Analysis of HVAC

control systems with radiators

Introduction

Society is currently facing energy-related challenges due to the scarcity of resources and the need to limit greenhouse gas emissions to mitigate the effects of climate change. Directive 2012/27/EU [1] estimates that 40% of end energy consumption occurs in buildings, and that approximately 50% of this is attributable to cooling and heating systems. Recently, through the REPowerEU Commission [2], the European Union has admitted that there is an urgent need for a rapid transition towards another energy model for Europe that diversifies gas supply and allows the territory's dependence on fuels to be gradually phased out by 2030. One of the measures is to double the annual rate of heat pump system installation (10 million installed in the next five years) [3]. In fact, the new Energy Performance of Buildings Directive (EPBD) has just agreed that fossil fuel-based heating systems will be eliminated from the European Union by 2040 [4]. Taking into account that, in the current European housing stock, the level of insulation is low and heating systems based on high temperature radiators with boiler production are common, it is necessary to analyse the technical and economic feasibility of introducing heat pumps in a range of different scenarios (level of insulation, type of climate, etc.), in which the control system will play a fundamental role in achieving greater efficiency and guaranteeing the thermal comfort of users.

In the United Kingdom, the domestic sector is responsible for approximately a quarter of greenhouse gas emissions, with heating accounting for 11% of the country's emissions [5]. The report *Decarbonising heat in homes*, conducted by the Business, Energy and Industrial Strategy Committee of the House of Commons [6] states that there are 29 million existing homes that need to be upgraded to low-carbon heating systems by 2050. This will require a £10,000 investment per household to install low-carbon heating systems and cover energy efficiency modernisation costs. The report focuses on heat pumps as a key element in domestic heating to achieve decarbonisation and sets the goal of supplying 600,000 heat pumps per year by 2028.

On the other hand, the document *Future Homes Standard* [7] developed by BEAMA states that 70% of UK homes do not have a basic level of heating system control and considers the installation and correct use of heating controls essential to increase the energy efficiency of heating systems. To this end, the ECO 4 programme [8] establishes a series of measures (improved insulation, heating systems and control systems), up to 2026 when more than 450,000 homes will be upgraded, with incentives to promote the implementation of these measures.

The aim of this document is to analyse the influence of smart control systems in hydronic heating applications and their contribution to the energy efficiency of a building. To this end, it presents a modelling of the multi-zone control strategies proposed by the company Airzone for hydronic systems using the TRNSYS18 software [9]. The objective is to evaluate the potential of installing an independent temperature control system in each zone of a residential building in a heat pump application with high temperature radiators. The results will be compared with different cases, the most common conventional case being that of a gas boiler and high temperature radiators. The study analyses the influence of the type of thermal envelope of the building, different control scenarios and the climatic zone. The results compare the energy savings, thermal comfort and economic viability results.

Description of HVAC and control scenarios

The study proposes the comparison of an HVAC system based on high temperature radiators as the head unit, comparing two different production systems: boiler and heat pump. It also presents different control strategies.

1| Conventional system: gas boiler and high temperature radiators (CALD)

This is the most common system used in older homes. Hot water is produced at a constant temperature and there is no radiator control. Conventional gas boilers supply hot water to the radiators located in each zone of the home, with a fixed production at 70°C. The system is considered to be balanced upon start-up with manual valves, but there is no type of control of the valve regulating the inlet of the water flow to the radiators (Figure 1).

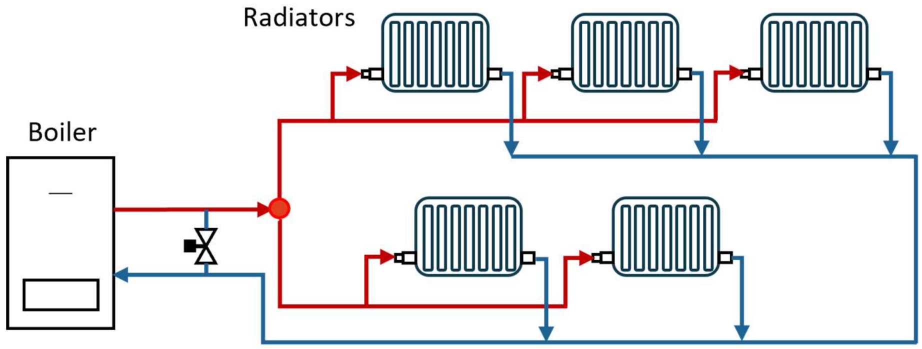

Figure 1. Conventional system: gas boiler and high temperature radiators without control.

2| Upgraded system, but without control: high temperature heat pump (BDC)

The HVAC system upgrade measure that users are encouraged to implement is that of replacing their boiler with a heat pump, leaving the radiators as head units. In this case, high temperature heat pumps are used, in which the hot water production temperature of the heat pump is regulated to maintain a set-point of 70°C, based on the heating curve incorporated by the system, which modifies the set-point according to the outdoor temperature and the indoor temperature, as shown in Figure 2.

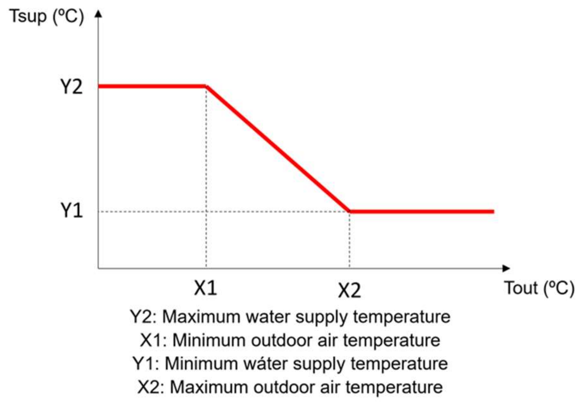

Figure 2. Heat pump behaviour curve. Determination of the supply temperature based on the outdoor temperature.

The outdoor temperature range depends on the climatic zone in which the system is installed, while the supply temperature range is conditioned so as not to generate thermal discomfort due to draughts or low efficiency of the distribution networks. For example, in this case, a minimum and maximum outdoor temperature of between 0 and 15°C has been established in the 3 cities analysed, and a minimum and maximum supply temperature of between 60 and 80°C, making the average supply temperature around 70°C.

The control system of the head units is referred to as a non-zoned system, since it offers ON/OFF control of the water circulation pump based on the temperature measured by the thermostat located in a zone of the home (Figure 3).

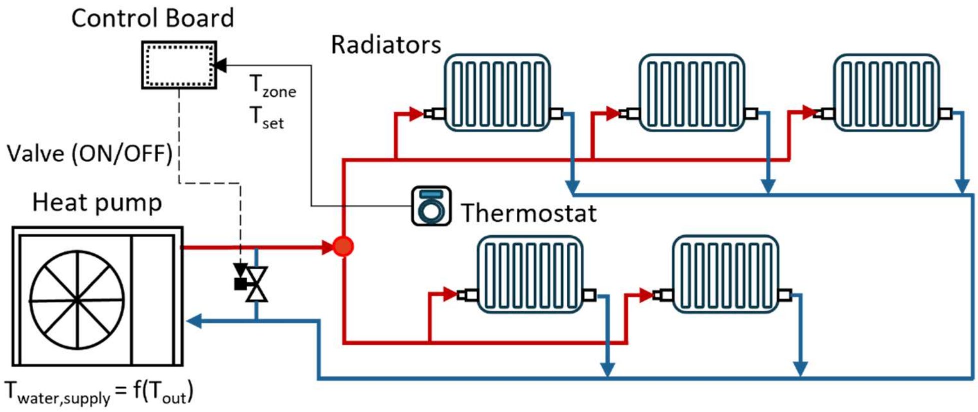

Figure 3. Upgraded system: heat pump and high temperature radiators with non-zoned control

Figure 4 shows how the pump is activated whenever the temperature difference between the temperature measured by the radiator head probe (T_z) and the established set-point temperature (T_{set}) is 0.5°C.

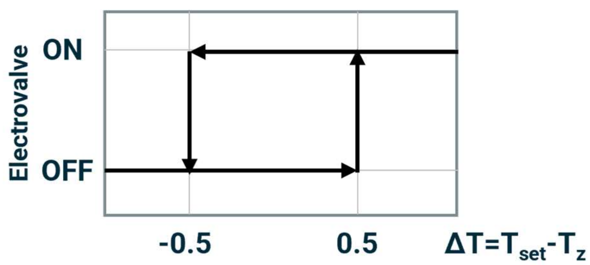

Figure 4. On/off control of the valve based on the temperature difference between the set-point and the master zone temperature.

3| Upgraded system with Airzone zoned control: high temperature heat pump and radiators (AIRZ)

It is becoming increasingly important and necessary to incorporate HVAC control systems as a differential element for improving efficiency in buildings. The ISO 52120 standard [10] regulates the use of HVAC control systems in buildings and, in particular, establishes mandatory thermal zoning, i.e., the individual control of temperatures in each zone of the building, as a fundamental action to ensure thermal comfort and efficiency in the system.

In this case, the heat pump production temperature is set as described in the previous case (Figure 2), taking outdoor conditions into account.

For the control of the head units, each of the valves located at the inlet of each radiator to open or close the water flow is controlled according to the temperature difference between the set-point temperature of the zone and the temperature measured by the thermostat installed in the zone, which reports the thermal status of the zone to the main control board. Installing a thermostat prevents the problem of the temperature probe located in the radiator head, the zone air temperature reading of which is influenced by the proximity to the radiator, causing the system to malfunction. Therefore, the temperature in each zone is controlled independently in order to ensure individual comfort and to adapt the consumption of the heat pump to the thermal needs of each zone (Figure 5).

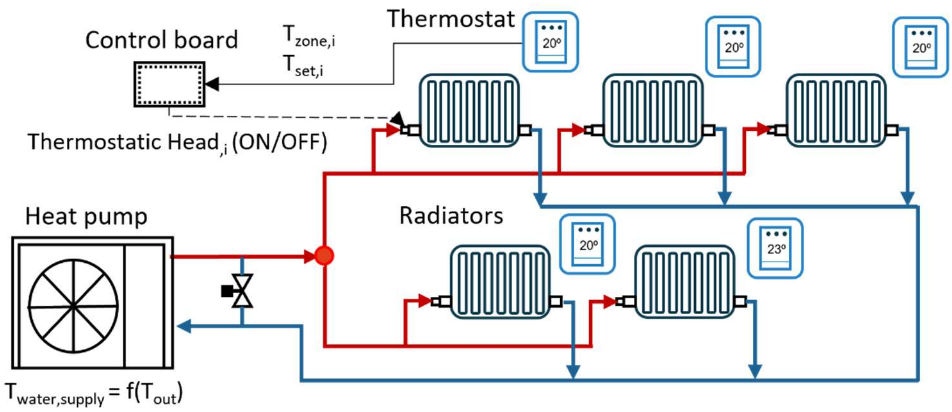

Figure 5. Upgraded system: heat pump and high temperature radiators with zoned control

The installation of the control elements is described in more detail below. Figure 6 shows a diagram of the system's different control elements.

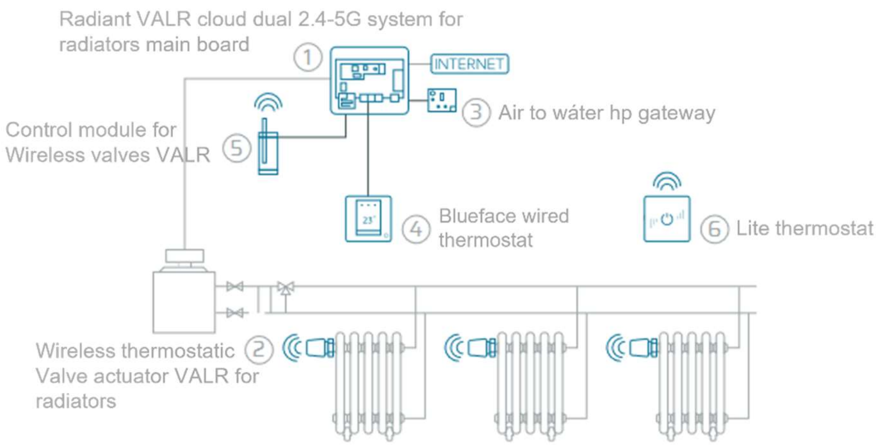

Figure 6. Diagram of a zoned control system with radiators and heat pump.

The Flexa 4.0 system performs zoned control for radiators. Airzone wireless thermostatic heads control the amount of heat emitted by the radiator in each of the zones of the home, guaranteeing the regulation of the comfort temperature set by the user. The Webserver allows the user to interact with the HVAC system to set their comfort requirements through the system application.

Implementation of models in TRNSYS

This study has been modelled using the TRNSYS18 software, a benchmark programme for research into thermo-energy systems. Mathematical models of all HVAC systems defined in the previous section have been run using this calculation platform. The control system described in section 2 has been modelled using mathematical equations in a bespoke model that enables interaction with the building and the rest of the elements of the simulation environment (Figure 7).

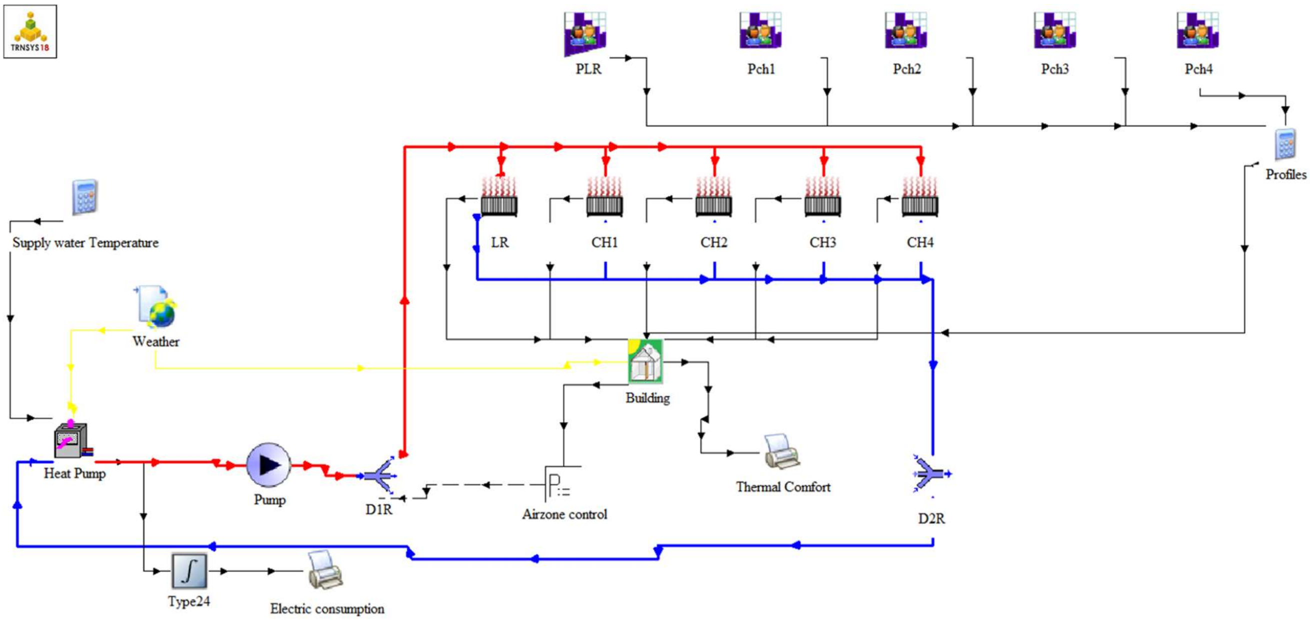

Figure 7. Simplified setting up of the control system in TRNSYS.

It is worth noting that the heat pump model developed is based on the typical operating curves obtained from manufacturers' catalogues. This model also makes it possible to incorporate the modification of the machine's efficiency (COP) due to the load fraction.

Results. Case study

The results of the study analyse the suitability of Airzone's hydronic control system from the perspective of thermal comfort and energy consumption. An economic study has also been conducted to evaluate the technical and economic feasibility.

Case study

The study is based on a single-family home with a total surface area of 120 m^2 with 5 air-conditioned zones: Living Room-Kitchen (LR), Bedroom 1 (CH1) on the ground floor, and Bedroom 2 (CH2), Bedroom 3 (CH3) and Bedroom 4 (CH4) on the top floor (Figure 8).

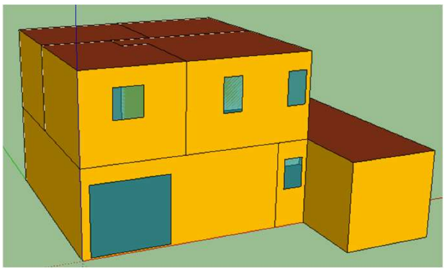

Figure 8. Floor plan of the home. 3D representation.

The home has been simulated for 3 typical UK cities: London, Birmingham and Glasgow in order of weather severity in winter. The minimum and maximum temperatures in the winter months for each of these cities are represented in Table 1 [11].

		JAN	FEB	MAR	APR	OCT	NOV	DEC
Minimum temperature (°C)	London	4	4	5	7	10	7	5
	Birmingham	1	1	2	4	7	4	2
	Glasgow	1	1	2	4	6	3	1
Maximum temperature (°C)	London	8	9	11	14	15	11	9
	Birmingham	7	7	9	12	13	9	7
	Glasgow	6	7	9	12	12	9	7

Table 1. Average monthly maximum and minimum temperatures in the months when heating is required.

Three levels of insulation have been considered for the home representing different thermal load scenarios: a high level of insulation typical of new buildings as defined by current regulations (AIS3), a building with a medium level of insulation (AIS2) and a building with a low level of insulation, typical of older homes (AIS1). The properties of the building envelopes are defined according to the overall heat transfer coefficient of each building element (U), as described in Table 2.

Area	AIS1	AIS2	AIS3
Outside wall	1.14	0.56	0.18
Inside wall	0.88	0.60	0.215
Ceiling	0.88	0.60	1
Floor	0.40	0.24	0.26
Roof	1.10	0.60	0.22
Window	5.68	2.90	1.3

Table 2. Thermal characteristics of the housing enclosures (U in W/m^2K).

Given that in a zoned system the thermal load of the unoccupied zones is not combated, it is important to determine the use profile of each room. (Figure 9).

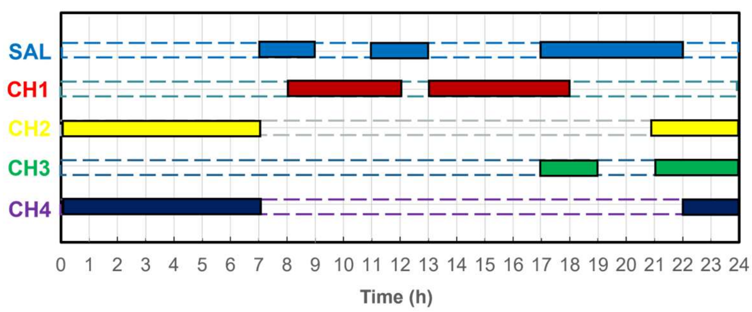

Figure 9. Home occupancy profile.

It is understood that, during unoccupied hours, the radiators continue to operate, but with lower set-point temperatures to avoid excessive heating load. The set-point of the heating zones is 20°C and 18°C during periods in which the zones are not occupied. The size of the units is based on the thermal loads of the zones to ensure that the system can ensure comfort conditions during the months in which heating is required.

The selected production units are a conventional gas boiler and the Altherma HT (High Temperature) model line by the manufacturer Daikin [12], which are suitable for use with high temperature radiators.

Results.

The results obtained from the simulations will compare the 3 HVAC and control scenarios described in section 2 (CALD, BDC and AIRZ), making a comparison as described below:

1. CALD-AIRZ. During home renovations, the boiler is replaced with a high temperature heat pump and the Airzone control system is installed. This case has been analysed for the 3 cities, although the boiler is only considered in homes with a low (AIS1) and medium (AIS2) level of insulation, since new boilers are not installed in new homes, given their insulation level (AIS3).

2. BDC-AIRZ. The installation of a heat pump with an Airzone control system has been compared to the case of a non-zoned heat pump. This case has been evaluated for the 3 study cities and the 3 levels of home insulation.

Thermal comfort

The comfort results do not focus exclusively on the zone temperature comparison, rather comfort has been evaluated according to the UNE ENE ISO 7730: 2006 standard [13].

Comfort parameters: PMV and PPD

In standard conditions of comfort associated with levels of clothing, metabolic rate and relative air speed, a comparison was made of the PPD and PMV parameters in a zoned and non-zoned system.

PMV (predicted mean vote) is an index that reflects the mean value of the votes cast by a large group of people with respect to a 7-level thermal sensation scale when subjected to different thermal environments, based on the thermal balance of the human body (Figure 10).

-3 **Cold**	-2 **Cool**	-1 **Slightly cool**	0 **Neutral**	+1 **Slightly Warm**	+2 **Warm**	+3 **Hot**

Figure 10. PMV scale

By calculating PMV it is possible to estimate the thermal sensation of the human body as a whole by estimating or measuring the parameters that condition the overall thermal balance of the body: metabolic rate of the subject, clothing insulation, air temperature, mean radiant temperature, relative air speed and air humidity.

The PPD (predicted percentage dissatisfied) index provides information about thermal discomfort or dissatisfaction by quantitatively predicting the percentage of people who are likely to feel too hot or too cold in a given environment. PPD can be obtained from PMV.

According to the UNE ENE ISO 7730: 2006 standard, the recommended values for providing overall thermal comfort to 90% of users are those shown in Table 3.

CATEGORY	PPD (%)	PMV
A	< 6	-0.2 < PMV < 0.2
B	< 10	-0.5 < PMV < 0.5
S	< 15	-0.7 < PMV < 0.7

Table 3. Thermal environment categories according to PPD and PMV.

Comfort requirements in buildings are currently high and attempts are being made to achieve category B, especially in efficient and sustainable buildings that obtain BREEAM or LEED certifications [14]. Figure 11 shows a comparison of the percentage of hours in which the comfort conditions are met, both in the master zone where the thermostat is installed (Living Room), and in the rest of the thermal zones of the home (Zones). It compares the results of the 3 case studies: boiler (CAL), non-zoned heat pump (BDC) and heat pump with Airzone control system (AIRZ), for the 3 study cities and, in each case, the 3 proposed insulation levels (AIS1, AIS2, AIS3) are included.

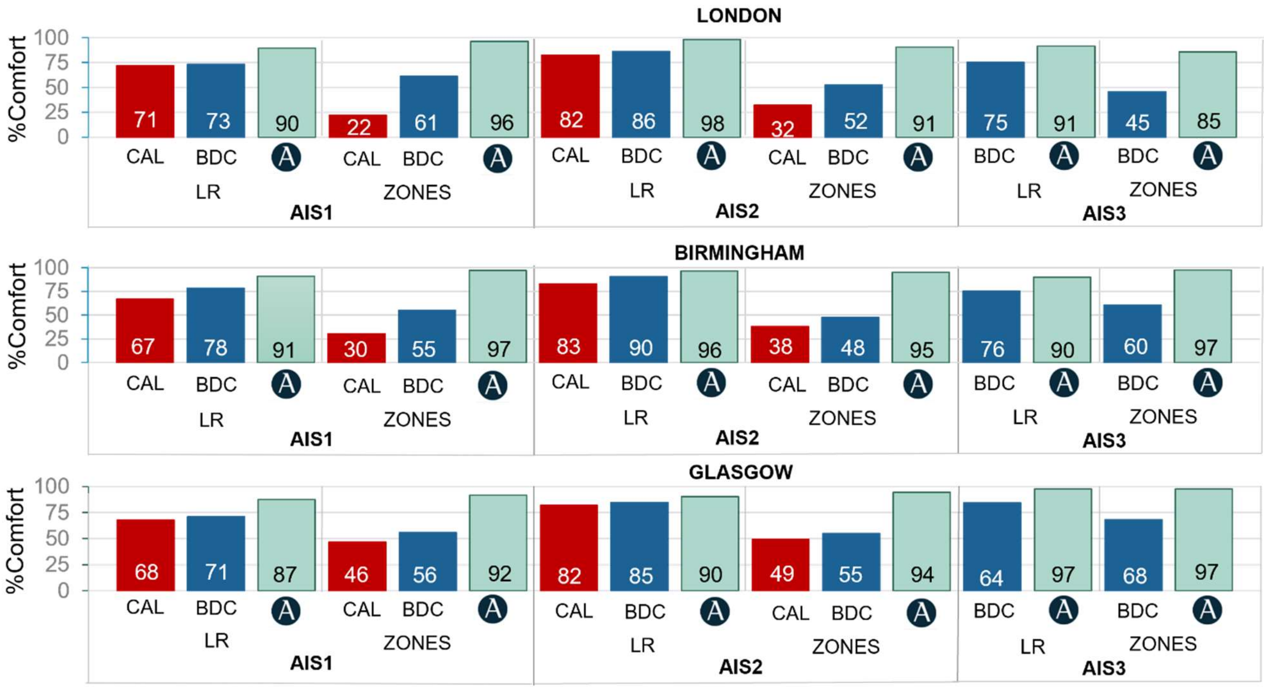

Figure 11. Comparison between systems to compare comfort categories.

In general, it can be observed that, in all cases, the comfort percentages obtained in the Living Room are more favourable than in the rest of the zones of the home. Furthermore, in the cases with a heat pump (BDC and AIRZ) with control, higher percentages were obtained than in the case of the boiler (CAL). As an example, it can be observed that the boiler obtained comfort percentages of around 64-83% in the living room, while these percentages were higher in the cases of heat pump control, with an average of between 71-98%.

In relation to comfort control in the rest of the zones of the home, it is worth noting that Airzone zoned control (AIRZ) obtained significantly more favourable results in the rest of the zones with respect to the non-zoned case (BDC) and boiler (CAL). This is due to the regulation of the valves of each radiator according to the individual regulation of the temperatures in each zone of the home, which ensures thermal comfort. Comfort percentages with zoned control ranged from 85-97% for the rest of the zones, while the average percentage varied from 45-68% in the non-zoned case and, in the case of the boiler, decreased to 22-49% due to the lack of control. In the BDC and CAL cases, without control of the rest of the zones, the results show PMV values of above 1.5-2. This implies unnecessary overheating in the home, which will lead to greater energy consumption as analysed in the following section.

Energy consumption and environmental study

Electric energy consumption of the heat pump

After evaluating the building's thermal comfort, the next step is to compare the energy consumption and the environmental study. The objective is to demonstrate that the control strategy of the zoned system is more efficient from an energy consumption point of view due to the ability to effectively meet the thermal needs of each of the zones, resulting in the better performance of the production system.

A comparison will first be made of the BDC-AIRZ case, analysing the electric energy consumption of the heat pump in the 3 cities and for the 3 levels of home insulation (Figure 12). The objective is to evaluate the influence of the zoned control system in terms of energy savings (indicated as a percentage in the figure).

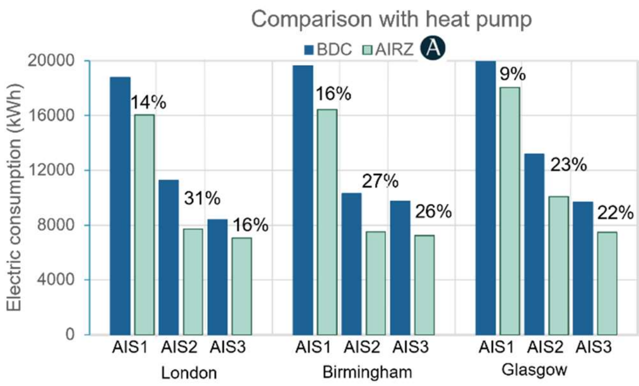

Figure 12. Electric consumption comparison in heat pump cases.

In all the cases compared, it can be observed that the electric energy consumption of an application with a heat pump and the Airzone zoned control system represents an energy saving with respect to the non-zoned case, in which the system is controlled according to the temperature measured in the room. Savings range from 9 to 31%, depending on the type of climate and the level of home insulation. In all cases, it can be observed that in homes with a higher level of insulation, energy consumption is lower. It can also be seen that the coldest city, Glasgow, has the highest energy consumption.

CO_2 emissions

In order to make a comparison with boiler scenario, it was decided to carry out a comparative analysis of the CO_2 emissions of the 3 case studies, since the boiler has a final energy consumption of natural gas and is not directly comparable with the electric consumption of the heat pump. For the calculation of CO_2 emissions, the coefficients for the conversion of final energy to CO_2 emissions given by the Department for Energy Security and Net Zero in the Government conversion factors for company reporting of greenhouse gas emissions collection [15] have been taken into account. These coefficients are 0.20707 $kgCO_2/kWh_e$ for the heat pump and 0.18293 $kgCO_2/kWh_e$ for the gas boiler.

Figure 13 shows the environmental study with the comparison of the CO_2 emissions of the 3 proposed HVAC applications (CALD, BDC and AIRZ), in the 3 cities and with the 3 levels of home insulation. The percentage of savings in CO_2 emissions of the heat pump system are also indicated, firstly in the case of non-zoned control with respect to the boiler and, secondly, the percentage of savings with the heat pump and the Airzone control system (AIRZ). Furthermore, it can be observed that the percentage of savings obtained with a zoned control system increases in all cases, achieving significant savings in CO_2 emissions from 16 to 47% compared to the case of the boiler for AIS1 and AIS2 insulation levels, respectively.

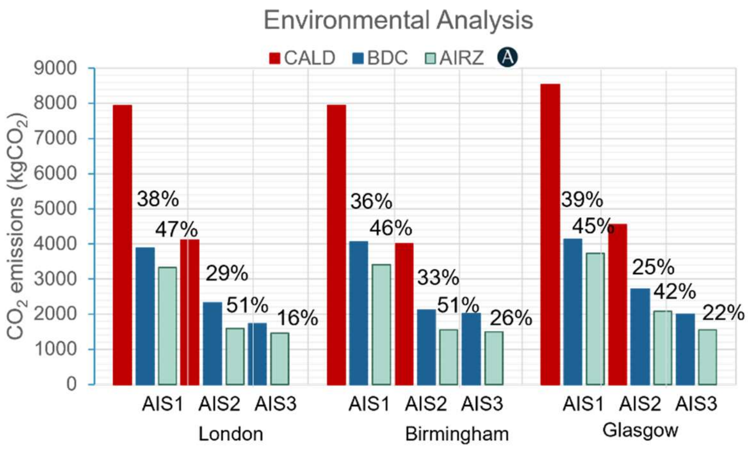

Figure 13. Environmental study. Comparison of CO_2 emissions.

Economic study. Amortisation of the Airzone control system.

The economic analysis is based on the comparison of the initial investment in production units and the control system and the operating costs of the consumption of the HVAC system obtained in the simulation. The time required for the amortisation of the Airzone control system has been calculated based on this information. The analysis has been carried out for the following cases: CALD-AIRZ (the replacement of the boiler with the Airzone zoned control heat pump) and BDC-AIRZ (comparison of the heat pump with a non-zoned control system versus Airzone zoned control). Table 4 shows the costs of units obtained from the manufacturers' catalogues, both for the conventional system and for the Airzone zoned system. The Airzone VALR pack includes the Flexa 4.0 main control board, the Webserver HUB Airzone Cloud Dual 2.4-5GHz/Ethernet and the wireless VALR valve control module.

Costs (£)	Conventional	Airzone
High temperature heat pump [12]	11,000	11,000
Airzone control	-	1,448
VALR pack for radiators with 5 thermostatic heads	-	889
Blueface Zero wired thermostat	-	249
4 Lite simplified wired thermostats	-	684
Total	11,000	12,822

Table 4. Initial costs of the systems.

Table 4 shows that the initial cost of the Airzone zoned system is higher than that of the conventional system due to the cost of the control system elements. However, as shown in Table 5, the return-on-investment period for the different case studies is between 1.9 and 5.4 years, which are very reasonable and economically viable periods, in addition to the improvement in thermal comfort analysed above, which cannot be quantified in economic terms. The operating costs have been calculated for the heat pump comparison cases (BDC-AIRZ) based on the annual electricity consumption of the heat pump obtained in Figure 12 and the cost per kWh of electricity for the heat pump, which has been estimated at £0.245/kWh on average over the last few months due to the large fluctuations of this value [16]. On the other hand, for the boiler comparison case (CALD-AIRZ), a value of £0.06/kWh has been used as a representative value of the cost of natural gas in the United Kingdom [16].

Insulation	AIS1		AIS2		AIS3
City/Case	CALD-AIRZ	BDC-AIRZ	CALD-AIRZ	BDC-AIRZ	BDC-AIRZ
London	2.6	2.5	4.3	1.9	5.1
Birmingham	2.7	2.1	4.4	2.4	2.6
Glasgow	2.6	3.5	5.4	2.2	3.0

Table 5. Years of amortisation according to the case studies.

As can be observed, the more extreme the climatic severity, the greater the savings, with shorter return times. It is worth noting that in 75% of the cases studied the amortisation period is less than 3 years. It is also important to highlight that, although it does have a certain influence, the type of home is not decisive, and that the investment is profitable for homes with different levels of insulation.

Conclusions

This study analyses the performance of the Airzone zoned radiator control system with heat pump in detail, showing that it is the most suitable alternative when updating the HVAC system in a residential home. This solution has been compared to two different systems: a natural gas boiler in an application without radiator control, and a heat pump with a non-zoned system, controlled by monitoring the temperature in one room of the home.

The conclusions of the study describe the main advantages obtained in the different comparisons made in terms of thermal comfort, electric energy consumption, CO_2 emissions, and also include an economic analysis to evaluate the amortisation period of the control system. The conclusions are defined below:

1. The zoned control system independently controls the temperature in each of the zones of a home, ensuring an average percentage of comfort hours of between 88-97% with thermal comfort values that are extremely favourable to the building's users. This system has been compared to a conventional system in which there is a single thermostat in a master zone to regulate the operation of the system, causing overheating in the rest of the zones, with percentages that decrease to 45-68% in the case of the heat pump and 22-49% in the case of the boiler.

2. The influence of the zoned control system on the heat pump in terms of electric energy consumption has also been evaluated. Savings range from 9 to 31%, depending on the type of climate and the level of home insulation.

3. In relation to the environmental study, the percentage of savings obtained with a zoned control system in terms of CO_2 emissions is greater, and this is accentuated for higher insulation levels, as well as for colder climates.

4. Although an initial investment in the control system is necessary, the economic study shows that the amortisation times are between 1.9 and 5.4 years, which are very reasonable and economically viable periods. The more extreme the climatic severity, the greater the savings, with shorter return times. It is worth noting that in 75% of the cases studied the amortisation period is less than 3 years.

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