyen S, Bolliger R, Venus D, Konstantinou T, Mlecnik E, Almeida M, Barbosa R, Terés-Zubiaga J, et al. Building renovation at district level–lessons learned from international case studies. Sustainable Cities Soc 2021;72:103037.
[66] Bianco V, Sonvilla PM, Reed PG, Prado AV. Business models for supporting energy renovation in residential buildings. the case of the on-bill programs. Energy Reports 2022;8:2496–507.
[67] Coyne B, Denny E. Mind the energy performance gap: testing the accuracy of building energy performance certificates in ireland. Energy Efficiency 2021;14.
[68] Cozza S, Chambers J, Brambilla A, Patel MK. In search of optimal consumption: A review of causes and solutions to the energy performance gap in residential buildings. Energy Build 2021;249:111253.
[69] Gaetani I, Hoes P-J, Hensen JL. Estimating the influence of occupant behavior on building heating and cooling energy in one simulation run. Appl Energy 2018;223:159–71.
[70] Võsa K-V, Ferrantelli A, Tzanev D, Simeonov K, Carnero P, Espigares C, Escudero MN, Quiles PV, Andrieu T, Battezzati F, et al. Building performance indicators and ieq assessment procedure for the next generation of epc-s. In: E3S Web of Conferences, volume 246. EDP Sciences; 2021. p. 13003.