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Benchmarking energy consumption in universities: A review

T.C. Quevedo *, M.S. Geraldi, A.P. Melo, R. Lamberts

Laboratory for Energy Efficiency in Buildings, Federal University of Santa Catarina, Brazil

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ABSTRACT

Universities have an important role towards a sustainable future. It is essential to understand their energy consumption and how to improve their efficiency. This paper aims to review the literature, between the years 2000 and 2023, investigating what influences energy consumption in universities, obtaining benchmarks for their energy consumption, and highlighting the potential for further research. Results showed that energy use in university campuses often presents great complexity due to the integration of several types of services in the same building or group of buildings. The studies in the literature categorized the end-uses by lights, plug loads, and HVAC system (the most prominent), highlighting the importance of monitoring them during the usage. Furthermore, it was observed that occupant behavior has a significant impact in energy usage, due to the building operation, and the space usage. Therefore, by comparing results and limitations of the studies reviews, we suggest addressing the space usage type in universities buildings for future benchmark development. Moreover, there is still a gap in developing more specific Key Performance Indicators for universities to improve the disclosure of benchmarking information.

Abbreviations

BES	Building Energy Simulation
CDH	Cooling Degree hours
CityBES	City Building Energy Simulation
DEC	Display Energy Certificate
EEU	Energy Use
EUI	Energy Use Intensity
GIS	Geographic Interface System
GHG	Greenhouse gas emissions
GPS	Global positioning system
IoT	Internet of Thinks
KPI	Key Performance Indicator
SDG	United Nations Sustainable Development Goals
UC	University Campus

* Corresponding author. Laboratory for Energy Efficiency in Buildings, Federal University of Santa Catarina, Brazil.
E-mail address: tiago.quevedo@posgrad.ufsc.br (T.C. Quevedo).

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1. Introduction

According to the IEA, the building sector is responsible for 33 % of global final energy demand, and 26 % of global energy-related emissions [1]. The energy consumed by this sector of the energy used for construction, heating, cooling and lighting for both homes and businesses [2].This highlights the necessity to improve the building sector efficiency. Among the multiple building types in this sector, this paper focuses on the university buildings since they have an important role in the development of a more sustainable and efficient future [3] for two main reasons: (a) universities help to develop and apply policies for the reduction of greenhouses emissions [4] and (b) universities educate people and citizens to be part of the society as professionals. According to Wright [3], the university can perpetuate a moral responsibility to society to become more sustainable through teaching, research, and administration.

Velazques et al. [5] define a sustainable university as an institution that minimizes negative environmental, economic, societal, and health effects generated by the activity developed on the campus. Alshuwaikhat [6] highlights the importance of developing a campus as a healthy environment, with good resource management (water and energy), waste conservation, and the conscience to promote equity and social justice, exporting these values to society. Furthermore, one components of a sustainable campus is energy management, regarding energy consumption and energy waste, as shown by Yoshida et al. [7].

It is evident that the sustainability of a university campus is complex, and can be measured by different metrics, as pointed out by Evangelinos et al. [8]. These metrics are aligned with the United Nations Sustainable Development Goals (SDG) number 6, 7 and 11, to reduce energy waste, ensure the access to more affordable and clean energy, promoting sustainable cities [9,10]. Furthermore, universities have an important position in promoting the SDG goals, contributing with discussion and information disclosure [11].

Regarding energy consumption and waste, it is essential to highlight that the energy consumed by universities may have a significative environmental impact, associated with high CO_2 emissions. Thus, studies evaluating university energy consumption are fundamental to improving campus sustainability, since it can affect the environment, economy, and society.

This evaluation is intricate for three main reasons: (a) buildings are composed of small systems that interact with occupants [12], (b) the university campus is composed of multiple buildings with different space usages, (c) the university campus can consume thermal energy, electricity or both.

To approach the different arrangements of systems in a building, it is possible to evaluate the end-use energy, classifying the energy consumption into three main groups, as shown by Litardo et al. [13]: HVAC system, lights, and equipment. However, acquiring specific equipment to monitor the end-use energy consumption is necessary, which increases the effort and costs to obtain such end-uses. Thus, it is usual to find studies that evaluate the total energy consumption based on utility bills rather than end-users.

Regarding the multiple buildings and different activities, it is possible to treat the university campus as one general category, composed of different space usages such as classrooms, lecture halls and others, as proposed by CIBSE TM 46 [14]. The same strategy is adopted by Energy Star [15] simplifying the multiple space usages into only one. In this method, it is also possible to inform if there is any space within the building with computer rooms. This strategy was discussed by Litardo et al. [16] and Vaisi et al. [17], highlighting that the classification proposed by CIBISE TM 46 may be limited since the University Campus (UC) category simplifies all activities found on the university campus into one. Rosiek and Battles [18] found three different spaces in one building: laboratory, offices, and seminar room, which emphasizes the limitation of simplifying university buildings into one category.

Therefore, the university campus is complex on many levels, leading to opportunities for improving energy savings. Chung and Rhee [19] evaluated the possibilities of energy savings for eleven university buildings, classifying them into eight different categories, and space usage. Additionally, since the authors evaluated the total energy consumption, they cannot evaluate the end-use energy consumption. Nevertheless, the study helps to propose better strategies to improve energy savings, such as correction in HVAC set points, changes in window systems to improve building insulation and changes in the lighting system.

Litardo et al. [13] evaluated the potential for energy savings in a welfare student center, in the Equator. Differently from Chung and Rhee [19], the authors studied the energy consumption by end-use for only one building, through a simulation model. Thus, they proposed retrofit strategies to reduce lighting usage and HVAC cooling loads. Furthermore, their work shows that the HVAC system has a significant influence on the energy consumption of university buildings.

Regarding the HVAC system, Ge et al. [20] evaluated how to reduce energy consumption based on adaptive thermal comfort and building simulation, reducing 45 % for cooling loads and 38 % for heating loads. Fahim and Wang [21] evaluated the energy consumption by monitoring the internal environment, and the HVAC VAV equipment, achieving more descriptive results and precise strategies to conduct building retrofits. Their work highlighted the importance of monitoring energy consumption and having a building management system, to improve the analysis of energy consumption. Moreover, Ligade and Razban [22] evaluated retrofitting strategies in the HVAC system, showing that evaluating end-use or system-use energy consumption is fundamental to proposing more assertive efficiency strategies. It was noted that for those works, the buildings evaluated had central HVAC systems, making monitoring the HVAC energy consumption easier. On the other hand, some universities adopt Split systems, for those cases, it is harder to meter the energy consumption since it is recorded with the lighting and equipment [23].

Even though the possibilities of energy savings and the importance of energy benchmarking for universities, there are still gaps in the literature to be fulfilled. It was noticed that there are studies which evaluate the energy consumption of educational buildings, including universities for specific regions [24,25], or studies that review the energy consumption in schools, aiming at elementary and high schools [26]. Even though multiple studies review the benchmark methodologies for commercial buildings, there is a lack of review papers regarding energy consumption and benchmark for universities. Therefore, developing a review paper helps to understand energy consumption in universities, identifying which characteristics influence energy consumption, and improve the development of energy benchmarking.

Due to the different and unique arrangement of services and occupancy inherent in university buildings, and the vast possibility of energy savings in this sector, it is essential to understand the studies that were already conducted in this matter, by discussing the findings of these studies and identifying the gaps in this research field. Furthermore, it is important to highlight how universities are different from simple commercial buildings, and the challenges to study the energy consumption for this typology. This paper is innovative since it helps to correlate the studies regarding energy consumption in universities and the ones that aim to benchmark university buildings, identifying possibilities for future studies. Thus, this paper aims to find the gaps in the literature regarding the energy benchmarking of university buildings by revising previous works in the literature and proposing research opportunities, proposing a framework to help the development of future studies.

Three initial strings were selected to conduct this research adopting the Scopus platform. Those strings were assumed to find studies that include energy consumption, energy savings, energy benchmark and universities, as presented in Table 1.

The results were treated to focus on journal papers, between the years 2000 and 2023. In addition, more papers were selected to further explore the benchmark processes, based on review papers concerning benchmark methodologies. The final database of 112 papers was obtained by excluding duplicated papers, and papers that did not explore energy consumption in universities.

This paper is divided into 4 sections. The first section presents an overview of energy consumption in universities. The second section presents methods to benchmark energy consumption, and how to disclose this information. The third section brings a general discussion about the previous sections emphasizing the gaps found in the literature. The final section presents the conclusions of this research and addresses the potential further works.

2. Energy consumption in universities

2.1. University space usage and energy consumption

The university campus is composed of multiple buildings and different space usage. Chung and Rhee [19], classified eleven university buildings into eight categories: Classrooms, Research, Library, IT Center, Accommodation, Office, Gymnasium, and Art Center. In another research, Khoshbakht et al. [27] classified the university buildings of Griffith University, in Australia, into six categories: Academic offices, Administration, Library, Research, Teaching and General. Besides those classifications, it is possible to find other space usage and building classifications, such as hospitals [28,29], museums [30], Coffee shops [31] and Restaurants [32].

Due to different buildings and space usage, it is possible to consider the university campus a small city, composed of multiple building typologies. On the other hand, metering and benchmarking the energy consumption for universities is more challenging than developing for stand-alone commercial buildings, since in one building it is possible to have multiple space usages. Aiming to summarize the space usage and classification of university buildings, a general classification is proposed in Fig. 1.

This classification was developed by summarizing the building and space usage of multiple studies found in the literature. It can help the comparison between studies, identify the buildings with higher energy demand, and develop further works to identify the space usage of university buildings. There is a lack of literature on works that summarize the studies that evaluate the energy consumption in universities, and compare themselves, in the function of country, weather classification and typology studied in each one. Thus, Table 2 groups related works regarding climate classification by ASHRAE 169 [33]. The adopted energy data for the development of each study was classified as "predicted", when the energy consumption was predicted by simulation or "measured", for studies that adopted data from utility bills or real-time monitoring systems. In addition, the table shows that energy consumption is measured in different units, adopting energy use (EEU), energy use intensity (EUI), and thermal loads, among others. The building typology was based on the data available in each study. Some studies evaluated the energy consumption of universities without specifying the space or building usage, for those cases, it was considered University Buildings, to represent a generic university building. When the entire university campus, with multiple building usage, was evaluated, it adopted the University Campus classification to represent the multiple buildings.

Table 2 presents energy consumption in universities, and the different metrics adopted to measure and evaluate such consumption. Eight studies (20 %) adopted the total energy consumption to represent the energy consumption of the campus or a building. Such an approach limits the analysis of the building efficiency since it is impossible to compare the building energy consumption with others within the same building typology, or even with different buildings in the same university. Moreover, the EUI in kWh/m^2 is widely adopted, since it can provide information about the overall building energy performance [72]. The use of EUI helps to compare the energy consumption between the same typology, and different studies, by normalizing the energy consumption by floor area. As stated by Monts and Blisset [73], in 1982, the EUI is a simple yet adequate measure of energy efficiency that can be easily understood; however, it may limit the representation of energy consumption. However, it is important to highlight

Table 1
Strings for literature review.

String	Results
TITLE-ABS-KEY (energy OR "energy characteristic" OR "energy performance" W/2 building) AND TITLE-ABS-KEY (universit OR campus OR college OR "higher education") AND NOT (material OR solar OR hpv OR bip) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (SUBJAREA, "engi") OR LIMIT-TO (SUBJAREA, "ener")) AND (LIMIT-TO (LANGUAGE, "english"))*	385
TITLE-ABS-KEY (energy OR "energy consumption indicator" OR "energy performance" W/2 building) AND TITLE-ABS-KEY (universit OR campus OR college OR "higher education") AND NOT (material OR solar OR pv OR bipv) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re")) AND (LIMIT-TO (LANGUAGE, "english"))*	496
(TITLE-ABS-KEY (energy) AND TITLE-ABS-KEY (building) AND TITLE-ABS-KEY (benchmark) AND TITLE-ABS-KEY (university))*	184

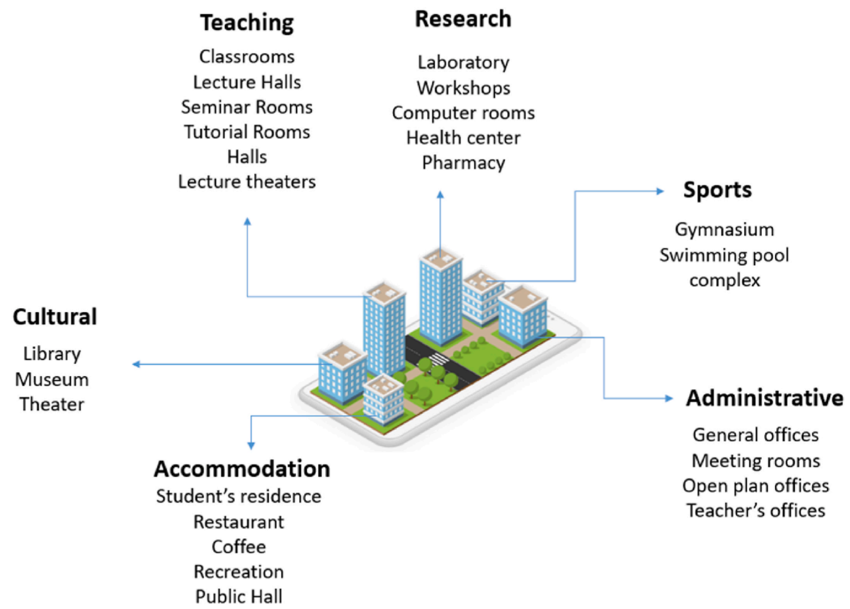

Fig. 1. University campus space usage classification as a small city.

that the majority of studies adopts the gross floor-plan area or does not specify the area adopted. Only few studies, such as Sekki et al. [74] and Almeida et al. [41] declared that they adopt the conditioned or useable area. Therefore, comparing the EUI between the studies should take in consideration the definition of the floor-plan area, since this can also impact the energy consumption.

Most of the studies adopted measured energy data, by monitoring the energy consumption of university buildings. This data can be adopted to develop predictive models, benchmarks, and validate simulation models, and is often collected through real-time monitoring [27], by in situ measuring [19], or by utility bills [16]. Monitoring systems and energy meters provide more precise measurements, leading to more complete benchmarks and studies, since they can show the energy consumption by end-use. However, real-time monitoring is not always available, and other strategies should be taken, mainly for developing countries.

Adopting simulation or predictive models helps to develop studies in countries with limited data access. Considering the university buildings in those countries, the development of simulations and predictive models are complex and may have lower accuracy, since it is challenging to validate these models. Even with limitations, the development of predictive models works as the first step towards energy efficiency and helps to keep track of the energy efficiency of university buildings.

Furthermore, simulations and predictive models can be adopted to evaluate retrofit possibilities. A practical example was presented by Chung and Rhee [19], in Korea. Nevertheless, the measured data is fundamental to validating the simulation and predictive models, highlighting the importance for universities to track their energy consumption.

It was elaborated a boxplot with values of EUI considering the climate classification as shown in Fig. 2. This helps to identify the impact of climate classification on energy use index. Furthermore, this also highlights the lack of data for some climates. Those values considered only the studies that displayed the energy use index normalized by area. Thus, for some climates classified as 0A and 2A, for example, no data was available for Gas EUI. Additionally, a scatterplot for distribution of EUI and Cooling Degree Hours (CDH), with a base temperature of 20 °C was developed, as shown in Fig. 3.

For climate classifications such as 6A and 4B, there is a lack of data. Only one study for each one of those climate classifications brings the energy consumption of universities. This emphasizes that developing more studies regarding the EUI in those climates is important.

The energy consumption is variable according to the climate classification, with studies in climates 0A and 2A consuming less energy than those in 3A and 4A. One reason can be the consideration of gas as total energy consumption by the studies located in cold climates.

Regarding electricity and gas consumption, it is possible to observe that only eleven studies (27.5 % of the sample) evaluated gas energy consumption. Those works refer mainly to cold climates, where gas consumption is adopted for space heating. For those studies, gas consumption is often higher than electricity, confirming the findings of Ma et al. [51], which showed that the energy consumption of universities located in North America is dominated by natural gas. Furthermore, it is not possible to directly compare benchmarks with different energy sources (gas or electricity). Adopting primary energy to benchmark a university building could help to compare buildings using different energy sources, improving the benchmarking process.

It is impossible to evaluate the energy consumption variation based only on the climate classification since it varies within the same weather, and with the CDH as shown in Fig. 3. It is noteworthy that for the same range of CDH, the EUI shows a considerable variation, indicating that other characteristics have higher influence in energy consumption for universities. However, this is also observed for other commercial buildings. This trend can be observed in Taiwan, where the energy use intensity for universities ranged between 56.5 and 93.2 kWh/m^2.year [43]. In London [56], there is a range between 50 and 230 kWh/m^2.year. When comparing the

Table 2
Studies that evaluate the energy consumption in universities.

City/Country	Weather classification ASHRAE 169 [33]	Gas consumption	Electricity consumption	Predicted or measured energy data	Typology	Reference
Bangkok, Thailand	0A	–	80-88 kWh/m^2.year	Measured	University Campus	Rewthong et al. [34]
Johore, Malaysia	0A	–	107.9 kWh/m^2	Measured	University Building	Shukri et al. [35]
Yogyakarta, Indonesia	0A	–	90.0 kWh/m^2.year	Measured	University Campus	Utami et al. [36]
Guayaquil, Ecuador	0A	–	87.1–106.2 kWh/m^2.year	Simulated and Measured	Classrooms	Litardo and Hidalgo-leon [37]
Brisbane and Gold Coast, Australia	2A	–	160.4 kWh/m^2.year	Measured	Laboratory, classrooms, academic, offices, residential, retail and sports	Gui et al. [38]
New Castle, Australia	2A	–	55.3 kWh/year	Prediction with simulation	Classrooms	Alghamdi et al. [39]
Brisbane and Gold Coast, Australia	2A	–	116–236 kWh/m^2.year	Predicted and Measured	Laboratory, classrooms, offices, library	Khoshbakht et al. [27]
Sydney, Australia	2A	–	317–403 kWh/week	Measured	University Building	Loengbudnark et al. [40]
Sydney, Australia	2A	–	998 kWh/year	Simulated	Not described	Almeida et al. [41]
Taipei, Taiwan	2A	–	180 kWh/m^2.year	Predicted with simulation	Laboratory, classrooms, offices, services	Tu et al. [42]
Multiple cities, Taiwan	2A	–	56.5–93.2 kWh/m^2.year	Measured	University buildings	J.C. Wang [25,43]
San Antonio, Texas	2A	–	8.3 GWh/year	Measured	University Campus	Jafray et al. [44]
Gainesville, Florida, USA	2A	–	85 - 116 MWh/month	Predicted and Measured	Laboratory, classrooms, offices, residential, sports	Fathi et al. [45]
Guangdong province, China	2A	0.04–1.02 m^2/m^2.year	12–35.6 kWh/m^2.year	Measured	Classified by disciplines and nature	Zhou et al. [46]
Florianopolis, Brazil	2A	–	83–96 kWh/m^2.year	Predicted and Measured	University campus	Quevedo et al. [47]
Anhui province, China	3A	–	100.53 kWh/m^2.year	Measured	Laboratory, offices, public area	Ding et al. [48]
Wollongong, Australia	3A	–	16 to 430 kWh/m^2.year	Measured	Laboratory, classrooms, offices	Li et al. [49]
South Africa	3A	–	12844 MWh/year	Measured	University Campus	Ntsaluba et al. [50]
Multiple cities, Japan	3A	–	465 - 582 kWh/m^2.year	Measured	University Building	Ma et al. [51]
London, United Kingdom	3A	–	54.75–146 kWh/m^2.day	Predicted and Measured	Academic Building	Amber et al. [52]
Almeria, Spain	3B	–	28.9–119.5 kWh/m^2.year	Measured	Laboratory, classrooms, offices, sports, restaurant buildings, library.	Chihib et al. [32]
Tehran, Iran	3B	–	284.1–368 kWh/m^2.year	Measured	Accommodation	Jami et al. [53]
Amman	3B	–	17.6 MWh/month	Measured	University building	Mohamed et al. [54]
Wien, Austria	4A	–	248.9 kWh/m^2.year	Measured	Accommodation	Elganar et al. [55]
London, United Kingdon	4A	78–380 kWh/m^2	50 to 285 kWh/m^2.year	Predicted and Measured	Laboratory, classrooms, offices, auditorium, library	Hawkins et al. [56]
Balikesir, Turkey	4A	56–334 kWh/m^2.year	12–319 kWh/m^2.year	Measured	Laboratory, classrooms, offices, library, sports, residential	Yildiz and Kocyigit [28]
Maryland, USA	4A	–	1322 kWh/m^2.year	Predicted and Measured	Laboratory	Levy et al. [57]
Purdue, Indiana, USA	4A	–	130 KBtu/sf/yr (410 kWh/m^2.year)	Measured	University Building	Ligade and Razban [22]
Seoul, Korea	4A	56–239 kWh/m^2.year	139–388 kWh/m^2.year	Predicted and Measured	Laboratory, classrooms, offices, library, residential, sports	Chung and Rhee [19]
Sheffield, United Kingdom	4A	80–210 kWh/m^2.year	45 -150 kWh/m^2.year	Measured	Laboratory, classrooms, library, computer room, coffee store, lecture theatre	Yaltan et al. [4]
Campobasso, Italy	4A	–	166 kWh/m^2.year	Measured	Classrooms and offices	Bellia et al. [58]
Perugia, Italy	4A	900-1800 MWh.year	50-200 kWh/m^2.year	Measured	Laboratory, classrooms,	Barelli and Bidini [59]

(continued on next page)

Table 2 (*continued*)

City/Country	Weather classification ASHRAE 169 [33]	Gas consumption	Electricity consumption	Predicted or measured energy data	Typology	Reference
Tianjin, China	4A	–	250–650 kWh/day	Predicted and Measured	Classrooms, offices, residential	Ding et al. [60]
Multiple cities, United Kingdom	4A–5A	–	92–539 kWh/m^2.year	Measured	Laboratory, offices, library	Birch et al. [61]
Dublin, Ireland	5A	120–440 kWh/m^2.year	95 - 160 kWh/m^2.year	Measured	Laboratory, classrooms, offices, hospital, residential, and theatre.	Vaisi et al. [62]
Dublin, Ireland	5A	388.14 kWh/year	–	Measured	Laboratory, classrooms, offices, library, stores, and coffee shop	Vaisi et al. [17,30]
Dalian, China	5A	–	500 - 2000 kWh/day	Predicted and Measured	Laboratory	Lei et al. [63]
Victoria, Canada	5A	200–1200 GJ/month	165–384 kWh/m^2.year	Simulated and Measured	University Building	Mahmoodzadeh et al. [64]
Cornell University	5A	250–800 kWh/m^2.year	80–200 kWh/m^2.year	Measured	University Building	Ma et al. [51]
Yale University	5A	739 kWh/m^2.year	188 kWh/m^2.year	Measured	University Building	Ma et al. [51]
Espoo, Finland	6A	–	229 kWh/m^2.year	Measured	University Building	Sekki et al. [65]
Al Bukayriyah	1B	–	145–155 kWh/m^2.year	Measured	Offices, classrooms, laboratories, Services, Sports, auditorium	Alfaoyzan et al. [66,67]
Xianyang, China	4B	–	227.2 GJ/year	Predicted with simulation	Classrooms	Sun et al. [68]
Merced, California	4B	0.82 kTh/m^2.year	28.83 kWh/m^2.year	Measured	Laboratory	K. Brown [69]
Vancouver, Canada	4C	–	125.5 kWh/m^2.year	Measured	Classrooms, offices, auditorium, café store	Salehi et al. [70]
Multiple cities, Canada	7	–	1.45 2.8 GJ/m^2	Measured	Laboratory, classrooms, offices, library, food service	S. Li and Y. Chen [71]

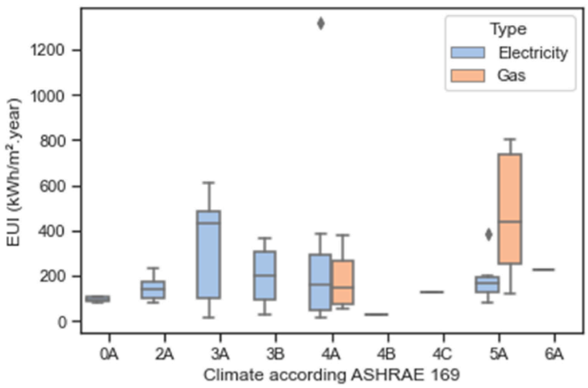

Fig. 2. Electricity EUI distribution according to the climate classification.

studies for 5A weather classification, it is possible to observe a higher variation, from 64 kWh/m^2.year to 1400 kWh/m^2.year. This trend is observed in the work of Zhou et al. [46], which evaluated 98 universities in Guangdong province, China. They found electricity consumption for the same weather classification varying between 12 kWh/m^2 and 35.6 kWh/m^2. The variation in energy consumption in the same weather indicates that there are other variables influencing energy consumption.

One of the reasons for such a difference in energy consumption is space usage, as shown by Birch [61]. The author found a range between 92 and 553 kWh/m^2.year for universities located in the United Kingdon. However, they highlighted that laboratories had the highest energy consumption (553 kWh/m^2.year), followed by libraries (220 kWh/m^2.year) and offices (92 kWh/m^2.year), values higher than the CIBSE good practices [14]. The same trend was observed by Vaisi et al. [62], who showed that the energy consumption for laboratories, healthcare buildings, sports centers, and restaurants was higher, consuming between 130 and 160 kWh/m^2.year. In the same direction, Fathi et al. [75] found that research buildings (760 MWh) consume more energy, followed by educational (180 MWh), residential (150 MWh), and sports (135 MWh). Additionally, Chihib et al. [32] also found that laboratories consume more energy (119.5 kWh/m^2.year) than other typologies, such as libraries (82.67 kWh/m^2.year), sports facilities (47.30 kWh/m^2.year), restaurants (41.11 kWh/m^2.year), classrooms (28.99 kWh/m^2.year), and offices (28.78 kWh/m^2.year). Such differences put in evidence the complexity of the university campus.

Space usage and the building occupation changes how energy is consumed in university buildings, affecting the end-use energy consumption. Zhang et al. [76], and Ding et al. [23] found that lighting systems and plug loads have higher energy consumption for

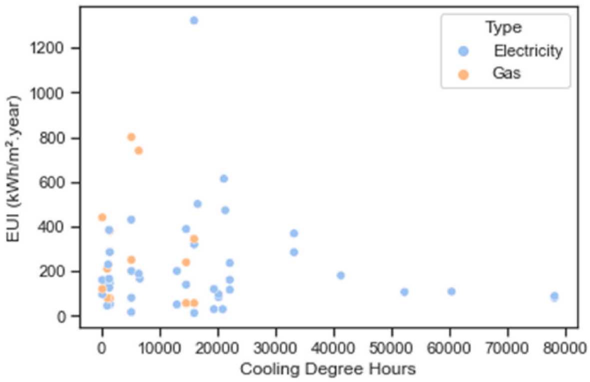

Fig. 3. Electricity EUI distribution according to the Cooling Degree Hours (20 °C).

universities in China, followed by the HVAC system. For the thirteen-building campus evaluated by Ding et al. [48], the light and equipment system consumption corresponds to 65.15 kWh/m^2. year while the HVAC system represents 18.63 kWh/m^2. year. However, for Osaka university in Japan, Yoshida et al. [7] found a different trend for end-uses energy consumption, with the HVAC system consuming more energy than lighting and plug loads. This trend is also observed in the studies of Gui et al. [38] and Alghamdi et al. [39], where the energy consumption of the HVAC system represents more than 50 % of the energy consumption for universities in Australia. Additionally, Alfaoyzan and Almasri [66] found the same trend for end-use energy consumption for the University of Sulaiman Al-Rajhi University, where the HVAC system has the higher energy consumption (79 %), followed by equipment (14 %) and lightning (7 %). This trend was also confirmed by Liu and Ren [77], that for library buildings in Chinese universities, the HVAC system consumes more energy followed by equipment and lighting. It is noteworthy that the climate classification for the study of Gui et al. [38], Alghamdi et al. [39], and Ding et al. [48] are the same (2A), showing that even for the same climate classification, the end-use energy consumption can be different. Thus, end-use energy consumption is a valuable study field, since it helps to identify the system with higher energy demand and define strategies to achieve energy efficiency.

Therefore, the building envelope, the operation of the HVAC, and the light system affect the energy consumption on the university campuses and plug loads. Furthermore, the aspects regarding occupant behavior, occupancy rate, space usage, and disciplines offered in the institution must be considered. This complexity leads to a demand for studies to evaluate the influence of each characteristic on building energy consumption. Table 3 classifies the studies that focus on evaluating the building envelope, HVAC system, light system, occupant behavior, space usage, nature (public or private), discipline and occupation.

2.2. The influence of building characteristics on energy consumption

University buildings have a great potential to save energy through retrofit, and improvements in HVAC and lighting systems. Table 3 shows that the building envelope and systems are the focus of multiple studies, of which 10 (37 %) of them evaluated changes in envelope building, 2 (7.4 %) in light systems, and 4 (14.8 %) in HVAC systems. This trend is in line with the study of Leal Filho et al. [81], which reviewed 50 universities around the world regarding investments in energy efficiency and renewable energy, observing that 54 % of the sample aimed to evaluate the building characteristics and improvements. However, fewer works correlate the efficiency strategies and the cost to execute them [53,58,64].

Chung and Rhee [19] evaluated the potential energy conservation opportunities for Korea's universities, finding possibilities to reduce energy consumption by 6 % and 29 %. Six strategies were evaluated, including automation of standby power and cut-off switches for appliances such as computers and coffee machines, reduction of power lights, adjustment of the internal thermostat, replacement of windows and change in thermal transmittance of walls and roofs. They applied the strategies in eleven different buildings, with different space usages, such as medical science, engineering, offices, social science, theatre, and others. With window replacement and adding insulation in the envelope, it was possible to reduce up to 22 % of the energy consumption of the older buildings. In comparison, new buildings reduced energy consumption by 6 %. It is noteworthy that the building envelope affects the energy consumption of university buildings. However, the capacity for improvements changes according to the original building envelope.

Mahmoodzadeh et al. [64] evaluated the thermal performance of building envelopes for universities in Canada. In their study, the authors investigated the heating loss through the building envelope, and retrofit strategies, with building energy simulation (BES). They proposed a reduction in thermal transmittance of walls (from 2.54 to 1.45 W/m^{2}K), roofs (from 0.57 to 0.19 W/m^{2}K), and windows (from 3.2 to 1.8 W/m^{2}K), and improvements in heat recovery efficiency, reducing the air leakage (from 0.25 to 0.125 l/s/m^2). The base case had a EUI of 384 kWh/m^2, while the case combining improvements in walls, roofs, and windows had a EUI of 368 kWh/m^2, a reduction of 5 %, closer to the findings of Chung and Rhee [19] for new buildings.

Both studies are in cold climates (classes 5A and 4A according to ASHRAE 169) where improvements in insulation to minimize heat losses are good strategies for reducing energy consumption. The best scenario found by Mahmoodzadeh et al. [64] combined the envelope improvements and the air leakage reduction, which dropped the EUI to 193 kWh/m^2, a reduction of 50 %. Therefore, they found that adopting strategies to reduce air leakage has better results for the evaluated building than envelope improvements.

Table 3
Aspects of influence on energy consumption in the university building.

Building envelope	HVAC System	Light systems	Occupant Behavior	Space Usage	Nature (Public or Private)	Discipline	Occupation	References
X								Sun et al. [68]
X								K. Brown [69]
X								Salehi et al. [70]
	X							Ligade and Razban [22]
	X							Quevedo et al. [47]
X	X	X						Ntsaluba and Mukadi [50]
	X							Li and Chen [71]
X		X	X					Chung and Rhee [19]
X				X				Hawkins et al. [56]
X			X	X				Ding et al. [48]
X			X					Li et al. [72]
X			X	X				Li et al. [49]
			X					Sekki et al. [65]
			X					Chen et al. [78]
			X					Zhou et al. [46]
			X					Rewthong et al. [34]
				X				Mont and Blisset [73]
				X	X	X		Alghamdi et al. [39]
				X	X	X		Lombard et al. [79]
				X	X	X		Utami et al. [36]
				X		X		Ma et al. [51]
				X				Shang et al. [80]
							X	Escrivá et al. [31]
							X	Fathi et al. [75]
							X	Zhang et al. [76]
							X	Bellia et al. [58]

Besides the energy savings, Mahmoodzadeh et al. [64] evaluated the cost savings, founding that the envelope strategies are not economically justifiable, since they have low electricity rates and reduction in energy consumption for the case study. Thus, it needs to add more incentives for building owners to justify the building envelope retrofit. Furthermore, the authors have shown that improvements in the building envelope cannot guarantee the best energy performance of a building.

Regarding HVAC systems for cold climates (5A), Ligade and Razban [22] showed that it is possible to save 28 % in utility costs, by including an electric reheat in the HVAC system, at Purdue University. Additionally, the authors found that steam heating did not save energy, but reduced the utility cost by 18 %, since the utility prices are lower for steam heating. The study of utility savings can help develop a more sustainable future and incentivize building owners to adopt more efficient strategies.

On the other hand, Celniker et al. [82] found that adopting cool paintings on walls for a university located in Davis, California, could save $45,000.00 each year. With a climate classification of 3B, the weather in Davis significantly impacts the strategies adopted by the authors. Therefore, it is limiting to affirm that improvements in envelopes are less important and efficient than the modernization of HVAC systems. To truly evaluate the impact of retrofit on building envelope and systems, it is necessary to consider the climate classification, the age of the building and the space usage. Thus, it is possible to discuss that, for different countries, different regions and climates classification; the envelope retrofit can be economically justified.

Moreover, envelope characteristics are not the only variables that affect the energy consumption of universities. As shown by Hawkings et al. [56], the envelope can influence by 45 % the energy consumption, while the activity by 65 % in the predictive model developed by the authors. Thus, studying the influence of occupants and the space usage in the university building is fundamental to understand how the energy is consumed in this typology.

2.3. The influence of building space-usage on energy consumption

The influence of building usage on energy consumption is widely discussed, and the studies evaluate occupant behavior, space usage, and end-uses energy consumption.

In 2023, Sonetti and Cottafava [83] showed that space usage could influence energy consumption. For four years, they evaluated the energy consumption of two universities with similar characteristics, including floor area and climate classification, and proposed five different clusters. The first cluster consumes 1 GJ/m^2 year (277.78 kWh/m^2.year), and is composed of art departments. The second cluster, composed of science faculties, consumes 2 GJ/m^2.year (555.56 kWh/m^2.year), while the third cluster consumes 3 GJ/m^2.year (833.34 kWh/m^2.year) and is composed of health departments, such as hospitals and medicine academic rooms. The fourth cluster comprises data centers, with an average consumption of 9 GJ/m^2.year (2500 kWh/m^2.year) while the fifth cluster is dedicated to special research facilities, consuming more than 10 GJ/m^2.year (2777.78 kWh/m^2.year). This study shows that it is possible, and necessary to study energy consumption in universities considering space usage.

The work of Zhou et al. [46], highlighted the influence of teaching type, and nature of the universities on electricity consumption. They classified the 98 universities surveyed based on the disciplines offered and by nature. The discipline classification comprises 10 classifications, such as medicine, teacher training, literature, financial, political science, art, sciences and technology, agricultural and physical culture. The results showed that energy consumption was higher for the agricultural discipline (35.67 kWh/m^2.year), followed by literature (30.61 kWh/m^2.year) and medicine (27 kWh/m^2.year). Thus, they showed that the discipline given at the university could influence electricity. However, when comparing the energy consumption per student, they found that the physical culture had the higher energy consumption, followed by medicine and agriculture. The nature classification categorizes the universities into public undergraduate, public vocational, private vocational and independent institutions. The energy consumption normalized by area and by the student was higher in the public universities, and independent institutions.

Others studies evaluated the influence of the teaching type and nature of the universities on energy consumption [25,43,59]. Wang [25] evaluated the energy performance of teaching buildings in Taiwan, including universities. To become a leading university, the university that received additional funds from the government had an energy use index 1.6 times higher than other universities. Thus, the author points out that electricity consumption is related to the budget invested. Public universities in Taiwan receive more investments and have higher budgets than private institutions; hence, such universities have more research facilities and can offer a wider range of disciplines, consuming more energy than private institutions. This fact leads students to choose public universities to graduate, leading to more students in public universities in Taiwan. The author showed that even though the central area of universities is classrooms, they consume more energy than high schools since they have more equipment, research facilities, and high use of air-conditioning systems. Wang [43], further investigated the energy use in universities, by identifying that universities that focus on research consume more energy than universities focused on practical skills. The main reason is that research facilities have specific equipment and necessities. For example, laboratories usually need to maintain constant temperatures, and constant air renovation, which leads to higher energy consumption, as shown by Yildiz and Kocyigit [28]. This trend was also observed by Zhou et al. [46], showing that public universities in China receive more investments and have higher energy consumption. Hence, the energy consumption in universities is also related to the investments made, and the budget available for each campus. Developing benchmarks considering the nature of the institutions would help to identify if a private university is more efficient because it demands less energy, or because it has better and more efficient equipment than public ones.

The work of Barelli and Bidini [59] highlighted the difference between teaching activities and the influence of laboratories on energy consumption. The authors evaluated the energy consumption of Perugia University, by classifying the teaching as veterinary, agriculture, medicine, humanities, and engineering. The authors found that the energy consumption was higher for engineering (2100 MWh.year), followed by medicine (1300 MWh.year), agriculture (1200 MWh.year), and veterinary (250 MWh.year). The main energy consumption of engineering and medicine comes from laboratories since they need more specific equipment and conditions. They monitored the energy by laboratory area, finding that engineering teaching consumes two times more energy per laboratory area than other activities.

The findings from Barelli and Bidini [59] are in agreement with the study of Hawkins et al. [56], for the same climate classification (4A). The work of Hawkins et al. [56] evaluated energy use in higher education buildings, in the United Kingdom. Through statistical analysis, the authors found that the activity developed (teaching, residential, medicinal research, laboratory, administration, and others) is a determinant of the energy consumption of university buildings.

Those studies highlighted the influence of teaching on the energy consumption of buildings, showing that laboratories are the main energy consumption on the university campus. It is evident the necessity to study energy consumption by evaluating the space area in universities and monitoring the energy consumption by department, or activity. It is noticed that researchers started to evaluate the influence of teaching type, or disciplines on energy consumption; however, classifying the activity only by teaching may lead to more generic classifications and limited evaluations.

This is circumvented by the study of Gui et al. [84], which discussed the limitation to classify space usage by teaching areas. They highlighted that important building areas are often classified as others, ignoring the space usage in universities. They proposed using space descriptors, where each room can be categorized, and described by function, discipline, and activity. For each classification, the authors adopted subcategories and descriptors. The function category has seven subcategories, and 139 descriptors, while the activity has eight subcategories and 35 descriptors, and the discipline adopts five subcategories and 28 descriptors. Thus, the authors achieved a high description level, making a complete description of a university building. The authors utilized energy data collected from five campuses of Griffith University in Australia, and a regression model to determine the relationship between space usage and energy consumption, highlighting that the laboratories had the higher EUI. As shown by previous studies by Wang [43] and Barelli and Bidini [59], the subject focused on research had higher energy consumption. For example, the school of medical science focused on research consumes more energy than subjects that do not need research facilities. Furthermore, the authors found that the main energy consumption for laboratories comes from experimental instruments and the ventilation system since wet laboratories need to comply with indoor environment quality rules.

These findings are aligned with Yildiz and Kocyigit [28], who found that laboratories in universities consume more energy since they need to maintain 22 °C for 24 h a day. The study showed that the academic buildings might use more energy, but the research buildings had higher energy use index. However, the authors found that an increase in the academic area has a more significant impact on building energy use than an increase in the research facility. The method adopted by the authors leads to more descriptive functions of the space type for university buildings. The findings of the study confirm the findings of less descriptive studies, showing that the laboratories may have a higher energy use intensity and that the academic buildings are responsible for the higher energy use for university buildings. Furthermore, the authors highlighted the diversity of space usage in university buildings and the difficulty of accessing end-use energy consumption. Thus, the description provided by the authors may be adopted to develop university benchmarks, since it helps to classify and understand the space usage for this typology.

The influence of teaching and the nature of the universities is evident since each subject has different needs. However, students, lecturers, and researchers are present in every university, independent of the discipline and nature.

Gui et al. [38] evaluated the impact of the measures to tackle COVID-19 on the energy use of 122 university buildings at Griffith University, in Australia universities. Thus, their work identifies how the occupation may change university energy consumption. During COVID-19 some activities were conducted off-campus, such as teaching and administration. However, some research activities remained on campus since it was needed to conduct laboratory experiments. The new configuration of occupation reduced the energy consumption by 24.88 kWh/m^{2}year, or 16 % of the total academic year energy consumption. It is important to notice that during the COVID-19 period, the university worked in a hybrid mode, with students and workers choosing to stay at home or to go to university. Furthermore, the university had the policy to return the activities to the campus, increasing the occupation during COVID-19, according to the reduction of the cases. To achieve a more precise influence on the occupancy in energy consumption, the authors evaluated the weekly energy use. They found a reduction of 57.1 % of the total weekly energy since the buildings turned off the air-conditioning (HVAC) system for 9–10 weeks. Thus, the work of Gui et al. [38] highlights the impact of occupancy on energy consumption and shows that the main energy consumption of universities is related to the HVAC system, as discussed before.

The study of Geraldi et al. [85] highlighted the savings in energy consumption for public buildings in Florianopolis, Brazil. They evaluated the energy consumption for different typologies, such as elementary schools, administrative buildings, and health centers. Even though they did not evaluate universities, it is possible to find the typologies and space usage analyzed in universities for the elementary schools, which are mainly composed of classrooms; they found a reduction of 50.3 % in energy consumption. Furthermore, the health centers reduced their energy consumption by 11 % and the administrative buildings by 38.6 %. Nevertheless, although the COVID-19 pandemic brought terrible outcomes, we found that it is possible to reduce the energy consumption of universities by adopting a hybrid mode in universities, which may benefit from lower occupancy rates.

To adopt strategies that optimize occupancy, Yongkai et al. [68] proposed a method to optimize the timetable of universities and save energy with optimal occupation patterns. Using optimization algorithms, the authors found an ideal timetable and reduced energy consumption by 3.6 % in one semester. It is noteworthy that the occupation schedule affects energy consumption. However, it is necessary to investigate strategies to help reduce the energy consumption of universities, based on occupation, or activity.

It is still a challenge to implement occupancy and occupant behavior in studies regarding university buildings. The occupancy rate in universities is variable, and difficult to track. The occupant's behavior is even harder to evaluate and needs to be further investigated. The work of Du and Pan [86] and Jami et al. [53] evaluated the impact of occupant behavior on the energy consumption of university buildings. However, both studies focused on accommodation in universities and found potential to improve the efficiency of buildings between 32 % and 80 %.

The study of Almeida et al. [41] shows the influence of occupant behavior in retrofitted buildings, in two academic buildings located in Sydney, Australia. Both buildings are similar, however, one is rated by the Green Star Australian Certificate [87] and the other one is non-rated. The rated building received actualizations, with automatic systems for lighting, and a more insulated envelope. The study showed that occupant behavior has 25 % more influence in non-rated buildings since it can affect the heating, lighting, and plug loads for those buildings. The study highlighted that green buildings are more automatized, reducing the impact of occupant behavior. In addition, the surveys found that the occupants of the green building had less efficient behavior; consequently, the rated building could use less energy. Thus, the work of Almeida et al. [41] highlights the findings of Jami et al. [53], showing that occupant behavior significantly impacts energy consumption. Furthermore, it is possible to reduce the impact of occupant behavior, by adopting more automatized systems, as shown by Chen et al. [78] that implemented smart control for HVAC and light systems, reducing the energy consumption by 28 % for the HVAC system and a maximum of 73 % for light system.

Therefore, energy consumption is highly affected by space usage, or the activity developed in universities. In addition, the end-use of HVAC systems and laboratory plug loads are responsible for the higher share of energy consumption. Thus, on a university campus, the academic buildings, composed of classrooms and research laboratories, had the higher EUI, since those areas had a higher concentration of students and equipment, demanding more of the HVAC system. Consequently, it is important to develop studies to reduce thermal loads or improve HVAC systems.

Furthermore, the development of studies regarding energy efficiency in universities is highly dependent on available data. This limits the development of studies in countries where the data is not easily accessed, like Brazil. Even the studies with simulation adopt energy-monitored data, to compare simulation results with real building energy consumption. Therefore, universities need to monitor their energy consumption, achieve a more efficient campus, and help develop studies such as benchmarks.

Notably, there are still gaps in the research on the energy consumption of universities. The main struggle is to find how to show the correlation between energy consumption and university activity. It is possible to split the university activity into several categories, and descriptions as proposed by Gui et al. [84], however, it is necessary to evaluate further how to display the energy consumption correlating with the activity.

The works investigating occupant behavior in student residential buildings highlighted the importance of further studies in this area. Furthermore, it is important to investigate how occupant behavior would influence the energy consumption for laboratories, offices, and other areas on a university campus.

3. Energy benchmarking for universities

Borgstein and Lamberts [88] defined the process of building energy benchmarking in three steps: (1) Identify an appropriate baseline; (2) Calculate the energy performance of the building following the baseline and (3) compare the building energy performance with the benchmark levels. There are a variety of methods to develop those three steps.

There are multiple studies that aim to evaluate and review benchmarking methods. The study by Chung [89] and Li et al. [90], discussed the classification, applicability, and methods of benchmarking for commercial buildings. They demonstrated that each model has its own properties and special characteristics, emphasizing the importance of understanding the limitations, applicability, available data, and training time associated with each model before selecting a method. Since universities comprise various types of commercial building, the findings of these works can also be applied to them.

However, it is common to find diverse space usage and building typologies within a single university building. Moreover, factors such as weather, occupant behavior, occupancy patterns and activities conducted in each space will influence energy consumption. Consequently, developing benchmarks for universities is more challenging compared to a single commercial building. Therefore, a further review is necessary to comprehend the challenges and solutions for implementing these benchmarking methods in the university context.

3.1. Predictive models for universities

Predictive models are important tools to help managers to track energy consumption and identify potential opportunities to reduce energy consumption. In that line, it is important to highlight the study of Monts and Blisset [73], which managed to explain 42 % of the EUI variance for schools and university buildings in Texas. Their work was one of the first to be published adopting statistical methods to evaluate energy consumption in schools and universities. The method adopted evaluated the effect of weather, occupancy pattern, HVAC design, and building type.

Liu et al. [91] adopted predictive models to test strategies to reduce the carbon emission of university buildings, finding a potential to reduce between 30 % and 60 % of carbon emissions. Additionally, the models can be adopted to understand the future energy demand, as shown by Fathi et al. [45]. In their work, the authors aimed to develop predictive models, with the ANN method, to understand how university buildings will consume energy in the future, considering climate changes.

Regarding the inputs for the development of predictive models, Liu et al. [91] considered the building envelope characteristics, such as thermal transmittance of windows, roofs and walls, infiltration rate and solar heat gain coefficient. They considered the power lighting and equipment density, cooling, and heating set point, for occupied and non-occupied hours. The same strategy was adopted by Fathi et al. [45], however, they also considered the activity, such as research, teaching, office and others as input, as adopted by Hawkins et al. [56]. Faiq et al. [92] adopted a different approach, considering environmental variables, such as temperature, pressure, wind speed, relative humidity and others, and the occupancy data. The study was developed with data collected during the COVID-19 pandemic, therefore they managed to adopt the different patterns of occupation of the building during the pandemic. Thus, the authors found that the different occupation patterns significantly influenced the predictive model results, while environmental characteristics, such as average wind speed, had lower influence. Furthermore, Abdo-Allah and Pope [93] developed a model to estimate HVAC system consumption adopting measured data from HVAC systems and helping to or control the internal environment and reduce the energy consumption.

There are limitations to applying predictive models. First, it is necessary to understand where the model can be applied. The methods adopted to elaborate such models are highly dependent on the training database, and the application of those models may be restricted. Akbar et al. [94] predicted the daily energy consumption of one academic building with Multiple Linear Regression and Artificial Neural Networks. To train the model, they adopted a limited database, based on one academic building, and validated the model by comparing the predicted and measured energy consumption. Therefore, the application is limited to this building, and further analysis is needed to apply the model to other buildings. Their work highlighted two main limitations and difficulties in developing predictive models. (a) The complexity of academic buildings, with different characteristics for each building, and the limited access to measured data to validate the models. (b) The difficulty of including occupancy in predictive model development. They simplified the occupation schedule, adopting a fixed value of 1 (occupied) for workdays and a value of 0 (non-occupied) for non-working days.

Since 2019, the number of studies published that track the occupancy of universities is growing [34,60,95–98]. Davis et al. [97] defined multiple occupancy factors for different buildings in universities. They adopted different methods to collect the data, such as manual observations, security camera systems, doorway counting sensors, semester schedules, and others. Hence, the method proposed shows multiple ways to collect and track the occupancy in universities. Even though the occupancy factors found by the authors are validated for Arkansas University, other universities can adopt the method proposed to track the occupancy and improve the accuracy of predictive models.

Tien et al. [98] adopted a real-time monitoring system with a deep-learning approach to track occupancy and occupant behavior. They used monitoring cameras and convolutional neural networks to identify the activities developed by the occupants such as sitting, standing, and walking, and window operating. With the proposed monitoring system, the authors adjusted the set point of the HVAC system based on the occupation, the activity developed, and the operation of windows, reducing the energy demand for the evaluated building.

Chen et al. [99] proposed a method to improve the accuracy of predictive models considering the occupancy, by predicting the building baseload and the occupant activities separately. To predict the building base load, they adopted non-working hours, and for the power demand of occupants' activities, they adopted the working hours. The application of the method is restricted to universities located in cold weather since they assume that the building is constantly heated. With the proposed method, the authors managed to reduce by 35 %–42 % the Root Mean Absolute Error of the predictive model, verifying and proving its potential. The concept of splitting the building's base load and the occupants' activities may help to understand the occupants' behavior even for universities located in a hot climate. Nevertheless, not all universities can maintain the HVAC system in constant operation, for heating or cooling, and further improvements in the method are necessary for those universities. Strategies to predict occupancy [107], or end-use energy monitoring systems can be adopted to improve the method.

To improve the building energy modelling, Lu et al. [100] extracted the occupancy schedules from social media and inserted them into the building energy simulation. To identify the hourly building occupation, the authors applied the method by collecting data from Twitter, Facebook and Google maps for a university building and public museum. Comparing the predictive models with and without the occupation, the authors found an improvement of 5 % in the Root Mean Square Error. The method proposed helps to identify the building occupancy by relying on social media postings, and the Global Position System (GPS). Social media posting may be a limitation for other university buildings, such as teaching and research buildings, however, the Global Position System and the connection with the university Wi-Fi can help to identify the occupancy for further studies. Chen and Ahn [101] adopted the connection and disconnection from the Wi-Fi in university buildings, to estimate the energy load variation derived from occupants'. Even though they showed a positive correlation between the energy demand and the number of Wi-Fi connections, they cannot directly represent the magnitude of the energy load. The use of technology to estimate the occupancy rate is growing and improving the accuracy of models.

It is possible to adopt statistical models to estimate the occupancy of university buildings. Ding et al. [60] split the occupation into long-term and short-term. The long-term occupancy shows regularity with time and is easy to predict. The short-term is the random occupancy, and harder to predict. With the proposed method, they estimated the total occupation for three university buildings, validating the results by comparing the prediction with real measured data. The method proposed can be applied to multiple buildings and can help to improve the accuracy of prediction models. However, the authors highlighted that the impact of occupant behavior on electricity consumption is not simple and cannot be calculated as a superposition of the energy consumption of a single person.

Zhao et al. [96] adopted predictive models to represent occupant behavior, considering their influence on lights, water boilers, and teaching equipment such as computers and slide projectors. To measure the occupant behavior, the authors adopted a variable K, which is the relation between the actual energy consumption and the daily demand of energy consumption. This relationship helps to identify the level of electricity management since values lower than one show that the actual energy consumption is lower than the demand. In addition, the authors evaluated retrofits based on occupant behavior, such as smart buildings and changes in classes' time-bins, achieving 6.8 % in energy savings. The main limitation of the method is the exclusion of heating or cooling demand since, for the database adopted the heating came from municipal hot water and is not measured.

Regarding the previous discussion, it is noteworthy that developing predictive models for universities is difficult. The first is to consider the building's occupation since there are different typologies and necessities. It is possible to estimate the regular occupation schedule for teaching areas and research buildings, based on the classes' time-bins; however, the variable occupation is difficult to track. Nowadays, it is possible to develop methods that track the occupation based on the Internet of Things (IoT), collecting data from GPS signals and Wi-Fi connections to estimate the building occupancy. In those cases, validating the collected data without field research is difficult. The other main limitation is the validation of predictive models since it is needed to track the actual energy consumption of buildings and to compare the predicted and measured energy consumption. Furthermore, each university has different limitations to data collection and specific characteristics.

Thus, each work developed a method that fits their necessities and is usually applied to a specific building, campus, or university. Furthermore, the data quality and viability are fundamental to developing an excellent predictive model, and it is a limitation for several studies.

3.2. Energy consumption benchmarks for university buildings

Besides studies that investigate the energy consumption in universities shown in Tables 2 and it is possible to classify and summarize studies that focus on developing energy benchmarks for those buildings. Table 4 summarizes those studies, regarding the year of publication, the energy index adopted, the period if it is total or end use, the method adopted and how they elaborate the dataset.

Notably, the number of benchmarking studies has grown from 2020 to 2021 since there are still gaps to be filled. Most works adopted statistical methods, with monitored data from universities to develop the benchmark, putting in evidence the importance of monitoring the energy consumption of universities. The energy consumption database is often adopted to train and validate a predictive model helping to investigate the energy consumption for the university campus or a specific building. The simulation models adopted help to develop benchmarks without measuring data. For those cases, it is challenging to validate the benchmark, since there is no measured data to compare with simulation results, as shown by Utami et al. [36]. Although limited, one solution is to compare energy benchmarks with other works in literature for the same weather, as made by Litardo et al. [37]. Furthermore, even when measured data is available, the simulation model may be limited to represent a university building, as shown by Quevedo et al. [47].

Since simulations and statistical methods simplify the university campus, it is expected to have gaps between the predicted and actual energy consumption. As discussed by Salehi et al. [70] multiple factors lead to performance gaps, such as differences between the designed building and its characteristics and the difference between the actual and predicted building operation. Hence, the validation of predictive models and energy benchmarks is important to understand how far the prediction is for existing buildings. Even with those gaps, energy benchmarks for universities are important tools to track the energy efficiency of university buildings; however, their development is challenging.

The study by Chihib et al. [32] highlighted the complexity of university campuses to develop benchmarks. They developed an energy benchmark for the University of Almeria, Spain, composed of 32 buildings, classified into six categories: Research, library, teaching and seminary, sports facilities, restaurant, and offices. The categorization of space areas helped to compare buildings with the same categories and to identify buildings with the highest or lowest EUI. The same strategy was adopted by Khoshbakht et al. [27], which classified the buildings of Griffith University into different categories. Furthermore, the authors divided the university by disci-

Table 4
Benchmarking models for universities.

Year	Energy index	Total or end use	Method	Dataset elaboration	Reference
2012	180 kWh/m^2.year	Total energy use	Simulation/predictive model	Simulated	Tu et al. [42]
2014	120–440 kWh/m^2	Total	Statistical	Measured data	Vaisi et al. [62]
2014	45 -150 kWh/m^2.year (electricity) 80–210 kWh/m^2.year (gas)	Electricity and Gas	Statistical	Measured data	Yaltan et al. [4]
2015	80 - 240 kWh/m^2.year	End-use of the HVAC system	Statistical/predictive model	Measured data and simulation	Levy et al. [57]
2018	100.53 kWh/m^2.year	End-use (HVAC-Lights and total)	Statistical	Measured data	Ding et al. [48]
2018	116–236 kWh/m^2.year	Electricity	Statistical	Measured data	Khoshbakht et al. [27]
2019	162 kWh/m^2.year	Total	Statistical/predictive model	Measured data	Alghamdi et al. [102]
2019	1.2–1062(kWh/m^2.year)	Total	Statistical	Measured data	Kim et al. [103]
2020	130 kWh/m^2.year	Total energy use	Statistical with Database	Measured data	Vaisi et al. [17,30]
2020	28.9–119.5 kWh/m^2.year	Total	Statistical	Measured data	Chihib et al. [32]
2020	140.7 kWh/m^2.year	Total	Statistical	Measured data	Li et al. [104]
2020	92–539 kWh/m^2.year	Total	Statistical	Measured data	Birch et al. [61]
2020	94.05 kWh/m^2.year	Total	Predictive model	Predicted data	Utami et al. [36]
2021	81.7–106.26 kWh/m^2.year	End-use (HVAC-Lights -Plug Loads)	Simulation	Simulation	Litardo and Hidalgo-leon [37]
2021	1.45–2.8 GJ/m^2	Total	Statistical	Measured data	Li and Chen [71]
2022	83–96 kWh/m^2.year	Total	Simulation	Simulation	Quevedo et al. [47]
2023	145–155 kWh/m^2.year	Total	Statistical	Measured data	Alfaoyazan and Almarsi [66]

pline and compared the EUI between different buildings and disciplines. Since they adopt different classifications for space usage and disciplines, their method can help managers understand the university's energy consumption. Yaltan et al. [4] adopted both detailed and straightforward classifications for space usage in universities. The simplified classification is similar to other studies, such as those presented by Khoshbakht et al. [27], with classrooms, open offices, cellular offices, a library, a computer room, and a science laboratory. The detailed classification includes coffee shops, toilets, and general uses. Both studies highlighted that the research facilities had higher energy consumption, and were difficult to benchmark since each building focused on research has particularities, as shown by The works of Salehi et al. [70] and Levy et al. [57]. Furthermore, they put evidence that is possible to categorize the building space used to represent the university building better.

To consider the importance of the laboratories in energy consumption, Brown [69] adopted as input for multiple linear regression the fraction of laboratory area, improving the accuracy of the benchmark. The same strategy was adopted by Li and Chen [71], with more detailed information, considering the laboratory area, classroom area, public spaces, and others as input for the regression equation, benchmarking the energy consumption for buildings with different space usage. However, the input adopted for regression relies only on space usage, thus it is difficult to evaluate the energy consumption by end use, and what parameter, besides the activity, is affecting the energy consumption.

Tu and Lin [42] proposed a method that classifies the space of the building, according to its use. Different from Li and Chen [71], the work of Tu and Lin [42] adopts a more descriptive and detailed level of information. Some benchmark inputs are the building infrastructure and the operation conditions, such as lighting systems, and occupancy patterns. The occupation condition is divided into existing and standard. The first is obtained through surveys, while the second is the expected operation conditions. With this detail level, the method allows dividing the same space into multiple subspaces. For example, one office may have the same standard operation, but different existing operations. The main drawback of the method is the necessity to survey the university spaces to obtain the existing operation patterns for every space. On the other hand, the method allows a better understanding of the operation of the university and includes occupant behavior in the benchmarking model.

The benchmark should help to identify why or where the building is consuming energy to work as a tool for improving the efficiency of universities. In this sense, the works that correlate the benchmark and space usage can help identify the occupation patterns, such as shown by Tu and Lin [42]. In addition, it is possible to develop benchmarks that evaluate energy consumption by end-use. However, in Table 4 it is possible to observe that the majority (85 %) of studies adopt the total energy consumption, showing a gap in the research field to develop benchmarks by end-use.

Summarize the space usage by area, and the end-use energy consumption is a challenge. To evaluate the space usage by area it is necessary to audit the building, correlating each room with the activity developed. Regarding the end-use, the process to collect the energy data is difficult, due to multiple end-uses in universities and the systems are mixed, as shown by Ding et al. [48].

Ding et al. [48] evaluated the total energy consumption and the end-uses of the HVAC, lighting, and power systems. Thus, their method shows the building manager what system is consuming more energy, helping to identify possibilities for improvements. To develop such a detailed benchmark, the authors needed to utilize data from a real-time monitoring system, with total and sub-entry electricity consumption. However, the energy consumption of an HVAC system is often measured within the light and plug loads systems and limits the benchmark development. In cases where the data is not available, simulation models can be adopted to estimate the end-use energy consumption, as shown by Litardo et al. [37]. In their work, the authors adopted simulation with Energy Plus and estimated the energy consumption by end-use. This approach is helpful for universities that do not have energy consumption data by system level, and comparing the total energy consumption of the simulation model with the total energy consumption of the university can validate the benchmark. Nevertheless, it is possible to calibrate the model by comparing the simulated and actual data to find more accurate results for end-uses. To improve the calibration and the accuracy of the benchmark, it is possible to audit the building, classify the light system, plug loads and HVAC system. To reduce the necessity of energy auditing, further research can be developed to establish a correlation between the end-use and the number of students, professors, and the nature and discipline of different climates.

3.3. Energy consumption benchmark disclosure

Besides developing energy consumption benchmarks, it is important to make the information accessible. Such information can help to understand the energy consumption of universities and identify the characteristics that may lead to a more efficient building, comparing them around the world. Moreover, as shown by Xing et al. [105], when students have access to energy consumption, they might improve their actions to save more energy.

Table 4 highlights that the predominant energy performance index adopted by benchmarking studies is kWh/m^2.year, the same trend observed in Table 2. As previously discussed, comparing the EUI between universities in different countries or regions can be difficult, since the usual EUI in kWh/m^2.year does not show the weather, activity, and occupation behavior influence on energy consumption. However, a key performance indicator (KPI) that shows the energy consumption and the activity would help compare the building's energy consumption worldwide. In this sense, there is a gap in the research field to find new KPI to represent the university building.

The KPI should reflect the goals of a project, and help to measure and manage the progress towards these goals [106]. In their review paper, Kylili et al. [106] classified the KPIs' into eight categories: Economics, Environmental, Social, Technological, Time, Quality, Disputes, and Project Administration. The environmental category is adopted to display indoor quality, energy consumption, and others. The authors have shown that most environmental KPIs’ scales are adopted to classify buildings making the information easy to understand. For example, Dunphy et al. [107] adopted a KPI based on energy consumption and displayed the energy savings per year in percentage. This indicator is easier to understand than the EUI. It is important to simplify the indicators since not all building managers and society are familiar with complex indicators.

Creţu et al. [108] utilized the final energy in kWh to elaborate different KPIs’, which display the energy avoided, energy savings or overconsumption, peak power reduction, and CO_2 reduction. The proposed KPIs are similar to energy savings per year, proposed by Dunphy et al. [107]. However, the disclosure of overconsumption and peak power may help further investigate buildings with high-energy consumption and propose energy-saving strategies. Therefore, it is necessary to find a balance between the necessity of KPIs that can represent universities, and yet make the information easy to understand.

Alghamdi et al. [102] proposed a new KPI to represent the sustainability of the university, that combines water, energy, and carbon (WEC) and helps to compare different buildings in the country, regarding the Greenhouse gas emissions (GHG). They proposed a function to establish the relation between GHG emissions and different parameters such as energy usage, number of students, floor area and water consumption. The intricacy of the function highlights how complex is the university campus. Although it helps to compare different buildings at the university campus, the meaning of the WEC performance indicator may not be evident to users (students, building managers and professors).

Another solution to better understand the energy consumption in university buildings is proposed by Li et al. [72], which elaborate KPIs' for the HVAC system, to display the efficiency of the system. The author's idea can be expanded for lighting and equipment systems, leading to an easier way to understand building energy consumption and identify the system with higher energy consumption. Nevertheless, to develop such indicators, it is necessary to monitor the energy consumption by end-use, and as discussed before, this is challenging for universities.

Furthermore, since the occupation highly affects energy consumption, it is possible to assume KPI based on the number of students and professors. The work of Litardo et al. [37], and Yildiz and Kocyigit [28] displayed the energy consumption by person, while, Wang [25,109] adopted the energy consumption by a student. Such EUI helped Wang [25] to identify that the energy consumption in public universities is higher than in private ones since public universities in Taiwan have more students. Those metrics, combined with climate and space usage, can help to estimate the energy consumption of new buildings.

Other EUI metrics can help access information, such as those adopted by Chihib et al. [32], that established a correlation between the energy consumption by each space category, such as research, teaching, and others. This correlation was also adopted by Khaled et al. [110], emphasizing the importance of data visualization of energy performance in universities.

The combination of multiple KPIs or EUIs can improve the understanding of energy consumption in universities. Thus, further studies that develop more descriptive KPIs or explore multiple EUIs for university benchmarks are necessary. Even though the studies that develop benchmarks for universities help to identify the energy use intensity, they do not explore how to disclose this information. Since the fundamental role of universities is to transmit knowledge to society, it is important to disclose the energy benchmarks, helping the students, professors, and society know how efficient or inefficient the building is.

Regarding the university as a large-scale building, it is possible to adopt a geographic information system (GIS) to disclose the information. Gassar and Cha [111] reviewed different methodologies for benchmarking the energy consumption of large-scale buildings. The methods are similar to those applied to stand-alone buildings, with simulations and statistical methods. However, the authors highlighted how to disclose this information with a GIS.

Vaisi et al. [62] adopted the Display Energy Certificate (DEC) adopted by CIBSE and proposed a simple GIS to display the energy consumption for each building in the university. Along the same line, Liu et al. [91] adopted a simple GIS to display the energy and carbon savings in university buildings. Chen et al. [112] adopted a city building energy simulation (CityBES) and graphic interface to display information about the EUI for each building, obtaining the energy consumption through EnergyPlus simulations. Another example is the work of Nouvel et al. [113] which displayed the energy savings for buildings in Rotterdam through a graphic interface, with statistical methods and urban heating modelling. Both strategies can also be applied to predict university energy savings.

The implementation of GIS helps to simplify the information for society, allowing comparing the energy use in buildings, without the necessity to develop a new KPI exclusively for universities. On the other hand, the GIS can be used to display university KPIs' making the information more accessible, helping campus managers to identify the buildings with higher energy consumption, and working as a tool for teaching the importance of energy retrofits for society [6].

4. Discussion

There are two main research topics which can work together to improve the energy efficiency of university typology: the study of energy consumption of universities and the energy benchmarking of universities. Since the study of energy consumption helps to understand which characteristics have a significant influence on energy consumption, energy benchmarking helps to develop more efficient buildings and disclose the information to the public. However, it is important to understand the aim of the study and the level of complexity to evaluate university buildings. Therefore, a framework proposed in Fig. 4 aims to help future studies regarding university buildings.

The proposed framework highlights that studies aiming to understand the building consumption and develop initial building analysis could adopt utility bills to achieve the EUI and aim to understand the building energy consumption. With better understanding of the building characteristics, it is possible to categorize the building as shown by Vaisi et al. and Tu et al. [42]. The next step must be building monitoring followed by the study of occupant behavior, which has the highest difficulty for this type of study. Nevertheless, it is fundamental to achieve this level of deepness since it can help to calibrate simulations and improve the Energy benchmark disclosure and the development of new KPIs.

Building energy simulation is a tool which can be adopted for both building analysis and energy benchmarking. As discussed by Pan et al. [114] the building energy simulation can be applied to determine the Building-to-Grid interaction, for Digital Twin analysis and for urban modelling. All these techniques can be applied to university buildings. If the building administrators have the capability to implement sensors and track the building usage, the digital twins' approach can help to develop benchmarks with higher precision. On the other hand, the urban building approach can be helpful to generalize the benchmark for university campus, conducting a model calibration for each campus building. This highlights the importance of increasing the complexity level to develop energy benchmarking for universities.

On the other hand, the studies that aiming to simple benchmark university buildings can adopt the utility bills and statistical analysis to complete a simple yet important energy benchmark. With more information from initial building analysis, the benchmark process can become more complex, aiming to develop benchmarks for multiple buildings, the university campus and proposing new KPIs.

Regarding the university characteristics and the influence in energy consumption, it was observed that energy consumption in universities is affected by building characteristics, space usage [28,56,59,84], teaching type and nature [25,43,59], and occupant behav-

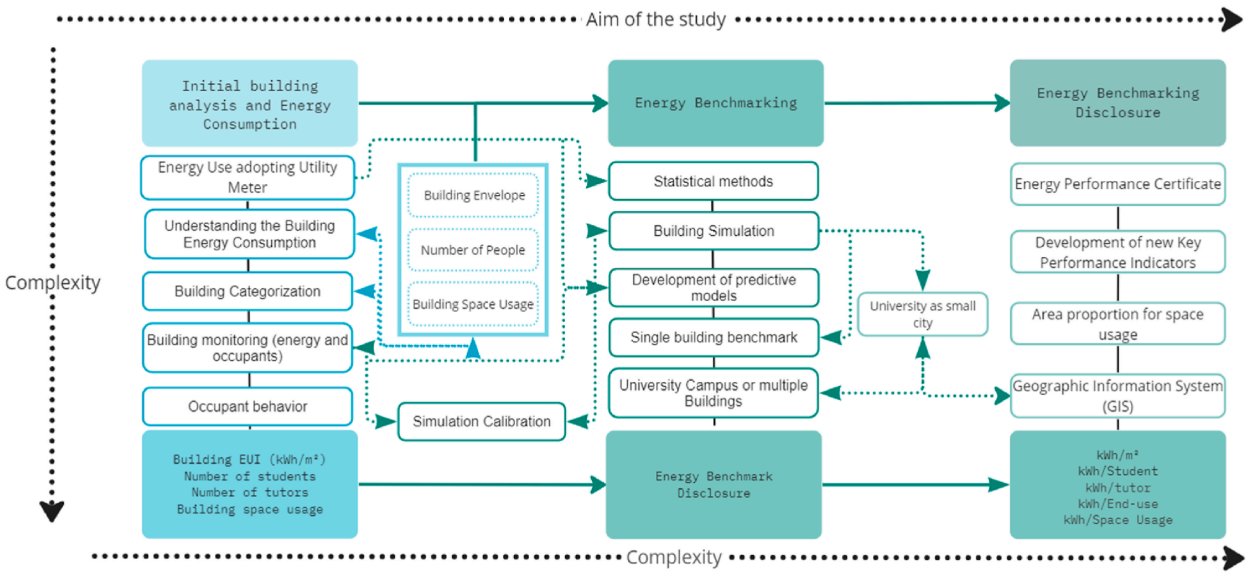

Fig. 4. Framework for energy consumption for universities.

ior [38,41,53,85,98]. Hence, simplifying the university building to only one, such as adopted by CIBSE, and Energy Star [15], does not reflect the space usage and reality of this typology. It is needed to improve the benchmarking process, expanding the university typology to consider the different space usages, teaching type and the nature (public or private).

The influence of building characteristics is and more straightforward to evaluate, and as shown by Chung and Rhee [19], the university campus has multiple opportunities to save energy by improving the building envelope. Additionally, it is possible to compare the impact of envelope characteristics between universities in the same weather, helping to identify good practices for construction. However, few studies correlate the energy savings and the cost to implement the strategies, and improvements in the building envelope cannot guarantee the efficiency of a university building [64].

Regarding space usage, the laboratories have the highest influence on energy consumption, since they have specific necessities, such as air quality and temperature control, and high plug loads [28]. This trend is confirmed when we analyses the influence of teaching type and nature and observe that universities that focus on research consume more energy than universities that develop practical skills [43], and universities with more laboratories use more energy than others [25].

Although a strong influence on energy consumption, the occupant's behavior is poorly evaluated in university buildings [53,86], since it the difficulty to track the occupation pattern. It is possible to use the Internet of Things (IoT), Wi-Fi connection, and social media database to predict the occupation pattern [101] to circumvent this. Those methodologies can be helpful to track the occupant pattern, but it is still a challenge to the association of occupancy and occupant behavior. Hence, more sophisticated methods, such as Convolutional Neural Networks and real-time monitoring can be adopted to identify occupation patterns and behavior [98].

Even with the difficulty of tracking the occupant pattern and behavior, the studies that developed predictive models for energy consumption in universities managed to consider the occupants [41,47,122,123,125,126]. In those cases, they adopted patterns based on time bins or the workhours and achieved a certain accuracy level, emphasizing the difficulty of implementing the occupancy in the benchmarking process. However, they do not develop energy consumption indicators that show the influence of the occupation on energy consumption.

The number of studies aiming to benchmark energy consumption in universities has grown since 2019, showing that despite the complexity of a university campus it is possible to develop a benchmark for this typology, adopting simulation and predictive models. Those methods are adopted in cases where there is no measured data available [47], to predict future energy consumption [42] or to estimate the energy consumption by end-uses [37]. The lack of measured data affects the validation of predictive models, limiting benchmarking applications. Additionally, adopting a simulation model to represent the university campus limits the benchmark application [47], and further studies are needed to improve the simulation models. Thus, it is important to track energy consumption in universities; however, this may be a challenge for developing countries such as Brazil [115], and methods that help to track energy consumption based on energy bills may be further developed.

It is essential to consider building characteristics and space usage, helping to identify the correlation between them to improve benchmarks. Developing a benchmarking per space could help to make it more generic and representative of multiple university buildings, improving the accuracy of the benchmark. It would help to identify areas and spaces without significant energy consumption, such as storage, emergency exits, and buildings not fully occupied. This approach helps to emphasize if the low energy consumption of a building is due to unoccupied spaces or due to building energy efficiency. On the other hand, this process is more complex, and relies on building audits to collect data for space usage. Therefore, the process of benchmarking for universities should consider space usage and achieve a more generic benchmark for the whole building or campus but it is more complex to develop.

Additionally, it is important to benchmark energy consumption by end-uses, leading to a better understanding of the building necessities and particularities. This approach helps to identify energy waste and the potential for improvements in university buildings. Hence, it is important to track the energy consumption by building, and consider the primary energy, helping to compare buildings with different energy sources (gas or electricity).

Regarding energy disclosure, the studies that benchmark universities usually adopt the EUI to indicate the performance of the buildings. This metric helps compare different buildings since is normalized by the gross-floor area, and to understand how much energy the building consumes [73] and is widely applied to commercial buildings. However, it limits the analysis since the energy consumption in universities is highly affected by other variables than the area. Therefore, to address this issue, and differ them from simple commercial buildings, it is possible to normalize the energy consumption by people, students, or even professors, correlating it with the occupation [25,28,37,109]. Furthermore, a performance indicator should be simple to understand and make comparing different buildings easier. Thus, further studies should develop new KPI for universities, aiming to correlate energy consumption, occupation, and space usage, improving information disclosure.

Moreover, it was observed that the studies reviewed usually adopt graphs or scales that display the energy consumption of the building, and how far they are from the benchmark. This approach helps identify how efficient the building is, and it is practical for academic purposes but not accessible to the public. Regarding the importance of universities to develop a more sustainable future, the benchmark disclosure for universities should be improved, being more accessible and easier to understand. Thus, further work should invest in elaborating an orographic information system to display the benchmarking, improving the disclosure to the public.

Adopting GIS to display that information is possible. This strategy is adopted in benchmarking large-scale and commercial buildings, granting access to much information about the buildings. Adopting GIS and developing new KPIs' for universities may help to improve the disclosure of university energy benchmarks and energy savings in university buildings.

5. Conclusion

This paper aimed to find the gaps in the literature regarding the energy benchmarking of university buildings by revising previous works and proposing research opportunities. The reviewed literature highlighted the importance of evaluating, monitoring, and benchmarking university buildings' energy consumption. The main conclusion was that, since universities are composed of multiple commercial buildings, it is necessary to find the proportional area for each space usage and correlate with the end-uses for multiple systems adopted in universities, leading to different challenges and possibilities for further studies.

Although the number of papers increased between 2019 and 2020, there are still gaps and research opportunities in this research field, such as: benchmarking the energy consumption by end-use and developing specific KPIs for universities.

Regarding the energy consumption in university typology and the benchmarking, it is noteworthy that energy consumption is highly affected by the occupants and space usage. Therefore, the energy benchmark of universities should consider the spaces regarding, at least, the classrooms, laboratories, offices, and cafes/restaurants, mainly the conditioned zones, since those spaces are presented in every university. Other spaces, such as museums, health centers, and students' residences can be considered, however, they have more specific uses and characteristics, and it is possible to develop a specific benchmark for each one.

The multiple space usages present in a university building, and how to represent it in energy benchmarks increases the difficulty of benchmarking this typology. Nevertheless, to develop more representative benchmarking, and fulfil the gaps in this research field, further studies should increase the complexity level of development, aiming to.

- Consider the multiple typologies and university complexity in the benchmarks by treating the universities as large-scale buildings.
- Consider the space usage by area in the benchmark development: university buildings usually concentrate several different services, uses and occupancies in near spaces.
- Benchmark the energy consumption by end-uses: this can help to identify the systems with high energy demand and develop retrofit strategies specifically.
- Develop KPIs that correlate energy consumption, occupation, and space usage, leading to an easier way to disclose information regarding the university's energy performance.
- Invest in elaborating a geographic information system to display the benchmarking and improve the disclosure to the public: since university campuses are composed of several buildings arranged in a large area, a GIS helps to disclose to the users how efficient the building is, helping to develop more sustainable universities.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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