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Research article

The need for scientific-area-related indicators for effective energy planning in higher education institutions

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ABSTRACT

The quest for improving energy efficiency is transversal to all areas of society. Higher education institutions represent an important sector in this quest due to their high demand, but also for the role model that they can play in educating energy-efficient citizens and piloting new approaches and experiences. Thus, decreasing energy consumption in higher education institutions, in addition to reducing the carbon footprint, contributes to ameliorating countries' energy bills, and, most importantly, contributes to a more sustainable society. The purpose of the paper, based on the energy consumption of the University of Minho, Portugal, between 2007 and 2022, is threefold: first, to evaluate how energy consumption and associated carbon footprint indicators have performed under a sustainable strategy program, second to reflect on total energy and specific energy indicators, and lastly to emphasize the need to improve energy metering and planning systems to account for the distinctive needs of the different scientific area buildings. This is not only relevant but also rare to find in scientific literature. Findings suggest that UMinho's energy consumption is in line with the numbers reported in the literature. Moreover, detailed indicators, specified by scientific area building, show diverse patterns in energy use, demonstrating the limitations of an overall analysis of buildings in the university campi. The results show that energy efficiency improved as a result of the implemented action plan, and demonstrate the need for detailed and specific indicators that reflect the different needs of each scientific area. The results provided by this refinement call for the design of tailored initiatives to decrease energy consumption, since they allow the planning of specific measures and programs for different energy use patterns, and therefore improve their efficiency. Finally, the preliminary results of the analysis of building specific energy use point to the need for more detailed data on hourly and daily consumption and academic term given the relative contribution of users' behaviour.

1. Introduction

The Millennium Development Goals, which have paved the way for the recent 17 Sustainable Development Goals, have been acting as a global and inclusive framework for the implementation of a new and sustainable development model. Energy production

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and consumption has assumed a central role in the attainment of multiple sustainable development goals and related objectives, namely by its close link to the carbon footprint.

Higher Education Institutions (HEI) are a privileged space for the analysis of policies envisioning sustainability, as they provide the theory and practice on the different areas involved, while reducing their impacts [1], extending their engagement to the activities that support and extend teaching and research. These include i) the management of the university campi and operations; ii) campus planning, design, construction, and rehabilitation of buildings and infrastructures; iii) purchasing practices; iv) mobility and v) involvement with the community [2]. Consequently, scientific studies on sustainability and energy use in HEI have been increasing in recent years.

The University of Minho (UMinho) started to implement an integrated sustainability strategy in 2010, as detailed in [3]. When addressing energy policy and associated indicators, the lack of informative energy indicators that reflected the specificity of each scientific area emerged as a limiting problem, which compromised the implementation of effective efficiency measures. This lack of knowledge is not only important for HEI campi energy management policies, but also for cities and industry, since energy represents a high cost and a significant carbon emission. In particular, Portuguese public buildings alone are responsible for the annual consumption of more than 9.6 TJ, which represented 5.5% of the total energy consumed in 2011, representing therefore a high potential for increasing national energy efficiency.

This paper presents novel evidence of the limitations of global energy consumption indicators for buildings, that are frequently presented in the literature. Based on energy consumption over a 16-year period (2007-2022), it evaluates the specific energy consumption, and related carbon footprint, by total and net built area, and per student and member of the academic community. To our knowledge, this is the first paper stressing that HEI buildings are not homogeneous across scientific areas, and consequently, energy efficiency programs should be tailored according to their specific energy use patterns.

The paper starts by a literature review (section 2) on measuring energy consumption and assessing energy efficiency initiatives, followed by specifying the objectives of the present research and detailing the followed methodology (section 3). Section 4 describes UMinho, its facilities and academic community, the evolution of energy consumption and energy efficiency initiatives, that are then evaluated in section 5. The next section presents the calculated energy intensity indicators by total area, net area, student and academic community member, concluding with the presentation of specific energy indicators per scientific-area. The paper concludes with the discussion of the results in section 7 and the conclusion in section 8.

2. Literature review

The analysis of energy consumption in HEI has been the subject of an increasing number of papers, aiming at either building a baseline characterization and/or aiming at evaluating the effect of energy reduction initiatives. In this section, a concise summary of both strands of literature is presented.

2.1. Measuring energy consumption

In the UK, energy consumption in HEI has been frequently analyzed ([4], [5]). Using a panel dataset over time and across institutions, integrating several control variables such as income, population, and energy prices, [4] found that energy efficiency increased over time and that research institutions have higher energy intensity than other institutions. Also focusing on UK HEI, [5] analyze energy consumption and its relation to the number of students and floor area finding significant differences across types of institutions (Ancient universities, Redbrick universities, Plate glass universities, Institutes and colleges, New universities, Colleges). A similar study conducted in HEI in Guangdong province in China [6], based on a five-year case study (2006-2010) on energy consumption and conservation measures implemented, found significant differences in energy consumption between different types of universities (field of study, nature, and level). In Brazil, [7] support these results based on the analysis of university buildings. Moreover [8] studied energy consumption at Universidade de São Paulo, aiming at defining priorities to support managers in establishing energy efficiency actions. The monitored buildings included a Museum, a University Hospital, and a Computation Centre, which were the most energy-intensive buildings with equivalent weekly consumption of 1.01, 0.59, and 0.27 GJ/m^2, respectively. These buildings were followed by the Oceanographic Institute (0.13 GJ/m^2), Geociensce Institute (0.12 GJ/m^2), Institute of Astronomy (0.12 GJ/m^2), Faculty of Veterinary and Zootecnic (0.12 GJ/m^2), and Institute of Chemistry (0.11 GJ/m^2). Humanities schools demonstrated to be the least energy demanding, with intensities that varied from 14 KJ/m^2 for the School of Communication and Arts and 40 KJ /m^2 for the Physical Education School. The need to perform analysis by specific building is also stressed in the literature focused on the influence of occupants' behaviour on building energy consumption ([9], [10], [3]). Their results reinforce the importance of user behaviour in buildings' energy consumption, and the need to develop building-specific approaches. [11] compared LEED (Leadership in Energy and Environmental Design) certified buildings' energy consumption, with non-LEED certified buildings within the same university campus. Although the main objective of the paper was to address the question of LEED's efficacy, it highlighted some limitations relevant to the present topic. Specifically, the need to introduce building energy demand into the equation. Additionally, it called attention to the variability of energy consumption by building, and thus the limitation of using the mean or median consumption as an indicator. [12] also stressed the need to evaluate buildings separately, namely by year of construction.

Taking advantage of the changes in occupancy in residential and education buildings during the COVID-19 pandemic, [13] and [14] compared buildings' energy consumption before and during the pandemic aiming to understand the importance of buildings users' behaviour on total energy consumption. In the same vein, [15] analysed the COVID-19 period and found significant differences in energy consumption between type of buildings and scientific area of the activities developed there, however, their results question the advantages of defining periods in which buildings are closed.

2.2. Assessing energy efficiency initiatives

Improvements in buildings' energy efficiency are typically addressed from an infrastructural perspective, from a behavioural perspective, or both. Technical, non-technical interventions were analysed by [16], while [17] did a similar study for eight Chinese HEI, stressing the role played by stakeholders, such as administrators, governmental agencies, networks, students and non-governmental organizations. Based on a survey of UK HEI [16] concluded that 83% of the surveyed institutions adopted technical (technology-based – most of which involved metering systems) and non-technical (behavioural and structural changes) initiatives to decrease CO_2 emissions and increase energy savings. The relevance of creating special bodies to develop long-term policies and manage daily operations in the area of energy management was analysed, and the role played by changing to more efficient lighting was highlighted in [17]. In this line, [18] analysed the implementation of Continuous Commissioning in the Texas A&M University Campus, and found significant energy savings by integrating energy metering and retrofitting projects. [19] examined the implementation of the same system in buildings with various functions (education, health, laboratories, office, and miscellaneous). Moreover, [20] concluded that not accounting for user occupancy data might lead to significant errors in energy consumption prediction. The effect of an energy program implemented at the American University in Beirut aimed at improving energy security through the use of batteries and photovoltaic panels was analysed in [21]. Results showed that the University's dependence on fossil fuels significantly decreased as did the operating costs.

Regarding awareness campaigns, [16] found that most HEI have "carrot-stick" awareness programs, many of which were developed by students. Moreover, a program for increasing pro-environmental behaviour, including energy use, at Rhodes University, in South Africa, was reviewed in [22]. Their results concluded that the program efficacy was strongly related to personal values and situational factors. In the same vein, [23] analysed energy efficiency awareness programs developed for households in Singapore and concluded that feedback information and its combination with communication tools, significantly increased programs' effectiveness. In a parallel line of research, [24] and [25] explored the subject of stimulating energy saving through the concept of energy culture in HEI. [25] concluded, based on a survey, that it was important to increase knowledge on energy issues in non-technical fields of study and urged the development and implementation of monitoring systems. In addition, the authors found that energy saving could enhance group cohesion and increase the flow of inter and intra-community knowledge. Along the same line, [26] had previously developed a similar analysis for high school students, analysing the role of education on technological and socio-economic issues to enhance adherence to energy-saving behaviours. [26] found a strong correlation between individual attitudes, energy habits, and school performance to environmental concerns and willingness to undertake actions. Consequently, energy efficiency and saving policies that typically focused on buildings, firms, and vehicles, should be broadened to include mechanisms to change behaviour and attitudes. [27] stated that the cultural model of energy consumption comprehends the engineering, economic, psychological, and anthropological dimensions. The behaviour of the energy user was the centre of the analysis, observing how the systems characteristics and external factors condition the behaviour, and then how interventions in the system and external conditions could achieve behavioural change. The main aim was to analyse the relationship between energy culture and saving energy potential. Their findings suggested that students could be categorized into three groups regarding their energy saving behaviour and that significant savings could be achieved by manipulating system characteristics and external conditions. The relationship between energy-saving behaviour and the frequency of cultural activities was also illustrated in [28]. In the author's interpretation, cultural activities signalled environmental concerns.

Simultaneous implementation of energy and water saving plans in schools in Spain was analysed in [29], finding that users' involvement was a key determinant of buildings energy consumption, and stressed that more information was needed, namely measures of hourly consumption and consumption during non-academic periods for the development of effective saving plans.

The effect of behavioural interventions on students' energy saving habits was analysed in [30]. The authors concluded that attitude, perceived responsibility, perceived behaviour control and subjective norms were important determinants, but organizational factors were also relevant. The same result was obtained by [31] which examined energy-saving behaviour in the context of a city. Using a multilevel hierarchical model they examined the effect of individual and city-level factors and concluded that individual and city level factors were important and their effects on saving behaviour was correlated.

Studies on Portuguese dwellings have shown the need for significant investments in heating and cooling in residential buildings [32], namely to address the expected effects of climate change on total heating and cooling degree hours [33]. Moreover, some studies have stressed the need to account for the difference between planned and actual energy consumption in residential buildings ([34], [35]). Finally, [36] analysed the effects of alternative energy standards on office buildings' energy consumption in 65 cities under different climate change scenarios. They concluded that the choice of standards was relevant for energy-saving potentials. These studies demonstrate the complex nature of energy rationality, which stands between social, infrastructural, operational, and climatic factors. Nevertheless, studying these variables over a long period can improve the understanding of these complex relations, improve the effectiveness of action plans and help alike institutions adopt a similar path. The promotion of energy efficiency has a large scope, being relevant in most sectors of society and economic activities. However, the strategy followed by each sector should be specifically tailored. HEI can be crucial for attaining national energy efficiency targets, not only for their significance on national total energy consumption but also because they can promote behavioural changes. It is a known fact that knowledge (formal or informal) conditions individual behaviour and that HEI produce and disseminate knowledge.

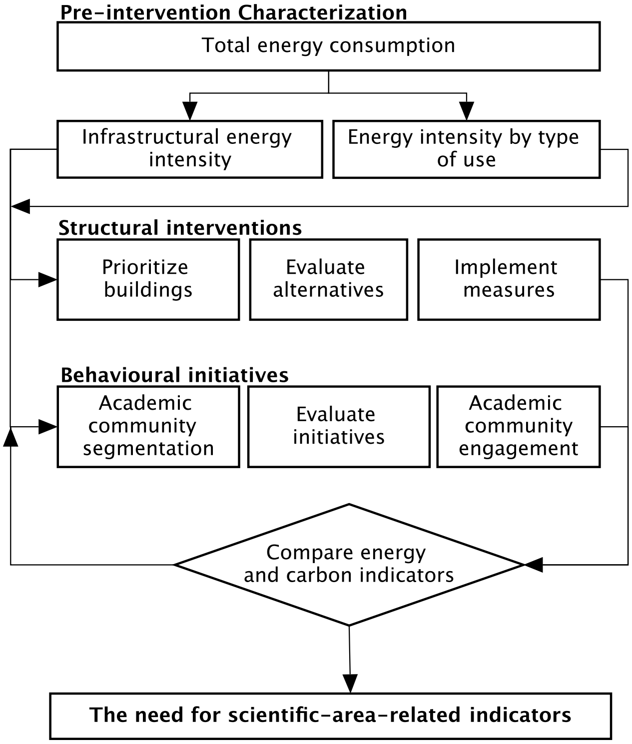

Fig. 1. Conceptual framework.

In sum, there is significant evidence that the energy efficiency performance of buildings strongly depends not only on the building's structural characteristics but also on its uses and users. However, there is a lack of studies examining the energy consumption of academic and research buildings by the scientific area.

3. Objectives and methodology

Energy efficiency interventions in HEI have mainly been motivated by two main reasons: reducing energy costs without compromising HEI's objectives and contributing to targets on environmental indicators. Due to the intense and diverse metabolism of HEI, these interventions require detailed knowledge of the status quo and its determinants. In other words, having a benchmark is essential for the development and monitoring of energy efficiency in any institution.

The conceptual framework of this research is depicted in Fig. 1.

The analysis baseline is established using total energy consumption (including electricity, natural gas, and propane), and associated carbon footprint. The characterization of this business-as-usual scenario is instrumental to identify the highest consumption units and to prioritize intervention areas (research, education, and support facilities). The acquired knowledge allowed the implementation of monitoring data-loggers in more than 50 buildings that constitute the case study campi, to better understand short-term patterns of each building, and to support specific actions and structural measures addressed at improving energy efficiency. They also supported the definition of information and behavioural interventions, which induced the academic community to have more responsible action toward energy.

To define the baseline and evaluate the effectiveness of the structural and behavioural interventions the following indicators were computed:

$$EC_T = EC_P + EC_{NG} + EC_E \tag{1}$$

Where:

EC_T represents the Total Energy Consumption (GJ);
EC_P represents the Propane Energy Consumption (GJ);
EC_{NG} represents the Natural Gas Energy Consumption (GJ);
EC_E represents the Electric Energy Consumption (GJ).

Furthermore, the (EC_P), that was less than 0.1% of EC_T, was canceled in 2012. Therefore, equation (1) can be simplified into equation (2).

$$EC_T = EC_{NG} + EC_E \quad (2)$$

The CO_2 emissions related to energy consumption can therefore be estimated by equation (3).

$$CE_T = CE_{NG} + CE_E \quad (3)$$

and detailed through equation (4) and equation (5).

$$CE_{NG} = EC_{NG} \cdot NG_f \quad (4)$$

$$CE_E = EC_E \cdot E_f \quad (5)$$

Where:

CE_T represents the Total Carbon Emission (Ton CO_2);
CE_{NG} represents the Carbon Emission due to Natural Gas consumption (Ton CO_2);
CE_E represents the Carbon Emission due to Electricity consumption (Ton CO_2);
NG_f represents the carbon emission factor for Natural Gas (Ton CO_2/GJ);
E_f represents the carbon emission factor for Electricity (Ton CO_2/GJ).

4. Case study description

The University of Minho (UMinho) is a Portuguese HEI founded in 1974 and located in two campi: Campus Gualtar, in Braga; and Campus Azurém, in Guimarães. The facilities comprise approximately fifty buildings spread through these two cities, with a total net construction area of approximately 210 823 m^2 (144 217 m^2 in Gualtar and 66 606 m^2 in Azurém). The UMinho has 9 academic buildings: School of Health Sciences (11 342 m^2); School of Science (12 616 m^2); School of Engineering (27 310 m^2); School of Education and Psychology (5 641 m^2); School of Law (3 300 m^2); School of Economics and Business (3 512 m^2); School of Humanities (1 386 m^2); School of Architecture (3 803 m^2); and Institute of Social Sciences (2 079 m^2)). In addition to these buildings, the university has forty-six more buildings. Although some of the buildings have less than 10 years, others have more than 40 years, representing important challenges when carrying out energy efficiency studies and designing energy efficiency policies.

Most of the buildings have mixed activities, schools and institutes are constituted by offices, labs and classrooms, while pedagogical buildings have classrooms and administrative offices, other buildings comprise social services, and service units.

The Academic Community (AM) comprises students in undergraduate studies, master courses, and Ph.D. courses, faculty members (96% of them with a Ph.D.), and technical and administrative staff. In 2007, the first year of analysis, the AM was composed of 17628 members (89% of them are students) ([37], [38]), that have grown to 23 960 in 2022, as depicted in Fig. 2. During the baseline period (2007-2010), AM increased by 3.59% average per year, while in the subsequent period the increase was significantly lower but steady at an average of 1.89% per year. Student population (ST) also increased more rapidly in the first period (4.23%) than after 2010 (1.68% average annual increase).

Although the Rectorate team and the administration were responsible for the overall management of the campi, in 2009, a specific unit was created to promote UMinho's strategic objectives for energy and environmental issues. AUMEA (Portuguese acronym for the University of Minho Agency for Energy and Environment), an agency dedicated to promote actions to raise awareness of faculty, staff, and students, regarding eco-sustainability practices and responsible energy use, has, since then, been responsible for promoting the integration of energy and environmental issues into the management priorities [39].

Energy consumption fluctuated significantly between 2007 and 2022. It is very clear that between 2007 and 2010, total energy consumption rose significantly (5.9% average per year), between 2010 and 2014 it significantly decreased from 84.36 GJ to 66.62 GJ (representing a 5.5% average yearly decrease); 2014-2016 is the year where energy consumption rose more rapidly, at an annual average of 11.5%. After 2016, energy consumption has been decreasing at an average rate of 3.3% yearly, as shown in Fig. 2.

In 2012, 61.5% of the total energy consumption was consumed by nine buildings (Schools and Institute) that compose UMinho, only 4.1% was consumed in service units and pedagogical buildings (Fig. 3). Given the significance of the energy consumption in these nine buildings, these were the first to be intervened.

4.1. Energy efficiency initiatives implemented

4.1.1. Structural measures

The structural technical interventions started in 2010 and extended until 2011. They consisted in:

1. Replacement of mercury vapour lamps with similar sodium vapour lamps with lower power and higher luminous flux.
2. Installation of voltage regulators to control the nominal power during the operation period.
3. Regulation of the operating periods according to the time of year and scholar calendar.
4. The implementation of an integrated HVAC management system
5. Installation of ice banks to allow thermal accumulation over the electricity off-peak periods.

The objective of these measures was to increase energy efficiency and save on outdoor lighting systems, while maintaining the levels of safety and comfort.

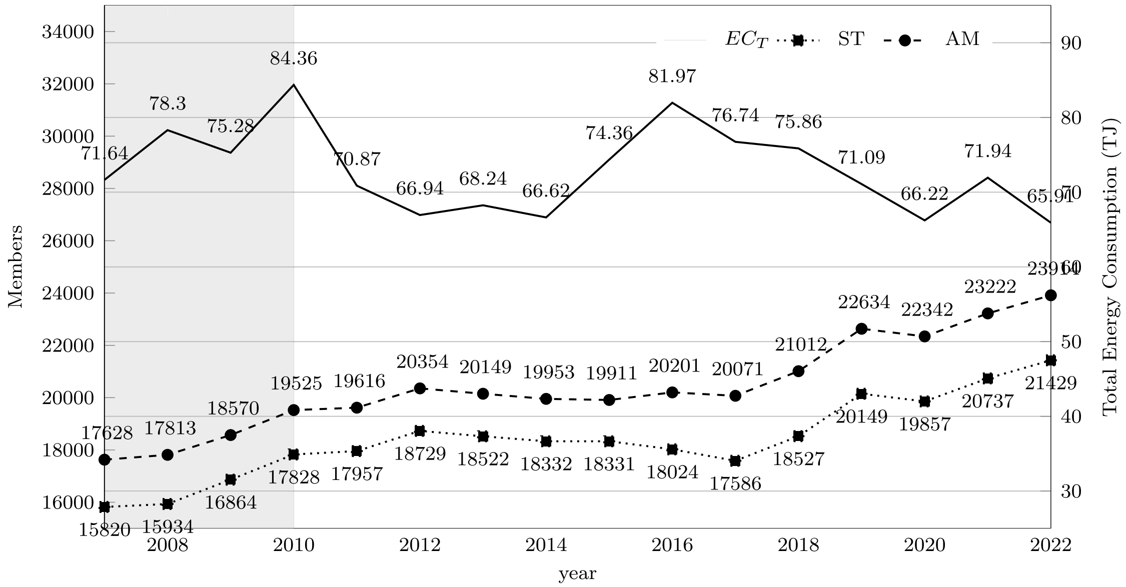

Fig. 2. Total Energy Consumption, Academic Members and Students (2007-2022).

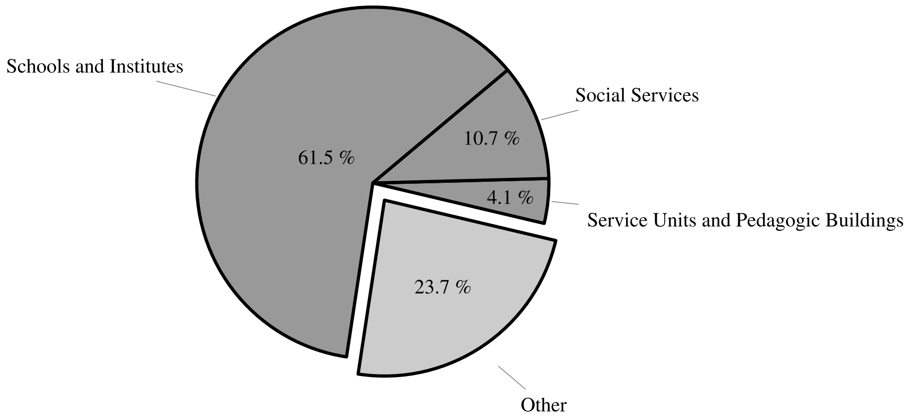

Fig. 3. UMinhoś Campi Energy distribution in 2012.

4.1.2. Behavioural initiatives

The first activity promoted under the AUMEA's Strategic Plan, and the University of Minho Action Program for Energy Efficiency and Rationality (that is presented in the 2012-2013 UMinhoś Sustainability Report [38]) consisted of a workshop on "Energy and Energy Efficiency", where AUMEA presented itself to the community and explained its objectives and the proposed Action Plan. Concrete measures and practices for energy efficiency were presented ti the academic community, as a prelude to discuss how should the energy efficiency process be implemented on UMinho's campi.

After this workshop, behavioural and information interventions were designed and implemented. The first phase was an awareness campaign "STOP". This action intended to mark, with STOP stickers, a set of sites with potential energy efficiency opportunities. First, students were called to develop a group of *energy vigilantes* who would point out inadequate energy behaviour by their colleagues. The Student's Association was an important partner and supported this teasing and awareness campaign. Subsequently, the AM was invited to expand the "STOP Campaign", by placing posters, stickers, and pads (depicted in Fig. 4) strategically on UMinho's campi and facilities. Preferential communication of these actions included UMinho's Intranet, mailing list, Facebook, and Radio. This first phase ended in June 2011.

As a reinforcement of these actions, a Good Practice Guide for Energy Efficiency and Rationality was materialized, by AUMEA, to brief, each year, all new members on these important topics. The "STOP Campaign" pioneered the involvement of all stakeholders, towards efficient use of energy, as a cross-action theme, motivated by budgetary, environmental, educational, and ethical issues.

Fig. 4. Awareness Campaign "STOP" - Posters.

Table 1
Heating (HDD) and cooling (CDD) degrees-day for the North of Portugal.

Year	HDD	CDD	HDD + CDD
2007	1 701	40	1 742
2008	1 788	46	1 834
2009	1 654	81	1 735
2010	1 836	144	1 980
2011	1 482	64	1 546
2012	1 797	75	1 873
2013	1 832	139	1 971
2014	1 559	43	1 603
2015	1 549	94	1 643
2016	1 724	156	1 880
2017	1 484	139	1 623
2018	1 742	126	1 868
2019	1 603	79	1 682
2020	1 453	150	1 603
2021	1 561	66	1 627
2022	1 408	226	1 635
Average	1 636	104	1 740

5. Measuring the effects of implemented initiatives

5.1. Environmental conditions

Environmental fluctuations in air temperatures have an impact on building's heating and cooling energy demand. The most common methods used to determine energy demand are based on parametric energy balance and degree-day methods [40].

According to the Koppen climate classification, Portugal has a warm Mediterranean climate with a hot-summer Mediterranean climate (CSa) and a warm-summer Mediterranean climate (CSb). Also, the Portuguese Institute for Sea and Atmosphere (IPMA) reports that the average annual temperature for the 1971-2000 period was 15.2ºC (with maximum and minimum values of 16.5 and 13.9, respectively).

The Portuguese Regulation on the Energy Performance of Residential Buildings (REPRS) defines 18.ºC related to the degrees-day of heating (HDD) and 25.ºC to the degrees-day of cooling (CDD). Table 1 depicts the historical HDD and CDD data for the 2007-2022 period, that was accessed on EUROSTAT [41]. In the studied period, the CDD represents only 6.4% of the HDD. Also, in this period, HDD has a mean value of 1636, with a standard deviation of 142.2.

These data indicate that the heating period is the most relevant and that its annual variation is normally below 10%, consequently heating and cooling needs can be assumed approximately constant across the period analysed.

5.2. Energy use and related CO2 emissions (2007-2022)

The overall energy use by primary energy sources (electricity and natural gas), is summarised in Fig. 5. Electric energy represents the most relevant energy source, justifying the decision to address, with special detail, this type of energy use. Despite some variations in the use of natural gas, an overall decrease over the years was observed. The use of propane gas was residual (less than 0.1% of total energy consumption) and limited to four departments, which changed to natural gas in 2012, and is therefore ignored in this analysis.

The implementation of energy efficiency measures and awareness campaigns in 2011 resulted in a significant decrease in energy consumption, following the steady increase of 17.75% that was registered between 2007 and 2010. In particular, in 2011 the overall energy use decreased by 15.99% (from 84.33 GJ to 70.87 GJ). In the 2010-2014 period a decrease of 29.94% and 17.84% was observed in Natural Gas and Electricity, respectively.

In 2014 UMinho started an ambitious infrastructural program to provide better services to the AM. The refurbishment of several older buildings and the construction of six new buildings between 2014-2016, represented a built area of 9 867 m^2, corresponding to 7 384 m^2 of net area. While these buildings (Central Library in Azurém, Central Archive in Braga, and dedicated research buildings in

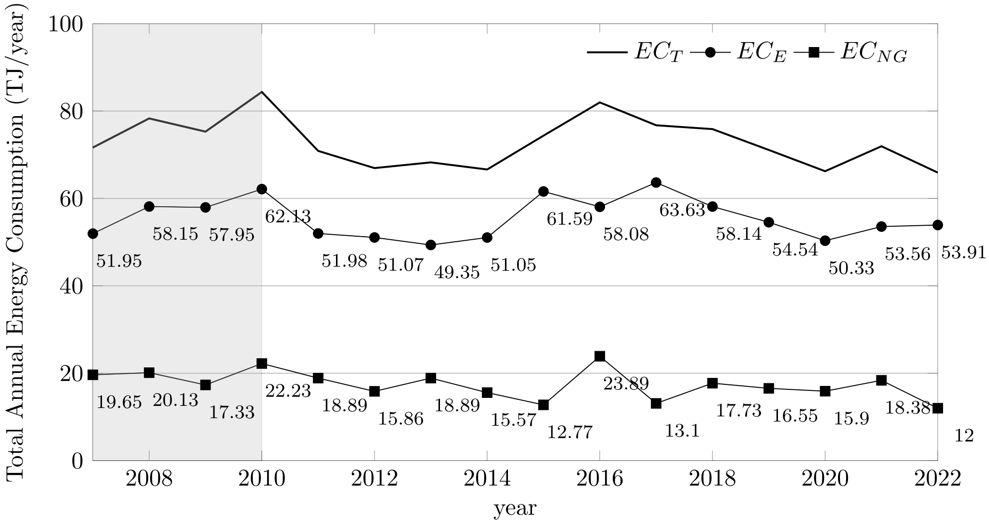

Fig. 5. Total Annual Energy Consumption by source. Source: UMinho Technical Services; UMinho Sustainability Report.

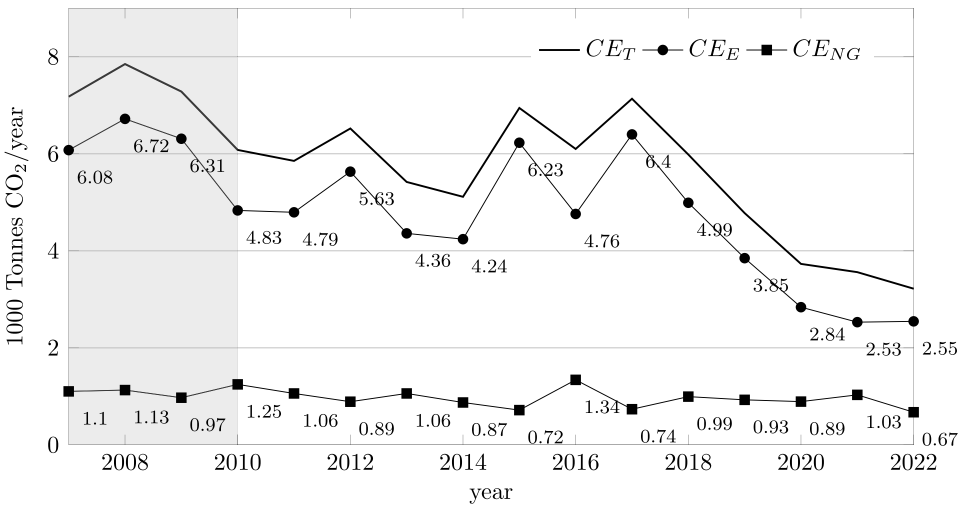

Fig. 6. Total Annual Energy related CO_2 Emission in UMinho campi. Source: UMinho Technical Services; UMinho Sustainability Report.

both campi) provided better facilities for education and research activities, they are responsible for the highest energy use observed in the 2014-2016 period, which was responsible for an increase of 53.41% in Natural Gas and 13.77% in electricity as is reflected in Fig. 5. It should however be stressed that this increase was in electricity consumption only. In fact, the consumption of natural gas decreased.

It is clear that the energy use associated with Natural Gas is mostly due to common infrastructures and mechanical equipment, which depends more on central control rather than on users' behaviour.

It should be noted that energy consumption did not decrease significantly during the COVID-19 lockdown which occurred between March 2020 and September 2020, contrary to the evidence provided in the literature ([13], [14], and [15]).

One important consequence of energy consumption is its related CO_2 emissions. Fig. 6 reports the evolution of energy-related CO_2 emissions, based on current emission factors. For Natural Gas, an emission factor of 0.0561 tonnes CO_2/GJ, was considered. The estimation of CO_2 emission intensity is more complex for electricity generation, since it depends on the ratio of CO_2 equivalent emissions from all electricity production, including electricity from renewable sources. Different annual emission factors were considered for electricity, depending on the energy mix of the year, varying from 0.4210 tonnes CO_2/MWh in 2007 to 0.170 tonnes CO_2/MWh in 2022, according to [42]. As depicted in Fig. 6, total CO_2 emissions, in the pre-intervention period were steadily decreasing. The reason behind this decrease is the rising penetration of renewable energies in Portuguese electricity production. It is interesting to note that UMinho's CO_2 emissions depend partly on its own actions, being mostly determined by the energy mix of the country in any given year. Thus, the reduction observed after 2017 is mostly due to the increasing penetration of renewable energies in Portugal, following the trend in the EU where in 2022, the electricity sector was 50% less GHG intensive than in 1990.

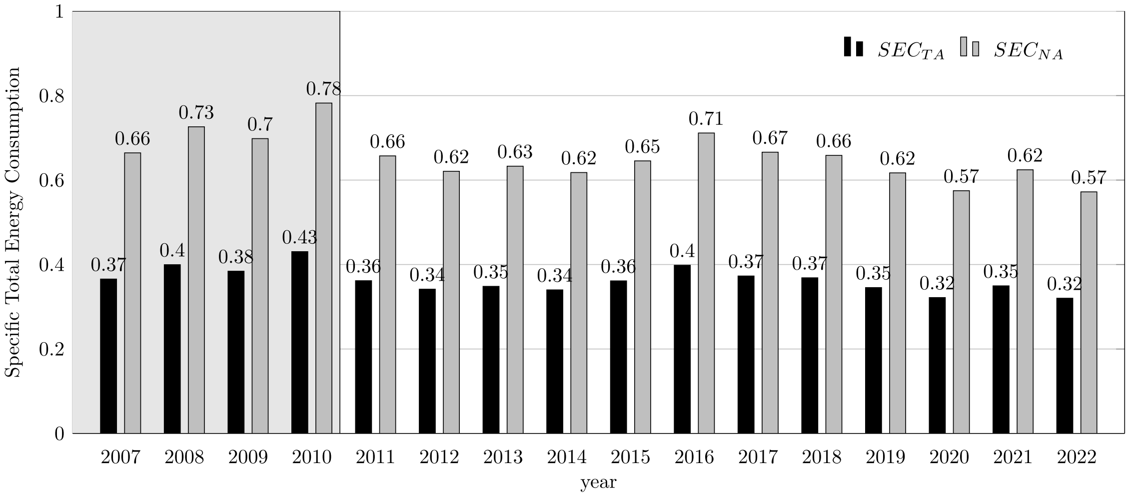

Fig. 7. Specific annual Energy Consumption per Total (TA) and Net (NA) built area.

Therefore, the effectiveness of the structural and awareness measures adopted, in addition to the cost advantages it brings, also contributes to the reduction of CO_2 emissions, thus contributing to UMinho's sustainability goals [39]. However, a complete analysis of energy efficiency cannot be limited to the quantity of energy use but requires the computation and analysis of the consumption per unit of output generated, i.e., energy intensity.

6. Energy intensity indicators

The implementation of energy efficiency and rationality measures on both UMinhoś campi resulted in a significant overall decrease in energy use, and higher energy efficiency. However this indicator does not take into account the energy outputs and outcomes. Energy Intensity indicators can reflect the quantity of energy required per unit of output or activity, therefore representing a valuable benchmark for comparing the different performances of similar activities. They also contribute to understanding energy patterns and pathways in the same institution, providing information to design effective efficiency measures. Due to the diverse nature of activities and the change of the AM composition through time, this analysis is particularly relevant.

When evaluating the energy consumption, several spacial and per capita indexes will be considered. While the first explains the consumption associated with the built infrastructure, the second represents consumption patterns and habits by academic members.

6.1. Energy intensity per built area

The Specific Energy Consumption of all built area SEC_{TA}, and the Specific Energy Consumption of the used built area SEC_{NA}, expressed in (GJ/m^2), can be estimated by equation (6) and equation (7), respectively.

$$SEC_{TA} = \frac{EC_T}{TA} \tag{6}$$

$$SEC_{NA} = \frac{EC_T}{NA} \tag{7}$$

Where:

TA represents the Total Built Area (m^2);
NA represents the Net Built Area (m^2).

The 2007-2010 period is considered as a baseline scenario, whereas the results in the 2010-2022 period represent the effects of the interventions designed. As measures were implemented at different moments in time, but they coincide in some periods, analysing the effectiveness of each measure separately is not possible.

Temporal analysis shows that the ratio of TA/NA remains relatively constant between 2007 and 2022. The total energy per built area was quite stable during the period analyzed, varying from 0.32 GJ/m^2 to 0.40 GJ/m^2 (Fig. 7). When looking at the same energy, but associated with the net area, these values almost double from a minimum of 0.57 GJ/m^2 to a maximum of 0.78 GJ/m^2. The different results obtained for total and net built area demonstrate that higher energy intensities can partially be explained by the architectural design of existing buildings.

Although these indicators provide a characterization of energy intensity they relate to the infrastructure and do not isolate this factor from the influence of user behaviour. We next turn to energy intensity per capita.

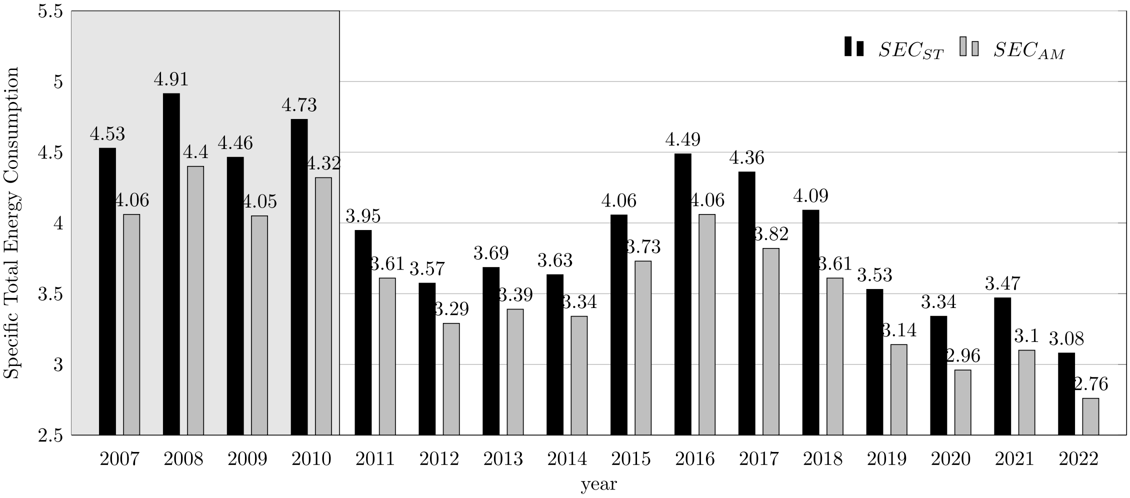

Fig. 8. Specific annual Energy Consumption per Student and Academic Member (GJ/capita).

6.2. Energy intensity per student and academic community member

Energy use is dependent on personal and collective behaviours, thus it should be analysed relative to specific AM groups. Therefore, the Specific Energy Consumption per Student SEC_{ST}, and the Specific Energy Consumption per Academic Member SEC_{AM}, in ($GJ/capita$), was estimated through equation (8) and equation (9), respectively.

$$SEC_{ST} = \frac{EC_T}{ST} \tag{8}$$

$$SEC_{AM} = \frac{EC_T}{AM} \tag{9}$$

Where:

ST Represents the total number of students;
AM Represents the total number of members in the academic community.

Considering the variation of the specific per capita energy indicators depicted in Fig. 8, it becomes clear that during the 2007-2010 period, an overall increase in energy use per capita on UMinhoś campi was observed.

From 2010 to 2014 energy intensity dropped from 4.73 GJ/ST and 4.32 GJ/AM in 2010 to 3.63 GJ/ST and 3.34 GJ/AM in 2014, representing a decrease of 23.20% and 27.72%, respectively, due to the implementation of the structural and behavioural initiatives. In 2014, as previously referred new buildings were constructed and old ones were refurbished, increasing the energy intensity from 2015 to 2017. After 2017 it is clear the reduction in energy intensity until the present day, translating the long term effects of the policies implemented.

Focusing on electricity consumption alone, Fig. 9 presents the ratio between electricity consumption and total energy consumption. Although the ratio varies considerably in the time analysed, it has a minimum of 72.51% in 2007 and 70.86% in 2016, and a maximum of 82.92% in 2017, it is clear that UMinho overwhelmingly uses electricity as the mains source of energy.

Moreover, as the number of students and academic community steadily increased over the period, decreases in electricity consumption are exacerbated when analysed on a per capita basis, while increases are ameliorated when the ratio is considered.

Nevertheless, when considering the whole period (2010-2022), and despite the addition of almost 10 000 m^2, the refurbishment of some older buildings, and an increase of 3.5% in the AM, a total decrease of 22% in total energy consumption was achieved (Fig. 5).

As it can be seen, between the 2010 and 2014, the period where structural and awareness campaigns were more prominent, the electric energy consumption decreased. Also, the Students and the AM at large, have the same consumption trend.

The results so far indicate that energy consumption was significantly reduced as a result of the behavioural and structural measures implemented, however it should be stressed that while structural measures may impact both electricity and natural gas consumption, behavioural initiatives are directed only at electricity use, as natural gas consumption decisions are mostly centralised. Moreover, the analysis also shows the limited ability of the University to decrease CO_2 emissions as they are heavily determined by the energy mix of the country.

6.3. Electric energy intensity per scientific area

To evaluate the role of AM behaviour on energy consumption, metering systems were installed on the electrical switchboards of the most relevant buildings that constitute the different scientific areas in 2011. The meters rotated between buildings during a

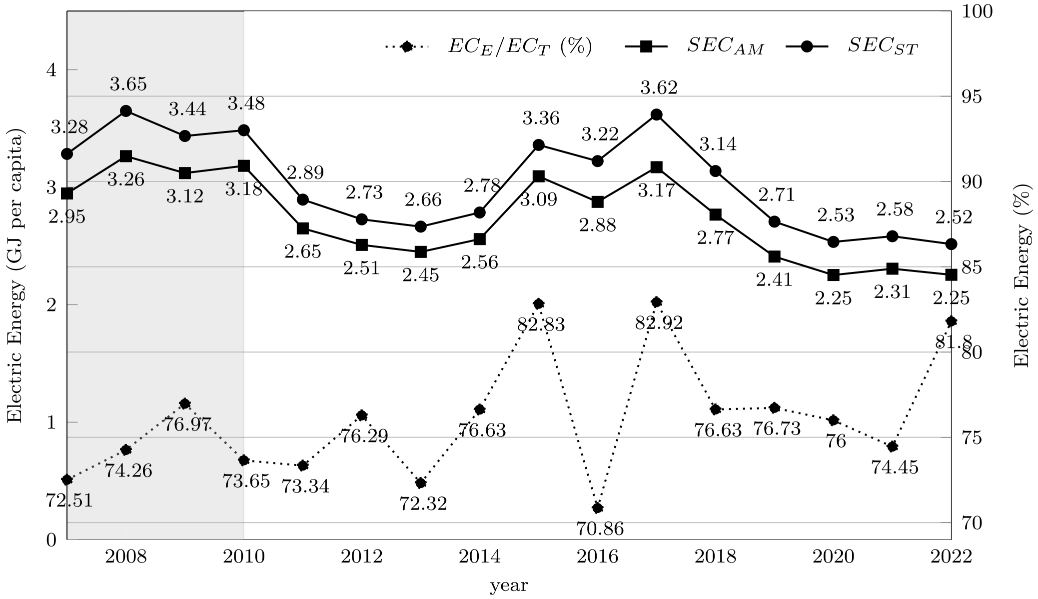

Fig. 9. Electricity Specific Consumption (GJ/capita).

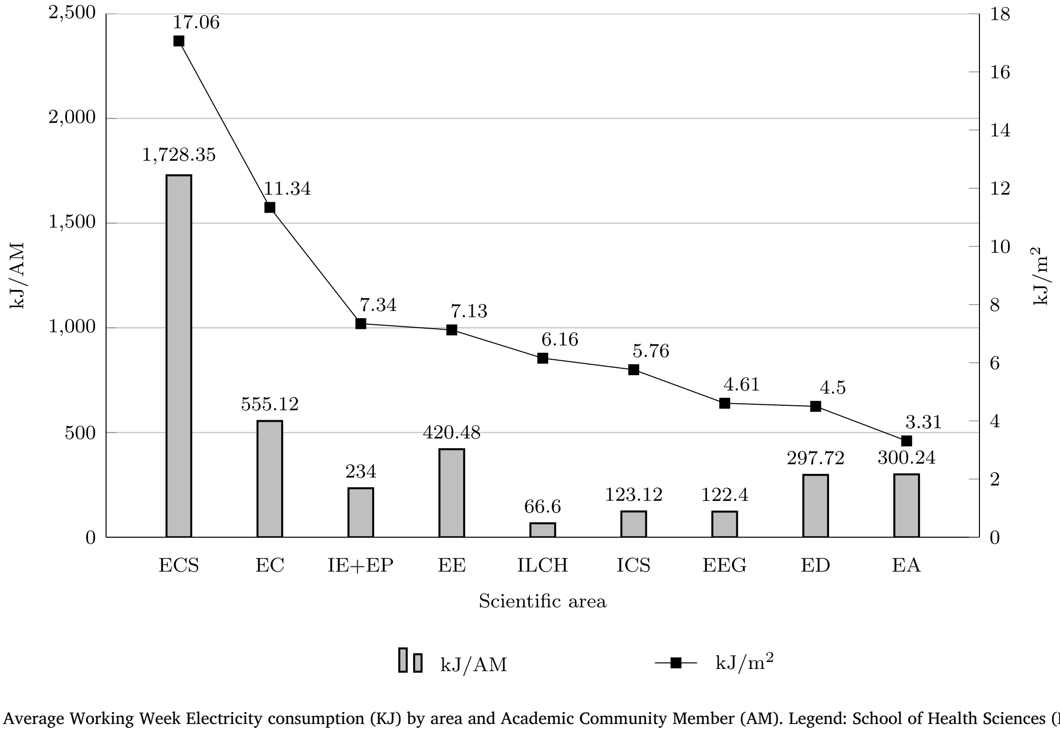

Fig. 10. 10. Average Working Week Electricity consumption (KJ) by area and Academic Community Member (AM). Legend: School of Health Sciences (ECS), School of Science (EC); School of Engineering (EE); School of Education and Psychology (IE+EP); School of Law (ED); School of Economics and Business (EEG); School of Humanities (ILCH); School of architecture (EA); Institute of Social Sciences (ICS).

testing period, and the average week consumption was computed. The findings on energy consumption by building and scientific net area, but also by academic member are presented in Fig. 10.

These results show the distinctive pattern of energy use by scientific area buildings within UMinhoś campi.

Health Sciences School (ECS) and Science School (EC) have the highest electricity consumption, both by area and academic member. However, the difference is overwhelming when comparing the electricity consumption per academic member, where the ECS represents three times the second highest consumer (EC), and twenty-six times more than the lowest consumption school (School of Humanities).

From the analysis it is clear that some schools (EA, EE, ECS) have a consumption of electricity per area and per user of similar relative magnitude, while for others (EC, ILCH) their relative measures are significantly apart. This suggests that energy policies should be area/use specific. Moreover, and in order to understand the differences in energy consumption it would be important to elicit patterns of energy use for shorter time periods.

7. Discussion

A reliable baseline of energy use is crucial to identify intervention areas and assess the effectiveness of energy efficiency measures. This paper provides a 16-year characterisation of energy use in a Portuguese HEI, describes the measures taken to increase energy efficiency, and illustrates the limitations of currently used energy indicators.

Between 2010 and 2014, UMinho deeply invested in awareness campaigns targeted at the Academic Community regarding saving resources, especially energy and water, and CO_2 emissions. As a result of this strategy, UMinho was the first HEI in Portugal to implement a public report of sustainability performance indicators through an institutional sustainability report (since 2010), and occupied the 48th global position, between 619 worldwide submissions, in the 2017 UI Green Metric Ranking. A clear association between a University, integrating the UI Green Metric and the quality of life of its stakeholders is shown in [43]. Energy was one of the first environmental indicators evaluated in this process.

Awareness campaigns were accompanied by effective measures, such as control of lighting and HVAC systems, which led to a significant reduction in energy consumption, visible through the three selected indicators: Energy per Total Built Area, Energy per Net Built Area and the contribution of students and academic members.

The analysis undertaken shows that the UMinho per student consumption of electricity varied between 3.57 and 4.91 GJ/student.year, which is in line with numbers reported for Chinese HEI where the same indicator varies between 2.12 and 5.76 GJ/student.year [17], and the approximately 3.24 GJ/student.year [6] for Comprehensive Universities in Malaysia. However, it is significantly lower than the numbers reported for UK HEI in [5].

Comparing energy use by area, the energy consumption at UMinho campi, in the 2007-2022 period, varied between 0.66 to 0.78 GJ/m^2 of Total Built Area and between 0.37 and 0.43 GJ/m^2 when considering the Total Net Area. These values are higher than those presented for Chinese HEI [17], which vary between 0.11 and 0.08 GJ/m^2 of Total Area, and those reported in [17] for Comprehensive Universities (0.10 GJ/m^2). However, the results obtained from this case study, for each working week, are between 0.03 GJ/m^2 (School of architecture) and 0.02 GJ/m^2 (School of Health Sciences), demonstrating to be significantly lower than those obtained at the University of São Paulo.

The results of the present investigation also allowed to decompose the overall indicators by the main scientific area. When considering a typical working week, from Monday to Sunday, the specific use per square meter varies from 3.31 to 17.06 KJ/m^2 while the same use per AM has a higher variation (from 66.6 and 1 728.35 GJ/AM). The School of Health Sciences is always associated with higher energy use (with 17.06 GJ/m^2 and 1 728.35 GJ/AM, representing as much as 5.15 and 25.95 times the values reported by the school with the lowest index, respectively), followed by the School of Science (11.34 GJ/m^2 and 555.12 GJ/AM). The hierarchy of energy consumption between scientific areas observed in UMinho is similar to the results obtained by [6] for Chinese HEI, where Medicine & Pharmacy, and Physical Culture are top energy consumers, while Political Science & Law are the lowest. The comparison with the results obtained for the University of São Paulo reported in [8] is not possible as they used a different definition of user.

8. Conclusion

The proposed energy intensity indicators, despite their limitations, show the effectiveness of the implemented measures on a heterogeneous environment and community, paving the way to other (additional) types of measures, especially those related to renewable energy harvesting and energy storage, needed to reach the nearly zero energy buildings (nZEB) level, already mandatory for public buildings in EU. It is important to highlight the limited capacity of institutions such as the University of Minho to decrease the CO_2 emissions associated with its own activities, as they increasing rely on electric energy provided by electric utilities whose source mix is not always a choice variable when designing contracts.

To deepen the understanding of energy fluxes, this research considered the monitoring and analysis of the energy consumption by scientific area building. The results demonstrate the heterogeneity across scientific areas and thus justify the adoption of building-specific energy-saving initiatives. However, more detailed information on energy use patterns by month, day of week, and hour of the day, would certainly give richer information for the design of structural and behavioural initiatives.

The presented analysis demonstrates five important lessons to be learned. First, is the importance of having permanent mechanisms of data collection to access the effectiveness of the implemented measures. Second, highlights the importance of available indicators, and the need for additional detail to deepen the knowledge of energy fluxes. Third, how crucial it is to have a reliable baseline of energy use to identify areas of intervention, also to assess the effectiveness of implemented measures. Fourth, this paper further presents specific energy uses per scientific area and adds evidence for the need to construct energy consumption indicators per scientific area and smaller time frames. Fifth, it demonstrates the importance of combining structural measures (energy demanded by buildings) with behavioural campaigns (energy demanded by users)for policy design as the combinations of both determine energy consumption.

CRediT authorship contribution statement

Paulo J. Ramísio: Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Lígia Costa Pinto:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Manuela Almeida:** Writing – original draft, Methodology, Investigation.

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

Raw data was generated by the University of Minho Technical Services, and published in annual reports. Derived data supporting the findings of this study are available from the corresponding author [PJR] on request.

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