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Comparative Analysis of Carbon Emissions in the Operation Phase of Different HVAC Systems

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Abstract:

This paper provides a comparative analysis of the energy consumption and carbon emissions of four typical HVAC systems (water-cooled chiller + gas boiler, ground source heat pump, air source heat pump, and variable refrigerant flow units) in the operation phase. The carbon emission performance of different HVAC systems in operation is quantitatively evaluated by establishing a building carbon emission model and a carbon emission calculation method for HVAC systems, combined with specific calculation examples. The results of the study show that the ground source heat pump system has a clear advantage in terms of carbon emissions, followed by the variable refrigerant flow system, while the carbon emissions of the water-cooled chiller + gas boiler system are similar to those of the air source heat pump unit. This study provides theoretical basis and data support for the energy-saving and low-carbon selection of building HVAC systems.

Keywords: HVAC system; carbon emission; energy consumption

0 INTRODUCTION

Along with the increasing severity of global climate change, in September 2020, China proposed that carbon dioxide emissions strive to peak with by 2030, and strive to achieve the dual-carbon goal of carbon neutrality by 2060. Energy saving and emission reduction in the building industry is also of great concern. HVAC systems, as a major component of building energy consumption, account for a sizable proportion of carbon emissions during the operation phase in the whole life cycle of a building. In public buildings, the proportion of HVAC energy consumption is about 40~50% [1], and the corresponding carbon emissions are also very considerable. Therefore, scientific analysis and comparison of carbon emissions during the operation phase of different types of HVAC systems is of great significance in promoting the low-carbon development of the building industry. This study aims to establish a scientific building carbon emission model, propose a carbon emission calculation method for HVAC systems, and comparatively analyze the energy consumption and carbon emission performance of four typical systems (water-cooled chiller+gas boiler system, ground source heat pump system, air source heat pump system, and variable refrigerant flow units) in the operation phase through specific examples. It provides reference for HVAC designers and owners in selecting low-carbon HVAC systems, and also provides reference for the selection of HVAC systems for public buildings under the background of “dual-carbon”.

1 Building Carbon Calculation Model

The Building Carbon Model (BCM) is a quantitative tool for assessing the environmental impacts of HVAC systems. The model takes into account multiple factors such as building characteristics, climate conditions, system performance and energy mix. Based on the principle of dynamic energy balance, the model calculates the cooling and heating loads of the building on a time-by-time basis, and then determines the energy demand of the HVAC system.

The carbon emission calculation adopts the "emission factor method", i.e. the system energy consumption is multiplied by the carbon emission factor of the corresponding energy source.

1.1 Carbon Emission Process Analysis

Building carbon emissions [2] is the sum of greenhouse gas emissions produced by a building during the production and transportation of building materials, construction and demolition, and operation phases of the building, expressed in carbon dioxide equivalent.

The calculation of building carbon emissions is usually based on a single building or a cluster of buildings on a campus, and accounts for the equivalent carbon dioxide emissions over its entire life cycle. The Carbon Emission Factor Method is a commonly used method to calculate the carbon emissions of each phase of a building by counting the amount of energy consumed by each activity, the type of energy and its corresponding carbon emission factor. Due to the differences between the actual operating conditions and the design conditions, the estimation of energy consumption by this method may have a large deviation, which leads to significant inconsistencies in the results of carbon emission calculations. In order to improve the reliability and comparability of the calculation results between different projects, therefore, GB/T 51366-2019 "Building Carbon Emission Calculation Standard" makes uniform provisions for the operational characteristics of different types of buildings and clarifies the calculation prerequisites to ensure that the carbon emission accounting of the same type of buildings is under a consistent benchmark [3].

According to the actual carbon emissions of the building, the formula for calculating carbon emissions is shown in equation (1):

$$\Delta C_J = C_{JC} + C_{JZ} + C_M + C_{CC} - C_P \tag{1}$$

ΔC_J: building-equivalent carbon emissions over the full life cycle, tCO_2

C_{JC}: carbon emissions during the production and transportation of building materials, tCO_2

C_{JZ}: carbon emissions during the construction phase of the building, tCO_2

C_M: carbon emissions during the operation of the building, tCO_2

C_{CC}: carbon emissions during the dismantling of a building, tCO_2

C_P: Carbon sequestration in building green spaces, tCO_2

The calculation of carbon emissions over the whole life cycle of a building involves a wide range of aspects, especially the lack of detailed and accurate data on building materials and construction. In this paper, we only calculate and analyze the carbon emissions of the HVAC operation phase in the building.

2 Calculation of carbon emissions from HVAC system

2.1 Carbon Emission Composition of HVAC System

Referring to the current status quo of HVAC system design in public buildings, four typical air-conditioning cooling and heat source programs are selected, which are as follows: Plan I is a combination of water-cooled chiller+gas boiler; Plan II is a soil-source heat pump system; Plan III is an air-cooled heat pump system; and Plan IV is a multi-connected unit system. Summer cooling and winter heating, the end of the fan coiler + fresh air way, multi-connected using multi-connected internal + fresh air way. Both hot and cold water systems use variable flow systems.

The building's HVAC system is mainly composed of cold and hot sources, transmission and distribution systems, and end parts, and the system carbon emissions are mainly analyzed and compared from these three aspects. Neglect the carbon emission of air-conditioning water consumption system, self-control system and so on. Neglect carbon sequestration by building green space carbon sinks.

Figure 1 Carbon sources during the operational phase of the HVAC system

Plans	Systems	Type of equipments	Operating carbon sources
plan I	Cooling and heating equipments	Electric chillers Gas boilers Cooling towers	Electricity, refrigerants Gas Electricity, water supply
	Piping distribution systems	Chilled water circulation pumps Cooling water circulation pumps Constant pressure make-up pumps Heat water circulation pumps	Electricity Electricity Electricity, water supply Electricity
	Terminal equipments	Fan coil units Outdoor air equipments	Electricity Electricity
plan II	Cooling and heating equipments	Ground source heat pumps	Electricity, refrigerant, renewable energy
	Piping distribution systems	User-side circulating pumps Ground source-side circulating pumps Constant-pressure make-up water pumps	Electricity Electricity Electricity, water supply
	Terminal equipments	Fan coil units Outdoor air equipments	Electricity Electricity
plan III	Cooling and heating equipments	Air source heat pumps	Electricity, refrigerant
	Piping distribution	Chilled water circulating pumps	Electricity

	systems	Constant-pressure make-up water pumps	Electricity, water supply
	Terminal equipments	Fan coil units Outdoor air equipments	Electricity Electricity
plan IV	Cooling and heating equipments	Variable refrigerant flow units	Electricity, refrigerant
	Terminal equipments	Multiple indoor fan-coil units Outdoor air equipments	Electricity Electricity

2.2 Carbon emissions calculation for HVAC systems

2.2.1 Carbon emissions calculation formula for the operational phase

Referring to GB/T 51366-2019 <Standard for building carbon emission calculation> carbon emissions factor method, the carbon emissions calculation formula for the operational phase of a building is as follows:

$$C_M = \left[\sum_{i=1}^{n} (E_i * EF_i) - C_P\right] * y \tag{2}$$

$$E_i = \sum_{j=1}^{n} (E_{i,j} - ER_{i,j}) \tag{3}$$

E_i： Annual consumption of energy type i,a
EF_i： Carbon emission factor of energy type i
$E_{i,j}$： Consumption of energy type i in system type j, a
$ER_{i,j}$： Amount of energy type i provided by renewable energy in system type j, a
i: Type of renewable energy in the system, including electricity, natural gas, fuel oil, and thermal energy
j:Type of system equipment, see Figure 1
y：Design service life of the building, a

2.2.2 Energy consumption calculation formula for HVAC systems

The equivalent full load operating time method [4] is used to calculate the energy consumption of each component of the HVAC system.

2.2.2.1 Definition of equivalent full load operating time

Equivalent full load operating time: The ratio of the total annual air conditioning cooling load (or heating load) to the maximum output of the refrigeration unit (or boiler).

That is:

$$\tau_{E.R} = q_c / q_R \tag{4}$$

$$\tau_{E.B} = q_h / q_B \tag{5}$$

$\tau_{E.R}$:Equivalent full load operating time in summer, h
q_c:Annual air conditioning cooling load, kJ/a

q_R:Maximum output of cooling machine, kJ/h
$\tau_{E.B}$:Equivalent full load operating time in winter, h
q_h:Annual air conditioning heating load, kJ/a
q_B: Maximum output of boiler, kJ/h

2.2.2.2 Load factor

Load factor: The ratio of the total annual air conditioning cooling load (or heating load) to the total maximum output of the refrigeration machine (or boiler) during the cumulative operating time.

That is:

$$\varepsilon_R = q_c/(q_R * T_R) \tag{6}$$

$$\varepsilon_B = q_h/(q_B * T_B) \tag{7}$$

ε_R:Summer cooling load factor
T_R: Cumulative operating time of equipment in summer, h
ε_B: Winter heating load factor
T_B:Cumulative operating time of equipment in winter, h
Therefore:

$$\varepsilon_R = \tau_{E.R}/T_R \tag{8}$$

$$\varepsilon_B = \tau_{E.B}/T_B \tag{9}$$

2.2.2.3 Calculation of annual energy consumption for air conditioning
Power consumption of chillers:

$$P_R = \left(\sum P_{R.N}\right) * T_R * \varepsilon_R = \left(\sum P_{R.N}\right) * \tau_{E.R} \tag{10}$$

Power consumption of chilled water pumps and cooling water pumps:

Constant flow :

$$P_P = \left(\sum P_{P.N}\right) * T_P \tag{11}$$

Variable flow:

$$P_P = \left(\sum P_{P.N}\right) * T_P * (\varepsilon_R + \alpha_R) \tag{12}$$

$$\alpha_R = (1 - \varepsilon_R)/n \tag{13}$$

Cooling tower power consumption:

Full operation:

$$P_{CT} = \left(\sum P_{CT.N}\right) * T_{CT} \tag{14}$$

Partial operation:

$$P_{CT} = \left(\sum P_{CT.N}\right) * T_{CT} * (\varepsilon_R + \alpha_R) \tag{15}$$

Power consumption of terminal equipments:

Constant air volume:

$$P_F = \left(\sum P_{F.N}\right) * T_F \quad (16)$$

Variable air volume:

$$P_F = \left(\sum P_{F.N}\right) * T_F * (\varepsilon' + \alpha') \quad (17)$$

$$\varepsilon' = (\varepsilon_R * T_R + \varepsilon_B * T_B)/(T_R + T_B) \quad (18)$$

$$\alpha' = (1 - \varepsilon')/n \quad (19)$$

Boiler fuel consumption:

One unit:

$$Q_{fB} = q_{fB.N} * T_B * \varepsilon_B = q_{fB.N} * \tau_{E.B} \quad (20)$$

Two or more units:

$$Q_{fB} = \sum q_{fB.N} * T_B * (\varepsilon_B + \alpha_B) \quad (21)$$

$$\alpha_B = (1 - \varepsilon_B)/n \quad (22)$$

$P_{R.N}$:Rated power of the chiller units, kW
$P_{P.N}$: Rated power of the chilled water pumps and cooling water pumps, kW
$P_{CT.N}$: Rated power of the cooling towers, kW
$P_{F.N}$: Rated power of the terminal equipments, kW
$q_{fB.N}$: Fuel consumption of the boilers at rated output, t/h or m^3/h
T_R: Cumulative operating time of chillers, h
T_P: Cumulative operating time of chilled water pumps and cooling water pumps, h
T_{CT}:Cumulative operating time of cooling towers, h
T_F: Cumulative operating time of terminal ventilation equipments, h
T_B:Cumulative operating time of boilers, h
n: Number of units

3 Calculation Case

3.1 Project Parameters

A comprehensive office building in Beijing with a total floor area of approximately 47,000 m^2, comprising 17 above-ground floors and 2 underground floors. Total cooling load: 4,200 kW; total heating load: 2,300 kW.

3.2 Different Operating Scenarios for the HVAC System

The cooling operation period is from June to September, with daily operation hours from 8 AM to 6 PM. The heating operation period is from 15 November to 15 March of the following year, with daily operation hours from 8 AM to 6 PM. The average monthly operating time is 25 days.

The cumulative operating time for summer cooling is 1,000 hours, and the cumulative operating time for winter heating is 1,000 hours. The equivalent full-load operating time is derived from the empirical statistical data compiled by Japanese researcher Toshio Ojima. For office buildings, the full-load operating time in summer is 560 hours, and in winter it is 480 hours. [4]

Among the four HVAC system schemes, the performance coefficient of the units is selected to meet at least a 2-level energy efficiency rating according to relevant standards. Centrifugal water-cooled chillers are selected, with a performance coefficient of no less than 6.2[5], and gas boilers with a thermal efficiency of no less than 92% [5]; the soil-source heat pump unit has an annual comprehensive performance coefficient of no less than 5.1[6]; the air-source heat pump uses a low-temperature air-source heat pump (chilled water) unit with an annual comprehensive performance coefficient of no less than 3.1[6]; the multi-split system uses an air-cooled multi-split air conditioning (heat pump) unit with an annual performance coefficient of no less than 3.5[5]. Equipment is selected based on manufacturer catalogues, with performance coefficients meeting or exceeding the above requirements. As shown in the table below:

Figure 2: Detailed list of equipment power and number of units

Parameters	Plan I	Plan II	Plan III	Plan IV
Cooling equipments	Chillers	Ground source heat pumps	Air source heat pumps	Variable refrigerant flow units
Heating equipments	Gas boiler	Ground source heat pumps	Air source heat pumps	Variable refrigerant flow units
Performance coefficient	EER:6.3 Boiler thermal efficiency:92%	EER:6.6 COP:5.0	EER:3.33 COP:2.82	EER:3.6 COP:3.3
Energy	Electricity + Gas	Electricity	Electricity	Electricity
Terminal equipments	Fan coil unist + outdoor air equipments	Fan coil units + outdoor air equipments	Fan coil units + outdoor air equipments	Multi indoor fan-coil units+outdoor air equipments
Cooling equipments	334kW, 2 units	347kW, 2 units	254kW, 5 units	15.75kW, 75 units
Heating equipments	123.5m^3/h, 2 units	464kW, 1 unit	220kW, 4 units	20kW, 37 units
Chilled water pumps	55kW, 2 units	55kW, 2 units	55kW, 2 units	0
Cooling water pumps	55kW, 2 units	55kW, 2 units	0	0
Cooling towers	20kW, 2 units	0	0	0
Heat water pumps	11kW,1 unit 30kW,2 units	55kW,1 unit 55kW,1 unit	30kW, 2 units	0
Fan coil units	Cooling capacity 5kW, rated power 0.053kW,	Cooling capacity 5kW, rated power	Cooling capacity 5kW, rated power	0

	504 units	0.053kW, 504 units	0.053kW, 504 units	
Multiple indoor fan-coil units	0	0	0	Cooling capacity 5kW, rated power 0.071kW, 504 units
Outdoor air equipments	1.5kW, 17 units	1.5kW, 17 units	1.5kW, 17 units	2.6kW, 17 units

Note: ① In Plan I, during winter heating, the gas boiler and terminal equipment are connected indirectly, with a plate heat exchanger added in between. The primary side uses a supply and return water temperature difference of 20°C and one circulation pump; the secondary side uses a supply and return water temperature difference of 5°C and two circulation heat water pumps.

② In Plan II, both the user side and ground source side pumps operate simultaneously in both winter and summer. In summer, two pumps operate simultaneously, while in winter, one pump operates.

③ Plan IIII and IV account for heating efficiency degradation in Beijing during winter.

④ Fan coil units or Multiple indoor fan-coil units bear 60% of the system's cooling or heating load. Outdoor air systems bear the remaining 40% of the load.

⑤ Fresh air units are considered at a rate of one per floor. In Scheme 4, the fresh air units are fluorine-based fresh air units.

3.3 HVAC System Energy Consumption Statistics

The chillers operate at fixed frequency, with a full-load operation equivalent time of 560 hours in summer. The chilled water pumps, cooling water pumps, and cooling towers operate at variable frequency. During winter, the gas boilers operate at full load for an equivalent time of 480 hours, and the heat water pumps operate at variable frequency. The terminal fan coil units and outdoor air equipments all operate at fixed frequency. Equipment power is based on manufacturer specifications. The statistics are summarised in the figure below:

Figure 3 HVAC System Energy Consumption Statistics by Operating Stage and Unit Time

Parameters	Plan I	Plan II	Plan III	Plan IV
Total power of chillers, kW	668	694	1270	1182
Total power of heat pumps, kW	0	464	880	740
Gas consumption, m^3/h	247	0	0	0
Total power of chilled pumps, kW	110	110	110	0
Total power of cooling pumps, kW	110	110	0	0
Total power of cooling towers, kW	40	0	0	0
Total power of heat water pumps, kW	71	110	60	0
Total power of fan coil units, kW	29	29	29	0
Total power of multiple indoor fan-coil units, kW	0	0	0	36
Total power of outdoor air equipments, kW	26	26	26	44

Calculations were performed separately using the full load equivalent operating time method. See the table below:

Figure 4 Summary of total energy consumption of HVAC systems

Parameters	Plan I	Plan II	Plan III	Plan IV
Total power of chillers, kW	374080	388640	711200	661920
Total power of heat pumps, kW	0	222720	422400	355200
Gas consumption, m^3/h	182780	0	0	0
Total power of chilled pumps, kW	85800	85800	85800	0
Total power of cooling pumps, kW	85800	85800	0	0
Total power of cooling towers, kW	31200	0	0	0
Total power of heat water pumps, kW	52540	81400	44400	0
Total power of fan coil units, kW	58000	58000	58000	0
Total power of multiple indoor fan-coil units, kW	0	0	0	72000
Total power of outdoor air equipments, kW	52000	52000	52000	52000
Total electricity consumption, kWh/a	739420	974360	1373800	1141120
Total gas consumption, m^3/a	182780	0	0	0

In accordance with the requirements of GB/T 51350-2019 <Technical standard for nearly zero energy buildings>, energy consumption is converted into primary energy consumption in terms of standard coal. The conversion factor for natural gas energy is $9.85(kWh)/(m^3_{\text{terminal}})$, and the conversion factor for electricity energy is $2.6(kWh)/(kWh_{\text{terminal}})$. The converted energy consumption analysis is presented in the table below.

Table 5 Comparison of various schemes converted to primary energy consumption

Parameters	Plan I	Plan II	Plan III	Plan IV
Total electricity consumption, kWh/a	739420	974360	1373800	1141120
Total gas consumption, m^3/a	182780	0	0	0
Electricity energy conversion factor,$(kWh)/(kWh_{\text{terminal}})$	2.6	2.6	2.6	2.6
Gas energy conversion factor, $(kWh)/(m^3_{\text{terminal}})$	9.85	0	0	0
Primary energy consumption of electricity, kWh/a	1922492	2533336	3571880	2966912
Gas primary energy consumption,kWh/a	1800383	0	0	0
Total energy consumption,kWh/a	3722875	2533336	3571880	2966912
Energy saving rate (compared with Plan I),%	-	-31.95%	-4.06%	-20.31%

3.4 Carbon Emissions Calculation During the Operation Phase of HVAC Systems

Plan I uses two types of energy sources: electricity and natural gas. The other three plans all use electricity as the energy source for cooling and heating. The carbon footprint factor data for electricity in 2023, as announced by the Ministry of Ecology and Environment of the People's Republic of China on 21 January 2025, provides the national average carbon footprint factor for electricity in 2023, which is 0.6205$kgCO_2e/kWh$

Table 6 Carbon Footprint Emissions During the Operation Phase of HVAC Systems

Parameters	Plan I	Plan II	Plan III	Plan IV
Total carbon emissions,kg	2310044	1571935	2216352	1840969
Carbon emission reduction rate (compared to Plan I), %	-	-31.95%	-4.06%	-20.31%

4 Conclusion

A carbon emissions analysis of different design schemes for HVAC systems in office buildings during the operational phase shows that using high-efficiency units is beneficial for building carbon reduction. Using ground-source heat pump units for cooling and heating is more energy-efficient than using chiller units + gas boilers, with a carbon reduction rate 31.95% higher. When compared to the air-source heat pump scheme, the chiller unit plus gas boiler scheme has a similar overall carbon emission level, with the air-source heat pump scheme being slightly lower. The multi-split system is more energy-efficient than the chiller unit plus gas boiler scheme, achieving a 20.31% higher carbon reduction rate. The HVAC system using a ground-source heat pump system achieves the best energy-saving effects and carbon reduction, so it is recommended to actively promote ground-source heat pump systems and other renewable energy HVAC systems.

This paper only analyses and compares the energy consumption and carbon emissions during the operation phase of building HVAC systems. In actual design, it is also necessary to comprehensively consider the carbon emissions throughout the entire lifecycle of the building, as well as requirements for comfort and economics, to scientifically select the appropriate HVAC solution.

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