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# HVAC SYSTEM MODELING AND INTELLIGENT CONTROL TECHNIQUES FOR ENERGY OPTIMIZATION IN BUILDINGS

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***Abstract*:** The rapid growth in energy consumption by buildings and the limitations of conventional HVAC control systems have created an urgent need for more efficient and intelligent solutions. Conventional control methods do not keep up with dynamic occupancy and environmental variability, and complicated thermal interactions, and result in unreasonable energy consumption and decreased comfort. In the paper, the detailed overview of the approaches of HVAC system modeling and intelligent methodology of building energy optimization is described. The paper is a systematic review of the basis of HVAC, system components, centralized, decentralized, and hybrid systems. Various gray-box models are introduced and examined with regard to their utility in predicting thermal behavior and making decisions pertaining to controls. These models include physics-based, data-driven, and hybrid versions. Fuzzy logic, ML, DL, and RL are some of the smart control technologies that are compared to more traditional PID-based methods. Energy efficiency and thermal comfort can be achieved with smart HVAC control, according to recent literature. The paper also points out major challenges, limitations and possible research directions to building adaptive, data-driven and sustainable HVAC system in the modern buildings.

***Keywords:*** Heating Ventilation and Air Conditioning (HVAC), Energy Optimization, Building Energy, System Modeling, Energy Intelligent Control.

## I. INTRODUCTION

Energy consumption has significantly increased as a result of the abrupt rise in global industrial, economic, and demographic expansion. In order to combat this increase, more energy-generating activities are required [1]. There are, however, two downsides to this surge in power generation: expensive prices and poor air quality. The potential for acid rain, climate change, and resource depletion-related environmental and political issues is another consequence. With the increasing interest in the area of sustainable buildings and the development of intelligent control technologies, there is a necessity to summarize existing knowledge in the field of HVAC modeling and intelligent control. The investigation of cutting-edge intelligent control techniques, the improvement of HVAC system modelling, and the evaluation of office data on control strategies' efficacy in optimizing energy use in existing buildings. It also establishes the gaps in research that exist and direction the research should follow in developing highly efficient, intelligent HVAC systems.

The uptake of HVAC differs markedly between areas in modern times. There is more than 90% air conditioning penetration in the US, Japan, and South Korea, according to the IEA, but less than 20% in developing nations like India, South Africa, Indonesia, Brazil, and Mexico [2]. Refrigeration technology is considered one of the most significant inventions of the 20th century, and it is crucial to food preservation, agricultural logistics and health of people. Regardless of the technological improvement, inappropriate storage temperatures and inappropriate cooling facility are still leading to the decline in quality, especially in areas where kokin have not taken proper measures of refrigeration. HVAC systems [3] have undergone a drastic development even though they started as rudimentary systems. HVAC systems have their roots in the first, more primitive attempts to improve human health and comfort [4]. Central heating systems in homes and in the public baths were under use during the Roman period and wind towers were used to cool the interiors.

Building builders, owners, and managers have been very worried about how energy-efficient HVAC systems are because they use 40% to 60% of all the energy used by the building [5]. These systems seek to reduce the amount of waste of energy through adjusting the performance of HVAC to the real occupancy and environmental situations. Two major goals usually activate the concept of HVAC optimization to minimize energy use and preserve or enhance thermal comfort. Multiple external factors, including air temperature, radiation temperature [6], air speed, and relative humidity (RH), as well as personal factors, including metabolic rate, clothing insulation, and human adaptation, affect thermal comfort. Conventional controls fail to strike the right balance between these nonlinear and complex variables, which normally translate to energy losses, or lack of comfort. AI [7] and ML have recently made significant strides and have now enabled the development of intelligent HVAC systems that are capable of real-time predictive control, fault detection, and energy optimization. In the meantime, the AI algorithms [8] consume real-time sensor data and a history of the users' habits in order to make the system more efficient, reduce energy consumption, and thus be part of the sustainable building management practices.

### A. *Structure of the Paper*

The paper is organized in the following way: Section I gives an overview of the study and its background. Section II goes over the basics of HVAC systems. Section III talks about different modelling methods. Section IV talks about smart HVAC control strategies and methods. Section V is a review of the literature. And finally, Section VI sums up the paper with key findings and suggestions for future research.

## II. Heating, Ventilation, and Air-Conditioning (HVAC) Systems

A heating, ventilation, and air conditioning (HVAC) system is made to meet the comfort needs of people who live or work in a building [9]. A lot of different kinds of buildings use HVAC systems, like industrial, business, residential, and institutional buildings. These systems are also used in big data [10]. HVAC systems' main job is to keep people comfortable by adjusting and changing the outside air conditions to match the needs of buildings that are filled. A lot of the energy used in buildings is from these systems, especially in business and industrial office buildings [11]. Some HVAC systems use between 30% and 50% of all the energy in a house. It is possible to save up to 40% of this energy, though, by installing HVAC systems that use less energy [12]. So, the size of the building, the number of people who work there, and the need for air flow can all affect which HVAC system is best for an office building.

### A. *Basic Components of HVAC Systems*

Heating, Ventilation, and Air-Conditioning (HVAC) systems are important for keeping the air quality inside buildings good while also making sure that people are comfortable with the temperature [13]. Here is a list of the basic parts or tools that make up an HVAC system that moves conditioned air to keep people and things inside comfortable and improve the quality of the air inside: Plenum for mixed air and outdoor air control, an air cleaner, a supply fan, two exhaust or relief fans, and a way for air to get out. Outside air flow, the ducts shown in Fig. 1 Devices for terminals, Bringing in fresh air, Coils for heating and cooling, self-contained unit for warmth or cooling, Tower for cooling, Power, Boiler, Cooler for water, Equipment for humidification and dehydration.

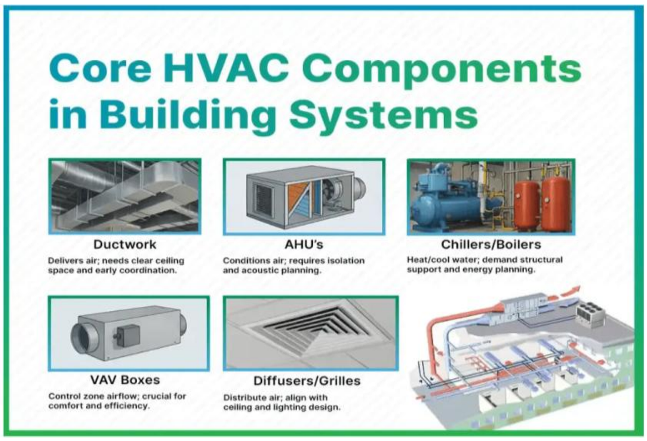


Fig. 1. Core HVAC Components

#### 1) *Ductwork*

The support system of HVAC systems is made up of ductwork, which brings conditioned air from the central units to public places. Optimal design of duct systems reduces leakage and pressure losses and minimizes noise which has a direct effect on energy efficiency and indoor comfort of thermal conditions.

#### 2) *Air Handling Units (AHUs)*

AHUs perform the task of conditioning and circulating air by heating, cooling, filtering the air and humidifying it [14]. AHUs are of utmost importance in ensuring the quality of indoor air and also assist the centralized temperature and humidity regulation measures.

#### 3) *Chillers and Boilers*

Chillers and boilers produce chilled and hot water that is needed in cooling and heating respectively. They are major sources of thermal energy in big buildings and require proper energy planning, management of loads and structural integration.

#### 4) *Variable Air Volume (VAV) Boxes*

VAV boxes are boxes that control the amount of conditioned air that flows to the various zones according to demand. They enhance occupant comfort, minimize the use of energy, and facilitate the flexible operation of the contemporary HVAC systems by providing the ability to control the work of zones.

#### 5) *Diffusers and Grilles*

Diffusers and grilles introduce the conditioned air into the occupied areas and support the supply of air return. They affect the patterns of airflow, the distribution of thermal, and the comfort of occupants, and can also be combined with architecture and lighting.

### B. *Types of HVAC Systems*

HVAC systems are generally of three basic types, and each of them offers a building heating, ventilation, and cooling in a unique manner. Unlike the decentralized systems, which make use of many smaller units to operate independently in various rooms or areas, the centralized systems apply one huge unit to serve the whole structure, as shown in Fig. 2. Hybrid systems are the best in terms of efficiency and adaptability. The size of the building, the energy requirement, and the degree of control also contribute to the choice of the most suitable type.

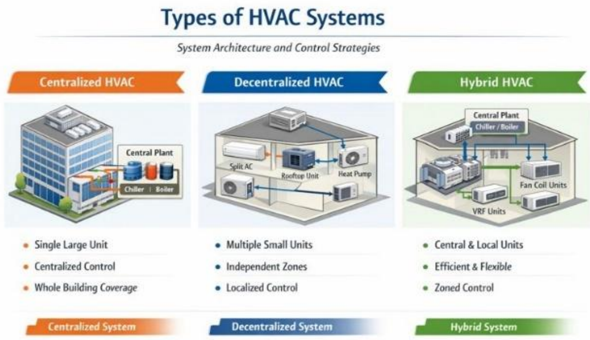


Fig. 2. Different Types of HVAC Systems

#### 1) *Centralized HVAC*

In the United States, centralised HVAC systems have served as the primary method for regulating indoor climate and ensuring occupant comfort in over 88% of commercial buildings. Commercial buildings' HVAC systems rank high among the costliest features, both in terms of initial investment and ongoing energy costs. Hvac systems fail, which makes both health and bank account suffer [15]. Sick building syndrome is a serious complication of malfunctioning HVAC systems that could be caused by poor ventilation, too much or too little humidity, and chemical pollutants and particulate matter in the air. The average adult spends over 40 percent of his or her working days at the workplace, and it is therefore crucial to proactively evaluate the level of efficiency of the HVAC system. HVAC problems can be tackled, though it can be an actual monetary strain.

#### 2) *Decentralized HVAC*

Decentralized HVAC systems consist of a series of smaller units located in various places at different locations in a building, and the rooms or zones can be independent of one another. They include split air conditioners, heat pump, rooftop and packaged terminal air conditioners. The systems are also popular at homes, hotels, small offices, and classrooms since they are simple to install, economical, and enable people to adjust the temperature of each area individually. One of the greatest benefits of the decentralized systems is that failure in one unit does not affect other parts of the building.

*3) Hybrid Systems*

The Hybrid HVAC systems represent a blend of advantages of both centralized and decentralized approach, which is more efficient in performance and temperature control. Under this kind of system there is centralization of some of the functions, like the generation of cold or hot water [16], and the zone-level conditioning is met by smaller units like fan coil units or VRF terminals. The most common applications of hybrid systems are on commercial buildings of the modern world and mixed-use settings that require a flexible zoning system and effective energy consumption. They minimize the amount of ductwork that is required in fully centralized systems and yet still offer the benefit of having a high level of central control in the use of energy.

### C. Challenges in Traditional HVAC Control

There are some main Challenges in Traditional HVAC Control:

- The number of people in a room cannot be changed by traditional HVAC systems since they follow predetermined schedules.
- They consume a lot of power since they keep running even when no one is there.
- These systems are not equipped to handle unforeseeable fluctuations since they cannot be used to monitor real-time information about air quality, humidity or temperature.
- Indoor comfort is unpredictable since they have trouble adjusting to changes in the weather outside.
- The necessity to manually alter numerous settings increases the workload and increases the likelihood of making mistakes.
- The total performance is lowered as the heating and cooling as well as the ventilation systems do not work effectively as a system.
- Costs of operation and maintenance of older HVAC systems are also high because of these inefficiencies.

## III. Modeling Approaches for HVAC Systems

The HVAC system [17] modelling methods are used to show how real heating, ventilation, and air conditioning systems work and to guess how they work. These approaches can be further categorized into white-box, black-box, and gray-box models for the sake of simplicity. Because they detail the components of a system using physical laws and mathematical calculations, white-box models are exhaustive, complicated and laborious [18]. Conversely, black-box models are trained on system behavior directly by historical data through data-driven methods such as ARX, ARMAX and machine learning; they may provide very good accuracy but they do not understand the underlying real physical processes. Gray-box models are equal in terms of source in filling in the gaps; they rely on both data-driven learning and physical knowledge.

### A. Importance of Modeling in Building Energy Optimization

The HVAC systems usually consume the most amount of energy in the buildings and hence the proper modeling of the HVACs system is important in meeting the energy efficiency objectives. Studies indicate that when better modeling and management are done, optimizing HVAC operation can reduce energy consumption by more than 25 percent and at the same time ensure the comfort of the interior environment. An accurate model may help with a lot of things, such figuring out how the HVAC system respond to changes in indoor temperature, building design, external weather, and internal loads [19]. It is also possible to test control schemes in a digital form and decide on how best to operate the system with less expensive equipment thanks to better models.

### B. Physics-Based Models

Physics-based models HVAC systems have their behavior described using the underlying thermodynamic and heat transfer principles. These models allow physical interpretations and manipulation of energy-performance by modeling buildings as thermal networks or state-space systems and showing the storage and transfer of heat and other dynamics in response to a smart-grid control system see Fig. 3.

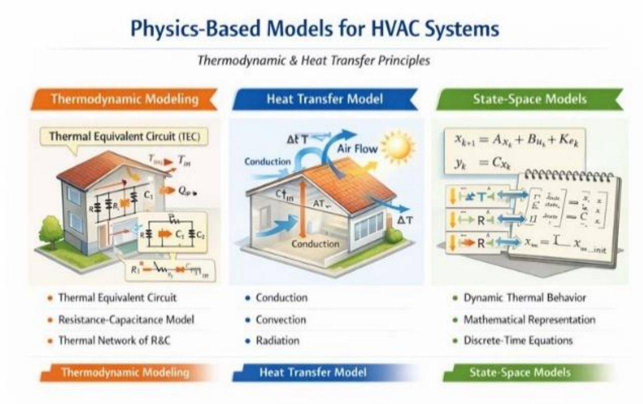


Fig. 3. Physics-Based HVAC Models

*1) Thermodynamic Modeling*

Thermodynamic modeling provides the analysis and control of HVAC systems using the physical foundation. Using simple principles of energy saving, these models demonstrate the heat transfer, storage and circulation mechanisms of the building. Two common ways of bringing the building down to a network of thermal [20] resistances and capacitances are the Thermal Equivalent Circuit Model (TECM) and the Resistance-Capacitance (RC) model. The design of thermodynamic models may not be easy to do due to a myriad of numerous variables that may include building materials, occupancy behavior, as well as environmental disturbances among others.

*2) Heat Transfer Model*

Hear transfer is the transfer of heat between two or more physical systems. This transfer of energy happens at a pace defined by the temperature differential between the systems and the thermal characteristics of the medium that separates them. As heat flows through a place that is hot to one that is cold it changes the internal energy of whatever it passes by. This move, without doubt, is likely to increase the entropy of the system. Conduction, convection and radiation are the three primary mechanisms through which heat can be transferred. Conduction or heat diffusion takes place through direct molecular interaction.

*3) State-Space Models*

State-space models have found extensive application in building energy modeling because the models allow the dynamic thermal behaviour of a building to be represented by a compact mathematical framework [21]. The standard notation for a discrete-time state-space model is:

$$\begin{cases} x_{k+1} = Ax_k + Bu_k + Ke_k \\ y_k = Cx_k \\ x_0 = x_{\text{init}} \end{cases} \tag{1}$$

In Equation (1), k is the discrete time index; u k denotes the input or control vector (e.g. weather conditions, internal gains, HVAC actions); $x_k$ denotes the state vector that characterizes the thermal conditions in the system; $y_k$ denotes the output vector (usually the indoor temperature); and $e_k$ denotes the error or disturbance vector. $A, B, C$ , and $K$ Area numerical matrices of the correct size, and $x_{\text{init}}$ is the estimated state of the identification algorithm.

The number of states chosen is a vital modelling choice; in this research, a second-order (two-state) model is taken following the suggestion of previous works. Different methods can be used to obtain state-space parameters: white-box (physics-based), black-box (data-driven) and grey-box (hybrid) modelling. This is a black-box identification strategy, and in this case, a Prediction Error Minimization (PEM) framework with N4SID subspace identification method is used, which is useful in approximating system matrices based on measured input-output data.

### C. Data-Driven Models

Data-based models are based on historical data on the behavior of the HVAC system to learn without the need to explicitly model physical processes. The machine learning [22], regression, and DL methods used to capture nonlinear dependencies, time relations, and multivariate relationships so that accurate energy prediction, fault detection and data-driven HVAC control and optimization could be achieved.

#### 1) Machine Learning Models

Machine learning systems [23] train on thermal behaviour data and make sound predictions on HVAC performance. ANNs are used to model nonlinear relationships between temperature and load prediction, although they require huge data. SVMs are well-suited to smaller datasets and predict/forecast the HVAC behaviour, but they should be carefully parameterized. Such models enhance better prediction of energy and aid intelligent HVAC decision making.

#### 2) Regression-Based Models

Regression models are statistical estimates of the energy performance based on statistical correlations of input factors and building performance parameters. This approach has 70 percent of data that is used in training and 30 percent in validation. The regression analysis involves deletion of non-numerical or non-contributing variables prior to creation of a model. Among the possible predictors, the most important variables are selected with the help of the stepwise selection [24]. Diagnostic tools such as adjusted R 2, AIC, BIC, RMSE and residual are used to measure the quality of the model and forward selection is used to cut out the predictors which do not help improve accuracy significantly.

#### 3) Deep Learning Models

Deep learning models offer complex HVAC modeling based on the learning of complicated time and space patterns. The time-series prediction of indoor temperatures and energy loads is more successful in LSTMs because it allows seeing long-term dependencies [25]. The CNNs derive local patterns on multi-sensor data, which helps in multi-zone prediction and detection of anomalies. The predictive accuracy is further improved by Hybrid CNNLSTM models. Despite the large input of both datasets and computation, deep learning is better at intelligent HVAC control and real-time energy optimization.

## IV. Intelligent HVAC Control Techniques and Technologies

Intelligent control methods like fuzzy logic, neuro-fuzzy systems, genetic fuzzy systems, neural networks, and evolutionary algorithms are being used more and more in HVAC systems to handle nonlinear indoor situations and make them more comfortable and energy efficient. A complex mathematical model is not necessary for fuzzy controllers, but genetic algorithms and neuro-fuzzy algorithms can automatically optimize rule and membership function bosses for better performance. Hybrid methods such as ANFIS and GA-tuned FLCs are always compared to be more efficient than traditional PID and on-off controllers because they are quick in responding, more stable, and they save energy, which is measurable. In general, smart controllers offer adaptive, data-driven, and robust HVAC control that is appropriate to a smart building of the present day.

### A. Traditional Control Techniques

Off/On control and PID control are the two main categories into which the conventional HVAC control systems fall [26]. The reason why these controllers are commonly used is because they are inexpensive to implement, their design is very simple, and deployment into the building systems is not complicated. Nevertheless, they tend to be less effective when working in complicated and dynamic HVAC conditions.

#### 1) On/Off Control

The simplest type of HVAC control is known as On/Off control which switches the system to the ON or OFF state only. This is a method which manages the thermostat, humidistat, and pressure switch. Although the method is economical and simple to set up, it does not have accuracy and can cause the temperature variation, ineffectiveness and a decrease in comfort. With such restrictions, On/Off control can normally be used with simple applications in which high control accuracy is not put upon.

#### 2) Proportional Integral Derivative (PID) Controllers

HVAC systems often use PID controllers, which function by comparing the desired and actual values of a process variable. They are divided into three elements:

- **Proportional (P):** responds to current error
- **Integral (I):** considers accumulated past errors
- **Derivative (D):** predicts future error trends based on rate of change

The most widely used control scheme in HVAC is PI and P-only control schemes as building thermal dynamics tend to be slow and stable. PID controllers have been used both at supervisory and local control levels, such as actuator control and system self-tuning by methods such as Ziegler-Nichols (Z-N) tuning.

#### 3) Soft-Computing and AI-Based Control Strategies

The HVAC control soft-computing methods are RL, ANNs, FL, and agent-based systems [27]. These models are successful in managing nonlinear behavior and uncertainty and enhancing the accuracy of response or energy efficiency.

### B. Energy Optimization Strategies in HVAC Systems

HVAC systems that are energy efficient save energy, decrease operating cost, and decrease environmental influence whilst preserving the comfort and air quality inside the building [28]. These technologies are necessary since the buildings take a significant portion of the world energy.

#### 1) Energy-Efficient Heating Technologies

The goal of energy-efficient heating technologies is to offer warmth efficiently with a lower consumption of energy and a less adverse effect on the environment. The use of high-efficiency furnaces and heat pumps enhance the performance of heating since they make the most out of the available fuel and transfer the available heat rather than creating it. These systems contribute to the minimization of energy usage, decrease in operational expenses, and more environmentally-friendly and comfortable buildings.

*2) Energy-Efficient Cooling Technologies*

The cooling technologies are energy-efficient and are thus used to control comfort in the interior as well as consume less energy as compared to traditional systems. They come with sophisticated air conditioners, heat pumps, and evaporative coolers that are efficient to use with minimal consumption of power. These systems make the use of smart controls and automation [29] less costly to operate, more efficient, and less harmful to the environment, which is why they are key to sustainable building cooling.

*3) Energy-Efficient Ventilation and Smart Control Systems*

Smart Control Systems and Energy-Efficient Ventilation enhance the quality of the indoor air, as well as reduce the energy loss by controlling the air flow depending on its real-time demands. Demand-controlled ventilation (DCV) systems like energy recovery ventilators (ERVs) and sensors and automation [30] to control the intensity of ventilation based on occupancy, temperature, and air quality are called demand-controlled ventilation. The automated thermostats and building management systems are also known as smart control systems, which provide further optimization of performance due to the ability to monitor usage patterns and minimize the use of unnecessary energy. These technologies combined are capable of making the process of building operations more comfortable, less energy-wasting, and sustainable.

## V. LITERATURE REVIEW

The evaluated articles show the progress of smart HVAC management with the help of learning-based, simulation-based, and occupancy-sensitive methods that prove to be more energy efficient, thermally comfortable, and adaptive to working in contemporary buildings.

Gharbi et al. (2025) offered a fresh comparison of the cognitive control approaches used by HVAC systems, evaluating both traditional proportional-integral-derivative (PID) control and reinforcement learning (RL). Furthermore, extensive simulations in various building environments have proven that RL-based control is superior to PID controllers in unpredictable conditions, and that it can improve a building's energy efficiency and thermal comfort in areas where environmental conditions are constantly changing [31].

Jin et al. (2025) provided a clearer understanding of the research problem that the literature review aims to address—namely, the control challenge of HVAC systems in DR scenarios, and it summarizes important review articles that have been published recently. Next, it explains how HVAC systems participate in DR, sorts optimization control methods, lists present problems and future research directions, and proposes integrating state-of-the-art computational technologies like LLMs, RL, and TL to fix the problems. Lastly, a holistic model is presented, which provides a guideline when developing optimized control solutions by the engineers of operations [32].

Li et al. (2024) suggested a system for the effective operation of the HVAC systems in a passive building in Jinan, China, using extensive modelling, control, and optimisation. To begin, various programs such as GenOpt, Java, and the transient system simulation tool (TRNSY) are used to model the HVAC system. Secondly, specific configurations are used to imitate the operation of the HVAC system throughout the year. An approach to improve the energy-saving effect was to increase the amount of heat storage and return air ducts; this resulted in a notable 17.31% reduction in energy consumption [33].

Loggia et al. (2024) in-depth examination of building automation systems, with a focus on large-scale structures where it is crucial to manage energy resources in relation to the number of occupants and their distribution throughout the building. Climate control (HVAC), lightning protection, access control, and video surveillance are the primary systems addressed. Connected systems, in conjunction with an access control system, can offer optimal energy management, putting more people's comfort first in high-traffic areas (always within the emergency protocols specified for each building type, of course) [34].

Herath, Paranamana and Chandrasena (2023) quantified the potential energy saving that is made by the new algorithm in the case of office buildings in Sri Lanka. Early results indicate that the formulated algorithm would result in energy conservation of up to 75 percent in the HVAC systems. This algorithm can optimise the consumption of energy by taking into account the level of occupancy and the condition of a building, i.e., whether the occupants are present or not. The suggested methodology can result in significant savings of energy and sustainable building practices in less developed countries [35].

Isikdemir et al. (2022) the two components of the proposed system are the air circulation system and the temperature regulation system. The ventilation system estimates the air quality index using a Random Forest algorithm, allowing fresh air to be circulated. The temperature regulation system makes use of the Mamdani Fuzzy Inference System, which has four inputs and a single output. Based on the results, it seems that the designed system is doing well in the simulation. An increase in thermal comfort for building occupants and a decrease in HVAC energy consumption are the goals of the proposed system [36].

Table I is an overview of key HVAC research studies, developed models, intelligent controlled methods, energy optimization methods in buildings, key findings, weaknesses, and future research opportunities to enhance building energy performance and system performance.

TABLE I. REVIEW OF RECENT STUDIES RELATED TO HVAC SYSTEM MODELING IN BUILDINGS

| Reference | Study On | Approach | Key Findings | Challenges / Limitations | Future Directions |
|---|---|---|---|---|---|
| Gharbi et al. (2025) | Cognitive control strategies for HVAC systems | Comparative analysis of Reinforcement Learning (RL) and PID control using simulations | PID offers stability in predictable environments, while RL improves energy efficiency and thermal comfort under dynamic conditions | RL requires extensive training data and higher computational complexity | Hybrid control combining RL adaptability with PID stability |

| | | | | | |
|---|---|---|---|---|---|
| Jin et al. (2025) | HVAC control in Demand Response (DR) scenarios | Systematic literature review and framework proposal | Identifies key optimization methods and proposes an integrated DR-oriented HVAC control framework | Integration complexity and lack of real-world large-scale validation | Use of RL, transfer learning, and LLMs for intelligent control |
| Li et al. (2024) | HVAC optimization in passive buildings | TRNSYS-based modeling, simulation, and optimization | Achieved approximately 17.31% energy savings through enhanced heat storage and duct redesign | Case-specific design limits generalization | Extension to different climates and adaptive real-time control |
| Loggia et al. (2024) | Building Automation Systems in large buildings | Integrated management of HVAC, lighting, access, and surveillance systems | Coordinated system interaction improves energy management and occupant comfort | High system integration cost and operational complexity | Smarter occupancy-aware and AI-driven automation strategies |
| Herath et al. (2023) | Occupancy-based HVAC energy optimization | Algorithm considering occupancy levels and building status | Demonstrated potential energy savings up to 75% in office buildings | Results based on preliminary simulations | Real-world deployment and scalability in diverse buildings |
| Isikdemir et al. (2022) | Intelligent HVAC control system design | Random Forest for ventilation + Fuzzy Logic for temperature control | Improved air quality, thermal comfort, and reduced energy consumption | Limited to simulation environment | Implementation in real buildings and hybrid AI control systems |

## VI. Conclusion and Future Work

Increasing HVAC energy needs of buildings and the inefficiency of the traditional HVAC operation brought the urgent need to consider more advanced modeling and smart control approaches. The paper has discussed the HVAC systems in terms of basic principles up to the advanced optimization methods, in which the systems play a leading role in terms of energy use in buildings. Different HVAC designs and elements were consulted to determine their working nature and energy cost. The paper has examined the white-box, black-box, and gray-box modeling techniques and the significance of the modeling techniques in the quality representation of building thermal dynamics and facilitating the design of effective controls. The applications of intelligent control methods, such as fuzzy logic, ML, DL, and RL, were demonstrated as better than conventional control techniques when it comes to addressing the nonlinearities, uncertainty, and dynamic conditions. The work summarizes the existing information, determines the gaps in the research, and gives systematic basis to the further development of intelligent HVAC systems in the sphere of sustainable buildings.

The next area of research needs to be the large-scale real-world applications of intelligent HVAC control systems to prove that the performance is not only in simulation applications but also in real-life. Further focus on explainable AI models should be given to increase transparency and user trust. Combination of reinforcement learning and physics-based models, demand-response models, and renewable energy systems can also enhance flexibility, scalability, and optimization of energy in the long run of smart and sustainable buildings.

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