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A Review of Energy-Efficient HVAC (Heating, Ventilation, and Air Conditioning) Systems for Smart Buildings

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***Abstract*—Effective HVAC (heating, ventilation, and air conditioning) systems management in buildings is necessary to attain energy saving and comfort. Adequate sophisticated control techniques that can adjust to changing environmental circumstances and occupant preferences are crucial for effectively balancing these goals. This paper discusses passive, active, and intelligent HVAC technologies, their advantages in energy conservation, indoor air quality, sustainability, and system reliability. A discussion on HVAC operations and popular systems type is provided in order to have background knowledge. An in-depth review of the literature will be done concerning recent machine learning and predictive control methods in optimization of HVAC, such as occupancy-based control, model predictive control, and gradient-based learning with a particular interest in energy savings and comfort of the occupants. Although progress is being made, the available literature tends to work with small scale or linear models and this restricts their usability to complicated and dynamic settings. The novelty of the research is that the multi-factor considerations, including the occupancy patterns, environmental uncertainties, renewable energy integration, and real-time adaptive control are put in a single framework. The primary contribution is that it suggests scalable and smart HVAC optimization that improves the energy use, cuts expenses, and guarantees the occupants comfort, which could not be done by linear or small-scale optimizations.**

Keywords—Energy-efficient HVAC systems, Smart buildings, Sustainable building design, Internet of Things (IoT), Energy optimization.

I. INTRODUCTION

Intelligent and energy-efficient infrastructures are becoming the norm in the construction industry as a result of the worldwide push for sustainability and environmental responsibility. In comparison to other building components, the Heating, Ventilation, and Air Conditioning (HVAC) systems of modern buildings utilise a disproportionate amount of energy and emit a disproportionate quantity of greenhouse gases. Optimization of HVAC performance is extremely important to attain the sustainable development goals as well as enhance energy resilience [1]. The key to this change is energy efficient HVAC solutions, which not only ensure optimum indoor environmental quality and occupant comfort, but also reduce operating costs and energy consumption. The combination of sophisticated control methods, data analytics, and Internet of Things (IoT) technologies in the framework of smart buildings has transformed the design and functioning of the HVAC system [2].

Smart HVAC systems can modify their functionality dynamically by analysing sensor data, weather forecasts, and occupancy patterns in real-time to attain and maintain some desired ambient conditions using minimum energy consumption [3]. Functional methods like variable speed drives, intelligent thermostats, predictive maintenance, and heat recovery are all a part of operational optimization and energy savings. Moreover, smart control algorithms can improve the system responsiveness and it is possible to address adaptive management in terms of changing building loads and external conditions. The introduction of energy-efficient HVAC systems in smart buildings promotes global certification systems like LEED (Leadership in Energy and Environmental Design) and WELL, which supports their sustainability in construction and management of the facilities [4]. The systems are a mirror of engineering innovation, digital intelligence, and environmental responsibility: the main pillars of contemporary sustainable architecture. This paper analyses emerging trends in energy-efficient HVAC in smart buildings focusing on integration schemes, state-of-the-art technology, and future research directions to fully capitalise on energy conservation and other global sustainability goals.

A. Paper Organization

The paper is organized are. Section II presents energy efficiency building system. Section III discusses various energy-saving HVAC technologies, along with their benefits and limitations. Section IV explains HVAC operations, fundamental principles, and commonly used system types. Section V presents a literature review highlighting recent studies. Subsequent sections VI: Conclusion and Future Scope.

II. ENERGY-EFFICIENT BUILDING SYSTEM STRATEGIES

Active measures include energy-efficient HVAC systems, LED lighting and renewable energy sources such as wind turbines and solar panels. The smart building technology such as sensors and energy management systems is integrated to optimize the use of resources. Lifecycle concerns are in favor of sustainability, such as low-embodied energy (EE) materials and DE constructible design. The use of green roofs and walls helps in minimizing the heat islands and enhances insulation [5]. Scenario planning and stochastic models help accommodate future uncertainties [6]. The compliance with the policies, such as the net-zero energy levels, and the cooperation with stakeholders guarantee long-term energy performance and flexibility. The combination of the mentioned strategies results in cost-effective, resilient, and environmentally sustainable buildings. Fig. 1 indicates that to reduce energy consumption and maximize occupant comfort, energy-efficient building design uses both passive and active solutions. Optimizing a building's orientation to take use of natural light, insulate it to keep inside temperatures stable, and use modern glazing and shading mechanisms are all examples of passive techniques.

Fig. 1. Design strategies of energy-efficient buildings [7]

These methods reduce energy use and are necessary to achieve sustainable design [8]. Conversely, active methods concentrate on cutting-edge technology including energy management systems, LED lighting, renewable energy sources, and high-efficiency HVAC systems. These kinds of innovations maximize the use of resources, reduce carbon emissions and provide long-term flexibility [9]. For urban areas, integrated solutions combining passive and active strategies play a crucial role.

A. *HVAC Capabilities*

In addition to improving wasted energy costs and temperature management for inactive rooms, infrared cameras may be used to detect a variety of HVAC issues and occupancy. Fig. 2 shows how infrared cameras may assist technicians in increasing HVAC system efficiency by recognizing temperature fluctuations of occupied and empty regions [21].

Fig. 2. Diagram of user-friendly HVAC system [10]

Infrared cameras allow personnel to monitor temperature changes on equipment surfaces, which might reveal potential issues that are causing the equipment to run inefficiently. A wide variety of scenarios may benefit from human occupancy recognition. Knowing whether or not a place is inhabited may be used to adjust ventilation and temperature systems and so reduce energy use. As the need for comfort levels in all areas grows, it is critical to be able to deliver new technological developments for hospitals, business spaces, and museums housing precious artefacts. A more complex HVAC system is necessary to keep these kinds of commercial facilities at a temperature that is close to the specified target.

III. Energy-Efficient HVAC Technologies

Efficiency in energy usage is of the utmost importance in today's society, particularly when it comes to HVAC systems [11]. There is a growing demand for HVAC systems that use less energy due to growing concerns about environmental effect and the cost of electricity. There are three primary kinds of energy-saving technologies often used in HVAC systems: passive, active, and intelligent.

- **Passive Energy-Saving Technologies:** These strategies target buildings where mechanical or electrical technology is used to minimize energy consumption. They tend to incorporate materials and design concepts that are energy efficient in themselves.
- **Active Energy-Saving Technologies:** These technologies are done through the use of mechanical systems to offer a pleasant and energy efficient interior ambiance [12], [13]. They can do this through selection of effectiveness components, system layout optimization and perfection of equipment.
- **Intelligent Energy-Saving Technologies:** The practices utilize the latest technology such as computer networks, AI, the IoT, and big data analytics [14]. This aims to become more energy efficient with intelligent technology and learn more about the real-time data [15].

A. *Benefits of Energy-Efficient HVAC Technologies*

Every building, resident and the environment have numerous benefits with regard to energy conscious HVAC solutions [16]. The primary benefits of these technologies discussed in this section include energy saving, improvement of indoor air quality, environmental sustainability, and building resiliency.

1) *Energy Saving*

The potential of significant energy efficiency and reduction in operating costs is one of the most significant benefits of energy-saving HVAC technology [17]. Constructions can reduce power and fuel consumption, which will lead to lower utility bills, with the latest technology and energy optimization strategies. Besides reducing the maintenance costs and increasing equipment life, energy-efficient HVAC systems can also eventually lead to additional cost reductions [18].

2) *Indoor air quality*

HVAC systems that are energy-efficient offer increased control of ventilation, humidity and temperature which can lead to better indoor air quality and occupant comfort. High-efficiency filters and ventilation systems could help improve indoor air quality by removing allergens and other pollutants in the air [19]. Moreover, zoning systems and advanced controls can make the conditions in certain areas of a building more specific, ensuring inhabitants with the greatest comfort.

3) Environmental sustainability

The other significant benefit of less energy consuming HVAC systems includes sustainability and a smaller carbon footprint. The innovations contribute to combating climate change because they reduce greenhouse gas emissions through the reduction in energy consumption. Energy-efficient HVAC systems can also promote the use of renewable sources of energy in order to further reduce their impact on the environment [20].

4) Resilience and Reliability

Energy-efficient HVAC solutions can make a building more resilient and dependable by reducing reliance on external sources of energy and improving their performance [21]. As an illustration, automation and intelligent controls can be used to see buildings adapt to new conditions and ensure occupants are comfortable even in harsh weather or power outages. Moreover, the energy efficiency of HVAC systems can be designed to be more robust and less prone to failure and enhance the overall reliability of a system.

B. Limitations of HVAC System

The old HVAC systems have been criticized on their high energy, poor indoor air quality and massive emission of greenhouse gases, even though they are ubiquitous in maintaining the temperature environment [10]. These limitations are even worse when green buildings are concerned as they are constructed to limit environmental degradation and to maximize the comfort of the occupants [11]. Table I displays the constraints of current HVAC systems.

TABLE I. THE LIMITATIONS OF HVAC SYSTEMS [11]

Limitation	Description
Energy Consumption	A major source of both operating expenses and environmental issues is the amount of energy used by HVAC systems.
Installation Cost	The initial cost of acquiring and installing HVAC systems may be significant, especially for big or complex systems.
Maintenance Requirements	The optimal operation of HVAC systems requires regular maintenance to avoid unnecessary expenses and downtime.
Space Requirements	Large HVAC systems take up a lot of room, which may be an issue in tight or densely developed areas.
Noise Levels	Noise from HVAC systems, particularly bigger or older models, may disrupt peaceful surroundings.
Refrigerant Environmental Impact	Leaks of refrigerants used by certain HVAC systems may add to global warming and ozone depletion.
Indoor Air Quality	Inadequately maintained HVAC systems may recirculate allergens, mould spores, and dust, further lowering the quality of the air inside a building.
Temperature Inconsistencies	There may be hot or cold areas in a structure due to the difficulty of maintaining constant temperatures.
Humidity Control Limitations	The comfort and indoor air quality of some HVAC systems may be impacted by their inability to maintain ideal humidity levels.
Lifespan	It may be necessary to replace or significantly improve HVAC systems due to their limited lifetime.
Adaptability	It may be difficult for older HVAC systems to adjust to new environmental requirements or emerging technology.
Aesthetic Impact	The aesthetics of a building might be negatively affected by large and obvious HVAC equipment.

IV. HVAC OPERATIONS AND TYPES

The work of HVAC systems is based on the principles of heat transportation and thermodynamics. These systems may increase or decrease the temperature within a building by using various mechanisms such as radiation, convection, and conduction. Optimal air quality is maintained by ensuring appropriate air movement, which is achieved by ventilation components. HVAC systems work together to provide a balanced interior environment that benefits residents' comfort and health [22]. In particular, HVAC systems use a medium (such as air, water, or refrigerant) to transfer heat and fans or pumps to help the air and medium move. HVAC systems include the following operations:

- **Cooling Operation:** An HVAC system's cooling process begins with the compressor, which heats and pressurises the refrigerant to create a high-temperature, high-pressure gas. After that, the gas passes through the condenser coils, which are usually located outside the structure. The refrigerant condenses into a high-pressure liquid as a result of the heat from the refrigerant dissipating into the surrounding air when a fan blows outside air over these coils [23]. The temperature of this liquid subsequently decreases significantly when it goes through the expansion valve, where its pressure abruptly reduces.
- **Heating Operation:** The evaporator coil within the structure receives the cold refrigerant. A second fan circulates interior air over these coils, and the refrigerant cools the air by absorbing its heat. The cycle is repeated with the warmed refrigerant returning to the compressor. However, this action is effectively turned backwards during the heating procedure. The system's evaporator coil carries the extracted heat from the chilly exterior air to the inside area, where it is amplified by the compressor and the temperature is heated to a comfortable level.

Several HVAC types are routinely employed in different areas and building types [24]. The following are the most prevalent kinds of HVAC equipment:

- **Air-Conditioners (A/C):** These are intended to chill the air in a room and may comprise central air conditioners, window units, or split systems. The control issue entails accurate temperature management while optimising energy usage, particularly for central systems that must account for the thermal dynamics of the whole structure.
- **Heat Pumps:** There are a variety of heat pumps that may be used for both heating and cooling purposes. These pumps can be classified as either air-source, ground-source, or water-source pumps. During the changing seasons, when there are few temperature changes, optimising heat transmission becomes a significant control task.
- **Air-Handling Units (AHUs):** These units are components of a bigger HVAC system that consists

of things such as filters, cooling or heating devices and blowers that operate to condition and move air. The control issue is the synchronisation of these components to provide maximum air circulation and conditioning efficiency at minimum energy consumption.

- **Variable Air-Volume (VAV) Systems:** These systems offer variable airflow rates in order to use less energy and enhance comfort[25]. Real time adjustment of airflow rates based on heat demand and occupancy is essential in an effort to potential optimise their performance.
- **Radiant Heating Devices:** These machines utilize electricity or links to boilers to carry thermal energy used to heat the rooms. The control challenges are to ensure effective heat production and to maintain constant heat production and effective heat transmission.
- **Boilers:** These produce hot water or steam to heat and this is then pumped through pipes. The potential control issue with this type of equipment is frequently the maintenance of the correct temperature and pressure to guarantee fuel is efficiently burned.
- **Coolers:** Evaporative coolers are effective in the arid places since they cool down the air by evaporating water. Their effective operation requires optimisation of the evaporation process and management of water consumption.
- **Furnaces:** These are high temperature central heating systems. The control problem is to balance out the even distribution of hot air and to produce high-temperature heating without fuel wastage.
- **Multi-HVAC Systems:** These systems permit zoning through assimilation of various HVAC equipment into one system. The control task is much more difficult here in comparison with single-HVAC units. A bigger challenge is to ensure that all the parts work together and also consider the specific thermal needs of each zone.

V. LITERATURE REVIEW

Various studies have examined the enhancement of the performance and efficiency of HVAC systems through the application of ML techniques.

Alfatmi et al. (2025) based on the measured intensity of light and humidity values, the collected data is used to train a supervised ML model, which relies on the Multiple Linear Regression algorithm to predict interior temperature. The system provides proactive suggestions to the most optimal temperature settings that are likely to enhance user comfort whilst reducing energy use through the analysis of historical data and weather predictions. The development of an accessible interface to predict that uses real-time temperature, incorporating environmental sensing information with weather forecasting information, and the development of an artificial intelligence-based climate control system are among the key achievements of the research. The proposed solution aims to revolutionize HVAC management through cost-efficient and sustainable way of improving interior climate control in buildings [26].

Darwish et al. (2025) uses an infrared camera to identify room occupancy. The HVAC system modifies the indoor temperature when occupancy is detected according to the threshold temperature (changeover temperature). On the other hand, when no one is present, the system will keep the default temperature settings to avoid drastic circumstances (not too hot or too cold). The working of the HVAC system is also affected by the outdoor conditions of temperature: the cooling system turns on when the outdoor temperature is above the set changeover, and heating in when the outdoor temperatures are below the set changeover. The findings of the study indicate that occupancy-based control can save a significant portion of energy, or 8,632 kWh per year in the case of their small-scale project, or savings of $627.06. These findings demonstrate how such devices can enhance energy efficiency and at the same time maintain occupant thermal comfort [27].

Alosta et al. (2024) explores predictive algorithm based control of a thermal system in real-time. In particular, they suggest that the MPC strategy should be used to manage a light bulb system using a Raspberry Pi and with minimum power consumption. This paper outlines the process structure and compares MPC to the traditional control systems in great depth, including the Proportional-Integral-Derivative (PID) controller. This comparison comprises energy efficiency, price estimates as well as hardware performance indicators with focus on the merits and demerits of both strategies [28].

Woo et al. (2024) propose an energy-efficient control method for HVAC systems by leveraging Model Predictive Control (MPC). To design the MPC, they develop AI-based prediction models and introduce a cost function that optimizes both energy consumption and user comfort simultaneously. Performance evaluation of the prediction model shows that the stacking ensemble model significantly improves prediction accuracy compared to individual models [29].

Alabdullah and Showmi (2023) minimise the AC's power use. As a result, the usual solar PV system installation losses, size, and cost were minimised. However, it was of the utmost importance to address the mechanical constraints in order to prevent any refrigeration cycle issues, such as a frozen coil, oil leaks, or mechanical wear and tear, from damaging the equipment or making it last less than expected. It is possible to save a significant amount of energy with the presented method even before installing a solar PV system [30].

Yang, Hu and Spanos (2022) suggest a GB-L approach to offline incremental learning of a stochastic control policy and subsequent online execution. Thirdly, they demonstrate the learning method's theoretical convergence to the optimal policies and its effectiveness for HVAC management through simulations, taking into account energy cost, thermal comfort, and online computation. The results show that the proposed method can still reduce energy costs by approximately 6.5% despite the drawback of being less than 1 s and the high probability of providing users with a comfortable temperature. This is in comparison to the existing method of model predictive control relaxation-based on future information, which is assumed to be perfect and is supposed to provide near-optimal bounds [31].

Sharma, Gudi and Samavedham (2022) explains a new way to optimise energy use while creating comfortable settings using indices that adequately represent human perception. As part of the proposed two-tiered control architecture, the top level is responsible for determining the setpoints (air velocity, humidity, and temperature) through energy load optimisation and the maintenance of a comfort index at a user-specified value. The MIMO system, which was previously only controlled for temperature, is now managed by the lower-level architecture at three defined setpoints using decoupled PI controllers. The outcomes demonstrate effective control over the three setpoints independently, while also demonstrating good leverage on fan load [32].

Schlichter et al. (2022) showcase an adaptable IWSN, along with the associated measurement approach and two distinct real-world implementations. Factors like temperature, air quality, and three-dimensional airflow are all within the sensor nodes' purview of measurement. Each node has a dual transceiver radio, meaning it can communicate reliably in both the sub-1 GHz and 2.4 GHz bands. A cyber-physical production system (CPPS) uses the gathered data to facilitate demand-driven HVAC system control and offer decision support. Their CPPS demonstrates that their excellent real-world deployments may save up to 3990.56t CO_2 -eq per year, even with energy savings as little as 5% [33].

TABLE II. COMPARATIVE ANALYSIS FOR LITERATURE STUDY ON ENERGY-EFFICIENT HVAC

Author	Technology	Advantages	Limitations	Recommendations
Alfatmi et al., 2025	Multiple Linear Regression; integrates light, humidity, and weather data	Real-time temperature prediction; cost-effective; environmentally friendly	Limited to linear relationships; may underperform with complex non-linear data	Explore advanced ML models (e.g., ensemble, deep learning) for improved accuracy
Darwish et al., 2025	Occupancy-based HVAC control using infrared cameras	Energy savings (8,632 kWh/year); cost reduction; maintains thermal comfort	Dependent on accurate occupancy detection; small-scale study	Implement in larger-scale buildings; integrate with IoT sensors for robustness
Alosta et al., 2024	Model Predictive Control (MPC) vs PID for thermal systems	Optimized energy efficiency and hardware performance; better control than PID	Requires computational resources; hardware-specific implementation	Extend MPC to larger HVAC systems; test with real-time environmental variations
Woo et al., 2024	MPC with AI-based prediction models and stacking ensemble	Optimizes energy consumption and user comfort; improved prediction accuracy	Complexity in model design; ensemble models require more computation	Simplify ensemble approach; integrate adaptive learning for dynamic conditions
Alabdullah & Showmi, 2023	AC optimization considering solar PV systems	Reduces energy loss, cost, and equipment wear; pre-solar energy savings	Sensitive to mechanical constraints; risk of equipment issues if mismanaged	Incorporate robust monitoring and fault detection; validate under varying load conditions
Yang, Hu & Spanos, 2022	Gradient-based Learning (GB-L) for stochastic HVAC control	Efficient online execution (<1 s); maintains thermal comfort under uncertainty	Slight reduction in energy cost savings (~6.5%); off-line training required	Combine with real-time predictive analytics; test under extreme weather scenarios
Sharma, Gudi & Samavedham, 2022	Two-level control with decoupled PI controllers for temp, humidity, air velocity	Independent multi-setpoint control; improves energy optimization and comfort	Limited scalability; may require tuning for different building types	Extend to larger MIMO systems; incorporate adaptive controllers for dynamic loads
Schlichter et al., 2022	Industrial Wireless Sensor Network (IWSN) for demand-driven control	Real-world energy savings; CO2 reduction; enhanced decision support	Energy savings moderate (~5%); deployment cost of sensors	Optimize sensor placement; integrate predictive maintenance and AI-based control

A. *Research Gap*

Although there have been considerable improvements in optimization of HVAC systems with the help of machine learning and predictive control, there are still a number of gaps. Majority of the current research as summarized in Table II have mainly been conducted on small or controlled settings, thus restricting their inferences to large or complex building infrastructures. Several of these methods are based on linear modeling or already trained predictive learning methods, and can be sensitive to very dynamic or non-linear conditions in the real world. Also, although energy saving and comfort optimization are commonly shown, the combination of various aspects of occupancy patterns, environmental uncertainties, renewable energy, and real-time adaptive controls is not well integrated. There is also the absence of unified structures, which integrate cost-effectiveness, mechanical stability, and sustainable energy consumption in a scalable real-time functioning environment. A solution to these gaps would potentially allow more robust, efficient, and widely deployable HVAC systems that would allow occupants to be comfortable, but with a high reduction in energy usage.

VI. CONCLUSION AND FUTURE WORK

HVAC systems are among the most important components of a building's energy usage. While somewhat successful, traditional methods that rely on physical models are time-consuming, arduous, and not scalable, which puts a significant strain on HVAC system controllers. This paper has shown that the combination of sophisticated control tools, including model predictive control and occupancy-based algorithms, may be used to maximize the performance of a given system. Intelligent control and real-time data-driven methods allow improving resiliency and flexibility and counteract certain limitations of traditional HVAC systems. The analysis of literature revealed that these methods like occupancy-based control, model predictive control, and gradient-based learning have the potential to decrease the energy consumption and operating expenses by a substantial degree. Nevertheless, the majority of available solutions are restricted to the small or linear context, which constrains the usage to dynamic and large-scale buildings. The future planning will engage the deployment of the AI-based HVAC management system based on the dynamic control of machine learning models, IoT sensors, and predictive analytics. The framework will be directed towards the optimal utilization of energy, ensure that there is comfort of occupants under different conditions, the incorporation of renewable energy, and fault detection to enhance system reliability and scalability.

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