



Article

Energy Benchmarking of Existing Office Stock in Spain: Trends and Drivers

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Received: 7 October 2019; Accepted: 8 November 2019; Published: 12 November 2019

Abstract: Buildings play a central role in the clean energy transition, which is why it is vital to understand how energy is consumed in this sector. Energy performance certificate databases are considered a key source of information on the characteristics of built building stock. Despite a growing portfolio of studies based on information from such databases, little is known about energy consumption in offices. This paper explores the modelled energy performance of existing offices in Spain, using data from 13,701 energy performance certificates collected by the Catalan Institute of Energy (ICAEN) in 2013–2018. Offices were found to consume between 202.66 and 212.10 kWh_p/m²-year and were mostly ranked in classes C and D (~64%). Offices with E, F or G labels represent ~28% of the sample while A and B energy ratings are very scarce (~8%). Key drivers of energy consumption variation were found to be the office type, construction period, climate zone, renewable energy use, energy certification procedure and motivation for obtaining an energy performance certificate. Ownership was not found to affect average calculated energy consumption. The results will help policy makers to plan future energy conservation strategies.

Keywords: offices; energy performance certificates; energy consumption; Spain

1. Introduction

In 2012, the European Union set a 20% energy savings target by 2020, under the Energy Efficiency Directive [1]. Six years later, in December 2018, the revised Energy Efficiency Directive [2] entered into force and established an EU energy efficiency target of at least 32.5% for 2030. In addition, Directive 2018/2001 [3] set a binding target of at least 32% energy from renewable sources at European Union level by 2030. Buildings play a central role in the clean energy transition [4] as they account for nearly 40% of final energy consumption [5] and represent approximately 36% of all CO₂ emissions in the European Union [6].

In Spain, data from the long-term strategy for energy renovation in the building sector [7] indicate that the energy consumption of current building stock stands at 31.3% of final national energy consumption. Most previous studies have focused on limiting the residential sector's energy demand, which is 18.5% of final consumption. In second place are non-residential buildings, which represent 12.5% of Spain's final energy consumption [7] and have an average carbon intensity of the final energy demand of 1.02 metric tons of CO_{2,eq}/toe [8]. In 2016, 283,532 offices with a total floor area of 111,291,436 m² [9] consumed 3118 ktoe, which is almost one third (29.34%) of the energy consumed by buildings that house services [10]. This figure is partly due to the growth of the services sector in recent years, especially in administrative, financial and consulting activities. In addition, the evolution of working methods and comfort standards have led to an increase in the energy intensity of offices. Offices tend to include an increasing amount of energy-consuming equipment such as

computers, data processing centers, printers, scanners and photocopiers. In addition, a higher level of comfort is required, which often leads to greater energy expenditure on air conditioning, ventilation and lighting. To reduce this energy expenditure, we must understand how energy is consumed in the office sector [11].

Energy performance certificates were introduced in response to the Energy Performance Buildings Directive [12,13]. They are designed to help achieve energy efficiency targets by informing stakeholders in the building sector about buildings' energy efficiency [14]. A high proportion of the building stock now has an energy performance certificate, as these certificates are mandatory for new buildings, public buildings and existing buildings or building units that are for sale or rent. Databases for registering energy performance certificates are not compulsory but are considered a key source of information on the characteristics of built building stock [15]. Such databases are used to produce statistics on regional or national building stocks [5]. Table 1 summarises previous research initiatives using energy performance certificate databases to describe the efficiency of a nation's building stock. Despite a growing portfolio of studies based on energy performance certificate databases, little is known about energy consumption in offices. An analysis by Dascalaki et al. [16], Fabbri et al. [17], Dascalaki et al. [18] and Gangoellés et al. [19] covered all the energy performance certificates included in their corresponding national databases, but unfortunately non-residential buildings were not differentiated by use. Only Armitage et al. [20] and Hjortling et al. [21] analysed in depth the final energy consumption of the office sector in England and Wales and Sweden, respectively.

Table 1. Previous research initiatives using energy performance certificate databases to describe the building stock. Source: own elaboration.

Research Paper	Number of EPCs	Domain	Country
Armitage et al. [20]	2600	Offices	England and Wales
Broberg and Egüez [22]	90,039	Residential	Sweden
Buratti et al. [23]	6500	Residential	Italy
Curtis et al. [24]	410,348	Residential	Ireland
Dall'O' et al. [25]	175,778	Residential	Italy
Dascalaki et al. [16]	250	Residential and non-residential	Greece
Dascalaki et al. [18]	355,000	Residential and non-residential	Greece
Dineen et al. [26]	304,814	Residential	Ireland
Drousta et al. [27]	650,000	Residential	Greece
Fabbri et al. [17]	1081	Residential and non-residential	Italy
Fabbri [28]	362,884	Residential	Italy
Gangoellés et al. [19]	129,635	Residential and tertiary	Spain
Godoy-Shimizu et al. [29]	12,000	Schools	United Kingdom
Hjortling et al. [21]	186,021	Commercial	Sweden
Hong et al. [30]	8732	Schools	United Kingdom
Hong et al. [31]	7731	Schools	United Kingdom
Johansson et al. [32]	138,444	Residential	Sweden
Kragh and Wittchen [33]	235,000	Residential	Denmark
Las-Heras-Casas et al. [34]	36,072	Residential	Spain
López-González et al. [35]	9416	Residential	Spain
Magalhães and Leal [36]	259,775	Residential	Portugal
Majcen et al. [37]	233,670	Residential	The Netherlands
Mangold et al. [38]	17,620	Residential	Sweden
Mangold et al. [39]	5697	Residential	Sweden
Prieler et al. [40]	2645	Residential	Austria
Reis and Escórcio [41]	519	Residential	Portugal

It is now five years since Royal Decree 235/2013 [42] was introduced in Spain and the database has reached a critical number of certificates that realistically reflect existing office stock. Therefore, the main objective of this paper is to characterise the existing office stock in terms of construction techniques and building systems through the information gathered in the energy performance certificates and to report on its energy performance on an aggregated level. This paper also examines

the effects that variables such as office type, construction period, climate zone, use of renewable energy, ownership, motivation for obtaining an energy performance certificate and the energy certification procedure may have on the modelled energy use in the office sector. This paper uses 13,701 energy performance certificates for offices, collected by the Catalan Institute of Energy (ICAEN) since the entry into force of Royal Decree 235/2013 [42] in June 2013 up until July 2018. Following the introduction, the second section summarises the main aspects of the energy certification process in Spain. The third section presents the method and describes the sample and the fourth section discusses the results. Finally, the last section outlines the conclusions and highlights implications and future research.

2. Energy Performance Certification in Spain

In Spain, energy performance certificates for new buildings came into effect in 2007 with Royal Decree 47/2007 [43], in response to the Energy Performance Building Directive [12]. Existing buildings were addressed six years later in Royal Decree 235/2013 [42]. Since then, energy performance certificates have been mandatory for new and existing buildings, building units that are rented for the first time to a new tenant or buildings in the process of being sold. Energy performance certificates are also mandatory for buildings or building units of over 250 m² occupied by a public authority and visited frequently by the public. Certificates are valid for 10 years, but they can be voluntarily updated before they expire. After the expiry date, the energy performance certificate must be renovated in the case of public buildings of over 250 m². For other buildings, it must be renovated in the case of a new rental or sale.

Energy performance calculation methodology is based on modelled data. Therefore, outcomes are theoretical values corresponding to standard operating conditions, calculated based on the buildings physical characteristics (i.e., thermal envelopes, building systems, etc.). In this way, the Spanish rating focuses on the energy performance of the building, without considering the effect that buildings' occupancy or users' behavior may have on it. According to the Spanish labelling scheme, a building or a building unit can be ranked in one of seven classes depending on the generation of carbon dioxide emissions (kg CO₂/m²-year), ranging from A (lowest generation of emissions) to G (highest generation of emissions). Energy performance certificates for new buildings erected after 2007 cannot have G or F labels. Energy performance certificates also include detailed information about modelled non-renewable primary energy consumption (kWh_p/m²-year) for heating, cooling, domestic hot water and lighting and the corresponding energy ratings (ranging from A to G).

Energy performance certificates must be issued by engineers and architects. The registration process is initiated when the technician completes an online form with basic data and attaches the software file (mandatory) and the energy performance certificate report (voluntary). In Catalonia, the Catalan Institute of Energy (ICAEN) is responsible for controlling, inspecting and registering energy performance certificates. Relevant data can be freely accessed online [44] and visualised using a geographic information system (GIS) tool [45]. Alternatively, the database of energy certificates including general data can be downloaded for offline processing [46]. Technical data is also available on request.

3. Materials and Methods

For the purpose of this research, the Catalan Institute of Energy (ICAEN) provided a complete database with all the information extracted from the energy performance certificates collected in Catalonia (northeast Spain). The certificates that were analysed were issued from June 2013 to July 2018, according to Royal Decree 235/2013 [42]. Due to confidentiality issues, the dataset was anonymised so that the building owner or the technician who issued the energy performance certificate could not be identified.

Original database files were gathered and organised into a single complete table, in which duplicated and non-relevant features were eliminated. For each energy performance certificate, over 150 features including general administrative data (i.e., registration number, building type, address, climate zone and other data), information related to energy performance (label, certification

procedure and detailed information on energy demand, energy consumption and emissions), main characteristics of the office including geometry (i.e., useful floor area), thermal envelope (both opaque closures and openings) and existing facilities (i.e., heating, cooling and domestic hot water) were analysed. The database, originally built in Oracle, was exported into IBM SPSS Statistics v25.0 [47] for analysis.

The database originally included 13,701 energy performance certificates for offices. Several consistency checks (Table 2) identified energy performance certificates containing errors. Along the lines of Dall'O' et al. [25], database variables and other derived variables (for example, the shape factor that was calculated by dividing the building thermal envelope by the building volume) were filtered to detect non-reasonable values (exceptionally large or small figures, equal to zero or empty fields). Limits were set according to physical limitations, current and former regulations and other factors (Table 2). Some textual values had to be standardised. Other data entry errors were also detected and if possible corrected or otherwise deleted. After discarding non-valid energy performance certificates, the original database was reduced to 13,076 energy performance certificates for offices. Therefore, the sample used in this research represents approximately 95.44% of all the energy performance certificates that have been issued in Catalonia for offices. According to the Spanish Government's General Directorate for Land Registry [48], Catalonia currently has 47,212 offices and therefore the sample (in other words, the number of entries in the energy performance certificate database) was deemed appropriate and representative.

Table 2. Variables and threshold values used to detect errors in the energy performance certificate database. Source: own elaboration.

Variable	Value Threshold
Useful floor area (S_u)	$S_u \geq 10 \text{ m}^2$
Headroom (h)	$2.2 \text{ m} \leq h \leq 5.0 \text{ m}$
Shape factor (SF)	$0.01 \text{ m}^2/\text{m}^3 \leq \text{SF} \leq 2.30 \text{ m}^2/\text{m}^3$
Thermal enclosure area (S_{te})	$S_{te} \geq 5 \text{ m}^2$
Non-renewable primary energy consumption (E_p)	$24.4 \text{ kWh}_p/\text{m}^2\text{-year} \leq E_p \leq 1000.0 \text{ kWh}_p/\text{m}^2\text{-year}$

3.1. Office Type

After the validation process, the database included 13,076 energy performance certificates for offices, which represents approximately 3 million m^2 (Table 3). The majority (10,131 certificates, 77.48%) correspond to offices in residential buildings. These offices are located at street level or on higher floors of residential buildings and tend to be small (between 40.60 m^2 and 215.00 m^2). Typical examples include doctors' offices, dental clinics, lawyers' offices, real estate agencies, agencies undertaking administrative work and small consultancy firms, among others. The remaining 2945 energy performance certificates (22.52%) were for office blocks (large buildings containing public or commercial offices) and offices in industrial buildings (offices located inside or adjacent to a building that is used for industrial activities). In this case, offices typically range from 47.68 m^2 to 941.74 m^2 . The percentages of floor area are much more balanced. Offices in residential buildings represent 51.74% of the total floor area of buildings with energy certificates, whereas office blocks and offices in industrial buildings represent 48.26%.

Table 3. Number of energy performance certificates and corresponding floor area according to office type. Source: drawn up by the authors using data from the Catalan Institute of Energy (ICAEN) database, July 2018.

Office Type	Number of Energy Performance Certificates		Floor Area	
	[u.]	[%]	[m^2]	[%]
Office blocks and offices in industrial buildings	2945	22.52	1,595,844	51.74
Offices in residential buildings	10,131	77.48	1,488,548	48.26
Total	13,076	-	3,084,393	-

3.2. Construction Period

Offices built before 1981 have no thermal protection, as the first legislation regulating buildings' thermal conditions, NBE-CT 79 [49], was introduced in Spain in 1979. This prescriptive code was in force from 1981 to 2006 and set minimum thermal requirements for individual building envelopes by establishing maximum heat transmission coefficients, and a maximum overall heat transmission coefficient for the entire building [50]. Thermal requirements were overhauled in 2007, when the Spanish Technical Building Code was introduced [51]. Another major change came in 2014 with the revision of the Spanish Technical Building Code's Section HE-1 on Energy Demand Limitation [52]. As shown in Table 4, offices listed in the energy performance certificate database were mostly built prior to 1981 (56.45%), which compares well with the national statistical average. Offices meeting NBE-CT 79 [49] requirements represent 37.06% of the total. Offices built under the first version of the Spanish Technical Building Code [51] account for 5.14%, whereas offices designed following the requirements of the 2013 revision of the Technical Building Code [52] represent just 1.35% of all entries in the analysed database (Table 4). In general, offices in residential buildings were found to be older than office blocks and offices in industrial buildings. Of all offices built in the latest period (2014–2018), 72.32% correspond to office blocks and offices in industrial buildings and only 27.68% are offices in residential buildings.

Table 4. Number of energy performance certificates according to office type and construction period. Source: drawn up by the authors using data from the ICAEN database, July 2018.

Office Type	Construction Year									
	Prior to 1981		1981–2006 period		2007–2013 period		2014–2018 period		Total	
	[u.]	[%]	[u.]	[%]	[u.]	[%]	[u.]	[%]	[u.]	[%]
Office blocks and offices in industrial buildings	1094	37.15	1485	50.42	238	8.08	128	4.35	2945	100
Offices in residential buildings	6287	62.06	3361	33.18	434	4.28	49	0.48	10,131	100
Total	7381	56.45	4846	37.06	672	5.14	177	1.35	13,076	100

3.3. Climate Zone

The latest modification of the Spanish Technical Building Code [52] defines 15 climate zones based on winter climate severity (WCS) and summer climate severity (SCS) [19]. Winter climate severity is a good indicator of energy demand for heating and is identified by a letter: A for locations with the warmest winter and E for locations with the coldest winter. Summer climate severity is an indicator of energy demand for cooling and is represented by a number: 1 for locations with the mildest summer and 4 for locations with the hottest summer.

In general, Barcelona and Girona provinces are in the C2 climate zone, whereas Tarragona is in the B3 climate zone and Lleida in the D3 climate zone (Figure 1). As shown in Table 5, most of the energy performance certificates included in the sample are in the C2 climate zone (76.36%). Offices erected in the B3 climate zone represent 2.07% of the database whereas offices in the D3 climate zone account for 2.65%. All locations in a province are considered to have the same climate zone as their capital, but a correction is devised for locations that differ by over 200 m of altitude from the corresponding capital. Therefore, in accordance with the population distribution, a high proportion of energy performance certificates in the database are from other climate zones such as D2 (12.30%), C3 (4.08%), D1 (1.77%) and E1 (0.78%).

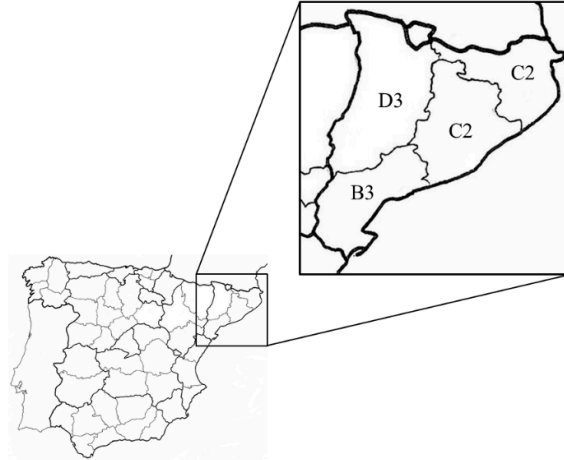


Figure 1. Climate zoning based on winter climate severity and summer climate severity according to the Spanish Technical Building Code [52]. Source: drawn up by the authors.

Table 5. Number of energy performance certificates according to office type and climate zone. Source: drawn up by the authors using data from the ICAEN database, July 2018.

Office Type	Climate Zone															
	Province Capitals Zones						Other Zones						Total			
	C2		B3		D3		D2		C3		D1				E1	
	[u.]	[%]	[u.]	[%]	[u.]	[%]	[u.]	[%]	[u.]	[%]	[u.]	[%]	[u.]	[%]	[u.]	[%]
Office blocks and offices in industrial buildings	1874	63.63	75	2.55	118	4.01	562	19.08	184	6.25	86	2.92	46	1.56	2945	100
Offices in residential buildings	8111	80.06	196	1.93	228	2.25	1046	10.32	349	3.44	145	1.43	56	0.55	10,131	100
Total	9985	76.36	271	2.07	346	2.65	1608	12.30	533	4.08	231	1.77	102	0.78	13,076	100

3.4. Renewable Energy Use

Only 1.39% of offices met energy demand with solar, biomass or geothermal energy (Table 6). This percentage was slightly higher (5.06%) for office blocks and offices in industrial buildings. In offices with renewable energy sources, the most widespread technology was solar thermal, followed by solar photovoltaics and biomass. Production of geothermal energy is still uncommon.

Table 6. Number of energy performance certificates by office type and renewable energy sources. Source: drawn up by the authors using data from the ICAEN database, July 2018.

Office Type	Renewable Energy Sources								Non-Renewable Energy Sources	
	Solar Thermal		Solar Photovoltaics		Biomass		Geothermal		[u.]	[%] ¹
	[u.]	[%] ¹	[u.]	[%] ¹	[u.]	[%] ¹	[u.]	[%] ¹		
Office blocks and offices in industrial buildings	95	3.23	46	1.56	17	0.58	6	0.20	2796	94.94
Offices in residential buildings	108	1.07	13	0.13	16	0.16	13	0.13	9990	98.61
Total	203	1.55	59	0.45	33	0.25	19	0.15	12,786	97.78

¹ The sum of all percentages of an office type might be over 100%. A single office can meet energy demand with more than one renewable energy source.

3.5. Ownership and Motivation

Regarding ownership (Table 7), the analysis revealed that most of the energy performance certificates in the database are for privately owned offices (96.50%). This percentage is even higher for offices in residential buildings (98.83%).

Table 7. Number of energy performance certificates according to office type and ownership. Source: drawn up by the authors using data from the ICAEN database, July 2018.

Office Type	Public		Private		Total	
	[u.]	[%]	[u.]	[%]	[u.]	[%]
Office blocks and offices in industrial buildings	339	11.51	2606	88.49	2945	100
Offices in residential buildings	119	1.17	10,012	98.83	10,131	100
Total	458	3.50	12,618	96.50	13,076	100

Most of the energy performance certificates were issued because of rent (62.33%) and sale (28.65%) transactions (Table 8). Energy performance certificates for public sector offices represent 2.91% of the database entries whereas voluntary certification accounts for 1.73%. The number of certificates in the newly built offices category (0.71%) was found to be negligible. The “others” category includes energy performance certificates needed for energy performance certificate renovation, grant applications and/or for building inspection reports. When the data were analysed by office type, a much higher proportion of energy performance certificates for public buildings was found in the office block subset (9.78%) than in the offices in residential buildings subset (0.91%).

Table 8. Number of energy performance certificates by office type and the reason for issuing them. Source: drawn up by the authors using data from the ICAEN database, July 2018.

Office Type	Rental		Sale		Newly Built		Public Offices		Voluntary Certification		Others		Total	
	[u.]	[%]	[u.]	[%]	[u.]	[%]	[u.]	[%]	[u.]	[%]	[u.]	[%]	[u.]	[%]
Office blocks and offices in industrial buildings	1344	45.64	942	31.99	88	2.99	288	9.78	91	3.09	192	6.52	2945	100

Office Type	Rental		Sale		Newly Built		Public Offices		Voluntary Certification		Others		Total	
	[u.]	[%]	[u.]	[%]	[u.]	[%]	[u.]	[%]	[u.]	[%]	[u.]	[%]	[u.]	[%]
Offices in residential buildings	6806	67.18	2,804	27.68	5	0.05	92	0.91	135	1.33	289	2.85	10,131	100
Total	8150	62.33	3,746	28.65	93	0.71	380	2.91	226	1.73	481	3.68	13,076	100

3.6. Energy Certification Procedure

According to Royal Decree 235/2013 [42], an energy performance certificate can only be obtained using tools recognised by the Spanish Ministry for the Ecological Transition (Table 9).

Table 9. Recognised tools for energy performance certification of tertiary sector buildings in Spain in 2019. Source: adapted from ICAEN [53].

Building Type	Certification Procedure	Recognised Tools
New buildings	General	HULC CYPETHERM SG Save
	Simplified	CE3X
Existing buildings	General	HULC CYPETHERM SG Save
	Simplified	CE3X CE3
Large tertiary sector buildings	General	HULC CYPETHERM SG Save
	Simplified	CE3X

As shown in Table 10, most of the energy performance certificates in the database were obtained using a simplified procedure (98.95%), mainly CE3X (98.13%). CE2 software was only recognised during the 2009–2014 period. The remaining 1.05% of certificates were issued using a general procedure. Of them, only 0.67% were obtained using HULC, a software tool that has replaced the former Calener VyP and Calener GT since 2016, and 0.38% were originally obtained using Calener VyP or Calener GT. The database did not include any energy performance certificates issued using CYPETHERM and SG Save, as these software tools were only recognised recently (2018) by the Spanish government. Most of the energy performance certificates obtained using a general procedure (89.78%) correspond to office blocks and offices in industrial buildings.

Table 10. Number of energy performance certificates by office type and energy performance certification procedure. Source: drawn up by the authors using data from the ICAEN database, July 2018.

Office Type	Energy Performance Certification Procedure																	
	General Procedures										Simplified Procedures						Total	
	HULC		Calener VyP		Calener GT		CYPE-THERM		SG Save		CE3X		CE3		CE2			
	[u.]	[%]	[u.]	[%]	[u.]	[%]	[u.]	[%]	[u.]	[%]	[u.]	[%]	[u.]	[%]	[u.]	[%]	[u.]	[%]
Office blocks and offices in industrial buildings	78	2.65	35	1.19	10	0.34	0	0.00	0	0.00	2803	95.18	19	0.65	0	0.00	2945	100
Offices in residential buildings	9	0.09	4	0.04	1	0.01	0	0.00	0	0.00	10,028	98.98	89	0.88	0	0.00	10,131	100
Total	87	0.67	39	0.30	11	0.08	0	0.00	0	0.00	12,831	98.13	108	0.83	0	0.00	13,076	100

4. Results

The following subsections examine the impact that office type, construction period, climate zone, renewable energy use, ownership, motivation for obtaining an energy performance certificate and energy certification procedure may have on the modelled primary energy consumption of offices.

The database had to be further filtered to discard energy performance certificates containing errors in energy consumption-related variables. All energy performance certificates with domestic hot water consumption above 0.40 kWh/m²-year (7488) and those with an undefined lighting system (7495) had to be discarded. Consequently, key drivers for energy consumption variation were investigated using 4529 energy performance certificates for offices: 1073 for office blocks and offices in industrial buildings and 3456 for offices in residential buildings.

4.1. Analysis by Office Type

Figures 2 and 3 illustrate the frequency histograms for the non-renewable primary energy index [kWh_p/m²-year] by office type, covering all climate zones and all construction periods. As reported in other similar studies [19,21,54], predicted non-renewable primary energy consumption was found to be highly positively skewed, because energy consumption cannot be negative, small numbers are rare, and there is high variability in aspects such as office geometry, thermal envelopes, HVAC systems and climate zones that clearly affect energy consumption. Figure 4 characterises the energy performance of each office type using a box-and-whisker plot. The top and bottom ends of the box respectively indicate the upper and lower quartiles (Q3 and Q1), while the band inside represents the median (or second quartile). The upper whisker (vertical line) marks the highest value below the limit defined by 1.5 interquartile ranges (IQR) added to the upper quartile (Q3 + 1.5·IQR). The lower whisker is the lowest value above the limit defined by 1.5 IQR deducted from the lower quartile (Q1 – 1.5·IQR). The floating point in the plot denotes the mean. Figure 5 and Figure 6 represent the number of energy performance certificates by office type and energy rating.

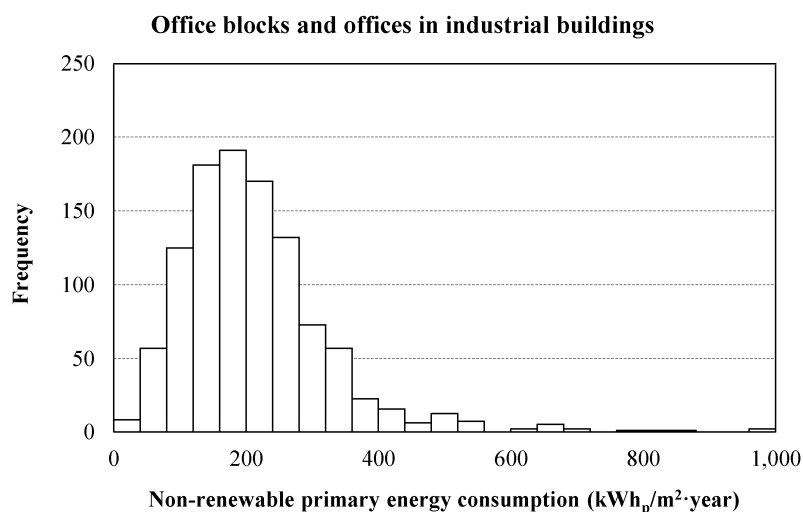


Figure 2. Frequency histogram of calculated non-renewable primary energy consumption [kWh_p/m²-year] for office blocks and offices in industrial buildings. Source: drawn up by the authors using data from the ICAEN database, July 2018.

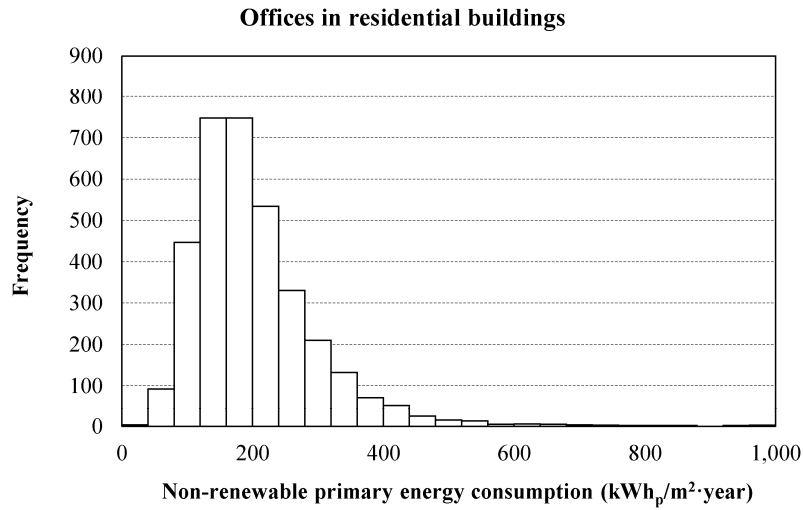


Figure 3. Frequency histogram of calculated non-renewable primary energy consumption [kWh_p/m²·year] for offices in residential buildings. Source: drawn up by the authors using data from the ICAEN database, July 2018.

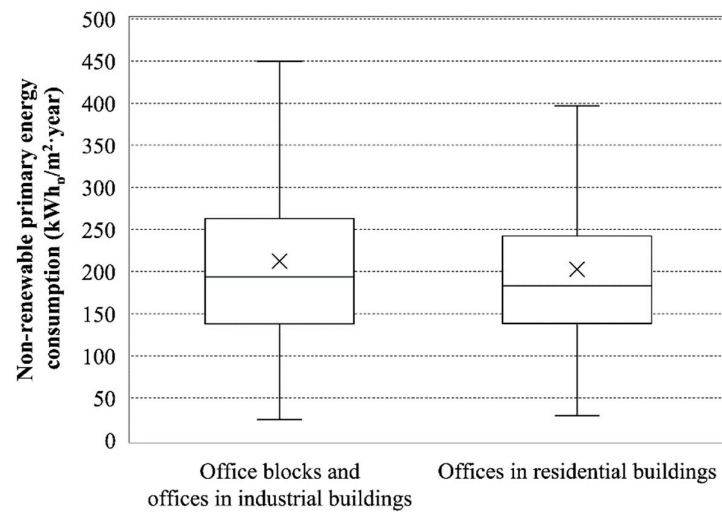


Figure 4. Box-and-whisker plot diagram for calculated non-renewable primary energy consumption [kWh_p/m²·year] by office type. Source: drawn up by the authors using data from the ICAEN database, July 2018.

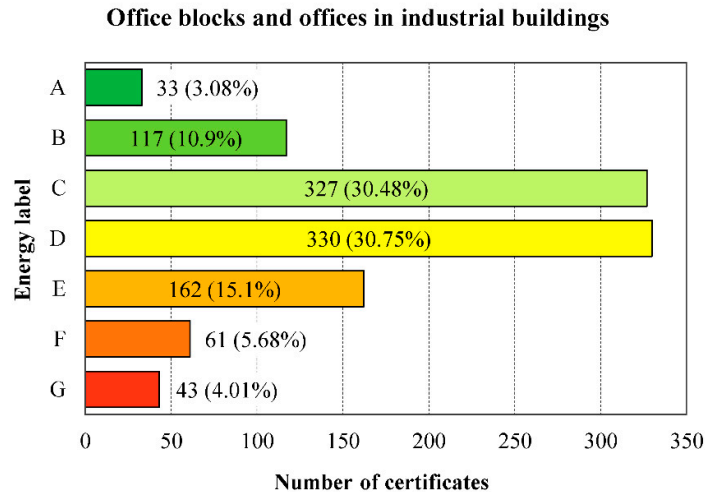


Figure 5. Number of energy performance certificates of office blocks and offices in industrial buildings according to the energy rating. Source: drawn up by the authors using data from the ICAEN database, July 2018.

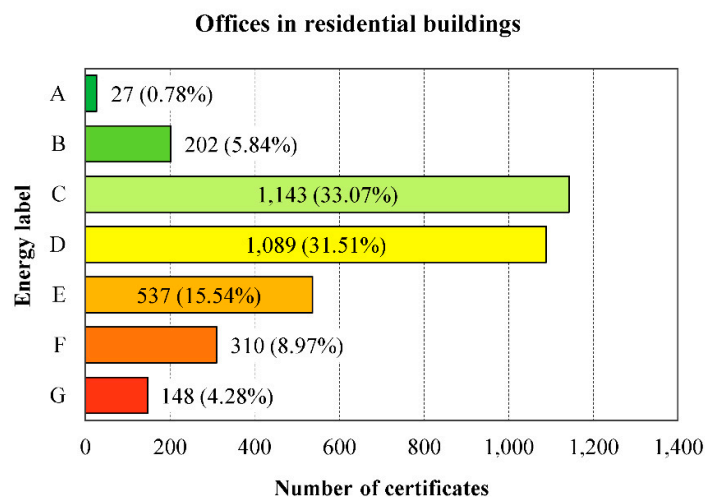


Figure 6. Number of energy performance certificates of offices in residential buildings according to energy rating. Source: drawn up by the authors using data from the ICAEN database, July 2018.

The mean calculated primary non-renewable energy use intensity of Spanish office blocks and offices in industrial buildings amounted to 212.10 kWh_p/m²-year (Figure 4). The median, sometimes used to define typical benchmarks [55], was 193.52 kWh_p/m²-year. According to the Spanish labelling scheme and as shown in Figure 5, 24.79% of office blocks were ranked in class E or below and therefore have great potential for energy savings through retrofitting measures. Offices with C and D labels represented 61.23% of the total. These offices can still provide energy savings through retrofitting solutions. Finally, just a few certificates (13.98%) were in the two most efficient categories (A and B), in which there is little room for improvement.

Offices in residential buildings had mean calculated primary annual energy consumption of 202.66 kWh_p/m²-year in Spain (Figure 4). The median was 182.87 kWh_p/m²-year. A total of 28.79% of offices in residential buildings had E, F or G labels (Figure 6). According to the results, 64.58% of offices in residential buildings were C and D classes. A and B energy ratings were very scarce (6.63%).

The lower simulated energy consumption of offices in residential buildings may be partially explained by a lower shape factor, that is, by lower exposure to external climate conditions and/or non-thermally conditioned spaces because they are generally surrounded by other buildings or building units. The shape factor (external surface-to-volume ratio) was $0.62 \text{ m}^2/\text{m}^3$ for office blocks and offices in industrial buildings and $0.44 \text{ m}^2/\text{m}^3$ for offices in residential buildings. Higher shape factors are related to a higher potential for heat transfer, solar gains, daylight, natural ventilation and infiltration [55]. Although the average energy and carbon intensity per square meter was around 4% lower for offices in residential buildings, the greater floor area of office blocks and offices in industrial buildings resulted in yearly energy consumption of around 227.84 GWh_p and over 41,000 metric tons of CO₂ (Table 11).

Table 11. Average and total calculated non-renewable primary energy consumption and emissions generation by office type. Source: drawn up by the authors using data from the ICAEN database, July 2018.

Office Type	Average Primary Energy Consumption	Average Emissions Generation	Total Primary Energy Consumption		Total Emissions Generation	
	[kWh _p /m ² -year]	[kg CO ₂ /m ² -year]	[GWh _p /year]	[%]	[t CO ₂ /year]	[%]
Office blocks and offices in industrial buildings	212.10	39.36	227.84	61.62	41,271.17	60.56
Offices in residential buildings	202.66	37.94	141.91	38.38	26,873.13	39.44
Total	-	-	369.75	-	68,144.30	-

4.1.1. Energy Breakdown

Although office blocks and offices in industrial buildings consume more energy per square meter, the end-use percentages predicted under the assumptions of the model were found to be quite similar (Figure 7). However, HVAC installed power was found to be 2.75 times higher in office blocks and offices in industrial buildings than offices in residential buildings.

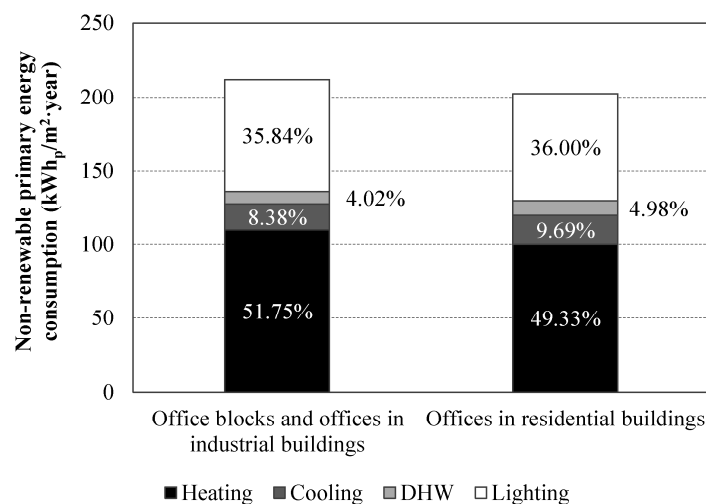


Figure 7. Breakdown of average calculated non-renewable primary energy consumption [kWh_p/m²-year] according to the office type and end-uses. Source: drawn up by the authors using data from the ICAEN database, July 2018.

4.1.2. Fuel Breakdown

According to the data in the energy performance certificate database, most existing offices were heated. Only 2.33% of office blocks and offices in industrial buildings and 2.14% of offices in residential buildings had no heating system. A high proportion of offices also had a cooling system (88.54% for office blocks and offices in industrial buildings and 88.92% for offices in residential buildings) to achieve a suitable level of comfort in summer (Table 12).

As shown in Table 13, most offices used electricity for heating (90.79%), followed by natural gas (5.59%). Electricity was the most common energy source for cooling (99.84%). Domestic hot water was heated by electricity in 89.24% of offices, while in 9.57% of cases it was heated by natural gas. Offices including renewable energy and/or combined systems including both conventional and renewable energy sources were very scarce for the three end-uses.

Based on the models and their assumptions, the calculated energy consumption of offices was mostly covered by electricity and to a much lesser extent by natural gas for the three end-uses. Heating mostly relied on electricity (89.57%) and natural gas (6.30%). Office cooling was mostly powered by electricity (99.89%). Energy consumption of domestic hot water was mainly covered with electricity (95.65%), with a small percentage powered by natural gas (3.96%). In all cases, the use of renewable energy sources was limited. No significant changes were detected by office type, except a slightly higher percentage of electricity use in the heating systems of offices in residential buildings.

In the analysis of fuel prevalence in relation to climate zone, biomass and diesel were found to be used most for heating in rural areas (such as the E1 climate zone) since natural gas distribution networks were less common in areas away from metropolitan cities. In terms of construction period, newer offices were most likely to include a heating and cooling system. Offices built after the introduction of the Spanish Technical Building Code mostly relied on electricity and never used diesel oil.

Table 12. Number of energy performance certificates according to available system and office type. Source: drawn up by the authors using data from the ICAEN database, July 2018.

Fuel	Heating		Cooling		Domestic Hot Water	
	[u.]	[%]	[u.]	[%]	[u.]	[%]
Office blocks and offices in industrial buildings						
Existing system	1048	97.67	950	88.54	595	55.45
No system	25	2.33	123	11.46	478	44.55
Total	1073	100	1073	100	1073	100
Offices in residential buildings						
Existing system	3382	97.86	3,073	88.92	1494	43.23
No system	74	2.14	383	11.08	1962	56.77
Total	3456	100	3456	100	3456	100

Table 13. Number of energy performance certificates according to fuel and office type. Source: drawn up by the authors using data from the ICAEN database, July 2018.

Fuel	Heating		Cooling		Domestic Hot Water	
	[u.]	[%]	[u.]	[%]	[u.]	[%]
Office blocks and offices in industrial buildings						
Electricity	520	84.42	745	99.73	503	88.87
Natural gas	51	8.28	1	0.13	50	8.83
Diesel oil	9	1.46	0	0.00	7	1.24
Renewable energy/combined systems	8	1.30	1	0.13	2	0.35
Others ¹	28	4.55	0	0.00	4	0.71
Total ²	616	100	747	100	566	100
Offices in residential buildings						
Electricity	1738	92.89	2308	99.87	1222	89.39
Natural gas	88	4.70	1	0.04	135	9.88
Diesel oil	21	1.12	1	0.04	5	0.37

Fuel	Heating		Cooling		Domestic Hot Water	
	[u.]	[%]	[u.]	[%]	[u.]	[%]
Renewable energy/combined systems	1	0.05	0	0.00	1	0.07
Others ¹	23	1.23	1	0.04	4	0.29
Total ²	1871	100	2311	100	1367	100

¹ Others includes liquefied petroleum gas, propane, butane and combinations of electricity with other fuels. ² Total includes those energy performance certificates with available information on fuel use. Missing values for office blocks and offices in industrial buildings are 432 (heating), 203 (cooling) and 29 (domestic hot water). Missing values for offices in residential buildings are 1511 (heating), 762 (cooling) and 127 (domestic hot water).

4.2. Analysis by Construction Period

The predicted energy performance of the offices was strongly influenced by construction period, in other words, by the building code (Figure 8). The average calculated energy consumption decrease between the oldest offices and the newest offices amounts to 52.71% for office blocks and offices in industrial buildings and 45.55% for offices in residential buildings. However, the first category in the graph of offices built prior to 1981 includes a high number of offices (2443) with varying construction quality levels [50]. Figure 8 clearly shows the impact of the Spanish Technical Building Code and its subsequent revision.

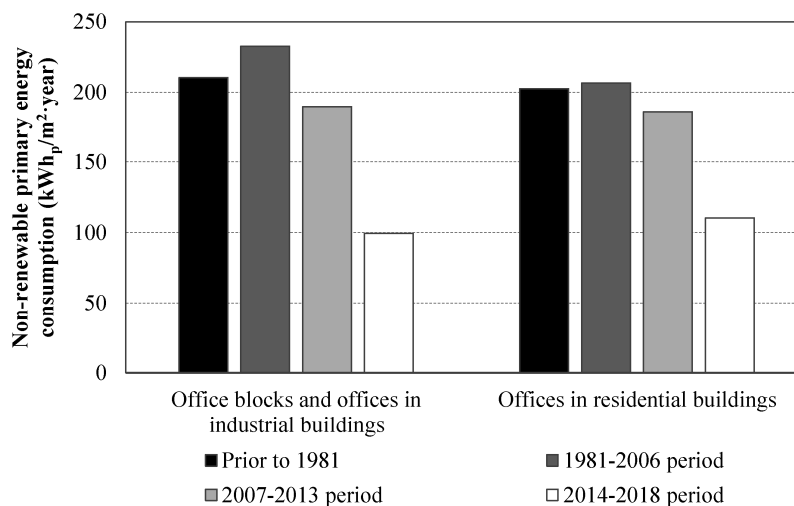


Figure 8. Average calculated non-renewable primary energy consumption [kWh_p/m²·year] by office type and construction period. Source: drawn up by the authors using data from the ICAEN database, July 2018.

Older buildings had the worst emission labels (Figure 9, Figure 10). A total of 4.46% of certificates for offices erected before 1980 were labelled G, but no new offices had this label. Of the modern offices, 26.53% were certified as class A and 57.14% were certified as class B. In contrast, 0.65% of pre-1981 offices were certified as class A and 5.24% as B. Similar results have been reported in other southern European countries such as Greece [27], Portugal [36] and Spain [19].

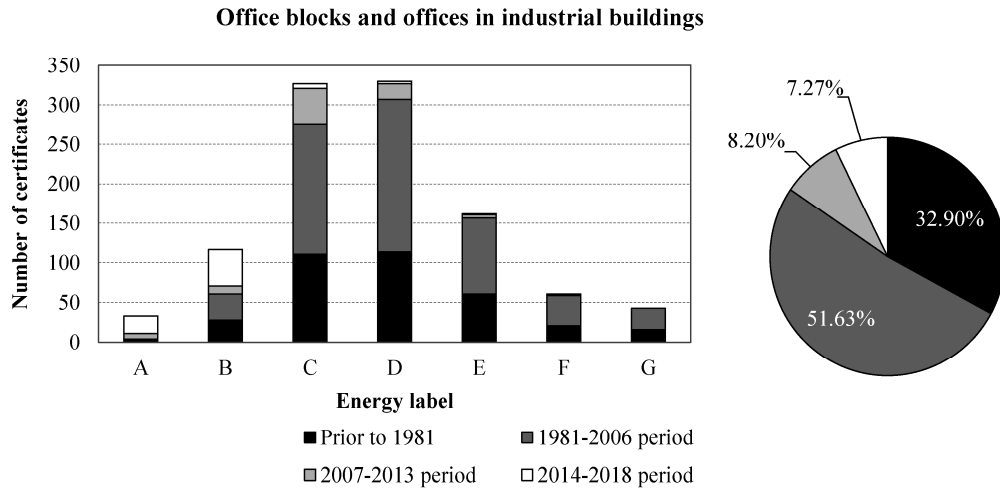


Figure 9. On the left, energy label of office blocks and offices in industrial buildings according to the construction period. On the right, share of energy performance certificates for office blocks and offices in industrial buildings according to construction period. Source: drawn up by the authors using data from the ICAEN database, July 2018.

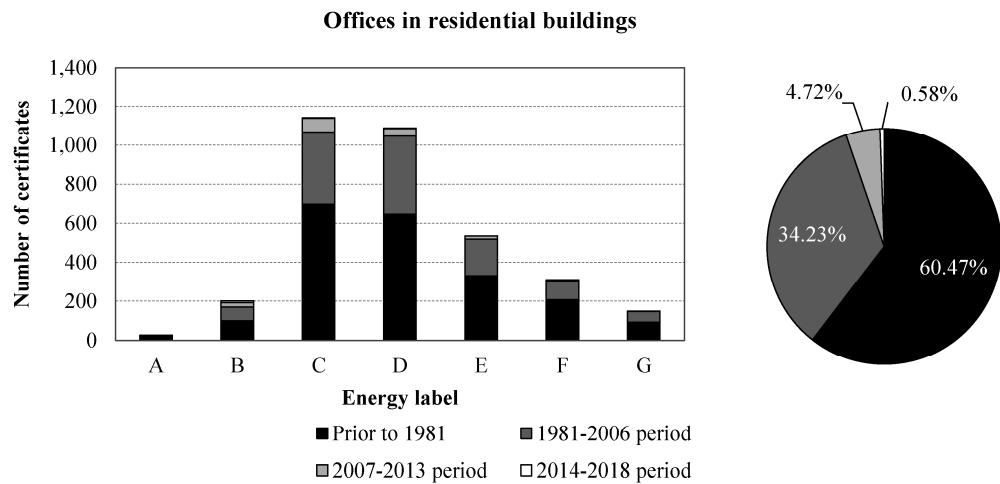


Figure 10. On the left, energy label of offices in residential buildings by construction period. On the right, share of energy performance certificates for offices in residential buildings according to construction period. Source: drawn up by the authors using data from the ICAEN database, July 2018.

The newest offices have clearly benefited from LED lighting (Figure 11). Offices built before 2014 are also expected to undergo progressive lighting renovation that will for sure result in a decreased energy consumption.

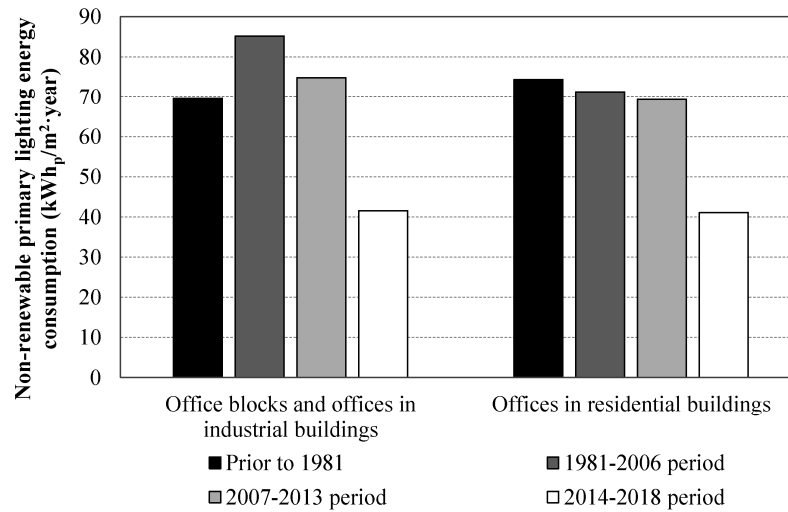


Figure 11. Average calculated non-renewable primary lighting energy consumption [$\text{kWh}_p/\text{m}^2\text{-year}$] by office type and construction year. Source: drawn up by the authors using data from the ICAEN database, July 2018.

4.3. Analysis by Climate Zone

Figures 12 and 13 show the average calculated non-renewable primary heating and cooling energy consumption by office type and climate zone. Focusing on the energy used for heating purposes (Figure 12), the coldest climate zones in winter (D and E) had the highest energy consumption. The lowest heating consumption was found in the warmest climate zones in winter (B and C). The largest difference between the mean energy consumption of an office in the coldest zone and one located in the warmest zone was found to be 39.78%. However, no significant trends could be observed in an analysis of the energy used for cooling and the hottest climate zones in summer (climate zones 2 and 3) (Figure 13). In general, the distribution of the energy label was not found to change significantly by climate zone.

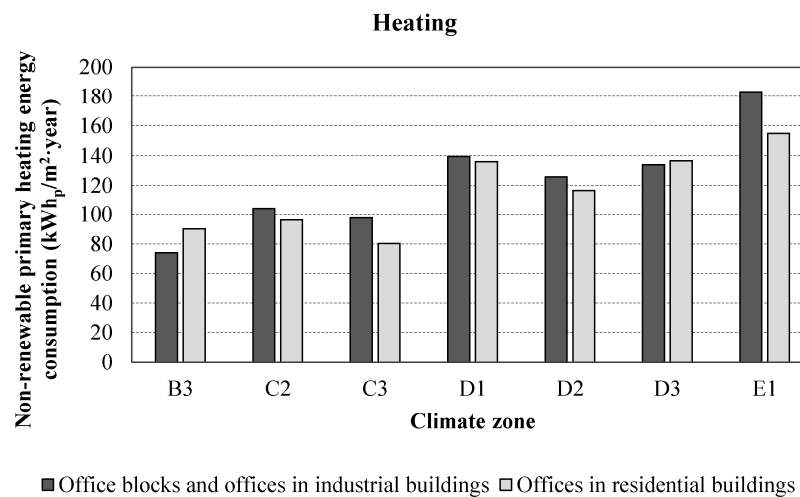


Figure 12. Average calculated non-renewable primary heating energy consumption [$\text{kWh}_p/\text{m}^2\text{-year}$] according to office type and climate zone. Source: drawn up by the authors using data from the ICAEN database, July 2018.

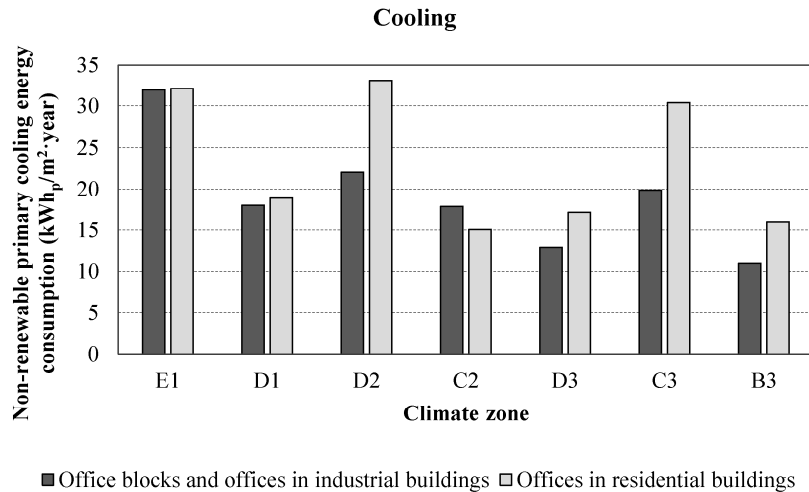


Figure 13. Average calculated non-renewable primary cooling energy consumption [kWh_p/m²-year] according to office type and climate zone. Source: drawn up by the authors using data from the ICAEN database, July 2018.

Figure 14 provides a closer look at the impact of construction period and climate zone on modelled energy consumption in the most populated climate zones (C2, D2 and C3), which represent 92.58% of the analyzed offices. For example, in climate zone C2, the average calculated non-renewable primary energy consumption ranges from 232.68 kWh_p/m²-year (office blocks built between 1981 and 2006) to 94.39 kWh_p/m²-year (office blocks built between 2014 and 2018). New offices have significantly lower energy consumption for all office categories in all climate zones. Results for offices in residential buildings of the D2 climate zone built in the 2014–2018 period and offices of the C3 climate zone built in the 2007–2013 and 2014–2018 periods were not plotted because the sample size (0 to 6 certificates depending on the combination) was not representative enough.

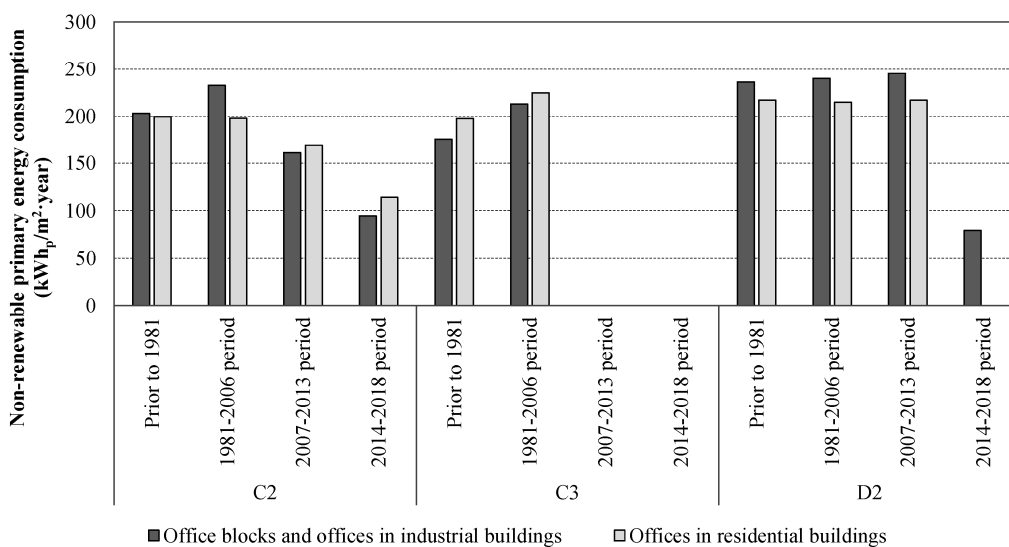


Figure 14. Average calculated non-renewable primary energy consumption [kWh_p/m²-year] by office type, construction period and climate zone. Source: drawn up by the authors using data from the ICAEN database, July 2018.

4.4. Analysis by Energy Use

The predicted renewable energy contribution under the assumptions of the model was found to range between 28.20% (offices in residential buildings) and 40.20% (office blocks and offices in industrial buildings) (Figure 15). As expected, modern offices had a higher penetration rate of renewable energy sources (Table 14). Data for offices in residential buildings built within the 2014–2018 period are not shown because of the small sample size (20 energy performance certificates).

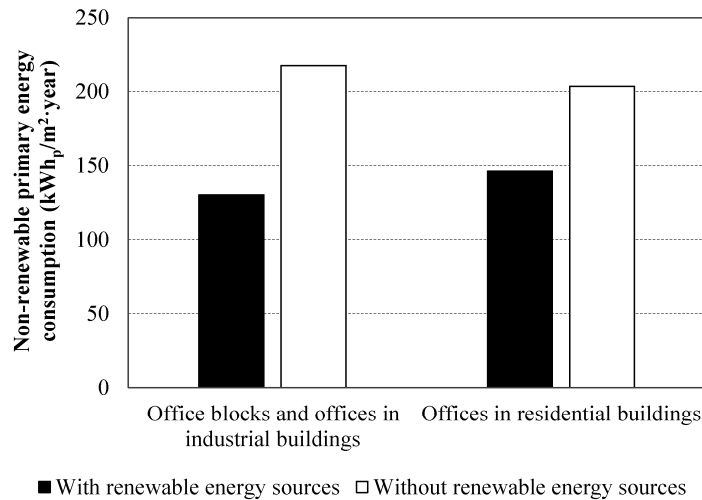


Figure 15. Average calculated non-renewable primary energy consumption [kWh_p/m²·year] by office type and existence of renewable energy. Source: drawn up by the authors using data from the ICAEN database, July 2018.

Table 14. Percentage of energy performance certificates including renewable energy by office type and construction period. Source: drawn up by the authors using data from the ICAEN database, July 2018.

Office Type	Construction Year				Total
	Prior to 1981	1981–2006 period	2007–2013 period	2014–2018 period	
Office blocks and offices in industrial buildings	1.70%	3.61%	15.91%	35.90%	100%
Offices in residential buildings	0.57%	0.68%	22.70%	-	100%
Total	0.74%	1.61%	20.32%	29.59%	100%

4.5. Analysis by Ownership and Motivation

Ownership did not significantly impact the predicted non-renewable primary energy consumption of offices (Figure 16). Regarding the motivation for obtaining an energy performance certificate, the analysis revealed that energy performance certificates for newly built offices were found to have a much lower average energy consumption than those issued for other reasons, as expected (Figure 17). Slight differences were found between offices for sale and offices for rent (Figure 17).

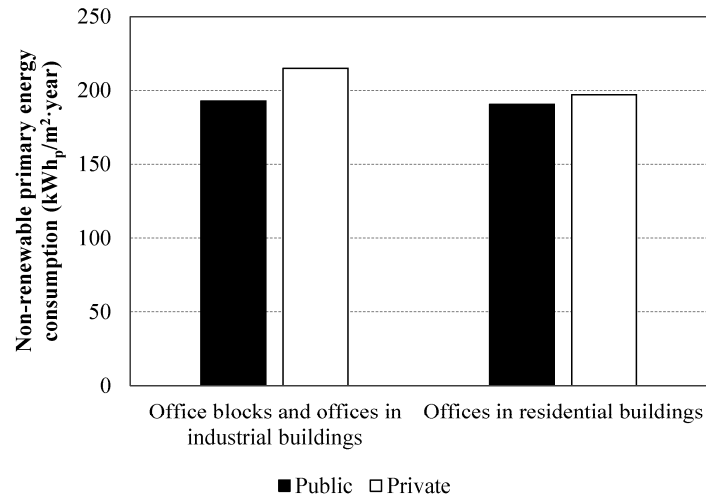


Figure 16. Average calculated non-renewable primary energy consumption [kWh_p/m²-year] according to office type and ownership. Source: drawn up by the authors using data from the ICAEN database, July 2018.

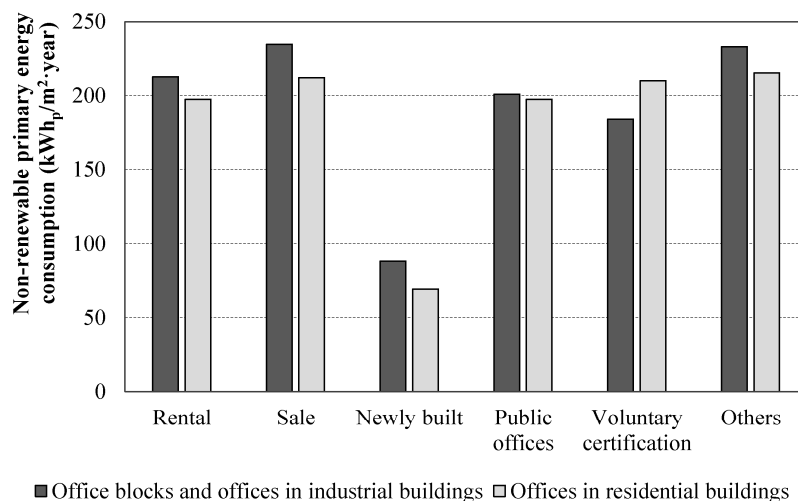


Figure 17. Average calculated non-renewable primary energy consumption [kWh_p/m²-year] according to office type and motivation. Source: drawn up by the authors using data from the ICAEN database, July 2018.

4.6. Analysis by Energy Certification Procedure

Although the calculation methodology should not determine the result, energy performance certificates drawn up using the general procedure were found to consume less energy than those produced with the simplified procedure (Figure 18). Energy performance certificates created using simplified procedures tend to rely on default values, which may overestimate energy consumption. In addition, general procedures are mostly used when new buildings are certified with lower energy consumption. However, this analysis should be corroborated with a larger sample of energy performance certificates drawn up using general procedures to ensure that the limited data population of energy performance certificates obtained using a general procedure (101 versus 4428 certificates) does not bias the results.

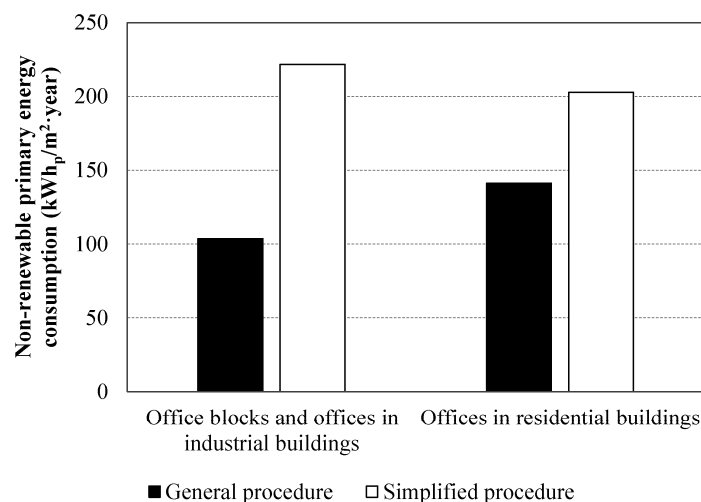


Figure 18. Average calculated non-renewable primary energy consumption [kWh_p/m²-year] according to office type and certification procedure. Source: drawn up by the authors using data from the ICAEN database, July 2018.

5. Discussion and Conclusions

The paper examines the energy performance of existing Spanish office stock through a statistical analysis of the energy performance certificate database. Similar studies have been performed and continue to emerge throughout Europe revealing a wealth of information [27], but few approaches have analysed office stock in depth.

In this study, the existing office stock was characterised using 13,701 energy performance certificates for offices, issued in Catalonia since 2013. After discarding energy performance certificates containing errors in energy consumption-related variables, modelled energy use was investigated using 4529 energy performance certificates for offices. Although the predicted energy consumption can differ from the actual energy consumption [56], studies based on calculated energy performance effectively avoid the variability introduced by occupancy, users' behavior, equipment and appliances. The average calculated primary non-renewable energy consumption of Spanish office blocks and offices in industrial buildings was 212.10 kWh_p/m²-year whilst offices in residential buildings consumed slightly less (202.66 kWh_p/m²-year). According to results reported by Gangoellis et al. [19] analysing the energy performance of both residential and tertiary sector buildings, it can be concluded that offices show a slightly better predicted energy performance than the average for tertiary sector buildings (317.8 kWh_p/m²-year). Offices consume slightly more energy than individual dwellings in multi-family blocks (183.2 kWh_p/m²-year) but less than single family houses (248.0 kWh_p/m²-year). Regardless of the office typology, the dominant energy classes were C and D (63.79%), followed closely by E, F and G (27.84%). Only 8.37% of offices were ranked in classes A or B. Under the assumptions of the model, most of the predicted energy was used for space heating (49.93%), followed by lighting (35.96%) and cooling (9.37%). Domestic hot water represented 4.75% of total predicted energy consumption. Electricity was the dominant energy carrier with a projected contribution of about 95.92%, varying from 93.09% in office blocks to 96.86% in offices in residential buildings. Natural gas was more commonly used in office blocks, with an average contribution of 3.49%, and less in offices in residential buildings (2.23%). Construction period and climatic conditions are key drivers of calculated energy consumption variation in offices. In general, old offices consume more energy and are mostly ranked in low energy classes. Although modelled energy consumption for space heating was found to correlate well with winter climatic severity, modelled energy consumption for office cooling does not depend on summer climatic severity. A small percentage of offices (2.22%) use renewable energy systems, but modern offices show a higher penetration rate than older ones. Whilst the analysis showed no impact of office ownership on average calculated

primary energy consumption, the motivation for obtaining an energy performance certificate was significant. Energy performance certificates produced with the general procedure showed lower energy consumption than those performed with the simplified procedure.

One of the biggest concerns is related to the reliability of energy performance certificates. In this case, 66.94% of energy performance certificates contained non-reasonable information. The implementation of consistency checks has certainly reduced the possibility of errors in energy performance certificates and thus has increased the reliability of results. Results obtained in this research revealed variables with abnormal values, which indicated the aspects that should be carefully checked and subsequently improved within the most common energy performance certification tools. In this case, when the entire dataset was examined, domestic hot water energy consumption was found to be extremely high for offices. Technicians using a simplified energy certification procedure tend to overestimate domestic hot water demand because they often use the hot water volume coefficient set for dwellings instead of that set for offices. According to the Spanish Technical Building Code [52], the hot water volume coefficient is 28 L/day per occupant for dwellings and 2 L/day per occupant for offices. In addition, energy for lighting is often underestimated because technicians do not define the lighting system in the energy certification software. This is again a misunderstanding related to the energy certification procedure set for the residential domain. Energy performance certificates for dwellings do not cover energy for lighting, but this is not the case for energy performance certification of small and large tertiary sector buildings, which must always include lighting energy consumption.

Despite the limitations, the study contributes to energy benchmarking of the national office stock and therefore represents a good starting point for the long-term renovation strategies planned in the new Energy Performance Building Directive [6]. Energy performance certificate databases provide a unique opportunity for systematic, longitudinal, long-term monitoring of the building stock, particularly within the context of national roadmaps and corresponding measurable progress indicators.

Author Contributions: Conceptualization, Marta Gangolells, Miquel Casals and Núria Forcada; Data curation, Jaume Ferré-Bigorra and Marcel Macarulla; Formal analysis, Jaume Ferré-Bigorra, Marcel Macarulla, Kàtia Gaspar and Blanca Tejedor; Funding acquisition, Marta Gangolells and Miquel Casals; Methodology, Marta Gangolells and Núria Forcada; Project administration, Marta Gangolells and Miquel Casals; Resources, Marta Gangolells and Miquel Casals; Supervision, Marta Gangolells and Miquel Casals; Validation, Marcel Macarulla; Visualization, Blanca Tejedor; Writing – original draft, Marta Gangolells, Jaume Ferré-Bigorra and Kàtia Gaspar; Writing – review & editing, Marta Gangolells, Miquel Casals and Núria Forcada.

Funding: This research was funded by the Spanish Ministry of Economy, Industry and Competitiveness under R&D project EOFF, reference no. BIA2016-75382-R (AEI/FEDER, UE).

Acknowledgments: The Catalan Institute of Energy (ICAEN) is gratefully acknowledged for allowing access to the energy performance certificate database.

Conflicts of Interest: The authors declare no conflict of interest.

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