Is IoT monitoring key to improve building energy efficiency? Case study of a smart campus in Spain

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Abstract

This work validates and demonstrates the potential of a methodology based on a continuous monitoring system with real time measurements, as a key support to make decisions on buildings energy systems based on quantitative data. For this work, a continuous loop-based monitoring methodology was designed and implemented to enhance the performance of Heating Ventilation and Air Conditioning (HVAC) systems by improving the energy efficiency of university buildings and the quality of life of the people who use them. The results from the case study, used to demonstrate the proposed methodology, can be extrapolated to the entire university in order to transform it into a smart campus. The case study also shows that the continuous measurement of temperatures allows to avoid excessive heating, reducing unnecessary energy consumption. Additionally, the case study shows the importance of monitoring CO_2 concentration in rooms where occupancy is fluctuating, since it enables a control of the HVAC system based on the instantaneous CO_2 level (and predictive in the immediate aftermath). This proposed measurement can save between 40% and 70% of HVAC energy consumption. The positive results obtained in this research show that implementing Internet of Things (IoT) smart ecosystems contribute to promote data-driven decisions in public tertiary buildings among decision-makers, politicians, and other stakeholders.

Keyworks

Building energy efficiency; Heating Ventilation and Air Conditioning (HVAC);
Internet of Things (IoT) monitoring; smart campus; Energy Performance Buildings Directive (EPBD)

Results and Conclusions

This study proposes a methodology to apply continuous monitoring of comfort parameters, such as temperature and CO_2 concentration, in public buildings, as a measure to ensure the energy optimization of HVAC systems. The analysis of these measures allows to predict and control in real time the operation mode of these equipment and reveals itself as a very powerful methodology to ensure the reduction of energy consumption while maintaining optimal comfort conditions. This work shows, using the university buildings and their facilities as a research laboratory, the potential of continuous monitoring and measuring. As *sensoriZAR* harmonizes mechanisms to manage data through APIs for third-party, it contributes with an indispensable support methodology to make decisions based on quantitative data that help to optimize the operation of HVAC equipment and to improve the energy efficiency of buildings and the quality of life of the people who occupy them. The implementation of increasingly demanding regulations from an energy efficiency point of view is not enough on its own, but must be accompanied by procedures to ensure compliance through real measurements to determine the degree of compliance and to obtain conclusions based on quantitative data.

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1. Introduction

Nowadays, climate change [1] and environmental degradation are a serious global challenge. Energy efficiency is essential to contribute to decarbonization and to limit, as set in the Paris Agreement in 2015, to 1.5°C the increase of global temperature [2]. In this context, the United Nations (UN) have established different Sustainable Development Goals (SDGs) for 2030 [3], including: affordable and clean energy; sustainable cities and communities; and climate action; with a commitment to save more than 32.5% of energy use by 2030 (compared to projections of the expected energy use in 2030) [4]. In the European Union (EU) it is estimated that 75% of the EU building stock is inefficient [5]. Additionally, as pointed out in the Energy Performance Buildings Directive (EPBD) [6], buildings are responsible for 40% of energy consumption and 36% of greenhouse gas emissions; accordingly, EPBD proposes to incorporate Internet of Things (IoT) technologies and Artificial Intelligence (AI) mechanisms into the Heating, Ventilation and Air Conditioning (HVAC) systems.

Buildings are energy consumers and carbon producers throughout their entire life cycle, including their construction, use, demolition and end of life. The operation and construction phases are, in that order, the most important energy consumers. The use or operation phase includes the energy required for maintaining comfort conditions, being the most relevant the energy for running HVAC systems, domestic hot water, lighting, and domestic appliances. The share between the primary energy consumption of these two phases has been extensively studied, being greater that of the use phase. However, this share has been changing considerably in recent years and will continue to change due to the efforts made to reduce the energy consumption of the operation phase in dwellings and tertiary sector buildings, e.g. through the nearly Zero Energy Buildings (nZEB) standard, and the forthcoming Zero Energy Buildings (ZEB) and Positive Energy Buildings (PEB) ones towards the Life Cycle Zero Energy Building (LC-ZEB) concept [7]. Another factor that is balancing the share is the use of renewable energies, whether it is on site energy production or at national level, as national plans are being designed to transform the electricity mix into a less polluting one. The share, in any case, also depends to a large extent, on the climatic conditions, the building design (its orientation, configuration, materials, etc.), and the use of the building, among other factors.

The operating energy reduction is a key point that concentrates and must still concentrate many scientific efforts to improve the real energy efficiency of buildings to be able to achieve the expected behaviour of the forthcoming standards, and as a necessary goal for the ecological transition. Several key actions to improve buildings operation management have been identified to reduce its energy demand, such as rating tools and disclosure [8], energy audits [9], energy management systems [10], smart controls, and building passports [11]. This paper focuses on smart controls, which is the use of digital sensors and controls to enable better managing of building operations, such as temperature, lighting, or ventilation system to improve the energy efficiency in buildings.

Most of the research studies and regulations concerning the energy efficiency of buildings are usually based on estimates of energy consumption in the design phase, by means of simulation. Numerous studies [12–14] show that there is a large difference between these theoretical values and the real consumptions, what has been called Building Energy Performance Gap (BEPG). These differences are due to the numerous simplifying assumptions required to model and simulate the real behaviour of buildings. Algorithms have been designed to reduce the BEPG (e.g. [15]). All this reveals that it is not only necessary to simulate buildings, but also to perform continuous monitoring and data analysis to understand how they behave, know their real energy consumption and identify inefficiencies. It is equally important to ensure that buildings are operated efficiently [16] in order to reduce energy demand. Moreover, monitoring buildings can facilitate energy audits [17]. To increase energy efficiency in buildings, achieve savings in carbon emissions and improve comfort, the European Commission, through Directive 2018/844/EU, introduced the Smart Readiness Indicator (SRI) implementation framework [18]. SRI is a parameter to make building owners and occupants aware of the level of building automation and digital monitoring of the building's technical systems, with the aim to bring considerable energy savings thanks to new intelligent functionalities. Continuous monitoring, as proposed in this work, helps to increase the SRI level of a building and to reduce the aforementioned BEPG.

Thus, to continue advancing in the improvement of energy efficiency and knowledge of the thermal behaviour of buildings, it is necessary to complement the simulation studies with quantitative real measurements in operating buildings. Incorporating IoT-based technologies enables to collect continuous data to know how buildings behave, and to make data-driven decisions to reduce its energy consumption and carbon footprint [19]. IoT allows the collection of vast amounts of data that, properly transmitted and processed (through cloud or in-house premises), will be converted into meaningful information [20]. This information, conveniently visualised and analysed (by means of AI tools), generates knowledge, induces feedback in the acquisition and processing of data, and most importantly, allows for intelligent decisions based on valuable data [21].

There are few studies on continuous monitoring systems aimed at improving energy efficiency in buildings in the tertiary sector in the literature. Batista et al. [22] used an equipment control system to investigate the performance of the air-conditioning system of a small auditorium in Brazil, obtaining a 20% of energy consumption and improving thermal comfort. More recently, a paper was published [23] on occupancy monitoring in an office building with the objective of developing occupancy models and determining their impact on the energy performance of building. Regarding thermal comfort, Li et al. [24] performed correlation analyses based on continuous thermal comfort measurements from four office buildings in Australia, supporting the use of continuous monitoring technologies for long-term thermal comfort evaluation. Literature evidences that buildings can be understood as complex systems; i.e. as systems that exhibit nonlinear behaviour, diversity, self-organization, feedback and memory that give rise to emergent properties. For this reason, although no two buildings are alike, some behavioural patterns can be found and studied in the interactions between weather, buildings use, and energy consumption, which can be of help in decision making for a more sustainable use of buildings energy systems.

With this aim, the University of Zaragoza (UZ), in Spain, is developing the UZ *smart campus* initiative through an IoT ecosystem (named *sensoriZAR, sensorizar.unizar.es*) for real-time monitoring of key variables in the building energy study [25]. The implementation of IoT ecosystems is economically viable and environmentally sustainable since it introduces very low environmental costs (both operational and embedded). Other solutions reduce operational energy costs with high embedded costs of energy consumption (insulation, concrete, etc.) or economic costs (ultra-expensive glass and carpentry, changes in production or distribution systems, etc.). As detailed below, *sensoriZAR* is built on the premises of free-hardware, free-software and ultra-low consumption.

This paper has two main aims. One of them is to validate a continuous loop-based monitoring methodology to optimize energy efficiency and comfort for university buildings towards the paradigm of a smart campus. This methodology is validated by means of its implementation in the so-called *Río Ebro* campus of the UZ. This methodology is based on a loop scheme of continuous improvement (see Figure 1), distinguishing six steps:

A. Continuous measuring of energy consumption (following ISO 50001 [26]), included in subsection 3.1 in this paper.
B. Identifying the Significant Energy Uses (SEUs) in the building, included in subsection 3.1. In the university campus, the main consumers are HVAC systems, except in some research buildings where there is a huge consumption associated with computing clusters and/or singular research infrastructures.
C. Continuous measuring and analysis of results, included in subsections 3.2 and 3.3. The key parameters/values analysed are:
    - From Supervisory Control And Data Acquisition (SCADA) system, HVAC circuits focused on energy consumption, water temperatures, etc.
    - From *sensoriZAR*, indoor air focused on temperature, humidity percentage, and CO_2 level.
D. Making improvements, included in the Discussion subsection. This involves analysing the measurements and proposing improvements.
E. Verifying the variation in energy consumption to know if it is reduced, by how much and, if it is necessary, re-measuring the energy consumption.
F. Conclusions and further research with an iterative loop restart. This iterative methodology moves towards understanding the behavioural patterns of buildings and adapting their use (schedules, teaching organization, sectorization, etc.) towards maximum efficiency.

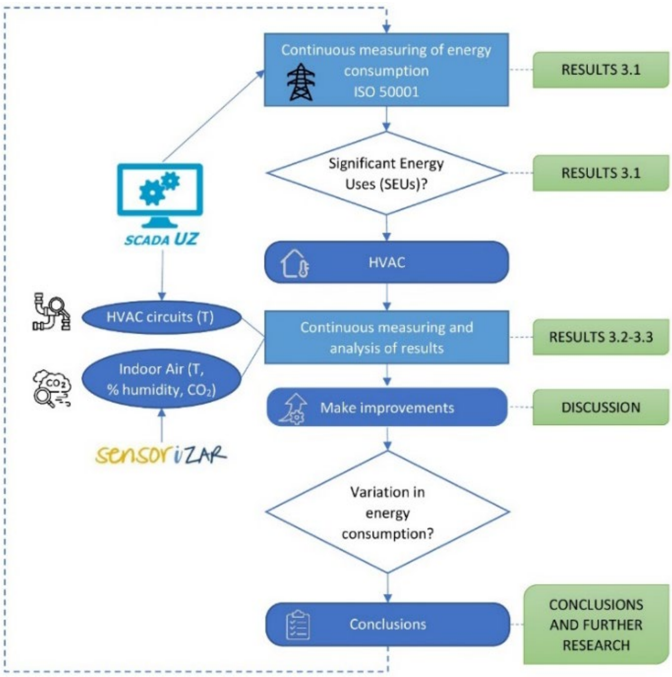


Figure 1. Loop methodology for improving energy efficiency in buildings.

The second aim of this paper is to demonstrate, by means of a case study, the potential of the continuous loop-based monitoring methodology to optimize energy efficiency and comfort towards the paradigm of a smart campus. Specifically, we study to what extent the IoT monitoring-based methodology proposed here contributes to promote actions for reducing energy consumption and saving costs, while keeping comfort levels.

2. Materials and methods

The study presented in this paper was developed within the aforementioned UZ *smart campus* initiative. The UZ *smart campus* addresses the holistic perspective of a university campus (see Figure 2) from the infrastructures (physical level) to applications and services (logical level), integrating the specific management systems through *sensoriZAR* IoT ecosystem [25] at 3 levels:

- Field elements for continuous monitoring of:
  - Levels of CO_2, lighting, humidity, temperature, occupancy and pollution in different locations of the university buildings (e.g., corridors, offices, classrooms, restaurants, libraries, parking, etc.) to assess thermal comfort and air quality conditions and determine when to use HVAC systems.
  - Access control and other parameters related to the flow mobility of the people (and vehicles) in the university buildings, such as timetables, and access frequencies.
  - Security and emergencies prevention systems to guarantee the public services in a university campus.
  - Presence of people in the different classrooms, obtained by different Quick Response (QR) code verification systems and mobile devices monitoring within specific classroom information (booking, resources, etc.).
- Management systems for continuous monitoring of:
  - Energy consumption, HVAC systems, identifying unforeseen consumption, analysing specific information through SCADA systems (such as temperatures in the heat-transfer fluids in supply and return), comparing with external data (as historical weather data and forecast), and integrating with other key variables, as electricity generation levels of the photovoltaic panels in order to analyse the efficiency of the renewable energies.
  - Traffic mobility, urban pollution, emergencies services, security systems, among other key information of the university campus to integrate all the data in a homogenous way in *sensoriZAR*.
- User experience to offer a wide variability for visualization and interaction through mobile apps, web interfaces, data dashboard with Key Performance Indicators (KPIs) and other cloud services. One of the goals of this work is to guarantee not only energy efficiency but also human efficiency: *sensoriZAR* evolves from complex dashboard (as SCADA systems) towards a user-friendly multi-platform environment that makes data-driven decision as easy as possible.

To homogenize data from all the field elements, management systems and user experience, *sensoriZAR* is built as a homogeneous IoT ecosystem of ultra-low consumption with free-hardware and free-software. Thus, *sensoriZAR* harmonizes different mechanisms to import, export, download, monitor and integrate data, through Application Programming Interfaces (APIs), for third-party use (including researching studies) and data-driven decisions.

University buildings are highly stationable and seasonal (following predetermined patterns of schedules, uses, flows of people, etc.) although in our case their use has significantly been changed after 2021 due to the pandemic, post-pandemic, and energy crisis contexts. Since Zaragoza has low temperatures in winter and very high temperatures in summer, the energy use reduction with the proposed methodology is envisaged for the whole year (except in closing periods, such as Christmas and the month of August) and it can be extrapolated to smart campuses regardless its weather and thermal difference.

With all these premises, the UZ *smart campus* initiative was born to advance towards the creation of digital twins of university buildings and, as first case study, analyses 3 buildings of its so called *Río Ebro* campus (see Figure 3): *Ada Byron* (AB, built in 1998 with 14,000 m^2 for 1,000 students and 250 university staff), *Torres Quevedo* (TB, built in 1986 with 21,000 m^2 for 1,500 students and 350 university staff) and *Agustín de Betancourt* (BB, built in 1999 with 27,000 m^2 for 2,000 students and 450 university staff). Some of their characteristics are detailed below:

- Although nowadays the regulations have been updated, on the construction date of these buildings, the European and Spanish regulations on energy efficiency were minimal.
- The different orientations (north, south, east, and west, as is marked in Figure 3) of the buildings and their spaces influence their behaviour and performance.
- These buildings have centralized energy systems without sectorization: TB has only one gas boiler heating system but AB and BB have electric HVAC systems (with phreatic supply) including Air Handling Units (AHU) for large spaces, and terminal units (fan coils) for classrooms, laboratories and offices.

- The mean energy consumptions of these building are around 200 kWh/m^2·year, above the thresholds of 184 kWh/m^2·year (recommend for Spanish Technical Building Code) and 120 kWh/m^2·year (following *Passivhaus* international recommendation).

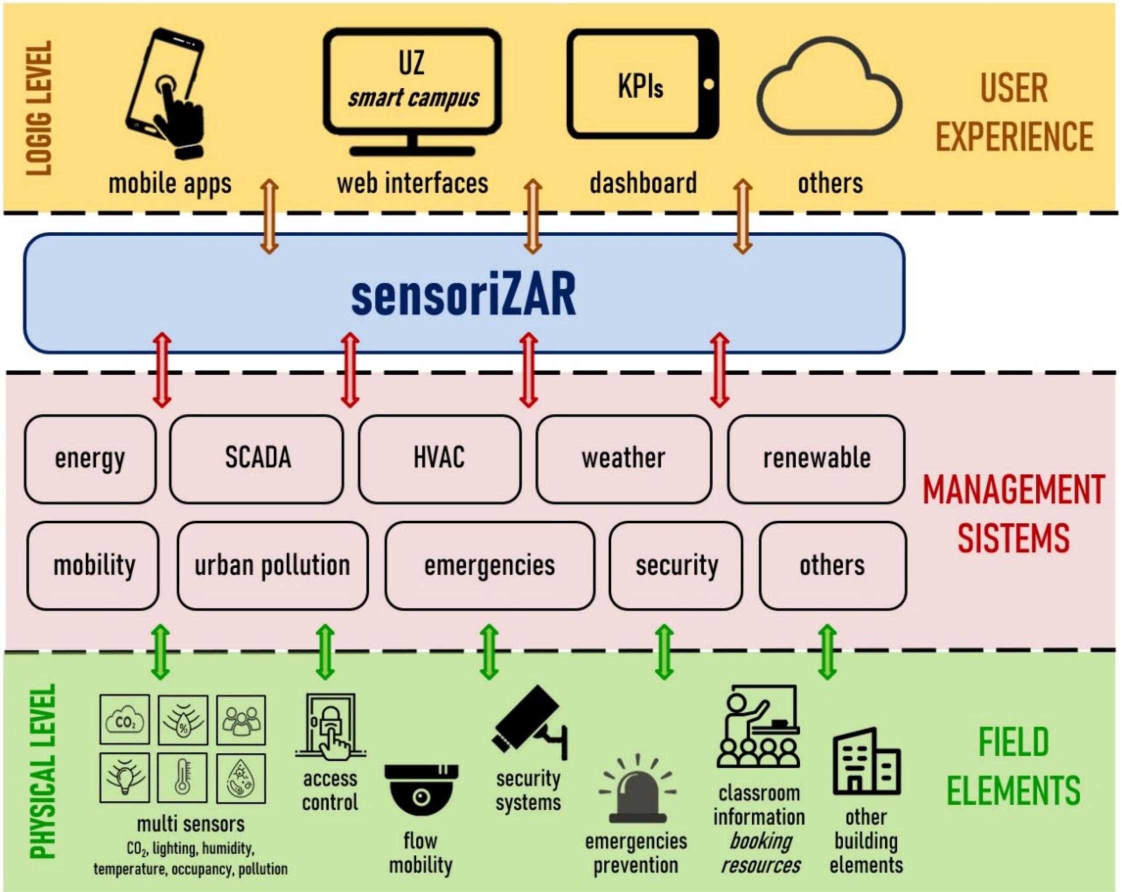


Figure 2. UZ *smart campus* initiative through *sensoriZAR* IoT ecosystem.

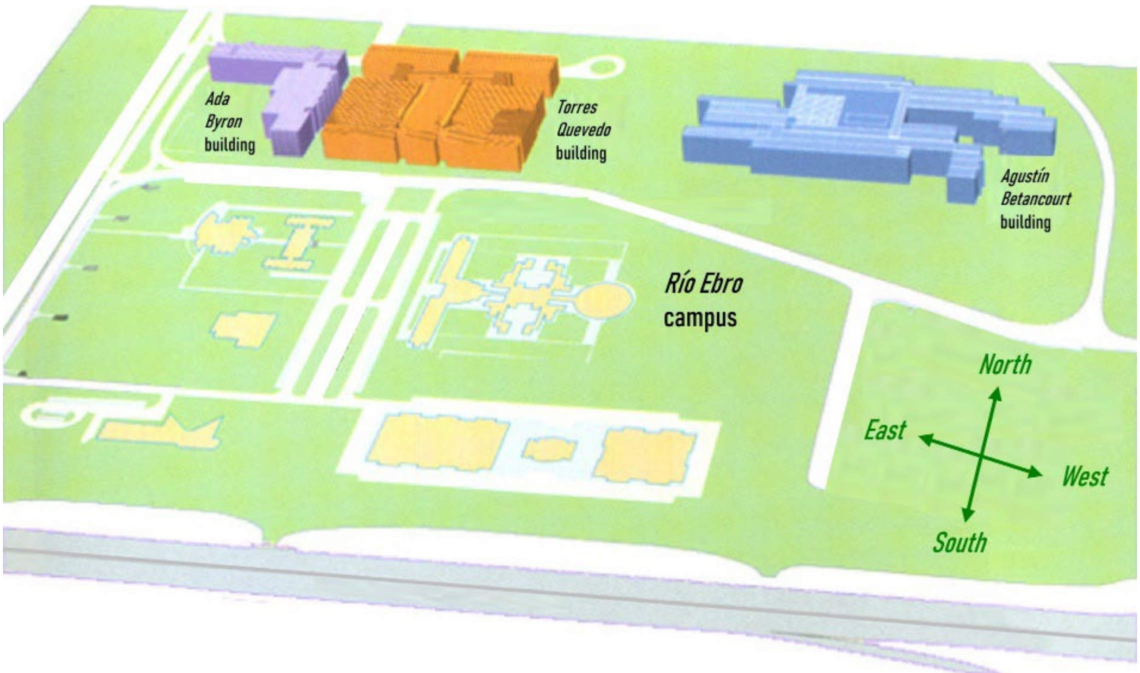


Figure 3. Case study of *Río Ebro* campus in University of Zaragoza.

To analyse the abovementioned 3 buildings of *Río Ebro* campus within UZ *smart campus* initiative, *sensoriZAR* has used electricity consumption measuring equipment (Landis+Gyr E550), which measure the total electricity consumed in the building and has installed more than 90 geolocated wireless sensors in more than 60 spaces (grouped by building and ordered by floors). *sensoriZAR* integrates wireless sensors of several manufacturers (Aranet 4 Pro [27], Siemens QPA1004 [28], senseCAP EU868 [29], Dragino LHT65 [30], and *hand-made* devices), with real-time measurements of: CO_2 level (CO_2), temperature, relative humidity, and atmospheric pressure. As it is detailed in Table 1, one of the goals of this work was to compare their performance to determine the most appropriate technology in order to propose homogeneous infrastructures. This comparison shows, among other issues, the importance of battery life and ease of battery replacement. The CO_2 sensors are based in Non-Dispersive Infrared Detector (NDIR) technology that guarantees a very precise CO_2 detection. Furthermore, all the sensors work through LoRaWAN technology that is a recommended by comparison with the rest of Low Power Wide Area Network (LPWAN) technological family, as it is detailed in Table 2. LoRaWAN specification [31] is a networking protocol, designed to wirelessly connect battery operated sensors with bi-directional communication and localization services, that targets key IoT requirements such as low consumption, long rage, end-to-end security, high interoperability, low maintenance, and monthly costs due to provider network fees. All these features are key factors in projects related to university campus and bring added value to *sensoriZAR*.

Table 1. Sensors installed in *sensoriZAR* (● = included measurement).

					
model	Aranet 4Pro	Siemens QPA1004	SenseCAP EU868	Dragino LHT65	*hand-made*
CO_2	●	●	●		●
temperature	●	●		●	●
humidity	●	●		●	●
pressure	●				

Table 2. Comparison between LoRaWAN and LPWAN technological family.
(● = fulfills that feature, ○ = it is included but not embedded in protocol specification)

feature	low consumption	long range	end-to-end security	high interoperability	low maintenance	monthly costs
LoRaWAN	●	●	●	●	●	
SigFox	●	●	○			●
NB-IoT	●	●	○			●
Bluetooth LE	●			●		
WiFi				●	●	
GSM/GPRS		●	●	●		●

NB-IoT = Narrow Band IoT, Bluetooth LE = Bluetooth Low Energy, WiFi = Wireless Fidelity, GSM = Global System for Mobile communications, GPRS = General Packet Radio Service

Finally, we defined as *case study building* the most recently constructed one (*Agustín de Betancourt*, BB) due to its diversity of uses, the heterogeneity of its classrooms and the possibility of sectorizing its HVAC systems since all of its energy consumption is electrical, among other key factors of its technical installations which make it more extrapolable to the rest of the university campus. This *case study building* has centralized energy production through 3 water-water heat pumps that use subsoil water as a source. Each heat pump consumes 152 kW of electrical power and provides 706 kW of heating power and 553 kW of cooling power in nominal operating conditions. The infrastructure works with secondary distribution (including AHU for large spaces, and fan coil terminal units for classrooms, laboratories and offices) and a primary air conditioner (with heat recovery that provides ventilation air to the fan coils). Following Results and Discussion section details the contributions studied in the proposed *case study building*.

3. Results and discussion

In order to explore to what extent the IoT monitoring-based methodology improves the building energy efficiency, we collected data during 2019, 2020, 2021 and 2022. With these data collection we made the first analyses to obtain information in order to carry out the subsequent measurements. With these measurements we turned information into knowledge to make data driven decisions and to obtain the results shown below.

Following the proposed loop methodology of Figure 1, section 3.1 presents the initial results of the building's electricity consumption due to the need to be energy efficient (referenced in Introduction) and to reduce energy costs (especially in the current European situation, with a scenario of energy resources scarcity and the consequent increase in the electricity prices).

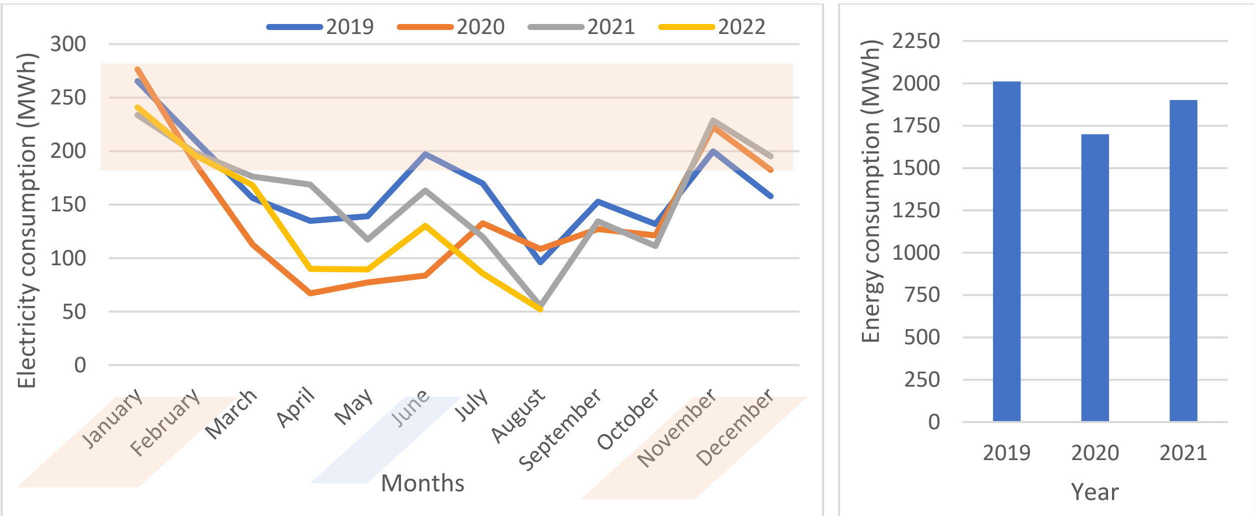
From these initial results, sections 3.2 and 3.3 analyse how IoT monitoring moves towards the building characterization in terms of temperature and CO_2, and propose several actions to decrease electricity consumption, to improve energy efficiency, to reduce the environmental impact and to increase indoor health conditions.

3.1. Building energy consumption

Electricity consumption was continuously monitored during 2019, 2020, 2021 and 2022. Since the consumption detailed by services is not available, it was necessary to find out the SEUs related to electricity production and consumption.

Figure 4(a) represents the electricity consumption by month for these four years. The winter months (November to February) are those with the highest electricity consumption, mainly due to an increase of heating and lighting demand; followed by June, due to the cooling systems. Consumption is lower in spring and autumn, owing to better weather conditions, and August is one of the months with the lowest consumption, because the building is closed.

Electricity consumption from March to October 2020, was significantly lower due to the confinement during the COVID19 pandemic. Figure 4(b) shows that in 2020 there was a 10.6% of reduction in energy consumption with respect to 2021 (more than 200 MWh of electric energy savings). On the other hand, consumption in 2022 is being lower, as a consequence of the energy saving measures, consisting mainly in the reduction of HVAC schedules, taken to face the energy crisis.



(a) monthly (b) yearly

Figure 4. Electricity consumption from 2019 to 2022.

In order to verify which is the most important SEU, daily electricity consumption in winter 2021 was correlated with the number of hours the heating was turned on. It is found that there is a proportional relationship, and the trend is linear with a regression coefficient of 0.86, as it is remarked in Figure 5. This relationship confirms that HVAC is the main electricity consumer of the building, therefore actions should be aimed at optimizing both its operation and on/off times, always maintaining temperatures that guarantee the comfort of users but minimizing energy waste (such as heating on, in unoccupied areas).

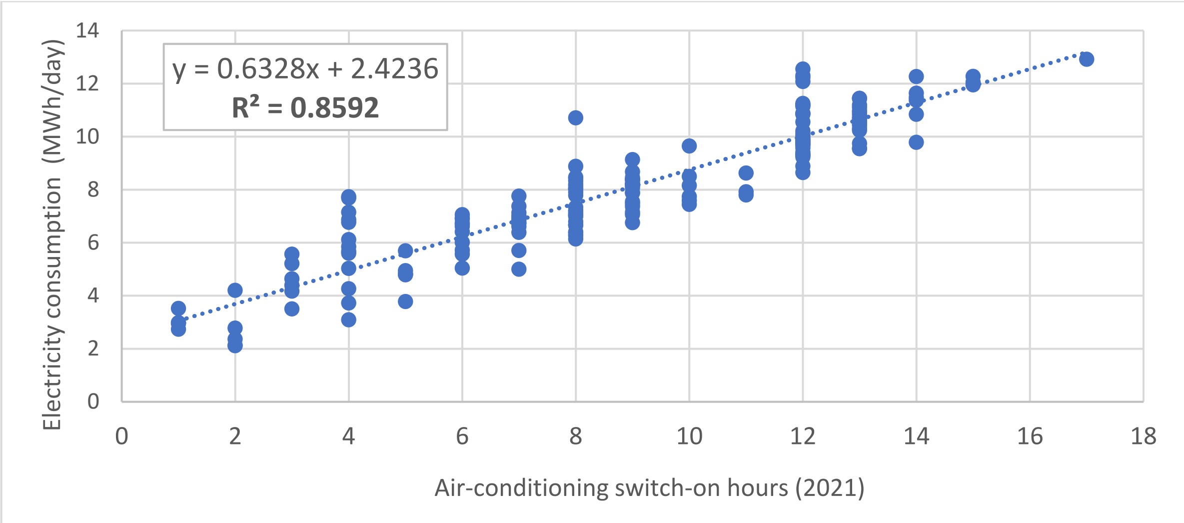


Figure 5. Correlation between electricity consumption (MWh/day) and air-conditioning switch-on hours.

To characterize the energy performance, data were analysed by determining, among other aspects, the *stand-by* consumption, which is the consumption of the building during closing hours (without occupation from 23 p.m. to 6 a.m.). Analysing data from 2021, the average for stand-by electricity consumption is 0.111 MWh for an hour of stand-by, which represents 40.7 MWh in one year, as can be shown in Figure 5 (shaded area in grey). In the entire stand-by period (7 hours), it represents a total of 285 MWh/year.

Figure 6 also shows that from 6 a.m. (the time at which the HVAC systems are generally switched on) to 23 p.m. (switched off) the electricity consumption increases, reaching 120 MWh/year. It can be appreciated that many days the equipment is shutdown during the lunch break (shaded area in yellow). Furthermore, the duration of the afternoon peak is shorter than in the morning.

The main electricity consumers in the stand-by period were identified as Data Processing Centres (DPC) together with their associated air conditioning, which consumes around 0.04 MWh, 36% of the total (0.111 MWh). The remaining electricity consumption (64%) offers a significant opportunity for savings and, therefore, it is of particular interest to expand the *sensoriZAR* IoT ecosystem with a greater number of electricity meters to identify where these consumptions occur (night lighting, surveillance and fire protection systems, electronic devices that remain connected at night, etc.) and propose specific measures to reduce energy consumption.

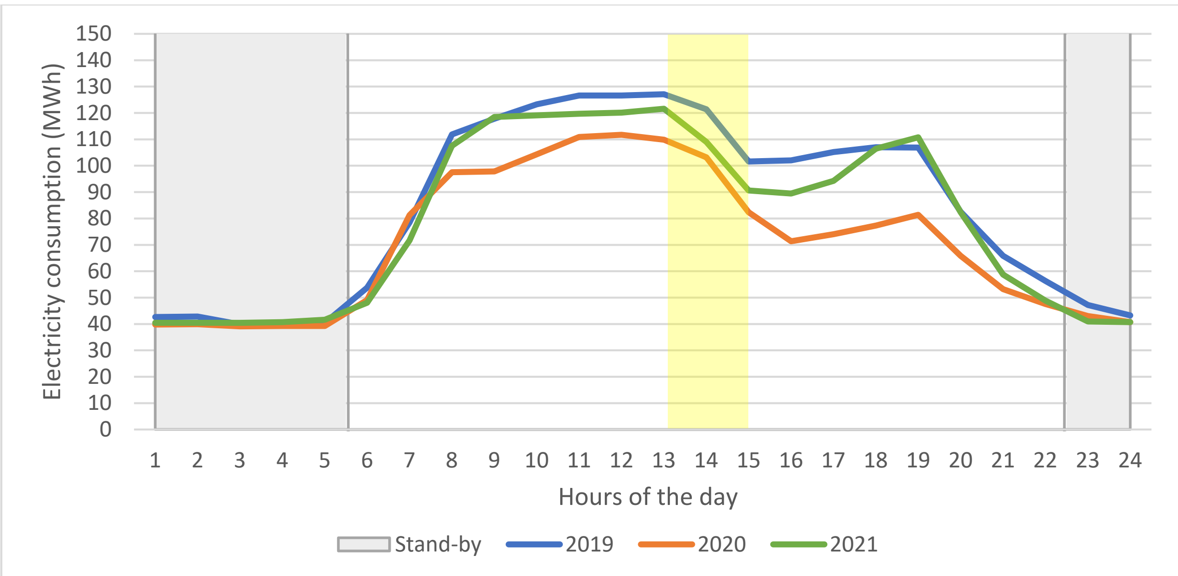


Figure 6. Load curve of annual electricity consumption per hour.

3.2. Analysis of temperatures

In Spain, as it is outlined in Figure 7, public buildings with associated HVAC energy consumption must keep indoor temperature between 17 and 21°C when heating and between 26 and 27°C when cooling [32]. During the development of this work, a new Order PCM/466/2022, published in BOE May 25, 2022 (for buildings of the General State Administration and institutional public sector entities), further limited these temperatures between 17 and 19°C for heating and 27°C for cooling (in this last case, it would be better to work with intervals since adjusting to a specific value is not realistic to put into practice).

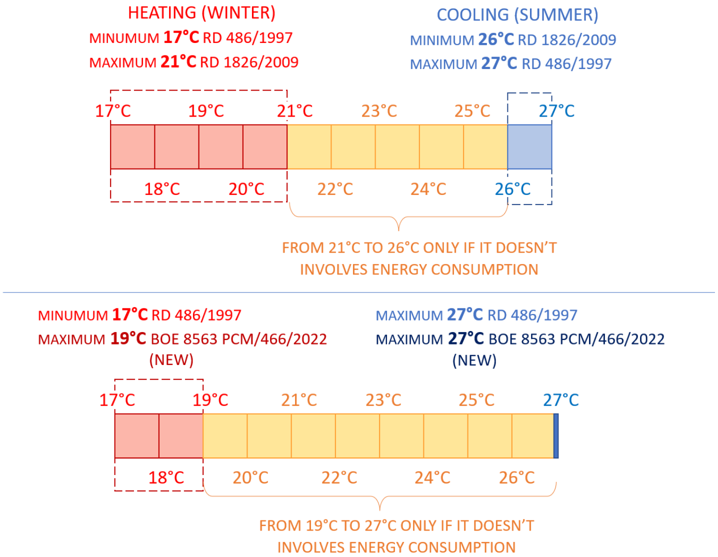


Figure 7. Indoor air temperature limits for HVAC systems, according to Spanish regulations.

To demonstrate the need of continuous follow-up and promote the implementation of IoT monitoring, *sensoriZAR* data were analysed in real-time both in winter and summer periods.

Firstly, in winter (from October 2021 to February 2022), Figure 8 shows the maximum (orange dots) and minimum (blue dots) temperatures measured in a representative classroom, chosen for their climatic orientation, size and average occupancy. The temperature limits indicated in the Spanish regulations, maximum temperature in summer (orange line) and minimum temperature in winter (blue line) are also represented. Holidays days when the building is closed are shaded in grey and specific days for which no data available are shaded in green. Figure 8 shows how the classroom temperature is less than 6% below 17°C (limit of the current Spanish regulations) and less than 18% below 19°C (as estimation of thermal comfort), which shows that HVAC system is mostly fulfilling both regulation and climatic conditions. However, it is remarkable that temperature is above 21°C (shaded area in yellow) more than 30%. Even when temperature is above 19°C (according to the new Spanish regulation 2022) the percentage is high (82%). This means that there is considerable margin for improvement, which could reduce the time that the heating is turned on and therefore reduce unnecessary energy consumption. This circumstance occurs when the classroom is occupied and therefore the heat generated into the room (by occupants, computers, lighting, solar heat gain, etc.) could reduce the time the heating is turned on.

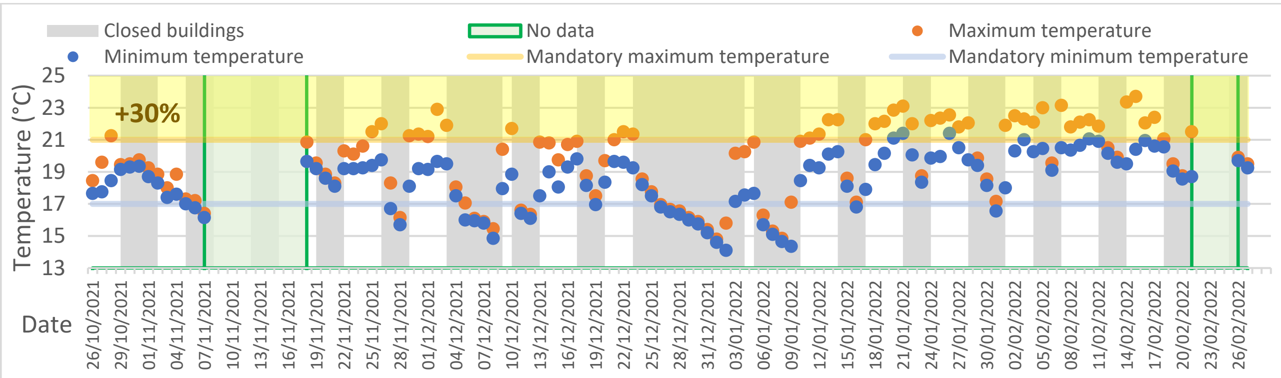


Figure 8. Maximum and minimum temperatures in a representative classroom.

To this end, as it will be remarked in Conclusions section, *sensoriZAR* has allowed us to evaluate the trend of temperature variation in the classrooms. As University of Zaragoza centralizes the on/off system of all campuses according to a standard schedule, the heating is turned on at 7 a.m. and it is turned off at 12 p.m. Analysing the thermal behaviour of a classroom, as it is shown in Figure 9, it could be verified that temperature increases above 25°C (when regulation establishes 21°C). Thus, knowing this behaviour allows acting on the fan coil to adjust its energy production towards a comfort level around 21°C.

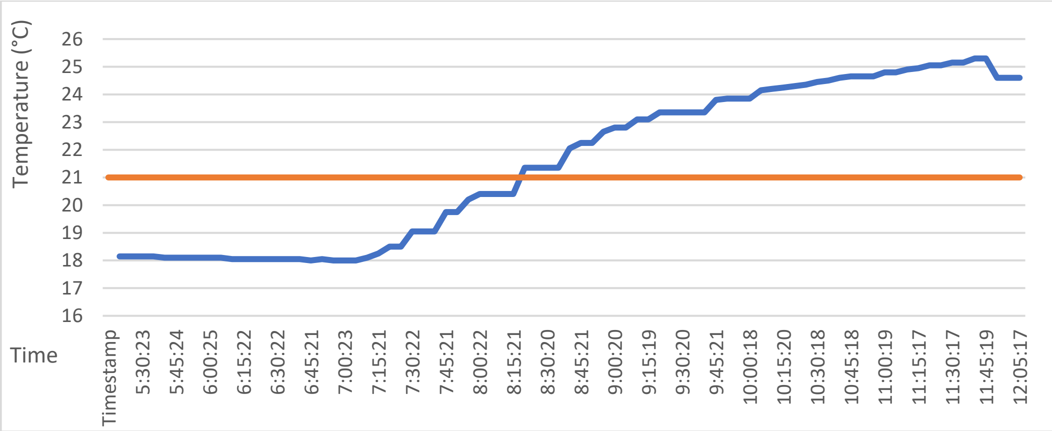


Figure 9. Temperature evolution in an empty classroom example.

In this context of centralized heating and considering the potential savings by switching off the fan coils when the classrooms are empty, *sensoriZAR* analysed in detail the classroom occupancy of the 3 buildings of UZ *smart campus*. Indicating as 100% when a classroom is occupied in its entire timetable (from 8 a.m. to 21 p.m.), Figure 10 shows the average occupancy percentage (in bars) for each day of the week: 37% in *Ada Byron* (AB) in blue, 39% in *Torres Quevedo* (TB) in red, and 47% in *Agustín Betancourt* (BB) in green. Thus, if potential savings can be estimated as the subtraction between 100% and the average occupancy, Figure 10 shows (in lines) these potential savings: between 58% and 72% (AB), 59% and 65% (TB), or 43% and 62% (BB). In addition, Table 3 details these figures for each building and day of the week, averaging 63% (AB), 61% (TB) and 53% (BB). As a contribution to exploit this savings potential, work is already underway to incorporate into *sensoriZAR* an automated control of fan coils, based on classroom occupancy. Furthermore, from the knowledge generated through *sensoriZAR*, the current energy saving plan of the University of Zaragoza propose a better adjust of the HVAC system to the building performance and a more efficient classroom occupancy.

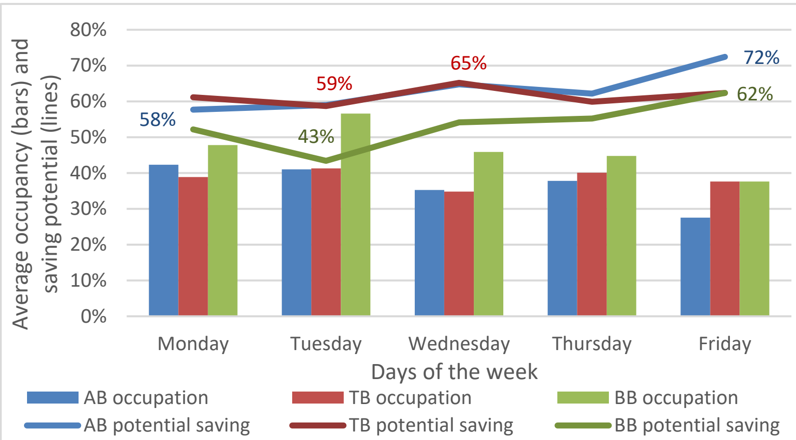


Figure 10. Average occupancy and potential savings.

Building	AB	TB	BB
Monday	58%	61%	52%
Tuesday	59%	59%	43%
Wednesday	65%	65%	54%
Thursday	62%	60%	55%
Friday	72%	62%	62%
Average	**63%**	**61%**	**53%**

Table 3. Potential savings (per building and day).

Secondly, during a week of June 2022, in order to better define the building performance both in the winter and summer periods, *sensoriZAR* also analysed the evolution of temperatures in several classrooms and in a study room. As it shown in Figure 11, the classrooms on the first floor have lower temperatures than those on the second floor and some classroom (such as 1.06) reaches temperatures below 26°C (RD 1826/2009). These first results of our case building behaviour will allow *sensoriZAR* to characterize it as complex system according its distribution, orientation, configuration, etc.

In addition, in all these spaces the temperature increases throughout the week until the last day (Friday 17/06/2022) over 27°C (maximum temperature established in the Spanish regulations RD 486/1997), despite the air cooling being on. When the HVAC is turned on (areas shaded in blue), the temperature drop is not sufficient and the temperature is not lowered below 27°C or is only achieved at the end of the day. This behaviour was real-time detected thanks to IoT monitoring from *sensoriZAR* and, therefore, it was possible to verify that the heat pumps do not have the cooling capacity necessary to keep the classrooms below the setpoint temperature. Next, it was verified that the inlet temperature of the water to the fan coils is higher than the temperature recommended by the manufacturer (supply at 18°C instead of 8°C).

As Figure 11 shows, *sensoriZAR* detected a potential anomalous behaviour in the study room because its temperature continues to rise despite switching on the cooling system (areas shaded in blue) reaching values of up to 31°C. This showed that the cooling capacity may be insufficient in situations of high thermal loads (high occupancy, solar radiation, etc.).

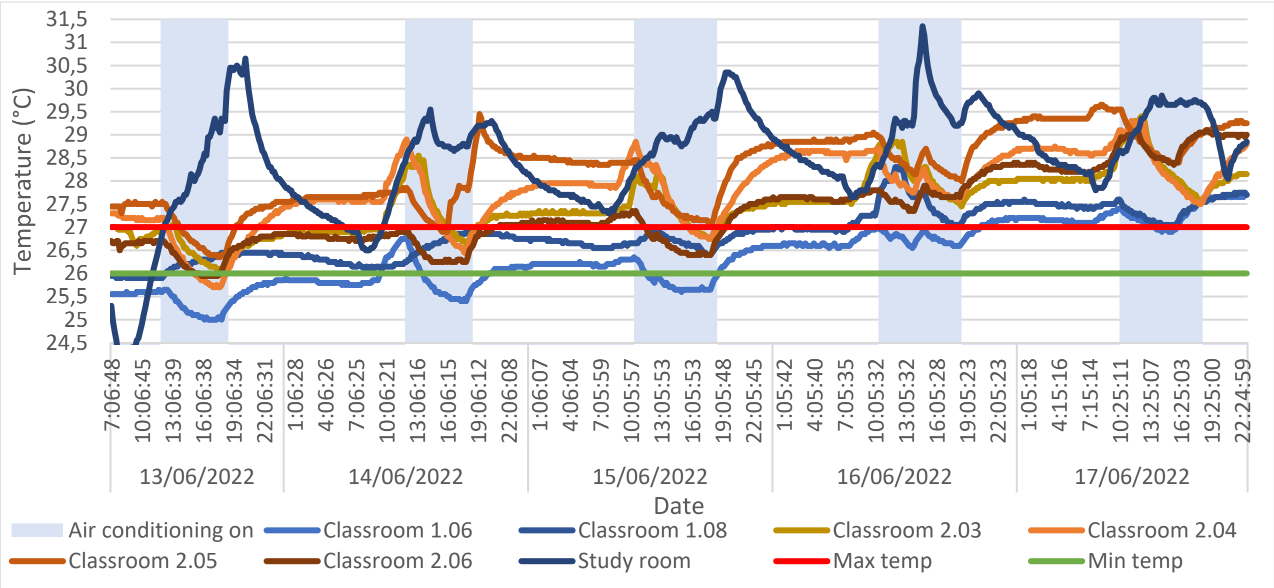


Figure 11. Temperature evolution in different spaces: classrooms and study room.

Summarizing, these first results show that IoT monitoring (through *sensoriZAR*) is able to detect patterns (different for winter and summer) of overheating and overcooling (above or below temperatures thresholds) to move towards continuous improvement of energy consumption and cost savings. Moreover, these savings through IoT monitoring are very suitable in contexts of economic scarcity (implemented with a very affordable IoT ecosystem of wireless devices and cloud services) with costs much lower than traditional control and automation systems or actions of thermal insulation, change in the production systems, etc.

3.3. Analysis of CO_2 level

As previously mentioned, one of the main goals of IoT monitoring is to ensure adequate ventilation in the classrooms to guarantee indoor health conditions (especially in post-pandemic times). Measurements and analyses developed with *sensoriZAR* are intended to help characterize when (and how much) to ventilate naturally (opening windows and/or doors), when (and how much) to ventilate through building HVAC systems, and when (and how) to combine both methods.

As first step, in order to determine if spaces are properly ventilated, *sensoriZAR* recollected data and analysed information of CO_2 measurements from October 2021 to February 2022 in several representative classrooms of the Río Ebro *smart campus*. The maximum concentrations in each classroom were obtained, as well as the number of hours in which the CO_2 level remained above 800 ppm. Figure 12 shows the evolution of the maximum daily CO_2 concentration in the classroom that achieved the highest CO_2 concentration values. This classroom spent 7.5% of the opening hours of the building with CO_2 > 800 ppm while the mean value was 5.4%. CO_2 concentration rises in classrooms with high occupancy in winter since the thermal load of the occupants causes the set point temperature to be reached, and the fan coil's fan stops. The classrooms are out of ventilation at the most critical moment, since the higher the number of occupants, the higher the ventilation flow required. The operation of the fan coil, linked to the heating set point temperature, means that the classrooms do not have mechanical ventilation if the heating is off, a situation that also occurs in the milder months (spring and autumn). This means that in highly occupied classrooms, the CO_2 concentration may exceed the recommended maximums at some point in time. These first results show that IoT monitoring (through *sensoriZAR*) is able to intelligently inform when indoor and outdoor conditions allow choosing between natural and mechanical ventilation (or combined).

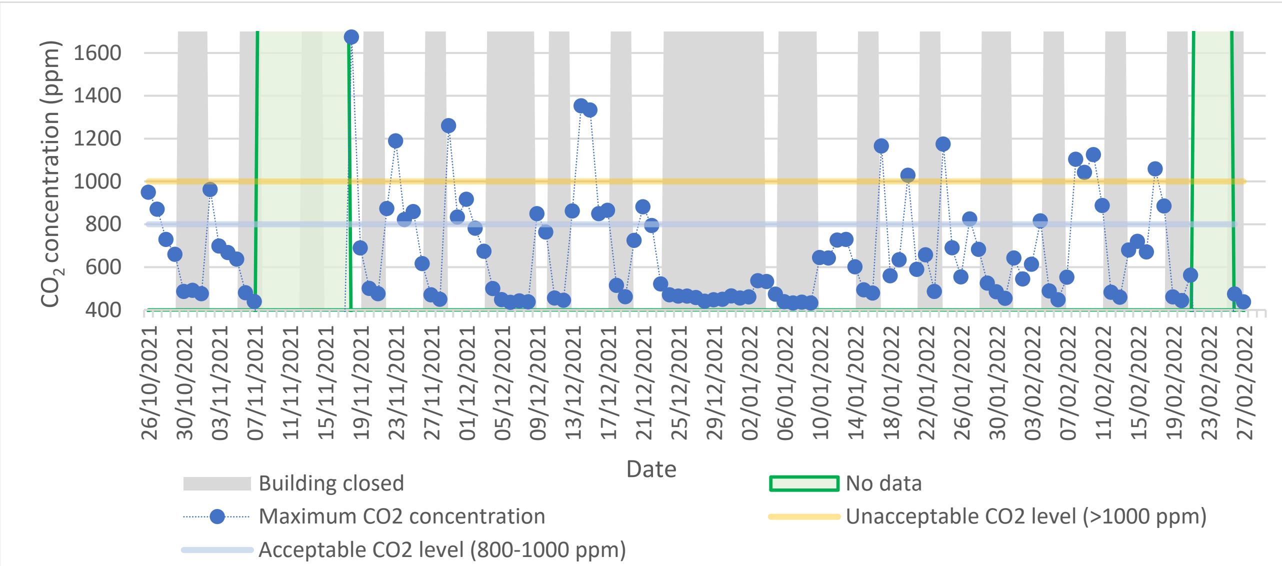
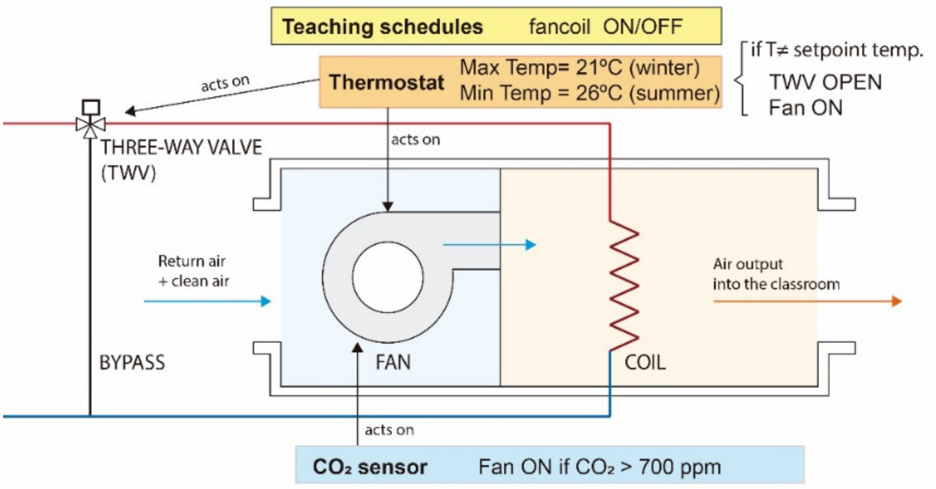


Figure 12. Maximum daily CO_2 concentration in a representative classroom.

To ensure indoor air quality in high occupancy areas, it is important that mechanical ventilation is controlled by real-time measurements of air quality parameters, such as CO_2 concentration. Moreover, this allows to ventilate the minimum necessary and therefore minimize the thermal losses caused by air ventilation, improving the energy efficiency of the building through a smart energy management according to space occupation. Figure 13 schematizes the performance of terminal units (fan coils) of the HVAC systems. In the case study, it is proposed to keep the fan of the fan coil running if the CO_2 level is above 800 pm, even though the heating is off because the set point temperature was reached. In practice, the three-way valve would have to be closed so that the water circulates through the bypass instead of the battery. In unoccupied spaces, by switching off the fan coil and preventing water from passing through the coil, there is no longer any consumption of thermal energy, which results in lower consumption. Switching off the fan also saves energy. Figure 13 outlines these proposed actions and how the fan and the three-way valve should behave regarding if the HVAC system is in cooling or heating mode depending on the knowledge provided by *sensoriZAR* about the occupancy level of the classroom, the indoor temperature, the outdoor weather, etc.



		FAN (AIR)	THREE-WAY VALVE (WATER)
UNOCCUPIED CLASSROOM		OFF	BYPASS
OCCUPIED CLASSROOM	WINTER	**ON** if HVAC on or **CO_2 > 800 ppm**	BYPASS if T ≥ 21°C * **COIL** if **T < 21°C ***
	SUMMER		BYPASS if T ≤ 26°C * **COIL** if **T > 26°C ***

*According to RD 1826/2009

Figure 13. Schematic design with proposals for energy savings in fan coils.

3.4. Discussion

The promising results obtained show the great potential that the proposed methodology offers, motivating the authors to promote IoT monitoring as a strong and reliable tool of data gathering and information analysis (in a compatible way with other complementary actions such as insulating or renewable production systems) to drive actions for reducing energy consumption and saving costs. Continuous IoT monitoring is a sustainable, cost-effective and ultra-low consumption way (with controlled implementation times, minimal operational impact and low economic costs) to advance on the energy efficiency of buildings. Moreover, these results could contribute to support the implementation of smart control systems in public tertiary buildings (hospitals, universities, residences) among decision-makers, politicians, and other stakeholders.

University campuses are one of the urban elements with the greatest potential for transformation and, therefore, a driving force in the urban dynamics that characterize the city [33]. In turn, campuses are organizational structures that are subjected to give answer to the emergence of the needs for citizens, companies, and institutions by, essentially, the generation of knowledge. A smart campus is "an emerging trend that allows educational institutions to combine smart technologies with physical infrastructure for improved services, decision making, campus sustainability" [34]. In this regard, a smart campus requires a strategy to evaluate how to react to dynamic changes and adapt to the environment that is continuously shaped by these three spaces: academic, infrastructural, and energetic.

In this context, the buildings can be understood as complex systems in which simulating is not the same as measuring due to several key elements:

- The interactions between systems that compose buildings, their inhabitants, and the located environment.
- Unexpected (or emergent) properties that occur with abovementioned interactions.
- Potential patterns in their configuration, functioning and behaviour.
- Evolution over time through new emerging pattern, adaptation (or not) to changes, etc. that usually arise from events or interactions, not from generalities.
- Dynamic equilibrium from fluctuating and open connections with the changing environment of buildings.

4. Conclusions

This study proposes a methodology to apply continuous IoT monitoring of comfort parameters, such as temperature and CO_2 concentration, in public buildings, as a measure to ensure the energy optimization of HVAC systems. The analysis of these measures allows to predict and control in real time the operation mode of these equipment and reveals itself as a very powerful methodology to ensure the reduction of energy consumption while maintaining optimal comfort conditions.

Firstly, the most relevant SEU was identified. There is a proportional relationship between the daily electricity consumption in winter and the number of hours the heating was turned on; the trend is linear with a regression coefficient of 0.86. This relationship confirms that HVAC is the main electricity consumer of the building, therefore actions should be aimed at optimizing both its operation and on/off periods. The methodology allowed for the identification of immediate measures to reduce electricity consumption, such as acting on standby consumption, which in the case of study is 285 MWh/y and represents 10.6 $kWh/m^2 \cdot y$. Up to 64% of this electricity consumption offers a significant opportunity for savings and, therefore, it is of particular interest to expand *sensoriZAR* to propose specific measures to reduce energy consumption.

The analysis of temperatures in winter helped to determine the building behaviour with regard to Spanish regulations (less than 6% below minimum limit of 17°C and more than 30% above maximum limit of 21°C) and thermal comfort (less than 18% below 19°C). In summer, IoT monitoring also made it possible to start to characterize the building complexity and to real-time analyse the performance of the air-conditioning system. This shows that there is a wide margin for improvement that justifies the need to implement continuous IoT monitoring systems such as *sensoriZAR*.

This study also allowed us to identify the need to monitor CO_2 concentration in rooms where occupancy is fluctuating, from very high to remain empty in non-negligible periods of time. A control of ventilation, heating and cooling based on the actual CO_2 level (and predictive in the immediate aftermath) could save between 40% and 70% of air conditioning energy consumption for the case of study. Currently, and thanks to the results obtained in this project, the University of Zaragoza has begun to promote actions to better adjust the HVAC systems to the building performance and to propose more efficient classroom occupancy.

This work shows, using the university buildings and their facilities as a research laboratory, the potential of continuous monitoring and measuring. As *sensoriZAR* harmonizes mechanisms to manage data through APIs for third-party, it contributes with an indispensable support methodology to make decisions based on quantitative data that help to optimize the operation of HVAC equipment and to improve the energy efficiency of buildings and the quality of life of the people who occupy them. Figure 14 graphically summarises the key points (why, what and how) of this methodology.

In the short term (i.e. monitoring a study room) *sensoriZAR* will be able to report instant overheating, cooling or hypo-ventilation (with health risks); in the medium term (i.e. analysing representative classrooms), *sensoriZAR* will be able to detect patterns (different for winter and summer) of overheating and overcooling to move towards continuous improvement of energy consumption and cost savings; in the long term (i.e. by crossing information), *sensoriZAR* will be able to provide knowledge to make data-driven decisions about recommended operational modes, non-optimal configurations, structural deficiencies, malfunctions and many other key elements in the building performance (specially in those with high seasonality, use and climate variability, etc.). The implementation of increasingly demanding regulations from an energy efficiency point of view is not enough on its own, but must be accompanied by procedures to ensure compliance through real measurements to determine the degree of compliance and to obtain conclusions based on quantitative data.

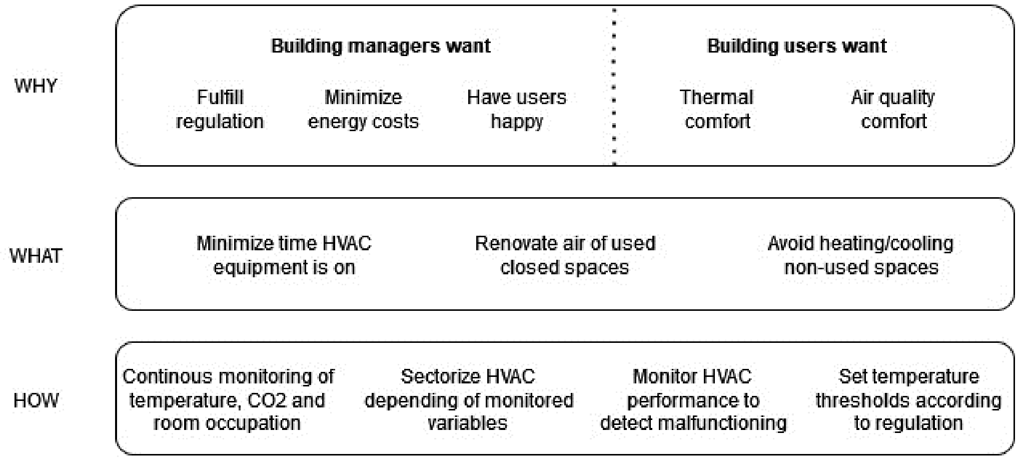


Figure 14. Graphical scheme of the proposed methodology.

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