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A UTILIZAÇÃO DA IOT COMO ESTRATÉGIA PARA A REDUÇÃO DO CONSUMO DE ENERGIA EM EDIFÍCIOS RESIDENCIAIS
THE USE OF IOT AS A STRATEGY FOR THE REDUCTION OF ENERGY CONSUMPTION IN RESIDENTIAL BUILDINGS
EL USO DE LA IOT COMO ESTRATEGIA PARA LA REDUCCIÓN DEL CONSUMO DE ENERGÍA EN EDIFICIOS RESIDENCIALES

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RESUMO

Introdução: A expansão das redes inteligentes sem fios aumentou a conectividade à Internet, facilitando a adoção da Internet das Coisas (IoT). Entender como o controlo inteligente e em tempo real de equipamentos de aquecimento já instalados permite ajustar automaticamente o seu funcionamento às necessidades específicas de cada ambiente, potencia uma utilização mais eficiente da energia e contribui para a sustentabilidade ambiental.
Objetivo: Analisar o impacto de dispositivos IoT de baixo custo na redução do consumo de energia, no conforto térmico e na perceção dos utilizadores em edifícios residenciais.
Métodos: Foi desenvolvido um estudo de prova de conceito numa habitação unifamiliar rural em Portugal, com monitorização de três zonas: quarto, sala/cozinha e casa de banho. Compararam-se condições de controlo manual e inteligente, complementadas por um questionário exploratório a 11 utilizadores de três edifícios residenciais.
Resultados: A solução permitiu maior estabilidade térmica, redução de períodos de sobreaquecimento e uma poupança média estimada de €1,51/dia nas três zonas monitorizadas. O retorno do investimento foi estimado em cerca de 2,3 meses, ou 3,4 meses incluindo custos simples de instalação.
Conclusão: O estudo evidencia o potencial das soluções IoT acessíveis para reduzir consumos energéticos e melhorar o conforto térmico sem substituir integralmente os sistemas de aquecimento existentes. Estas tecnologias podem constituir uma alternativa gradual, económica e eficaz para apoiar a transição para habitações mais eficientes.

Palavras-chave: internet das coisas; conforto térmico; edifícios residenciais; eficiência energética

ABSTRACT

Introduction: The expansion of wireless smart grids has increased Internet connectivity, facilitating the adoption of the Internet of Things (IoT). Understanding how smart, real-time control of existing heating equipment allows its operation to be automatically adjusted to the specific needs of each environment promotes more efficient energy use and contributes to environmental sustainability.
Objective: To analyze the impact of low-cost IoT devices on energy consumption reduction, thermal comfort, and user perception in residential buildings.
Methods: A proof-of-concept study was carried out in a rural single-family dwelling in Portugal, monitoring three zones: bedroom, living room/kitchen, and bathroom. Manual and intelligent control conditions were compared, complemented by an exploratory questionnaire administered to 11 users from three residential buildings.
Results: The solution enabled greater thermal stability, reduced overheating periods, and achieved an estimated average saving of €1.51/day across the three monitored zones. The payback period was estimated at approximately 2.3 months, or 3.4 months when basic installation costs were included.
Conclusion: The study highlights the potential of affordable IoT solutions to reduce energy consumption and improve thermal comfort without fully replacing existing heating systems. These technologies may represent a gradual, cost-effective, and efficient alternative to support the transition towards more energy-efficient homes.

Keywords: Internet of Things; thermal comfort; residential buildings; energy efficiency

RESUMEN

Introducción: La expansión de las redes inteligentes inalámbricas ha aumentado la conectividad a Internet, lo que ha facilitado la adopción del Internet de las cosas (IoT). Comprender cómo el control inteligente y en tiempo real de los equipos de calefacción ya instalados permite ajustar automáticamente su funcionamiento a las necesidades específicas de cada ambiente potencia un uso más eficiente de la energía y contribuye a la sostenibilidad medioambiental.
Objetivo: Analizar el impacto de los dispositivos IoT de bajo coste en la reducción del consumo energético, en el confort térmico y en la percepción de los usuarios en edificios residenciales.
Métodos: Se desarrolló un estudio de prueba de concepto en una vivienda unifamiliar rural en Portugal, con monitorización de tres zonas: dormitorio, salón/cocina y baño. Se compararon condiciones de control manual e inteligente, complementadas por un cuestionario exploratorio a 11 usuarios de tres edificios residenciales.
Resultados: La solución permitió una mayor estabilidad térmica, redujo los períodos de sobrecalentamiento y alcanzó un ahorro medio estimado de 1,51 €/día en las tres zonas monitorizadas. El retorno de la inversión se estimó en aproximadamente 2,3 meses, o 3,4 meses incluyendo costes básicos de instalación.
Conclusión: El estudio destaca el potencial de las soluciones IoT asequibles para reducir el consumo energético y mejorar el confort térmico sin sustituir completamente los sistemas de calefacción existentes. Estas tecnologías pueden constituir una alternativa gradual, económica y eficaz para apoyar la transición hacia viviendas más eficientes.

Palabras clave: internet de las cosas; confort térmico; edificios residenciales; eficiencia energética

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INTRODUCTION

The energy sector plays a central role in modern societies, requiring reflection on its environmental, sociopolitical, and economic implications, particularly in the context of increasing energy demand, the climate crisis, and recent instability in energy markets. In Europe, the energy crisis has contributed to higher energy costs, with prices remaining above pre-2021 levels for both households and businesses (European Commission, 2025). In response, the European Union has reinforced its energy efficiency and decarbonisation policies, recognising buildings as a priority area, since they account for approximately 40% of energy consumption in the European Union and are responsible for a significant share of greenhouse gas emissions associated with energy use (European Commission, 2024).

The recast of the Energy Performance of Buildings Directive, through Directive (EU) 2024/1275, strengthens the need to improve the energy performance of existing buildings, promote the digitalisation of building technical systems, and support the European objective of climate neutrality by 2050 (European Parliament and Council of the European Union, 2024). Within this framework, the residential sector is particularly relevant, as household energy consumption is strongly associated with space heating, domestic hot water, lighting, and electrical appliances. According to Eurostat, in 2024, space heating represented 61.5% of final energy consumption in households in the European Union, followed by water heating, with 15.6%, and lighting and electrical appliances, with 14.8% (Eurostat, 2025b).

In Portugal, although the share of energy used for space heating is lower than the European average, this consumption remains relevant, especially in dwellings with poor thermal performance, insufficient insulation, or inefficient heating systems. At the same time, energy vulnerability remains significant, with a considerable proportion of the population reporting difficulties in keeping their homes adequately warm (Eurostat, 2025a). This situation is associated with the thermal quality of the housing stock, household income, energy prices, and the efficiency of space-conditioning equipment, all of which influence occupants' thermal comfort and their ability to manage household energy consumption (Delgado et al., 2022; Presidência do Conselho de Ministros, 2024).

In response to these challenges, the Internet of Things (IoT) emerges as a practical solution to support more efficient energy management in existing residential buildings. Through connected devices, sensors, actuators, and digital platforms, IoT solutions enable the collection and processing of real-time data, the monitoring of indoor environmental conditions, and the automated or semi-automated control of equipment. This logic of data collection, transmission, and decision-making support has been identified as one of the main applications of IoT in the energy management of smart buildings (Poyyamozhi et al., 2024).

In residential heating, monitoring variables such as temperature and humidity allows system operation to be adjusted according to the actual conditions of the spaces and the needs of occupants. This can reduce unnecessary operating periods, adapt schedules, and promote a more rational use of energy, contributing to lower consumption and costs without compromising thermal comfort. Such an approach is particularly relevant in existing residential buildings, where deep renovation measures or the replacement of installed systems may not be feasible in the short or medium term. Due to their relatively low cost, simplified installation, and potential for gradual implementation, IoT solutions can provide an accessible alternative to more complex home automation systems, improving thermal control and reducing energy costs with limited intrusion into the dwelling (Correia, 2023; O'Neill et al., 2024).

In addition to technical control, energy feedback can promote more conscious energy use. Digital interfaces, mobile applications, and web platforms can provide users with information on consumption, operating patterns, and indoor environmental conditions. Recent studies suggest that digital energy applications can support changes in energy-related habits, particularly when information is understandable, personalised, easy to apply, and integrated into an accessible interface (Cellina et al., 2024; Paneru et al., 2024). However, data alone is not sufficient; feedback must be useful, interpretable, and connected to everyday decisions. Canale et al. (2025) further argue that feedback systems tend to be more valued when they relate energy consumption to comfort and indoor environmental quality indicators, such as temperature, humidity, or air quality. This connection is especially important in residential heating, since energy savings must be compatible with occupants' thermal comfort.

Building on this problem, the present study analyses, as a proof-of-concept study, the implementation of a low-cost IoT solution for monitoring and controlling heating in an existing residential building in Portugal. The aim is to assess its potential to reduce energy consumption, improve thermal comfort, and support more conscious energy use, without requiring the full replacement of the installed heating systems. The experimental analysis is complemented by questionnaires administered to users of three residential buildings, including the intervention building and two comparable buildings, allowing user acceptance and perceptions regarding this type of solution to be contextualised.

The main contribution of this study does not lie in the development of new IoT devices, but rather in the practical evaluation of an accessible, easy-to-install retrofit solution applied to existing heating systems in a residential dwelling. By combining thermal monitoring, rule-based control, economic estimation, and user perception, the study seeks to demonstrate the potential of low-cost IoT solutions as a complementary measure to reduce energy consumption and improve thermal comfort in contexts where deep renovation interventions or the full replacement of space-conditioning systems are not financially viable.

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1. METHODOLOGY AND SYSTEM ARCHITECTURE

This section presents the methodological design of the study and the architecture of the implemented IoT system. The adopted methodology combines two complementary approaches. The first consists of an experimental proof-of-concept study, based on the implementation of a low-cost IoT solution in a rural single-family dwelling, with the aim of assessing its technical, energy, and economic feasibility. The second, exploratory in nature, consists of a questionnaire administered to users of residential buildings with comparable characteristics, aimed at contextualising heating system use patterns, perceptions of thermal comfort, and acceptance of smart solutions in a domestic context.

The section describes the intervention dwelling, the existing heating systems, the monitored zones, the devices used, the adopted control logic, and the criteria considered to estimate the energy and economic impact of the solution. The questionnaire-based component complements the experimental analysis, enabling the technical results to be related to everyday usage practices and to users' willingness to adopt this type of technology.

1.1 Case study and experimental design

The analysed dwelling is a rural single-family residential building located in central Portugal, with approximately 150 m² of conditioned floor area. The building was constructed in the 1970s and presents thermal characteristics that are representative of a significant part of the Portuguese housing stock, including single-leaf masonry external walls and double-glazed windows.

The study was developed as a proof-of-concept assessment, with the objective of evaluating the technical, energy, and economic feasibility of a low-cost IoT solution designed to improve heating management in a rural residential context. The solution was designed according to three fundamental principles: economic accessibility, ease of installation, and limited intrusion into the dwelling. For this purpose, wireless devices with simplified configuration and the possibility of gradual integration into the existing heating systems were selected, avoiding construction work or major changes to the dwelling's infrastructure.

The dwelling was previously equipped with a main heating system consisting of a gas boiler, responsible for heating the water distributed through radiators. In addition, auxiliary electric heating devices were available, namely fan heaters installed in the bathrooms. Although these devices were operational, their use depended heavily on direct user intervention, through the manual adjustment of thermostatic valves, thermostats, or switches. Consequently, there was no automatic adjustment of heating operation according to room occupancy, usage schedules, or the specific thermal needs of each zone.

The implementation focused on three zones with distinct usage patterns: a bedroom, an open-plan area comprising the kitchen and living room, and a bathroom. The bedroom was considered a predominantly night-time occupancy zone, with thermal needs concentrated mainly during rest periods. The living room/kitchen area, due to its larger size and more frequent use throughout the day, is characterised by greater thermal variability, influenced both by occupant presence and by internal heat gains associated with meal preparation. The bathroom, in turn, corresponds to a zone of occasional and short-duration use, equipped with fast-response electric heating, where time-based control and occupancy-based activation are particularly relevant.

The experimental analysis compared two operating conditions. The first corresponded to the initial manual control condition, in which users directly adjusted the heating equipment according to their perceived comfort and daily routines. The second corresponded to the period following the implementation of intelligent control, in which equipment operation was automatically adjusted based on indoor temperature, expected usage schedules, and/or occupancy of the analysed zones.

As a complement to the experimental implementation, a questionnaire was administered to users of three residential buildings with similar functional characteristics, including the intervention dwelling. This component was not intended to produce a statistically representative sample, but rather to collect contextual information on heating system use practices, thermal comfort perception, familiarity with smart technologies, and willingness to accept automated energy management solutions. The inclusion of these additional buildings made it possible to frame the proof-of-concept study within a broader, albeit exploratory, residential context, contributing to the interpretation of the practical suitability of the proposed solution.

Thus, the assessment integrated a technical and energy component, focused on the intervention dwelling, and an exploratory component, focused on users. This approach made it possible to analyse not only the performance of the implemented IoT solution, but also its compatibility with real domestic routines and its potential adoption in dwellings with similar characteristics.

1.2 IoT architecture and control strategy

The IoT system architecture was designed to monitor indoor environmental conditions and automatically control the existing heating equipment, without requiring major changes to the dwelling's installation. The solution integrated wireless sensors, smart actuators, a ZigBee/Wi-Fi gateway, and a digital platform for local and remote management. This infrastructure was complemented by Wi-Fi-enabled touch panels, used for data visualisation and local interaction with the system.

Temperature and relative humidity sensors, presence sensors, smart plugs with energy metering, and electronic actuators for radiator thermostatic valves were used. The field devices communicated mainly through ZigBee, while the connection to the digital platform and local touch panels was ensured via Wi-Fi/Ethernet. The platform, accessible through a mobile application or web interface, allowed data visualisation, configuration of operating rules, and remote control of the equipment.

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Communication between the different components was established bidirectionally. The sensors installed in the analysed zones collected temperature, relative humidity, and presence data, transmitting this information to the gateway through the ZigBee network. The gateway communicated with the management platform, where the data were recorded, visualised, and used to apply the defined control rules. When the measured conditions justified an action, the platform sent commands to the actuators, regulating the operation of the radiators or electric heating devices. In this way, the system enabled heating operation to be adjusted according to the actual conditions of use of each space.
The implemented architecture is shown in Figure 1.

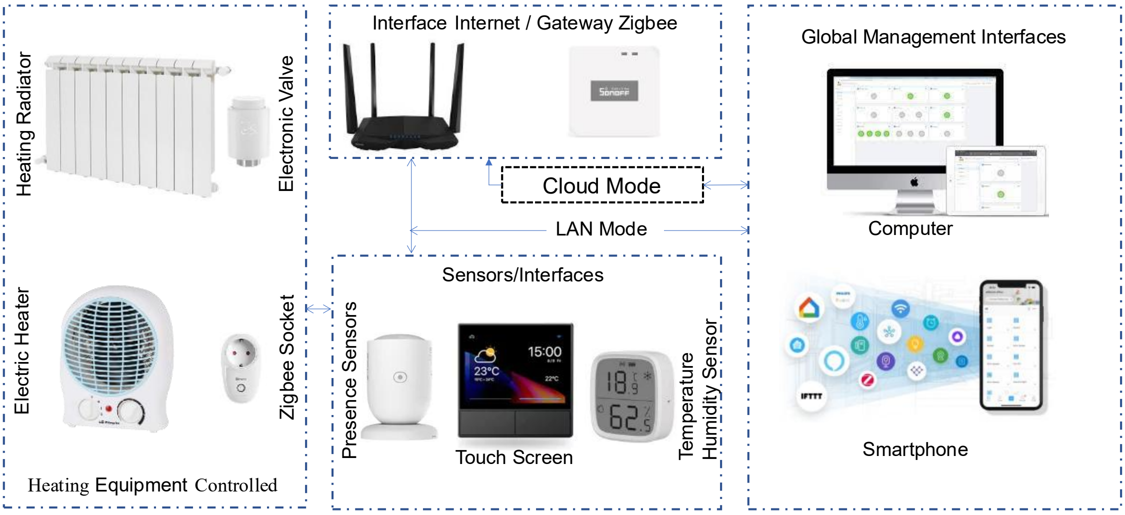

Figure 1 - Architecture of the IoT system implemented for heating monitoring and control in the analysed dwelling. Source: Author's own elaboration

Figure 1 illustrates the communication between the temperature, relative humidity, and presence sensors, the actuators installed on the heating equipment, the ZigBee/Wi-Fi gateway, and the local/remote management platform. The data collected by the sensors are sent to the digital platform, which enables monitoring, configuration of operating rules, and the transmission of commands to the actuators. According to the manufacturers' specifications, the devices used have an approximate nominal accuracy of ±1% for the measured electrical variables and ±0.2 °C for temperature measurement. Data were recorded and aggregated with a temporal resolution of 1 minute, enabling the evolution of indoor conditions, electrical consumption, and equipment status to be monitored throughout the monitoring period.
The sensors were distributed to ensure representative measurements, avoiding proximity to direct heat sources, windows, doors, and areas subject to draughts. In the bedroom and bathroom, one sensor was installed in each room. In the open-plan living room/kitchen area, three sensors were installed at representative points, and the average temperature of the three sensors was considered for analysis and control purposes. This option enabled a more robust characterisation of the thermal behaviour of this larger area and reduced the risk of control decisions being influenced by localised readings associated with heat sources, such as kitchen appliances or radiators.
The intelligent control system was configured based on indoor temperature, expected occupancy periods, and thermal comfort parameters for the heating season. The Regulation on the Energy Performance of Residential Buildings, under the Portuguese Building Energy Certification System, considers 18 °C as the conventional temperature for calculating nominal heating needs, whereas the former Regulation on the Thermal Performance Characteristics of Buildings adopted 20 °C as a reference value. In this study, an operational range between 19 °C and 20 °C was adopted only during expected occupancy periods and therefore did not correspond to a continuous 24-hour condition.
The control logic was based on three main criteria: activation of heating when the indoor temperature was below the defined minimum threshold and the zone was within an expected period of use; reduction or interruption of heating when the temperature approached or exceeded the established maximum threshold; and automatic deactivation of equipment when no occupancy was detected for a predefined period.
For electric heating devices, such as fan heaters, additional criteria related to safety, occupancy, and thermal need were also considered, preventing prolonged operation during periods of absence. The use of presence sensors was particularly relevant for reducing situations in which equipment might be unintentionally left on, especially in spaces with occasional and short-duration use, such as the bathroom. This functionality is also important from a safety perspective, as it limits the operation of electric heating devices during unoccupied periods.

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The architecture was limited to functionalities requiring simple installation and configuration, in order to keep the solution accessible to users without advanced technical knowledge. Additional functionalities, such as the integration of outdoor weather data, geolocation, air quality sensors, ventilation automation, or predictive algorithms, were not included in the operational configuration evaluated and were considered only as possibilities for future development.

1.3 Energy, economic and user assessment

To assess the energy and economic impact of implementing the IoT system, the existing heating systems, energy sources, equipment efficiency, energy cost, investment in smart devices, occupancy profiles, and space-use practices were considered.
The heating systems installed in the dwelling were analysed, including the gas boiler, radiators, and auxiliary electric heating devices, as well as their distribution across the studied zones. The cost of energy per kWh, excluding taxes and charges, was used to estimate the direct economic impact of reduced consumption. The investment required for the acquisition of IoT devices was also considered, excluding labour costs, since the solution was designed for simplified installation by the users themselves. However, this assumption represents a limitation of the economic assessment, as more specialised technical intervention may be required in some cases. Based on the technical data of the equipment and the respective operating periods, energy consumption was estimated before and after the implementation of the IoT solution. This comparison made it possible to quantify the estimated consumption reduction associated with intelligent control and to assess its effect on operating costs. The economic assessment also considered the initial investment in the devices and the estimated annual savings, allowing the potential payback period of the solution to be analysed.
Direct electrical consumption was monitored for the auxiliary electric heater connected to the smart plug. For the hydronic radiator system, energy consumption was estimated based on the operating time, the characteristics of the heating system, and the unit cost of natural gas, since individual room-level gas consumption could not be directly measured.
The questionnaire component aimed to characterise users' relationship with energy consumption and with smart technologies applied to housing. The questionnaire included questions on consumption habits, thermal comfort, ease of use, previous knowledge of smart devices, perceived usefulness of the information provided, and willingness to adopt more energy-efficient behaviours.
Given the sample size, the questionnaire results should not be interpreted as statistically representative, but rather as exploratory information supporting the experimental analysis. Nevertheless, this component provides contextual insight into the acceptance of low-cost IoT solutions in residential settings, particularly in contexts where energy vulnerability, household income, the thermal quality of the housing stock, and energy costs limit the ability to invest in deep renovation measures or in the full replacement of space-conditioning systems. This situation is particularly relevant in the Portuguese context, where improving thermal comfort and energy efficiency in dwellings remains a significant challenge (Eurostat, 2025a; Delgado et al., 2022; Presidência do Conselho de Ministros, 2024).

2. RESULTS AND DISCUSSION

The implementation of the IoT system in the dwelling made it possible to assess the impact of intelligent control on the thermal stability of the analysed spaces and on the reduction of energy consumption associated with heating. The analysis focused on three zones with distinct usage patterns: a bedroom, an open-plan living room/kitchen area, and a bathroom. Data were collected during the actual operation of the heating equipment, comparing two conditions: manual control, corresponding to direct operation by the occupants, and intelligent control, based on automatic rules defined according to indoor temperature, occupancy, and expected periods of use.
The results show that manual control tends to generate greater thermal variability, with periods of overheating and prolonged equipment operation. This behaviour is largely associated with the manual adjustment of thermostatic valves and thermostats, which are often set to high levels at the start of heating and maintained in that position for extended periods. By contrast, intelligent control enabled equipment operation to be adjusted to the actual conditions of the spaces, contributing to greater thermal stability and to a reduction in the operating time of the heating systems.

2.1. Thermal monitoring of the analysed spaces

Figure 2 presents the evolution of the temperature in the bedroom over three days of monitoring. Under manual control, there were periods in which the indoor temperature exceeded the defined operational range, indicating situations of inefficient energy use. This behaviour may be related to excessive adjustment of the thermostatic radiator valves and to internal heat gains associated with the presence of occupants and the use of equipment.

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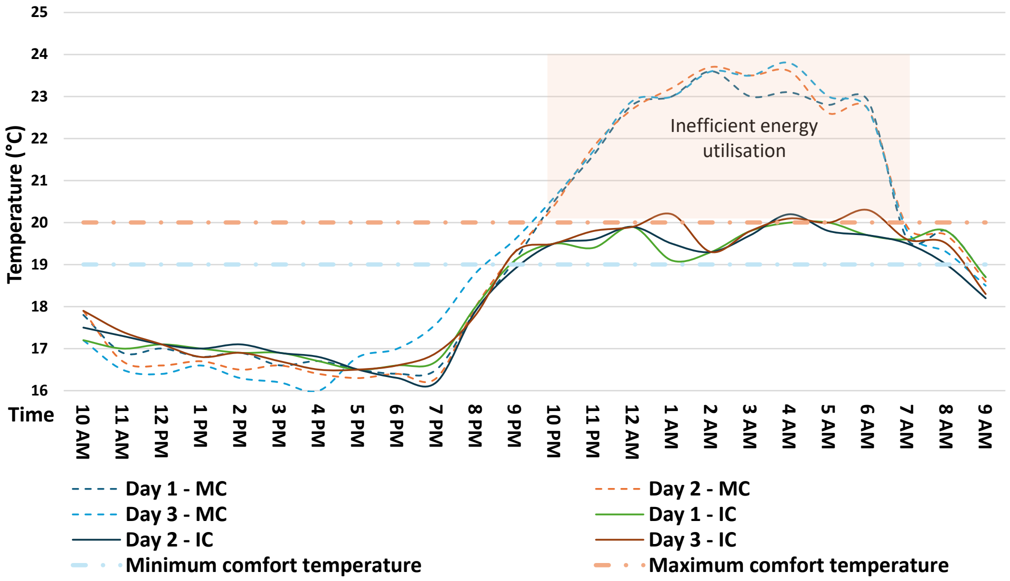

Figure 2 - Indoor temperature monitoring in the bedroom over three days, comparing Intelligent Control (IC) and Manual Control (MC). Source: Author's own elaboration

Under intelligent control, the temperature remained closer to the defined operational range, reducing periods of overheating and avoiding unnecessary system operation. It should be noted that, in this zone, heating was generally deactivated during the daytime period, between 10:00 and 19:00, as this corresponded to a period when the bedroom was not in use.

Figure 3 presents the results obtained in the living room/kitchen area. In this space, occasional temperature increases were observed, especially during periods associated with meal preparation. In manual control mode, the heating system did not automatically respond to these additional thermal loads, resulting in overheating situations. With intelligent control, equipment operation was adjusted according to the average temperature recorded by the sensors installed in the open-plan area, contributing to reducing the likelihood of the temperature exceeding the defined maximum limit.

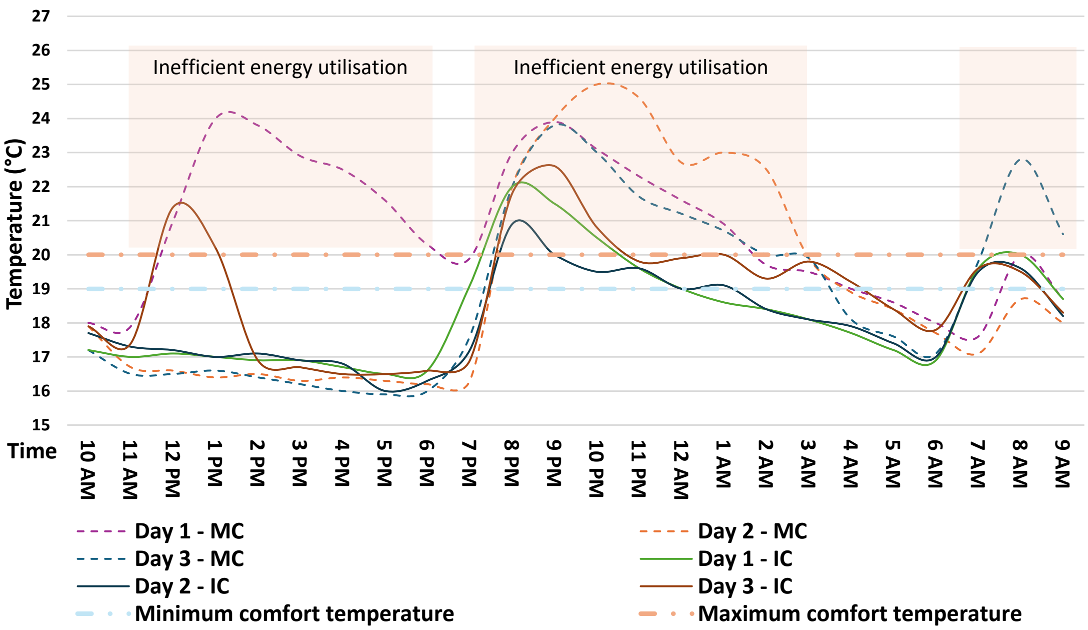

Figure 3 - Indoor temperature monitoring in the open-plan living room/kitchen area over three days, comparing Intelligent Control (IC) and Manual Control (MC). Source: Author's own elaboration.

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Figure 4 presents the evolution of the temperature in the bathroom. In this space, intelligent control proved to be particularly relevant, since electric heating has a fast response and is used during short and specific periods. Automation made it possible to activate the equipment only when there was a thermal need and during expected periods of use, reducing situations of forgetfulness and limiting operation during unoccupied periods. This functionality is also relevant in terms of safety, as it prevents the prolonged operation of electrical equipment during periods of absence.

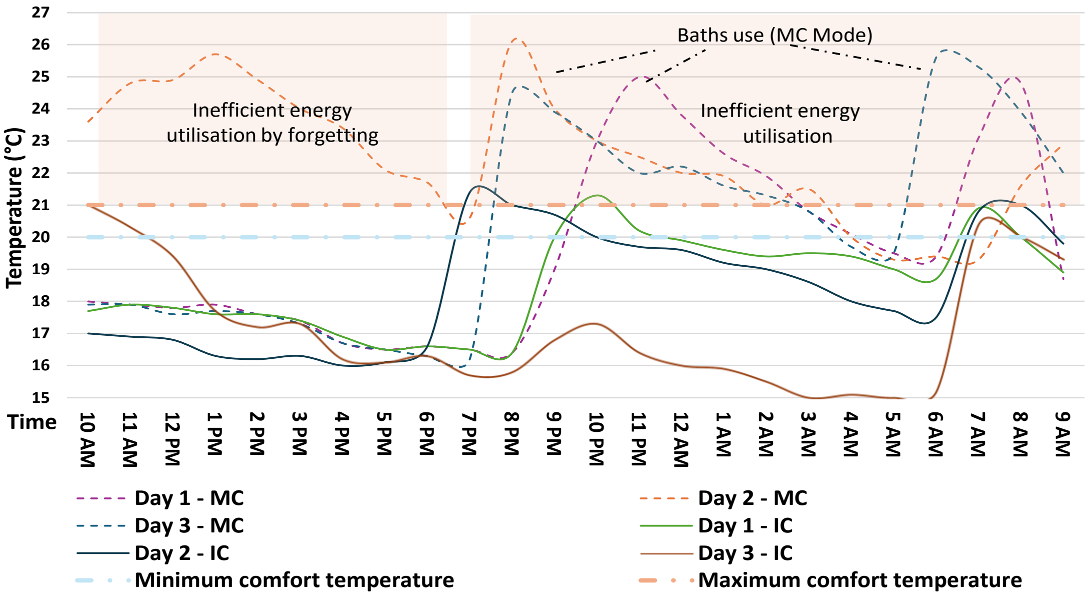

Figure 4 - Indoor temperature monitoring in the bathroom over three days, comparing Intelligent Control (IC) and Manual Control (MC). Source: Author's own elaboration.

In the case of the bathroom, it should be acknowledged that the comfort temperature may vary according to the type of use. Although the operational range between 19 °C and 20 °C was considered suitable for most of the analysed spaces, specific situations, such as using the bathroom for bathing or showering, may justify temporarily higher temperatures. Therefore, the system parameters can be adjusted according to the usage profile of each room and the occupants' preferences.

2.2. Estimated Energy Consumption and Savings

Table 1 presents the comparison between the estimated energy consumption under the manual control scenario and the estimated consumption after the implementation of intelligent control, considering the three-day monitoring period. Energy savings were determined as the difference between the two scenarios. For the purpose of presenting the results, Room A corresponds to the bedroom, Room B to the open-plan living room/kitchen area, and Room C to the bathroom.

Table 1 - Estimated energy consumption and heating costs for Rooms A, B and C.

	Room A			Room B			Room C			Room A + B + C		
	Day 1	Day 2	Day 3	Day 1	Day 2	Day 3	Day 1	Day 2	Day 3	Day 1	Day 2	Day 3
Estimated energy consumption (kWh/day) Without intelligent control	4.8	5.5	5.4	6.3	6.9	6.5	1.6	7.8	1.4	12.7	20.2	13.3
Estimated energy cost (€/day)	0.91	1.04	1.03	1.20	1.31	1.24	0.32	1.56	0.28	2.43	3.91	2.55
Estimated energy savings (kWh/day) with intelligent control	1.7	2.8	2.4	3.1	2.7	3.3	0.5	6.7	0.3	5.3	12.2	6.0
Estimated cost savings (€/day)	0.32	0.53	0.46	0.59	0.51	0.63	0.10	1.34	0.06	1.01	2.38	1.15

The values presented in Table 1 were calculated using the average estimated consumption over the monitored period. Natural gas was considered at €0.19/kWh and electricity at €0.20/kWh.

The results indicate that, across the three analysed rooms, the implementation of intelligent control enabled an average daily saving of approximately EUR 1.51. Although this value may appear modest when considered in isolation, its relevance increases when analysed from a seasonal perspective. Assuming similar usage patterns over a 180-day heating season, the estimated accumulated savings could reach approximately EUR 272. However, this value should be interpreted as an indicative scenario-based extrapolation, since the experimental monitoring period was limited.

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The estimated reduction in consumption results mainly from the decrease in unnecessary operating periods and from the limitation of overheating situations, particularly during periods when spaces were unoccupied or when the indoor temperature was already close to the defined comfort range. These results suggest that the use of simple control rules, based on indoor temperature, occupancy, and expected usage schedules, can contribute to more efficient residential heating management without requiring the replacement of existing systems.
This result is particularly relevant in the Portuguese context, where energy poverty remains a significant concern, reflected in the difficulties faced by some households in ensuring adequate thermal comfort conditions, particularly among socioeconomically vulnerable groups (Energy Poverty Advisory Hub, 2024). The National Long-Term Strategy to Combat Energy Poverty 2023–2050 highlights the importance of building energy efficiency and more efficient energy consumption management as instruments to reduce energy vulnerability in Portugal (Direção-Geral de Energia e Geologia [DGEG], 2024).
Additionally, considering that Portuguese GDP per capita in purchasing power parities corresponded to approximately 83% of the European Union average in 2024, according to data from Instituto Nacional de Estatística (INE, 2025), consumption reductions achieved through intelligent control systems may contribute to reducing the pressure of energy expenses on household budgets. Although these savings do not, by themselves, constitute a solution to energy poverty, they demonstrate the potential of these technologies as complementary measures to promote energy efficiency and reduce operating costs associated with residential heating.

2.3. Impact of Occupancy Detection

During the monitoring period, occupancy-based automatic deactivation contributed to reducing avoidable energy use across different types of equipment. The estimated reduction was approximately 20% for lighting, 10% for electric heating, and 5% for hot-water radiators. These values should be interpreted as indicative estimates, since they were obtained by comparing the recorded or estimated operating time of each type of equipment before and after the activation of occupancy-based automatic deactivation, rather than through a dedicated long-term metering campaign.
For lighting and electric heating, the reduction was mainly associated with shorter operating periods after the room became unoccupied. For hot-water radiators, the estimated reduction was lower due to the slower thermal response of the hydronic system and because radiator operation was also influenced by temperature-based control rules. These results suggest that occupancy detection can help reduce consumption associated with inefficient usage behaviours, such as leaving lights or heating equipment switched on after leaving a room.
However, automation also revealed some limitations related to user behaviour. Some users, particularly children, became more dependent on the automatic system to switch off lights and equipment, rather than doing so manually. This behaviour, together with the time delay between the absence of occupancy detection and automatic deactivation, partially reduced the expected energy gains. Nevertheless, the functionality proved useful both in reducing avoidable consumption and in raising users' awareness of more efficient energy-use practices.

2.4. Economic assessment and payback period

The economic assessment considered the cost of the essential devices required for the operation of the IoT system: temperature and humidity sensors, a ZigBee smart plug, electronic actuators for thermostatic valves, and a ZigBee gateway (Table 2). The total cost of the devices used for intelligent heating control in the three analysed zones was estimated at €105.

Table 2 - Cost of the IoT devices used in the study

IoT devices for intelligent heating control	Quantity x Cost of Devices		
	Room A	Room B	Room C
Temperature and humidity sensor	1 x €8	3 x €8	1 x €8
Electric actuator - Electric socket ZigBee	-	-	1 x €8
Electronic actuator ZigBee for thermostatic valve	2 x €9	1 x €9	-
ZigBee gateway		1x €30	

Note: The integration of additional components, such as touchscreen displays or occupancy sensors, may contribute to a further reduction in energy consumption; however, their acquisition and installation costs should be considered.

The investment payback period was determined by dividing the initial investment by the average daily economic savings obtained. Considering an initial system cost of €105 and average daily savings of €1.51/day, the resulting payback period was approximately 70 days, corresponding to about 2.3 months.
Thus, the proposed solution presents a short payback period, reinforcing its economic feasibility in residential contexts where the complete replacement of heating systems is not financially viable. However, it should be noted that this calculation considers only the cost of the devices, assuming simplified installation by the user. In situations requiring specialised technical installation, the payback period would be longer. For example, considering an additional labour cost of €50, the total investment would increase to €155, resulting in an estimated payback period of approximately 103 days, or about 3.4 months. This analysis shows that, even when basic installation costs are included, the payback period remains relatively short.

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2.5. Exploratory questionnaire results

The questionnaire component aimed to collect exploratory information on users' familiarity with IoT technologies, their perceived usefulness of these systems, and their willingness to adopt them in a residential context. The sample included 11 adults living in three residential buildings, including the dwelling where the intervention was implemented.

The results, presented in Figure 5, show that approximately 30% of the respondents reported prior knowledge of the Internet of Things concept or previous interaction with devices based on this technology. However, after being introduced to the system and its functionalities, all respondents considered the use of intelligent control systems to be positive for improving thermal comfort and reducing energy consumption. In addition, approximately 80% of the respondents considered that access to real-time energy consumption data could help increase awareness of energy efficiency and encourage changes in everyday behaviours. All participants expressed interest in testing IoT devices to reduce energy consumption in their homes.

Although the small sample size limits the generalisation of the results, these exploratory findings suggest a favourable perception of the adoption of IoT solutions for residential energy management.

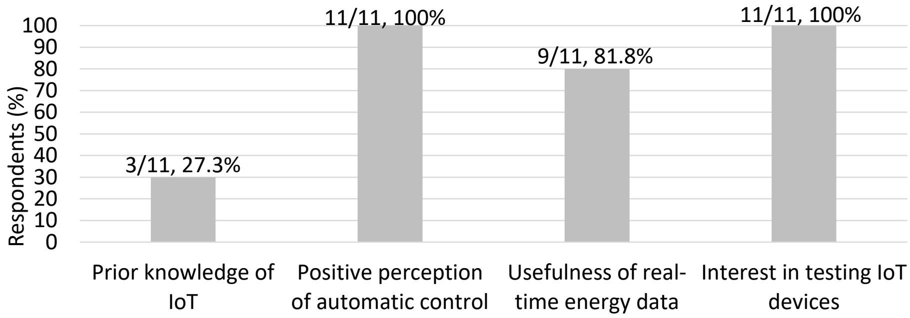

Figure 5 - Questionnaire results from residents of the analysed buildings.
Source: Author's own elaboration

2.6. Study limitations and future developments

Despite the promising results, this study has some limitations. First, it is a proof-of-concept study conducted in a single dwelling, with experimental monitoring limited to a short period. Extending the monitoring period and applying the solution to additional rooms and dwellings would improve the robustness of the results and allow system performance to be assessed under different weather conditions, occupancy profiles, and building characteristics. In addition, the comparison between manual and intelligent control was not normalised for outdoor weather conditions, which may have influenced heating demand during the monitoring period.

Second, part of the energy consumption was estimated based on equipment specifications, operating time, and unit energy costs. Although suitable for a preliminary assessment, direct and longer-term energy measurements would provide more accurate results.

Third, the questionnaire sample was small and not representative of the Portuguese population. Its results should therefore be interpreted as exploratory and may have been influenced by the fact that participants were introduced to the system before expressing their perceptions.

The implemented solution was intentionally limited to simple, low-cost functionalities to ensure ease of installation and use. Future developments could include outdoor weather data, geolocation, open-window detection, air quality sensors, ventilation automation, or predictive algorithms. However, these functionalities involve greater technical complexity, additional costs, and, in some cases, privacy and data protection concerns. The integration of machine learning could also support the anticipation of heating needs based on indoor and outdoor data, occupancy patterns, and the dwelling's thermal inertia, but would require longer monitoring periods, larger datasets, and specific model validation.

CONCLUSION

This study highlights the potential of IoT technologies as supporting tools for improving energy efficiency and thermal comfort in existing residential buildings. The implemented solution showed that low-cost devices, when integrated into simple monitoring and control strategies, can reduce the operating time of heating equipment, prevent overheating situations, and decrease energy consumption associated with inefficient user practices.

The results obtained in the analysed dwelling indicate that intelligent control enabled more stable indoor temperature management, while ensuring an estimated average saving of €1.51 per day across the three monitored zones. Considering the initial investment in the devices used, the payback period was estimated at approximately 2.3 months, or around 3.4 months in a simplified scenario including additional installation costs. These results reinforce the economic feasibility of the solution, particularly in contexts where the full replacement of existing heating systems is not financially accessible.

The occupancy detection functionality also showed potential to reduce energy consumption associated with lighting and unnecessary equipment operation. However, the results demonstrate the importance of considering users' habits and behaviours when configuring automated systems, in order to ensure an appropriate balance between energy efficiency, comfort, and ease of use. The questionnaires indicated limited initial familiarity with IoT technologies, but also a high level of acceptance once

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participants understood their potential benefits.

Although the results obtained are promising, this study represents a first stage in validating the proposed solution under real operating conditions. Its application in an existing dwelling made it possible to demonstrate the technical and economic feasibility of the approach, while identifying opportunities for improvement in future implementations. Extending the monitoring period, incorporating direct energy measurements, and applying the solution to a wider diversity of buildings and user profiles could help strengthen the robustness of the results and deepen the understanding of its impact. In addition, the integration of outdoor data or predictive algorithms could improve system performance and enable control strategies that are even more closely adapted to real operating conditions. Therefore, the results confirm the potential of affordable, flexible, and easy-to-install IoT solutions to support the gradual transition towards more efficient, comfortable, and energy-sustainable homes.

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AUTHOR´S CONTRIBUTION

Conceptualization, P.C.; data curation, P.C.; formal analysis, P.C.; investigation, P.C.; methodology, P.C.; software, P.C.; supervision, A.F.; validation, P.C.; writing – original draft, P.C.; writing – review & editing, P.C.

CONFLICT OF INTERESTS

The authors declare no conflict of interests.

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