NTU Journal for Renewable Energy (2026) Vol. 10 (1): 21-30
DOI: https://doi.org/10.56286/1rpz0d67

IRAQI Academic Scientific Journals

JRE NTU

ISSN: 2788-9912 (print); 2788-9920 (online)
NTU Journal for Renewable Energy
Available online at:
https://journals.ntu.edu.iq/index.php/NTU-JRE

Energy-Efficient HVAC Technologies and Strategies: A Comprehensive Overview

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Article Information

Received: 07 – 12 – 2025
Received in Revised form: 28-12-2025
Accepted: 21 – 01 - 2026
Published: 16 – 02 – 2026

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Key words:
HVAC technologies, HVAC control strategies, Energy Efficiency, HVAC Optimization, Variable Refrigerant Flow (VRF), Ground Source Heat Pumps (GSHP), Thermal Energy Storage (TES).

ABSTRACT

This review paper examines state-of-the-art energy-efficiency technologies and techniques in the heating, ventilation, and air conditioning (HVAC) field. Specifically, the analysis focuses on the following advanced technologies: Variable Refrigerant Flow (VRF) systems, Thermal Energy Storage (TES) systems, renewable energy integration (solar and geothermal), drying cooling, and state-of-the-art control technologies. This analysis focuses on the systematic study of the relevant peer-reviewed articles available in the Scopus, Web of Science, and ScienceDirect databases released between the years 2010 and 2024. The primary methodology included in the analysis was the use of experimental studies and high-fidelity simulations, which provided the evaluated criteria on which the research was premised. The advanced energy systems are more energy-efficient than the traditional air conditioning systems, and the research provides clear, demonstrable findings of this claim. For example, energy savings in cooling load use from VRF systems were around 70%. This rivew work also provided the geothermal heat pumps (GSHPs) of which the author focuses on a single performance parameter in this climate model: the GSHPs of which despite the high initial capital expenditure are the most energy efficient systems in extreme climates, which are the most energy. The review also provides evidence of wide scope limitations, including: A global absence of long-term comparative studies on the most mature systems (VRF and GSHP) in a variety of buildings, and a lack of comprehensive economic models, which effectively incorporate lifecycle analysis LCA and the local cost of electricity to facilitate meaningful investment. This review additionally provides an analysis of energy-efficient air conditioning technology, evaluates its performance, and suggests future research to fill the remaining empirical and knowledge-based economic voids.

Introduction

The buildings' thermal comfort and air quality are in part determined by HVAC systems. Due to rising energy consumption and climate change, the development of new technologies and effective methods to improve HVAC system efficiency is essential. The purpose of this research paper is to provide a review of the literature to identify the recent technological innovations in HVAC systems, especially in sustainable cooling, smart systems, and renewables. A significant portion of the energy utilized in buildings is HVAC systems energy, which underlines the importance of appropriate methods and solutions tailored to buildings' energy consumption and efficiency. Some methods include advanced control of the indoor climate, different types of insulation, and the use of passive cooling. The primary purpose of this review is to illustrate the recent technological innovations and new methods to minimize energy consumption and improve HVAC systems efficiency, which are critical for sustainable development and minimizing the damage caused by extreme energy use and gas emissions [1].

1. Energy principles for efficient HVAC systems

Energy efficiency in HVAC systems is achieved by improving the performance of their units and optimizing operations to reduce energy consumption while maintaining indoor air quality, temperature, humidity, etc. The main principles include [2]:

- Energy recovery and avoidance of waste.
- Use of advanced control management systems.
- Utilization of renewable energy.

2. Benefits of efficient HVAC systems

When using effective strategies to improve the efficiency of heating, ventilation and air conditioning systems, this brings many benefits that improve daily operations, including the following [3]:

- Lower costs: The most important advantage of efficient HVAC systems is reducing the costs of large energy bills.
- Reducing CO_2 emissions: Reducing energy consumption leads to reducing emissions, which leads to achieving sustainability goals and getting closer to zero emissions.
- Operation when needed: Ensures less system downtime, less maintenance, and avoids loss of productivity and equipment.
- Increased equipment life: This is due to less stress on the components of the devices and thus less waste.
- Increased comfort for building occupants after these improvements, which creates a positive environment.

3. Efficient HVAC Systems Technologies

Efficient HVAC systems technologies seek to achieve a balance between occupant comfort and energy efficiency, which in turn contributes to reducing financial and environmental costs. They include many technologies, including:

1. Variable Refrigerant Flow (VRF) Systems.
2. HVAC systems with thermal energy storage (TES).
3. HVAC systems with Renewable Energy Sources.
4. Geothermal heat pumps integrate with HVAC systems.
5. Desiccant Cooling Systems.

Below is a review of the most important studies conducted for each type of these technologies:

4.1. Variable Refrigerant Flow (VRF) Systems

- In a 2016 study, Xinqiao Yu et al. examined variable airflow (VAV) and variable refrigerant flow (VRF) systems for five office buildings in China. The cooling energy consumption of these systems was compared using a field survey and a site-based data collection system. A building simulation system was used to determine the impact of these systems on cooling loads. The Variable Refrigerant Flow (VRF) Systems demonstrate a significant reduction in energy consumption, using less than 70% of the energy required for conventional cooling loads. [4]
- A 2020 study by Byeongmo Seo et al. compared the energy consumption of a water-cooled VRF system and a chiller-based AHU in a 10-story commercial building in Seoul, South Korea. Integrated simulation software such as Energy Plus and Matlab. The results showed that the VRF system consumed 113 MWh less energy. [5]
- A 2009 study conducted by Tolga N. et al. in the United States compared the performance of VRF and VAV air conditioning systems in an office building in terms of energy consumption, indoor temperature control, and operational efficiency during the cooling season. The Energy Plus program was used. The results showed that the VRF system was 27.1% and 57.9% more energy efficient than the VAV system. The VRF system also consumed 38% less energy. [6]
- In 2009, Xiaobing Lin and Tian Zheu Hong presented a study comparing the energy efficiency of VRF and GSHP systems for a small office building in two different climates in the United States. Using simulation tools such as Energy Plus and eQuest, the

results showed that the GSHP system was more energy efficient than the VRF system. The system saved 9.4% of energy consumption in Miami and approximately 24.1% in Chicago. [7]

- In 2017, Emrah Ozahi and others presented a study comparing a conventional HVAC system with a VRF system in terms of thermal efficiency and economic costs in an 8,852-square-meter building located in Turkey. Quantitative analysis and weather data were used to conduct energy-economic modeling and analysis. The results showed that the VRF system was 44% more efficient than conventional systems. [8]
- A 2015 study by Chao Liu et al. analyzed the electricity consumption of VRF systems and the centralized system for two office buildings on a university campus in China. Data from the energy monitoring and management system was analyzed, and the results showed that the VRF system had better operational flexibility than the centralized system. [9]
- A 2017 study by Dongsu Kim et al. aimed to evaluate the performance of VRF systems compared to RTU-VAV systems in the United States. Energy Plus software was used to model a medium-sized office and simulate 16 different climate locations. The analysis results showed that the VRF system provided energy savings of 15% to 42% compared to the other system, and also demonstrated cost savings of up to 32%. [10]

Therefore, the efficiency of VRF systems is highly sensitive to proper installation and climatic factors, while they offer great flexibility and energy savings under partial load conditions.

4.2 HVAC systems with thermal energy storage (TES)

- A study presented by M. Ortiz et al. in 2010 aimed to design and model a solar-powered heating, ventilation, and air conditioning (HVAC) system with thermal storage, and to evaluate the performance of this system in an educational building in a high desert climate in New Mexico, USA. This was done using a numerical performance prediction model. TRNSYS software was used. The results showed that solar energy can meet more than 90% of heating requirements and reduce external cooling energy consumption by 33% to 43%. [11]
- In 2010, R. Parameshwaran et al. presented a study aimed at implementing a new system combining a VAV system and a thermal energy storage (TES) system using phase change materials (PCM) in India. Temperatures sensors were used. The results of this system implementation showed energy savings of 28% using DCV technology and 47% using ECV technology compared to conventional air conditioning systems, and it also reduced energy consumption by 42%. [12]
- In a study presented by Apple, L. S. Chan, and others in 2006, the aim was to evaluate the performance of a central cooling system (DCS) when integrated with an ice storage system. A hypothetical site in Hong Kong, China, was modeled using TRNSYS and DOE-2 simulation software to analyze performance. The analysis results showed that a DCS system with 40% ice storage had better energy performance and reduced environmental impact, but the financial costs were not favorable. [13]
- In a study conducted by Na Zhu et al. in 2011, the aim was to study the effect of integrating SSPCM into building walls on energy consumption, peak demand, and electricity costs in air conditioning systems. A VAV system was simulated in a four-story commercial building in Hong Kong. The simulation results showed an 11% reduction in electricity costs and a 20% reduction in peak load. [14]
- In a study presented by Meng Zhang et al. in 2005, they developed a phase change thermal wall, As shown in (Fig. 1), to reduce air conditioning demand. Measurement equipment and simulation software were used to evaluate thermal performance. This study was conducted in Lawrence, Kansas, USA. Field tests showed that phase-change frame wall (PCFW) reduced heat flow through walls by 38%, lowered energy consumption, and reduced thermal loads. [15]

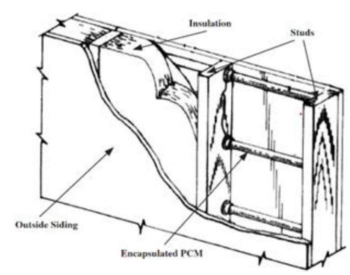

Figure 1: Schematic of the phase-change frame wall. [15]

- A study conducted by Guobing Zhou et al. in 2011 aimed to analyze the thermal performance of a hybrid cooling system using SSPCM panels with nighttime ventilation in office buildings in Beijing, China. Numerical simulations were conducted throughout the summer. The use of SSPCM panels showed that maintained indoor temperatures and saved approximately 76% of daytime cooling energy consumption, (Fig. 2) shows the location of the SSPCM panels in the room. [16]

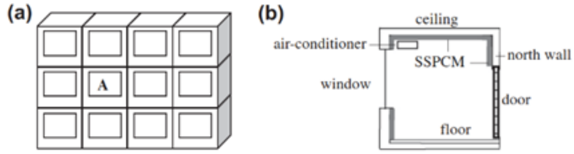

Figure2: (a) location of the simulated room (b) profile of the room with SSPCM. [16]

- Another study, presented by Jisoo Jeon in 2012, aimed to explore phase change materials (PCMs) as a means of thermal energy storage (TES) in buildings. The study focused on floor heating systems in Korea. Simulation software such as ANSYS and Matlab was used. Results of using this material showed reduced energy consumption, improved thermal comfort. [17]

TES systems achieve high efficiency when combined with phase change materials or renewable energy sources, so they are a strategic solution for shifting electrical loads from peak to off-peak periods. However, they face the challenge of high cost.

4.3 HVAC systems with Renewable Energy Sources

- In a 2011 study, researchers Shiwei Li and Shihua Song Zhang sought to develop and design a new air conditioning system that combines absorption cooling with membrane absorption technologies, (Fig.4). Photovoltaic solar collectors were used as the system's power source. The results showed that the proposed system was capable of achieving a performance factor that may exceed that of conventional cooling systems, and was also environmentally friendly [18].
- In 2005, a study by Q. Ma et al. focused on the performance evaluation of a hybrid air conditioning system, particularly designed for green buildings (an absorption chiller coupled with a solar collector). The system was used in a building in China. For the performance evaluation, the authors used a set of performance measuring instruments, specific software designed for computation and a set of models. The evaluation revealed that the hybrid system is 44.5% more effective than the conventional system [19].
- In 2007, Zhai Xiaoqin also conducted a study with the aims of analyzing the use and the design of solar-powered air conditioning units and the principles of green building. The project was done in China and used 150 square meters of solar collectors. The study concluded that the system is highly reliable in the use of solar energy (i.e. solar radiation), especially during the summer months, with 71% of the electricity used by the system was derived from solar energy [20].
- A study by Yaehong Bi et al. in 2020 analyzed the performance of a solar air conditioning system based on a polarized mirror collector (PTC), an energy storage device, and a single absorption chiller. Solar radiation simulation software and measurement devices were used, and the study was conducted in China. The results showed the system's ability to provide continuous and stable cooling. The solar collector efficiency was 67.5%, the energy storage efficiency was 0.8%, and the total solar energy generated reached 82.4% [21].
- In a 2015 study, Bin Juine Haung et al. designed and analyzed a direct solar-powered air conditioning system using stand-alone PV panels, six air conditioners of different sizes were selected for the solar panels, and control, monitoring, and performance measurement devices were used. The study was conducted in Taiwan. Results showed that this system was a suitable design and achieved high energy performance compared to conventional air conditioning systems [22].
- A 2013 study by Boonrit Prasart Kaew and S. Kumar aimed to explore the effectiveness of a hybrid air conditioning system combining solar energy and biomass as a sustainable solution. Data measurement and temperature control systems were used, along with a set of 26 flat-panel solar collectors. The study was conducted in Bangkok, Thailand. The results showed that the system achieved an efficiency of 75% and a coefficient of performance of 0.11, outperforming conventional systems [23].
- C. Koroneos et al. (2010) presented a study aimed at analyzing the feasibility of solar-powered air conditioning systems, evaluating their economic and environmental benefits. Exergy analysis was used to evaluate performance, and thermal simulation software was used to calculate loads for a medical building located in Greece. Results showed that the system covered a significant portion of the cooling demand, up to 35% [24].

The ideal solution for achieving environmental sustainability may lie in integrating renewable energy into HVAC systems, as solar and geothermal heat pump systems offer the highest energy savings but require very large initial investments.

4.4 Geothermal heat pumps integrate with HVAC systems

- A study by A. D. Chaisson P.E. et al. in 2004 aimed to improve the energy efficiency of an air conditioning system for a school building in southeastern Wyoming, USA by Using a geothermal heat pump (GHP) system with a solar thermal collector. BLAST was used to analyze heat loads and energy consumption, GLHEPRO to design and estimate the performance of a ground-based heat exchanger, and TRNSYS. The results showed energy savings of up to 74%, making it an effective option for improving school air conditioning systems. [25]
- In a 2016 study by G. Angrisani et al., the aim was to study the dynamics of a heating and cooling system

based on low- or medium-temperature geological sources, in addition to providing domestic hot water. The TRNSYS software was used to design and analyze renewable energy systems, and the study was conducted in Italy. The results showed that initial energy savings ranged between 77% and 95%, with a payback period of 1.2 to 1.4 years. [26]

- In 2020, a study by Jian Yong Wang et al. introduced a system that integrates geothermal energy-based cooling, heating, and power generation, while using Matlab and other programs as computational platforms for numerical simulations. This study was carried out in China, and its findings exhibited exergy efficiency of 43.69% on geothermal water of 170°C [27].
- In 2023, Alok Dhaundiyal et al. investigated the hybrid heating system using either surface heat or natural gas. This study used the Least Advanced Regression (LAR) algorithm and employed temperature and humidity measuring devices, as well as data processing software, to formulate equations for specific thermodynamic variables. The research was conducted in Hungary and was able to show that the system had a performance coefficient (COP) of 2.07, exergy efficiency of 3%, and a total energy reduction of 26.25 Wh/m^2 [28].
- In 2019, Lü Weihua et al. aimed to create a design to optimize a closed-loop geothermal integrated air conditioning system. Tools and software available during that time were limited to simulating buildings' energy consumption and heat transfer within buildings, and this research was being done in China. The study demonstrated a system that could remain below 28 °C all year and reduce the use of air conditioning for the indoor temperature to 34 %, cooled load to 29 %, and total annual load of 43 % [29].
- In 2018, Selvaraj S. Naicker and Simon J. Rees studied the differentials of a high geothermal heating and cooling system composed of 56 vertical heat exchangers and 4 large heat pumps. The data measurement systems consisted of temperature and flow meters and statistical analysis software, while the data was analyzed in the UK on a mathematical model. The systems seemed to perform as expected, although the efficiencies varied depending on the current operation conditions of the systems [30].
- In 2018, Selvaraj S. Naicker and Simon J. Rees carried out a performance evaluation research for large-scale geothermal heating and cooling systems with 56 vertical heat exchangers and four large heat pumps. They used temperature and flow meters and statistical analysis software to process in mathematical models. This research was carried out in the United Kingdom. Their systems did operate within the expected range, but the efficiencies were influenced by the prevailing operational circumstances [31].

Geothermal heat pumps systems are highly energy-efficient and offer stable performance in harsh climatic conditions, making them a strategic investment for sustainable buildings. However, they face the challenge of high initial costs.

4.5 Desiccant Cooling Systems

- A study by S. White and M. Goldsworthy in 2010 was aimed at improving a solar active air conditioning system with a desiccant. This system incorporated a desiccant wheel and evaporative cooler. Relative humidity and temperature data were used in the study, which was conducted in Australia with the aid of some simulation programs. The results claimed that this system can achieve considerable energy saving and considerable reduction of CO_2 emissions [32].
- In 2011, Ertaç Hurdoğan, carried out a study concerning the efficiency and improved performance of a refrigeration system using a nitric acid-based desiccant. This study took place in Turkey, where temperature measuring devices, humidity measuring devices, and a data measuring system were used. Efficiency of the system was recorded as having 10 – 32 % [33].
- In 2009, T. S. Ge et al. published a study comparing the dynamic, thermal, and economic characteristics of a solar-powered rotary adsorption refrigeration system with a traditional vapor compression refrigeration system under different climatic conditions in Berlin, Germany and Shanghai, China. The results showed that adsorption refrigeration systems have advantages in improving air quality, reducing power consumption, and protecting the environment [34].
- In 2012, Ali M. Baniyounes et al. conducted a study assessing the technical, economic, and environmental impacts of solar absorption cooling systems in public buildings and comparing them with conventional cooling systems. The study employed various performance evaluation tools. The results showed that solar absorption cooling systems have a high coefficient of performance (COP), can absorb heat(s) from the solar environment, and reduce CO2 emissions by approximately 44.4 tons [35].

In 2010, K. F. Fong et al. conducted a study aimed at improving and absorption system solar strategy and improving the hybrid design and systems used. TRNSYS is one of the simulation software used in the study conducted in Hong Kong. The system was able to retain to attain 35.2% of the total energy [36].

- In 2020, a number of researchers, including Yu Lho Lee, conducted research aimed at exploring the effectiveness of solid absorption cooling systems. One-dimensional mathematical models were developed using Matlab Simulink to compare the performance of three types of cooling systems: DEC, IEC, and HDC. The study was conducted in South

Korea. The comparison results showed that the HDC system achieved a superior performance coefficient compared to other systems and achieved a higher cooling capacity, making it the ideal choice for use in hot and humid climates. [37]

- Mehmet Kanôglu et al. (2003) conducted a study to analyze the energy and exergonic properties of open-cycle absorption refrigeration systems and improve their performance. Temperature and humidity measuring devices and software such as Matlab were used. The study was conducted in Turkey. The analysis results showed that the system's coefficient of performance was 0.35, the reversible coefficient was 3.11, and the exergonic efficiency was 11.1%. The absorption wheel contributed 33.8% to the exergonic destruction, while the heating unit contributed 31.2%. [38]

Integrating Desiccant Cooling Systems with renewable thermal energy achieves high operational efficiency, making them strong competitors to traditional systems in air quality applications. These systems also represent an ideal solution for humid climates.

Table 1 shows the comparison between the aforementioned HVAC technologies.

4. Efficient HVAC Systems strategies

In addition to the above techniques, there are many strategies that help manage energy and improve performance when integrating HVAC systems. The following is a review of the most important studies that addressed most of these strategies:

- A study conducted by S. Rosiek and F.J. Batlles in 2010 aimed to present a model for improving the performance of solar-powered air conditioning systems using artificial neural networks (ANNs). Statistical analysis was conducted, experimental data was collected, and Matlab software was used. The study was conducted in Spain. The results showed high accuracy in predicting system efficiency using ANNs, with the root mean square error (RMSE) being less than 1.9%, demonstrating the model's good performance. [39]

- Qiu Tu et al. implemented a research project in 2010 to develop an effective control strategy for an air conditioning system based on Variable refrigerant flow (VRF) with several outdoor units. Temperature and pressure measuring devices, experimental data loggers, and system modelers.

- via MATLAB. This research was conducted in China. According to the results, the suggested methods reduced the consumption of energy in comparison with other methods [40].

Table 1: The Comparison of HVAC Technologies

Technology	Max. Energy Savings Potential (vs. Conventional)	Initial Capital Cost	Ideal Climate/Application	Primary Challenge/Knowledge Gap
Variable Refrigerant Flow (VRF) [4-10]	Up to **%70** vs. (VAV/Chillers)	Medium to High	Moderate to Diverse Climates, Buildings with varied zones/loads**.**	Requires advanced control for optimal part-load operation**.**
Thermal Energy Storage (TES) [11-17]	Up to **%76** (Daytime Cooling)	High	High Demand Climates, Commercial/Institutional Buildings**.**	High initial costs **;**Need for updated Life Cycle Cost (LCC) analysis**.**
Solar HVAC (Absorption/PV) [18-24]	Up to **%82** (Solar energy contribution)	High	High Solar Radiation Regions (where heat/electricity demand correlates with sun exposure)**.**	High initial costs; Low absorption COP in some systems**.**
Geothermal Heat Pumps (GHP) [25-31]	**%74**to 95% (The Highest)	Very High	Extreme Climates, Large Stable Loads (Schools, Hospitals)**.**	Very High initial investment; Efficiency variability based on operating conditions (requires sophisticated control)**.**
Desiccant Cooling [32-38]	Up to **%76** (Daytime Cooling)	Medium to High	Hot and Humid Climates (Superior humidity control).	Lower COP range; Complexity of hybrid systems and thermal regeneration process**.**

• Nabil Nassif introduced a study in 2011 that aimed to concentrate on a CO2-based ventilation strategy as an efficient method for the control of airflow. The study used eQuest and CO2 sensors, as well as data analysis tools. This research was conducted in the United States. The results of the research proved that the CO2-based ventilation strategy can be used to achieve a considerable amount of energy savings, about 23%, and also assist in controlling CO2 concentrations [41].

• M. Mohanraj et al. in 2011 conducted a comprehensive review to focus on the applications of artificial neural networks (ANN) in the energy and elixir analysis of refrigeration and air conditioning systems. This review was conducted in India. The research examined demonstrates that the proper application of ANN models increases the energy efficiency and decreases the consumption of HVAC systems [42].

• A study by Younghua Zhu et al. in 2014 aimed to develop an energy-saving control strategy for a combined air conditioning system that combines a VRF system and a VAV system in heating mode. Several tools and software were used to develop the model, including TRNSYS. This study was conducted in China. The results demonstrated the effectiveness of the proposed strategy in achieving energy savings of 5.17%. It also maintained specific temperatures within the area. [43]

• A study conducted by Liu Xuefeug et al. in 2015 examined and analyzed different control strategies for parallel pump systems for chilled water in air conditioning systems, and identified the most appropriate strategy to improve system performance. The research incorporated multiple tools and software to analyze the performance of the strategies. This study was conducted in China. Results showed that using a hybrid strategy was the best for chilled water systems. [44]

• A 2016 study by Geun Young Yun et al. aimed to develop a control model that could adjust the evaporation temperature in a VRF system in response to cooling loads. Multiple tools and software were used to achieve this goal, including the Energy Plus program, as well as temperature, humidity, and flow rate measuring devices. This study was conducted in South Korea. The results showed that increasing the evaporation temperature reduced the energy consumption of the VRF system by 35%. [45]

• A study presented by Abdul Afram et al. in 2017 aimed to review current trends in the use of neural networks (ANNs) in the design of modular predictive control (MPC) systems. A new algorithm was developed using multiple tools and software such as Matlab, TRNSYS, and others. The study was conducted in Ontario, Canada. The results showed improved prediction performance, with prediction quality improvements ranging from 6% to 59%. Using a predictive MPC model resulted in operating cost savings ranging from 6% to 73%. [46]

5. Obstacles to the application of technologies and strategies to HVAC systems [47]

1. High costs: as updating HVAC systems requires a large financial investment.
2. The integration process is complex as it requires experience and knowledge.
3. Lack of skilled workers in the field of technologies.
4. Lack of consumer awareness of the benefits of these advanced technologies leads to low demand for them.
5. Poor infrastructure does not accommodate new technologies.
6. Difficulty in maintenance as it requires specialized and expensive maintenance.
7. Energy efficiency may not be at the required level and does not justify the investment for some users.
8. Market competition as there are multiple options that may confuse consumers and complicate the decision-making process.

6. Future trends in efficient HVAC technologies and strategies [48]

1. Using Internet-based IOT systems to automatically control temperatures and air quality.
2. Analyzing data with artificial intelligence, where artificial intelligence techniques are applied in data analysis, such as predicting ventilation and air conditioning needs.
3. Renewable energy: Integrating renewable energy types such as solar energy with other sources to reduce dependence on traditional sources such as electricity.
4. Predictive maintenance using fault sensors, which reduces maintenance costs and increases reliability.
5. Awareness: Increasing awareness about the benefits of the technologies and strategies used and energy efficiency.

All of the above contribute to increasing energy efficiency, reducing consumption, improving indoor air quality, and reducing environmental impact.

Conclusion

This work represents a review of various studies (theoretical and experimental) on several techniques and strategies that improve the performance and efficiency of air conditioning systems, in addition to comparing them with traditional systems. It can be said that the following conclusions were reached:

- When using VRF systems and comparing them with other types, it was found that they are more energy efficient compared to VAV systems and others [4,6]. Therefore, these studies that included VRF systems showed that these systems have high energy efficiency and lower costs compared to traditional systems.
- When using HVAC systems with thermal energy storage systems, solar energy meets the majority of the demand and reduces energy consumption [11]. When combining a VAV system with thermal energy storage systems using phase change materials, the total consumption was reduced by 42%. [12] Using SSPCM panels also maintains internal temperatures and saves 76% of energy consumption [16]. However, these systems can have high financial costs [13]. This technology can reduce environmental costs.
- When renewable energy sources are used with air conditioning systems, it has been found that these systems are environmentally friendly [18]. They also achieve 44.5% better performance compared to traditional systems [19]. In addition, solar energy contributed 71.7% of the energy required in the summer [20]. These systems achieve high energy efficiency, but costs still represent a challenge.
- Using geothermal sources with air conditioning systems saves up to 74% of energy, making it an effective option for improving air conditioning systems [25]. It also improves the coefficient of performance, reaching 2.07[28], reduces air conditioning use by 34%, and reduces heat by 29% [29]. These systems work satisfactorily, but their efficiency varies according to operating conditions [30]. Geothermal heat pumps improve energy efficiency and reduce operating costs for HVAC systems.
- Using an absorption material with air conditioning systems can achieve significant energy savings and reduce CO_2 emissions [32]. The absorption system also provides better air quality and lower electricity consumption [34]. Using improved absorption system strategies has achieved energy savings of up to 35.2% [36]. Absorption cooling systems offer high energy efficiency and better environmental performance compared to traditional systems.

As for the use of certain strategies, their use improves the efficiency of air conditioning systems and reduces consumption. The results of using the ANN strategy showed high accuracy in predicting system efficiency [39], improving performance and reducing operational costs [46]. Also, the use of an effective control strategy reduced energy consumption compared to traditional systems [40]. Using a ventilation strategy based on CO_2 achieved energy savings of up to 23% [41].

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