Energy Use Intensities for Asset Rating of Hellenic Non-Residential Buildings

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Abstract: This work present the results from an in-depth analysis of data from about 120,000 energy performance certificates in order to gain a better understanding of the energy use and carbon emissions of non-residential (NR) buildings in Greece. The analysis is performed for all different building uses, construction periods and Hellenic climate zones. This is a first step for generating new knowledge about the NR building stock in Greece and deriving compatible energy asset metrics that can be used for assessing NR buildings independent from their operation and occupancy. The mean (median in parenthesis) primary energy use intensity is 539.5 (442.6) kWh/m^2 and emissions reach 170.0 (141.4) $kgCO_2/m^2$. The derived energy baselines reveal that indoor sports halls/swimming pools are the most energy intensive facilities, while schools have the lowest energy use, due to their operational patterns. Lighting is the most energy consuming service, followed by cooling, space heating and a very low domestic hot water use.

Keywords: Non-residential buildings, energy performance certificates, baselines, primary energy use, CO_2 emissions, energy use intensity, EUI.

1. INTRODUCTION

Europe has for a long time recognized the importance of the building sector in achieving its near- and long-term energy savings targets and supporting its key energy policies, and has committed itself to high performance buildings. The European Directive on the energy performance of buildings (EPBD 2002/91/EC and its recast 2010/31/EC) is driving the national efforts in all European Union (EU) Member States for lowering energy use in new and existing buildings. It is estimated that there are 25 billion m^2 of useful floor space, with non-residential (NR) buildings accounting for 25% of the total European building stock [1]. The NR buildings comprise a more complex and heterogeneous sector compared to the residential sector. The NR building categories are dominated by retail and wholesale buildings representing 28% of the NR building stock floor area [1], followed by office buildings (23%), education (17%), hotels and restaurants (17%), hospitals (7%), sports facilities (4%) and buildings with other uses (11%).

According to the latest officially reported data, the total final energy use in the NR building sector reached 146.9 million tonnes of oil equivalent (Mtoe) in 2015 [2]. Overall, the available data for the NR building stock is far less comprehensive than similar databases for residential buildings, as a result of the difficulties in tracking the numerous NR building categories, the variations in usage pattern (operating hours) and the different construction practices [1]. As a result, the NR building sector lacks detailed and specific information on floor areas, construction characteristics, energy use breakdown for different services and other characteristic parameters. National studies and European surveys underline this gap of knowledge and the limited availability of comprehensive data that handicap the efforts to track the energy performance of NR buildings, develop appropriate databases [3-4] and facilitate building stock modeling [5].

The energy performance certificate (EPC) is one of the mandatory requirements imposed by EPBD, with hundreds of thousands of certificates for existing and new buildings being issued every year throughout Europe. As the EPC databases are progressively enriched with more data, studies have emerged that exploit this information to map the characteristics of NR buildings and gain a better insight on the energy performance metrics of NR buildings. For example, in Catalonia-Spain [6], in the UK [7-8] and in Greece [9] based on the first findings using a small number of NR buildings.

In this paper, the work exploits available information from the Hellenic EPC database in order to bridge the gap of knowledge on the existing NR building stock in Greece, and to derive practical baselines on the

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specific energy use for different building categories and services (e.g. heating, cooling, lighting). The results provide new insight for practically all NR building uses defined in Greece that may be used to facilitate building stock modeling. Section 2 sets the stage and highlights some relevant background information and results from previous studies, revealing the lack of related data in Greece. Section 3 outlines the method implemented in this research, the national calculation approach and details the contents of the available EPC database. The results are elaborated in section 4, documenting the specific primary energy use intensities (EUI_p), i.e. primary energy use per unit floor area (kWh/m^2) and CO_2 emissions ($kgCO_2/m^2$) for all NR building uses. Section 5 concludes with the main findings, highlighting the limitations and future work.

2. BACKGROUND

Comparing a building's energy use intensity to that of peer buildings can be a useful first measure of energy efficiency [10]. Benchmarks can also be used as self-reference over time to assess performance before and after the implementation of energy conservation measures. There are various ways to develop reference values or baselines for benchmarking the energy performance of NR buildings [11-15].

Relative energy use is usually expressed by the energy use intensity (EUI) that is defined as the building's annual energy use per unit floor area. This straightforward and easy to understand numeric metric is associated with a building's energy performance as a result of the building's characteristics. This is the most commonly used energy related key performance indicator for buildings [16].

The EUIs can be clustered for the different building:

- Uses that relate to the representative systems and equipment for different building services, and occupancy;
- Vintages that relate to construction periods with specific construction practices or landmark years that correspond to the introduction of new building energy codes or thermal insulation regulations; they are practically used in all clustering efforts in order to further relate with other data from building Census or national statistical surveys;
- Locations that relate to the prevailing weather conditions.

Actual (operational) energy use (e.g. measured or from energy bills) is inherently influenced by occupant behavior and actual operating conditions that may deviate from optimum and normative specifications, even at the expense of indoor environmental quality. As a result there may be significant variations of actual energy use among similar buildings (i.e. with the same use, services and location). To overcome these issues, a data envelopment analysis can be utilized for benchmarking building energy performance of existing buildings and account for the degree to which a building secures proper indoor conditions and satisfies occupants [17-20].

Calculated (asset) energy use metrics enable building owners and managers to evaluate the as-built physical characteristics of buildings and overall building energy efficiency, independent of occupancy and operational choices [21]. The energy asset baseline is generated by calculating the building performance under typical (or normative) operating and occupancy conditions. This way, one can focus only on buildings' physical characteristics and removing occupancy and operational variations, it is possible to compare "apples-to-apples" between differently operated buildings [21].

In this context, the present work considers the results of the calculated energy use intensities from the official EPCs issued for NR buildings in Greece. The available information is clustered to match the key determinants from other national data resources, i.e. building use, vintage and location, available from building Census or national statistical surveys. The results may then be use to populate the national building stock modeling efforts for NR buildings along the lines of similar work for residential buildings [22].

2.1. Energy Use in Non-Residential Buildings

The most detailed information on NR buildings is currently available from the United States (US). The main resource of building energy performance data is the Commercial Buildings Energy Consumption Survey (CBECS). It provides detailed information on energy-related building characteristics and actual EUIs based on a national sample survey on the US stock of about 6,700 commercial buildings (e.g. hotels and lodging, offices, restaurants, stores, warehouses) and other NR uses (e.g. schools, hospitals, correctional institutions) [23].

The publically available data is broken down by building size, vintage, principal building activity, region, climate zone and other building attributes. The latest CBECS survey was conducted in 2012. The mean total final energy use dropped from 287.0 kWh/m^2 in 2003 to 252.0 kWh/m^2 in 2012.

The CBECS data is the basis for many metrics, labels and policies for commercial buildings in the United States, including the Energy Star program (https://www.energystar.gov/buildings) that provides a benchmark to assess energy performance and identifies top performers with the Energy Star building label. In addition, the aggregated CBECS data provides the basis to calculate the rating for ASHRAE's building energy labeling program (http://buildingenergyquotient.org) and generate the building energy quotient (bEQ) label, with letter grade rating scale similar to the European EPCs. The bEQ In Operation rating is based on the building's metered energy use. Alternatively, the bEQ As Designed rating uses an energy model with standardized inputs as compared to a baseline EUI to evaluate a building's potential energy use independent of operational and occupancy variables.

ASHRAE has also developed standard benchmark energy use intensities that presents the calculated EUIs for 16 different commercial buildings (which represent ~70% of the US commercial buildings) and a range of climate zones for pre-1980 and post-1980 construction characteristics (http://cms.ashrae.biz/EUI). Benchmarks that are derived from actual (operational) energy use (calculated from CBECS) and expressed as EUI targets are also available for different US commercial building types and climate zones [24].

Over the past 20 years, the total final energy consumption in the European Union Member States (EU-28) has remained practically stable from 1082.8 Mtoe in 1995 to 1084.0 Mtoe in 2015 [25], of which 13.6% for NR buildings. The final energy consumption in NR buildings has boomed by 28.5%, from 114.3 Mtoe in 1995 to 146.9 Mtoe in 2015. For 2050, the projection is that the NR buildings sector will keep a stable share of about 17% of the total final energy use [26].

The total final energy use intensity in European NR buildings averages 280 kWh/m^2 (about 40% greater than the corresponding average value for the residential sector), while electricity use over the last 20 years has increased by 74% [1]. The variations of specific energy use for different NR building categories are significant, depending on the operational characteristics for the various building uses. Hospitals are at the top of the energy use scale at 252-434 kWh/m^2 due to the continuous occupancy, high-energy specific operations and space functions, but this represents only 10% of the total energy use in NR buildings. This is also the case for other energy intensive building uses like hotels & restaurants with 213-426 kWh/m^2 that represent 12% of the total energy use in the NR building sector. On the other hand, wholesale & retail trade buildings with 200-335 kWh/m^2 (or 28% of the total) and offices with 205-316 kWh/m^2 (or 26% of the total), represent more than half of the energy use in NR buildings. Education with 142-243 kWh/m^2 (12%), sports facilities with 110-255 kWh/m^2 (6%) and all other buildings at 6% makeup the remaining composition.

In-line with EPBD mandates, building energy audits and issuing EPCs have been well progressing throughout Europe when buildings are constructed, sold, or rented out. The available data constitutes a valuable resource for gaining an insight on the energy performance of existing buildings, revealing scarce information that can be used by policymakers to map and monitor national and European building stocks, assess real market needs and the potential for energy efficiency improvements in the building sector [27]. They are of great value especially in regions and countries where such data has been scarce or unavailable. Previous work has mainly focused on the residential sector [6, 28-33], since the implementation of European certification schemes were initiated in the residential sector and the number of issued EPCs in national databases was mainly populated with certificates for residential buildings and building units (apartments).

Studies for NR buildings are rather scarce. A notable effort in Sweden exploited 186,021 EPCs (of which 31.4% NR buildings) to derive baselines for actual energy use intensities for various building categories, construction periods and climate zones [34]. The certification scheme in Sweden is based on energy bills rather than normative calculations. Accordingly, the actual mean energy use is 151.0 kWh/m^2 in offices, 169.2 kWh/m^2 in health care, 171.8 kWh/m^2 in schools, 174.0 kWh/m^2 in sports facilities, 175.0 kWh/m^2 in hotels and restaurants. In Spain, a similar analysis using 10,673 EPCs disclosed that the calculated mean EUI_p for NR buildings is 317.8 kWh/m^2 [6]. Baselines are also provided for characteristic construction periods, climate zones and different services, but without any breakdown for different building categories.

2.2. Energy Performance of Buildings in Greece

Hellenic buildings accounted for 38.2% of the total final energy consumption [25] and reached 6.3 Mtoe in 2015, the year with the latest officially-reported data. The NR buildings sector consumed 1.87 Mtoe in 2015, but detailed breakdown information for the different building uses is limited to a few field and empirical studies [35-36].

Overall, the currently available data for NR buildings in Greece is very abstract. According to the most

Table 1: Assumptions and Default Values of the National Calculation Methodology for Assessing the Energy Performance of NR Buildings

Building Category*	Building Use	Operation Hours per day / Days per week / Months	Set point Temperature (°C) / Relative humidity (%)		Fresh air ($m^3/h/m^2$)	Annual DHW consumption	Annual artificial lighting (h)	Internal heat gains (W/m^2)	
			Winter	Summer				Occupants	Appliances
I.	BU1-Hotel (annual)	24 / 7 / 12	20 / 35	26 / 45	3.00	21.90 - 36.50 (m^3/bed)	6989	11	1.5
	BU2-Hotel (summer)	24 / 7 / 7 (Apr-Oct)	20 / 35	26 / 45	3.00	12.74 - 21.23 (m^3/bed)	4077	6.38	0.87
	BU3-Guest house (annual)	24 / 7 / 12	20 / 35	26 / 45	3.00	21.90 (m^3/bed)	6989	11	1.5
	BU4-Guest house (summer)	24 / 7 / 7 (Apr-Oct)	20 / 35	26 / 45	3.00	12.74 (m^3/bed)	4077	6.38	0.87
	BU5-Guest house (winter)	24 / 7 / 8 (Sep-Apr)	20 / 35	26 / 45	3.00	14.56 (m^3/bed)	4659	7.26	1.32
	BU6-Boarding school / Quarters / Dormitory	24 / 7 / 12	20 / 40	26 / 45	1.50	18.25 (m^3/bed)	6989	8	2
II.	BU7-Restaurant	12 / 7 / 12	20 / 35	26 / 50	17.50	2.04 (m^3/m^2)	4368	26.5	5
	BU8-Pastry / Coffee shop	15 / 7 / 12	20 / 35	26 / 50	20.00	0.58 (m^3/m^2)	5460	37.2	6.2
	BU9-Night / Music hall	6 / 4 / 12	20 / 35	26 / 50	45.00	0.62 (m^3/m^2)	1248	10.5	1.05
	BU10-Theater / Cinema	7 / 7 / 12	20 / 35	26 / 50	25.00	-	2548	21.75	0.348
	BU11-Exhibition hall / Museum	6 / 7 / 12	20 / 35	23 / 50	10.00	-	2184	11.25	0.3
	BU12-Conference hall / Auditorium / Courthouse	6 / 5 / 12	20 / 35	26 / 45	27.50	-	1560	14.94	0.108
	BU13-Bank	8 / 5 / 12	20 / 35	26 / 45	6.00	-	2080	3.6	0.144
	BU14-Multi purpose venue	14 / 3 / 12	20 / 35	26 / 50	22.50	-	2184	15	0.25
	BU15-Sports hall / Swimming Pool	14 / 7 / 12	18 / 35	25 / 45	33.75	3.29 (m^3/m^2)	5096	52.2	0.58
III.	BU16-Kindergarten	8 / 5 / 8 (Oct-May)	20 / 35	26 / 45	11.00	-	1387	6.4	0.12
	BU17-Primary / Secondary School	8 / 5 / 9 (Sep-May)	20 / 35	26 / 45	11.00	-	1560	7.2	0.135
	BU18-University / College / Lecture rooms	13 / 5 / 10 (Sep-Jun)	20 / 35	26 / 45	11.00	-	2817	12.8	0.24
	BU19-Private cram school / Conservatory	7 / 5 / 9 (Sep-May)	20 / 35	26 / 45	12.10	-	1365	7.04	0.12
IV.	BU20-Hospital/ Clinic	24 / 7 / 12	22 / 35	26 / 50	10.50	22.00 – 43.90 (m^3/bed)	7571	27	7.5
	BU21-Health care / Rural outpatient clinic / Consultation room	12 / 5 / 12	22 / 35	26 / 50	7.50	0.20 (m^3/m^2)	3120	5.04	2.7
	BU22-Foundling hospital / Nursing home / Asylum	24 / 7 / 12	22 / 40	26 / 45	3.75	18.25 (m^3/bed)	7571	12	5
	BU23-Nursery	8 / 5 / 11	20 / 40	26 / 45	11.25	0.30 (m^3/m^2)	1907	5.06	0.99
V.	BU24-Police station	24 / 7 / 12	20 / 35	26 / 45	3.00	-	5824	8	3
VI.	BU25-Shopping mall / Large retail building	12 / 6 / 12	19 / 35	25 / 45	6.60	-	3744	11.61	1.075
	BU26-Small retail building / Drugstore	9 / 6 / 12	20 / 35	26 / 45	3.08	-	2808	4.16	0.64
	BU27-Fitness center	12 / 6 / 12	20 / 35	26 / 45	6.75	4.68 (m^3/m^2)	3744	6.02	2.58
	BU28-Barber shop / Hair salon	12 / 6 / 12	20 / 35	26 / 45	4.50	0.70 (m^3/m^2)	3744	6.02	2.58
VII	BU29-Office	10 / 5 / 12	20 / 35	26 / 45	3.00	-	2600	2.4	1.35
	BU30-Library	6 / 5 / 12	20 / 35	26 / 45	6.60	-	1560	3.06	0.09

*Building categories: I. Temporal Residence; II. Public assembly; III. Educational; IV. Health and Social Welfare; V. Justice/public order/safety; VI. Commercial; VII. Office/Library.

recent buildings Census in Greece [37], there are about 785,500 exclusive-use NR buildings (Table **1**) that represent 21% of the Hellenic building stock, with a total floor area of about 159 million m². The majority are educational buildings (33.4%), followed by wholesale and retail trade (22.1%), offices (20.0%), hotels & restaurants (19.9%), sport facilities (3.0%), hospitals (1.5%), and other building uses [3]. About 8% of the Hellenic building stock has a mixed-use (329,790 buildings) of which about 22.5% are buildings with NR main use.

About 58% of the Hellenic buildings were built before 1980 [37], the year that marks enforcement of the first Hellenic thermal insulation regulation (HBTIR). As a result, the majority of the Hellenic buildings have no thermal protection and they are equipped with old and inefficient heat generation systems, thus exhibiting the greatest potential for energy savings [38].

2.2.1. The Hellenic EPC

The EPBD (2002/91/EC) transposition in Greece was fully implemented in 2010 by the national regulation on the energy performance of buildings – KENAK, introducing more strict thermal insulation requirements than the first Hellenic regulation (HBTIR) introduced in 1980 and system efficiency standards for the first time. The regulation is supported by a series of four technical guidelines that govern its practical implementation. The EPBD recast (2010/31/EC) was introduced by a national law (N.4122/2013) that simply covers the general regulatory framework and provisions [39]. The inspections of heating and air-conditioning systems are still struggling for full-scale implementation, while the results from the recently completed cost-optimal study were used to define more stringent new building requirements and update KENAK in July 2017.

The EPC is compulsory for all buildings over 50 m^2 that are being sold and for whole-buildings with the same exclusive-use (e.g. stand-alone office buildings) that are being rented out for the first time to a new tenant as of January 2011. An EPC is also issued for a part-building (e.g. an individually owned part of a building that has specific use like an independent office within a multi-floor residential apartment building) or a building unit (e.g. an apartment in a residential multi-family building) that is being rented out for the first time to a new tenant as of January 2012. A qualified energy inspector performs the building energy audit to collect all relevant data and perform the analysis. All the input and output data are stored in an electronic repository (buildingcert).

The two-page certificate [40] includes data collected during the building energy audit, e.g. building use, vintage (based on the construction period), address and location (in terms of the four national climate zones of the country), and the total and heated areas. A summary of the calculated data provides the energy class ranking, annual calculated and actual (if available) final and primary energy use, CO_2 emissions, an optional evaluation of indoor environmental quality, and a breakdown of energy carriers and different services. The certificate also includes up to three cost effective recommendations for improving the building's energy performance with calculated energy savings and payback period.

According to the Hellenic labelling scheme, a building is ranked in one out of nine energy classes ranging from class-G (lowest performance) up to class-A+ (highest performance) according to the ratio of its calculated primary energy use (asset rating) over that of the corresponding reference building. The reference building is a carbon copy of the real (audited) building, with the characteristics of its envelope and systems automatically adapted to meet the minimum requirements defined in the national regulation, e.g. U-values, system efficiencies etc. The reference building is a ‘‘good’’ building, i.e. by definition an energy class-B building. All other building classes for labelling a building are defined as a percentage of the reference building's primary energy use.

The normative calculations are performed using the official national software (TEE-KENAK) that was developed by the National Observatory of Athens for the Technical Chamber of Greece (TEE), to support the implementation of the national regulation on the energy performance of buildings (KENAK) and issue EPCs [40]. The tool is in accordance to the European standards and the calculation engine for estimating the building's energy demand uses the quasi-steady state monthly method. The software incorporates the relevant national technical libraries, weather data and other technical specifications outlined in four supporting technical guidelines.

3. METHODOLOGY

This work is based on data from the national EPC electronic repository (buildingcert). According to the national technical guidelines for KENAK, a total of 60 different building types are defined, which are grouped into 7 building categories (I-VII) and 30 building uses (Table **1**) that have common assumptions and default values. To facilitate the following analysis, the available data are clustered and analysed in two main subgroups, namely whole-buildings (i.e. stand-alone buildings with the same exclusive-use) and part-building (i.e. individual unit of a whole-building, with a specific non-residential use).

Inherent to the overall national approach are several default values that are used in the normative calculations. They are summarized in Table **1** for the different NR building uses according to the national methodology and technical guidelines. These default values minimize the uncertainties of model variants and reduce the complexity of the model calculations. The space heating period depends on location (i.e. defined in terms of the four national climate zones; from November to mid-April for climate zones A and B, and from mid-October to mid-April for climate zones C and D). The space cooling period is from mid-May to mid-September for climate zones A and B, and from June to August for climate zones C and D. The annual domestic hot water (DHW) demand is given either on m^3 per bed or per heated floor area, while the mean hot water temperature is set at 45^{o}C. For some building uses the DHW is considered negligible (e.g. BU17-Primary / Secondary School). The minimum fresh air requirements are covered only by mechanical ventilation, since natural ventilation is not taken into account. The infiltration rate from openings ranges between 4.8-15.1 $m^3/h/m^2$ of the opening, depending on the type of the opening, glazing and frame. Infiltration rate from chimneys and exhaust grilles is assumed constant at 20 m^3/h and 10 m^3/h, respectively.

For example, referring to Table **1**, under building category I – Temporal residence, the first building use (BU1) refers to hotels with annual operation that has continuous usage patterns (i.e. 24 h/day, 7 days per week for 12 months), space heating operating conditions at 20^{o}C and 35% relative humidity and for summer indoor conditions set at 26^{o}C and 45% relative humidity, fresh air requirements at 3 $m^3/h/m^2$ heated floor area, DHW consumption at 21.9 to 36.5 m^3/bed depending on the hotel class, annual operating hours for artificial lighting at 6989 hours, internal heat gains from occupants at 11 W/m^2 heated floor area and appliances at 11 W/m^2 (internal heat gains from lighting are calculated based on the installed power and the annual artificial lighting operating hours).

3.1. The Database

This work is based on data from the official Hellenic EPC database. Since January 2011, a total of about 960,000 EPCs have been issued by the end of 2016, out of which 17% are for NR buildings (whole- or part-buildings). The relevant information retrieved from the EPCs include the building's general characteristics (i.e. building use, construction period (age), climate zone, total and heated area), as well as the calculated data (i.e. energy class ranking, primary energy use intensity, CO_2 emissions, energy carrier, recommended energy conservation measures, energy savings and payback period).

The overall approach for organizing and analyzing the available data for the different NR building categories and the corresponding building uses is based on two additional classification parameters, along the lines of the Hellenic TABULA residential typology [41], i.e. the building:

- Vintage, based on the year of building construction; the T1 (pre-1980) band refers to a time period that buildings are considered not thermally insulated, since they were constructed before the introduction of HBTIR (i.e. the 1980 national energy code); the T2 (1981-2000) band includes buildings that are partly thermally insulated in compliance with HBTIR, followed by T3 (2001-2010) that are fully insulated according to the first code; the T4 (post-2010) is the last band that refers to the KENAK era and buildings that are constructed or refurbished according to the more strict requirements and are expected to have a higher performance.
- Location, in terms of the four climate zones defined by KENAK on the basis of the heating degree days (Figure **1**), i.e. zone A in the south that includes most of the Hellenic islands with mild conditions (with a mean of 2502 cooling degree hours - CDH), to zone D in the north with the coldest conditions (with a mean 2260 heating degree days - HDD).

3.2. Quality Control

The quality of data from EPCs depends on several parameters, including the qualifications of the inspectors [42], the methodological framework and software tools, to the building energy audit process for the collection of input data, etc. As a result, there is a

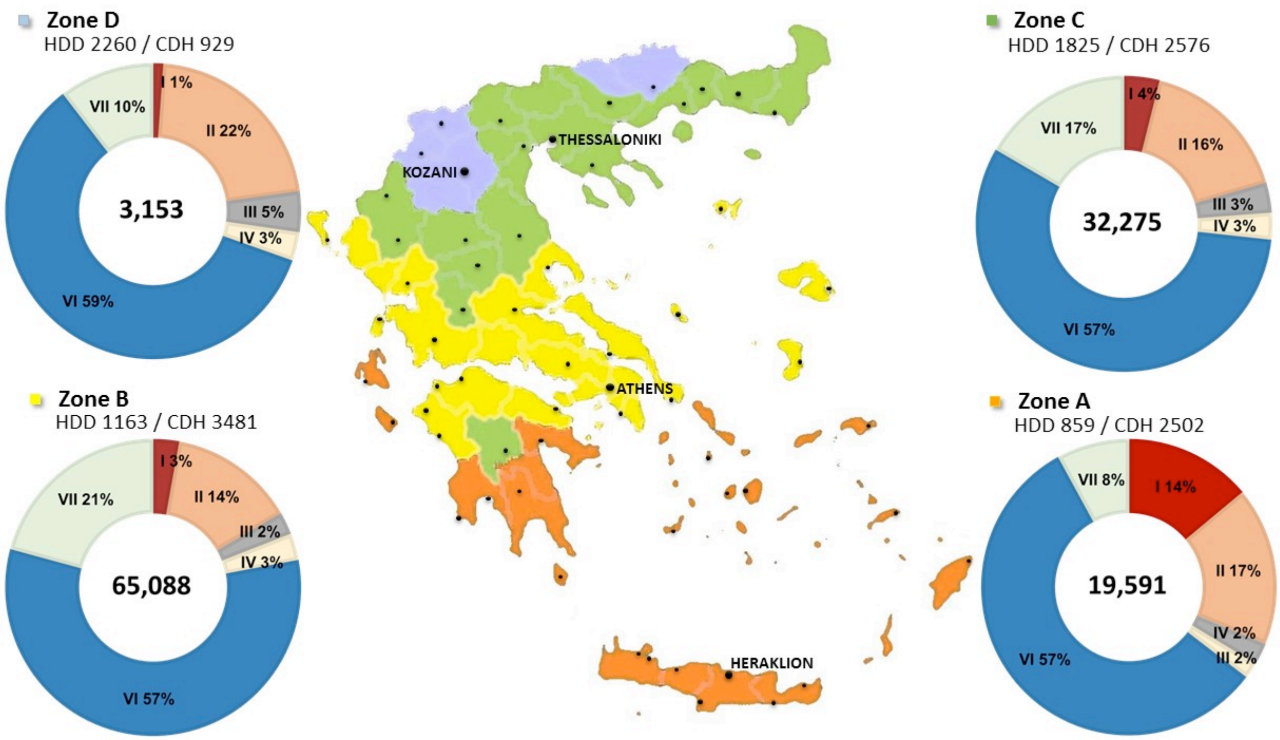


Figure 1: Map of Greece with the four climate zones and the corresponding mean values for Heating Degree Days (HDD) and Cooling Degree Hours (CDH). The doughnut charts illustrate the percentage breakdown of the NR building stock per building category (I-VII, identified in Table **1**) in each of the four climate zones (A-D). The corresponding total number of the audited buildings in the available EPC data set is presented in the center of each chart. The bullets on the map indicate the cities (locations) of the audited buildings.

variability of EPC credibility and usefulness among the EU Member States [27]. In Greece, the task of EPC quality control is centrally undertaken by the authority having jurisdiction, i.e. the Hellenic Ministry of Environment & Energy. They carry out checks on specific criteria and random samples to ensure the consistency and reliability of the EPC records, enforce penalties on the experts that issue problematic certificates, etc.

At the time of this study, a total of about 160,000 certificates for NR buildings were available from the national EPC repository. As a first step, the available certificates were screened in order to increase confidence on the data that was used for the analysis. EPCs were excluded in order to:

- Increase data confidence, if they were issued by energy inspectors that have been at a later date penalized and their temporary license revoked, as a result of the routine independent quality control process implemented by an executive agency of the Ministry that is responsible for the central EPC repository; incomplete (i.e. missing some data entries) or not officially submitted (i.e. temporarily entered and stored data in the EPC repository); including questionable data (e.g. negative input values, heated area greater than total area, zero CO_2 emissions (when the energy carrier is not biomass), possible erroneous data or outliers of extreme values (i.e. EUI_p less than 5 kWh/m^2 and greater than 8000 kWh/m^2), and cases with heated floor areas less than 20% of the total building floor area.
- Ensure compliance, if they were issued for buildings deviating from the national regulation requirements (i.e. buildings with uses that are not required to issue an EPC, buildings with total floor area smaller than 50 m^2 issued before the end of 2015, building uses for which the normative calculations specify no DHW consumption as shown in Table **1**);
- Avoid data duplication, if they were issued for the same building during the second phase of the national energy efficiency subsidy programme following the renovation of existing buildings.

Screening the available data was a learning process and some of the criteria evolved at different stages of the work in an effort to reveal and flag possible user errors, discrepancies or other deviations from the national regulation requirements. These certificates were progressively removed from the database. Apparently the number of cases that fail to pass a specific criterion and removed from the database, will change depending on the sequence of their implementation. The indicative results that follow provide some relevant insight. For example, the process for screening out the EPCs issued by penalized energy inspectors, certificates with missing data or not officially submitted and the ones that included negative input values, excluded a total of 4,120 cases or about 2.55% of the initially available data. The screening process on certificates that deviated from the national regulation requirements (e.g. issued for buildings with a total floor area smaller than 50 m^2 before the end of 2015), cases with unrealistic heated floor areas (e.g. greater than or less than 20% of the total building floor area, cases with zero CO_2 emissions and outliers of extreme values, excluded a total of 1,728 EPCs or about 1.10% of the remaining database. The final screening stage excluded a total of 9,650 EPCs or about 6.19% of the remaining database that were issued for the same building following a building renovation and the certificates that included DHW consumption for those building uses that deviate from the national regulation requirements. At the end, the remaining database included 120,122 EPCs.

Furthermore, in order to identify and possibly exclude extreme values from the database that may bias the results, an effort was made to check data that deviate from certain limits. For example, for the heated floor area of the audited buildings, the statistical method of truncated samples [43] was used to process the valid data. For the different building uses and for whole- and part-buildings with over 40 cases, the analysis was performed to 95% of the valid data trimming 2.5% of the upper and lower values, as well as to the 97.5% of the valid data cutting off only 2.5% of the lower values. Defining the mean EUI_p (total and for each specific service, i.e. heating, cooling, DHW, lighting) and CO_2 emissions in each of these three cases (100%, 97.5% and 95% of the valid data), the results indicated no significant differences in these values. Accordingly, it was decided to maintain, as much as possible, a large pool of data covering all building uses and thus it was decided to use the entire validated database. This way, there is no discrimination between truncated and not data, depending on the number of cases.

The resulting valid data set for NR buildings used in this work reached about 120,000 EPCs or ~75% of the initial database. The breakdown for the different building categories at the four climate zones is illustrated in Figure **1**. The locations of the audited buildings that appear on the map identify the main cities with available weather data that were used for the EPC calculations. The majority of the available data (65,088 or ~54% of the total) originate from EPCs issued in climate zone B that includes Athens, which is the largest metropolitan region of Greece. In all cases, the commercial buildings (category VI) dominate the available data (57% to 59%). On the contrary, Justice/public order/safety buildings (category V) have the lowest percentages in all zones (0.01% to 0.05%) and for simplicity they are not included in Figure **1**. Under category I (hotels) the highest concentration occurs in zone A that includes most of the Hellenic islands, which is in agreement with the building Census data [37].

3.3. Energy Use and Emissions

Various metrics may be easily associated with a building's energy performance (i.e. lower or higher energy use) as a result of the building's characteristics, e.g. building materials that relate to different construction periods, weather conditions depending on location, etc. One of the most common energy performance indicators that is also included on the EPCs is the calculated (or actual, if available from utilities) final energy use. The final energy is used at the site of a building (also known as site energy), includes the energy supplied to the technical systems of a building through the system boundary to cover all different services. The primary energy, i.e. the source energy that has not been subjected to any conversion or transformation process (e.g. power plant), is used to produce the energy delivered to the building (e.g. electrical energy). In the normative calculations according to KENAK, the primary energy is estimated using the national conversion factors for different energy carriers, i.e. 2.9 for electricity, 1.1 for heating oil and 1.05 for natural gas. The carbon emissions are estimated using the following national conversion factors: 0.989 $kgCO_2/kWh$ for electricity, 0.264 $kgCO_2/kWh$ for heating oil and 0.196 $kgCO_2/kWh$ for natural gas. In this work, the results presented in section 5 are based on the calculated (asset) primary energy use intensity (EUI_p), i.e. primary energy use per unit floor area (kWh/m^2), for the different building categories and services (e.g. heating, cooling, lighting).

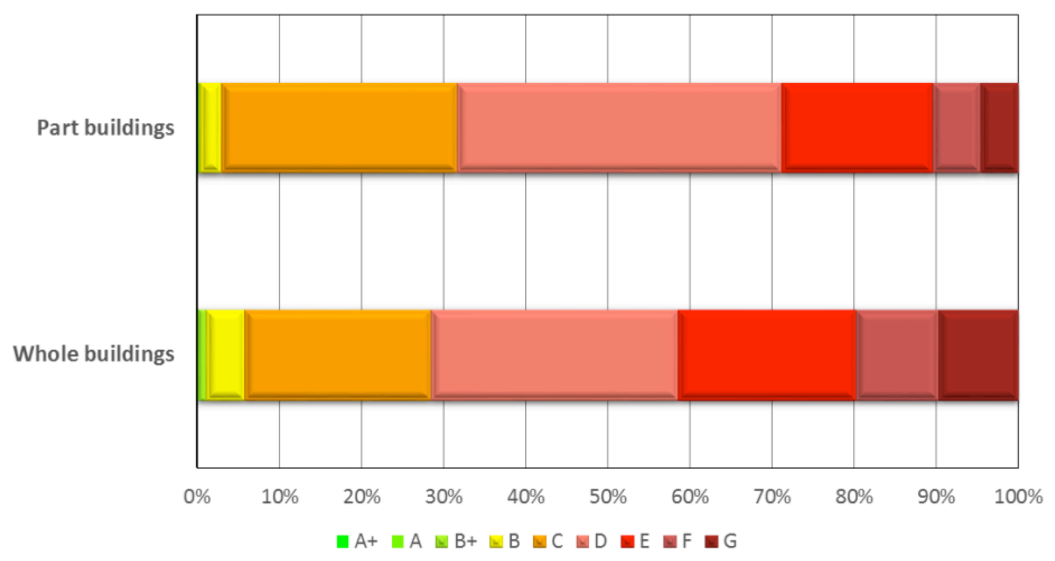


Figure 2: Distribution of energy classes for Hellenic NR buildings.

4. RESULTS

The vast majority of the NR buildings in the available data set are commercial (56%) and office buildings (18%) that are considered as the main NR building types. Most of them are old buildings, with 53% of them constructed pre-1980, 32% that belong to the second construction period of 1981-2010, while only 2% are new constructions (post-2010) corresponding to the KENAK era. This breakdown is in-line with the latest building Census and national statistical data [37]. The audited buildings are located in 61 different cities with an overall good spatial coverage in all four climate zones (Figure **1**). Specifically, 16% of the buildings are located in the southern Zone A (18% of which are in Heraklion), 54% in Zone B (69% of which are in metropolitan Athens), 27% in Zone C (50% of which are in Thessaloniki) and only 3% in the northern Zone D (48% of which are in Kozani).

Most of the EPCs (85%) were issued for part-buildings (Table **2**). This is common for specific building uses and properties that are most frequently rented or sold (e.g. BU29-Office) since for these transactions an EPC is issued according to the mandates of the EPBD and the national law. These may be small size properties that are usually part of whole-buildings (with the same exclusive-use) or part of mixed-use buildings (e.g. an independent office unit within a residential apartment building). For about 67% of the building uses, part-buildings dominate the number of analyzed data, ranging from 59% to 97%.

4.1. Energy Classes

The analysis of the available data from the EPCs confirmed the low energy performance of existing Hellenic buildings. Accordingly, about 85% are ranked at an energy class-C, D or E (Figure **2**), while only 12% is ranked in the lowest two energy classes (F and G). Comparatively, Hellenic residential buildings have a lower energy performance, since 51% are ranked in the last two energy classes (F and G), while only 3% are ranked in energy classes B or higher [33]. Similar results are reported in Spain [6] where NR buildings have a slightly better energy performance than residential buildings, with 26.4% of NR buildings rated at class-D, followed by class-E (22.8%) and class-C (19.8%).

4.2. Energy Use and Emissions

The calculated mean (median in parenthesis) annual primary energy use of NR buildings is 539.5 (442.6) kWh/m^2 for whole-buildings and 463.0 (391.9) kWh/m^2 for part-buildings (Table **2**). These are considerably higher than the mean of 261.6 kWh/m^2 for Hellenic residential buildings [33]. The variations of primary energy use can be significant given that some NR buildings have highly energy intensive use spaces (e.g. operating rooms and intensive care units in hospitals, or an indoor swimming pool and health spa in a hotel).

Buildings with the lowest primary energy use are the ones under category III – Educational buildings, i.e. BU16-Kindergarten, BU17-Primary/Secondary school and BU19-Private cram school/Conservatory, since

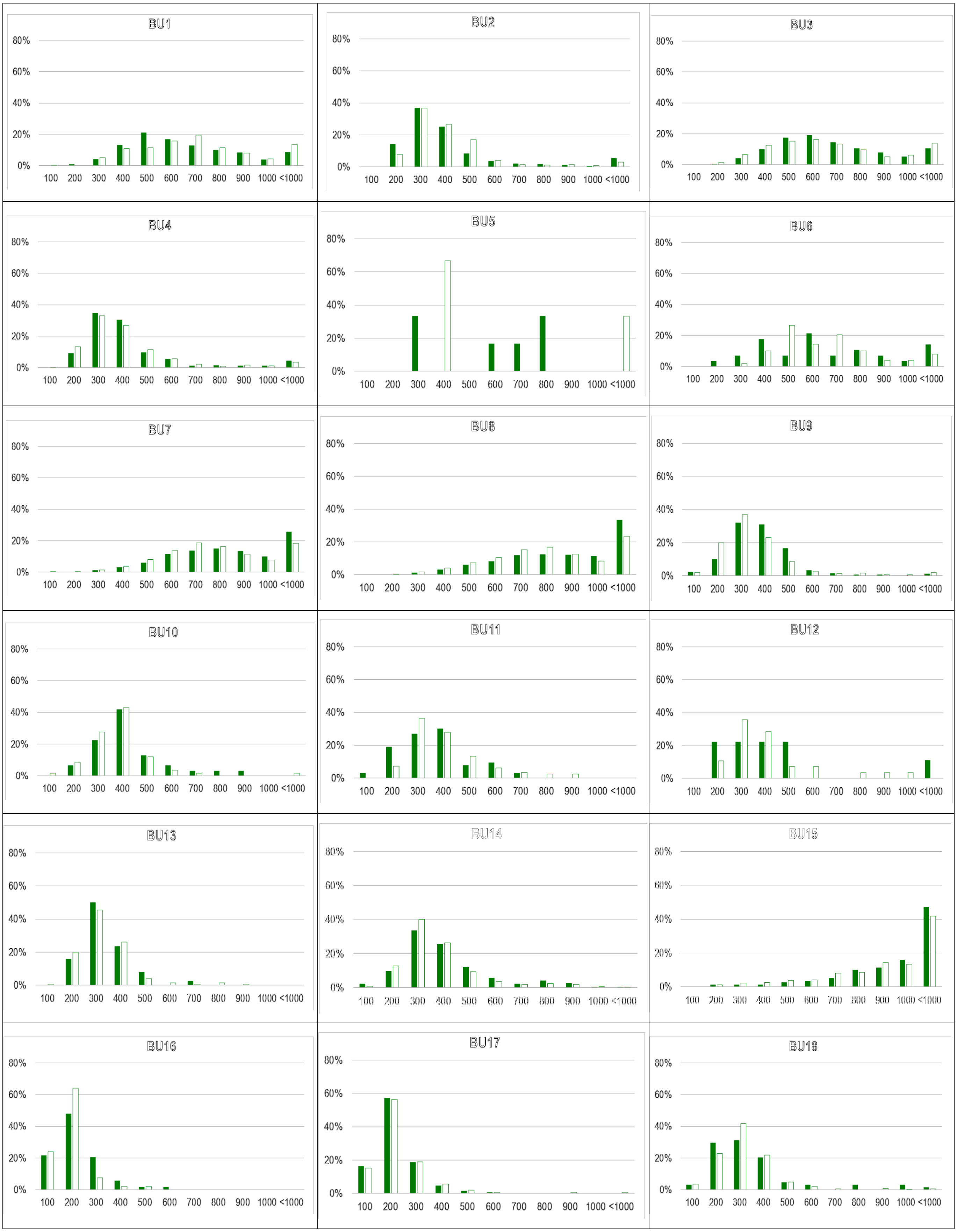
Table 2: Number of EPCs in the Data Set, Calculated Primary Energy for Real (Audited) and Reference Buildings (kWh/m^2) and CO_2 Emissions ($kgCO_2/m^2$) Per Building Use, for Whole- and Part-Buildings

Building Category*	Building Use	Whole-Buildings				Part-Buildings			
		Number of cases (EPCs)	Primary energy (kWh/m^2)		CO_2 emissions ($kgCO_2/m^2$)	Number of cases (EPCs)	Primary energy (kWh/m^2)		CO_2 emissions ($kgCO_2/m^2$)
			Real building	Reference building			Real building	Reference building	
I.	BU1-Hotel (annual)	541	650.8	369.6	205.1	237	717.5	376.7	224.1
	BU2-Hotel (summer)	1433	384.7	230.9	124.9	609	376.3	226.9	121.2
	BU3-Guest house (annual)	621	663.9	378.5	209.4	431	697.3	393.3	223.1
	BU4-Guest house (summer)	1291	383.1	219.6	123.3	813	375.1	221.1	121.7
	BU5-Guest house (winter)	6	554.3	302.4	167.1	3	690.1	200.1	138.5
	BU6-Boarding school / Quarters / Dormitory	28	691.2	380.9	205.7	49	640.0	347.4	200.5
II.	BU7-Restaurant	1857	848.5	499.8	263.5	4908	786.4	506.4	248.1
	BU8-Pastry / Coffee shop	1750	930.9	510.3	281.2	7393	833.7	503.8	263.2
	BU9-Night / Music hall	400	341.6	195.8	107.9	547	326.3	194.9	103.2
	BU10-Theater / Cinema	31	380.1	208.0	124.0	58	350.2	199.9	114.4
	BU11-Exhibition hall / Museum	63	312.0	173.3	101.8	82	355.0	197.1	116.9
	BU12-Conference hall / Auditorium / Courthouse	9	672.0	529.1	224.9	28	351.9	230.2	114.5
	BU13-Bank	38	281.0	189.5	92.3	200	281.9	202.6	94.4
	BU14-Multi purpose venue	172	362.2	199.4	116.9	499	328.4	206.4	107.1
	BU15-Sports hall / Swimming Pool	150	1028.3	677.3	322.4	475	953.6	618.5	309.9
III.	BU16-Kindergarten	106	179.3	96.2	50.5	92	147.2	78.5	42.3
	BU17-Primary / Secondary School	693	170.6	83.4	48.9	158	180.4	99.9	54.0
	BU18-University / College / Lecture rooms	64	336.8	188.8	110.5	302	274.0	185.6	89.8
	BU19-Private cram school / Conservatory	116	200.1	107.4	63.6	1602	183.7	108.6	57.8
IV.	BU20-Hospital/ Clinic	80	741.5	476.5	227.6	55	625.0	330.7	194.3
	BU21-Health care / Rural outpatient clinic / Consultation room	138	513.1	309.1	161.3	2614	430.3	287.3	138.7
	BU22-Foundling hospital / Nursing home / Asylum	72	736.4	435.7	224.6	29	758.1	390.0	241.2
	BU23-Nursery	199	272.9	172.4	85.2	167	249.1	160.4	77.1
V.	BU24-Police station	10	558.2	383.4	173.8	17	742.3	428.3	240.2
VI.	BU25-Shopping mall / Large retail building	282	397.0	244.1	131.2	728	461.5	247.2	151.6
	BU26-Small retail building / Drugstore	6580	504.5	243.7	161.4	58659	434.0	248.2	140.5
	BU27-Fitness center	33	692.3	402.9	218.4	596	711.8	410.7	230.0
	BU28-Barber shop / Hair salon	34	690.9	346.7	219.3	911	546.2	327.4	179.7
VII.	BU29-Office	1681	374.4	219.7	121.2	19333	346.5	215.8	112.9
	BU30-Library	13	310.5	173.4	94.2	21	310.2	166.5	97.6
Non Residential Buildings (Total means)		18491	539.5	294.1	170.0	101616	463.0	274.6	149.2

* Building categories: I. Temporal Residence; II. Public assembly; III. Educational; IV. Health and Social Welfare; V. Justice/public order/safety; VI. Commercial; VII. Office/Library.

they have low usage patterns (operating hours) and no special requirements for specific services. On the other hand, BU15-Indoor Sports Hall/Swimming pool, BU8-Pastry/Coffee shop and BU7-Restaurant have the highest primary energy use due to their large volumes, latent loads, internal heat gains and other unique operational characteristics.

The variation of the calculated primary energy use intensity (maximum, first quartile, median, third quartile, minimum and mean values) as well as the corresponding CO_2 emissions for the different building uses, are presented in Figure **3**. The data include the calculation results for the real (audited building) and the reference building used for ranking purposes in the


BU1
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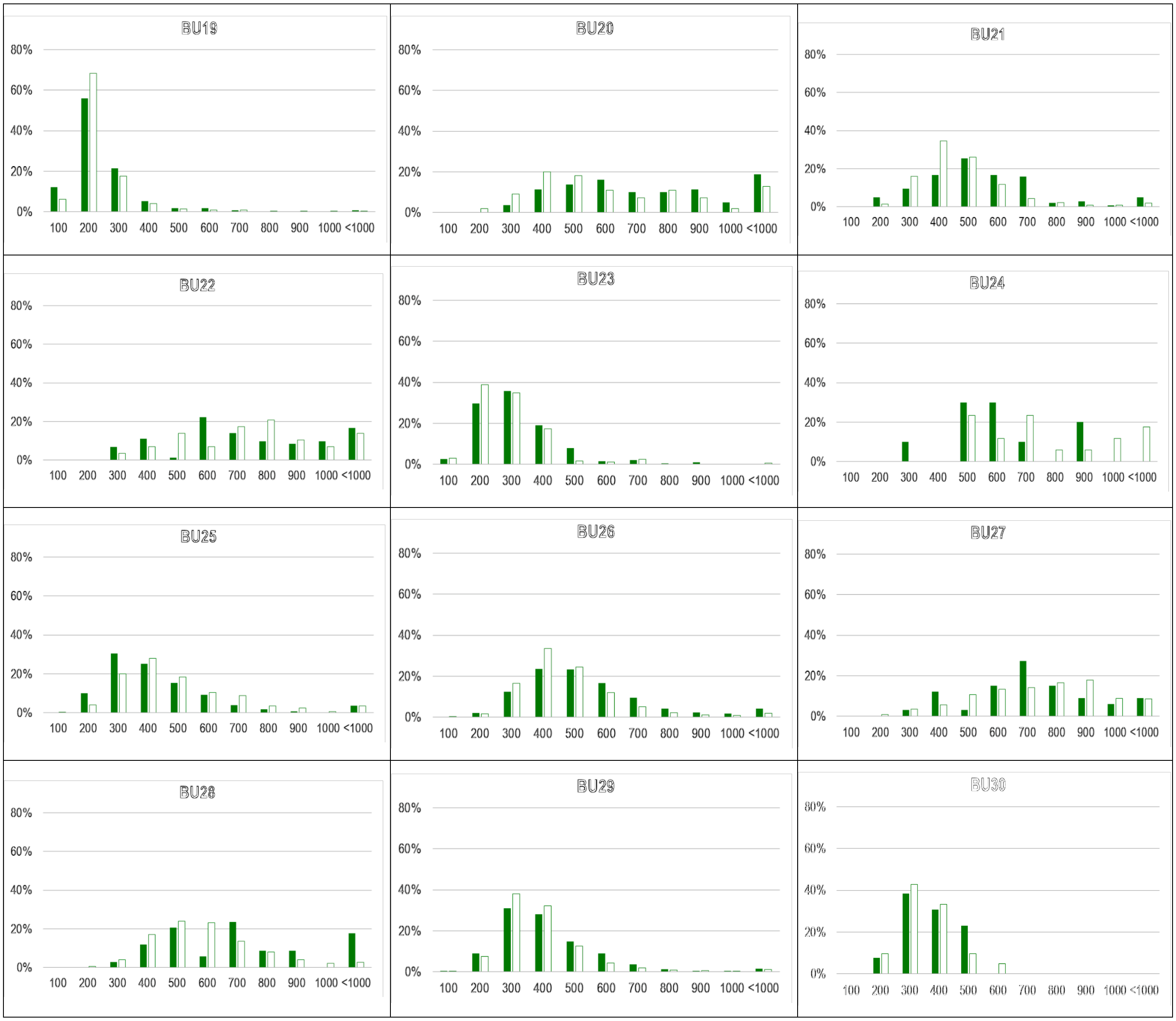

Figure 3: Calculated primary energy use intensity (kWh/m^2) box-and-whisker plots (maximum, first quartile, median, third quartile, minimum) and mean EUI_p (black dashes) per building use (BUs are defined in Tables **1** and **2**), for the real (R) and reference (Rf) buildings. The calculated mean CO_2 emissions (secondary axis, diamonds) correspond to real buildings.

normative calculations. The mean primary energy use of real buildings exceeds by 71% the corresponding value of the reference buildings, ranging from 41% in BU13-Bank to 123% in BU5-Guest house (winter).

The calculated mean EUI_p per building use ranges from 170.6 kWh/m^2 to 1028.3 kWh/m^2 for whole-buildings and from 147.2 kWh/m^2 to 953.6 kWh/m^2 for part-buildings. The mean CO_2 emissions range from 48.9 kgCO_2/m^2 to 322.4 kgCO_2/m^2 and from 42.3 kgCO_2/m^2 to 309.9 kgCO_2/m^2, respectively (Table **2**). The frequency distribution per building use of the calculated EUI_p for whole- and part-buildings is illustrated in Figure **4**. Although the EUI_p variations are significant, there is a good distribution for most building uses indicating that the available data set has acceptable overall characteristics. However, as shown in Figure **3**, some cases have left-skewed distributions, i.e. mean values are lower than medians. Caution should be exercised for building uses with extremely high EUIs (e.g. BU12 and BU15 as illustrated in Figure **4**) that shift the means away from the middle of the distribution.

The primary energy use is influenced by the building's vintage, decreasing from older buildings (e.g. not thermally insulated, with inefficient equipment) to newer ones (e.g. better thermal envelope protection

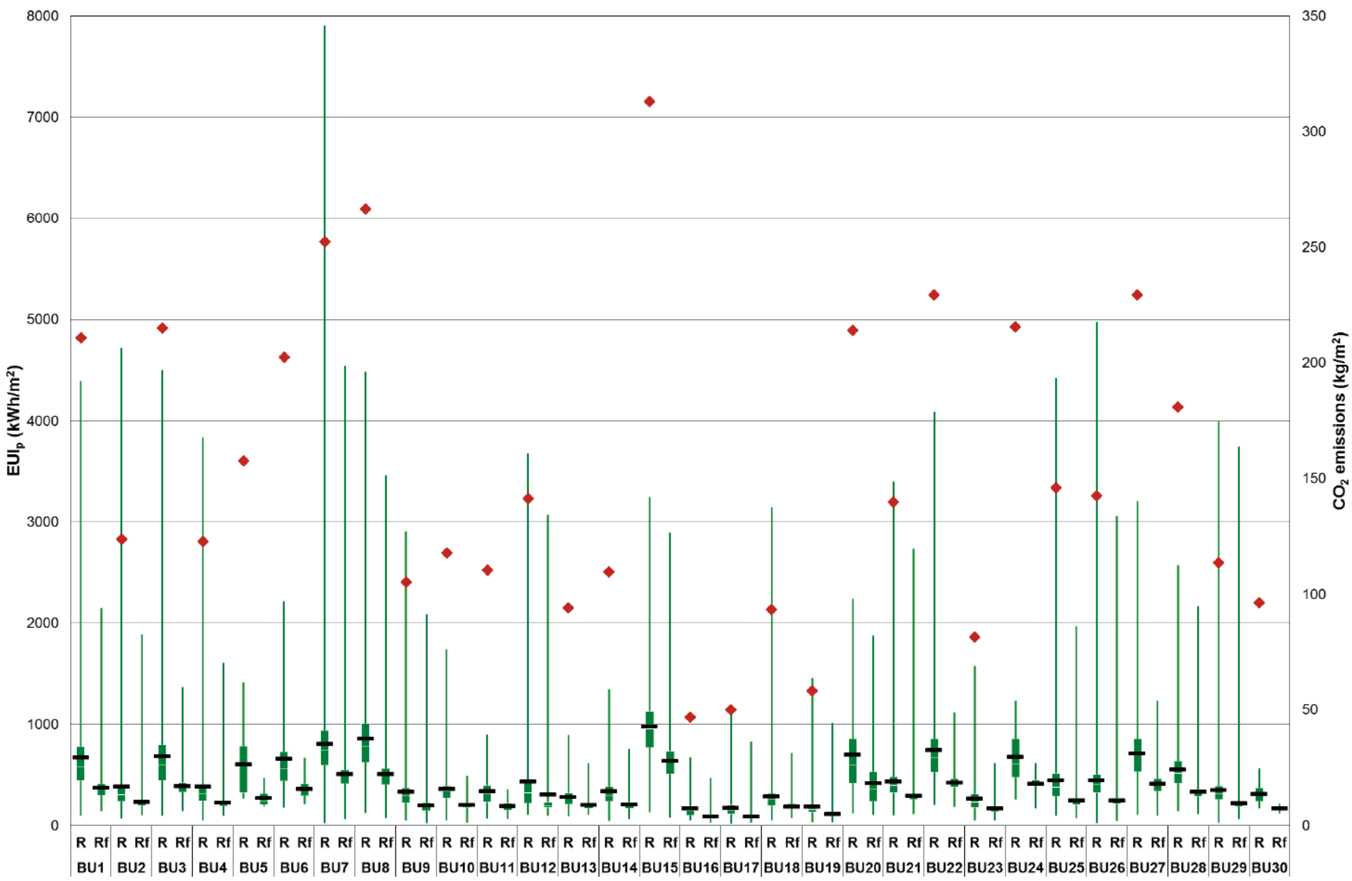

Figure 4: Frequency distribution of calculated mean primary energy use intensity (kWh/m^2) for whole-buildings (solid columns) and part-buildings (empty columns), per building use (BUs are defined in Tables **1** and **2**).

and equipped with more energy efficient equipment). Specifically, the calculated mean EUI_p is 512.3 kWh/m^2 for T1 buildings, 450.7 kWh/m^2 for T2 buildings, 401.9 kWh/m^2 for T3 buildings and 306.5 kWh/m^2 for T4 buildings.

Location relates to the prevailing weather conditions and as a result there is a direct impact on a building's energy performance. The calculated mean EUI_p for each city in the four climate zones, as well as the corresponding mean value for each zone, are presented in Figure **5**. The primary energy use intensity increases from the south part of the county (ZA) to the north (ZD). The observation that warmer climate zones have a lower EUIp is in line with the results from Sweden [34] and Spain [6]. For whole-buildings, the mean value of ZD cities is lower than ZC cities. This can be attributed to the fact that zone D has only four cities and one of them has low mean primary energy use, because it is dominated (46%) by educational buildings, with low energy use.

4.3. Breakdown for Different Services

Analysis of the calculated primary energy use for NR buildings included in the EPC data set reveals that lighting is the most consuming service (38%), followed by cooling (32%), space heating (26%) and DHW (4%). Similar breakdowns are also reported in Spain [6] for space heating (38.3%), lighting (37.2%), cooling (13.3%) and DHW (11.1%). A more detailed analysis presented in section 4.4 provides more insight and reveals the large variations for the different building uses. Comparatively, for Hellenic residential buildings [33] the highest share of the calculated primary energy use is for space heating (67%), followed by DHW (20%) and cooling (13%); other services like lighting, cooking, white appliances and other plug-loads are not taken in to account according to the national calculation method for energy labeling of residential buildings.

For lighting, the EUI_p values range between 100-200 kWh/m^2 for 56% of the whole- and 67% of the part-buildings. For space cooling, the values range between 100-200 kWh/m^2 for 36% of whole- and 39% of part-buildings. For space heating, the EUI_p range between

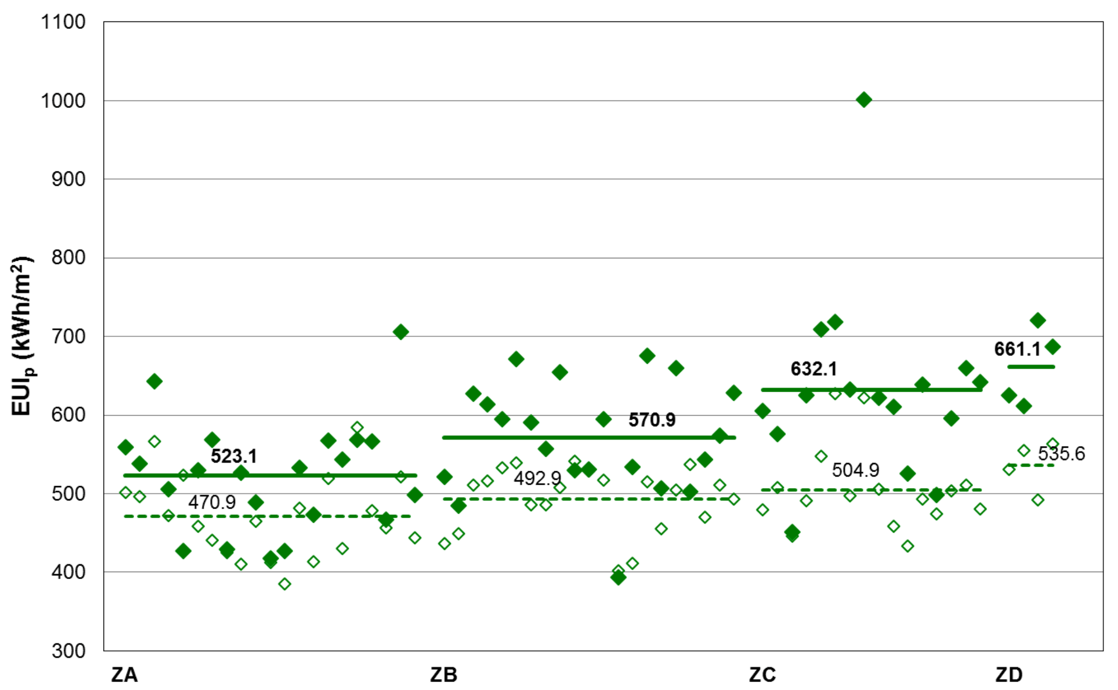

Figure 5: Calculated mean primary energy use intensity (kWh/m^2) for each city in the four climate zones (ZA-ZD) for whole-buildings (solid diamond) and part-buildings (empty diamonds). The solid lines identify the mean EUI_p of all cities in each zone for whole-buildings and the dashed lines the corresponding mean value for part-buildings.

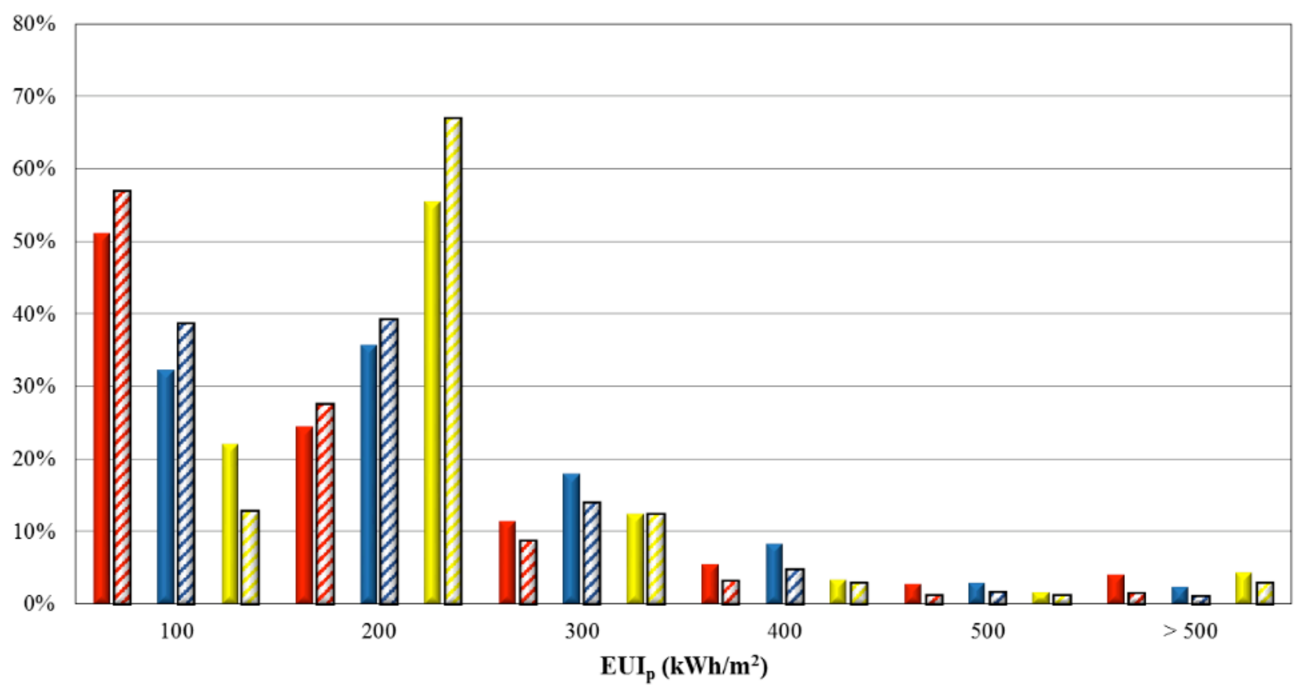

Figure 6: Frequency distribution of calculated mean primary energy use intensity (kWh/m^2) for space heating (red), space cooling (blue) and lighting (yellow) for whole-buildings (solid columns) and part-buildings (dashed columns).

0-100 kWh/m^2 for 51% of whole- and 57% of part-buildings. Finally, for DHW the values range between 0-100 kWh/m^2 for 89% of whole- and 95% of part-buildings (Figure **6**).

4.4. Normalized Energy Use Intensities

In order to use the calculated primary energy use intensity for assessing the relative energy performance of the different building uses, it is necessary to account for their different usage patterns (e.g. operating hours and artificial lighting hours presented in Table **1**) and their location. The normalized mean EUI_p was calculated for the data corresponding to whole-buildings. Accordingly, the EUI_p for space heating and space cooling was normalized for continuous use (8760 hours per year) and placing the buildings at the same location of Athens. If necessary, missing records for weather data at specific locations (cities of audited buildings) from the national technical guideline were populated using a mean value for the corresponding climate zone. Primary energy use intensity for DHW was normalized only for continuous use (8760 hours per year), since the requirements do no change for the different climate zones (locations). Finally, the EUI_p values for artificial lighting were normalized for the maximum lighting hours (7571 hours per year).

The results are illustrated in Figure **7** for the real buildings using their corresponding normative specifications (denoted with "R") and the corresponding normalized (denoted with "N") results. As anticipated, there is a significant impact of usage patterns on the resulting primary energy use. The ranking of the normalized values can reveal the building uses that have a low energy performance as a result of their poor thermal envelope performance or their low efficiency technical installations. Building uses with low primary energy use (e.g. educational buildings, banks and libraries) have much higher normalized EUI_p values. On the other hand, sports halls / swimming pools have higher EUI_p, as well as very high normalized values, due to their large volumes. This is in-line with the ranking of the most energy intensive building uses based on actual operational energy use from utilities [35].

5. CONCLUSIONS

The work elaborated for the first time at this level of detail the energy performance of existing Hellenic NR buildings, by exploiting the data included in the energy performance certificates that have been issued in Greece in compliance with EPBD. Similar studies have been performed and continue to emerge throughout Europe revealing a wealth of information. This approach is the first step for gaining a better understanding of the characteristics and energy performance of the non-residential building stock. The available data from the Hellenic EPC database are clustered in thirty building uses, four construction periods and four national climate zones to derive various energy asset baselines.

The quantitative analysis of the EPC data provides detailed information on the building characteristics (e.g. envelope constructions and heating systems), energy carriers and services for different building uses. This valuable insight can be used to complement the limited

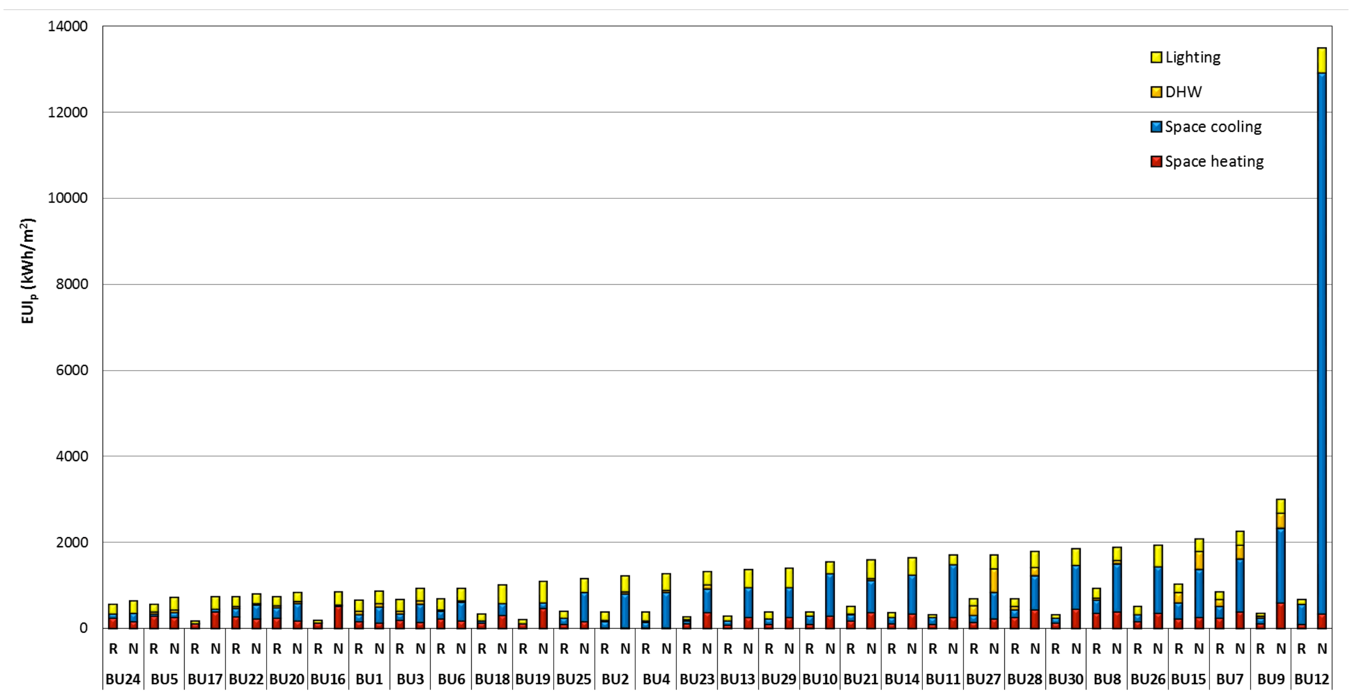

Figure 7: Calculated mean primary energy unit intensity (kWh/m^2) R-Real and N-Normalized for the different services (space heating, cooling, domestic hot water-DHW and lighting) per building use (BUs are defined in Tables **1** and **2**). The ranking is according to the normalized EUI_p values.

building Census data, while the specific energy asset metrics can help building owners, managers and other stakeholders evaluate their buildings with its peers in an independent manner from operation and occupancy.

5.1. Energy Performance and Asset Baselines of Hellenic NR Buildings

The findings from this in-depth study were based on the analysis of about 120,000 valid EPCs for NR buildings in Greece, the vast majority of which (85%) concern part-buildings. Hellenic NR buildings exhibit relatively low energy performance since 53% of the existing buildings are constructed pre-1980, with insufficient thermal protection and inefficient heat production systems. They average an energy class-D (38%), class-C (28%), class-E (19%), class-F (7%), class-G (5%), while only 3% are ranked in energy class-B (i.e. a good building satisfying the minimum requirements of the currently enforced EPBD regulation) or better.

The results from this work provided specific energy asset baselines for all NR Hellenic building types. The building use with the lowest calculated primary energy use intensity is BU16-Kindergarten (179.3 kWh/m^2 for whole-buildings and 147.2 kWh/m^2 for part-buildings), because of low annual operation hours and simple energy system requirements. On the other hand, BU15-Indoor Sports Hall/Swimming pool has the highest EUI_p (1028.3 kWh/m^2 for whole-buildings and 953.6 kWh/m^2 for part-buildings) due to large volumes, latent loads, internal heat gains and other unique operational characteristics.

On average, lighting is the most consuming service, followed by cooling, space heating and DHW. The EUI_p for lighting for the different building uses ranges between 53.1-265.1 kWh/m^2 in whole- and 60.9-329.0 kWh/m^2 in part-buildings. For space cooling the values range between 3.3-460.4 kWh/m^2 in whole- and 3.2-345.0 kWh/m^2 in part-buildings. For space heating, the EUI_p range between 10.7-340.9 kWh/m^2 in whole- and 13.0-296.3 kWh/m^2 in part-buildings. For DHW, the values range between 19.0.0-243.2 kWh/m^2 in whole- and 13.3-254.9 kWh/m^2 in part-buildings.

5.2. Limitations and Future Work

A significant limitation to the findings of this work is that for some building uses there is currently an insufficient number of available cases. On the other hand, some building uses (e.g. BU26-Small retail, BU7-restaurant, BU8-coffee shops) that are commonly engaged in market transactions have a relatively high number of cases in the data set that is not necessarily representative of the building stock. As the EPC database is progressively populated with new data it will be possible to refine and update, if necessary, the derived baselines.

This work was based on a database from Greece and it was made possible due to the availability of a national electronic EPC repository. This underlines the main advantage of having a central electronic registry in order to facilitate data collection and follow-up analysis. Although the quality of EPC data has been challenged in many European countries, the fact remains that this big data can be a unique resource for gaining a deeper understanding of national building stocks. Among the lessons learned during this work is that it is necessary to derive and implement suitable control checks to increase the quality of the available data and the level of confidence on the results. More work is also underway to incorporate plausibility checks of input data in the calculation software and the EPC depository that will further facilitate the EPC validation and verification, with minimum human and financial resources.

Looking into the future, there is a need for more work on gaining a better understanding of the actual energy use in buildings. One needs to be aware of the anticipated deviations between calculated (asset) and actual (operational) energy use or achieved energy savings. Several studies have documented that there is a significant gap between normative calculations of theoretical energy performance and actual energy use [44] or potential energy savings after building renovations [45]. In general, occupants in NR buildings are less concerned with energy use than they are at home, since the energy bills are paid by commercial building owners or civil authorities for public buildings. This may lead to higher actual energy consumption than calculated, which is usually referred to as the rebound effect (i.e. the operational energy use is higher than the asset metric). Space heating rebound effects after thermal retrofits of public office and administration buildings that have been reported in the literature range from 17% to 55% [45]. On the other hand, shorter operating conditions, more relaxed indoor conditions and milder local weather data that deviate from the specified inputs in the normative calculations may result to lower actual energy use. This is usually referred to as the prebound effect (i.e. the operational energy use is lower than the asset metric). Preliminary results for Hellenic buildings indicate that the actual heating energy use is 17% lower than calculated value for schools and 31% higher than calculated value for offices [46].

Along these lines, there is a need for more empirical evidence on actual energy use in NR buildings and savings before and after the implementation of energy conservation measures in different building types. To overcome this data shortage one can consider large NR buildings equipped with building management systems that can readily provide relevant information. Another possible resource is to use available information from EPCs that include both calculated and actual energy use. Overall, the use of this data can support stakeholders to make more realistic estimates of the national energy balance and projections of total energy use and savings in the building sector.

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