Energy Performance Certification of Faculty Buildings in Spain: the gap between estimated and real energy consumption

María Herrando[1], David Cambra[1], Marcos Navarro[1], Lucio de la Cruz[2], Gema Millán[1] and Ignacio Zabalza[1*]

[1]CIRCE - Centre of Research for Energy Resources and Consumption- University of Zaragoza.
Mariano Esquillor 15, 50018, Zaragoza, Spain

[2] University of Zaragoza - Head of the Energy and Environment Section, Spain

ABSTRACT

A systematic method has been established to perform and analyse in detail the Energy Performance Certification of 21 faculty buildings located at the University of Zaragoza (Spain), according to the transposition of Directive 2010/31/EU. First of all, the problem background and a review of the state-of-the-art of the energy certification in buildings is outlined, regarding both the actual state of the Government regulations and the studies undertaken in several countries to assess the energy performance of different types of buildings, residential and non-residential. A summary of the causes found in other studies for the discrepancies between the estimated (by simulation) and actual energy consumption is shown which is afterwards tested and compared with the results found in the present study. Thereafter, the method followed to undertake the buildings' energy performance certification is explained, and the main results found together with the discussion are detailed, comparing

---

*Corresponding author: izabal@unizar.es

actual *vs*. estimated energy consumption in the different case studies and proposing reasons for these deviations. The energy consumption breakdown by uses for several buildings is also analysed, and potential improvements for the simulation software are assessed.

KEYWORDS

Building Energy Certification, energy consumption, user behaviour, energy efficiency measures, invoiced energy consumption, faculty buildings.

1 INTRODUCTION

1.1 Background

Nowadays, there is a significant and continuing desire to increase the energy efficiency and to diversify and decarbonise the energy supply, due to the rise in energy demand, together with the high dependence on fossil fuels and the Climate Change that the Earth is experiencing. In particular, in Europe 50% of the energy demand is imported from countries outside the EU [1], with the energy consumption of buildings accounting for 40% of the total final energy use and 36% of total CO_2 emissions of the EU Member States [2]. All these issues led the United Nations to sign the Kyoto's protocol in 1997, whose main objectives are to reduce the energy demand, increase energy efficiency and reduce greenhouse emissions. In this regard, several directives have already been implemented in Europe, such as the Directive 2010/31/EU on energy performance of buildings [3] and the more recent Directive 2012/27/EU on energy efficiency [4]. These directives aim to implement the measures adopted to reduce the energy consumption in the EU, which will allow, together with an increase in the use of renewable energies, the EU Member States to comply with the Kyoto's protocol, and hence the consecution of the triple objective: 20% reduction of greenhouse gas emissions, 20% increase in energy efficiency and 20% of the energy supply provided by renewable energies.

In the Construction sector, where our study is based, the Directive 2010/31/EU [3] (recast of the Directive 2002/91/EC [5] and reinforced by the Directive 2012/27/EU [4]) has established a common framework for a general methodology to calculate the buildings' energy efficiency, and has also set the minimum cost-optimal requirements for energy performance of buildings that should be applied to both new and existing buildings, to guarantee that the energy cost savings throughout the lifecycle of a building outweigh the investments involved [6]. Additionally, this Directive requires that all new buildings (residential, offices and services) constructed in the EU from 2020 onwards, should be nearly zero-energy buildings, promoting the thermal envelope improvement, in situ renewable energy production and installation of high energy efficient equipment [3].

On the other hand, the Directive 2012/27/EU establishes that, as from 1 January 2014, each Member State shall ensure that 3% of the total floor area of heated and/or cooled buildings owned and occupied by its central government is renovated each year, provided the useful surface is greater than 500 m^2, in order to meet at least the minimum energy performance requirements set in application of Article 4 of Directive 2010/31/EU [4].

In compliance with these Directives, in April 2013, the Spanish Government approved the Royal Decree 235/2013 [7], in which the basic procedure for the energy performance certification of buildings is established. This document requires that the existing buildings rented or on sale shall obtain the Building Energy Performance Certificate. According to the Spanish normative, specific tools for the certification of buildings were generated, which use thermal modelling to simulate the whole building in order to determine its energy performance. In Spain, those tools are CALENER VyP for dwellings and small tertiary sector buildings and CALENER GT (based on DOE-2 calculation engine) for the rest of tertiary sector buildings. These tools are connected with the software LIDER, which has a graphic interface through which the 3D model is implemented and all required inputs are introduced, such as the thermal envelope materials, HVAC installations data and operating hours according to the building user, occupancy profiles, etc. With this information, the software then calculates the energy demand of the building, so as the final energy consumption of the building is calculated, and based on this result, the building energy performance certificate can be obtained.

1.2 State of the art

Andaloro A.P.F *et al.* [8] studied to what extent the 27 European countries had adopted energy certification in buildings. The results concluded that, in 2010, most countries were still at a halfway stage towards achieving excellence, which means that they had not completely implemented and activated the buildings' certification and that they had not adopted yet measures to enhance energy efficiency, or the measures adopted were not fully applied so far. Among the different countries studied, some of them should be highlighted, such as Denmark which was one of the first EU countries to make certification compulsory before the Energy Performance of Buildings Directive (EPBD) (2002/91/EC) [5] and had in 2010 more than half of its buildings already certified. Besides, in this country there are different National Calculation methodologies for residential and non-residential buildings. The study [8] also showed that other countries such as Austria also have different methods of calculation, differentiating residential and non-residential buildings, and dividing the latter into 11 categories: office buildings, nurseries and compulsory schools, secondary schools and colleges, hospitals, care homes, guest houses, hotels, bars and restaurants, meeting places, sports facilities and sales outlets. While other countries such as Germany, United Kingdom, Spain and Portugal only have different calculation procedures distinguishing between residential and non-residential buildings [8]. However, even though these energy policies (Directive 2010/31/EU, Directive 2012/27/EU) are already implemented in most of the countries, a review undertaken by the Buildings Performance Institute Europe (BPIE) [9] concluded that there is still a lack of strong commitments with clear targets to enforce these regulations, as well as a deficit of qualified professionals to undertake the quality control and verification of the energy performance of buildings in most European countries [6]. A more recent study of the BPIE [10] stated that, by October 2014, all 28 EU Member States (MS) had formally transposed the EPBD requirements for the Energy Performance Certification (EPC) in their national legislation. Nevertheless, not all of them had implemented yet an Independent Control System, and only 19 of them had approved official software for the EPC calculation (in the rest of the MS any software that follows the national calculation methodology can be used, but they are not officially verified). Finally, a series of conclusions and recommendations were extracted by the BPIE, such as the need to further improve the enforcement of the EPC schemes in the MS and strengthen the monitoring of the EPC compliance at national and European levels.

Several studies, such as [11], have corroborated the difference between the energy performance of buildings calculated with the simulation software (which is based on Standard Conditions) and their actual energy performance. Specifically, Bordass B. *et al.* [12] studied 16 non-domestic buildings between 1995 and 1999 and concluded that the actual energy consumption of most of the buildings considered was higher than the calculated energy use, which was associated, among others, to the discrepancies between the values assumed in the simulation tool and the actual values found in the buildings. This energy performance gap was also confirmed in other studies in the UK, in secondary schools [13], where Pegg I. *et al.* found that 80% of the buildings studied used more energy than expected; as well as in other type of buildings such as retail, education, offices and mixed use residential buildings [14]. Those studies found several reasons for this discrepancy, in the former case [13] they identified that the introduction of IT equipment such as computers, white boards, etc. in schools, the increase in the indoor environmental quality standards, the extension of the extracurricular activities and the poor control of the building equipment (i.e. HVAC systems) were the major causes for the higher than expected energy consumption; while in the latter study [14] they concluded that the complexity of control strategies, the poor construction practices, the inadequate commissioning and the lack of involvement of contractors in the buildings' adjustment and refinement after completion were also causes of this energy performance gap. From these findings it can highlighted that one of the major causes of these discrepancies is that the actual energy uses in buildings are considered in the design for regulatory compliance.

There are also other case studies in other European countries, in Italy [15] and Denmark [16], which have shown discrepancies of up to 30% between the actual energy consumption and the energy consumption estimated in the simulation tool. These results are in accordance with the results reported by CarbonBuzz within the UK, which show deviations of around 40% for offices and around 30% for educational buildings [17], which corroborates the existence of an energy performance gap between estimated and real energy consumption.

In general terms, this discrepancy is attributed to the following causes [6]:

- Regarding the modelling software and design assumptions:

    - Inaccuracies [18] and uncertainties in the implementation of the modelling inputs [19].
    - Simplifications and inadequacies of the simulation tool [20], which can lead to unrealistic inputs concerning the building quality and design, as well as user behaviour, occupancy patterns and building management [21].

  Some of these inadequacies could be avoided by using modelling software appropriately validated with procedures for Software Accreditation and Verification, such as the ones defined by CIBSE TM33 [22].

- Built quality: Deficiencies and provisioning issues during the construction process and commissioning [23], such as gaps in the insulation and thermal bridges, which usually are not considered in the calculation of the energy consumption [24].
- During the usage stage of the building [25]:
    - Unsuitable building management: if building managers implement inappropriate strategies, a significant portion of the energy can be wasted [18].
    - Operational inefficiencies [23].

  This unnecessary energy waste could be avoided with regular energy audits and re-commissioning exercises [26].

Apart from the previous causes, another important factor which is expected to significantly influence in the real building energy performance is the user behaviour [27], which cannot be implemented in the simulation software, so it can increase the aforementioned energy performance gap. Specifically, Hirst E. *et al.* [28] confirmed that building occupants tend to increase the indoor temperature above the modelling assumptions in winter to feel more comfortable in new buildings, which leads to a shortfall in the expected energy savings. This behavioural response, known as the *rebound effect* [29], was also evidenced by other study undertaken in 2000 in Austria [30] and more recently in a review carried out by Sorrel S. *et al.* [31] in which several studies undertaken in different countries (UK, Austria, Norway, Canada and the US) are reviewed and the main results regarding the *rebound effect* are shown, concluding for example that, in most of the UK cases reported, the mean shortfall is around 55%. Even though most of these studies were undertaken in residential buildings, it is expected to obtain similar results in the case of non-residential buildings, as the building user typically behaves similarly in different environments. For example, Hamilton *et al.* [32] compared predicted and actual electricity consumption in three non-residential buildings and concluded that the measured electricity demand was approximately 60-70% higher than predicted in schools and general offices, while for university campus was over 85% higher [18].

Regarding the Building Shape, some studies refer to it as *relative building compactness (RC)* and define it as follows [33]:

$$RC = \frac{\left(V/A_S \right)_{building}}{\left(V/A_S \right)_{Rf}} \qquad (1)$$

where V and A_S, are the volume and the exterior wall area of the building analysed and of a reference (*Rf*) building respectively [34].

While others call it *shape coefficient* and define it as the total façade surface area to the space volume of a building inside the envelope [35], that is:

$$S/V\,ratio = \frac{A_S}{V} \qquad (2)$$

The latter definition (eq. 2) is used in the present study, due to the particularities of the different buildings considered.

Even though these are different ways to calculate the Building Shape, in general similar conclusions can be extracted: the lower is the *relative building compactness*, the higher is the annual energy use of the building [33]; or the higher the *S/V ratio*, the higher the building's energy consumption is.

1.3 Contribution and main objectives

All the aforementioned studies evidence the energy performance gap between the real and the estimated energy consumption in both non-residential and residential buildings, which must be addressed to ensure that the actual energy policies are effectively complied. In an attempt to identify this gap and provide alternatives to overcome it, in the present study a method has been established to assess the Spanish official software for the Energy Performance Certification of Buildings (EPCB), which has then been applied to 21 different faculty, both academic and research, buildings. This method details: i) the different steps to gather all relevant data and features of the building, ii) how to extract and analyse important information regarding the building's energy performance provided by the software and iii) how to use the results obtained to evaluate the differences between the estimated energy consumption from the thermal modelling and the actual energy consumption obtained from utility bills. It should be noted that the method established could be extrapolated and adapted to assess other energy simulation software.

Specifically, the main objectives of the study are:

- Establish a method to analyse in detail the Spanish official software for the EPCB.

- Characterise the Faculty Buildings’ stock of the University of Zaragoza (Spain).
- Establish a method to perform the Energy Performance Certification of those buildings, adapting the data required by the software to the data available within the Faculty Buildings.
- Detect the points of the major energy consumption and evaluate the reasons.
- Assess the differences between estimated (by simulation) and actual energy consumption.
- Detect limitations of the simulation tool used and propose improvements to shorten the energy performance gap.
- Propose a series of energy efficiency measures to decrease the energy consumption of the buildings.

Therefore, the main contribution of this research paper is the establishment of a method to assess any simulation tool used to obtain the EPCB, which is applied to the specific case of Faculty Buildings in Spain, but that can be extrapolated to other case studies. This specific type of buildings was selected both for their peculiarities and diversity of features, which allows a better detection of restrictions and limitations of the simulation tool.

2 MATERIALS AND METHODS

The Faculty Buildings’ stock of the University of Zaragoza considered in this study consists of 21 Buildings, 15 of them mainly Academic (A) buildings and the other 6 mainly Research (R) buildings. As it can be seen in Figure 1, the buildings studied are significantly different, with a useful area ranging from 800 to 27600 m^2, and a construction year (or refurbishment year when applicable) between 1990 and 2013 (except A12 Building). As consequence, the characteristics of the different buildings are rather different, with several singularities in the constructive solutions, especially in older buildings which have been refurbished (A6 was built in 1946 but refurbished in 1994, A7 was built in 1975 but refurbished in 1995).

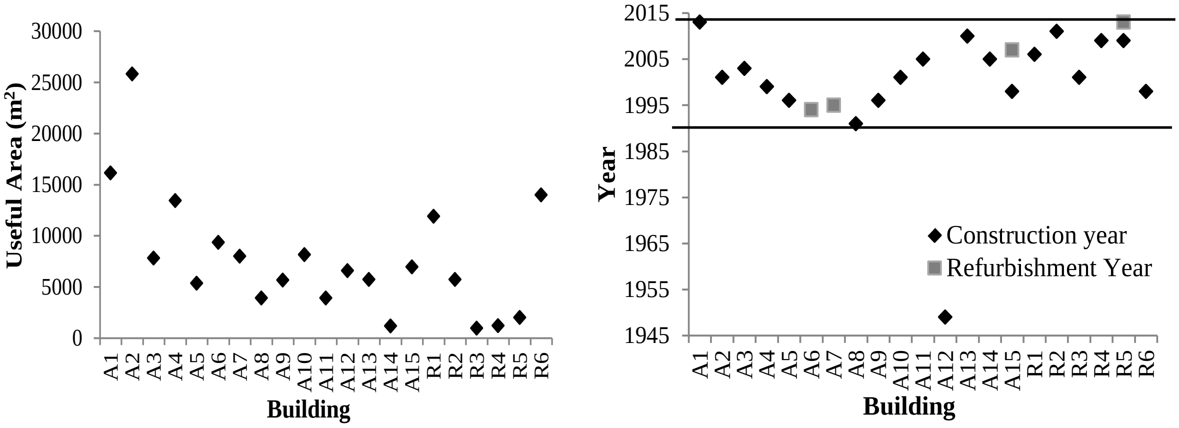

Figure 1. (left) Useful Area and (right) Construction year and refurbishment year for the different Faculty Buildings studied (A = Academic, R = Research).

The method followed in this research for the energy certification process and assessment of the simulation software is detailed in Figure 2.

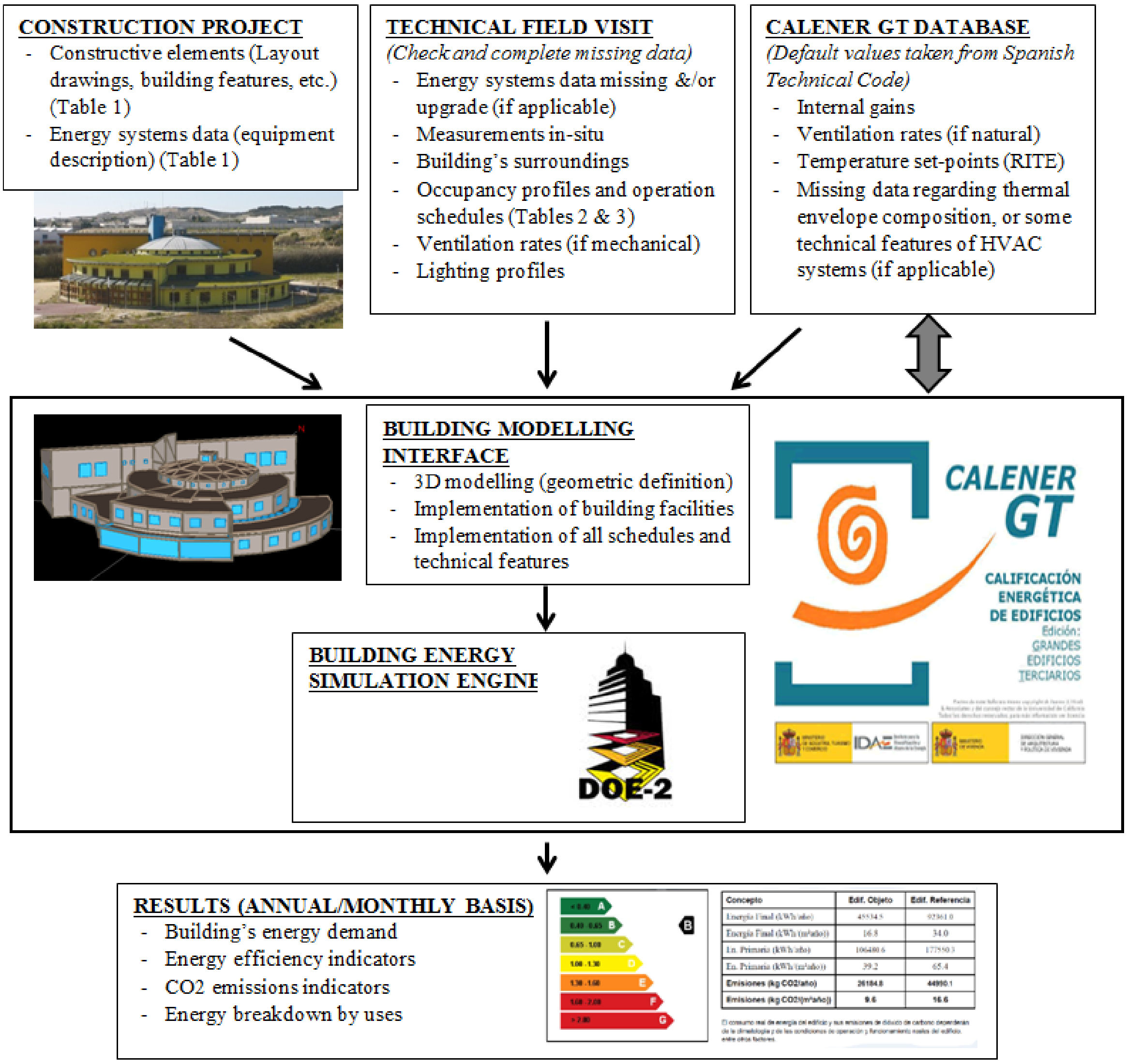

Figure 2. Method followed for the energy certification process and assessment of the simulation software.

The first step consists in gathering all required information to fully characterise the buildings (similar as in other studies such as Ref. [35]). To this end, the following tasks were undertaken:

1. Find the information available in the database of projects in execution and refurbishment in the University of Zaragoza.

2. Field visit to the different buildings to check possible alterations respect to the Project Documentation and to gather information regarding internal loads, as well as HVAC systems and other equipment installed.
3. Take measurements in-situ of the building features: lighting system, glazing, etc.
4. Check the technical features' document of the HVAC systems.
5. Study the building's surroundings to determine the building's shading.

The thermal modelling software used, CALENER GT, utilises DOE-2.2 as calculation engine, developed by the Energy Department of the USA and the Berkeley Laboratory. It includes in its database typical performance curves of different equipment, indispensable for the simulation of the systems, which can be substituted for the curves of specific manufacturers, if the data is provided in the form required by the DOE-2 algorithm [36]. This tool has a graphic interface (LIDER) through which all required inputs are introduced (see Figure 2):

- *Geometric definition and thermal envelope composition* – Introduction of the materials of each layer, thermal properties and thickness, so as the software can establish the building's energy demand.
- *Data of all installations* – technical features of the installations (i.e. HVAC systems), such as nominal power, performance curve, flow-rates and energy consumptions.
- *Occupancy profiles and operation schedules* to establish the building operation profile.

The software then calculates the energy performance of buildings following the procedure and under the general operating conditions specified in the normative. The main outputs are the energy efficiency and environmental indicators required to complete the Energy Performance label requested in the EPBD [5], provided through the energy consumption per square meter of the building (both in terms of primary and final energy), the building's energy demand of heating, cooling, lighting and Domestic Hot Water (DHW) and the global and partial CO_2 emissions (for the different aforementioned services). Apart from that, CALENER-GT incorporates a results analysis tool to analyse the different energy uses within the building (pumps, fans, lighting, etc.), adding an additional value to this tool (see Figure 3). Besides, as it allows a detailed modelling of the thermal and optical properties of windows, it is possible to study the temperature effects on U-value, as well as the incident angle correlations for the solar heat gain properties and visual transmittance [37], serving as a useful tool to provide potential energy efficiency improvements.

Even though the electricity consumption of the office IT equipment (computers, printers, fax/scanners, etc.) and the laboratory equipment (water/vacuum pumps, smoke extractor, furnaces, etc.) could be estimated mathematically (considering the equipment's inventory and their approximated operation hours), or even measured with a Network Analyser, the present study did not consider this item for the Energy Performance assessment. The reason is that the Spanish Regulation for the Energy Performance Certification of Buildings states that only heating, cooling, ventilation, DHW and lighting (only for tertiary buildings) should be included, and therefore the Spanish Official Software does not allow the introduction of office IT and laboratory equipment. However, other commercial software such as *Energy Plus* allows the implementation of IT and laboratory equipment, through the introduction of the nominal power and schedule, but, as that tool is more focused on the building's thermal modelling, the results regarding electricity consumption are not itemised, simply differentiating the lighting energy consumption from the total electricity consumption.

This fact is considered as one of main the drawbacks of this tool, especially in the type of buildings studied in this manuscript, Academic and Research buildings, because those devices account for a significant share of the energy consumption.

The data that should be introduced in the simulation tool to obtain the Energy Performance Certificate is summarised in Table 1. These data is required to characterise: i) the thermal envelope, ii) the building's equipment and iii) the building's use in terms of schedules and internal loads. It should be emphasised that it is significantly complicated to gather all this information, as each building has its particularities and, as shown in Figure 1, some of them are rather old.

Table 1. Data input in the thermal modelling software to define the Building Energy Performance.

Constructive Elements	Energy Systems	Schedules	Internal Load
Plant Layout Drawings	Equipment description:	Heating	Occupancy
Building Sections	Boilers	Cooling	Equipment
Building envelope	Coolers	Ventilation	Internal gains
Glazing data and location	Pumps	Lighting	
Façade description	Lighting		
Roof description	Fan coils		
Floor description	Heaters/radiant floor		
Internal partitions	Domestic Hot Water		
Interior and exterior slab	Solar thermal system		
Walls in contact with ground	Indoor-air conditions' distribution		

Due to the singularities of the buildings and the difficulty of establishing an operation pattern for each of them, general profiles have been defined depending on the main use of the building, that is, the building's stock has been divided in: i) Academic Buildings, in which the main activity is teaching and, ii) Research Buildings, in which research and laboratory activities are predominant. According to this division, Table 2 shows the occupancy profiles in terms of percentage of occupancy throughout the opening times of the building, for weekdays (Monday to Friday) and weekends (Saturday). These percentages are determined based on access control of workers, University Authorities' estimations and academic schedules (there are classes throughout the day from 8 h to 20 h). The occupancy profiles shown in Table 2 are considered constant throughout the year as during summer there are also summer courses and students studying.

Table 2. Schedules and occupancy percentages of the Faculty Buildings studied.

Building	**Occupancy profile**				
	8-9 h	9-14 h	14-16 h	16-18 h	20-22 h
Mon. – Fri.					
Academic (A)	40	100	30	40	20
Research (R)	80	100	35	70	30
Saturday					
Academic (A)	0	2	0	0	0
Research (R)	0	40	5	10	0

Similarly, the hours of operation of the different building facilities should be defined. Despite each building operates the systems differently; a common pattern can be established distinguishing Academic and Research Buildings, as shown in Table 3.

Table 3. Hours of operation of the Faculty Buildings' facilities.

Building	**Heating System**			**Cooling System**		
	Nov.	Dec.-Mar.	Apr.	Jun.	Jul.-Aug.	Sep.
Mon. – Fri.						
Academic (A)	7-13 h	7-21 h	7-13 h	12-18 h	10-20 h	12-18 h
Research (R)	7-17 h	7-21 h	7-17 h	8-21 h	8-21 h	11-19 h

Saturday						
Research (R)	7-17 h	7-21 h	7-17 h	8-21 h	8-21 h	11-19 h

It is observed that Research Buildings have a wider schedule than Academic Buildings, with the former extending the systems’ operation through the evening and also during the weekend (Saturday). Finally, it should be noted that in May and October both cooling and heating systems are turned off due to an energy saving criterion established by the University Authority.

Apart from this, other inputs required are lighting profiles, internal gains due to occupancy and existent equipment and ventilation rates (see Figure 2). In this study, it is particularly difficult to obtain and/or estimate internal gains due to the Buildings’ dimensions, the difficulty of measuring them and the lack of relevant data gathered. Consequently, default values provided in the simulation tool were used, which vary depending on the building’s occupancies and are the ones established in the Spanish Technical Code [38] and other Regulations [39], based on ASHRAE Standards commonly accepted. Specifically, two types of occupancies were considered, one for classrooms and offices (2.5 m^2/person) and other for the rest of rooms and spaces (10 m^2/person), together with the associated internal loads per person provided by CALENER GT: 79.01 W/person for sensible heat and 50.99 W/person for latent heat. Apart from this, the default value for lighting internal gains was also considered, 15W/m^2.

Regarding ventilation rates, the values were obtained depending on the building’s installation (HVAC systems) and when there is no mechanical ventilation installed, the reference values according to Spanish Regulations, which are the air exchanges equivalent to 15m^2/h per person in each space, were used [38], considering the aforementioned occupancies. Lighting profiles were implemented based on the estimations provided by the University Authorities, and the lighting system nominal power was gathered in the technical field visits. Finally, the same temperature set-points were defined for all the buildings: 20ºC in winter and 25ºC in summer, to meet with the requirements established in the Thermal Installation Regulations of Buildings (RITE) [40].

One of the problems found in most of the cases was the absence of sufficient data to complete the inputs required by the simulation tool. The missing data was mainly concentrated in the buildings definition, in particular, in the thermal envelope composition, the absence of the technical features information of the HVAC systems (principally due to their age), and the difficulty to access other facilities to gather the corresponding data. In these cases the default values established in the Spanish Technical Code [39] and provided in the simulation tool were used. Another difficulty detected in the building simulation process was the geometric definition of the buildings. This is implemented graphically through the Spanish tool LIDER [38] which allows a visual 3D building definition where floors, conditioned spaces and enclosures' composition are defined with XYZ coordinates and the corresponding polygons of those parts are created. The complexity of this definition falls on the limitation of the vertex number forming each polygon (maximum of 30 vertexes), the scarce graphic resolution of the software and the geometric complexity of the buildings, which should be simplified to polygons.

Once all information is gathered and implemented in the software, the next step of the method is to analyse the results obtained in the energy simulation in order to assess both the simulation tool and the buildings' energy performance. To this end, first of all the causes for the discrepancies found in the implementation of the buildings are analysed (geometrically and regarding operation schedules) (Section 3.1). Afterwards, the energy breakdown by uses provided by the tool is studied both to identify potential inconsistencies between simulation and reality and correct them as far as possible, and to evaluate the building’s performance (Section 3.2). In this line, the next step is to analyse the energy performance gap between estimated (by simulation) and real (through utility bills) energy consumption (Section 3.3) to identify possible mistakes during the building’s implementation process as well as to propose potential improvements in the simulation software (Section 3.4). Finally, as part of the Energy Certification process and based on the information provided by the software, a series of energy efficiency measures to improve the buildings’ energy performance are outlined (Section 3.5).

3 RESULTS AND DISCUSSION

3.1 Discrepancies in the implementation of the buildings

As it was mentioned in the previous section, the graphic implementation of buildings in the simulation software involves a number of simplifications which consequently generate a deviation in the final buildings’ dimensions. In this particular case, the discrepancy found between the real and the simulated buildings’ surface area is on average 8%, being in most cases the area implemented in the software larger than the real surface area of the building. This is attributed to several factors: i) the stairwell, which in the simulation software is considered as a different zone in each of the floors, ii) installations’ spaces, which sometimes are considered as conditioned zone due to its lack of proper definition, and iii) simplifications required to establish a realistic building’s envelope. All this is expected to consequently impact at some extent the specific energy indicators provided by the simulation software. For example, in R6 building, the surface area deviation found is 7%, being in this case the area implemented in the software lower than the real surface area of the building. In an attempt to correct this deviation, the total energy consumption estimated with the simulation tool was increased by a factor of 1.07 (see column *Simulation Corrected* in Table 4). As consequence, the deviation between estimated and real energy consumption is reduced from 36.4% to 32.3%, when the building is considered as Research. In other cases, the results show important discrepancies in the area simulated, for example in building R5, due to the complication in its geometric definition as this is a singular circular building with a dome that presents significant difficulties in its implementation. As consequence, it can be concluded that an improvement in the implementation mode of the buildings' geometry would reduce the difference between the estimated and real energy consumption. This will be further explained afterwards.

On the other hand, it should be noted that throughout the present study it was observed that the operation schedule established in the different buildings significantly affected the simulation results; therefore it was very important to correctly select the buildings' main use between Academic and Research (see Table 3), to obtain a proper estimation of the building's performance with the software. For example, R6 was initially simulated as Academic building, because it has an important academic load, but the results showed that the discrepancy between the estimated and the real energy consumption was substantial (82%, see Table 4). If on the contrary the operation schedule was incremented by considering it as a Research building, the deviation decreased to 36%. Therefore, it can be concluded that the comparison of estimated *vs*. real energy consumption is very important as it allows the detection of possible mistakes made in the building's definition and implementation in the simulation software.

Table 4. Total energy consumption (estimated and real) and percentage of deviation for R6 building considering it as Research and Academic. Columns "Simulation Corrected" and "Deviation Corrected" shows the total energy consumption and percentage of deviation respectively when the surface area deviation is corrected.

Operation Schedule	**Building Type**	**Total Energy Consumption (kWh/m^2-year)**			**Deviation (%)**	
		Simulation tool	Simulation Corrected	Utility bill	Actual	Corrected
Extended	Research	98	104.4	154.2	36.4%	32.3%
Academic	Academic	28.1	29.9	154.2	81.8%	80.6%

3.2 Energy consumption breakdown by uses

Apart from the Energy Performance Label obtained in the simulation with CALENER GT tool, this thermal modelling software also provides several outputs which can be further analysed to study the energy performance of the building and be able to extract conclusions and suggest possible improvements, both in terms of simulation and building performance. For example, Figure 3 illustrates the itemisation of the electricity consumption in six representative faculty (4 Academic and 2 Research) buildings, including lighting, cooling, heating, fans and pumps and ancillary equipment. A3 and A4 buildings were selected for the heat pump system installed, and A8 is a similar building but with a conventional boiler, so it can be compared with the formers. Additionally, A10 building was selected as it is similar to A8 but it is located in a less warm climate. Regarding Research buildings, R3 is a characteristic Research building with some particularities, and R5 is a singular building constructed with bioclimatic criteria. In general terms, it is possible to observe that, even though there are some similarities within buildings A3, A4 on one side, and A8, A10 and R5 on the other side, there are particularities worthy to comment for each case.

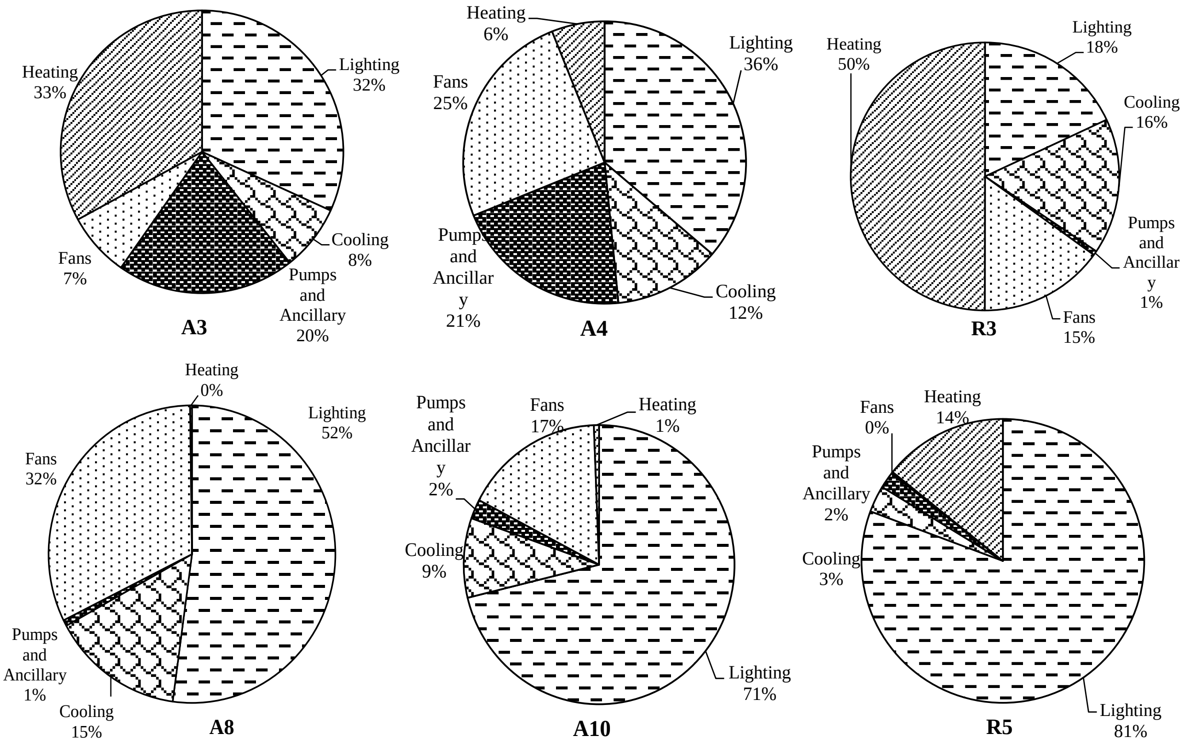

Figure 3. Itemisation of the electricity consumption per year for six representative Faculty buildings.

First of all, it should be highlighted that Figure 3 only considers electricity consumption, and buildings A8, R5 and A10 have a heating system fed with Natural Gas in the two first cases, and Propane in the latter. Details of the energy consumption per year are shown in Figure 4. Figures 3 and 4 show that in A3 and A4 Buildings, pumps and other ancillary equipment have a significant electricity consumption compared to the rest of the buildings, which can be attributed to the open-loop geothermal heat pump system installed, in which the water condensation is achieved with water from a well, at constant temperature (around 17ºC), reducing the heat pump electricity needs. However, a pump system is required to extract water from the well located at 15 m depth; hence significant amount of energy is consumed in pumping. In contrast, R3 building has important energy consumption (50%) for heating, as this is provided by a series of air heat pumps which consume more energy than the well water pump. In this line, Figure 4 shows that the heating consumption for the different buildings analysed differs considerably, which is due to several reasons: i) the disparity of heating systems integrated, mainly regarding the terminal units (hot-water radiators, fan-coils, heat pumps or radiant floors); ii) the dissimilar thermal transmittances of the building's envelope, attributable to the different project requirements; and iii) the location of the buildings, as the cities in which they are located have different climatic conditions.

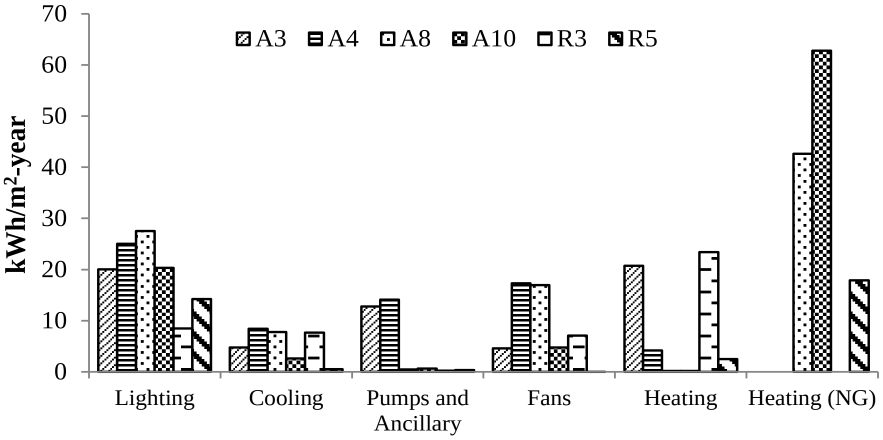

Figure 4. Breakdown of the energy consumption per year for five representative faculty buildings (NG = Natural Gas).

On the other hand, another point to highlight is the high electricity share of lighting in buildings R5 and A10 (81% and 71% respectively), which can be attributed to several reasons. First of all, as commented above, both buildings have a heating system fed with Natural Gas and Propane respectively, therefore the heating share in terms of electricity is very low and negligible respectively. Besides, as shown in Figure 4, the rest of items have very low electricity consumption, with the cooling, pump and fan systems consuming less than 5 kWh/m^2-year in case of A10 and less than 0.5 kWh/m^2-year for R5 building. In fact, both R5 and A10 buildings have within the lowest lighting consumption and the lowest total electricity consumption from the six buildings selected (17.7 kWh/m^2-year and 28.6 kWh/m^2-year respectively). Particular attention should be paid to R5 building, in which the HVAC systems have a very low energy consumption (0.53 kWh/m^2-year for cooling and ventilation). The reason is that the design of the building was undertaken following bioclimatic criteria to achieve a nearly-Zero Energy Building [41]. As consequence, the natural ventilation of the building allows achieving comfort temperatures with very low contribution of mechanical systems.

Therefore, it can be concluded that important information can be extracted from the energy analysis provided by the simulation tool, which allows the identification of the main energy uses, serving as a starting point for the analysis of potential energy efficiency measures, as it will be further detailed in Section 3.5.

3.3 Energy performance gap

Regarding the differences between estimated (by simulation) and actual energy consumption, Table 5 shows a comparison between both consumptions (Simulation tool *vs*. Utility bill) in terms of natural gas, electricity and total energy consumption, as well as the percentage of deviation for each case. The simulation results show that both Academic and Research buildings have a similar energy performance with an average of 83 kWh/m^2-year (A11 and A13 are not included in the calculation due to their particularities), which implies that, at least theoretically, Faculty buildings are constructed similarly concerning HVAC and lighting needs. However, a different conclusion can be extracted when comparing the actual energy consumption of the buildings obtained from the utility bills. In this case, a differentiation can be made between Academic buildings, which have an average total energy consumption of about 85 kWh/m^2-year (A11 and A13 are not included in the calculation due to their particularities), and Research buildings, with around 167 kWh/m^2-year on average (see Figure 5). This distinction reveals the importance of the IT and laboratory equipment in the latter type of building, which would have to be considered in the simulation of buildings, especially when a realistic representation of the building's energy performance is required.

Concerning the Building shape, the results obtained in the present study show that the trend mentioned in Section 1.2, found in previous studies [33,34], is not that clear in this type of buildings, in which the energy consumption is more influenced by other factors such as user behaviour or IT equipment. Table 5 shows that all buildings are within the range 0.17-0.33, with an average of 0.28, being the lowest *S/V ratio* A11 Building, which has a significant part dedicated to sports (high heights), and the highest *S/V ratio* is a typical value (most of the buildings have an *S/V ratio* between 0.27-0.33).

Table 5. Building Shape (S/V ratio); natural gas, electricity and total energy consumption, both estimated by the simulation tool and real consumption detailed in the utility bills, as well as the percentage of deviation for each case, for the 21 faculty buildings studied. The exceptions explained further in the text are highlighted in bold.

ID	**S/V ratio**	**Natural Gas (kWh/m^2-year)**			**Electricity (kWh/m^2-year)**			**TOTAL (kWh/m^2-year)**		
		Simul. tool	Utility bill	% Deviation	Simul. tool	Utility bill	% Deviation	Simul. tool	Utility bill	% Deviation
A1	0.29	39.7	0.0^+	-	79.9	0.0^+	-	119.6	0.0^+	-
A2	0.27	0.0	0.0	-	50.6	75.3	*-33%*	50.6	75.3	*-33%*
A3	0.32	0.0	0.0	-	62.9	71.6	*-12%*	62.9	71.6	*-12%*
A4	0.32	0.0	0.0	-	69.1	52.9	*31%*	69.1	52.9	*31%*
A5	0.31	0.0	0.0	-	36.4	40.3	*-10%*	36.4	40.3	*-10%*
A6	0.26	69.4	42.8	*62%*	29.6	95.4	*-69%*	99.0	138.2	*-28%*
A7	0.27	62.7	42.8	*47%*	67.9	95.4	*-29%*	130.6	138.2	*-5%*

A8	0.33	42.6	75.4	***-43%***	53.0	45.1	*17%*	95.6	120.6	*-21%*
A9	0.29	32.1	69.3	*-54%*	37.6	33.1	*14%*	69.7	102.3	*-32%*
A10**	0.27	62.8	64.0	*-2%*	28.5	37.3	*-23%*	91.3	101.3	*-10%*
A11[†]	0.17	107.6	98.7	*9%*	82.7	54.0	*53%*	190.3	152.7	*25%*
A12	0.31	44.8	21.2	***111%***	44.0	37.1	*19%*	88.8	58.3	***52%***
A13*	0.32	169.3	233.7	*-28%*	76.8	162.3	***-53%***	246.1	396.0	***-38%***
A14	0.30	47.5	86.5	*-45%*	44.1	40.9	*8%*	91.6	127.4	*-28%*
A15	0.31	26.5	30.3	*-12%*	61.8	54.2	*14%*	88.3	84.5	*5%*
R1	0.28	89.2	77.3	*15%*	42.2	302.8	***-86%***	131.4	380.1	***-65%***
R2	0.32	40.8	66.0	***-38%***	34.9	89.7	***-61%***	75.7	155.6	***-51%***
R3	0.28	0.0	21.2	***-100%***	46.9	37.1	*26%*	46.9	58.3	*-20%*
R4	0.22	73.3	96.8	*-24%*	15.3	24.0	*-36%*	88.6	120.9	*-27%*
R5	0.26	17.9	29.6	***-39%***	17.7	102.5	***-83%***	35.6	132.2	***-73%***
R6	0.27	39.5	61.2	*-35%*	58.5	93.0	*-37%*	98.0	154.2	*-36%*

**A significant part is a Residential building hosting students.*

***Heating system fed by Propane.*

[†] *Building with a significant part dedicated to sports.*

[+] *New building in which there are not available yet utility bills for a whole year.*

As regards the discrepancies found between the estimated and real energy consumption, the results show an average deviation of 30%, which is in accordance with previous studies [15–17]. It should be noted that these deviations are significantly higher for Research buildings than for Academic buildings (45% *vs*. 23% on average), which is consistent with the previous statement about the importance of considering IT and laboratory equipment in the former case. Table 5 shows that most Academic buildings have negative deviations as the simulation results are lower than the actual energy consumption. In particular, the discrepancies found in buildings A2, A6, A9 and A14 should be noted, which are mainly due to the significant number of offices with usually high occupancy levels. As consequence, the IT equipment increases notably and the user behaviour becomes more important, due to the manual management of the installations in these offices (in the field visits it was observed that in many cases the equipment is not disconnected when not in used nor at night).

Additionally, some exceptions which are considered worthwhile to explain further are highlighted in bold in Table 5. In A12 building the estimated natural gas consumption is more than double the real consumption, being the estimated electricity consumption also higher, which infers that the building is being significantly underused. This was corroborated in the field visit, when it was observed that several zones and rooms of the building were empty and hence the terminal heating units in these spaces were closed. However, from the Energy Performance Certification point of view, these zones are habitable and therefore the Official simulation software considers them with the general building's profile. On the other hand, Figure 5 shows that A13 building has significantly higher energy consumption than the rest of Academic buildings, because part of the building is dedicated to host students (some rooms are dorms). Consequently, the heating needs are higher than for a pure academic building, and also the Domestic Hot Water needs are considerably higher. Another consequence of being a partially residential building is the greater influence of the user behaviour, especially in the electricity consumption, which is confirmed with the large deviation found between estimated and real electricity consumption (more than 50%).

One limitation of the software was found when simulating A8 building, which has a swimming pool heated at constant temperature that cannot be properly implemented in the tool. Consequently, even though several simplifications and approximations were made, the natural gas consumption estimated is still rather lower than the actual consumption (see Table 5).

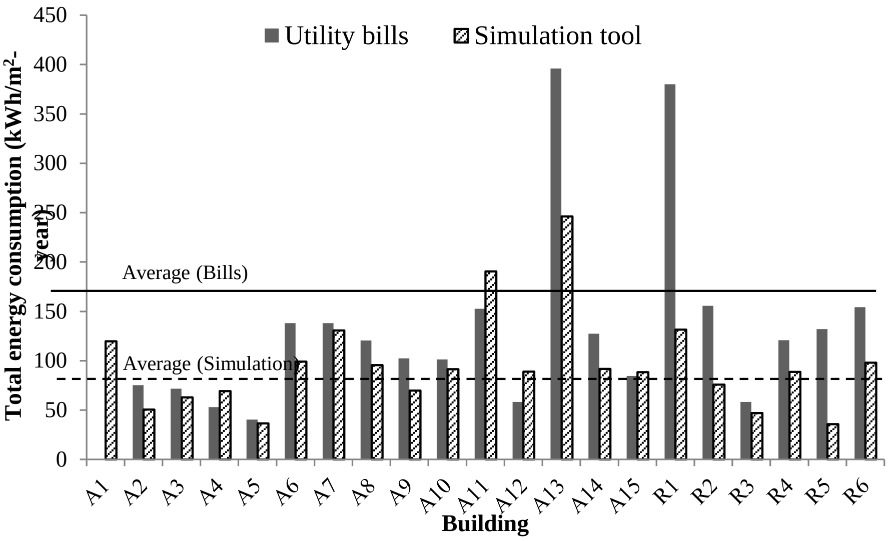

Figure 5. Total Energy consumption, both estimated by the simulation tool and real consumption detailed in the utility bills for the 21 faculty buildings studied. Solid line represents the average real energy consumption and the dotted line the average estimated energy consumption.

As previously commented, the larger discrepancies are found in Research buildings. The greatest deviation occurs in R5, which shows an overall deviancy of 73% (39% in natural gas consumption and 83% in electricity consumption (see Table 5 and Figure 5)), due to several reasons. First of all, it should be considered that this building was designed under the nearly-Zero Energy Building criterion [32] and hence the passive elements of the buildings theoretically yield to a very low energy demand. However, due to the real building characteristics and the underestimation of the building occupancy in the design phase, the actual energy consumption of the building is significantly higher than expected. For example, the important increase in building users has consequently augmented the IT equipment (computers, printers, etc.) and hence their correspondent thermal loads, requiring more ventilation and cooling to achieve thermal comfort. The lighting requirements are also considerably higher than expected for the same reason. Furthermore, it should be kept in mind that this Research building has several laboratories whose equipment cannot be implemented in the simulation software. Similarly, R1 is a pure Research building with numerous auxiliary equipment, clean rooms (with strictly controlled parameters such as temperature, humidity, air renovations, etc.), IT equipment, internet servers, etc., which cannot be implemented in the simulation tool. As consequence of all the above, the real electricity consumption of R1 is around 7 times higher than estimated (see Table 5 and Figure 5).

Another software limitation found for the simulation of research buildings is the impossibility of implementing specific equipment, typical in this type of buildings. For example, in R2 there is an important deviation both in natural gas and in electricity consumptions due to the furnaces, forge, sculpture equipment and other installations available in the different workshops of the building. In this line, R3 building does not have natural gas consumption according to the simulation results, but the actual building has a natural gas bill. The reason is that natural gas is required for the stoves located in the laboratories, but this consumption cannot be implemented in the software (see Table 5 and Figure 5).

It can be concluded that the study of the differences between estimated (by simulation) and actual energy consumption allows the identification of not only potential mistakes made during the building's energy modelling, but also software limitations which increase the energy performance gap.

3.4 Potential improvements in the simulation software

Bearing in mind all previous results and the software limitations found throughout the present study, some possible improvements in the simulation tool are proposed to shorten the energy performance gap existent between the real and the estimated (simulated) energy consumption in Faculty buildings:

- *Improvement in the surface area graphic implementation*: the impossibility of defining curve shapes in building surfaces (only polygons can be introduced) entail an error in the surface area to simulate. Other issues to be improved are the definition of stairwell zones, communication centres and installation cabinets to avoid the consideration of these spaces are conditioned zones.
- *Default usage profiles,* to properly define in the simulation tool the operation schedules of buildings, as this is crucial to achieve reliable results. As sometimes it is difficult to precisely know the building operation schedules, it is believed that a broaden database that includes different operation schedules in diverse spaces, buildings, installations, etc., should be integrated in the software.
- *Data implementation:* as commented in previous sections, one of the difficulties in the Energy Performance Certification of Buildings is the data collection due to the significant amount of data to be gathered. To facilitate this process, it is proposed to establish a database with typical constructive solutions of façades (according to regulations, construction type, climatic zone, etc.), interior partitions, roof or any other envelope part. Besides, for installations' implementation, the establishment of a link to the manufacturers' catalogue will ease the data introduction process.
- *Possibility of implementing the energy consumption of specific equipment*: as observed in the results shown previously, usually Faculty buildings have a significant energy consumption in specific equipment such as IT equipment, engines, serves, fridges, etc., which cannot be implemented in an Energy Performance Certification software. However, if the simulation tool allowed an easy estimation of the energy consumption of these

equipment, it would provide more realistic results, reducing the energy performance gap and adding another interesting indicator in the Building Energy Performance Certificate.

3.5 Potential energy efficiency measures to improve the building’s performance

Finally, as part of the Energy Performance Certification of Buildings, the Spanish regulations [7] indicate that the Certificate should incorporate a proposal of technical and economically viable energy efficiency measures to decrease the energy consumption of the buildings. As an example, this paper presents the application of two different energy efficiency measures to reduce the thermal energy consumption and another two to reduce the electricity consumption of the building. The potential implementation of the energy efficiency measures proposed depends on two main factors, the technical easiness of implementation, subject to each specific building due to its different features, and the energy performance results obtained in the simulation, which provide interesting energy efficiency indicators.

3.5.1 Reduction of the thermal energy consumption of the building

The two main alternatives to reduce the thermal energy consumption of a building are, first of all, to improve the building’s envelope to reduce the thermal energy demand and secondly to improve the energy efficiency of the heating system to reduce the energy consumption.

The building’s envelope plays a major role in regulating the indoor environment, as it controls the flow of energy between the interior and exterior of the building. A well-designed envelope allows the building to provide comfort for the occupants and respond efficiently to heating, cooling, ventilating, and natural lighting needs.

One option to improve the building’s envelope is to increase the insulation in walls through the implementation of a thermal insulation material in the interior of the façade, reducing the useful surface of the habitable areas. This measure is especially interesting in some of the buildings considered in this work as in some of them it is not allowed to act on their exterior appearance due to their historical value. The other possibility is to incorporate the insulation in the exterior, without occupying useful surface and removing the potential thermal bridges of the building.

In this case, it is proposed to improve the building’s envelope insulation of R1 building. Due to the façade composition, ventilated with detachable metal panels, it is possible to increase the thermal insulation without losing useful surface, without disrupting users’ work and in an economical way. The solution proposed consists in the implementation of an extra XPS layer of 5 cm (0.029 W/K-m) between the metal structure and the precast concrete panels. The results show that it is possible to achieve around 1.5% energy savings after the application of this measure, which is expected to cost around 7.3 €/m^2. Consequently, the discounted payback period associated is notably high, around 40 years (considering an electricity price of 0.13 €/kWh, a natural gas price of 0.05 €/kWh and an interest rate of 5%). It should be noted that this low percentage of energy savings is due to the already good thermal transmittance of R1 building (U-value around 0.4 W/m^{2}K). As all buildings considered in this research have a similar U-value, this building was selected because it allows an easier implementation of an extra insulation layer due to the ventilated façade, and therefore the investment required is lower.

On the other hand, when it is not possible or feasible (both economically and/or technically) to reduce the building’s thermal demand, the improvement of the heating system installed should be considered. In particular, in several of the Faculty Buildings considered, which have installed low efficiency heating systems (usually conventional boilers with an efficiency of 75-85%), it is especially interesting to replace them for high efficient systems available in the market, such as the condensing boiler, with an efficiency up to 98% [42] (or beyond 100%, as Ref. [43] states, when it is measured on the lower heating value). With this upgrade, both the final energy consumption and the associated CO_2 emissions are reduced.

For example, it has been identified that in A8 building the energy consumption due to heating accounts for 45% of the total energy consumption and this is provided by a conventional boiler. Therefore, potential energy savings are expected if the heating system is improved. Table 6 shows that it is possible to achieve nearly 25% of energy savings if the actual conventional boiler is replaced by a condensing boiler. Considering an estimated investment of around 5 €/m^2, the discounted payback period of this energy efficiency measure is less than 8 years (considering a natural gas price of 0.05 €/kWh and an interest rate of 5%), value much lower than the one obtained with the previous energy efficiency measure.

Table 6. Energy consumption before and after the replacement of the conventional boiler by a condensing boiler in A8 Building, energy savings achieved and investments necessary.

Building	**Energy Indicator (kWh/m^2-year)**		**Final Energy Consumption (kWh/m^2-year)**		**Energy Savings**	**Investment**
	Final	Primary	Electricity	Natural Gas	%	€/m^2
Actual	95.6	181	52.96	42.66		-
Improved	85.1	170.4	52.96	32.16	24.6%	4.74 €/m^2

3.5.2 Reduction of the net electricity consumption of the building

Similarly as before, the two main options to reduce net electricity needs of a building are: firstly to decrease its electricity consumption, and secondly to generate electricity within the building to reduce the amount of energy to be imported from the grid.

As Figure 3 shows, the type of buildings analysed have a significant share of electricity consumption for lighting, due to the specific requirements of Faculty Buildings in this regard (Academic and Research environments need high illuminance values). For instance, in the case of R5 building, the electricity consumption of lighting accounts for 81% of the total electricity consumption and 40% of the total energy consumption, so it is believed that energy efficiency measures applied to this item may lead to important energy savings. Hence, the first energy efficiency measure proposed is the replacement of the actual lighting system, composed by tubular fluorescent lamps of 36 W, by LED lamps of 18 W, reducing the total installed capacity by 50%.

As shown in Table 7, the replacement of the actual lighting system allows energy savings of around 40% per year which, together with the reduction in maintenance costs and in lights replacement (as the lifespan of LED technology is significantly higher than for fluorescent lamps), leads to a discounted payback period of around 6 years (considering an electricity price of 0.13 €/kWh, and an interest rate of 5% for electricity and 2% for O&M costs).

Table 7. Energy consumption before and after the replacement of the actual lighting system in R5 Building, energy savings achieved and investments necessary.

Building	**Energy Indicator (kWh/m^2-year)**		**Final Energy Consumption (kWh/m^2-year)**		**Energy Savings**	**Investment**
	Final	Primary	Final	Primary	%	€/m^2
Actual	35.6	64.1	17.66	45.97	-	-
Lighting upgrade	30.7	47.9	10.60	27.59	40%	20 €/m^2
Integration PV system	35.6	61.6	17.66	43.54	5.3%*	2 €/m^2

**Primary energy savings*

On the other hand, to reduce the amount of electricity bought from the grid, it is proposed to integrate a Photovoltaic (PV) system in the building's roof with a peak capacity of 5.2 kW. As shown in Table 7, the investment required per square meter is significantly lower than before (around 10 times lower) but the energy savings achieved are also lower, around 5% (of primary energy per year). As consequence, the discounted payback period of this option is about 7 years, slightly higher than for the former case. It should be considered that this measure does not reduce the energy consumption of the building; the primary energy needs decrease thanks to the generation in-situ of renewable energy.

This Section 3.5 demonstrates that an adequate assessment of the information provided by the simulation software allows detecting the main energy consumption points and inefficiencies of a building in which there is more potential to achieve energy savings through the application of feasible energy efficiency measures.

4 CONCLUSIONS

Within the present study, a method has been established to obtain the Energy Performance Certification of Faculty Buildings. To this end, and according to the Spanish Regulations, the Spanish official software, CALENER GT, was used. The results provided by this tool have been analysed in detail to extract as much information as possible about the building's energy performance as well as to identify limitations of the software and propose potential improvements to shorten the difference between real and estimated energy consumption.

With this method, the Faculty Buildings' stock of the University of Zaragoza has been characterised, and the Energy Performance Certificate of each building has been obtained. The characterisation undertaken shows that, even though the stock has been divided between Academic and Research buildings, the useful area and the construction year significantly vary for each of them, with most of them in the range of 800 to 27600 m^2 useful area and a construction year (or refurbishment year when applicable) between 1990 and 2013 (except A12 Building).

The Certification results show that 62% of the buildings have an energy efficiency label C and 24% have a D label (in an A to G scale); therefore it can be concluded that most of the Faculty buildings studied are within the average of CO_2 emissions. Regarding the final energy consumption, the simulation results show that both Academic and Research buildings have a similar energy performance with an average of 83 kWh/m^2-year. These results suggest that all these buildings were designed and constructed with similar patterns regarding HVAC and lighting needs.

The singularities of these buildings represented a significant effort in their implementation in the software, due to both the particularities of each building, difficult to simulate in the tool, and the limitations inherent to the existent Certification software. The following restrictions were found in the official Energy Performance Certification software (CALENER GT): the graphic implementation of buildings is complex, buildings' operation schedules available in the simulation tool are considerably generic and the inputs required regarding the building's envelope, materials and installations are substantially exhaustive.

Similarly as in other studies, the actual energy consumption of the majority of the buildings studied is higher than what it is estimated in the Certification software. An average deviation of 30% is found, value in accordance with previous studies, being, as expected, the discrepancies for Research buildings significantly higher than for Academic buildings (45% *vs*. 23% on average). One of the main reasons attributed to these discrepancies is that standard operating conditions are considered in the simulation tool instead of the real ones. This issue makes it very difficult to identify to what extent the discrepancies found are due to this deviation or to other specific issues associated with the building construction. In this line, other subsequent consequence is that the energy efficiency measures which should be proposed in the Energy Performance Certificate are estimated considering standard conditions instead of real operating conditions and therefore they may not actually produce the expected results to comply with the Building Regulation requirements.

Another factor that notably increases this energy performance gap is the energy consumption of IT and laboratory equipment, especially in the case of Research buildings, as these equipment cannot be implemented in the software, even though in these type of buildings an important share of the total energy consumption is due to their energy consumption. In this regard, the simulation results for Research buildings (such as R2 and R3) show how the impossibility of implementing specific equipment, such as furnaces, forge, sculpture equipment and other workshops' installations, typical in this type of buildings, notably intensifies this gap. Therefore it can be concluded that, if a realistic representation of the building's energy performance is required, IT and laboratory equipment should be considered.

One important factor that cannot be implemented in the simulation tool but has proved to significantly affect the real energy consumption of the building is the user behaviour. The influence of the user in the actual energy consumption was especially discerned in buildings A2, A6, A9 and A14, which have a significant number of offices with usually high occupancy levels. As consequence, although the IT equipment increases notably and hence the energy performance gap is expected to increase; the user behaviour becomes more important. The reason for this is the manual management of the installations in these offices, which in most cases do not coincide with the operation schedules set in the simulation tool. In fact, during the field visits it was observed that, in many cases, the office equipment (computers, printers, etc.) is not turned off when not in used and the users confirmed that they do not usually disconnect computers at night. Consequently, the real energy consumption of the building is significantly higher than expected. Even though the user behaviour is very difficult to implement in a simulation tool, mainly due to their unpredictable nature, it is believed that the discrepancies between the estimated and the real energy consumption could be reduced by implementing more realistic operation schedules.

Bearing in mind all the previous software limitations and restrictions, a series of potential improvements in the simulation tool are proposed in this research, such as the improvement in the surface area graphic implementation, for example through the importation of an AutoCAD 3D model; the definition of default usage profiles and a more detailed database within the software or the possibility of implementing the energy consumption of IT equipment.

To complement the present study, and in accordance with the Spanish regulations, a proposal of various technical and economically viable energy efficiency measures to decrease the energy consumption of the buildings has been undertaken. Four different measures to reduce the thermal (two of them) or the electrical (the other two) energy consumption are proposed, applied to three Faculty buildings. These measures cover from simple actions such as lighting replacement to refurbishment actions like envelope insulation improvement. The results show that the investment required for energy efficiency improvements as well as the payback period significantly vary depending on the specific building and the measure, therefore general rules cannot be established. However, some guidelines can be defined:

- *The energy consumption breakdown by uses should be carefully studied before making any decision*: the items with higher energy consumption share should be first considered as a small change in them can lead to significant energy savings.

- *The reduction of the energy demand should be prioritised:* for example, the reduction of the lighting energy consumption by lamps replacement should be considered before installing a PV system to satisfy this energy demand. However, in some cases, the high investment required to reduce the energy demand may not outweigh the energy savings, especially when a more affordable measure to reduce the final energy consumption can be implemented. For instance, the improvement of the building's envelope insulation proposed for R1 building has a high investment cost (over 7 €/m^2) and payback period (40 years), while the replacement cost of a conventional boiler by a condensing boiler, proposed for A8 building, is significantly lower (less than 5 €/m^2) as well as its associated payback period (less than 8 years).

Finally, an energy efficiency measure that should be always considered in the first place is to raise the user behaviour awareness. It is believed that by teaching building users good practices as well as by increasing the public awareness in this matter, potential energy savings can be achieved.

NOMENCLATURE

(A) Building – Academic Building

BPIE – Buildings Performance Institute Europe

DHW – Domestic Hot Water

EPBD – Energy Performance of Buildings Directive

EPC – Energy Performance Certification

EPCB – Energy Performance Certification of Buildings

EU – European Union

HVAC – Heating Ventilation and Air Conditioning

IT – Information and Technology

NG – Natural Gas

O&M – Operation and Maintenance

MS – Member States

(R) Building – Research Building

RITE –Thermal Installation Regulations of Buildings

ACKNOWLEDGEMENT

The authors acknowledge the collaboration of the University of Zaragoza (Spain) in the study undertaken for facilitating the data access of the buildings analysed.

REFERENCES

[1] European Commission. Towards a European strategy for the security of energy supply. Brussels: 2000.

[2] European Commission. Energy efficiency: delivering the 20% target. Brussels: 2008.

[3] The European Parliament and the Council of the EU. Directive 2010/31/EU of the European parliament and of the council of 19 May 2010 on the energy performance of buildings (recast). 2010.

[4] The European Parliament and the Council of the EU. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC. 2012.

[5] The European Parliament and the Council of the EU. Directive 2002/91/EC of the European parliament of the council of 16 December 2002 on the energy performance of

buildings. 2003.

[6] Burman E, Mumovic D, Kimpian J. Towards measurement and verification of energy performance under the framework of the European directive for energy performance of buildings. Energy 2014;77:153–63. doi:10.1016/j.energy.2014.05.102.

[7] The Ministry of Presidency of the Spanish Government. Royal Decree 235/2013, of 5th of April 2013, by which it is approved the basic procedure for the Energy Performance Certification of Buildings. 2013.

[8] Andaloro APF, Salomone R, Ioppolo G, Andaloro L. Energy certification of buildings: A comparative analysis of progress towards implementation in European countries. Energy Policy 2010;38:5840–66. doi:10.1016/j.enpol.2010.05.039.

[9] Building Performance Institute Europe (BPIE). Europe's buildings under the microscope, A country-by-country review of the energy performance of buildings. Build Perform Inst Eur 2011. http://www.bpie.eu/uploads/lib/document/attachment/20/HR_EU_B_under_microscope_study.pdf (accessed March 27, 2015).

[10] Arcipowska A, Anagnostopoulos F, Mariottini F, Kunkel S. Energy Performance Certificates across Europe: A Mapping of National Approaches. Build Perform Inst Eur 2014:60.

[11] Cohen R, Standeven M, Bordass B, Leaman A. Assessing building performance in use 1: the probe process. Build Res Inf 2001;29:85–102.

[12] Bordass B, Cohen R, Standeven M, Leaman A. Assessing building performance in use 3: energy performance of the probe buildings. Build Res Inf 2001;29:114–28.

[13] Pegg IM, Cripps A, Kolokotroni M. Post-Occupancy Performance of Five Low-Energy Schools in the UK. ASHRAE Trans 2007;113.

[14] Carbon Trust. Closing the gap - Lessons learned on realising the potential of low carbon building design. Carbon Trust 2011.

[15] Tronchin L, Fabbri K. A Round Robin Test for buildings energy performance in Italy. Energy Build 2010;42:1862–77. doi:10.1016/j.enbuild.2010.05.022.

[16] Petersen S, Hviid C. The European energy performance of buildings directive: comparison of calculated and actual energy use in a Danish office building. Ibpsa-engl. first Build. Simul. Optim. Conf. (BSO 2012), Loughborough: 2012.

[17] UCL Energy Institute. Summary of audits performed on CarbonBuzz. 2013.

[18] Menezes AC, Cripps A, Bouchlaghem D, Buswell R. Predicted vs. actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap. Appl Energy 2012;97:355–64. doi:10.1016/j.apenergy.2011.11.075.

[19] Ahmad M, Culp CH. Uncalibrated Building Energy Simulation Modeling Results. HVAC&R Res 2006;12:1141–55.

[20] Lomas KJ. The U.K. applicability study: an evaluation of thermal simulation programs for passive solar house design. Build Environ 1996;31:197–206. doi:10.1016/0360-1323(95)00050-X.

[21] Raslan R, Davies M. Results variability in accredited building energy performance compliance demonstration software in the UK: an inter-model comparative study. J Build Perform Simul 2010;3:63–85.

[22] Chartered Institution of Building Services Engineers. CIBSE TM33: standard tests for the assessment of building services design software. London, UK: 2006.

[23] Dasgupta A, Prodromou A, Mumovic D. Operational versus designed performance of low carbon schools in England: bridging a credibility gap. HVAC&R Res 2012;18:37–50.

[24] Bordass B, Cohen R, Field J. Energy performance of non-domestic buildings – closing the credibility gap. Int. Conf. Improv. energy Effic. Commer. Build., Frankfurt, Germany: 2004, p. 1–10.

[25] Bordass B, Cohen R, Standeven M, Leaman A. Assessing building performance in use 2: technical performance of the Probe buildings. Build Res Inf 2001;29:103–13.

[26] Way M, Bordass B. Making feedback and post-occupancy evaluation routine 2: Soft landings – involving design and building teams in improving performance. Build Res Inf 2005;33:353–60.

[27] Barker T, Ekins P, Foxon T. The macro-economic rebound effect and the UK economy. Energy Policy 2007;35:4935–46. doi:10.1016/j.enpol.2007.04.009.

[28] Hirst E, White D, Goeltz R. Indoor temperature changes in retrofit homes. Energy 1985;10:861–70. doi:10.1016/0360-5442(85)90119-7.

[29] Herring H. Energy efficiency—a critical view. Energy 2006;31:10–20. doi:10.1016/j.energy.2004.04.055.

[30] Haas R, Biermayr P. The rebound effect for space heating Empirical evidence from Austria. Energy Policy 2000;28:403–10. doi:10.1016/S0301-4215(00)00023-9.

[31] Sorrell S, Dimitropoulos J, Sommerville M. Empirical estimates of the direct rebound

effect: A review. Energy Policy 2009;37:1356–71. doi:10.1016/j.enpol.2008.11.026.

[32] Hamilton I, Steadman P, Bruhns H. CarbonBuzz – energy data audit. 2011.

[33] Ourghi R, Al-Anzi A, Krarti M. A simplified analysis method to predict the impact of shape on annual energy use for office buildings. Energy Convers Manag 2007;48:300–5. doi:10.1016/j.enconman.2006.04.011.

[34] AlAnzi A, Seo D, Krarti M. Impact of building shape on thermal performance of office buildings in Kuwait. Energy Convers Manag 2009;50:822–8. doi:10.1016/j.enconman.2008.09.033.

[35] Lam JC, Chan RYC, Tsang CL, Li DHW. Electricity use characteristics of purpose-built office buildings in subtropical climates. Energy Convers Manag 2004;45:829–44. doi:10.1016/S0196-8904(03)00197-3.

[36] IDAE - Instituto para la Diversificación y Ahorro de la Energía. CALENER-GT: Grandes Edificios Terciarios. Manual Técnico. Madrid: 2009.

[37] Chua KJ, Chou SK. A performance-based method for energy efficiency improvement of buildings. Energy Convers Manag 2011;52:1829–39. doi:10.1016/j.enconman.2010.12.007.

[38] The Ministry of Housing of the Spanish Government. Royal Decree 314/2006, of 17th of March 2006, by which the Building Technical Code is approved. 2006.

[39] The Ministry of Presidency of the Spanish Government. Royal Decree 47/2007, of 19th of January 2007, by which the basic procedure for the energy performance certification of new buildings is approved. 2007.

[40] The Ministry of Presidency of the Spanish Government. Royal Decree 1027/2007, of

20th of July, by which the Thermal Installation Regulations of Buildingsis approved. 2007.

[41] Zabalza I, Valero A, Aranda A, Llera E. Methodological aspects and design implications to achieve life cycle low emission buildings. A case study: LCA of a new university building. Strojarstvo 2013;55:87–102.

[42] Viessmann Werke Gmbh. Heating with Gas 2014.

[43] Fabrizio E, Seguro F, Filippi M. Integrated HVAC and DHW production systems for Zero Energy Buildings. Renew Sustain Energy Rev 2014;40:515–41. doi:10.1016/j.rser.2014.07.193.