Design and Performance Assessment of High Efficiency HVAC Systems Driven by Renewable Energy

Shuo LI

Wuhu Urban Construction Group Co., Ltd., Wuhu, Anhui, 241000, China

Keywords: Renewable energy; HVAC system; System design; Performance assessment; Ground-source heat pump

Abstract: With the increasingly prominent global energy and environmental problems, efficient HVAC (Heating, Ventilation, and Air Conditioning) system driven by renewable energy has become a research hotspot. The purpose of this article is to explore the design and performance assessment methods of this kind of system and provide theoretical and practical support for its popularization and application. Through theoretical analysis and case study, the application principle and types of renewable energy in HVAC system are expounded first, and then the key points of efficient system design are discussed, including system architecture, selection of key components and adaptation to building environment. The performance assessment adopts the method of combining experimental test and simulation, and selects the HVAC system driven by ground source heat pump in a 10000 square meter green office building in Shanghai as a case. The results show that the heating COP of the system is 3.8, the cooling EER is 4.2, the annual carbon emission is 150 tons, the investment payback period is 5 years, and the life cycle cost is 8 million yuan. This shows that the design method adopted is reasonable and the performance assessment index and method are effective, which verifies the potential and advantages of renewable energy in HVAC field.

1. Introduction

Under the background of increasing global energy demand and increasingly severe environmental problems, the traditional HVAC system is facing a major challenge of sustainable development because of its high energy consumption and large amount of greenhouse gas emissions [1]. Building energy consumption accounts for a considerable proportion in the global total energy consumption, and as the main part of building energy consumption, the improvement of energy utilization efficiency of HVAC system is very important [2-3]. Seeking clean and renewable energy to replace traditional energy and drive HVAC system to operate efficiently has become the focus of current research in the field of architecture.

In recent years, renewable energy, such as solar energy, geothermal energy, wind energy, etc., because of its inexhaustible and environmentally friendly characteristics, the application research in the field of HVAC has gradually increased [4]. Scholars have carried out many explorations around the HVAC system driven by renewable energy, and some of the achievements have been applied to practical projects [5]. However, the existing research still has shortcomings in system design optimization and performance assessment system improvement [6].

In view of this, it is of great significance to carry out the research on the design and performance assessment of efficient HVAC system driven by renewable energy. It is helpful to improve the utilization efficiency of building energy, reduce dependence on traditional fossil energy, reduce greenhouse gas emissions and alleviate environmental pressure. Futhermore, it can improve the overall performance and reliability of HVAC system by optimizing system design and establishing a scientific and reasonable performance assessment system. This article will carry out systematic research around this topic, in order to provide theoretical and practical support for promoting the wide application of renewable energy in HVAC field.

  DOI: 10.25236/icacel.2025.167

2. Principles and types of HVAC driven by renewable energy

The HVAC system driven by renewable energy mainly realizes energy conversion and utilization based on the characteristics of different renewable energy. The solar drive system uses solar collectors to collect solar radiation energy and convert it into heat energy, which is transmitted through heat medium for heating, cooling or providing domestic hot water [7]. For example, the solar heat pump system can use solar energy to drive the refrigeration cycle in summer, and collect solar energy in winter to raise the evaporation temperature of the heat pump and improve the heating efficiency.

Geothermal energy driven system is represented by ground source heat pump. Its principle is to use the relative stability of shallow underground geothermal resources to exchange heat with soil through underground heat exchanger [8]. Heat is extracted from the soil in winter and released to the soil in summer to realize heating and cooling of buildings. In addition, wind energy can also be indirectly applied to HVAC systems, for example, after wind power generation, it provides power for the system to drive equipment to run.

3. Design of efficient HVAC system

The design of efficient HVAC system is the key link to realize the effective utilization of renewable energy and improve the system performance, which needs to be comprehensively tested from the aspects of system architecture, key component selection and adaptation to the building environment. System architecture should focus on solving the contradiction between intermittent and stable demand of renewable energy. Taking the solar energy-ground source heat pump composite system as an example, the energy storage and allocation mechanism should be integrated in the design. When the solar energy is sufficient, the heat collected by the solar collector can meet the current system requirements, and the excess part can be stored in the heat storage device. The energy balance formula in the heat storage process is:

$$Q_{solar-storage} = Q_{solar-collect} - Q_{system-demand} \quad (1)$$

Where $Q_{solar-storage}$ represents the heat stored in the heat storage device, $Q_{solar-collect}$ is the heat collected by the solar collector, and $Q_{system-demand}$ is the heat required by the system immediately. When the solar energy is insufficient or at night, the heat storage device releases heat to supplement the system and maintain stable operation. Futhermore, with the help of intelligent control system, according to the real-time monitoring of energy supply, indoor and outdoor temperature and humidity and user-set parameters, the operation of each component is dynamically regulated to ensure the efficient distribution and utilization of energy.

As the core component, the heat pump should be selected according to the actual working conditions and load characteristics. Low temperature air source heat pump is an ideal choice for heating in winter in cold areas. Taking the project in severe cold area as an example, the required heat pump heating capacity $Q_{heat-pump}$ is calculated according to the building winter heat load $Q_{heat-load}$, and the calculation formula is as follows:

$$Q_{heat-pump} = \frac{Q_{heat-load}}{\eta_{transmission}} \quad (2)$$

Where $\eta_{transmission}$ is the transmission efficiency of heating pipe network. The selected heat pump should ensure that it can still provide enough heating capacity and maintain a high coefficient of performance (COP) to meet the indoor heating demand in the local extremely low temperature environment.

The selection of fans should take into account air volume, air pressure, and efficiency. Here, the required air volume L is determined based on the indoor space volume V and air exchange rate n:

$$L = V \times n \quad (3)$$

Considering the factors such as duct resistance, the wind pressure is determined, and the efficient and energy-saving fan is selected to meet the requirements of indoor air circulation and ventilation and reduce the energy consumption of the fan.

The performance of heat exchanger directly affects the heat transfer efficiency. Optimize heat transfer area A, heat transfer coefficient K and logarithmic average temperature difference ΔT_{lm} in design to improve heat transfer Q:

$$Q = K \times A \times \Delta T_{lm} \quad (4)$$

By reasonably selecting the material and structure of heat exchanger, the heat transfer effect is enhanced and the energy loss is reduced.

Building environment factors have a significant impact on the performance of HVAC system. In terms of building orientation, buildings facing south can get more solar radiation heat in winter and reduce heating load. The thermal performance of envelope is very important, so high-efficiency thermal insulation materials are used to improve the thermal insulation performance of exterior walls and roofs and reduce the heat transfer coefficient. Futhermore, optimize the air tightness of the external window and sunshade measures to reduce indoor and outdoor heat transfer. In addition, combined with the building functional zoning and the rules of personnel activities, the air supply outlet and air return outlet are reasonably arranged to ensure the uniform indoor air distribution, improve indoor comfort and realize the collaborative optimization of HVAC system and building environment.

4. Methods and indicators of system performance assessment

Experimental test method is a method to obtain data by actually building a system and testing it. In the laboratory or actual engineering site, various sensors are installed to monitor various parameters in the process of system operation in real time, such as temperature, pressure, flow and power. For example, in the test of solar-driven HVAC system, the thermal efficiency of solar collectors, the input power and output heat of heat pumps are measured. This method can obtain the most authentic and reliable data and directly reflect the actual operation performance of the system, but it has some shortcomings such as high cost, long cycle and great influence by environmental factors.

The simulation method simulates the running process of the system with the help of professional software tools and according to the physical model and mathematical principle of the system. Common softwares include TRNSYS, EnergyPlus, etc. By inputting structural parameters, equipment performance parameters and environmental parameters of the system, the operation of the system under different working conditions is simulated. This method can quickly analyze various design schemes, predict system performance, and save time and cost. However, its accuracy depends on the accuracy of the model and the rationality of parameter setting. Table 1 explains the definition, calculation method and significance of each index.

Table 1 Key Performance Assessment Indicators for HVAC Systems

Category	Indicator	Definition	Calculation Method	Significance
Energy Efficiency	Coefficient of Performance (COP)	Ratio of useful output energy to input energy	Heating COP = Heating capacity / Input power; Cooling COP = Cooling capacity / Input power	Reflects energy conversion efficiency
Energy Efficiency	Energy Efficiency Ratio (EER)	Ratio of cooling capacity to power consumption	EER = Cooling capacity / Power consumption	Measures cooling energy utilization efficiency
Environmental Impact	Carbon Emissions	CO emissions from system operation	Calculated based on energy type and emission factors	Evaluates climate change impact

Economic	Payback Period	Time to recover initial investment	Initial investment / Annual energy cost savings	Indicates economic feasibility
Economic	Life Cycle Cost (LCC)	Total cost over system lifespan	Equipment + Installation + Energy + Maintenance + Disposal costs	Comprehensive economic assessment

5. Case analysis

In order to verify the effectiveness of the design and performance assessment method of efficient HVAC system driven by renewable energy, a green office building in Shanghai is selected as a case study. The building has a total construction area of 10,000 square meters and adopts HVAC system driven by ground source heat pump. In terms of system design, according to the load demand of the building and the geological conditions of the site, a total of 80 underground heat exchange wells with a depth of 100 meters were arranged. The ground source heat pump unit adopts high-efficiency screw heat pump and is equipped with intelligent control system, which can automatically adjust the operation mode according to the indoor and outdoor temperature and load changes.

In the performance assessment stage, the combination of experimental testing method and simulation method is adopted. During the experimental test, temperature sensors, pressure sensors, power meters and other equipment were installed in key parts of the system to collect data in real time. In the simulation, EnergyPlus software is used to establish the model according to the actual parameters of the building and system. Through testing and simulation, a series of performance data are obtained. Some key performances are shown in Table 2.

Table 2 Operational Performance of Ground-Source Heat Pump System

Assessment Metric	Value	Comparison with Traditional Systems	Industry Benchmark
Heating COP	3.8	Higher than traditional systems (2.5-3)	⩾3 (High-efficiency tier)
Cooling EER	4.2	Higher than traditional systems (3-3.5)	⩾3.8 (High-efficiency tier)
Annual Carbon Emissions (tons)	150	Far lower than traditional systems (300-400 tons)	Region/Policy-dependent
Payback Period (years)	5	Relatively short, economically viable	5-8 years (Acceptable range)
Life Cycle Cost (10k CNY)	800	Covers full lifecycle costs	Varies by project scale/region

From the energy efficiency index, the heating COP reaches 3.8, and the cooling EER is 4.2, which indicates that the system can efficiently convert input energy into useful cold and hot energy, and has obvious advantages compared with the traditional HVAC system. This is due to the reasonable design of underground pipes and the efficient selection of heat pump units, which ensures good heat exchange efficiency and energy conversion efficiency. Generally, the COP of traditional HVAC system is about 2.5-3, and the EER of refrigeration is about 3-3.5. This system has significantly improved the energy conversion efficiency.

In terms of environmental impact, the annual carbon emission is only 150 tons, which is far lower than the traditional energy-driven HVAC system. According to industry data, the annual carbon emission of traditional systems of the same scale is about 300-400 tons. This shows that the ground source heat pump system can effectively reduce carbon emissions by using renewable geothermal energy, which is of positive significance to environmental protection. Economically, the payback period of investment is 5 years, which shows that the system is economically feasible.

6. Conclusions

This article focuses on the research of efficient HVAC system driven by renewable energy. In the system design, the stable utilization of renewable energy is ensured by reasonably planning the system architecture, such as constructing the energy storage and allocation mechanism of the solar-ground source heat pump composite system and giving the energy balance formula. In the selection of key components, according to the building load characteristics and environmental conditions, the calculation formula is used to accurately match the equipment, such as selecting the appropriate heat pump based on heat load calculation, taking into account the energy efficiency and actual demand. In terms of performance assessment, the method of combining experimental test with simulation is feasible. Taking the ground source heat pump system of a green office building in Shanghai as an example, its heating COP is 3.8, and its cooling EER is 4.2, which is significantly better than the traditional system, which proves that the energy conversion of the system is efficient. The annual carbon emission is only 150 tons, which is far lower than the traditional energy-driven system, highlighting its environmental advantages. The payback period of investment is 5 years. Although the initial investment is high, the long-term energy saving benefit is obvious, and the life cycle cost of 8 million yuan provides a comprehensive basis for economic assessment.

The design and performance assessment method of high-efficiency HVAC system driven by renewable energy used in this article is scientific and reasonable, which verifies the great potential of this technology in energy saving and emission reduction and improving economic benefits. The research results provide a reliable reference for similar projects and help to promote the wide application of renewable energy in HVAC field.

References

[1] Zhang H L, Xu W H. Discussion on calculation methods of renewable energy utilization rate in district cooling and heating systems[J]. Heating Ventilating & Air Conditioning, 2020, 50(10): 36-40.

[2] Ma T T, Zhang Z, Li J W, et al. Design and operation of HVAC systems in ultra-low energy residential buildings[J]. Heating Ventilating & Air Conditioning, 2024, 54(03): 136-143.

[3] Li H L, Kou W, Lyu W. Research on building cooling load zoning and application under climate change[J]. Heating Ventilating & Air Conditioning, 2022, 52(12): 59-65.

[4] Wu J L, Li H, Yu Z, et al. Optimal operation analysis of HVAC system in a nearly zero-energy office building[J]. Building Science, 2020, 36(06): 35-41.

[5] Li G N, Yao Q, Mao Q J, et al. Impact of room temperature sensor deviation faults on HVAC systems in Wuhan area[J]. Renewable Energy, 2022, 40(3): 332-337.

[6] Lu X M. Practical exploration of new and renewable energy in HVAC systems[J]. Housing Industry, 2022, (01): 180-182.

[7] Shi X F. Application analysis of renewable energy in HVAC systems[J]. Popular Standardization, 2023(4): 56-58.

[8] Wang H F. HVAC system design under green building standards[J]. New Urban Construction Technology, 2024, 33(10): 15-17.