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Article

Efficient Heating System Management Through IoT Smart Devices

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Abstract

A novel approach to managing domestic heating systems through IoT technologies is introduced in this paper. The system optimizes energy consumption by dynamically adapting to electricity and fuel price fluctuations while maintaining user comfort. Integrating smart devices significantly reduce energy costs and offer a favorable payback period, positioning the solution as both sustainable and economically viable. Efficient heating management is increasingly critical amid growing energy and environmental concerns. This strategy uses IoT devices to collect real-time data on prices, consumption, and user preferences. Based on this data, the system adjusts heating settings intelligently to balance comfort and cost savings. IoT connectivity manages continuous monitoring and dynamic optimization in response to changing conditions. This study includes a real-case comparison between a conventional central heating system and an IoT-managed electric radiator setup. By applying automation rules linked to energy pricing and user habits, the system enhances energy efficiency, especially in cold climates. The economic evaluation shows that using low-cost IoT devices yields meaningful savings and achieves equipment payback within approximately three years. The results demonstrate the system's effectiveness, demonstrating that smart, adaptive heating solutions can cut energy expenses without sacrificing comfort, while offering environmental and financial benefits.

Keywords: energy consumption; heating; intelligent device management; IoT applications

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1. Introduction

Energy plays a fundamental role in modern society; it is needed in various productive sectors, services, and the domestic domain [1,2]. Germany has the highest energy per capita consumption, followed by Russia and Japan [3]. These nations have high expectations for their standard of living, which implies considerable energy demand. It is crucial to start implementing changes now to avoid severe consequences in the future.

Spain has made significant progress in reducing its energy consumption over time. Between 1980 and 2013, the country's average annual electricity consumption decreased by 21%, and gas consumption decreased by 31% [3]. It is important to note that this study specifically focuses on regions with cold climates, such as the city of León, where heating needs far exceed those of cooling. These data demonstrate that it is possible to reduce resource consumption without sacrificing quality of life to a large extent. However, continued effort is required to reduce consumption and avoid significant ecological damage. Excessive energy consumption has various adverse environmental effects. For instance, the combustion of fossil fuels releases carbon dioxide into the atmosphere, significantly contributing to climate change. Fortunately, there are alternatives that can alleviate these issues, although multiple sources of pollution persist in our environment [4]. International cooperation and individual commitment are essential to ensure a sustainable future in terms of energy and the environment [5].

Figure 1 illustrates the distribution of electricity consumption in Europe across sectors. One area where a significant contribution can be made is in the management of residential heating systems since they constitute one of the main energy consumptions and, therefore, one of the main sources of greenhouse gas emissions [6,7].

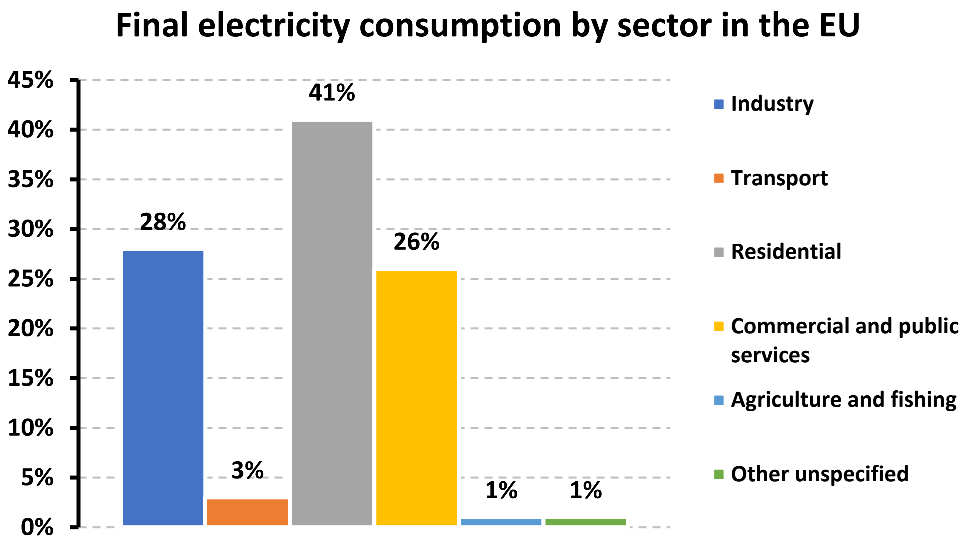

Figure 1. Final energy consumption is by the European Union (EU) sector. Own elaboration. Data from [8].

In the context of the residential sector, Figure 2 shows the distribution of energy consumption by different applications according to 2019 data [9].

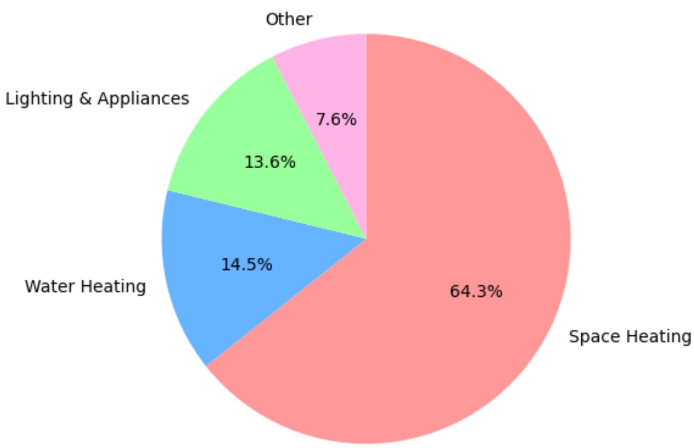

Figure 2. Residential energy consumption by end use in the EU. Own elaboration. Data from [9].

The distribution of energy use in EU households is dominated by space heating, which accounts for 64.4% of final energy consumption, followed by water heating, at 14.5%, and appliances and lighting, representing around 13.6%. Cooking takes up approximately 6%, while cooling and other uses each make up less than 1% of total consumption.

Managing home heating systems is a critical consideration, particularly in geographic regions prone to cold winters. Such is the case in certain areas of Spain, where low temperatures are expected during the winter season. To provide context, Spain has approximately 18 million households [10]. This situation presents a significant opportunity to assess and enhance energy efficiency in the heating sector. Traditional heating methods, relying on the combustion of fossil fuels, stand as one of the primary contributors to CO_2 emissions in the country. According to data from the Ministry for Ecological Transition and Demographic Challenge, in 2019, CO_2 emissions linked to residential heating amounted to 35.7 million tons [11].

In this context, it is crucial to explore various home heating alternatives [3]. Presently, conventional central heating systems utilizing water boilers to feed water radiators distributed throughout the house are still the most prevalent choice. However, alternative options are worthy of exploration, such as electric radiators powered by electricity. Electric radiators provide several advantages, including enhanced energy efficiency, minimal maintenance requirements, and straightforward installation procedures. However, their primary drawback lies in their cost, particularly compared to other heating systems, due to the relatively high price of electricity [12]. Moreover, conventional central heating systems with water boilers and radiators have certain advantages—notably, their lower energy cost and ability to quickly and effectively heat large spaces. However, these systems also have certain disadvantages—notably, their higher environmental impact due to greenhouse gas emissions and more significant maintenance needs [12].

It is crucial to recognize that there are sustainable alternatives for home heating, such as biomass heating systems or heat pumps, which use renewable energy sources and produce fewer greenhouse gas emissions [13].

Furthermore, it is essential to use it efficiently and appropriately to further mitigate the environmental impact of home heating. This includes setting the temperature to a comfortable yet not excessive level, scheduling on/off times to avoid unnecessary heating, and ensuring proper home insulation. Addressing the impact of residential heating on indoor air quality is equally vital, a concern often underestimated but with significant implications for human health. Inadequate ventilation and improper use of heating systems can lead to heightened pollutant levels in indoor air, potentially causing respiratory problems and other adverse health effects [14].

An accurate prediction of future electrical loads plays a crucial role in improving energy efficiency. In this sense, artificial intelligence (AI) techniques (in particular those using recurrent neural networks) allow for more precise planning of electrical demand [15].

Smart management of heating devices through IoT allows for real-time data collection on energy consumption, user preferences, and energy costs. This data is utilized to automatically adjust heating device settings, adapting to fluctuations in energy costs and striving to achieve an optimal balance between thermal comfort and economic efficiency [16].

While this study focuses on the integration of IoT devices for smart heating management, it does not yet incorporate advanced machine learning (ML) or deep learning algorithms. Instead, the IoT system automates the switching on and off of devices based on predefined parameters such as energy prices and user comfort settings. Although this approach provides significant improvements in energy efficiency, future work will explore the integration of ML algorithms to further enhance the system's intelligence, enabling it to learn user habits, predict energy needs, and optimize performance in real-time without manual intervention.

This paper introduces innovative solutions for home heating management, specifically focusing on implementing automation and control systems to allow for efficient and precise temperature control and energy consumption management. The relevance of exploring intelligent heating strategies has been previously emphasized in studies such as Zhang et al. [17], which emphasize the importance of optimizing residential energy systems through control and storage solutions. Using the Internet of Things (IoT) as a tool to optimize energy usage based on electricity or diesel fuel prices presents an opportunity to enhance efficiency and reduce heating-related costs. This approach has garnered significant attention in scientific research [18]. A real case was conducted in a residence in the city of León. This city experiences cold, dry winters and hot summers, with an average annual temperature of 12.2 °C. The coldest months are January, February, March, and December, with average low temperatures not exceeding 1.5 °C, according to data from [19].

As a representative sample, Figure 3 illustrates the temperature trends in this area on January 7th, 8th, and 9th, 2023, the days on which the heating strategies outlined in this paper were implemented.

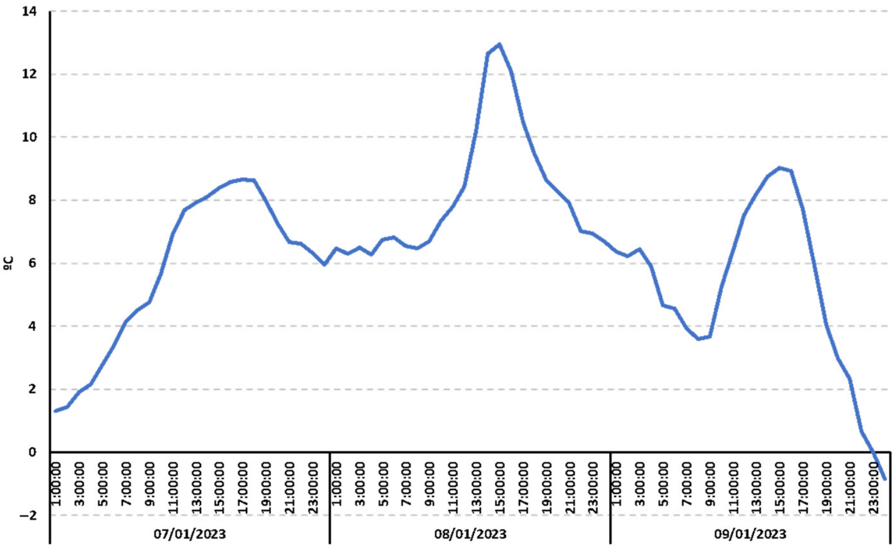

Figure 3. Evolution of outside temperatures in Leon City during the 7th, 8th, and 9th of January, 2023. Own elaboration. Data from [19].

1.1. State of the Art

This section presents a review of recent studies related to the use of IoT devices for intelligent heating management in residential settings. The aim is to contextualize the proposed approach within the framework of previous research and to highlight the differences and contributions of this work.

The control of kitchen emissions is analyzed through IoT sensors and connected air quality measures, demonstrating how this technology can significantly improve indoor air quality in innovative, smart, and healthy homes [20].

Adequate data transmission in IoT devices is also sought. Given the limitation of bandwidth, storage, processing power, and resources in sensor networks, an approach is proposed that uses predicted intervals of sensor readings to reduce unnecessary transmissions [21].

In addition, IoT devices have gained popularity in the smart home arena, providing several advantages in terms of energy efficiency and user convenience. The integration of IoT devices with AI has enabled the development of smarter, more automated systems that optimize energy consumption in homes. The following are the most prominent developments in this field.

1.1.1. IoT Applications in Residential Buildings

IoT devices support smart metering and monitoring of energy consumption in homes. Sensors and connected devices collect data on the energy consumption of different appliances and systems, providing detailed information on usage patterns and savings opportunities [22]. This data can be analyzed using AI algorithms to identify areas for improvement and make optimal decisions to reduce consumption [23].

A continuous monitoring system based on IoT can significantly improve the energy efficiency of heating, ventilation, and air conditioning (HVAC) systems in university buildings [24].

IoT devices are managed for automation and smart control of home energy systems. Smart thermostats implement adjustment of heating and air conditioning temperatures based on occupancy and user preferences, leading to more efficient energy use. In addition, smart lighting systems can automatically adapt to lighting needs at any given time, reducing unnecessary consumption [25]. Integrating IoT technology and machine learning transforms ordinary buildings into smart spaces that are cost-effective, energy-efficient, safer, and more comfortable for inhabitants [26].

While these applications illustrate the broad utility of IoT in residential contexts, one of the most significant areas of impact is energy efficiency, particularly in the intelligent management of heating systems, which is explored in the following section.

1.1.2. IoT for Energy Efficiency and Heating Optimization

Substantial advancements have occurred in recent years in the realm of IoT-based intelligent management of heating devices. Researchers have delved into diverse strategies and techniques to optimize energy consumption and enhance heating efficiency. Several noteworthy approaches from the current state of the art are outlined below.

Integrating IoT with data analytics has facilitated the gathering and analysis of vast amounts of data concerning energy consumption, usage patterns, and energy prices. This integration has paved the way for creating predictive models and optimization capable of real-time adjustments to heating device configurations [27].

Some studies highlight the importance of offloading techniques, which help overcome hardware limitations in resource-constrained IoT devices by offloading computation or communication tasks to external servers or gateways. Although the devices used in this study operate with continuous power supply and do not depend on battery, the principles of low-latency communication and resource optimization remain relevant, particularly when designing scalable and low-cost smart home systems [28].

Geolocation of a dwelling enables the optimization of energy consumption by dynamically adjusting heating and ventilation systems in response to site-specific energy consumption patterns [29]. By incorporating real-time data such as outdoor temperature, solar radiation, and weather forecasts, energy usage is precisely modulated, minimizing unnecessary consumption. This enhances energy efficiency, maximizes the utilization of local renewable resources, and reduces both costs and environmental impact. Furthermore, geolocation is critical for detecting user proximity or occupancy, allowing the system to automatically fine-tune comfort parameters based on whether occupants are inside or outside the home.

Adaptive control systems use algorithms that learn and adapt to changes in environmental conditions and user preferences. These systems can automatically adjust the temperature and operation of heating devices based on outdoor temperature, home occupancy, and energy prices, achieving a balance between comfort and energy efficiency [30].

Real-time feedback and data visualization are essential components in the intelligent management of heating devices. Through interactive interfaces, users can monitor energy consumption, prices, and usage patterns. This allows them to make informed decisions and adjust heating settings to optimize consumption [31].

Smart heating device management has also analyzed the integration of renewable energy sources, such as solar or geothermal energy. By combining smart heating devices with renewable generation, it seeks to maximize the use of clean energy and reduce dependence on fossil fuels, thus contributing to energy sustainability [32]. The importance of controlling individually controllable heating and cooling zones and the ability to analyze data allows for better management [33].

Efficient management of heating in a home relies on careful consideration of several comfort parameters. The first key factor is the indoor temperature, which should be maintained within an optimal range of 18 °C to 21 °C for people at rest. However, this figure may vary according to individual preferences. The activity level of occupants is also crucial, as active individuals generate additional heat and may require slightly lower temperatures. Choosing clothing is another important element, as appropriate attire allows for the maintaining of a comfortable temperature without raising the heating. Lastly, indoor relative humidity, which should be kept between 40% and 60%, contributes to thermal comfort by preventing environmental dryness [34].

To achieve optimal heating management, it is essential to have precise control systems, such as programmable thermostats or smart devices that automatically adapt the temperature to changing needs throughout the day. Additionally, regular heating system maintenance is recommended, along with ensuring that the home is well insulated to prevent heat loss [35]. Educating occupants about the efficient use of heating and promoting practices such as turning off radiators in unused rooms and sealing windows and doors tightly also plays a crucial role in effectively managing indoor temperature and reducing energy consumption [36].

Although IoT-based systems have already demonstrated substantial benefits in heating optimization, the integration of artificial intelligence is expected to further enhance energy management through predictive and adaptive capabilities, as discussed next.

1.1.3. Artificial Intelligence and Future Perspectives

Integrating AI with IoT devices enables smart home energy optimization and management. AI algorithms can analyze data collected by IoT devices and generate personalized recommendations to maximize energy efficiency. For example, an AI-based energy management system can suggest optimal times to turn appliances on and off, considering electricity prices and user preferences [18,35]. Table 1 compares the various types of residential heating systems in Europe, providing an overview of their energy sources, thermal efficiency, average cost, and associated environmental impacts. It offers a clear picture of the different options available and their implications for energy consumption and environmental sustainability.

Table 1. Comparison of residential heating systems in Europe. Adapted from [37].

Heating System Type	Energy Source	Thermal Efficiency	Average Cost (EUR/year)
Central heating with boilers	Gas, Diesel	80%	1200
Electric radiators	Electricity	100%	900
Heat pumps	Electricity	300%	600
Biomass heating	Wood, Pellets	70–90%	700
Solar thermal systems	Solar energy	50–70%	500

The convergence of IoT and artificial intelligence thus represents a promising direction for future smart home technologies, paving the way for increasingly autonomous, efficient, and user-centered energy management solutions.

1.2. Contribution and Structure of the Paper

The main contribution of this work lies in the practical implementation and evaluation of a home heating system managed through low-cost IoT devices. Unlike previous studies, this article compares two real-world scenarios under actual winter conditions, directly measuring both thermal and economic performance. The originality of the work lies in demonstrating that efficient energy management can be achieved without relying on complex algorithms, using simple logic based on real-time energy pricing.

Although electricity use for heating has been considered inappropriate in the past, technological advances have improved its efficiency and performance. In addition, electric radiators do not emit CO_2 during operation, which contributes to reducing greenhouse gas emissions. With a large number of households in the country, adopting more sustainable heating systems can significantly reduce emissions, thus facilitating the transition to a more environmentally friendly society.

This paper focuses on two aspects. The first compares the energy cost and heating efficiency of two popular options (electric radiators versus central heating systems with water boilers and radiators) for heating a specific house. The second explores the possibilities and benefits of intelligent management of heating devices using IoT. The application of machine learning algorithms for data processing, the optimization of energy consumption, and the development of intelligent systems capable of learning and continuous improvement will be considered in future works, as potential enhancements to the current system.

Section 2 explains the different equipment used. Section 3 presents the system setup and programming needed to work automatically and provide accurate and personalized results. Section 4 shows the two scenarios considered. Section 5 shows the results obtained from a technical point of view (considering exclusively heating aspects), while Section 6 shows the economic considerations for these results. Finally, Section 7 develops the conclusions.

2. Materials and Methods

In this comparative study, two scenarios for heating a specific house are analyzed: conventional central heating systems with water boilers and radiators and electric radiators. The main objective is to determine which of these alternatives is more efficient and cost-effective, considering both the price of electricity and fuel, as well as the performance of the boiler. This aligns with the premise of energy efficiency, which seeks to reduce energy demand and its economic cost without reducing or minimally reducing thermal comfort.

IoT devices control electric radiators. These devices allow for measuring and monitoring energy consumption and adjusting their operation according to heating needs.

In addition, intelligent thermal sensors are installed in different rooms of the house to record the temperatures and allow for data collection for comparative analysis. The information obtained from the sensors is used to develop algorithms that contribute to evaluating the efficiency and performance of the heating systems.

The main parameters used to evaluate the comfort configuration entered as setpoints in the programming system have been proposed in agreement ISO 7730:2005 [38] and are as follows:

- Air velocity: 0.4 m/s.
- Clothing level: 1.30 clo.
- Metabolic Rate: 1.6 met.

- Mean Radiant Temp: 18 °C.

Room 1 is a double bedroom with an approximate area of 20 m^2, Room 2 is a single bedroom with an approximate area of 14 m^2, and the volume of treated air is 48.0 m^3 and 33.6 m^3, respectively. Figure 4 shows a 3D-rendered view illustrating the rooms, their surface areas, and the location of the temperature sensors, valves, and smart plugs installed in the areas under analysis, generated using the HA software (version 2023.1) employed in the research.

Figure 4. Three-dimensional rendered floor plan of the test house. Own elaboration using the Home Assistant platform as part of the system design and simulation process.

The tests were conducted in a single-family home located in León, a city in Spain with a continental climate characterized by cold, dry winters. The measurement campaign spanned over 100 days during the 2022–2023 winter season. During this period, minimum temperatures typically dropped to around 1.5 °C, consistent with the city's average annual temperature of 12.2 °C. This study focused on monitoring two rooms with different thermal properties and sizes, allowing for the evaluation of the system's performance under varied real-life conditions.

2.1. Description of the Heating Systems

(A) Conventional central heating system with water boiler and radiators

The main element of a conventional central heating system is the thermal boiler used to heat the water that will circulate through the water radiators distributed around the house. In our case, this is a 30 kWt diesel boiler. Devices for precise fuel consumption measurement are expensive, and a residential user cannot assume their cost. Therefore, we will specify an indirect method for evaluating this cost based on the estimation of the global performance of this system.

(B) Electric radiators

These radiators are designed to generate heat using electrical resistances and distribute it efficiently. Several radiators with 1 kW of power have been used.

2.2. Description of the IoT Management Platform

Home Assistant has been selected as the home automation manager for operating the system's intelligent devices. This open-source system allows users to control and automate various home devices through an easy-to-use interface, such as lighting, heating, and security. Users can access and control devices from a computer or smartphone.

The choice of Home Assistant is due to its versatility and compatibility with a wide range of home automation devices and systems. This allows users to customize their automation system according to their specific needs. Being open source, it also offers the possibility of modifications and improvements by the developer community.

Home Assistant is a highly versatile and powerful home automation software that allows you to integrate an infinite variety of smart devices and services into a single system [39]. Designed to simplify device management, Home Assistant stands out for its ability to set up complex automation, review historical data, and provide complete control over the home environment. This software was created by Paulus Schoutsen and first released in 2013. It became an open-source project that has evolved thanks to the contribution of an active community of developers and enthusiasts.

Home Assistant's advantages include its open-source nature, which means it is free and highly customizable to suit individual needs. In addition, it offers integrations with a wide range of devices and services, providing a seamless home automation experience. However, some disadvantages may include a learning curve for novice users and the need for some technical knowledge to set up advanced integrations. Despite these drawbacks, Home Assistant remains popular for those looking for comprehensive, personalized control of their smart home devices. In addition, implementing the Node-RED extension is proposed as an effective solution for process automation. Node-RED is an open-source visual programming platform that allows for the creation of automated workflows by connecting different nodes or code blocks [40]. This functionality is especially useful in the case of home heating management since it allows for the creation of automatic workflows to control energy consumption, among other relevant aspects.

Device and sensor integration is achieved through communication protocols such as MQTT or HTTP, allowing real-time data to be collected and used to optimize automated processes. This means that the data provided by the sensors installed in the electric radiators and the boiler can be collected and used in conjunction with the home automation management system to optimize the energy efficiency and performance of the heating devices.

2.3. Description of IoT's Smart Equipment

The heating management system of the house has the following controllers and sensors.

Smart thermostatic valves (Figure 5a): These valves have wireless connectivity, such as Bluetooth or Wi-Fi, which allows for easy integration with home automation management systems. Tado smart thermostatic valves use advanced communication protocols like Zigbee and Bluetooth Low Energy (BLE). In addition, they have the user geolocation function, which would allow for temporary power-on programming to be enabled or disabled.

Smart temperature and humidity sensor (Figure 5b). This sensor combines a high-precision temperature probe with a Wi-Fi connectivity module, enabling wireless measurement and transmission of temperature data. The sensor accurately captures temperature changes in its environment and converts the analog signal into a digital signal transmitted through the Wi-Fi module. These sensors can be configured and controlled via a mobile app or web interface, making it easy to monitor and access data from any location with an Internet connection. It has an IEEE 802.11 b/n/g Wi-Fi connectivity at 2.4 GHz. Its technical capabilities include humidity detection between 0% and 90% RH and temperature measurement from −9 °C to 99 °C. Smart temperature and humidity sensors use communication protocols such as Wi-Fi, Zigbee, or Z-Wave.

(**a**) (**b**) (**c**)

Figure 5. IoT's smart equipment: (**a**) smart thermostatic valves; (**b**) smart temperature and humidity sensor; (**c**) smart Wi-Fi plug. Image adapted from the web.

Smart Wi-Fi plug (Figure 5c). This type of plug is connected to a standard power outlet and communicates with a Wi-Fi network, allowing it to establish a connection with mobile devices or home automation systems. In electrical terms, the smart plug operates with a standard input of 230 V~ and 50 Hz, offering a maximum output of 16 A. Wi-Fi smart plugs use the standard Wi-Fi communication protocol (802.11).

3. System Setup and Programming

3.1. User-Configuration Parameters

Defining a series of data or key variables is necessary for the system to work automatically and provide accurate and personalized results. These variables will allow the system to adapt to each user's specific needs and preferences, providing a more complete and relevant analysis. These variables will enable the system to automatically perform the calculations and analysis, adapting to particular circumstances and needs. This ensures that the results and recommendations provided are relevant and applicable to each user's specific situation, facilitating informed decisions regarding energy consumption and resource efficiency. The variables to be defined by the user are described next.

3.1.1. Geolocation Variable

Geolocation is a key variable for optimizing energy consumption in home heating as it allows heating systems to be adjusted according to the climatic conditions of each location. By knowing the latitude, longitude, and altitude of the home, it is possible to adapt the operation of heating systems based on factors such as outdoor temperature and the availability of renewable energy sources, like natural gas or solar energy, helping to improve efficiency and reduce costs [41,42].

In addition to considering environmental conditions, geolocation can also monitor the presence or proximity of people in the home. This allows the system to adjust comfort parameters, such as indoor temperature, depending on whether the occupants are inside or outside the house, avoiding unnecessary energy use when the home is unoccupied [29,43]. In this way, the available energy resources are optimized, improving both sustainability and the comfort experience at home.

3.1.2. Scheduling Heating Requirement

The user must specify the schedule and duration in which heating is required. This will allow the system to automatically adjust calculations and optimize energy use during periods when heating is needed. Table 2 shows the scheduling applied to the house under study.

Table 2. Hourly heating is implemented in the different rooms.

Room	Day	Hour
Double Room	Mon–Fri	23–08
	Sat–Sun	00–09
Single Room 1	Mon–Fri	16–18, 23–08
	Sat–Sun	00–09
Single Room 2	Mon–Fri	16–18, 23–08
	Sat–Sun	00–09
Kitchen	Mon–Fri	14–15, 21–22
	Sat–Sun	14–15, 22–23

Proper scheduling of heating in homes offers numerous advantages. First of all, it allows for the optimization of heating according to the actual thermal comfort needs of the residents. Setting specific schedules and appropriate durations prevents energy loss by heating unoccupied spaces or when heating is not necessary. This translates into more efficient energy consumption and associated cost reductions.

In addition, proper heating scheduling allows the heating to be adapted to residents' living patterns. For example, the heating can be programmed before residents arrive home, ensuring a warm and comfortable environment upon arrival without the need to keep it active throughout the day. Similarly, it can be programmed to turn off or lower the temperature when residents are absent. This adaptation to residents' schedules and routines allows for greater control and comfort while optimizing energy consumption.

Table 2 shows the specific hours of operation of the heating system for different rooms during the week. In the double room, heating is activated during Monday through Friday nights, from 23:00 to 08:00, and during weekend nights, from 00:00 to 09:00. Single Rooms 1 and 2 follow a similar pattern during weekdays, with heating periods from 16:00 to 18:00 and 23:00 to 08:00, and on weekends, with heating periods from 00:00 to 09:00 and 16:00 to 18:00, respectively. As for the kitchen, the heating is used at shorter intervals, from 14:00 to 15:00 and from 21:00 to 22:00 on weekdays and from 14:00 to 15:00 and from 22:00 to 23:00 on weekends. These detailed schedules provide a clear view of the periods of highest heating demand in different areas, which can be useful for optimizing the heating system and improving the home's energy efficiency.

The decision to focus on Rooms 1 and 2 was made to ensure a precise comparison in spaces with different thermal characteristics and air volumes. Additionally, the availability of IoT devices limited their implementation across all rooms of the house. However, these two rooms provide sufficiently distinct thermal conditions to evaluate the system's efficiency in different scenarios. In future studies, the system will be implemented in other areas of the house, such as the kitchen, to gain a more comprehensive perspective.

3.1.3. Electric Heating Priority

The user can set the heating priority relative to other electric systems or devices. For example, if there are additional ventilation or cooling systems, the user can indicate whether electric heating should take priority over them in case of electric energy demand conflict.

Setting an appropriate priority for heating ensures that, even in situations of high electric energy demand, the heating system can meet the priority heating needs in the home, as shown in Figure 6. This means that in the event of supply or energy resource constraints, priority would be given to maintaining heat in critical areas or rooms, such as bedrooms or main living areas, thus ensuring the residents' comfort.

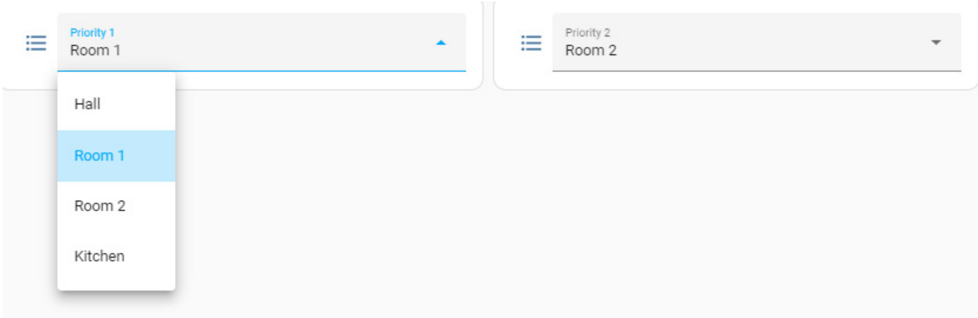

Figure 6. Selecting the priority of the different rooms to be heated. Own elaboration.

The correlation between the heating priority variable and its use is based on the ability to adapt to the specific preferences and needs of the residents. For example, some homes may have areas or rooms that require a higher temperature due to the presence of more vulnerable people, such as young children or older adults. Setting an appropriate priority ensures that these areas receive the required amount of heat, even if the temperature in other parts of the home is reduced. This ability to customize and adapt contributes to personalized comfort and energy savings by focusing resources on the spaces that require the most attention, thus optimizing the home's heating use.

In intelligent heating management for a home, it is essential to allow users to select different variables to establish an order of heating rooms according to their individual preferences and needs. Users can define the priority of heating rooms to suit their daily routine, making the most of heating at key times and reducing consumption at times of lower occupancy.

3.1.4. Energy Efficiency Preferences

The user can set preferences related to energy efficiency, such as target temperatures for heating and energy consumption limits, or even, in future works, include a preference for renewable energy sources. These preferences will influence system calculations and recommendations.

3.2. Procedure

It should be noted that although the system does not incorporate predictive algorithms or machine learning, its operation is based on automated logic that compares the hourly electricity price with an economic threshold (setpoint) derived from the cost of fuel oil. This control enables the intelligent activation of electric radiators only when it is economically advantageous, while also ensuring thermal comfort. This logic is illustrated in the flowcharts shown in Figures 7–9. The flowchart in Figure 7 shows the procedure implemented in the management platform. First, the system evaluates the geolocation to determine the climate conditions of the home. Then, heating scheduling would be used to adjust heating on and off times, optimizing its operation according to the needs of the residents.

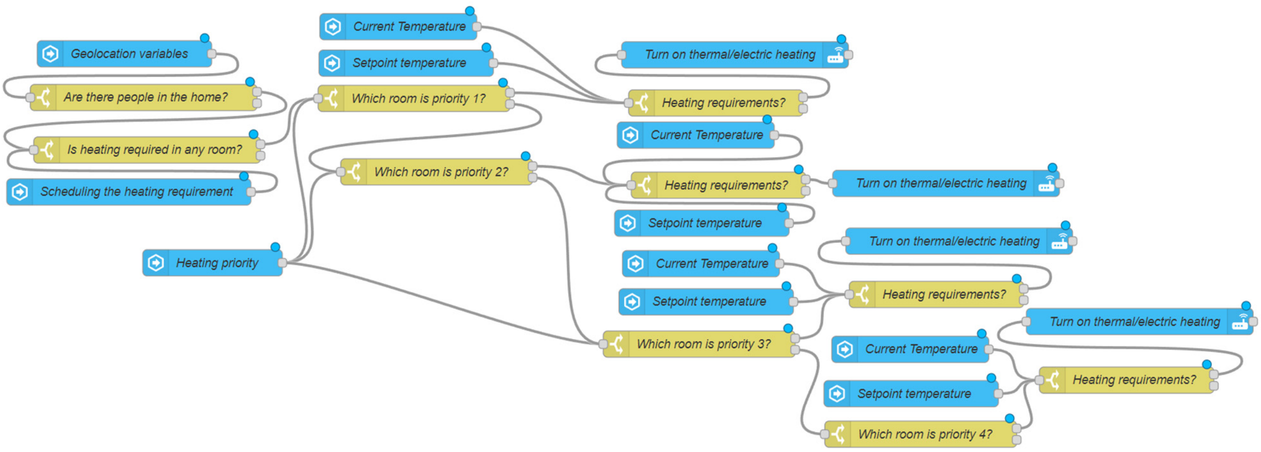

Figure 7. Heating operation priority flowchart according to the variables considered. Own elaboration.

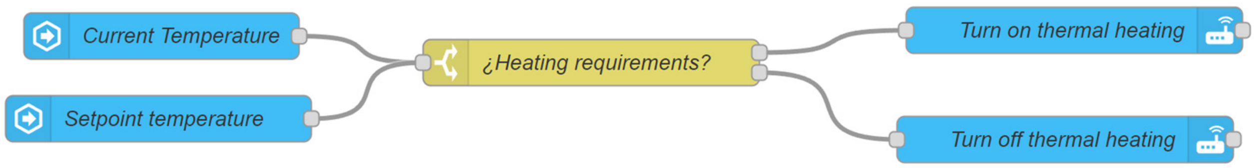

Figure 8. Flowchart of Scenario 1. Own elaboration.

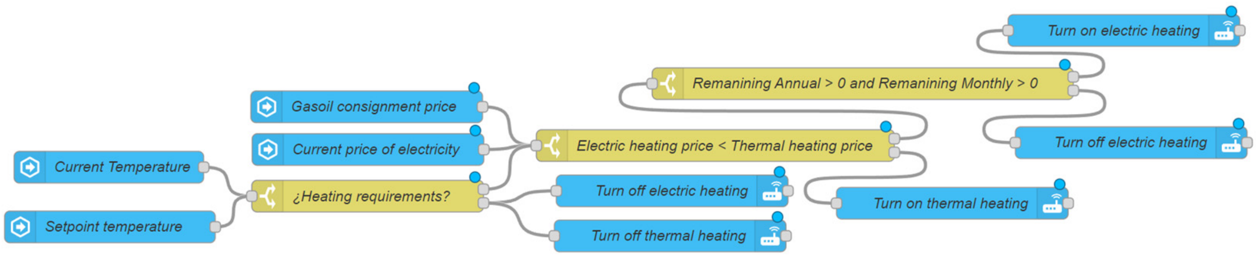

Figure 9. Flowchart of Scenario 2. Own elaboration.

In addition, the priority assigned to different areas of the home is considered. The procedure ensures that an appropriate temperature is maintained in priority areas, even if heating is reduced in other lower-priority areas. This would be achieved through a decision-making process based on defined parameters and current conditions, ensuring comfort and energy savings.

Once the relevant calculations and decisions have been made, the system can execute the heating scheduling instructions according to the set parameters. This process would be repeated periodically or depending on changes in relevant variables, such as geolocation or heating scheduling, to ensure optimal and efficient use of heating in the home.

It is worth noting that this household benefits from the social electricity tariff, which implies the existence of maximum energy consumption limits, both monthly and annually [44]. Therefore, the management system incorporates control variables called Remaining Monthly and Remaining Annual, which monitor accumulated consumption and allow for the heating strategy to be adjusted in order to avoid exceeding those thresholds.

In addition, the system includes a backup thermal boiler that is automatically triggered if the established comfort temperature is not reached, regardless of the electricity price. This condition ensures that the scheduling always prioritizes user comfort without relying exclusively on economic criteria.

4. Scenarios Evaluated

This section examines and compares two different scenarios. The first considers exclusively heating all the rooms of the house through a fuel-central heating system, while the second also uses electric radiators to heat some of the rooms controlled by smart devices.

The main focus is on evaluating the energy cost associated with each scenario, considering both energy consumption, energy efficiency, and the cost–benefit ratio.

In both scenarios, the same thermal comfort must be maintained, understood as the level of human satisfaction, with the thermal conditions [45] measured via the Adaptive Thermal Comfort Theory (ADT) [46]. This methodology defines, among other things, two parameters by which to evaluate thermal comfort in the case of replacing heat-generating elements: the mean radiant temperature [47] and the air velocity [48].

The temperature measurement in both scenarios is carried out at the same point (thermostatic heads described in Section 2.3). The heat generation points are, in Scenario 1, the thermal radiators themselves (on which the thermostatic heads are located), and in Scenario 2, the electric radiators, further away from the measurement points. The set temperature of both scenarios cannot be the same. Therefore, a black globe thermometer has been used to measure the temperature at the room's central point. A satisfaction survey of room users established that the optimal comfort temperature (measured at the central point of the room) was 17.5 °C. To achieve this target temperature, the target temperatures of the room's thermal radiators in Scenario 1 had to be increased to 18 °C, remaining at 17.5 °C in Scenario 2. The difference in the setpoint between the two scenarios is due to the fact that in the boiler system (Scenario 1), the sensor is located very close to the radiator, which results in slightly higher readings. In contrast, the electric radiators in Scenario 2 are positioned farther from the sensor, allowing the target temperature at the center of the room to be maintained without overheating areas near the heat source.

On the other hand, the measurement of relative humidity resulted in a value of 50%. In the psychometric chart shown in Figure 10, this point corresponds to a comfort situation.

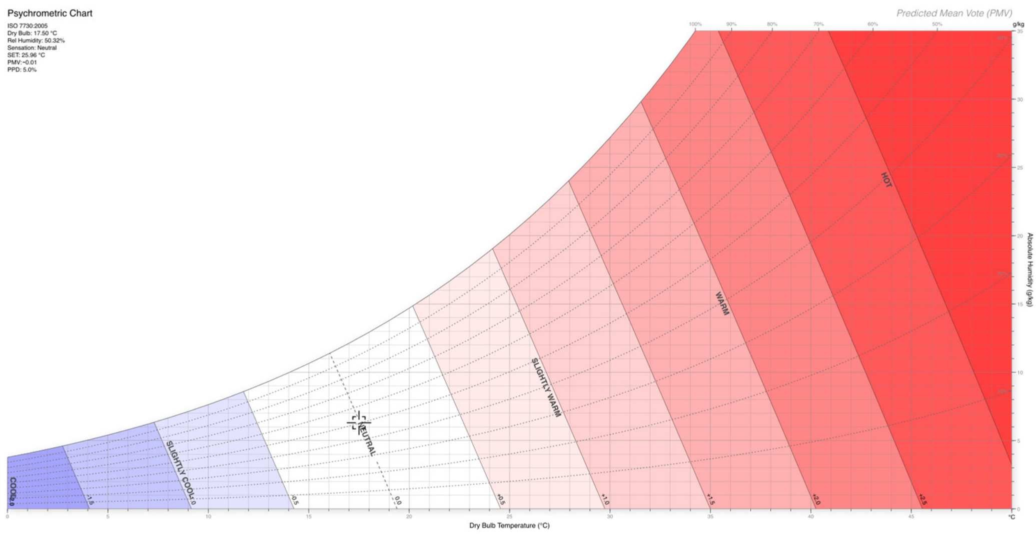

Figure 10. Psychometric chart [38].

The aim is to determine which scenario offers a more efficient and economical solution for the thermal conditioning of a house. This evaluation will provide valuable information for informed decision-making in the selection of the most appropriate heating strategy in terms of cost and energy efficiency. The characteristics of each scenario are detailed below.

4.1. Evaluation of Scenario 1

In this scenario, all the rooms in the house are heated by a fuel central heating boiler feeding water radiators distributed throughout all the rooms. The heating system is formed by a 30 kWt fuel thermal boiler operating in conjunction with a system of hot water radiators. The water circulates through the circuit with the help of a drive pump. This heating method is commonly used in residential environments and is considered a traditional technique. However, it should be noted that this scenario is characterized by a high energy cost due to its high diesel consumption and its corresponding CO_2 emissions, generating an increase in the greenhouse effect.

Regarding the greenhouse effect, residential heating based on fossil fuels, such as diesel, is one of the main sources of greenhouse gas emissions. When fossil fuels are burned to generate heat, significant amounts of carbon dioxide (CO_2) and other polluting gases are released into the atmosphere. These emissions trap heat in the atmosphere, contributing to global warming and climate change.

This task is executed out on a daily basis, with the corresponding operating time per day. To determine the energy consumption and, therefore, the associated economic cost, Equation (1) is used.

$$Consumption_{Energy} = Time_{Operating} * Power_{Boiler} \tag{1}$$

Likewise, the economic cost is calculated using Equation (2). It is important to remember that the economic cost is a crucial indicator of the feasibility of a specific project or scenario and should be considered against the benefits obtained and the energy savings.

$$Cost_{Economic} = \left(Consumption_{energy} * Price_{Diesel}\right) / Efficiency_{Boiler} \tag{2}$$

Figure 8 shows the process used to heat the home to reach the appropriate temperature and the corresponding programming of the thermostat.

4.2. Evaluation of Scenario 2

In this second scenario, 1 kW electric radiators heat some of the rooms, controlled by smart devices, such that they will come into operation when the price of electricity is lower than a certain price of fuel (setpoint value), which will be explained later. The flow diagram in Figure 9 details the process involved in this scenario. The electricity prices used in the decision logic are automatically retrieved through an API connection to the Spanish electricity market operator (OMIE), ensuring a real-time and dynamic system response.

The equations presented above will be used for the energy consumption (Equation (1)) and the economic cost (Equation (2)) of the thermal heating system. In addition, Equation (3) will be used for electricity consumption, and similarly, Equation (4) will be used for economic cost.

$$Consumption_{Electric} = Time_{Operating} * Power_{Electric} \tag{3}$$

$$Cost_{Economic} = (Consumption_{Electric} * Price_{Electric}) \tag{4}$$

Each start-up will be evaluated whenever the current temperature of the room and its corresponding setpoint temperature are modified to carry out the corresponding switches off and switches on in an intelligent way. With this approach, the aim is to integrate/replace diesel thermal heating with a more sustainable and efficient option, using electrical energy as the main heating source. This is expected to reduce energy costs and improve the efficiency of the system, providing a comfortable environment that is more sustainable and economical.

5. Results

This section presents the results obtained in each of the scenarios to compare the peculiarities. The economic assessment of the equipment's cost also includes an estimated cost of the energy associated with each scenario, which allows for the calculation of the energy savings that can be achieved with the use of the equipment. With this information, it is possible to determine the payback period for each scenario, which indicates how long it will take to recover the initial cost of the equipment through the energy savings generated.

5.1. Results of Scenario 1

The results of the energy and economic cost of this scenario are obtained by applying Equations (1) and (2), shown above.

Figure 8 presents the programming used in this case. The graphs below show the heating results for two rooms of the house: Room 1 and Room 2.

Figure 11 shows the results of scenario 1 for Room 1 of the house on 7 January. In this scenario, the focus is on performing the heating through a specific schedule controlled by the thermostatic valves installed in the water radiators. This figure shows how the electric radiator was not used, as the heating system relied solely on the fuel oil boiler (the bar is always red) since only the central system was used.

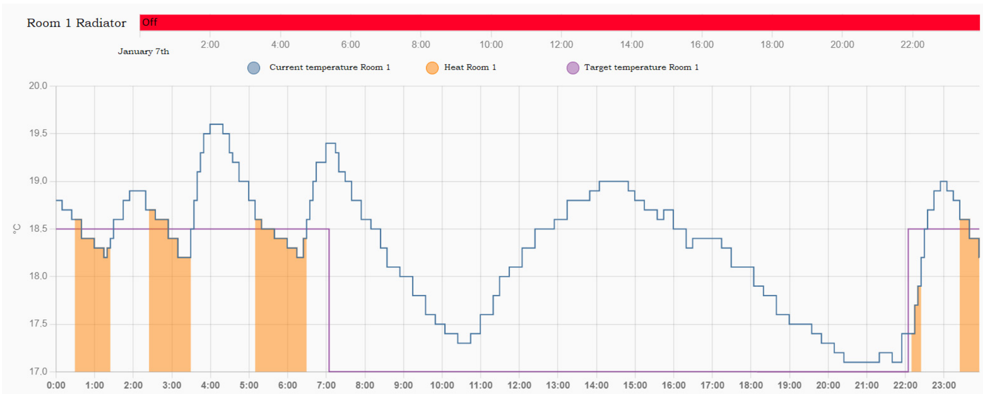

Figure 11. Heating process of Room 1 for Scenario 1. Own elaboration.

Figure 12 shows the result of Scenario 1 for Room 2 of the house on January 7th. Again, the permanent red bar shows that the electric radiator was not used, as the heating system relied solely on the fuel oil boiler.

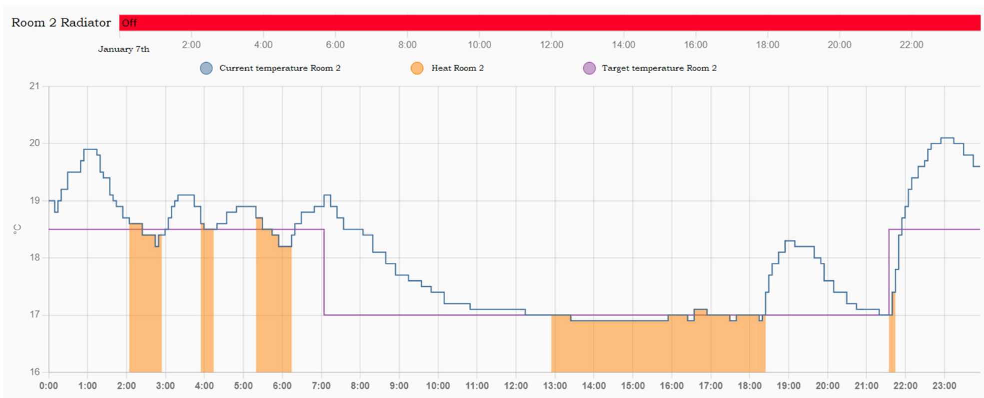

Figure 12. Heating process of Room 2 for Scenario 1. Own elaboration.

5.2. Results of Scenario 2

In this scenario, additional IoT devices are installed to control the switches on and switches off of the electric radiators. Through the programming flowchart shown in Figure 9, the electric radiator of the room is activated. This logic only works under parameters in which it is determined that it is necessary to heat the room at times when the price of electricity is cheaper than that of the fuel setpoint. This value will be explained later in Section 6, which deals with economic issues. Figures 13 and 14 show the results for both rooms. Both curves have been obtained from 8 January, midnight, to 9 January midnight (covering 24 h).

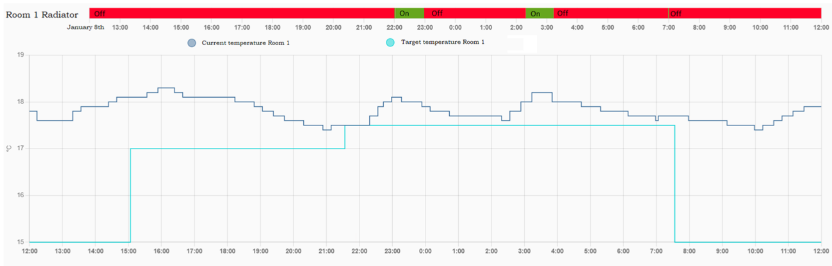

Figure 13. Heating process of Room 1 for Scenario 2. Own elaboration.

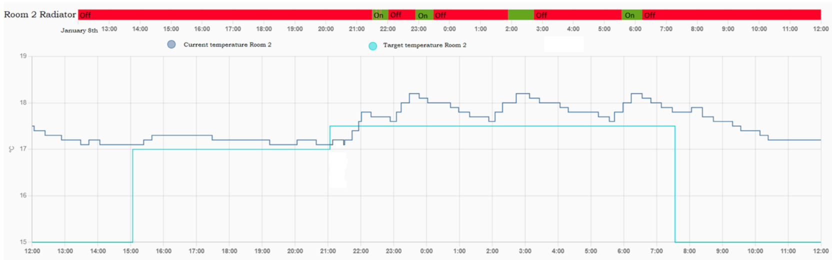

Figure 14. Heating process of Room 2 for Scenario 2. Own elaboration.

In Figure 13, it can clearly be seen when the electric heating is switched on (green zone in the upper bar). The electric radiator is switched on between 10:00 p.m. and 11:00 p.m. and between 2:15 a.m. and 3:30 a.m.

The comparison between Figures 11 and 13 shows that in Scenario 2, the room's comfort is not only maintained but even increased because the room temperature curve is flatter and does not lead to overheating and more extensive cooling. Electric heating has clearly reduced fuel consumption.

Similarly, the comparison between Figures 12 and 14 shows how, in Room 2, electric heating has also clearly reduced the use of fuel. Figure 14 shows how the electric radiator is turned on four times during the night hours when the temperature drops.

The graph clearly shows that the recorded temperature curve is almost flat due to thermal stability over the period analyzed. This is reflected in the small temperature variation along the horizontal axis of the graph, indicating that fluctuations in temperature are minimal. This stability can be attributed to consistent weather conditions, an adequate temperature control system, or a combination of both factors. In particular, the presence of a modulating thermostat plays a significant role in maintaining a flat temperature curve as it adjusts the output of the heating or cooling system continuously and gradually to achieve and maintain the desired temperature accurately, which contributes to comfort and energy efficiency in the space being analyzed.

In this research, thermostat modulation is achieved through home automation management, adding a level of control and precision to temperature regulation. Home automation enables the intelligent, automated management of heating or cooling systems based on environmental conditions and occupant preferences. In doing so, the modulating thermostat adjusts continuously and gradually to maintain the desired temperature efficiently, responding to changes in real time. Integrating home automation into thermostat control contributes significantly to keeping the temperature curve flat and improving thermal comfort and energy efficiency in the investigated space.

The results obtained show that the integration of intelligent control systems through IoT devices can significantly optimize energy performance and thermal comfort in residential environments. Compared to the conventional setup (Scenario 1), Scenario 2 demonstrated reduced fuel consumption, greater stability in indoor temperatures, and considerable daily cost savings thanks to the strategic use of electric radiators during lower-cost periods. These improvements not only have a positive impact on energy efficiency but also shorten the payback period of the initial investment. Therefore, the implementation of home automation in thermal management emerges as a viable and sustainable solution to enhance the performance of residential heating systems in Europe.

6. Economic Considerations

Although the objective of this article is to present the strategy and procedure for heating the house, it is necessary to carry out at least some basic economic considerations, which we include in this section.

6.1. Setpoint Value

To assess the cost of heating using Scenario 1 (fuel central heating boiler feeding water radiators distributed throughout all the rooms), the parameters shown in Table 3 are considered.

Table 3. Parameters to assess the cost of heating using Scenario 1.

Parameter	Value
Fuel calorific value (CV)	10 kWh/L
System performance (includes the performance of the boiler, the water impulsion pump, and the efficiency of the water radiators) (η)	80%
Price of fuel (considered constant, equal to the value of purchase, since there is a 2.000 L tank for storage) (PF)	1.13 EUR/L

To assess when Scenario 2 should come into operation, the fuel price (setpoint value) must be considered first. Above this value, the use of electric radiators will be profitable.

Based on the data shown in Table 2, to generate 1 kWh of heat in a room from a central heating system, consuming 0.125 L of fuel at the cost indicated in Table 2 will be necessary. As shown in Equation (5), this yields a cost of 0.141 EUR, which is the setpoint value. This means that when the cost of the electric kWh is below this value, it will be profitable to switch on the electric radiators.

$$1 \text{ kWh} \times \frac{1}{CV} \times \frac{1}{\text{n}} \times PF = 0.141 \text{ EUR} \tag{5}$$

6.2. Cost of Additional Equipment in Scenario 2

Scenario 2 incorporates, for each room, the cost overruns for the acquisition of an electric heater and a smart plug, which are shown in Table 4.

Table 4. Cost of additional equipment in Scenario 2.

Equipment	Cost (EUR)
Electric heater	70.00
Smart plug	13.00
Total	83.00

6.3. Savings Evaluation

A cursory calculation will be considered to evaluate the savings obtained using the heating Scenario 2 heating strategy. To do this, the cost of electricity will be calculated for each room based on the time each electric radiator is used.

Table 5 shows the evolution of the price of electricity in a 24 h interval from midnight on January 8th to midnight on the 9th. The cost shown for heating each room is obtained by multiplying the price of electricity at that specific time by the operating time (the radiator's power is 1 kW). As can be seen, the cost for the period considered is 0.1691 EUR for Room 1 and 0.1036 EUR for Room 2.

Table 5. Electric energy cost for each room in a 24 h interval. Own elaboration.

Day	Time	Electricity Price (EUR/kWh)	Energy Room 1 (kWh)	Cost Room 1 (EUR)	Energy Room 2 (kWh)	Cost Room 2 (EUR)
01/08/2023	12:00:00	0.0346	0	0	0	0
01/08/2023	13:00:00	0.0341	0	0	0	0
01/08/2023	14:00:00	0.0333	0	0	0	0
01/08/2023	15:00:00	0.0333	0	0	0	0
01/08/2023	16:00:00	0.0354	0	0	0	0
01/08/2023	17:00:00	0.0362	0	0	0	0
01/08/2023	18:00:00	0.0447	0	0	0	0
01/08/2023	19:00:00	0.0493	0	0	0	0
01/08/2023	20:00:00	0.0675	0	0	0	0
01/08/2023	21:00:00	0.0677	0.5	0.0338	0	0
01/08/2023	22:00:00	0.0464	0.25	0.0116	1	0.0464
01/08/2023	23:00:00	0.0410	0.5	0.0205	0	0
01/09/2023	0:00:00	0.0411	0	0	0	0
01/09/2023	1:00:00	0.0431	0.25	0.0108	0	0
01/09/2023	2:00:00	0.0445	0.75	0.0333	0.75	0.0333
01/09/2023	3:00:00	0.0476	0	0	0.5	0.0238
01/09/2023	4:00:00	0.0498	0	0	0	0
01/09/2023	5:00:00	0.0490	0.5	0.0245	0	0
01/09/2023	6:00:00	0.0692	0.5	0.0346	0	0
01/09/2023	7:00:00	0.1216	0	0	0	0
01/09/2023	8:00:00	0.1846	0	0	0	0
01/09/2023	9:00:00	0.1895	0	0	0	0
01/09/2023	10:00:00	0.2332	0	0	0	0
01/09/2023	11:00:00	0.2275	0	0	0	0
01/09/2023	12:00:00	0.2166	0	0	0	0
		Total	3.25	0.1691	2.25	0.1036

By applying Equation (5) in this case for the generation of 3.25 EUR/kWh and 2.25 EUR/kWh, based on the data provided by Table 2, the costs that would be obtained working with Scenario 1 (central heating system) can be obtained. This procedure yields 0.459 EUR and 0.318 EUR for each room. The savings produced are the differences between these values and those used to heat each room using electric radiators. Table 6 shows the savings for each room on a 24 h basis.

Table 6. Savings for each room on a 24 h basis. Own elaboration.

Room	Savings (EUR)
1	0.29
2	0.21

Averaging these values, a saving of 0.25 EUR can be considered for each room. For the house that we are studying, located in a relatively cold area, the operation of the electric radiators has been recorded for more than 100 days during this winter. This represents an annual saving of more than 25 EUR, which indicates an amortization of the equipment in Table 4 in a little more than three years. The amortization period will be longer in other regions with more moderate climates or with more expensive electricity prices.

The setpoint value used in the smart management system determines the switch point between fuel and electricity costs. This value ensures that the electric radiators are only activated when the cost of electricity is lower than the equivalent cost of generating heat through the central heating system. In this study, the setpoint value was calculated as 0.141 EUR/kWh for fuel, meaning that when electricity prices fall below this threshold, the electric radiators are used. This threshold allows for the dynamic optimization of heating costs based on real-time energy prices.

On the other hand, it must also be considered that the savings calculation has been very conservative. In fact, if electric radiators are deployed in the four rooms of the house, likely, the central heating system will not work for many hours. In other words, not only would individual water radiators be shut down; the number of boiler starts would also be significantly reduced. This would indicate much greater savings due to an increase in the useful life of the boiler and lower maintenance costs.

7. Discussion and Conclusions

Two different scenarios of the smart management of electric radiators as an alternative to fuel thermal heating were analyzed under real conditions. The results showed that Scenario 2, which used an electric radiator controlled by IoT devices and smart programming, offered a more efficient and economical solution for home air conditioning. The use of electric heating made it possible to reduce the number of thermal heating switches on and to take advantage of the times when the price of electricity was lower. This resulted in lower energy and economic costs compared to Scenario 1, which used traditional thermal heating.

These results highlight the potential of the IoT in energy management and HVAC optimization in homes. The ability of IoT devices to collect and analyze data in real-time, as well as to communicate with each other and with the user, enables the more accurate and efficient control of heating systems. In addition, intelligent algorithm-based scheduling can adapt to usage patterns and environmental conditions to maximize comfort and minimize energy costs [49].

The integration of IoT technology with passive thermal management in buildings offers significant opportunities to enhance energy efficiency and indoor comfort. Passive technologies such as advanced insulation, natural ventilation, and thermal mass can be combined with IoT-managed active systems, allowing for automated adjustments to heating and cooling based on environmental conditions. IoT-compatible systems can efficiently regulate indoor relative humidity through sensors that monitor and adjust humidity levels by activating dehumidifiers or humidifiers when necessary. This approach is particularly beneficial in climates with fluctuating humidity, helping to maintain a comfortable environment and prevent issues like mold, thereby improving occupant health and well-being [50].

In the context of efficient home climate control, it is crucial to consider IoT device technology instead of modulating thermostats. These IoT devices are essential to achieve more precise and adaptive temperature control in heating and cooling systems. By using advanced IoT devices, intelligent temperature management is achieved, continuously adjusting the system's power based on real-time heating or cooling needs. This technology not only significantly enhances user comfort by avoiding abrupt temperature fluctuations but also optimizes the system's performance by preventing frequent on–off cycles, leading to a notable increase in energy efficiency [51]. The adoption of IoT devices has marked a significant advancement in efficient home climate management. This technology has replaced both the expensive modulating thermostat and boiler, offering a more economical and technologically advanced approach to temperature control.

The quantitative results obtained in this study show that the use of electric radiators managed by IoT devices made it possible to reduce energy consumption of up to 15%, which translates into an annual saving of approximately 25 EUR per room. Additionally, the investment in the intelligent management system offers an updated payback period of three years, making it not only an energy-efficient solution but also economically viable and environmentally sustainable. These results highlight the importance of integrating IoT technologies to improve energy efficiency in households.

As future lines of research, the integration of AI techniques in home energy management can be explored. AI can improve the accuracy and predictive capability of heating systems, enabling even more efficient and adaptive control. For example, machine learning algorithms can analyze historical consumption data and user preferences to anticipate air conditioning needs and automatically adjust system parameters. In addition, AI can leverage external data, such as weather information, to optimize radiator operation and minimize energy consumption. The combination of IoT and AI techniques has the potential to take home energy management to a higher level of efficiency and comfort.

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