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ORIGINAL RESEARCH

Assessing the nearly zero-energy building gap in university campuses with a feature extraction methodology applied to a case study in Spain

Marc Medrano[1] · Josep Maria Martí[1] · Lídia Rincón[1] · Gerard Mor[2] · Jordi Cipriano[2] · Mohammed Farid[3]

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Abstract

Public universities face the challenge of retrofitting the actual campus buildings into nearly zero-energy buildings (NZEB). In this study, a novel methodology for evaluating historical energy use and renewable energy production for all the buildings of a university, including hourly, daily and monthly data assessments is presented. This analysis is useful as a baseline for comparisons with future energy retrofits and enables determining the current gap between actual energy indicators at building and campus levels and the established limits for NZEB non-residential buildings in the European Union. The methodology is applied to a case study at the University of Lleida, a typical average-size university in Spain. Results show a wide variation in energy use among campus buildings, ranging between 50 and 470 kWh/m^2 year. Constant or slightly increasing energy use and decreasing trends in renewable energy generation are observed. The daily electricity profiles have shown similar patterns among buildings and substantial potential energy savings during unoccupied periods. In the NZEB analysis, the average non-renewable primary energy use is about 4 times higher than the maximum estimated Spanish threshold range of 45–55 kWh/m^2 year. Deep energy renovation strategies are, thus, needed for universities to meet EU NZEB targets.

Keywords Energy consumption · University building · Building performance lines · PV generation · Nearly zero-energy buildings · NZEB EU requirements

Abbreviations

4*P*	Four parameters linear regression model
5*P*	Five parameter linear regression model
F	Gas consumption for a heating period (kWh) (1)
UH = HLC/A	Overall building heat loss coefficient per gross floor area (W/m^2 K)
HLC	Overall building heat loss coefficient (W/K) (1)
HDD	Sum of daily degree days for the billing period of about 1 month (day ºC) (1)
B	Gas consumption independent of heating (kWh) (1)
η	Overall heating system efficiency for that period (1)
D_d	Daily degree days (day ºC) (2)
T_{hb}	Building heating base temperature (ºC) (2), (6)
$T_{ext,i}$	Exterior air temperature for every hour of a day (ºC) (2)
m	Slope of regression line (kWh/m^2 K day) (3)
b	Gas consumption independent of heating per day per gross floor area (kWh/day m^2) (3)
n	Number of days for each gas billing period (day) (4)
T_{cb}	Building cooling base temperature (ºC) (5)
E	Daily electricity consumption per gross floor area (kWh/m^2) (5)

✉ Marc Medrano
mmedrano@diei.udl.cat

[1] Department of Computer Sciences and Engineering, Edifici CREA Universitat deLleida, Pere de Cabrera s/n, 25001 Lleida, Spain

[2] Building Energy and Environment Group, Centre Internacional de Mètodes Numèrics en Enginyeria (CIMNE), 08224 Terrassa, Spain

[3] Department of Chemical and Materials Engineering, University of Auckland, Private Bag 92019, Auckland, New Zealand

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C	Constant value in the 4P and 5P models (kWh/m^2) (5)
B_1	Slope of the line at the right, for $T > T_{cb}$($kWh/K\ m^2$) (5)
B_2	Slope of the line at the left, for $T < T_{cb}$($kWh/K\ m^2$) (5)
EER	Energy efficiency ratio (7)
DX	Direct expansion
A	Building gross floor area (m^2)
HVAC	Heating, ventilating and air conditioning
NZEB	Nearly zero-energy building
ZEB	Zero-energy building
EU	European union
EPBD	Energy performance of building directive
PV	Photovoltaic
UdL	University of Lleida

Introduction

The building sector is the main contributor to the total energy use in the European Union (40%) and accounts for 36% of the associated CO_2 emissions [1]. The European legislation (Directive 2010/31/EU on energy performance of building, EPBD) has established ambitious targets for achieving high energy performances, with the aim for new buildings to reach nearly zero-energy use (NZEBs) by the end of 2020 [2, 3]. Similar initiatives have been adopted recently in some of the most developed and environmentally conscious regions of the World, such as the Net-Zero Energy Commercial Building Initiative in the US, by 2030 [4]; the California Public Utilities Commission energy action plan to achieve net zero energy for all new residential construction by 2020 and net zero energy for all new commercial construction by 2030 [5], or other published actions in Canada and Japan [6]. An international agreement for defining and evaluating the performance of NZEB is difficult, as discussed elsewhere [6, 7]. In this context, the EPBD of the EU has established a broad definition for NZEB, i.e., "a building that has a very high energy performance. The requirements for nearly zero or very low energy should be covered to a large extent by energy from renewable sources, including those produced on-site or nearby". Actually, most of the EU member states have not established, as of 2017, a definition that comprises both a numerical target and a share of renewable energy sources [8]. As an example of a Member State that has been able to give detailed figures for the broad framework of EU NZEB definition, Denmark has established a primary energy consumption limit for non-residential buildings to be below 25 kWh/m^2 year by 2021 [9]. Spain has not established yet this limit, but there is already a draft document for the new Building Technical Code [10], where the basis for the determination of NZEB is commented.

Despite the dazzling energy targets for new buildings, the big potential for energy conservation would come from the existing building stock, which is characterized by an average age of about 55 years [11]. However, the European directives in this regard are not as ambitious as the recast of the Energy Performance of Building Directive (EPBD). Among other measures, EPBD requires the Member States to ensure that, as from January 2014, only 3% of the total floor area of heated and/or cooled buildings owned and occupied by its central government is renovated each year [11]. Some recent projects demonstrate the efforts made to optimise energy through renovation of existing non-residential buildings [12, 13]; to evaluate building refurbishing strategies combining measured energy consumption with geographic information systems (GIS) [14]; and to improve the design of new low energy office buildings [15]. Buildings in university campuses are not an exception, and in general are far away from the NZEB requirements. Universities, playing an exemplary role in modern societies, should take the lead in analysing energy efficiency and proposing retrofit measures in their own buildings, targeting NZEB, at least as mid-long-term goals. These actions should play an important role in a broader target for campus sustainability [16]. Some recent studies about energy assessments and audits of university campus buildings have worked towards this direction [17–22]. However, none of them include the combination of a detailed, hourly resolved analysis of up to 20 university buildings, including weather and occupancy, and combined with PV self-generation.

In this context, the purpose of this work is to propose a novel methodology for assessing the historical energy consumption and renewable self-generation performance of university buildings and then apply it to a case study for all the buildings in an average-size university in the Catalonia region (northeast of Spain), the University of Lleida. These buildings belong to four different campuses in the city of Lleida. Photovoltaic arrays placed on the roofs of some buildings have been operative since 2010 in two of these campuses. The assessment includes the compilation and study of relevant building geometric and operational data, impact of climatic conditions on energy use, and also hourly resolved energy data analysis, for detecting outliers and possible energy system inefficiencies. This assessment can serve as a pre-retrofit energy baseline for measuring savings in future university energy renovations. Moreover, the paper aims to illustrate how far the actual energy use and generation at Mediterranean universities are from current EU NZEB targets, and also to propose potential energy efficiency strategies for approaching these targets.

Description of university campuses

The University of Lleida is a young average-sized university, created in 1991, although its roots date back to year 1300 during King James II of Aragon. The University of Lleida has four campuses scattered across the city (Fig. 1). These campuses are described briefly below.

The Cappont Campus (C1) is the newest university campus, opened in 1998. The campus is composed of the library (E1), an academic management building (E2), an Energy research building (E3), the Polytechnic School (E4), the Faculty of Law and Economics (E5), the Faculty of Educational Sciences (E6), and a block of classrooms (E7).

The Rectorate campus (C2) holds the Rectorate, the general university services, and the Faculty of Humanities. Built in the nineteenth century, it is the historical building of the UdL. It was refurbished in 1991.

The Campus of the School of Agricultural Engineering (C3) was opened in 1972. It contains several research, teaching and building services in the city north outskirts.

Finally, the Health Sciences Campus (C4) is located on two sites. The first of these is the Arnau de Vilanova University Hospital. It houses the health sciences teaching unit (E19) and the new Biomedicine research building (E20), built in 2012. The second is the Hospital of Santa Maria that houses the Faculty of Medicine (E17) and the University School of Nursing (E18).

The University of Lleida is associated with a cluster of Catalan universities, research centres and research parks who have access to the Spanish high voltage tariff 6.1 A, for great consumers, with power demand above 450 kW. This aggregation is done to pay lower energy prices and involved a common electricity use of 283 GWh/year in 2016. Similar strategies have been applied for the gas purchases, achieving a reduction of 24% in the gas prices in 2015. Although these

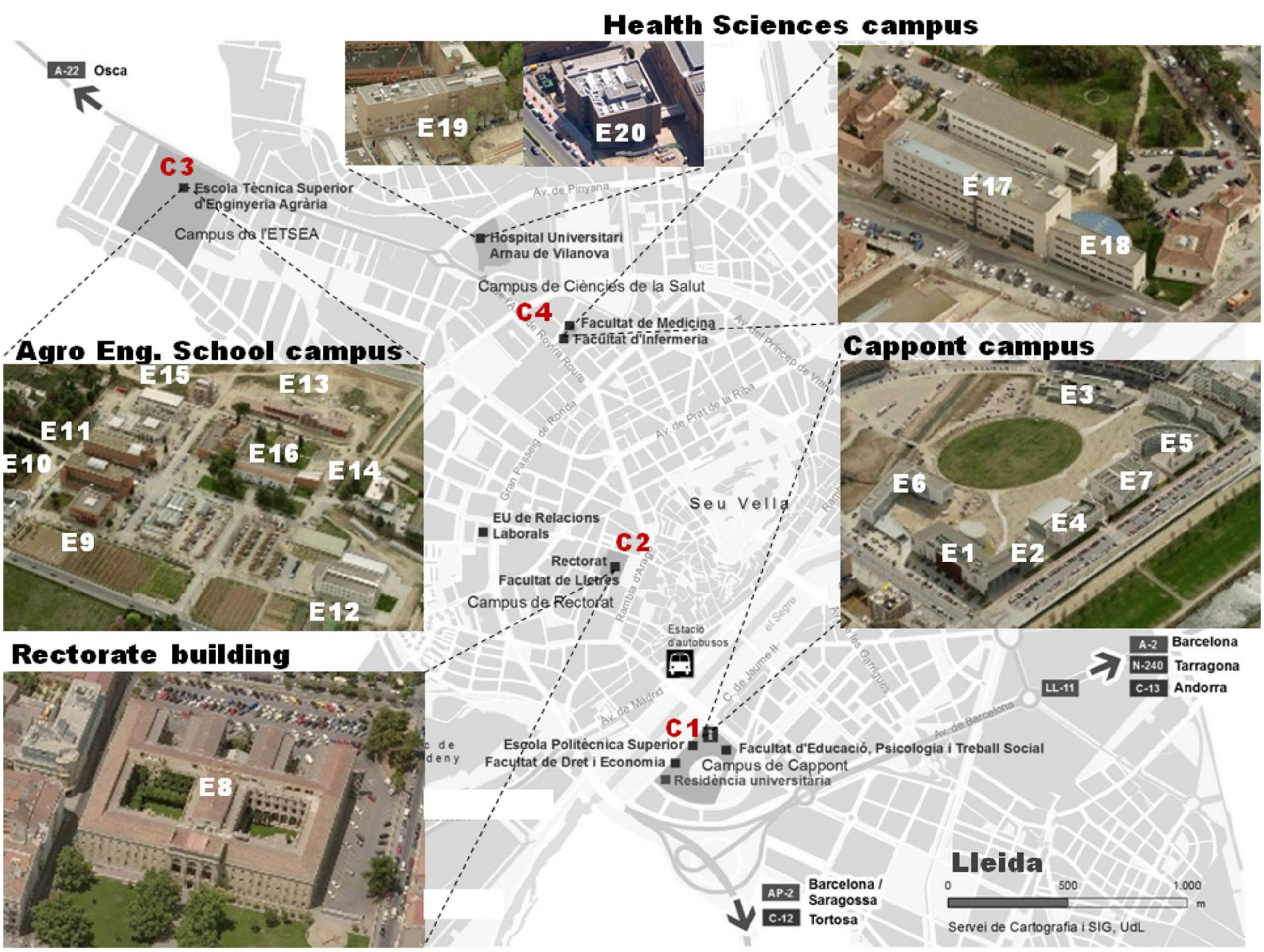


Fig. 1 Location of the campuses in Lleida and identification of the selected buildings

actions result in a decreasing trend for the cost of energy services paid by the UdL, it is still to be determined whether or not these cost reductions have associated energy consumption decreases as well.

Methodology

In the following paragraphs, the methodology applied for realising this study is presented. It includes the following steps: selecting the university, compiling building data and energy use, performing overall and detailed analysis, assessing the actual gap between university building energy performance and NZEB goals, and proposing energy improvements.

Selection of a case study

For a thorough description of the methodology, the quality and amount of energy data available from university buildings should be known. In this context, the University of Lleida (UdL) has been selected in this work for several reasons. First, the access to a recent energy building data is facilitated as most of the authors are professors and/or researchers of the same university making communication with the responsible university energy managers easier. Second, the climate of Lleida (BSk for Köppen-Geiger classification) is a dry semiarid climate and has more extreme winters and summers requiring more cooling and heating compared to other Mediterranean cities. Third, the UdL represents an average-size university in the Spanish system, and fourh it has been pioneer in Spain and Catalonia in installing PV arrays in several buildings, so the required presence of renewable systems for NZEB is accomplished.

Compilation of building data

As a first task, several important building features are compiled, such as campus location, year of construction, energy generation systems for each building, gross floor area, and occupancy estimates per building. Table 1 shows a summary of these factors for the buildings studied in each campus as well as the building IDs used in the following plots and tables.

Collection of energy use and self-generation data

Gas and electricity consumption have been compiled with the maximum time resolution available. In the case of gas, monthly bills for the last 7 years (from 2010 to 2016) are available. For electricity, a new monitoring system enables us to get energy readings every 15 min for the last 2 years (2015 and 2016). Power meters are installed in each building and the data loggers of each building send the information via RS-485 to campus concentrators, which in turn transmit all data to a general server in the cloud. This server can be accessed through an online platform. This software is called DEXCell Energy Manager, of DEXMA Company. The same system is planned to be installed for the gas metres by 2019. The renewable energy production is also monitored every hour since the year 2010 and has been collected for analysis. All the existing PV installations consists of a total of five polycrystalline PV systems located in two different campuses, 2 in Campus 1, with a peak nominal power of 96.6 kW (on E1 roof) and 95.9 kW (on E4 roof); and the other 3 in Campus 3, with peak nominal powers of 79.2 kW (on roofs of E9, E10 and E11), 47.95 kW (on E12 roof) and 95.9 kW (on roofs of E13 and E14). All the PV modules are mounted on flat roofs, with inclined supports. They are non-tracking modules, oriented to the South, in the range 135°–225°, and with tilt angles between 20 and 25 °C, depending on the building. The total area of PV modules installed is of 3029.1 m^2 with a total installed power of 416.3 kWp. To be able to assign a particular annual PV energy generation to the buildings that share the same installation, weighting factors based on installed peak power on each roof are applied. These factors are 20, 40 and 40% for roofs E9, E10 and E11, and 83 and 17% for E13 and E14, respectively.

Overall and detailed analysis of energy data

Annual energy overview

Annual energy consumption for gas and electricity and annual PV production at a campus and individual buildings levels have been plotted and analysed. Besides the actual values, which can be very different among buildings due to their size and activity, normalised plots have been generated and discussed, using both construction area and number of users per building as reference variables. The bigger consumers are identified, applying absolute and relative figures, and possible reasons to describe the observed performance are discussed.

Monthly analysis of gas data

To achieve a better understanding of the use of gas for heating and other possible uses such as domestic hot water production, performance lines for every building are generated using the degree-days theory [23]. These performance lines are useful for measuring savings derived from energy conservation retrofits and to identify and correct operational and maintenance problems [24]. The estimated gas consumption for a heating period can be calculated as (Eq. 1):

Table 1 Summary of information for the buildings selected in the four University campuses

Campus	Build.ID	Building description	Year of construction	Gross floor area (m^2)	Users*	Cooling system	Heating system	PV on roof?
Campus 1 (Cappont campus)	E1	Library	2002	9697	1486	DX AC	Gas boiler	Yes
	E2	Offices	2002	1834	94	DX Heat Pump	DX Heat Pump	No
	E3	Research, classrooms, offices	2004	3259	302	Air–Water chiller	Gas boiler	No
	E4	Engineering School	1998	5251	1396	Air–Water chiller	Gas boiler	Yes
	E5	Law School	2001	4617	826	Air–Water chiller	Gas boiler	No
	E6	Faculty of Education	2007	6660	1394	Air–Water chiller	Gas boiler	No
	E7	Classrooms and services	2002	7119	2120	Air–Water chiller	Gas boiler	No
Campus 2 (Rectorate building)	E8	General services and Humanities Faculty	1991**	20,889	2075	Air–Water chiller and DX AC	Gas boiler	No
Campus 3 (Agro Eng. School campus)	E9	Research, classrooms, offices	1990	2145	327	Air–Water chiller	Gas boiler	Yes
	E10	Research, classrooms, offices	1993	4547	1015	Air–Water chiller	Gas boiler	Yes
	E11	Research, classrooms, offices	1995	5395	1287	Air–Water chiller	Gas boiler	Yes
	E12	Research, classrooms, offices	1996	4041	524	Air–Water chiller	Gas boiler	Yes
	E13	Services, bar and offices	2008	2742	479	Air–Water chiller	Gas boiler	Yes
	E14	Research	2011	2187	–	Air–Water chiller	Gas boiler	Yes
	E15	Research, classrooms, offices	2008	876	29	DX Heat Pump	DX Heat Pump	No
	E16	Research, classrooms, offices	1984	6430	999	DX AC	Gas boiler	No
Campus 4 (Health Sciences campus)	E17	Medicine School	1988	5930	1295	Water–Water chiller	Gas boiler	No
	E18	Library and Nursing School	1998	3220	728	Air–Water chiller	Gas boiler	No
	E19	Animal facility and classrooms	1997	6069	573	Air–Water chiller	Gas boiler	No
	E20	Biomedicine, research	2012	3846	515	Air–Water chiller	Gas boiler	No

* According to estimates for University auto protection plans

** Renovated, built in XIX century

$$F = \frac{24 \cdot \mathrm{HLC} \cdot (\mathrm{HDD})}{\eta} + B, \quad (1)$$

where F is the fuel consumption for the period (kWh), η is the overall heating system efficiency for that period, HLC is the overall building heat loss coefficient (kW/K), which includes the heat conduction losses, the air infiltration and the ventilation losses, and B is a constant value that corresponds to other possible non-weather dependant gas consumptions. The degree-days for the period, HDD, are found as the sum of the daily degree days, D_d, over the considered billing period (about a month) using the most rigorous method, with exterior hourly temperature data. The daily degree days can be expressed according to (Eq. 2):

$$D_{\mathrm{d}} = \frac{\sum_1^{24} \left(T_{\mathrm{hb}} - T_{\mathrm{ext,i}}\right)_{\left(\left(T_{\mathrm{hb}} - T_{\mathrm{ext,i}}\right) > 0\right)}}{24}, \quad (2)$$

where T_{hb} is the heating base temperature and T_{ext} is the outdoor air dry-bulb temperature. For determining the value of T_{hb} in each building, several guess values for every 0.5 °C are used, in the range from 12 to 19 °C, and the base temperature yielding to the best fitting (best R^2) is selected.

As the billing periods for gas are not always regular in the number of days between gas readings, for each period, the gas consumption per day has been correlated with the HDD per day, by dividing both the gas readings and the HDD by the exact number of days of that particular billing period [25].

Thus, for each building, the slope (m) and the intercept (b) of a regression line (Eq. 3) is determined:

$$\left(\frac{F}{n \cdot A}\right) = m \cdot \left(\frac{\mathrm{HDD}}{n}\right) + b, \tag{3}$$

where n is the number of days for each billing period and A is the gross floor area (m^2).

Monthly gas consumptions are also divided by the gross floor area of each building for the purpose of comparison. So, the values of m and b correspond to the following physical interpretation (Eq. 4):

$$m = \frac{24 \cdot \mathrm{HLC}}{\eta \cdot A}; \cdot b = \frac{B}{n \cdot A}. \tag{4}$$

A summary of the procedure followed to determine the heat loss coefficient, *HLC*, the baseload gas consumption, B, and the heating base temperature, T_{hb} is shown in the flowchart of Fig. 2:

Most of the readings for gas consumption for the 7 years of data are actual values, according to the statement of the gas distributing company in the bills. The ones which are estimated have been removed to avoid possible outliers with no physical meaning.

The comparison of the values of the slopes, m, of the different buildings will be used to rank them with respect to the level of building heating efficiency. The larger is the slope, the higher the dependence (less efficient building) on the external temperature.

Hourly analysis of electricity data

Two years of electricity data (2015 and 2016) are analysed for all the building in the 4 campuses of UdL with a time resolution of 1 h using the programming language and software environment R [26]. As a first step, weekly plots of electricity consumed every hour for the 104 weeks of the 2-year period are generated in the same figure. This overall view is useful for quickly identifying daily and weekly patterns, level of activity during weekends and holiday periods, base loads during unoccupied hours, extra power used for the compression chillers or heat pumps in summer period, errors in readings or missing values, fault detection, etc. Comparisons can also be made among buildings of the same campus or among different campuses.

Hourly data are also available for external temperature from a weather station in Lleida city. Both electricity consumption and weather raw data are pre-processed with R to detect outliers and fill in possible blanks, using powerful libraries that are able to detect them and provide appropriate interpolations for missing or outlying data.

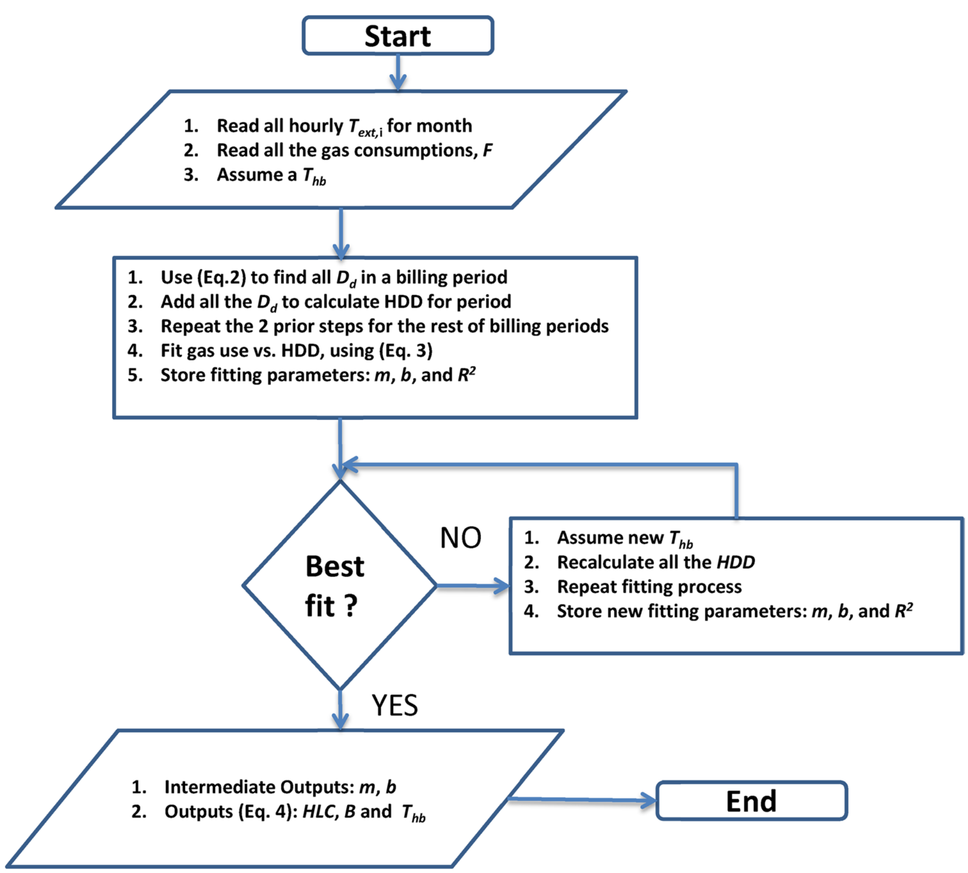


Fig. 2 Flowchart describing calculation procedure with monthly gas data

Daily aggregated electricity consumption values for the 2 years are plotted versus average daily exterior temperature values to determine the climatic dependence of electricity consumption. For the 18 buildings with natural gas heating, a cooling 4 parameters (4P) model will be applied. This model has the following mathematical formulation, [24, 27] (Eq. 5):

$$E = C + B_1\left(T - T_{cb}\right)^+ + B_2\left(T_{cb} - T\right)^+, \quad (5)$$

where C is a constant, E is the daily electricity use per gross floor area, T is the daily average outdoor air dry-bulb temperature, B_1 and B_2 are the regression coefficients, and T_{cb} is the cooling base temperature, also called change point temperature. The $()^+$notation indicates that when the term in parenthesis results in a negative number it is set to 0.

Using R package "Segmented" [28] for finding change points in linear regression analysis, all the above parameters are determined. Unoccupied days corresponding to weekend or holiday periods are removed before the regression.

For the two buildings that use electricity both for heating and cooling, via heat pumps, a 5-parameter model (5P) is applied, to account for the weather dependence both in heating and cooling seasons [29, 30]. The mathematical expression for this 5P model is (Eq. 6):

$$E = C + B_1\left(T - T_{cb}\right)^+ + B_2\left(T_{hb} - T\right)^+, \quad (6)$$

where T_{hb} is the heating base temperature.

NZEB gap and proposals for energy improvements

To evaluate how far the buildings of the campus are from the NZEB definition, the methodology adopted in the Spanish building regulation will be used. In Spain, the regulation linked to the definition of NZEB has been mostly focused on new buildings and has been evolving from the initial set up of the minimum requirements for the building energy demand, in 2006, to the definition of the methods to evaluate the non-renewable primary energy portion, in 2013. In 2018, there is a mandate (M/480) to adopt the overarching standard of the EPBD (FprEN 15603-1 or its new update, the draft prEN ISO/DIS 52000-1) [31] as the new reference document within the Spanish building regulation. This overarching standard assumes that the use of only one requirement, e.g., the numeric indicator of primary energy use, can be misleading. In this proposal, different requirements are combined to a coherent assessment of a NZEB that fits the definition given by the EPBD (2010/31/EU), in article 2. In Table 2, a summary of the requirements needed to fit the NZEB category is shown. As can be seen, the total primary energy use is split between the non-renewable primary energy portion ($f_{p,nren}$) and the renewable primary energy portion ($f_{p,ren}$). To fulfil the nZEB requirements, another factor, the exportation factor (K_{exp}) must be considered. The (K_{exp}) defines the fraction of exported energy in case local or nearby renewable energy generation systems exist.

Results and discussion

Annual energy overview

Absolute annual electricity use values for the twenty university buildings studied in 2015 and 2016 are shown in Fig. 3a. They are ordered from largest to smallest figures starting from the left, for each campus. The three main consumers are clearly highlighted, with electricity uses above the 1000 MWh/year. The rectorate building, E8, is comparatively larger than the average size of the buildings (21,000 vs 5250 m^2), so this may explain this extra energy. On the other hand, E19 and E20 buildings have similar or even smaller gross floor areas than the average. In this case, other reasons, such as the extra power required for animal labs and other bio-research equipment, may explain these large consumptions results. The rest of the buildings are in the range 50–600 MWh/year, with very small differences between the 2 years studied. The exception is building 19, which has doubled its consumption, probably due to the opening of new, high energy intense research labs. The historical evolution of gas use at the UdL is shown in Fig. 3b. Note that two buildings, E2 and E15, do not have gas use, as their heating needs are covered by an electrically driven heat pump (see Table 1). Again, E8 building is the highest consumer, probably due to its size, followed by the same Health Science campus buildings found in the electricity analysis, E20 and E19. Average gas use in 2016 is around 320 MWh/year, being all the

Table 2 Requirements to achieve the NZEB category defined in the prEN ISO/DIS 52000-1

Calculation direction → → →			
1st Requirement	2nd Requirement	3rd Requirement	Final NZEB rating
Build. Fabric (UA)	Tech.Build.systems + related energy carrier only nearby, distant	Renewable source on-site, nearby, distant	Compensation by exporting on-site, nearby, distant
Energy needs	Total primary energy use $f_{p,tot}$	Non-renew. Prim. energy $f_{p,nren}$	Tot + nren.Prim.energy $f_{p,nren}$, K_{exp}

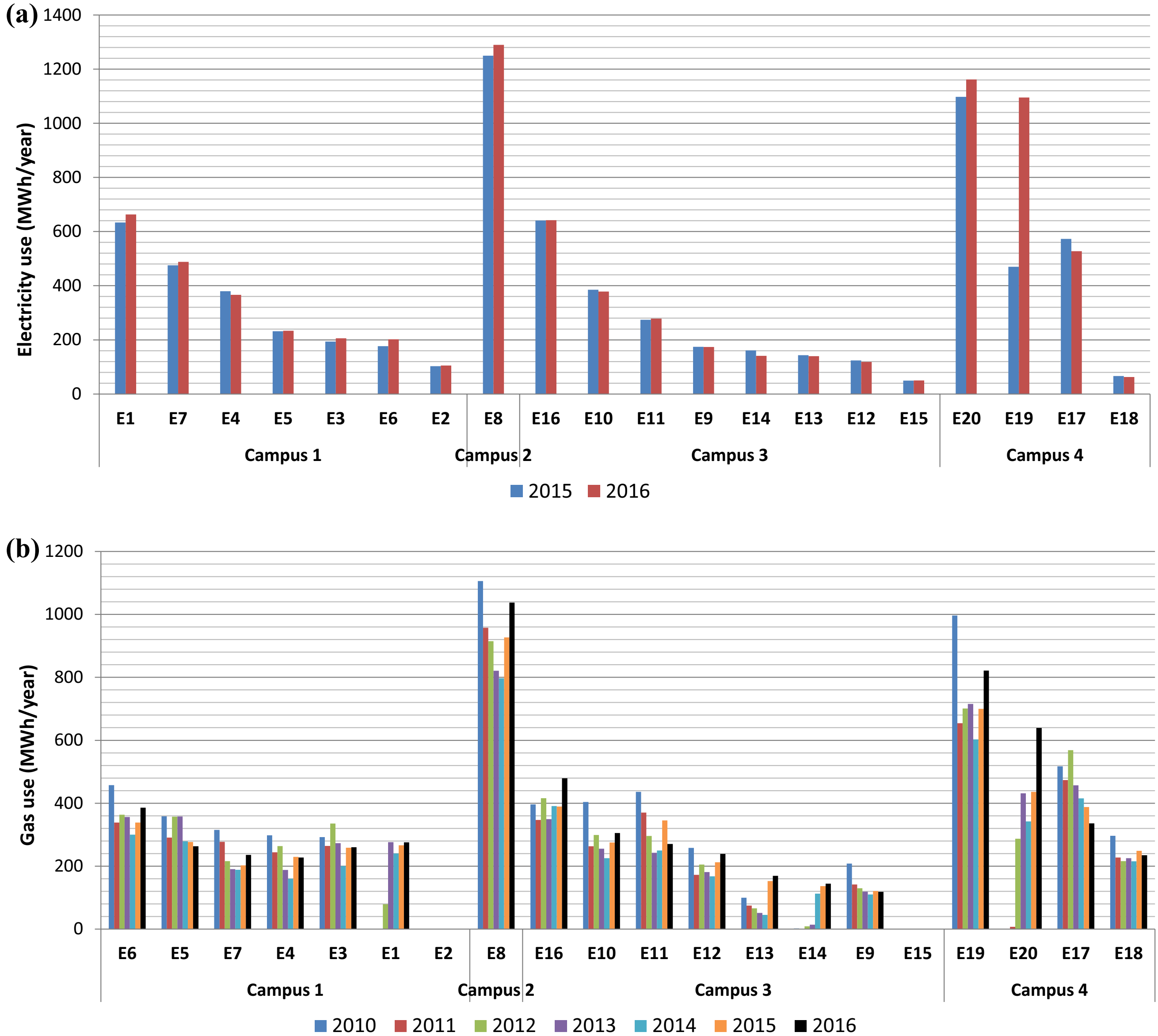


Fig. 3 Historical annual energy consumptions for electricity (2 years) and gas (7 years): **a** Electricity, **b** Gas use

buildings in the range 150–1000 MWh/year. In general, a decreasing gas consumption trend is observed until year 2014, whereas an increasing trend is detected in the last 2 years in many buildings. Whether or not these ups and downs in gas annual use are due to different climatic severities along these years is illustrated in Fig. 4. The historical evolution of gas consumption for each campus is presented in a weather normalised way, dividing the annual MWh per the calculated heating degree days of Lleida each year. Campus 1 and Campus 4 have a slight increase of gas use along the years, with a pronounced increase in years 2015 and 2016. On the other hand, campuses 2 and 3 show a decreasing trend in the first 4 years, followed by an increasing trend in the last 3 years, again with a peak in year 2016. Unfortunately, this weather normalised behaviour indicates a deterioration in the envelope transmission and infiltration heat losses and/or a decrease in the campuses gas heating efficiency in the last years, which should be further analysed and reversed, if the path for sustainability and NZEB targets is to be followed.

Figure 5 shows the historical evolution of the annual renewable energy production in the two campuses with installed PV systems. Most of the PV systems started operation in late 2010 and some in January 2011. For that reason, the energy generation values of 2010 are very low and have not been included in the linear regression. Note that the two campuses have a decreasing trend in PV output production, with about 3% reduction per year. This observed efficiency

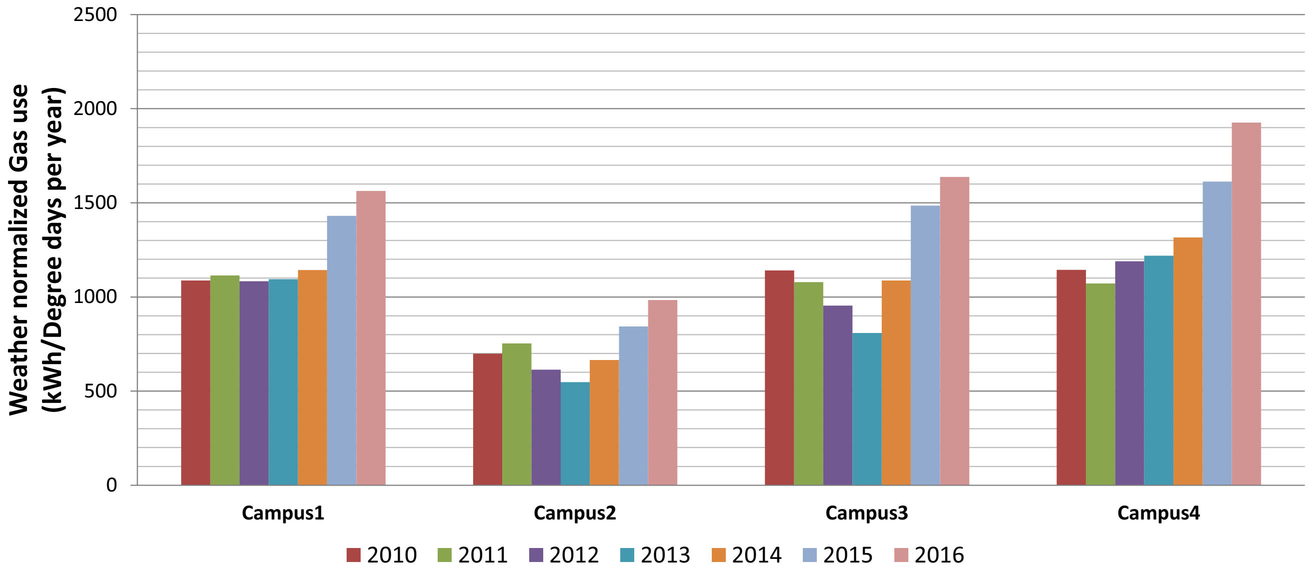
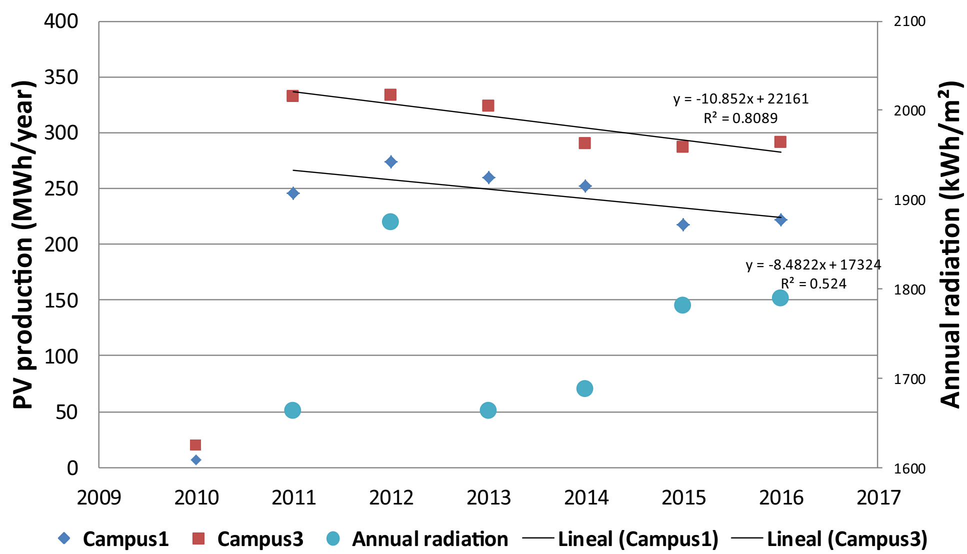


Fig. 4 Historical weather normalised gas consumption in the four campuses

Fig. 5 Historical renewable energy production, solar radiation and linear regressions in the two campuses with PV systems



drop per year is higher than the typical 1% drop given by many PV manufacturers and should be studied in more detail. The oscillating, rather declining, annual solar radiation values during this 6-year period (Fig. 5) cannot explain this behaviour. Thus, the deterioration of the PV cells is the most likely reason.

Figure 6 shows annual aggregated gas and electricity use per gross floor area for all the buildings. With this normalisation per floor area, the two Health Sciences buildings are highlighted as the major consumers even more than in the absolute comparison shown before. On the other hand, the other big consumer, the E8 building, moves down several positions, with values 20% smaller than the average, which is 140 kWh/m^2 year. Excluding the two high energy consuming buildings E20 and E19, with values above the 300 kWh/m^2 year, the rest of the UdL buildings are in the range 50–175 kWh/m^2 year, comparable to the values reported by the Polytechnic University of Barcelona (UPC) for up to sixty buildings in different campuses, which are between 40 and 200 kWh/m^2 year [19]. Another study for eleven buildings in a university campus in Korea shows energy use intensities for gas and electricity in the range 106–399 kWh/m^2 year [17]. Important differences are observed between the larger and smaller consumers in each campus. These are 60, 67 and 80% for campuses 1, 3 and 4, respectively.

If the same comparison is made by the number of users per campus (Table 1) as the normalisation parameter, results are different (Fig. 7). The energy use gap between Campus

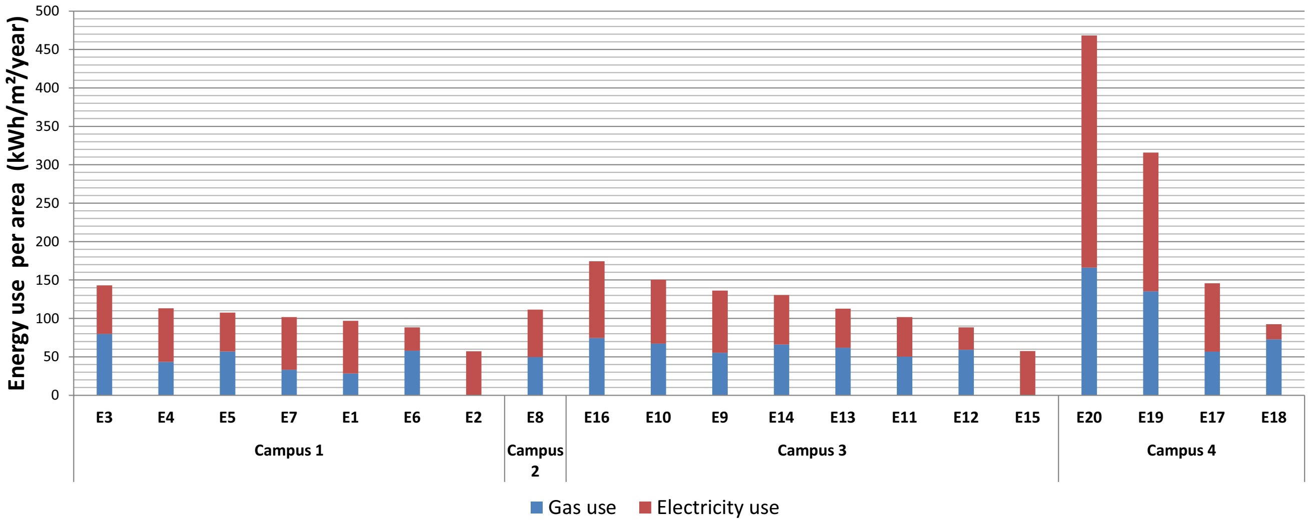


Fig. 6 Annual energy use per gross floor area in year 2016 for 20 buildings in four university campuses

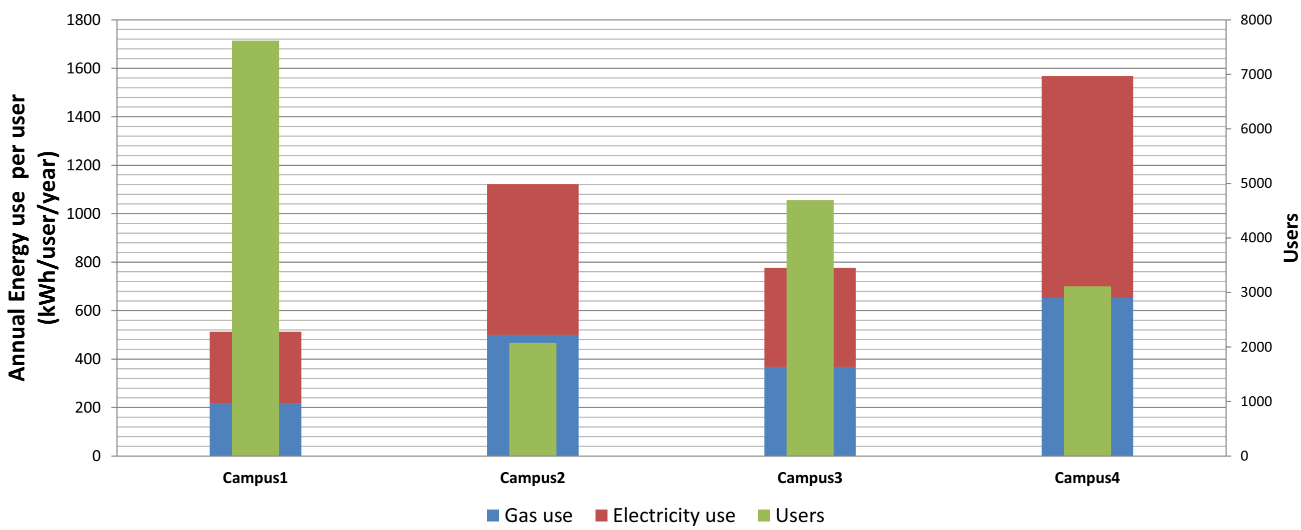


Fig. 7 Annual energy use per users in year 2016 in the four university campuses

4 and the rest of the campuses is emphasised, as the number of estimated users is relatively small, compared to Campus 1 and 3, and absolute energy consumption is higher. Based on the number of users, which is only an estimate of maximum occupation given by the UdL self-protection and evacuation plan, the annual energy use per user of campus 1, 2, and 3 is between 500 and 1100 kWh/user/year, whereas Campus 4 achieves almost 1600 kWh/user/year. Campus 1 is the second energy consumer in absolute terms, but the high estimates of users, above 7000 people, moves it to the last position in energy per user, with a 67% reduction compared to Campus 4.

Monthly analysis of gas data

Figure 8 shows the heating performance lines for two buildings with extreme slope values in the Cappont campus (Campus 1). Similar curves are obtained for the rest of the buildings (not shown). The results of these linear regression models are summarised in Table 3. Buildings E2 and E15 are not included in the analysis because they have electricity driven systems for both space heating and cooling. The availability of 7 years of monthly bills has increased significantly the number of data points with respect to a typical performance line with gas readings for only 1 year. For this reason the coefficient of determination, R^2, for the

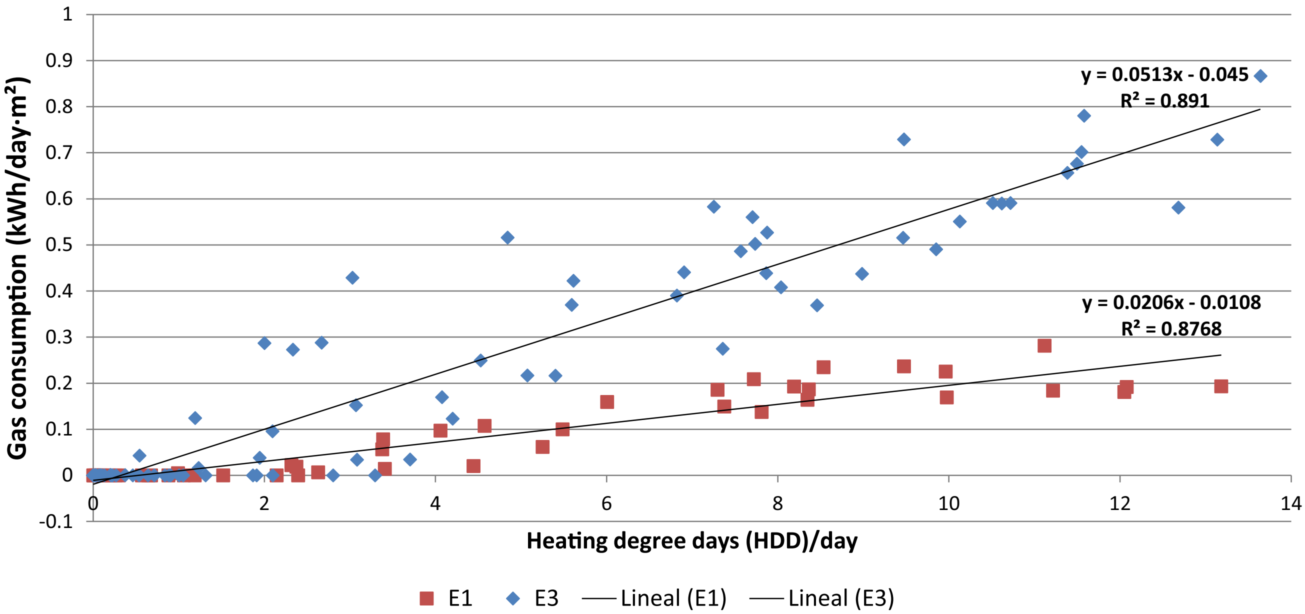


Fig. 8 Heating performance lines for two buildings (E1 and E3) in Campus 1 with extreme slope values, based in monthly gas bills for 7 years

Table 3 Parameters for heating performance lines from gas monthly data

Campus	Building ID	Base temp., T_{hb} (°C)	Slope, *m* (kWh/m^2 K day)	UH = HLC/A (W/m^2 K)	Intercept, *b* (kWh/day m^2)	R^2
Campus 1	E1	16.5	0.021 ± 0.002	0.613 ± 0.06	− 0.011	0.877
	E3	18.0	0.051 ± 0.005	1.750 ± 0.15	− 0.045	0.890
	E4	14.5	0.037 ± 0.003	1.079 ± 0.09	− 0.004	0.879
	E5	15.5	0.052 ± 0.004	1.517 ± 0.12	− 0.016	0.900
	E6	17.5	0.032 ± 0.004	0.933 ± 0.12	− 0.011	0.797
	E7	14.5	0.029 ± 0.002	0.788 ± 0.06	− 0.006	0.879
Campus 2	E8	17.0	0.029 ± 0.002	0.846 ± 0.06	− 0.016	0.887
Campus 3	E9	16.0	0.036 ± 0.003	1.050 ± 0.09	0.022	0.854
	E10	18.0	0.033 ± 0.003	0.963 ± 0.09	− 0.004	0.842
	E11	17.5	0.033 ± 0.004	0.963 ± 0.12	− 0.003	0.770
	E12	18.5	0.028 ± 0.003	0.817 ± 0.09	− 0.022	0.835
	E13	18.0	0.014 ± 0.003	0.408 ± 0.09	0.019	0.499
	E14	19.0	0.032 ± 0.005	0.933 ± 0.15	− 0.003	0.824
	E16	17.0	0.036 ± 0.004	1.050 ± 0.12	− 0.012	0.821
Campus 4	E17	16.0	0.045 ± 0.004	1.313 ± 0.12	0.022	0.883
	E18	17.0	0.048 ± 0.003	1.400 ± 0.09	− 0.022	0.912
	E19	18.0	0.053 ± 0.005	1.546 ± 0.15	0.049	0.866
	E20	19.0	0.054 ± 0.009	1.575 ± 0.26	0.005	0.735

regression lines is in general quite high, above 0.8 in most of the buildings. The only exception is E13 building, where the goodness of fit is rather low ($R^2 = 0.50\%$), suggesting that many gas monthly bills are not actual readings, but company estimates. Standard deviations of the slopes, *m*, for the linear regression lines obtained are in the range 3–6%. Thus, the observed almost threefold differences among extreme building performance lines cases are statistically significant.

The overall heat loss coefficient per gross floor area, UH = HLC/A, W/m^2 K) can be isolated from the transformation of Eq. 4. To determine its value, an approximate estimation of the seasonal efficiency of the gas boilers of the buildings should be obtained. Although each building has a different boiler and space conditioning system, a simplified homogenous seasonal gas heating boiler efficiency of 70% is used. This energy efficiency is determined according to the official annex document of the Spanish energy certification scheme [32]. This is a first estimation of the efficiency of the boilers in real use; however, since no more in situ measurements are available, it will be used to facilitate a practical example on how to obtain the overall heat loss coefficient of buildings based on data obtained from smart meters. As it can be seen in Table 3, that building E13 has the lowest UH value, this is not representative since its R^2 is too small. The next building with the lowest value of UH is building E1, which corresponds to the library of Campus 1. The E20 has the highest UH value, which is in contradiction with its recent date of construction. This building hosts many different medicine labs and further detailed analyses are needed to understand if thesee high values are due to the envelope heat losses, poor control of HVAC set-points, or ventilation loads. The E3 building in Campus 1 exhibits a higher overall heat loss coefficient than E1 building and/or the efficiency of E1 heating system is higher. As the boiler and the heating distribution systems in both buildings are very similar, the hypothesis of higher heat losses in E3 is more likely to be the reason. In any case, more energy efficiency insights should be gained to better understand the differences in these two buildings.

In Fig. 9, the correlation matrix among the estimated UH, the year of construction and the number of users is shown. This graphical visualisation shows the Pearson's correlation coefficients among each pair of variables (lower section), the density functions of each variable (diagonal) and the regression lines with their corresponding confidence intervals (upper section). As it can be seen, there is no correlation between the UH and the year of construction, which means the overall heat loss coefficient, including the ventilation losses, is not lower for newly constructed buildings. It can also be observed that there is a relatively small negative correlation between the UH and the maximum number of users. This low correlation could be due to the increase of the gross floor area with the number of occupants, which is the denominator of the UH. Indeed, given the same U values and air changes per hour, the theoretically calculated UH value gets smaller in a logarithmic trend with the size of the building (and so with the gross flow area and the number of users).

In Table 3, it can be seen that all the values for the intercept point, b, are around zero, meaning that there are no weather independent consumptions (gas base loads), such as domestic hot water.

Besides the HLC, intercept and goodness of fit (R^2) values, this degree-days methodology has enabled the determination of the heating base temperatures in each university building, showing values in the range 14.5–19 °C. This base temperature or balance-point is defined as the outside temperature above which the building does not require heating. The slightly higher base temperatures found in Campus 3 and 4 suggest that these buildings have smaller average internal gains than the ones in campus 1 and 2.

Figure 10 illustrates the variation of the slopes for the building performance lines in the different campuses, as well as the base temperature found for each building. Note how Campus 1 buildings have a larger variation in extreme slope (53%), whereas the other campuses with more than one building (3 and 4) show more similar normalised weather dependence (excluding E13), with slope differences of 17% (Campus 3) and 13% for (Campus 4).

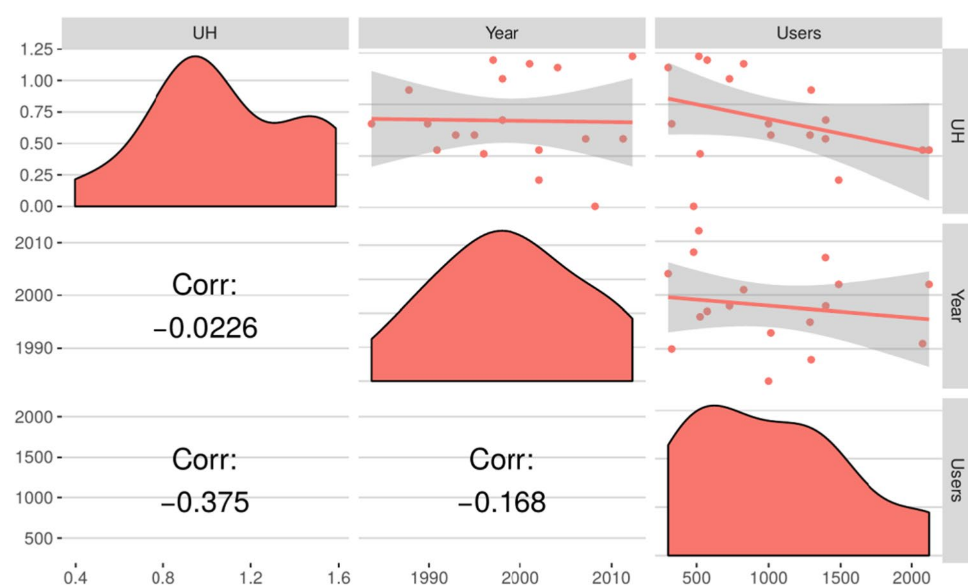


Fig. 9 Correlation matrix among the estimated HLC and some building features (year of construction and number of users)

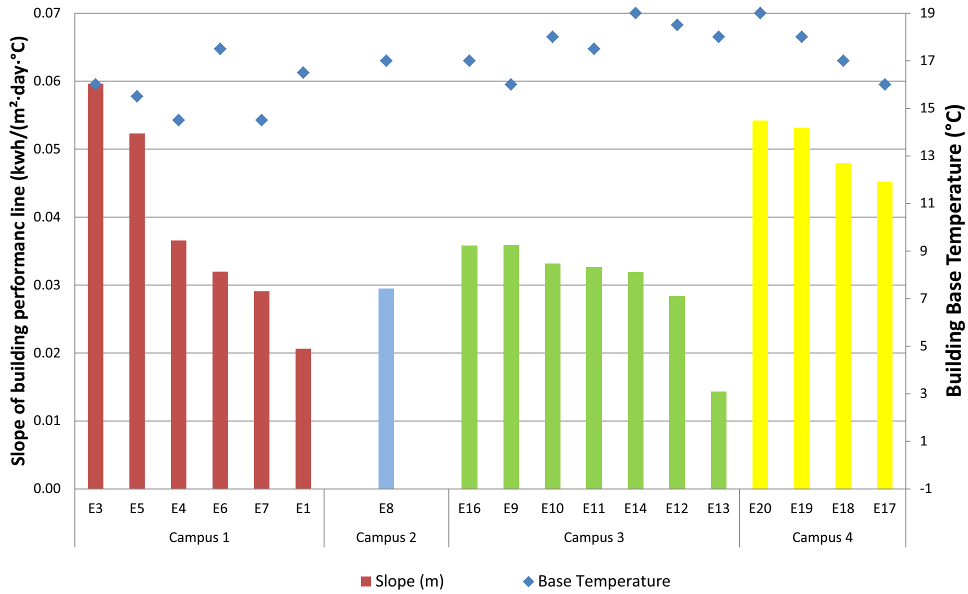


Fig. 10 Comparison of slopes of heating building performance lines and base temperatures, found using the degree-days method

Hourly analysis of electricity data

Figure 11 presents a compilation of weekly plots of hourly electric consumption for years 2015 and 2016 (104 weeks) in the Rectorate building (E8), which is the largest electricity consumer. The vacation periods are easily identified, with a baseload profile of about 100 kWh. For year 2015, these include weeks 0 and 1 (Christmas Holidays), week 13 (Easter), and weeks 31, 32 and 33 (summer vacation). Similar trends are seen in 2016. The other local or national holidays are clearly identified as well, for instance, the two-day period on the 28th and 29th of September 2015 (two first days in week 39). Electric profiles along the weekdays with no cooling are very similar, with peaks in midday between 200 and 300 kW and valleys during night, reaching the baseload of about 100 kW. Weekends' behaviour indicates very low occupancy, with some slight increase from base load during the day. The activation of the refrigeration chillers for the cooling season is clearly observed during the second or third week of May for both years, with a significant increase in the peak loads, reaching values above 400 kW for the weeks of July (weeks 27–30). Electricity use in Saturdays represents almost 11% of the total electricity annual consumption. This is a rather high contribution for a day without activity and suggests that substantial energy savings could be achieved with an energy audit that points out unnecessary consumptions during nights, weekends and holiday periods and achieves a reduction of the baseload. Although not shown, similar trends are observed in the rest of the buildings, but with peak and baseloads proportional to the level of annual electricity consumption of each building. These observed similarities in the daily load profiles for weekdays, weekends and holidays in all the buildings studied may be explained because all of them are managed by the same institution and are of the same building type, educational buildings. Saturdays' share of electricity use is in the range 4 to 13% of the total annual use.

Table 4 shows the main results from the regression model with segmented relationship for the buildings in study. Points of daily electric consumption per gross floor area over average daily temperature are fitted to a 4P model for the 18 buildings with natural gas heating and to a 5P models with the two buildings (E2 and E5) with heat pumps, both for heating and cooling. The table includes the coefficients for the linear regression presented in the methodology section and the adjusted R^2 value. Most of the cases have R^2 values between 0.6 and 0.85, indicating a reasonably good fit. Exceptions with bad fits are buildings E3, E6, E10, with R^2 below 0.4. B1 parameter value, the slope of the line in the cooling region with temperatures above the cooling base temperature, is in the range 0.004–0.024 kWh/m^2 K day and the average value is 0.0115 kWh/m^2 K day, 3 times smaller than the average slopes found in the heating performance lines of previous section. This means that the climatic dependence of energy consumption for cooling is smaller than the one for the heating season, probably due to the higher efficiency of chillers compare to boilers. Note also how the much higher energy consumptions per gross floor area observed for the Health Sciences buildings E19 and E20 can be explained partially due to the higher outdoor temperature dependence (higher slope) of these two buildings, but mainly due to the much larger base load consumption, represented by parameter C, which is 2 times bigger than average for E19 and almost 4 times for E20.

The outcomes of the segmented models shown in Table 4, in combination with the UH of Table 3, can be used to obtain a first estimate of the averaged Energy Efficient Ratio (EER)

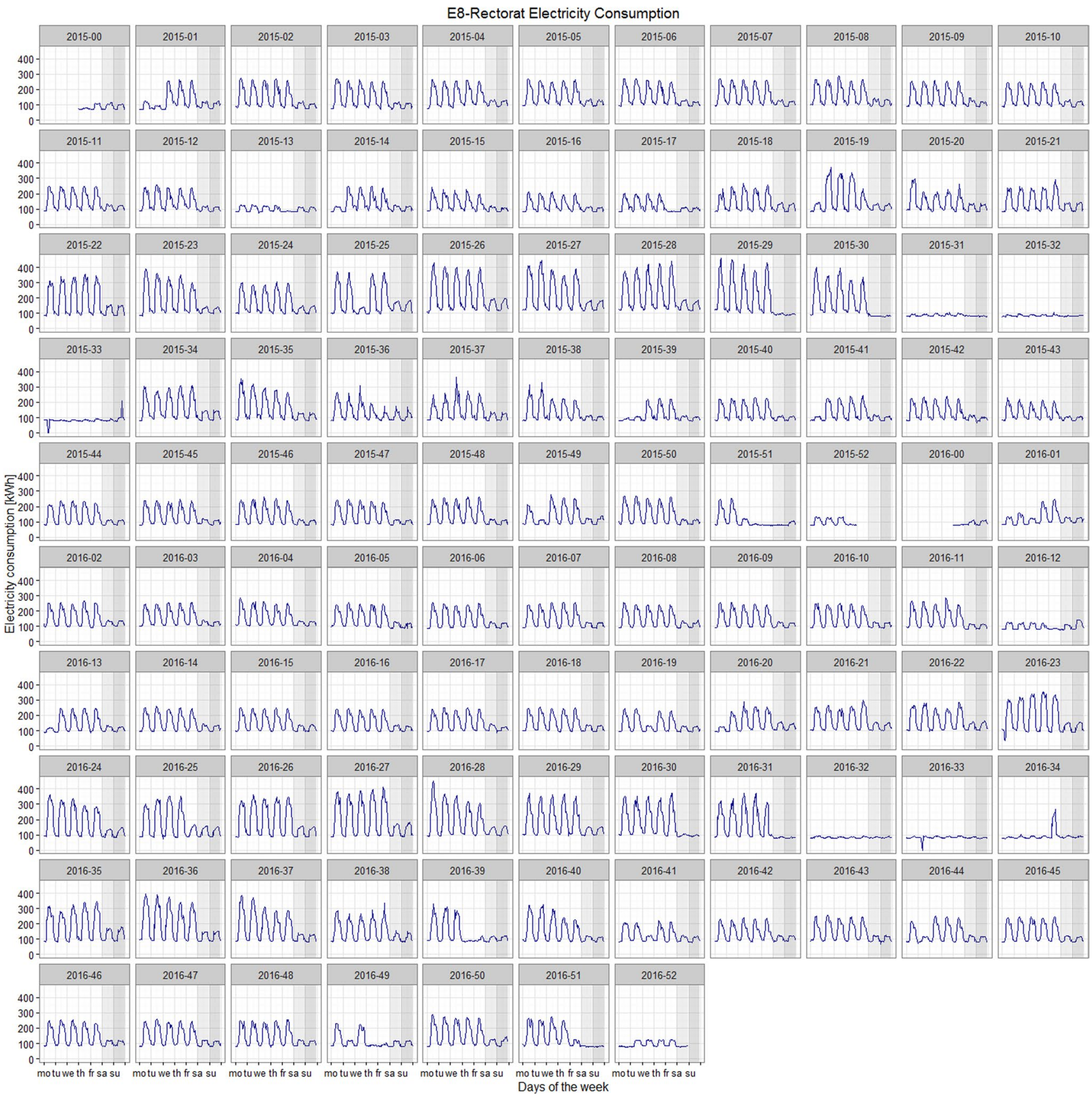


Fig. 11 Example of overview plot for average hourly power along the 104 weeks in 2 years (2015 and 2016) for building E8

of the electrically driven cooling system of each building. The slope of the cooling season of the segmented model, B_1, can be expressed as:

$$B_1 = \frac{\mathrm{UH} \cdot 24}{\mathrm{EER}}. \quad (7)$$

The *EER* can be calculated from the Eq. 7. As previously mentioned, this is a very approximate way to obtain an estimation of the *EER* for each building. This is shown here to illustrate a practical example on how to determine HVAC systems efficiency in function of smart metering data. If monitored data of the delivered energy for space cooling were available, the reliability of the estimated results would be improved. In Fig. 12 a bar plot of the estimated values of the EER for each building, as well as the histogram of frequencies are shown. The building E6 has not been included in the analysis since the R^2 of the segmented model is too small. The buildings E2 and E15 are neither included in the analysis since their UH could not be determined due to the lack of gas data. As can be seen, the mean value is

Table 4 Obtained change point model parameters for daily electricity use of UdL buildings. Cooling 4-P model for 18 buildings, and 5-P model for 2 buildings

Campus	Build.ID	Model	C (kWh/m^2 day)	B_1 (kWh/m^2 day K)	B_2 (kWh/m^2 day K)	T_{cb} (°C)	T_{hb} (°C)	R^2
Campus 1 (Cappont campus)	E1	Cooling 4P	0.194	0.0132 ± 0.001	0.0034 ± 0.002	15.34	–	0.601
	E2	5P	0.126	0.0152 ± 0.002	0.020 ± 0.001	21.42	16.82	0.803
	E3	Cooling 4P	0.148	0.0134 ± 0.002	0.0044 ± 0.002	17.79	–	0.383
	E4	Cooling 4P	0.197	0.0140 ± 0.001	0.0040 ± 0.001	17.34	–	0.728
	E5	Cooling 4P	0.123	0.0177 ± 0.001	0.0060 ± 0.001	17.40	–	0.768
	E6	Cooling 4P	0.081	0.0041 ± 0.0009	0.0019 ± 0.0007	17.89	–	0.226
	E7	Cooling 4P	0.191	0.0108 ± 0.001	0.0070 ± 0.002	16.16	–	0.481
Campus 2 (Rectorate building)	E8	Cooling 4P	0.173	0.0080 ± 0.0005	0.0013 ± 0.0003	18.43	–	0.839
Campus 3 (Agro Eng. School campus)	E9	Cooling 4P	0.202	0.0152 ± 0.001	0.0038 ± 0.001	17.56	–	0.646
	E10	Cooling 4P	0.229	0.0076 ± 0.001	0.0002 ± 0.001	17.93	–	0.374
	E11	Cooling 4P	0.166	0.0060 ± 0.0007	0.0011 ± 0.0005	18.33	–	0.580
	E12	Cooling 4P	0.086	0.0050 ± 0.0005	0.0018 ± 0.0004	17.90	–	0.000
	E13	Cooling 4P	0.136	0.0050 ± 0.0005	0.0011 ± 0.0008	14.58	–	0.653
	E14	Cooling 4P	0.165	0.0167 ± 0.001	0.0004 ± 0.001	18.12	–	0.799
	E15	5P	0.169	0.0065 ± 0.004	0.0068 ± 0.0007	27.18	17.07	0.568
	E16	Cooling 4P	0.270	0.0148 ± 0.002	0.0056 ± 0.0006	20.68	–	0.650
Campus 4 (Health Sciences campus)	E17	Cooling 4P	0.264	0.0238 ± 0.002	0.0068 ± 0.002	17.58	–	0.682
	E18	Cooling 4P	0.040	0.0090 ± 0.0009	0.0011 ± 0.0007	18.35	–	0.666
	E19	Cooling 4P	0.418	0.0243 ± 0.003	0.0147 ± 0.002	18.09	–	0.612
	E20	Cooling 4P	0.776	0.0203 ± 0.002	0.0056 ± 0.002	18.70	–	0.533

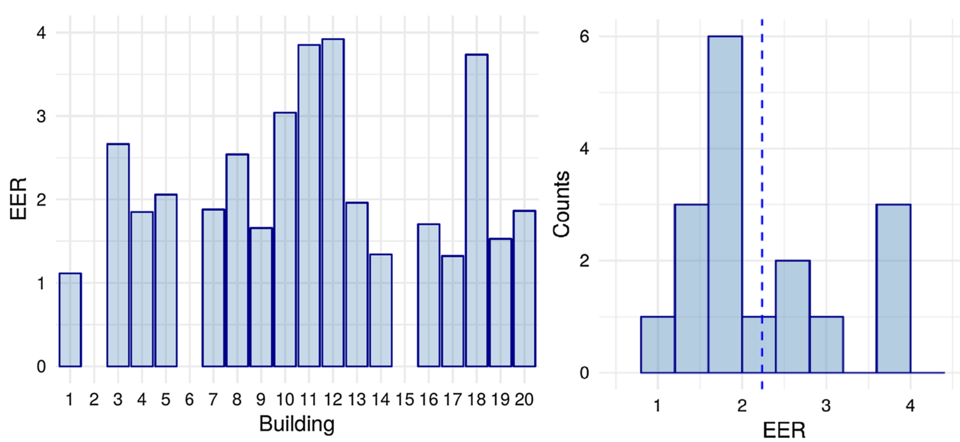


Fig. 12 Bar plot and histograms of the estimated EER of each building

EER = 2 and the median is EER = 1.85, meaning 11 of the 17 analysed buildings are below this level. It can also be seen than only 4 buildings have EER over 3. Considering a high efficient air conditioning unit should have an EER around 2.5-3, it is clear that at least 14 buildings need some improvements in their energy systems efficiency, including better control and regulation systems. Nevertheless, these simplified models for energy consumption cannot capture all the complexities of the real building physics and more insights should be gained to confirm these cooling efficiency estimates.

Figure 13 illustrates the resulting 4P linear model for the daily values of electricity consumption over average daily external temperature, for the E5 building, in Campus 1. Weekends and holiday days have been discarded, as occupancy is very low. The adjusted R^2 for the 4P regression model is 0.77. The resulting change point temperature obtained is 17.4 °C. For temperatures above this cooling base temperature, there is an important dependence of daily electricity consumption with average temperature, mainly associated to cooling loads required in summer period. The slope is also showing an increasing trend with decreasing temperatures below the change point, but the dependence is threefold smaller. This may indicate an increase in consumption for lighting in winter days and/or the use of electric

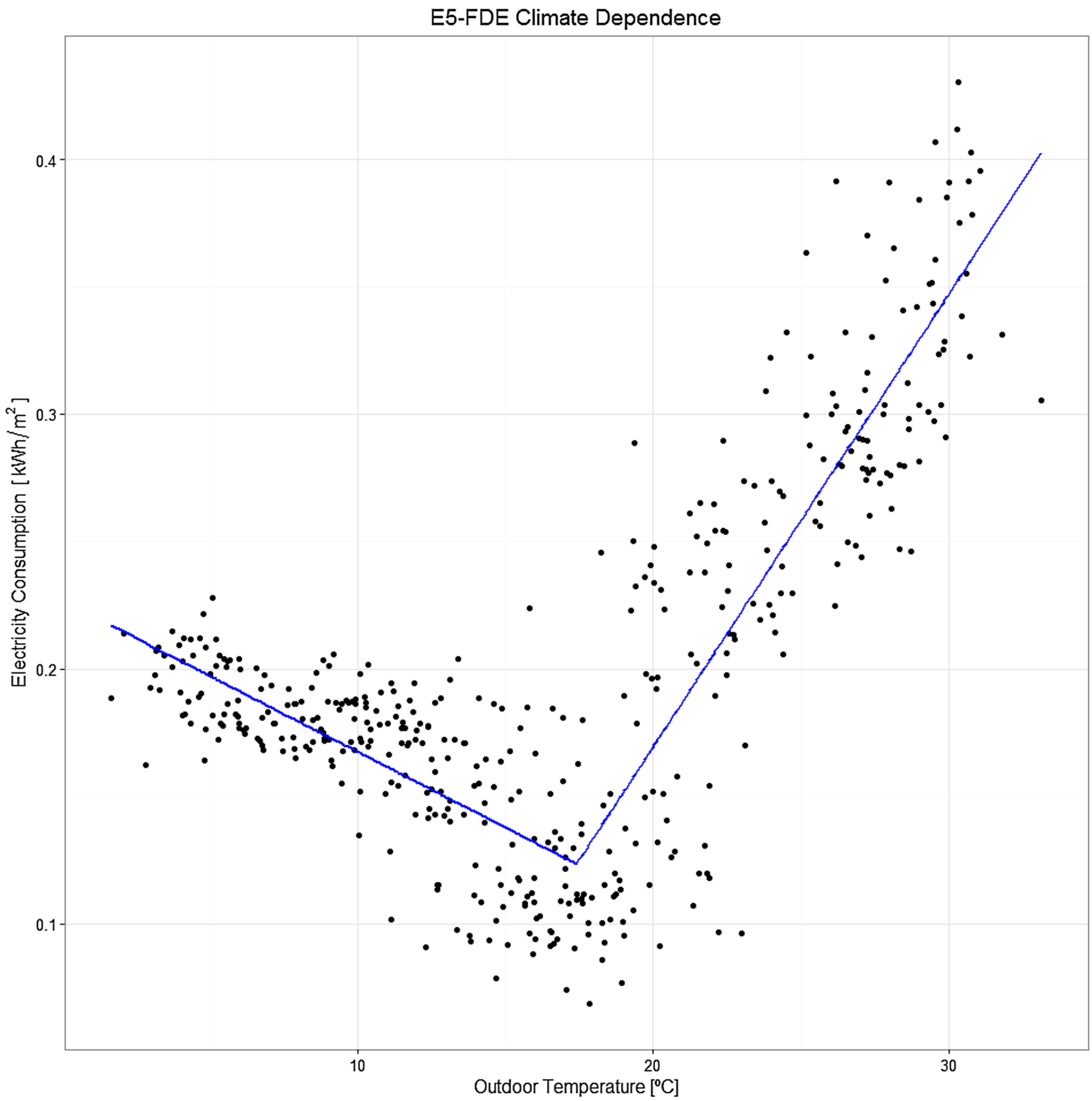


Fig. 13 Two-year points for daily electricity use per gross floor area and cooling 4P regression model for building E5, in Campus 1

heaters in offices to complement the central heating with gas boilers.

Figure 14 shows an example of 5P regression model adjusting the daily electricity consumption as a function of daily average external temperature. This corresponds to E2 building, in Campus 1, where electricity is used both for cooling and heating purposes. In this case, the better fit corresponds to a 3-region model, and two change points, at 16.8 and 21.4 °C, being the former the heating base temperature, and the latter the cooling base temperature. The adjusted R^2 for the model is 0.76. Strong dependence of consumption with temperature is found both in the cooling and heating regions, having the heating region at the left a slightly higher slope. This may point out a lower average COP of the heat pump during the winter season. The inter-seasonal region daily electricity consumption shows a weak correlation with temperature.

NZEB gap and proposals for energy improvements

An analysis of the fulfilment or failure of the four requirements proposed in the draft prEN ISO/DIS 52001-1 and explained in the Methodology section is performed below:

First requirement: building fabric

The existing Spanish building regulation does not incorporate a maximum threshold in relation to the overall heat

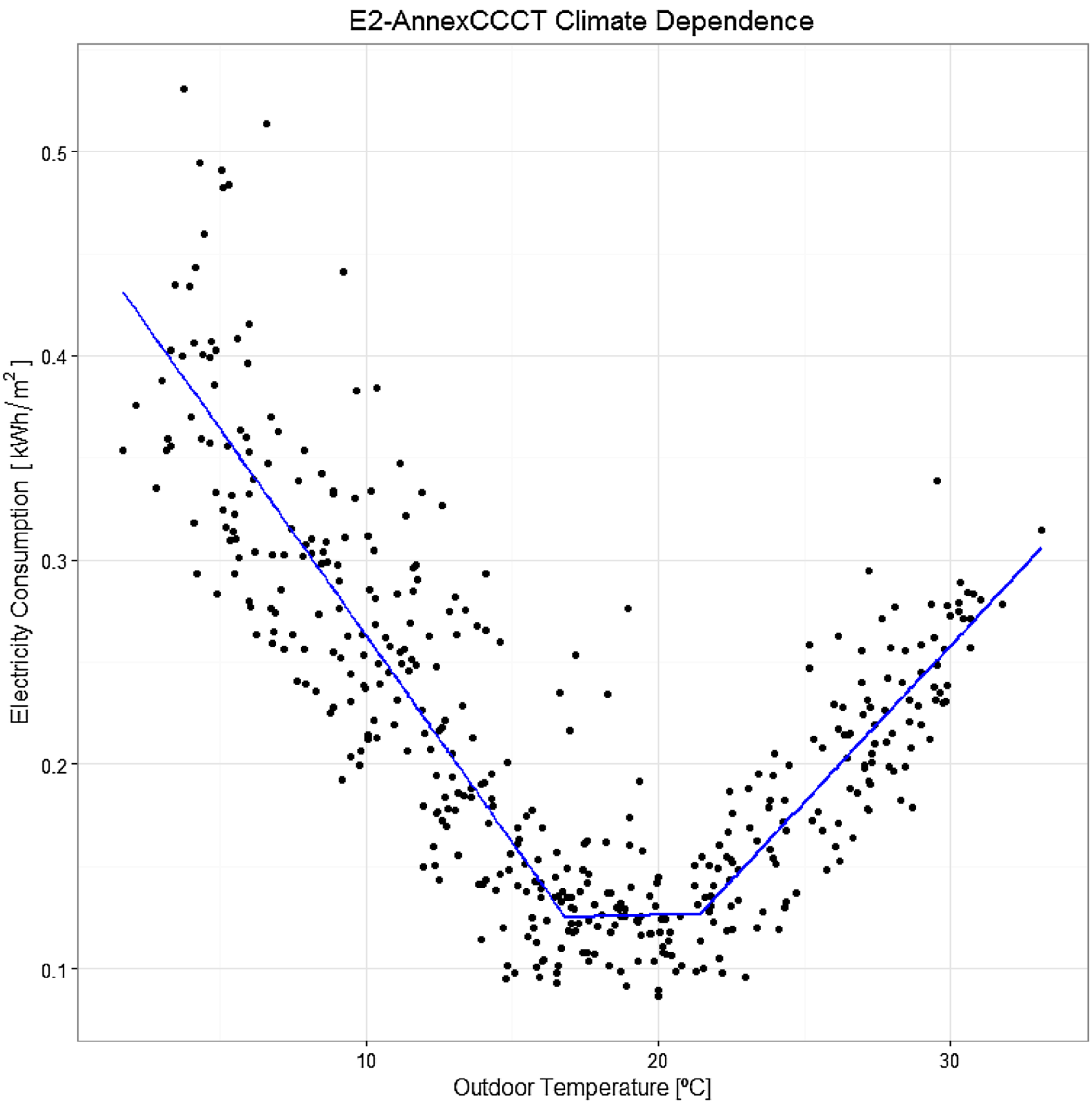


Fig. 14 Two-year points for daily electricity use per gross floor area and cooling and heating 5P regression model for building E2

transfer coefficient. Besides, the estimated heat loss coefficient by gross floor (UH), cannot be assimilated to an overall heat transfer coefficient because the ventilation and air infiltration losses are included and the gross floor area is related but not equal to the overall envelope heat transfer surface. Because of these limitations, this first step is not checked in this research. In any case, most of the buildings were constructed under less stringent regulations in terms of U values than the current Spanish ones. For instance, for the climatic zone of Lleida (D3), the U value of walls should be lower than 0.66 W/m^2 K and the U value of roofs lower than 0.38 W/m^2 K. It is likely then that the actual U values for the UdL buildings are higher than current Spanish thresholds, and these thresholds will be probably higher than the future ones established for Spanish NZEBs. Thus, the probability that all the UdL buildings studied do not meet this first requirement of minimum building fabric quality is very high.

Second requirement: total primary energy use

Thresholds of maximum allowed total primary energy consumption are not yet defined in the Spanish building regulation. However, in December 2016, the Ministry of Development published a document to update the methodology to evaluate high efficient buildings [10]. This document suggested some thresholds based on the ones defined in the Commission Recommendation (EU) 2016/1318 of

July 2016 [33]. For the city of Lleida, which falls within the continental weather region, these maximum thresholds are 85–100 kWh/m^2 year of total primary energy consumption for commercial and offices buildings. Within this maximum limit, the maximum threshold for the non-renewable contribution is in the range of 45–55 kWh/m^2 year and the renewable contribution to the primary energy should be in the range of 45 kWh/m^2 year. These figures represent an overall RES percentage contribution around 45–52% and a primary energy balance, obtained as the difference between the non-renewable primary energy and the primary renewable energy portion, in the range of 0–10 kWh/m^2 year. To evaluate the fulfilment of the maximum thresholds for the total primary energy, the primary energy intensity is calculated for each building. The method to determine it follows the procedure defined in the overarching standard of the EPBD: the total primary energy is calculated as the gas final consumption multiplied by its primary energy factor, added to the multiplication of the primary energy factor for the electricity and the difference between the electricity final consumption and the PV solar production. In the case of Spain, these primary energy factors are defined in the Spanish Code for Thermal Installations (RITE) [34]. Table 5 summarises the primary energy factors for each energy source. The difference between step A and step B is defined in the overarching standard of the EPBD and the main difference between these two procedures is related to the method to evaluate the electricity delivered to the grid. The step A assumes the energy produced on-site is consumed by the building in the same time step and it is used for Energy Performance Building (EPB) services. The Step B assumes that if there is a surplus of energy, it is consumed, at a first instance, by other (non-EPB) services and then it is delivered to the grid. Two components of this delivered energy are defined in the step B, the "grid exported" energy, which is the surplus permanently exported to the grid, and the "temporary exported" which will be redelivered to the building in another time step to compensate a shortage. The steps A and B are controlled by the coefficients K_{exp} and K_{del}, which can take values from 0 to 1. In our case, since the energy generated by the PV systems is relatively small compared to the overall energy consumption of the buildings, the step B will not be activated and only the scenario of step A will be considered.

Table 5 Primary energy factors defined in the Spanish building regulation

Energy	Source	Use	Step	$F_{p,ren}$	$F_{p,nren}$
Electricity	Grid	Input	A	0.414	1.954
Electricity	On-site	To grid	A	1.000	0.000
Electricity	On-site	Input	A	1.000	0.000
Electricity	On-site	To grid	B	0.414	1.954
Natural Gas	Grid	Input	A	0.003	1.190

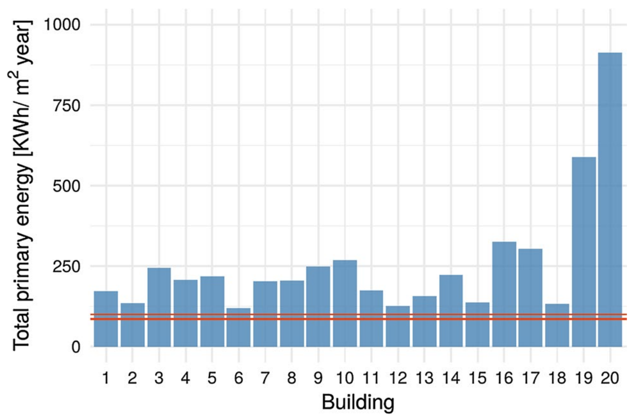


Fig. 15 Calculated total primary energy of each building. The red lines correspond to maximum thresholds estimated for the new Spanish building regulation

In Fig. 15 the calculated total primary energy consumption of each building is shown. The horizontal red lines correspond to the maximum threshold range before estimated for the Spanish building regulation. As can be seen in Fig. 15, the buildings E2, E6, E12, E13, E15 and E18 have primary energy consumption values close to the maximum thresholds (135.68, 119.0 3, 125.49,157.45, 136.14 and 133.38 kWh/m^2 year, respectively). It can also be seen that buildings E19 and E20 are very far from the NZEB concept. The high values of primary energy consumption of these buildings indicate that the non-EPB services, such as specific labs, have a critical impact over the energy performance of these buildings. A more detailed analysis of these other electrical services should be performed. The other 12 analysed buildings have total primary energy consumption values around 2.5–3 times higher than the maximum thresholds, indicating that many improvements should be implemented to reduce this gap.

Third requirement: non-renewable primary energy

As previously mentioned, the maximum threshold for the non-renewable primary energy portion should be in the range of 45–55 kWh/m^2 year. In Fig. 16 the two components of the primary energy, the non-renewable (nren_PE) and the renewable (ren_PE) portion, is shown. The red line corresponds to the maximum threshold of non-renewable primary energy while the green line corresponds to the minimum renewable primary energy contribution. As can be seen in Fig. 16, the buildings E12 and E13 are the ones with lowest non-renewable primary energy consumption; however, their values (97.97 and 97.08 kWh/m^2 year, respectively) are around 2 times bigger than the maximum threshold. Again, the buildings E19 and E20 have

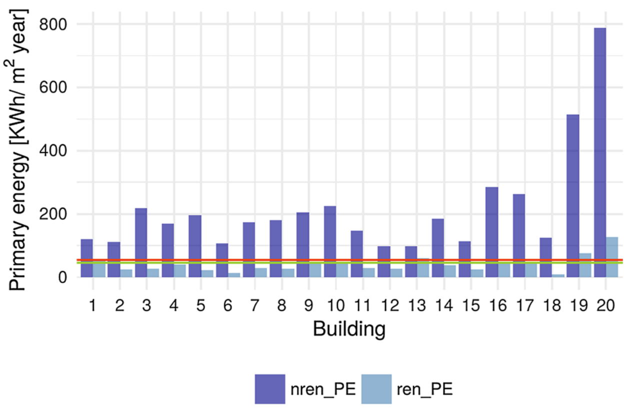


Fig. 16 Calculated renewable and non-renewable primary energy portion of each building

the worse building energy performance. The other buildings oscillate between 106 and 284 kWh/m^2 year which is around 3–5 times bigger than the maximum thresholds for non-renewable primary energy.

Fourth requirement: renewable primary energy and overall NZEB balance

The renewable primary energy contribution is shown in Fig. 16. It should be highlighted that the PV systems are installed in the buildings E1, E4, E9, E10, E11, E12, E13 and E14. However, only the building E13 has a RES contribution higher than the thresholds (60 kWh/m^2 year). The buildings without PV systems and with highest non-renewable primary energy also have the highest contribution of renewable energy. This is due to the primary factors defined for Spain which include a relatively high percentage (17%) of renewables coming from main electricity grid. Because of these primary factors, some buildings have values of renewable primary energy contribution over the maximum threshold. However if we calculate the percentage of RES generated on-site, by removing the renewable energy coming from the grid (see Fig. 17, left graph), we obtain a maximum value of 25% of on-site-renewable primary energy contribution for the building E13, which is almost half of the range of 45–52% established before for the new Spanish building regulation. The other buildings with PV systems have contributions ranging from 3 to 14%. The right plot of Fig. 17 shows the overall primary energy balance of all the analysed buildings. As it can be seen, only the building E13, with a primary energy balance of 36 kWh/m^2 year, is close to the NZEB balance (threshold of 10 kWh/m^2 year). The buildings E1, E2, E6, E12 and E15 are the next buildings with lower primary energy balances, with 68, 88, 93, 70 and 88 kWh/m^2 year, respectively. The other buildings have values in the range of 116–242 kWh/m^2 year which is very far from a nearly zero balance. Again, the buildings E19 and E20 have the worse energy performance with very high values of their primary energy balance.

Although not included in the proposed requirements for NZEB, net CO_2 emissions indicators are worth to be analysed. In this sense, using the Spanish conversion factors from natural gas to CO_2 emissions and from electricity to CO_2 emissions [34], the UdL annual CO_2 emissions associated to energy use are determined. They are above 4700 tonnes of CO_2 in year 2016. This figure takes into account the saved electricity coming from PV production, around 6% of the total electric energy consumption. Electricity use contributes with a 66% and the remaining 34% is associated to gas use. Achieving or at least getting closer to the NZEB limits will of course reduce significantly the current emissions.

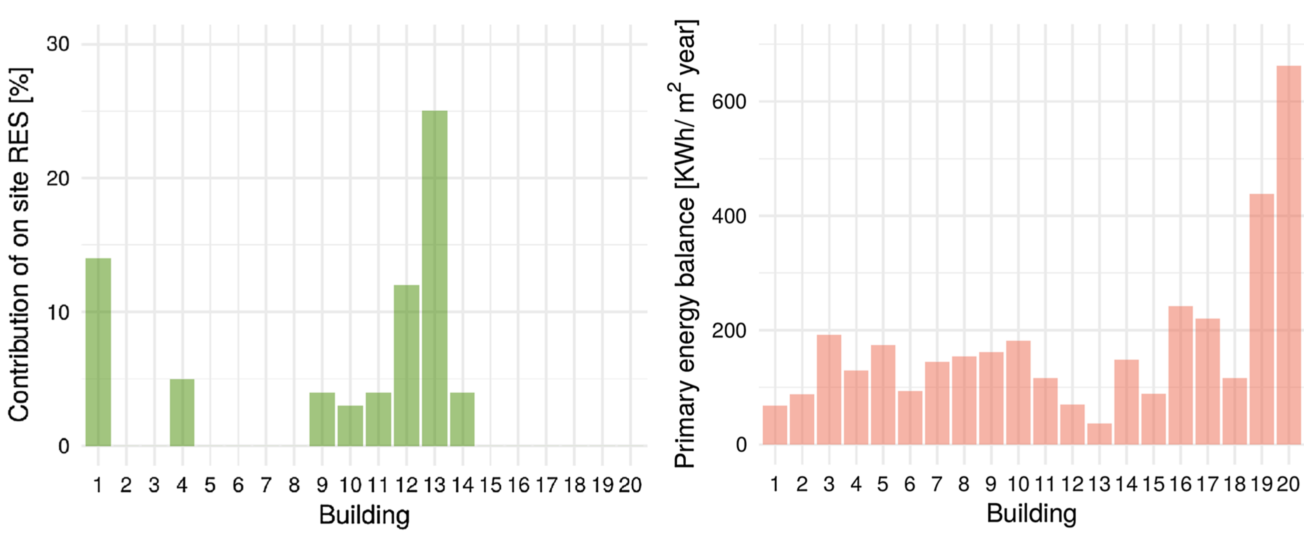


Fig. 17 Percentage of primary renewable energy generated on-site (left plot) and the overall primary energy balance (right plot)

Conclusions

A valid methodology for (1) assessing the energy performance of university campuses, (2) extracting the main energy features of single university buildings, and (3) determining the degree of accomplishment of the proposed requirements for NZEB in the overarching standard of the EPBD have been presented. This methodology is applied to 20 buildings of the University of Lleida (UdL), a Spanish average-size university located in a dry semiarid climate, similar to the one in Madrid. The main conclusions that can be drawn upon the study are:

- Big differences are observed among UdL buildings, both in absolute kWh/year terms and in relative terms, kWh/m^2 year.
- With the exception of Health Science buildings E19 and E20, the energy use ranges for the University Polytechnic of Barcelona (UPC) (40–200 kWh/m^2 year) are similar to UdL range, (50–175 kWh/m^2 year).
- Normalised annual gas consumption per degree days shows a worrying increase in gas usage in all campuses in the last years, a moving trend against achieving efficient buildings. The cause for this trend should be determined, addressed and reversed in the following years.
- A 3% per year efficiency reduction for PV is observed in the UdL PV installations, which is higher than the 1% expected. The probable cause for this reduction is the excess deterioration of the PV cells, which should be verified and properly addressed.
- Electricity usage during unoccupied hours, at nights, weekends and holidays is high. So, substantial energy savings could be achieved with an energy audit that points out unnecessary consumptions during these unoccupied periods and achieves a reduction of the baseload.
- Outdoor temperatures correlate well with monthly gas usage using the degree-days method. Important differences in heat loss coefficients among buildings are observed. Heating base temperatures in the range 14.5–19 °C are also determined.
- Daily aggregated electricity consumption is used together with average daily outdoor temperature to find 4P and 5P linear models for UdL buildings. Cooling base temperatures for the 4P type buildings and cooling and heating base temperatures for the 5P are found in the range 15.7–20.7 °C.
- Assuming an average efficiency value for the gas-driven space heating system, and using the slopes from the 4P and 5P models, estimates for average EER values for the chillers and DX heat pumps used in the cooling period are found for all the buildings. A mean value of EER = 2 is found, below typical values of air conditioning units in the range 2.5–3.
- The detailed procedure to fulfil the requirements to achieve the NZEB category defined in the prEN ISO/DIS 52000-1 was applied for the UdL buildings, to find out the distance from the actual energy balance and the Spanish NZEB future targets. This includes the evaluation of the building fabric quality, the total primary energy use, the non-renewable primary energy use and the percentage of renewable primary energy contribution.
- Results for this procedure in UdL buildings show that none of the 20 buildings is meeting the NZEB requirements, and most of them are between 2 and 16 times above the maximum non-renewable primary energy thresholds. So, actual energy figures are far away from future Spanish NZEB targets and deep energy restoration is needed if University buildings in Spain are to meet these targets in the future.

Recommendation

Future work should be directed to performing detailed energy audits to all buildings, starting with the most inefficient ones. Concrete energy saving measures should be proposed in three main aspects:

- the construction and design of the buildings; by improving the thermal insulations and elimination of thermal bridges in the building envelope and by applying the passive design principles in the building renovation to reduce energy demand,
- the installations; by improving systems efficiency and by incorporating extra renewable energy production,
- user's behaviour; optimising the time and space use of the buildings.

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