

Article

Empowering Energy Transition: IoT-Driven Heat Pump Management for Optimal Thermal Comfort

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Abstract: This paper analyzes the process of energy transition from traditional solid fuel heating to an air-to-air (A2A) heat pump-based heating system. Special emphasis was placed on the implementation of new technologies for improved management of energy systems, aiming to elevate both comfort levels and energy efficiency. This paper explores the use of the open-source software Home Assistant as an integration platform for home automation, designed to manage smart home devices while preserving local control, user privacy, and increasing cybersecurity. The proposed hardware platform includes a Raspberry Pi with appropriate IoT modules, providing a flexible and economically viable solution for household needs.

Keywords: energy transition; Internet of Things; thermal comfort; heat pump; smart home; Home Assistant; Raspberry Pi

1. Introduction

The energy transition is one of the major challenges facing modern society. This transition entails a shift from traditional energy sources, such as fossil fuels, to renewable and cleaner sources that reduce negative environmental impacts. The goal is to reduce greenhouse gas emissions, increase energy efficiency, and achieve sustainability. In this context, the Republic of Croatia, as a member of the European Union, sets high goals for the development of green and digital energy policy by 2030 [1].

One of the key elements of Croatia's energy strategy is aimed at decarbonizing the construction sector and encouraging green investments. According to data, heating accounts for 40% of total energy consumption in Europe [2], indicating an urgent need to optimize heating systems. Studies indicate that a considerable portion of energy usage results from the unnecessary overheating of indoor spaces, where the air temperature exceeds the intended design range of 22 to 24 °C. Addressing this overheating issue has the potential to reduce energy consumption by as much as 15% [3].

Accordingly, heat pumps with the application of new technologies of the fourth industrial revolution (Industry 4.0, 4IR) [4] are becoming important elements of the energy transition, providing efficient heating solutions and maintaining comfort.

In the construction of new residential buildings in Croatia, the combination of a low-temperature heating system with underfloor heating is most often promoted as an optimal solution. Such systems often imply a complex technical design that includes a number of components such as piping, pumps, hydraulic manifolds, storage tanks, and heat exchangers, which ultimately increases the initial investment, but also the operating costs. On the other hand, systems that use heat transfer directly through the air [5–7] are



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often unjustifiably underestimated and perceived as a simple and inferior solution that cannot meet modern heating requirements. Nevertheless, it is precisely such systems that prove to be very suitable for the renovation of existing buildings.

In the case of already built residential buildings, the question arises of whether it is possible to achieve an energy transition from conventional heating to more energy-efficient alternatives with relatively small financial resources, without the need for large financial investments in complex systems. That is why it is crucial to explore whether existing facilities can be included in the energy transition using simpler and cheaper solutions while achieving a significant reduction in energy consumption and emissions. In order to get a reliable answer to this question, it is necessary to conduct a detailed energy analysis of the building, taking into account its construction characteristics, heating system, and actual conditions of use. By comparing theoretical calculations with real data collected at the facility, the justification for investing in simpler energy upgrades using new technologies can be assessed. However, the introduction of new technologies alone is not enough; effective management is also necessary, a factor that was not found in the literature overview. Internet of Things (IoT) technology is playing an increasingly important role, enabling devices to connect to each other and exchange data over the Internet. This connectivity enables monitoring, forecasting, and optimization of energy consumption, thereby increasing efficiency and reducing overall costs.

There has been a notable increase in recent research addressing the integration of information and communication technology (ICT) in the construction field. In paper [8], the authors analyze the energy consumption of the A2A heat pump, with special emphasis on the application of the Internet of Things (IoT) for the purpose of optimizing energy processes. Paper [9] analyses energy efficiency and thermal comfort after retrofit in different climate zones of the United Kingdom, with an emphasis on real-time data collection and analysis using IoT technology, enabling system validation under on-site conditions. Furthermore, papers [10–15] deal in detail with various aspects of the implementation of IoT technologies in building systems, including energy management, facility automation, the smart device market, and the integration of sensory and sensor networks into smart buildings.

One of the main challenges is the fragmented smart device market, where manufacturers often offer closed systems. This opens the door to independent free, open-source solutions such as openHAB [16] and Home Assistant [17] that can integrate different smart devices from different ecosystems and can significantly contribute to reducing energy consumption by optimizing the operation of devices in real time and adapting consumption and comfort to the needs of the user.

The assessment of the energy efficiency of the building was carried out using an analytical model of heat load in accordance with the HRN EN 12831-1:2017 standard [18], which defines methods for calculating the required thermal energy taking into account local climatic conditions, construction characteristics, and user requirements for thermal comfort. The model includes an analysis of heat losses through the building envelope and ventilation, using static data such as object geometry and thermal properties of materials, along with dynamic influences such as outdoor temperatures and indoor conditions. Since Croatia, according to the mentioned standard, is divided into two climatic zones—northern and southern—, this paper brings a new scientific contribution by applying the model in the area of southern Croatia, which has not been covered in detail so far. The aim of this research is to examine whether a heat pump, in combination with IoT technologies for monitoring and control, can meet the heating needs during the winter period in this specific climate zone.

2. Objectives

The aim of this paper is to examine the justification of the energy transition from conventional heating to a more sustainable solution using an air–air (A2A) heat pump in the heating system in southern Croatia by applying Internet of Things (IoT) technology to an existing facility. This paper’s goal is to examine the efficiency of the transition with the help of a central system for the control of smart home devices aiming to achieve the desired thermal comfort within the defined limits of temperature and relative humidity, reduce the concentration of harmful particles (PM2.5) in the air and, with careful selection of the process management strategy, reduce the overall environmental footprint of the building. This study used Home Assistant (HA) version 2024, a free and open-source home automation software designed to be an integration platform independent of the Internet of Things (IoT) ecosystem and a smart home hub for controlling smart home devices, with a focus on local control, privacy, and cybersecurity. The hardware platforms are Raspberry Pi (RPi) [19] and associated IoT-based modules. The task of the server (HA) is to collect data through various sensors and manage the operation of the heat pump in order to reduce energy consumption.

3. Background

For a house built in Zadar, in the Republic of Croatia, an energy transition of the heating system from the basic heating method (wood heating from a fireplace-stove) to heating with a heat pump was conducted, resulting in an environmentally acceptable heating method and, at the same time, financially affordable, while the quality of living was not impaired.

The house in which the transition was carried out is divided into two zones (Figure 1). The first zone consists of the living room and kitchen, while the second zone contains the bedrooms, toilet, and bathroom. Previously, the site had a wood-burning stove with a nominal power of 8 kW, located in the central part of the house, which enabled relatively good heat distribution in the first zone, while the temperatures in the second zone were maintained in acceptable comfort settings by heating the rooms through electric convectors.

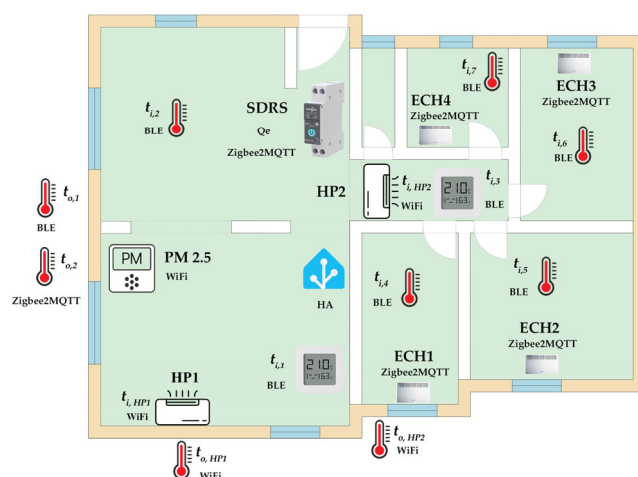


Figure 1. IoT placement on the floor plan of the house.

The existing system was replaced with two A2A heat pumps, each covering half of the house. Electric convectors were retained, to which smart sockets were added (Zigbee2Mqttt).

4. IoT

The Internet of Things (IoT) is a new paradigm that has changed the traditional way of life to a high-tech lifestyle. Smart cities, smart homes, pollution control, energy saving, smart transportation, and smart industries are transformations made by the IoT [20].

The term smart home implies a set of integrated network devices that automate various functions within the home. These internet-connected devices can be managed and automated from different locations. The central place where all smart home devices connect is the server. The server can be accessed through various hardware clients such as a cell phone, tablet, laptop, or computer.

Home automation became widely available to people when the industry made it possible to apply sensors and actuators at home. The first devices of this type appeared in 1975 under the name X10 through Pico Electronics and were commercially available in 1978. Initially, with limited computer availability, the systems used a non-centralized architecture based on a sensor–controller–actuator configuration that provided limited capabilities. Today's technology allows us to use a centralized client–server architecture through wireless communication [21].

Such an architecture allows other devices to be managed through a central system. The core of such a system is a server with the associated operating system and services, which serves as a central control unit. The services on the server can be accessed via the client applications of a smartphone, tablet, or computer. Smart devices connect wired or wirelessly to the server via communication protocols such as Wi-Fi, Bluetooth, BLE, ZigBee, Ethernet, Thread, and Matter.

The Internet of Things (IoT) plays a significant role in optimizing the operation of heat pumps, providing numerous benefits in terms of efficiency, energy savings, and user comfort. Additionally, all are based on real-time data monitoring and analysis.

Some of the key benefits of this approach are:

- Smart management: the IoT enables the creation of smart homes and buildings in which heating and cooling systems automatically adapt to external conditions and user habits.
- Optimization of operation: Sensors installed in different parts of the building can collect data on temperature, humidity, and air quality. Based on these data, machine learning algorithms can optimize the operation of the heat pump and other systems to ensure maximum comfort with minimal energy consumption.
- Demand forecasting: IoT systems can predict future heating or cooling needs based on historical data and weather forecasts. This makes it possible to proactively manage the system and avoid unnecessary costs.
- Integration with other systems: Heat pumps can be integrated with other systems in the home, such as solar panels and batteries. In this way, an energy self-sufficient system that will further reduce dependence on the public grid can be created.
- Remote monitoring and management: users can monitor energy consumption and manage their heating system via a mobile app, even when they are not at home.

Some of the key challenges of this approach are:

- Cost: Investing in IoT systems and heat pumps can be significant, but it pays off in the long run due to savings on energy bills.
- Security: As more devices connect to the internet, the risk of a cyberattack increases. Therefore, it is important to ensure that IoT systems are well protected.
- Standardization and fragmentation: There are still no universal standards for IoT devices and communication protocols, which makes it difficult for different systems to

interconnect and causes market fragmentation through the closure of devices from individual manufacturers into their own ecosystems.

5. Smart Home Topology

The smart home system consists of smart devices, such as temperature, pressure, relative humidity, air quality, and smart sockets, that are connected to the Gateway via WiFi, Zigbee, and Bluetooth protocols. The usual commercial way of connecting to the IoT is based on the gateway, device, router, and cloud systems (Figure 2). In this architecture, the cloud is the storage space on the Internet. The gateway connects IoT devices through its own network (Zigbee, Bluetooth, or WiFi). Management and monitoring of the device takes place through the application and can be performed via mobile phone, tablet, or computer. Communication between the gateway and the cloud is facilitated through a WiFi network, where the cloud is a server on the Internet. Such solutions are suitable for quickly creating your own smart home heating system. However, they entail some disadvantages, including:

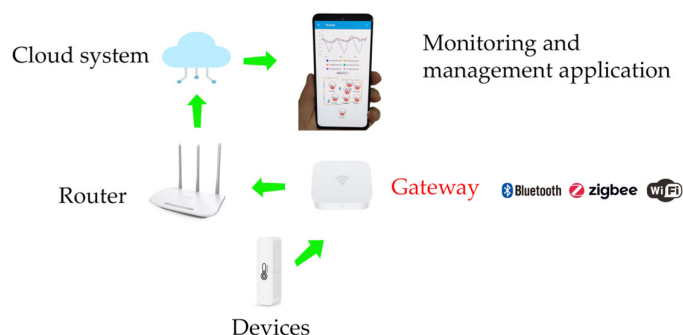


Figure 2. Configuration of IoT smart homes.

- Certain devices require their own gateways and their own monitoring applications that make up their own ecosystem. This results in an increase in the number of gateways and management applications, which can heighten the risk of network interference, complicate management efforts, and ultimately lead to system dysfunction.
- High dependence on a stable Internet connection, potential security risks when transmitting data over the Internet, and the possibility of interception of communications by unauthorized persons. In addition, centralized data processing in the cloud can lead to data availability issues in the event of sudden server or network outages.
- Data privacy issues, where all collected data are stored on remote servers, increasing the risk of unauthorized access. Also, there is a possibility that the data may be used for marketing purposes without the user's knowledge.

To avoid these shortcomings, an internal server solution can be employed as an integration platform independent of the ecosystem (Figure 3). The system consists of a Home Assistant server built on Raspberry Pi hardware (RPi 5). Home Assistant is a complete solution consisting of a Linux server and services for monitoring, management, and data storage.

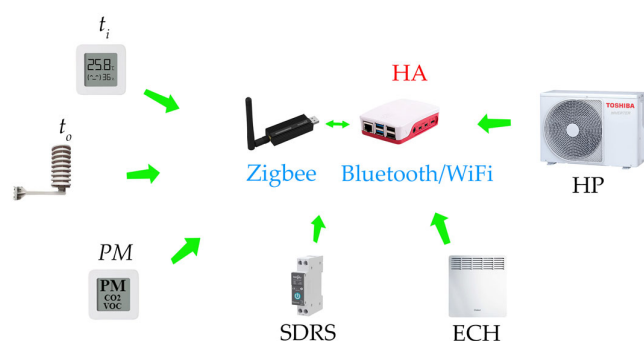


Figure 3. Configuration of a home heating IoT network.

The smart home system was applied to a family house with a net floor area of 106 m², as shown in Figure 1. Smart items were placed around the rooms of the house. The system is intended for home heating, which is based on the operation of an air-to-air (A2A) heat pump. For the purpose of satisfying the thermal load of the building, two heat pumps A2A with a total heat output of 9 kW [22] and electric convector heaters (ECH) with a total power of 4 kW were installed. The HA system, located in the central part of the house, acts as the brain of the entire smart home. Devices for measuring current, voltage, and electricity consumption are located in the distribution cabinet (SDRS, Smart Din Rail Switch). Indoor temperature sensors, $t_{i,1}$ – $t_{i,7}$, are strategically placed in different rooms to enable precise measurement and regulation of temperature in every part of the house.

External temperature sensors, $t_{o,HP1}$ and $t_{o,HP2}$, located on the outdoor units of the heat pumps, allow the system to adjust the operation of the heating cranes depending on the external conditions. Figure 4 shows a one-day sample of collected temperatures from different devices for measuring external and internal temperature.

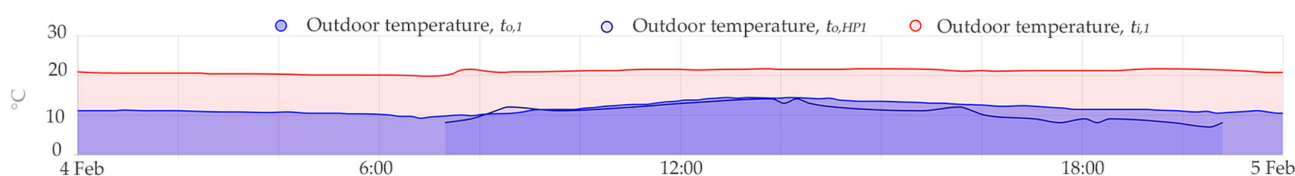


Figure 4. One-day sample of measured temperatures from sensors $t_{o,1}$, $t_{o,HP1}$, and $t_{i,1}$.

Sensors $t_{o,1}$ and $t_{o,2}$, installed outside the home, provide additional information about weather conditions, which is useful for predicting heating needs. Smart sockets are placed in the rooms for the purpose of possible additional heating of the space. Based on these data, the system intelligently manages the operation of heat pumps and smart sockets, adjusting the room temperature according to presets or user needs, all with the aim of achieving optimal comfort and maximum energy efficiency.

6. Climatological Days

The climatological data presented (Figure 5), which were collected at the nearest measuring station of the Zadar building [23], Republic of Croatia (Southern Croatia), indicate extremely favorable climatic conditions for the efficient operation of heat pumps during the winter months.

According to the measured and collected values of outdoor temperature and relative humidity during 2024 at the site of the building (in situ), shown in Figures 6 and 7, it was determined that the outdoor temperature did not fall below 2 °C, while the relative humidity rarely exceeds 80%, which shows that the outdoor temperature is mostly within the limits of the average values of the nearest climatological station.

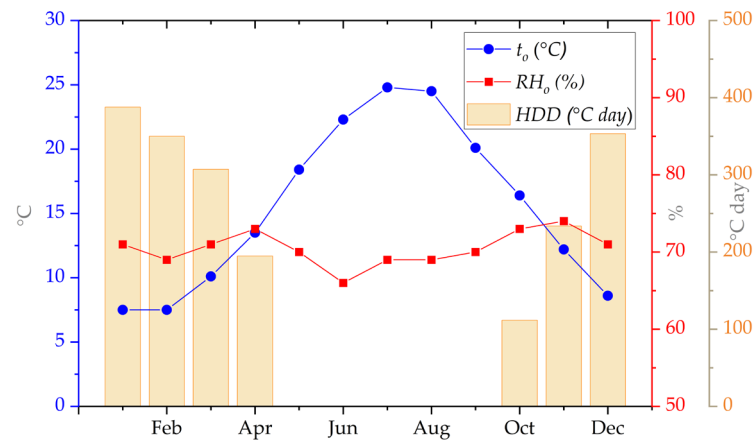


Figure 5. Climatological data for the reference station in Zadar, Croatia.

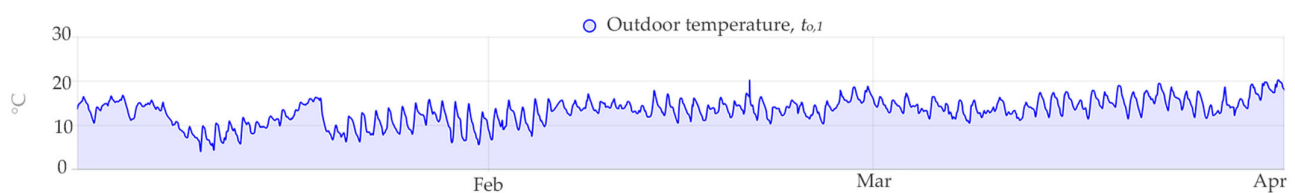


Figure 6. Collected outdoor temperature, in situ, $t_{o,1}$.

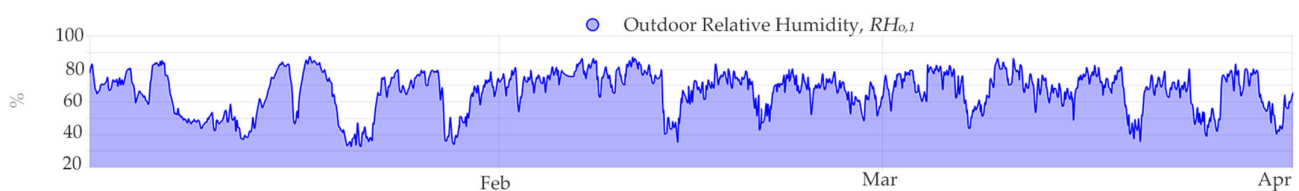


Figure 7. Collected outdoor relative humidity, in situ, $RH_{o,1}$.

These climatological data are important because when the outside temperature is low and the humidity is high, a layer of ice can form on the external heat exchanger of the heat pump. Following this, the heating crane is required to undergo a defrost cycle to melt the ice, resulting in a reduction of its efficiency [24]. Favorable climatological conditions at the site of the building enable continuous operation of the heat pump without the need to enter the defrosting phase, which ensures the efficiency of the system and the optimal coefficient of performance (COP), further increasing the energy efficiency of heating.

7. Energy Analysis

The methodology used in this paper is based on the application of Internet of Things (IoT) technology for data collection and analysis with the aim of determining the energy efficiency of heat pump operation and the automated management of this operation. In order to determine energy efficiency, the calculation of heat losses due to transmission and ventilation was carried out using an analytical model of heat load in accordance with the HRN EN 12831-1:2017 standard [18], which defines procedures for calculating energy needs for heating and cooling, taking into account the specifics of climatic conditions. The calculation is based on the static parameters of the building, such as the geometry and thermal properties of the materials (Table 1) of the already built building, and dynamic parameters, which include meteorological conditions and indoor comfort requirements.

Table 1. Thermal characteristics of the building.

Name	U-Factor
Symbol	U
Units	W/m ² K
Windows	1.20
Exterior doors	4.00
Wall	0.45
Floor	0.41
Roof	0.33

The data for the analysis were generated by the Home Assistant/Raspberry Pi platform. In order to assess the energy needs and efficiency of the heating system, a comparison was made between the theoretical calculations and the actual, experimentally measured values on a specific building. For this purpose, two models were created: one based on an analytical approach according to applicable standards, and the other a simulation model with detailed input parameters specific to the observed object. The results obtained from both models were then compared with real data collected through sensors and an on-site monitoring system. This methodology makes it possible to identify discrepancies between design and actual performance, which is crucial for optimizing system operation and increasing energy efficiency in future applications.

Model 1 is based on location reference data and prescribed extreme temperature conditions (outdoor design temperature -4°C , indoor temperature 20°C) according to applicable regulations. Model 2 uses measured average minimum temperatures at the site (7.5°C [23]), which more realistically depicts the actual energy needs of the building. The calculation of the required heating energy was carried out using the data on heating degree day (1600 for the area of southern Croatia) prescribed by the ordinance [24]. The output values of both models were compared with data collected by on-site measurements via the Home Assistant/Raspberry Pi platform. In the real system for which measurements were made, indoor temperatures varied between 19°C and 21°C , with an average value of 20°C .

The thermo-technical characteristics of the building and the heat pump used in the modeling are shown in Tables 2 and 3, while the results of simulations and measurements are shown in Table 4. The comparison of simulated and measured data made it possible to verify the sufficiency of energy needs and the efficiency of heat pumps in real conditions.

Table 2. Thermo-technical characteristics of the residence.

	Mark	Units	Model 1	Model 2
Area	A	m ²	106	106
Volume	V	m ³	378	378
Outdoor design temperature	t_o	$^{\circ}\text{C}$	-4	7.5
Indoor design temperature	t_i	$^{\circ}\text{C}$	20	20
Heat loss	$\dot{Q}_l$	W	4830	2465
Heat loss per square meter	$\dot{q}_l$	W/m ²	46	23.5

The results shown in Table 4 provide a complete picture of the energy performance of the facility under different operating conditions. Due to the growing environmental awareness, it was not justified to carry out a detailed energy comparison with traditional wood heating, as well as with electric heating, which consumes on average up to four times more energy compared to a heat pump. Such systems, due to their lower efficiency and negative impact on the environment, are no longer an acceptable alternative. The measured

data show a significantly lower specific energy consumption compared to the design values from Model 1, which indicates that the thermal energy provided by the A2A heat pump is sufficient to heat the building. Furthermore, the actual annual electricity consumption is lower than the one assumed in the design, which indicates that the building actually belongs to a more favorable energy class than the one envisaged by the project budget [25].

Table 3. Technical characteristics of the heat pump [22].

	Mark	Units	
Type	HP1	-	Toshiba, Seya, RAS-18J2KVG
Power	$\dot{Q}_{e,HP1}$	kW	1.6
Heating	$\dot{Q}_{h,HP1}$	kW	5.4
Coefficient of performance	COP_1	-	3.38
Seasonal Coefficient of performance	$SCOP_1$	-	4
Type	HP2	-	Toshiba, Seya, RAS-B13J2KVG
Coefficient of performance	COP_2	-	3.72
Seasonal Coefficient of performance	$SCOP_2$	-	4

Table 4. Summary of energy quantities of models.

	Mark	Units	Model1	Model2	Measured
Seasonal Coefficient of performance	$SCOP$	-	4	4	4.2
Annual electrician energy consumption	Q_e	kWh a*	1932	1578	771
Annual heating energy consumption	Q_h	kWh a	7730	6310	3238
Annual heating energy consumption per square meter	$Q_{h,A}$	kWh/m ² a	73.1	59.7	30.6
Annual electric energy consumption per square meter	$Q_{e,A}$	kWh/m ² a	18.3	14.9	7.3
Energy class	-	-	C	C	B

*a, annual.

8. Automation and Process Control

Home Assistant provides exceptional flexibility in the automation of IoT devices. It allows you to create custom automations through an intuitive visual editor (Figure 8a) or using YAML configuration files for more advanced users [26]. Integration of different devices into HA is easy thanks to extensive support for existing integrations and the ability to add new ones through the Home Assistant Community Store (HACS). This module facilitates the straightforward management and installation of additional third-party integrations and components. For example, Figure 8 shows how HA can be used to control a heat pump through integration for Toshiba air conditioners [27]. The Home Assistant uses sensor data to automate the operation of the heat pump. Automation includes:

- Time management: automatically turns the system on and off at predefined time intervals.
- Maintaining the set temperature: the current room temperature is compared with the preset desired temperature, and the device is activated as needed to maintain the desired temperature.
- Flexibility: The system allows adjustment of the temperature and operating time settings according to the individual needs of the user.

Integrating additional sensors into smart homes represents a significant step towards improving comfort and energy efficiency. For example, the Thermal Comfort [28] sensor for HA (Figure 9a) provides valuable information on key parameters such as absolute humidity, dew point, heat index, and subjective heat perception. Together with information from other sensors, such as presence detection, meteorological measurements, and air

quality sensors (Figure 9b) [29], this technology allows heating and cooling systems to automatically adapt to current conditions. This reduces the possibility of inconveniences such as dry air or excessive humidity. Through this approach, smart homes not only become more functional but also focus on a personalized experience that ensures maximum comfort with minimal energy consumption. The future of smart homes lies in further automation, which will enable even better adaptation of user needs.

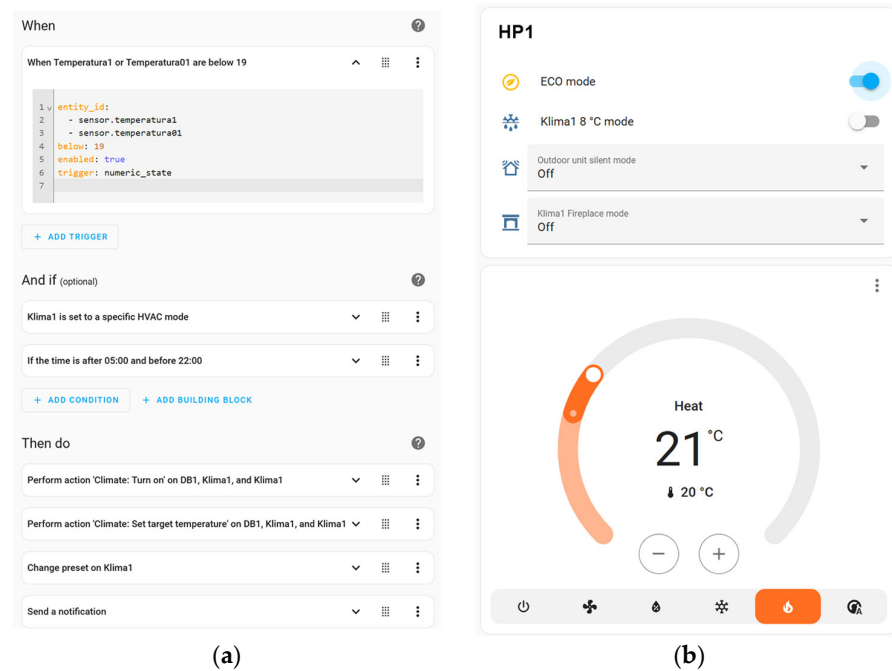


Figure 8. (a) An example of creating an automation script through a visual editor. (b) Heat pump operation control via Toshiba AC integration into HA.

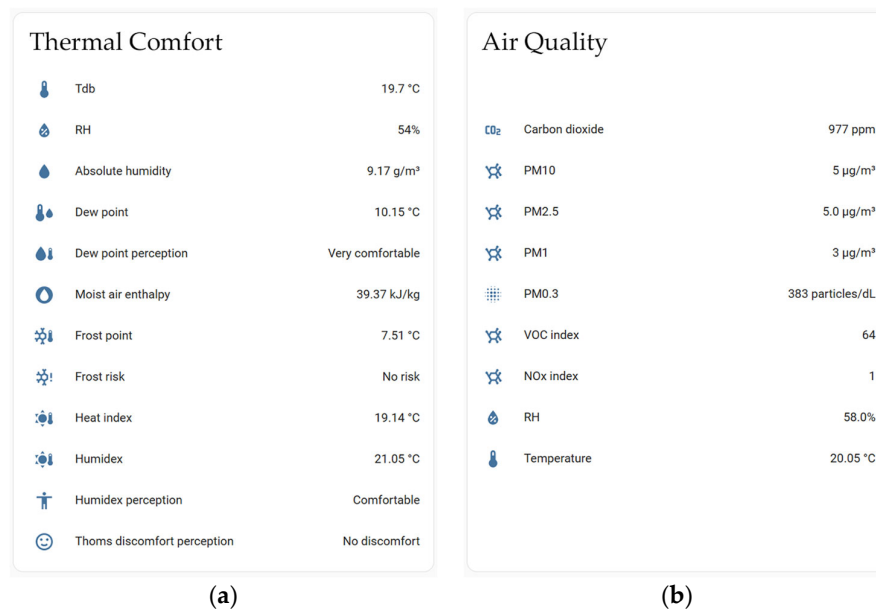


Figure 9. (a) Thermal comfort sensor, (b) air quality sensor, and air gradient.

Home Assistant/Raspberry Pi platform was used in order to collect data and automate control. In this paper, the authors did not use any other software nor dealt with the development of new algorithms for the management of the PCB. The PCB is factory programmed and contains algorithmic data required for the operation of the heat pump.

The intention of the authors was to investigate whether full functionality may be achieved with the present algorithms.

9. IoT Security

One of the main challenges of the IoT is the risk of a cyberattack. Cybersecurity in the analyzed system is strengthened by the integration of Zigbee and BLE networks, which enable reliable and encrypted communication between connected devices. These protocols use AES-128 encryption to protect data transmission, making it significantly more difficult to intercept and manipulate information. In addition, the SSL protocol, which is implemented for secure access to the Home Assistant (HA) outside the home network, further strengthens data protection through the use of RSA Public-key cryptography. Communication takes place through the NGINX Home Assistant SSL proxy, which provides an additional layer of protection against potential attacks. Two-factor authentication (2FA), integrated into the system, provides additional security by requiring multiple user identification, which reduces the risk of unauthorized access and enables system stability with a high level of protection of sensitive data.

10. Measurement Results

The analysis of the data collected by the Home Assistant for the heating period, shown in Figure 10, gives us an insight into the electrical power of the heat pump. The peak values on the graph indicate the moments of maximum electrical power of the heat pump, which is necessary to quickly reach the desired temperature in the room.

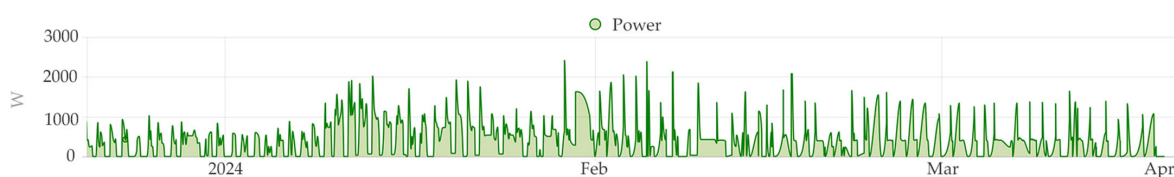


Figure 10. Electric power, W.

In Figure 11, the electricity consumed per day is shown. On the graphs, we can see the maximum values of energy consumption in the period of the lowest ambient temperatures, which did not exceed 20 kWh/day. Monthly consumption is shown in Figure 12, from which we can see that the total electricity consumption for the heating period was 771 kWh, which is significantly less than the projected values (Table 4). However, the consumption itself does not correspond to a sufficiently important parameter of the heat pump, whose aim is to achieve comfort in the room. The success of achieving comfort in the building can be seen in Figures 13–15.

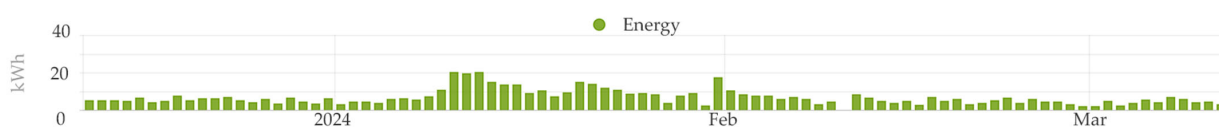


Figure 11. Consumption of electrical energy, daily, kWh.

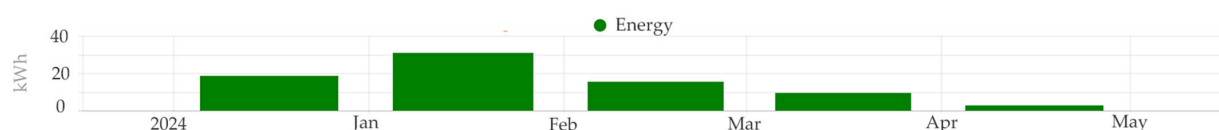


Figure 12. Consumption of electrical energy, monthly, kWh.

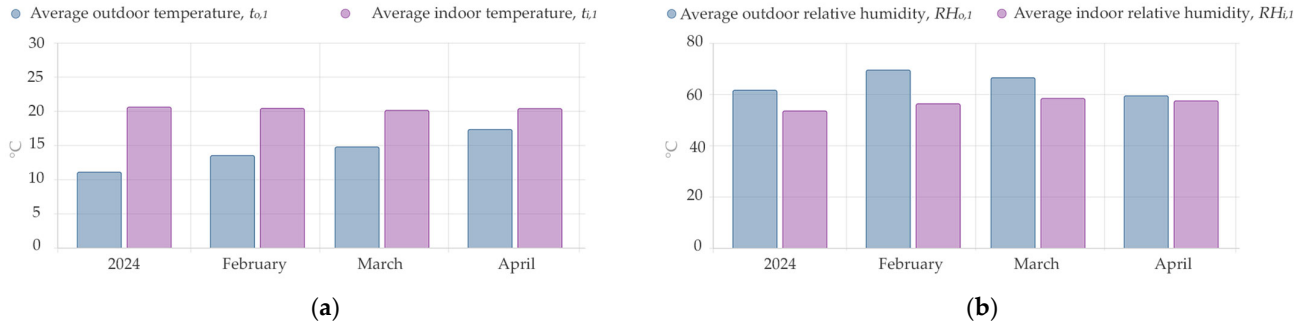


Figure 13. (a) Average monthly outdoor and indoor temperatures, $t_{o,1}$ and $t_{i,1}$. (b) Average monthly outdoor and indoor relative humidity, $RH_{o,1}$ and $RH_{i,1}$.

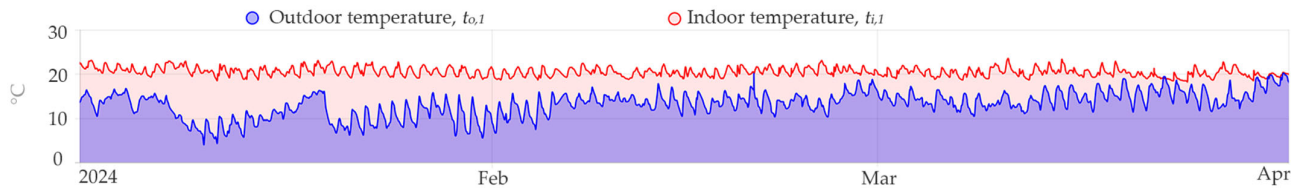


Figure 14. Collected temperature, $t_{o,1}$ and $t_{i,1}$.

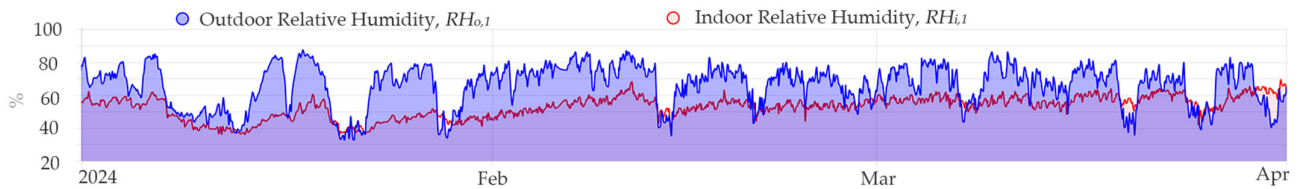


Figure 15. Collected relative humidity, $HR_{o,1}$ and $HR_{i,1}$.

Figure 13a shows the average daily values of the outdoor temperature ($t_{o,1}$) and the temperature in the living room ($t_{i,1}$) during the heating period, while Figure 13b shows the corresponding relative humidity values. These graphs clearly show the efficiency of heat pump automation, and can be used to conclude whether the temperature and humidity in the living room are maintained within the desired comfort (21 °C, 40–60%), which corresponds to the recommended values (20–24 °C, 30–70%) in accordance with the HRN EN 16798-1:2019 standard [30].

Figure 14 shows the living room temperature $t_{i,1}$ and the ambient temperature for the heating time period. Figure 15 shows the collected relative humidity of indoor and outdoor environments for the captured period of time.

For a better insight into the operation behavior of heat pumps at different temperatures and loads, we can use the collected data measurements on smaller record steps, such as the second, because the data collection system allows us to do so. Figure 16 shows a sample of the average daily electricity consumption profile of a heat pump. From the picture, we can see that at the beginning of work, the crane turns on at maximum load in order to reach the desired temperature as quickly as possible. However, after a relatively short time, the load is significantly reduced to approx. 30% of the nominal value, which indicates a quick adaptation of the heat pump to the actual heating requirements.

The automation of the heating system is based on a strategy of discontinuous operation, where heat pumps are activated when temperatures drop below 18.5 °C and turn off daily at 23:00. The analysis of the measured results shows that the average load on the heat pump is 40% for the heating period. Given that the heat pump works at a time when daily temperatures are higher, with the average daily temperature in the heating period being 9.9 °C in the time from 7 to 23 h, it results in an increase in COP.

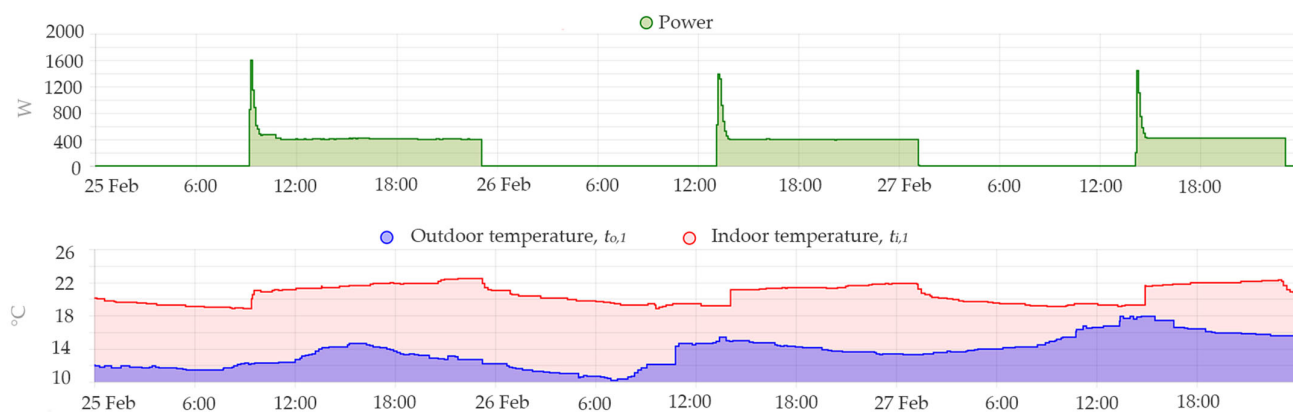


Figure 16. Collected sample electric power $\dot{Q}_{e,HP1}$ and temperature, $t_{o,1}$ and $t_{i,1}$.

The analyses for the period 2020–2024 show that electricity produced at night in Croatia mostly comes from sources with a higher share of fossil fuels, resulting in higher greenhouse gas emissions ($\text{CO}_{2\text{eq}}/\text{kWh}$) whose values are collected through the HA sensor (formerly known as “CO₂ Signal”), as shown in Figure 17. The sensor queries the Electricity Maps API for the CO₂ intensity of a specific region. Data can be collected for your home using the latitude/longitude or a country code [31].

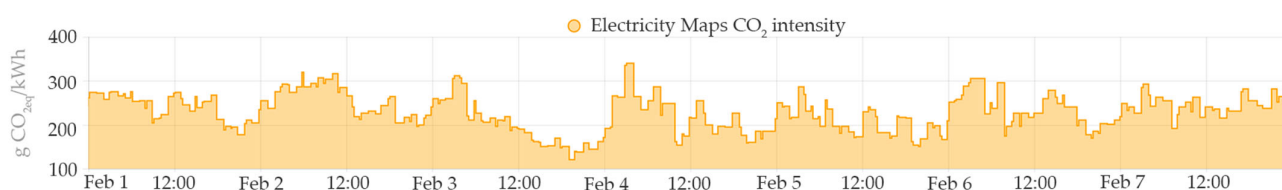


Figure 17. Collected sample CO₂ intensity, $\text{gCO}_{2\text{eq}}/\text{kWh}$.

To reduce the overall environmental footprint and increase the COP, the operation of the system is adapted to the daily heating needs, thus prioritizing sustainability and energy efficiency over lower electricity costs. This approach allows for a more efficient use of resources while reducing the negative impact on the environment.

Heating a house with a wood stove can affect the concentration of PM_{2.5} particles (particles with a diameter of less than 2.5 μm) in the air. Long-term exposure to these particles can cause health problems [32]. Particulate emissions depend on the type of wood, humidity, burning method, and type of stove/fireplace. For the purposes of this work, the values of PM_{2.5} particles [29] were measured in a room heated using an A2A heat pump and a fireplace wood stove. The results of the measurements are shown in Figure 18, where the left part of the graph compares the values of particles in the air when heated with a heat pump, while the right part represents wood heating. It is evident that the concentration of particles resulting from wood heating has surpassed the allowable limit of 15 $\mu\text{g}/\text{m}^3$ [33], further supporting the need for an energy transition.



Figure 18. Collected PM_{2.5} sample in a space heated by a heat pump (11–17 h) and a wood stove (17–23 h).

Unfortunately, the authors have not collected all the required data for the comparison of the thermal comfort between the proposed solution and the situation without that solution. This comparison will be investigated in the future. However, the primary goal of this study was to reduce the carbon footprint, as the energy produced during nighttime is mostly generated from fossil fuels and imported from the Republic of Serbia and the Republic of Bosnia and Herzegovina, where electricity is dominantly generated from coal [31].

11. Conclusions

The energy transition represents a crucial step towards a sustainable future, enabling a gradual transition from traditional fossil fuels to renewable and cleaner energy sources. Air-to-air (A2A) heat output systems play an important but often underestimated role in this process. Although they are often perceived as simple and inferior solutions incapable of meeting the requirements of modern heating, the application of modern technologies shows that A2A systems can successfully provide the necessary thermal comfort, especially with the limitations of the existing infrastructure and budget. Their application contributes to the reduction of greenhouse gas emissions, the reduction of the negative impact on the environment, and the increase of energy efficiency and overall sustainability. The implementation of the Home Assistant software solution, based on the open-source platform and the Raspberry Pi hardware system, proved to be an economically acceptable, efficient, flexible, and secure solution for integrating and managing smart home devices. Such a system enables the connection of devices from different closed ecosystems, thus overcoming the limitations of individual manufacturers and providing a centralized platform for monitoring, optimization, and automation, while increasing user security and privacy, which further confirms the importance of IoT solutions in the context of the global energy transition.

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Abbreviations

The following symbols are used in this manuscript:

List of Symbols

A	area, m^2
V	Volume, m^3
Q	Energy, Wh
$\dot{Q}$	Power, W
$\dot{q}$	Heat flux density, W/m^2
U	U-value, $\text{W}/\text{m}^2 \text{ K}$
PM	Particle Matter, $\mu\text{g}/\text{m}^3$
HR	Relative Humidity, %

<i>a</i>	Annual, a
<i>p</i>	Pressure, Pa
<i>t</i>	Temperature, °C

Indexes

<i>e</i>	Electric
<i>h</i>	Heating
<i>i</i>	Indoor
<i>o</i>	Outdoor
<i>eq</i>	Equivalent

Abbreviations

4IR	Industry 4.0
AES	Advanced Encryption Standard
A2A	Air to Air
COP	Coefficient of Performance
ECH	Electric Convective Heater
HA	Home Assistant
HDD	Heating Degree Day
HP	Heat Pump
HVAC	Heating Ventilation and Air Conditioning
ICT	Information and Communication Technology
IoT	Internet of Things
MQTT	Message Queuing Telemetry Transport
PCB	Printed Circuit Board
RPi	Raspberry Pi
SDRS	Smart Din Rail Switch
SSL	Security Socket Layer

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