Research on the Green Development of the HVAC Industry

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Abstract. The green development of HVAC industry (Heating, Ventilation, and Air Conditioning) refers to the adoption of energy-saving, environmentally friendly, and efficient technologies and products, as well as systematic design and management methods, in order to reduce negative environmental impacts while meeting people's needs for a comfortable living environment. Research on the green development of HVAC is of great significance for promoting energy efficiency, protecting the environment, achieving sustainable development, and realizing the goals of peaking carbon dioxide emissions & achieving carbon neutrality. The development is highly valued internationally, with scholars continuously conducting in-depth studies and explorations on the green development of HVAC, using technologies such as variable frequency technology, artificial intelligence, etc., providing academic theoretical support and guidance for its development direction. Therefore, this overview will summarize the current state and trends of green development research in the HVAC industry, focusing on the introduction of research results in the areas of technical principles, technological innovation, market promotion, and development trends in the HVAC field, and will look forward to the trends in the green development of the HVAC industry in the future.

Keywords: HVAC; green development; Energy conservation and environmental protection; peaking carbon dioxide emissions & achieving carbon neutrality

1 Introduction

As an important component of building energy consumption, the green development of the HVAC industry plays a significant role in energy saving, emission reduction, and achieving sustainable development. In recent years, researchers have conducted extensive studies on the green development of the HVAC field and have achieved a series of important results. Therefore, it is necessary to review these research achievements to provide references for the green development of the HVAC industry.

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2 Overview of Technological Development in the Hvac Industry

2.1 Study on the Characteristics of Hvac Technology and System Composition

Hao C, et al. pointed out in his study, as an indispensable part of modern buildings, HVAC systems create a comfortable and pleasant environment inside buildings through the integrated use of heating, ventilation, and air conditioning technologies. This system is a complex and refined integration, encompassing multiple key components that work together to maintain the stability and comfort of the environment. The entire HVAC system, include advanced the control technologies and sensors, improves the system's energy efficiency and ensures the stability and comfort of the usage environment through precise control, meeting people's pursuit of a high-quality living environment[1].

Anil S, et al. believe that among the numerous heating methods, electric heating, gas heating, and hot water/steam heating dominate, with there unique advantages and application scenarios. Electric heating is characterized by fast response speed and precise control, but it has higher energy consumption. Gas heating has the advantages of high thermal efficiency and low cost, but gas supply and safety issues need to be considered. Hot water/steam heating is known for its low thermal inertia and good stability, making it very suitable for large buildings and public facilities. After years of development and optimization, their operation is stable and reliable[2].

Aswani A, et al. pointed out that air conditioning technology, as the most core technology in the HVAC system, plays a crucial role in regulating and improving indoor environmental quality. It mainly adjusts the people's needs for a comfortable living environment[3].

Combining the above research shows that the HVAC system creates stable and comfortable climatic conditions for the indoor environment through precise control and various technological means, fulfilling people's pursuit of a high-quality living environment.

2.2 Study on the HVAC System Composition

The energy consumption of HVAC systems has always been an important direction of research for researchers. In modern buildings, HVAC systems often constitute a major part of energy consumption, sometimes even accounting for more than 50% of the total energy consumption of the entire building.

Table 1. Typical behavior and its impact on reducing energy consumption

Behavioral mode	Energy-saving effect	Behavioral mode	Energy-saving effect
Shading	5 ~ 20%	electricity-saving propaganda reminders	20 ~ 60%

window opening	10 ~ 25%	information disclosure	20 ~ 30%
heating	20 ~ 30%	pricing models	20 ~ 30%
air conditioning	8 ~ 40%	building envelope structure	8 ~ 10%
lighting	4 ~ 10%	urban heat island effect/greening settings	4 ~ 10%
comprehensive use of technology-related behaviors	10 ~ 40%	energy-saving appliances selection/home appliance standby	60 ~ 80%

As can be seen from Table 1, the potential for reducing energy consumption through technological usage behaviors is roughly between 10% and 40%; external policies such as energy information disclosure and pricing models have the potential to reduce residential energy consumption by 20%～30%; consumer behaviors related to appliance choice for residents have a higher potential for reducing energy consumption, which can exceed 60%, and the potential for reducing energy consumption through reminders to save electricity is also significant, roughly between 20% and 60%[4].

O'Connor T believes that improper design of HVAC systems is an important reason for high energy consumption. If the design does not meet the actual needs of the building or the local climate conditions, it will lead to the waste of energy. Errors in load calculation, selection of meteorological parameters, and configuration of air conditioning capacity can all lead to energy waste[5].

Yoon J H , et al. argues that over time, various components of the HVAC (heating, ventilation, and air conditioning) system, especially key components like compressors, fans, and sensors, may experience wear and performance decline. This degradation not only reduces the efficiency of the system's operation but also leads to an increase in energy consumption. This results in the system needing to consume more energy to achieve the desired air flow rate and temperature distribution[6].

Heather Ramsden pointed out in her research that a building's insulation performance is one of the important indicators for evaluating its energy efficiency, especially under variable or extreme climate conditions. Insulation materials, such as fiberglass, polyurethane, and rock wool, can effectively reflect or absorb thermal radiation and prevent heat transfer[7].

Combining the aforementioned research, the energy consumption issue of HVAC systems is a multifactorial and multi-level problem that needs comprehensive consideration from aspects such as design, equipment, operation, and architecture. To reduce the energy consumption of HVAC systems, it is necessary to adopt optimized designs and improve the building's insulation performance, which can effectively lower the energy consumption of HVAC systems and achieve the goal of energy saving and emission reduction.

2.3 The Current Status of Green Development in the HVAC Industry

MATT JACHMAN, et al. believes that the rational selection of HVAC system types is crucial for achieving high efficiency and energy saving. For instance, Variable Refrigerant Flow systems, which adjust the flow of refrigerant to match indoor load changes, offer flexible temperature control and thus enhance energy utilization efficiency. Additionally, water-source and geothermal heat pump systems, which utilize groundwater or geothermal energy for cooling and heating, are efficient, clean, and stable, making them a commendable green HVAC option[8].

SELENA COTTE mentioned in her research that IoT technology could be utilized for remote monitoring and intelligent control of HVAC systems. By transmitting real-time data from sensors and controllers in the HVAC system to the cloud, management can monitor system status at any time. With technological advancements, adaptive learning functions are gradually being applied in HVAC systems, gradually achieving automated operation of HVAC system equipment. Based on the analysis of historical data, potential equipment failures can be predicted and maintenance can be performed in advance, thus reducing the failure rate, extending the equipment's lifespan, and reducing maintenance costs[9]. Nicole Krawcke mentioned that intelligent HVAC systems could simplify operations, thus improving efficiency and reducing energy consumption. This indicates that leveraging modern technology to develop intelligent tools has significant implications for energy-saving innovations in HVAC systems[10].

Satomi Kakuya notes that traditional refrigerants, such as chlorofluorocarbons, damage the ozone layer and contribute to an increase in greenhouse gas emissions, exacerbating global climate change. Hence, switching to environmentally friendly refrigerants, like hydrocarbons and ammonia, represents an effective way to reduce environmental harm. Furthermore, establishing relevant laws and regulations to control the emission of refrigerant pollutants is essential[11].

Eamonn Ryan discussed the application of IoT in the HVACR field. He pointed out that the integration of IoT could enable more refined management of HVAC systems, optimizing energy allocation to achieve energy savings. This offers a new perspective: using IoT technology for intelligent retrofitting of HVAC systems to achieve energy-saving goals[12]. Darrell Sterling researched the optimization of the HVACR supply chain. He found that optimizing the supply chain could ensure HVAC system components arrive more timely where needed, thus improving the system's operational efficiency and reducing energy consumption. This provides a new idea: achieving energy-saving goals for HVAC systems through optimized supply chain management[13]. Dave Richards researched the selection of HVAC refrigerants. He found that the right choice of refrigerants could significantly improve the system's energy efficiency ratio, thus achieving energy savings. This suggests that in the energy-saving innovation of HVAC systems, the selection of refrigerants should be emphasized to improve the system's energy utilization efficiency[14]. Andrew Gaved proposed suggestions for the reform of F-Gas regulations. He believes that clear guidance on the reform of F-Gas regulations has a significant impact on the adoption of new environmentally friendly refrigerants in HVAC systems[15]. In modern architectural environment control, the selection and application of HVAC systems are particularly critical. Researchers unanimously believe that efficient and energy-saving HVAC systems are essential for achieving environmental and low-carbon goals, and realizing the efficient, energy-saving, and environmentally friendly operation of HVAC systems requires comprehensive consideration of multiple aspects.

From the choice of system type and refrigerant replacement to the application of intelligent technologies, every link is crucial. Only by comprehensively optimizing and enhancing the performance of HVAC systems can we better meet the dual needs of modern buildings for a comfortable environment and energy conservation and emission reduction.

3 Research Pathways for Green Energy-Saving Technology Innovation in HVAC

Energy-saving technology is key to the green development of heating, ventilation, and air conditioning. Researchers have conducted in-depth studies in areas such as refrigeration system optimization, heat pump technology, and heat recovery technology. Jacques Gandini used a single thermodynamic space HVAC system as a case study to propose an energy-saving concept based on unified control, which centralizes energy-saving directions based on heat loss. It automatically adjusts the operation of the HVAC system based on indoor-outdoor temperature differences, occupancy, and energy efficiency ratios, avoiding excessive cooling or heating to improve energy utilization efficiency and achieve energy-saving goals[16]. Ioan URSU and others noted that a quality HVAC system has two goals: ensuring comfort and saving energy. HVAC systems with variable frequency control systems can achieve the lowest energy consumption and comfortable.

JOANNA R. TURPIN designed an AI-driven HVAC system using GPT. The system, through establishing temperature control cycles and humidity ratio control cycles, achieves precise control over the operation of HVAC systems. GPT analyzes the operation mechanism and energy consumption characteristics of the entire HVAC system, accurately assessing and optimizing the system's performance. In HVAC systems, GPT uses sensors to collect data on temperature, humidity, air quality, etc., analyzing these data with deep learning algorithms to predict indoor environmental needs. GPT can also automatically adjust the HVAC system's operation mode according to outdoor climate conditions and indoor load changes, achieving energy-saving and emission reduction purposes[17]. Staff from the Department of Building Research at the Korea Institute of Civil Engineering and Building Technology utilized ChatGPT to analyze the HVAC system of an office building, evaluating that the energy saving rate could reach up to 24.1% while ensuring the office CO_2 concentration remained below 1000 ppm. This ultimately met the requirements for environmental health and comfort as well as low energy consumption[18].

Junjie Chu, et al. use evaporative cooling air conditioning system to reduce the energy consumption of the refrigeration and air-conditioning system in the Data center, the applica-tion conditions and scenarios of the different forms of evaporative cooling air-conditioning systems should be considered comprehensively, it can use a lot of clean energy and low environment affluence[19]. Wu Lei, et al. have compiled statistics on the PUE (Power Usage Effectiveness) of air conditioning cooling systems in data centers[20]. Based on the statistical results of Wu Lei, et al., make the table as shown in Table 2.

Table 2. PUE of the main forms of data center air conditioning systems

forms	PUE
Water-cooled chiller air conditioning system	1.3 ~ 1.5
Fluorine pump and heat pipe air conditioning	1.25 ~ 1.4
Evaporative cooling air conditioning system	1.15 ~ 1.25
Water-cooled chilled water and Modular heat pipe multi-split	1.2 ~ 1.25
Water-cooled chilled water and Fresh air AHU system	1.25 ~ 1.3

From the above table, it can be seen that among the main operating forms of data center systems, the comprehensive energy efficiency of the indirect evaporative cooling system is higher than other compression refrigeration forms. The Chuanxi Big Data Center has adopted the Yimikang indirect evaporative cooling system solution, which ultimately can reduce the annual electricity consumption by 33.1%. The indirect evaporative cooling system is a comprehensive product that encompasses wind heat, water heat, variable frequency compression technology, and intelligent control. Moreover, it is cost-effective, making it the most cost-effective green HVAC solution at this stage[21~22].

Layan Dahhan reviewed the latest developments in the HVAC field, including new refrigerant research, the application of IoT technology in HVACR systems, and the development of intelligent control systems. These innovative technologies provide new directions for improving HVAC system energy efficiency[23].

Jian Cen, et al. using the multi-strategy improved sparrow search algorithm to reduce energy consumption during the operation of central air conditioning systems[24].

Table 3. Energy saving rate of the HVAC system in IoT mode of a building in Shanghai

Inspection Item		Inspected Data
Standard mode cooling power consumption	July, 2022	1607.8kW·h
	August, 2022	1491.7kW·h
	September, 2022	923.7kW·h
IoT mode cooling power consumption,	July, 2022	1195.9kW·h
	August, 2022	1157.9kW·h
	September, 2022	710.7kW·h
Relative energy saving rate	July, 2022	25.62%
	August, 2022	22.37%
	September, 2022	23.06%

Table 3 presents the results of tests conducted by the author in the summer of 2022 on the multi-split air conditioning (heat pump) central system designed by Qingdao Haier Air Conditioning Electronics Co., Ltd. and used by the Shanghai Institute of Building Science. The table takes the HVAC system as the test subject. In IoT mode, the optimization algorithm constrains the compressor suction pressure, cooling capacity, and superheat.. By familiarizing with users' habits, environmental factors, and the relationship with users' comfort habits, it predicts the most comfortable environmental conditions in real-time, thus accurately providing the required cooling capacity, achieving a maximum energy saving rate of up to 25.62%.

ROBERT BEVERLY discussed the impact of A2L refrigerant integration technology on HVACR service calls. By choosing and applying refrigerants wisely, HVACR system energy efficiency can be improved, and operating costs reduced[25]. John G. Falcioni at the ASHRAE Global HVACR Summit highlighted the necessity of improving building energy efficiency, using renewable energy, and developing advanced HVAC technologies[26]. Satomi Kakuya suggested using efficient HVAC equipment, such as variable frequency compressors, high-efficiency heat exchangers, and intelligent control systems[27]. Gordon White mentioned the application of IoT, big data analytics, and artificial intelligence in HVACR systems in the HVACR Briefing. These technologies can help engineers better design and optimize HVAC systems[28].

From the table 4 , it can be seen that the refrigerant R32 in A2L refrigerants has an ODP of 0 and a GWP of 675. The GWP value is moderate, significantly lower than R410A and R22, which aligns with the international advocacy for low GWP refrigerants as a replacement direction. Moreover, the molar mass of R32 refrigerant is only 0.6 times that of R22 and 71.7% of R410A. Since the charge amount is generally proportional to the molar mass, the charge amount of R32 is only 0.6 times that of R22 and 71.7% of R410A, greatly reducing the amount of refrigerant used. The relative CO_2 emission equivalent of R32 when leaked is 405, thus compared to R22, the CO_2 emission reduction ratio can reach 77.6%. This is in close agreement with the measures required by the US Environmental Protection Agency's SNAP (August 2009) to reduce CO_2 emissions by 50% to 90% in residential and commercial air conditioning, making it a key research direction.

Table 4. Common refrigerant physical properties used in the refrigeration and air conditioning industry

Refrigerant	molar mass	GWP	relative charge amount	relative CO_2 emission equivalent when leaked	CO_2 reduction ratio
R22	86.47	1810	1.0	1810	/
R32	52.02	675	0.5	405	-77.6
R290	44.10	20	0.51	10.2	-99.5
R161	48.06	12	0.56	6.7	-99.6
R410A	72.58	2100	0.85	1764	-2.5
R407C	85.20	1800	1.0	1800	0
R134a	102.03	1430	1.18	1687	-0.1
R1234yf	114.04	4	1.32	5.3	-99.7
CO_2	44.01	1	0.51	0.51	-100

In summary, researchers have achieved a series of technological innovations in the green development of HVAC systems. These innovations mainly include intelligent control methods, overall design, and optimization techniques. These research achievements not only offer new ideas for improving the energy efficiency of HVAC systems and reducing environmental pollution but also provide strong support for improving indoor air quality.

4 Conclusion

Against the backdrop of increasing global emphasis on environmental protection and sustainable development, the green development of HVAC (Heating, Ventilation, and Air Conditioning) systems has become an important research direction in the construction field. Researchers in this area have conducted extensive studies and explorations, achieving many significant results. They have proposed innovative ideas and technical solutions from multiple aspects, such as system type selection, refrigerant replacement, and the application of intelligent technologies, providing important guidance for achieving efficient energy use and environmentally friendly operation. By reasonably selecting HVAC system types, such as Variable Refrigerant Flow systems and water source heat pump systems, high energy efficiency can be achieved. Additionally, the selection of new refrigerants, waste heat recovery, and optimization of combustion equipment can help reduce the environmental impact of HVAC systems. Utilizing IoT technology and intelligent control algorithms can achieve remote monitoring and optimized control of HVAC systems, further improving energy utilization efficiency and indoor air quality. By summarizing successful experiences and technological innovations, the HVAC industry will continue to advance its green development, making greater contributions to energy conservation, emission reduction, and sustainable development.

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