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Economic and environmental impacts of different ventilation systems in detached rural houses in severe cold climate

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A R T I C L E I N F O

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Cold climate

A B S T R A C T

The growing demand for energy efficient and environmentally friendly buildings with improved comfort drives the need for advanced ventilation systems. Chinese rural houses in severe cold climate struggle with inadequate ventilation in winter, while the extremely low temperatures and huge heating demands hinder the effective implementation of mechanical ventilation. This study aims to identify the optimal ventilation system for rural detached houses in severe cold climate by examining the potential combination of earth-air heat exchanger and heat recovery, as well as comparing this system to other common ventilation solutions. Using a case building in Harbin, four mechanical ventilation configurations were simulated with IDA ICE. A multi-objective evaluation combining economic and environmental factors was employed to design the earth-air heat exchanger and evaluate different ventilation options. Results show that integrating an earth-air heat exchanger into a balanced ventilation notably reduces ventilation heating demand by 64 %, with its effectiveness particularly pronounced in colder conditions. Among all mechanical ventilation options, the balanced ventilation with both heat recovery and earth-air heat exchanger achieves the lowest CO_2 emissions at 44 kg CO_2/m^2. Exhaust ventilation emerges as the most cost-effective option. These findings illuminate the earth-air heat exchanger's heating performance in severe cold climate. Practical recommendations balancing economic effectiveness and environmental impacts were provided to guide the design of sustainable mechanical ventilation systems for detached rural houses in extreme climatic conditions.

Nomenclature

Abbreviations	
AHU	Air handling unit
BV	Mechanical balanced ventilation system
BV-E	Mechanical balanced ventilation system with earth-air heat exchanger
BV-E-H	Mechanical balanced ventilation system with earth-air heat exchanger and heat recovery
BV-H	Mechanical balanced ventilation system with heat recovery
COP	Coefficient of performance
EAHE	Earth-air heat exchanger
EX	Mechanical exhaust ventilation system

(*continued on next page*)

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(*continued*)

HR	Heat recovery
LCC	Life cycle cost
NPV	Net present value
NV	Natural ventilation system
NVc	Natural ventilation system with original coal-based heating system
TOPSIS	Technique for order of preference by similarity to ideal solution
Variables	
E_a	Annual energy cost, CNY/a
I_{tot}	Total investment cost of renovation measures, CNY
k_i	Year from the beginning of the life cycle period until a renewal measure is implemented
LCC_{20a}	Net present value of life cycle cost during a 20-year life-cycle period, CNY
MR_a	Annual maintenance and repair cost, CNY/a
n	Life cycle period, a
P	Electric power, kW
r	Real interest rate, %
r_e	Escalated real interest rate, %
R_a	Annual renewal cost, CNY/a

1. Introduction

With the growing need for a comfortable and healthy living environment, ventilation in residential buildings is receiving increasing

Table 1
Summary of configuration and system performance of EAHE in previous works.

Refs.	Location	Climate	Duct shape	Duct parameters	Main findings
Cooling performance					
[20]	Marrakech, Morocco	Hot semi-arid climate	Horizontal Single-layer Parallel U-shape	Diameter: 150 mm Length: 72 m Depth: 2.85 m Number of parallel ducts: 3	- The supply air temperature was decreased by 18.3–19.5 °C in summer, with cooling capacity of 55–58 W/duct-m^2.
[21]	Crotone, Italy	Hot-summer Mediterranean climate	Horizontal Single-layer Parallel	Diameter: 566 mm Length: 50 m Depth: 3 m Number of parallel ducts: 8	- When integrating EAHE, the proposed mechanical ventilation system reduced the peak temperature during summer by 5 °C.
[22]	Temixco, Mexico	Tropical savanna climate	Vertical Serial U-shape	Diameter: 76 mm Length: 11.55 m Depth: 2.75−2.85 m Number of serial ducts: 3	- The supply air temperature was increased by 5.1–9.4 °C affected by airspeed. - The maximum cooling efficiency and COP were 88.4 % and 12.8.
Heating performance					
[23]	Chongqing, China	Humid subtropical climate	Horizontal Single-layer U-shape	Diameter: 160 mm Length: 40 m Depth: 3 m	- The supply air temperature was increased by 5.53 °C in winter. - EAHE reduced average building heating loads by 40.43 W/m^2.
[24]	Harbin, China	Monsoon-influenced warm-summer humid continental climate (severe cold)	Horizontal Double-layer U-shape	Diameter: 260 mm Length: 36 m Depth: 2.5 m, 5 m	- EAHE raised the average temperature by 14 °C without auxiliary heating in winter. - The maximum overall COP was 16.3.
[25]	Olsztyn, Poland	Humid continental climate	Horizontal Single-layer	Diameter: 200 mm Length: 41 m Depth: 2.12 m	- EAHE reduced ventilation heating demand by 45 %. - EAHE helped heat supply air to 0 °C and prevented the heat exchanger from freezing.
[26]	Algeria	Temperate climate (Oran), Arid climate (Bechar) Steppe climate (El-Bayadh)	Horizontal Single-layer	Diameter: 120 mm Length: 20 m Depth: 2 m	- EAHE reached a heating COP of 7.6, 8.4, and 9.4 in a temperate, steppe climate, and arid climate respectively.
[27]	Imola, Italy	Humid subtropical climate	Horizontal Single-layer Parallel 3 EAHE fields	Diameter: 250 mm Length: 70 m Depth: 2.6 m Number of parallel ducts: 12, 12, 8	- The air temperature was increased significantly by EAHE but still needed further treatment to meet the appropriate temperature.
[28]	Kerman, Iran	Hot semi-arid (steppe) climate	Horizontal Single-layer Serpentine	Diameter: 300 mm Length: 25 m, 50 m, 75 m Depth: 1 m, 2 m, 3 m	- Under the local climate, EAHE saved more heating energy than cooling.

attention. Existing studies prove that insufficient ventilation rate would lead to poor indoor air quality and possible adverse health impacts [1,2]. In China, most residential buildings rely on natural ventilation through manual window operations [3], which doesn't appear to be a stable and effective ventilation approach and also leads to significant heat loss during cold winters [4]. This problem becomes more pronounced in severe cold climate where drastic temperature differences between indoor and outdoor environments accelerate heat transfer, resulting in elevated energy demands and thermal discomfort.

China is actively pursuing the goal of achieving peak carbon emissions by 2030 and carbon neutrality by 2060 [5]. There is a considerable quantity of naturally ventilated houses that are undergoing envelope renovations to reduce energy consumption. Retrofit measures, such as window replacement and insulation improvement, have been widely implemented to enhance the building's thermal performance. However, several studies [6–8] have provided evidence indicating a decline in indoor air quality following such renovations. To address this issue, integrating energy-efficient mechanical ventilation systems in these renovated buildings is critical for balancing indoor air quality, thermal comfort, and energy conservation.

In cold climates, achieving sufficient ventilation often leads to a particular financial challenge to meet the additional thermal load required for preheating supply air [9]. It is reported that up to 60 % of the overall energy demand of an apartment building could be allocated to ensure sufficient ventilation [7]. Therefore, indoor air quality goals should be balanced against energy uses [10]. Energy-efficient ventilation strategies are imperative. For example, heat recovery units and earth-air heat exchangers offer promising solutions by reducing ventilation heating demand.

Heat recovery (HR) units can capture 60−95 % of heat from exhaust air, leading to a notable enhancement in building energy

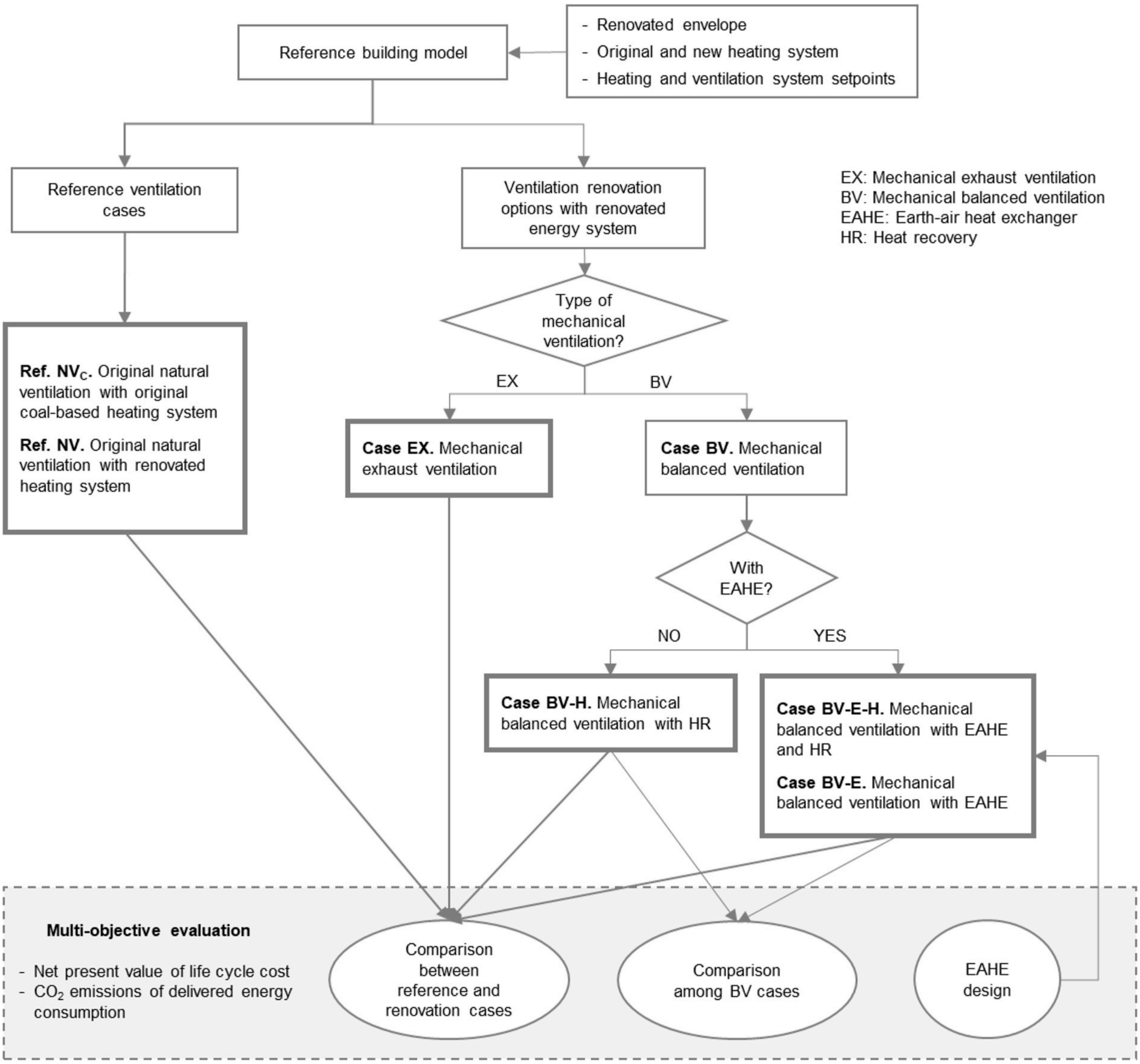

Fig. 1. Research process diagram.

efficiency [11]. Ji [12] demonstrated that the integration of a centralized ventilation system with heat recovery in a new apartment building in northern China leads to a notable reduction of building energy consumption to 75 % compared to a system without heat recovery. The required investment for this ventilation system was only 19.5 CNY/m^2, with a dynamic additional investment payback period of less than 4 years. Dodoo [13] highlighted that annual energy savings of space heating for a Swedish multi-family building with the heat recovery air handling unit (AHU) ranged from 19 to 24 kWh/m^2. The semi-centralized heat recovery with rotary heat exchanger yielded the highest energy savings compared to centralized and counter-flow systems. Berquist et al. [14] reported that, in a house located in Canadian Arctic, a CO_2-based demand-controlled heat recovery ventilation system achieved a sensible recovery efficiency of 72 % for the heat recovery ventilator, with an energy use intensity of only 12.25 Wh/m^3 of supplied outdoor air.

The frosting problem is an inescapable problem when heat recovery is applied in cold climates. Multiple frosting control strategies, such as frosting prevention and defrosting, could be employed to prevent the frosting occurrence or remove the frost from exchanger surfaces, thereby avoiding an excessive decrease in their performance [15]. In Finland, for instance, a setpoint temperature of exhaust air leaving the energy exchanger was defined to determine if defrost strategies should be operated [16].

Earth-air heat exchanger (EAHE) has gained considerable interests for their ability to pre-condition supply air using the heat stored in the ground. While outdoor air temperature experiences daily and annual fluctuations, the soil under a specific depth remains relatively stable in temperature [17]. EAHE is built with a number of ducts that are either vertically or horizontally buried underground. The thermal mass in the soil is employed by EAHE to facilitate heat transmission between the air flowing in the ground duct and the surrounding soil. Thus, the ground functions as a heat sink in summer and as a heat source in winter. EAHEs have been widely studied and utilized in various climatic conditions and building types [18,19]. Table 1 presents an overview of the configuration and system performance of EAHE applied across various climatic contexts.

Although significant progress has been made in energy-efficient mechanical ventilation systems, there remains notable gaps in this research area. Existing studies primarily focuses on urban residential buildings, with limited attention paid to the feasibility of mechanical ventilation in detached rural houses, particularly under severe cold conditions. This building type presents unique challenges, including extremely high heating demands, poor indoor air quality, and limited adoption of advanced ventilation technologies. Besides, while numerous studies highlight the benefits of combining EAHE with mechanical ventilation systems for precooling supply air, its heating performance in extreme climatic context remains underexplored. Additionally, few studies comprehensively assess the economic and environmental impacts of mechanical ventilation systems, especially from a life cycle perspective. These gaps highlight the need to develop sustainable, energy-efficient ventilation strategies for rural houses in severe cold climate.

This study aims to figure out the optimal mechanical ventilation system for detached rural houses in severe cold climate. A model of existing detached rural house was used and renovated for mechanical ventilation with a controlled airflow rate. The novelty of this study lies in its focus on the combined use of EAHE and heat recovery for energy conservation purposes in severe cold conditions. Multi-objective evaluations were conducted to optimize the design of EAHE system and evaluate various mechanical ventilation options based on their effectiveness, environmental benefits, and life cycle economic performance. Additionally, sensitivity analysis examined how future changes in thermal comfort and environmental factors may influence the proposed ventilation systems. The findings are intended to provide valuable insights in designing energy-efficient and adaptable ventilation systems, thereby contributing to sustainable building renovation and operation in cold climates, as well as aligning with China's objectives for energy conservation and environmental sustainability.

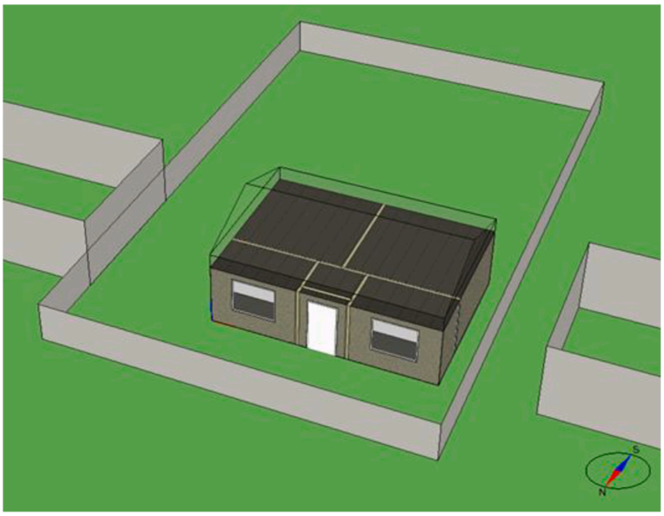

Fig. 2. 3-D simulation model of case building.

2. Methodology

Fig. 1 illustrates the process of this study. Initially, a reference building model was established and simulated using the dynamic energy simulation software IDA ICE. Next, reference cases and renovation options for the ventilation system were created independently. The reference cases utilized the existing natural ventilation strategy. The renovation cases implemented mechanical exhaust and mechanical balanced ventilation systems, with potential integration of heat recovery and/or EAHE. One reference case (Ref. NVc) maintained the original heating system, while the other reference case (Ref. NV) and all renovation cases adopted a new heating system. To determine the optimal ground duct length for cases incorporating EAHE, a multi-objective evaluation approach was applied. Finally, comprehensive analyses were performed to evaluate the renovation cases and identify differences between the reference cases and renovated cases.

2.1. Building model description

2.1.1. Main features and structures

The case building is a single-family detached house situated in rural area of Harbin, serving as a representative example of the typical Chinese residential building in this climate and rural setting. It reflects common features of local rural houses, including building layout, construction techniques, energy use patterns, and ventilation systems [29]. The house is a single-story structure with two bedrooms and three auxiliary rooms, including an entrance, a kitchen and a storage. Fig. 2 presents a 3D view of the case building and its surroundings.

The load-bearing structures of the case building are constructed from brick, the most commonly used construction material in the region. Built in the 1990s by local builders, the house was completed before the introduction of energy-efficient building standards in rural areas, meaning there were no requirements for airtightness or specific envelope materials at that time. The material choices and construction details of the case building are representative of typical construction practices in this climatic context. The envelope renovation strategy has been designed by the authors' previous study [30] using a multi-objective optimization which considering minimizing both life cycle cost (LCC) and CO_2 emissions. Following the energy-efficient renovation, the envelope performance was able to meet the requirements set for Chinese rural houses [31]. These basic building envelope properties are listed in Table 2. The internal gains of lighting and household appliances were estimated at 5 W/m^2 and 3.8 W/m^2, respectively, based on the recommendations from the local residential building design standard [32].

2.1.2. Heating and ventilation systems

Fig. 3 presents the concepts of the original heating and ventilation systems in the case building, together with the studied renovation options for these systems.

The original heating system comprised a coal boiler in kitchen, along with two water-based radiators in two bedrooms, and a heated bed (known as Kang [30]) in bedroom 1, as shown in Fig. 3 (a). Under the heating system renovation plan, the space heating was managed using a high-efficiency biomass pellet boiler, as shown in Fig. 3 (b)–(d). The original water-based radiators in two bedrooms remained operational, with additional radiators installed in the kitchen and storage room. The heating setpoint in bedrooms was increased to 17 °C to align with the thermal neutral temperature preferred by local rural residents [33]. The heating setpoint in the kitchen and storage was set at 14 °C, meeting the standard requirements for rural houses [31].

The original case building did not include a mechanical ventilation system, relying instead on air exchange facilitated by envelope infiltration and the manual operation of windows. The occupants, guided by their sense of comfort, generally avoid opening windows during winter due to extremely low outdoor temperatures. Consequently, outdoor air intake primarily depends on envelope infiltration. The building's airtightness was estimated at 7 air change rates (ACH) at 50Pa over the envelope, based on average measurement data from rural houses in this area [34]. The original natural ventilation strategy employed by the case building is detailed in the authors' previous study [30]. Fig. 3 (a) and (b) depict this natural ventilation strategy. Fig. 3 (c) proposes the installation of mechanical exhaust ventilation, with exhaust air terminals located in the kitchen and storage. Fig. 3 (d) shows a mechanical balanced ventilation system, with supply air terminals in the bedrooms and the AHU in the storage. Optional energy-efficient measures to this system include the integration of an EAHE and a heat recovery unit.

Table 2
Basic building properties after envelope renovation.

Parameters	Value
Heated net floor area, m^2	54
Window-to-wall ratio, %	27 %
U-value of external wall, W/m^2 K	0.17 (southern); 0.19 (others)
U-value of ground floor, W/m^2 K	0.53
U-value of roof, W/m^2 K	0.42
Internal heat gains of lighting, W/m^2	5
Internal heat gains of household appliances, W/m^2	3.8

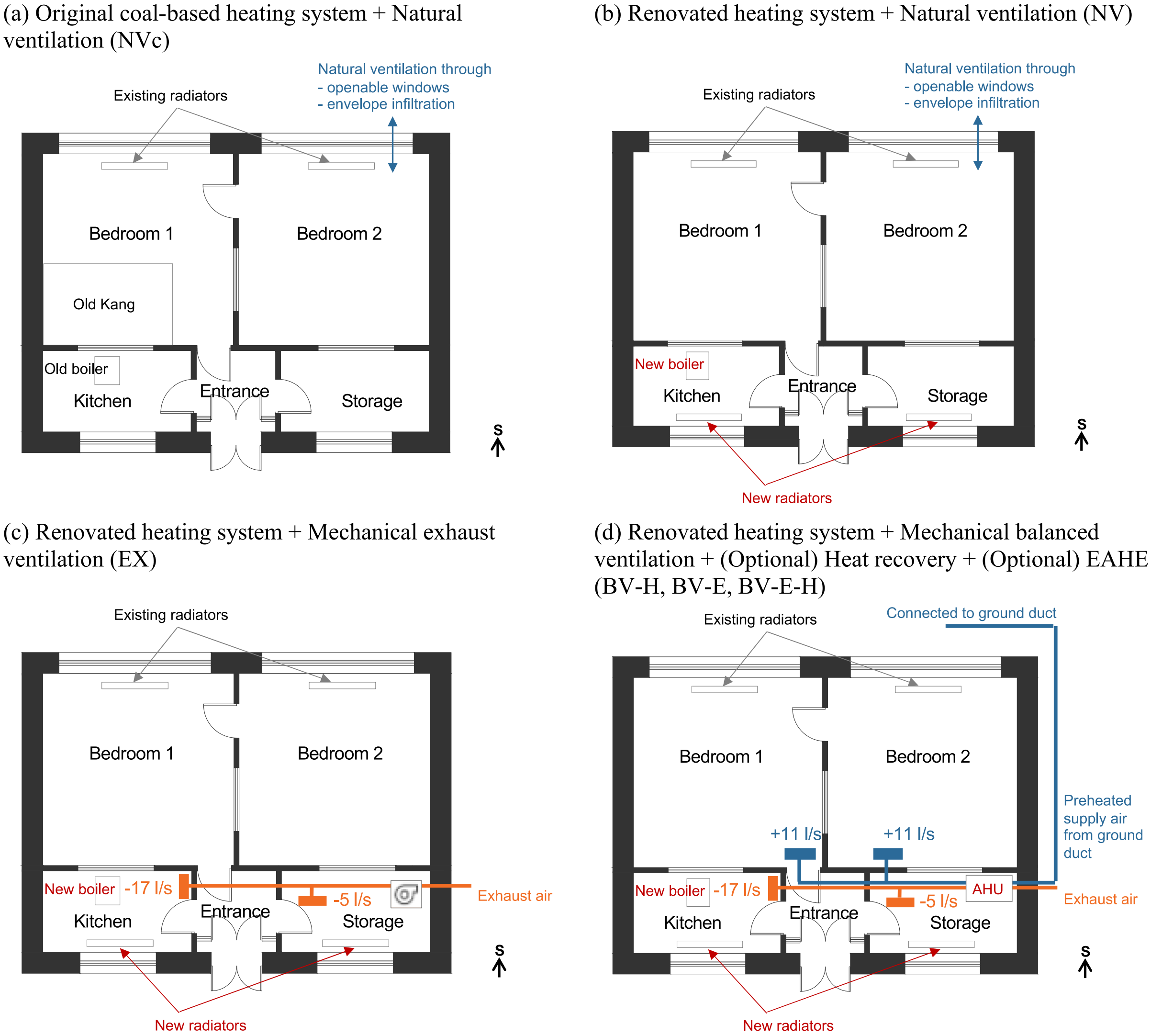

Fig. 3. Proposed heating and ventilation options.

2.1.3. Weather data

The case building is situated in a rural area of Harbin, characterized by a severe cold climate. The winter in Harbin is known for its lengthy duration and extremely low temperatures. The local heating season usually spans 183 days, from October 20 to April 20 of the following year [35]. The IWEC 2 weather file for Harbin, representing a typical year, was selected to depict local weather conditions. More climate features and ground properties are listed in Table 3.

The entire heating season was divided into three distinct weather categories, defined by the weekly average outdoor temperature: slight cold, cold, and severe cold groups. To represent the typical weather conditions of each category, one representative week was systematically chosen.

Table 3
Climate and soil features of typical city in severe cold region, Harbin [36,37].

Features	Value
Average annual temperature, °C	5.2
Average temperature during heating season, °C	−7
Average temperature of the coldest month, °C	−17.4 (January)
Daily temperature ≤5 °C, day	169
Soil thermal conductivity, W/m K	1.3
Depth of frozen soil, m	2.1

Fig. 4 displays the hourly outdoor temperature profile of Harbin and highlights the chosen typical winter weeks. More justification for this categorization is detailed in a previous study [38]. Examining system performance under various weather conditions provide valuable insights for applications in regions beyond those with severe cold climates.

2.2. Modeling of EAHE

2.2.1. Description of ventilation system with EAHE and heat recovery

Fig. 5 depicts a ventilation system incorporating both an EAHE and heat recovery. During the non-heating season, the building uses its original natural ventilation strategy, which involves manually opening windows. The proposed mechanical ventilation system with EAHE and heat recovery only operates during the heating season. During operation, the supply air first flows through the ground duct, where it exchanges heat with the warmer soil. Then it flows into an indoor heat recovery unit, where it exchanges heat with warmer exhaust air, further increasing its temperature. The rotary heat recovery unit in this system prevents frosting by adjusting its effectiveness, achieved in practice by controlling the rotation speed [39]. A defrost limit threshold was set at 1 °C. If the supply air temperature after heat recovery remains below the ventilation setpoint (16 °C), it is heated by an electric reheater before being supplied to the ventilated rooms.

Given the typically elevated expenses associated with vertical positioning, the ground duct was oriented horizontally in the yard. A single-layer, single-duct serpentine arrangement was more fitting for this single-family house than a multi-layer or multi-duct arrangement, which would require more excavated soil and more complicated construction. The ground duct was buried at 3 m below the soil surface, deeper than the frozen soil depth, which also ensured the soil temperature remained undisturbed. The calculation of fan pressure rise accounted for additional pressure losses in the ground duct, which varied from 10 to 100 m of duct length, including both straight sections and fittings. Detailed parameters for each component are listed in Table 4.

2.2.2. Simulation tool

The tool IDA Indoor Climate and Energy simulation software (IDA ICE) was applied to model and simulate the case building. It is a dynamic simulation tool capable of accurately modeling building systems and providing outputs of building energy consumption and indoor climate. This tool has been validated under the Standards EN 15255–2007 and EN 15265–2007 [47]. The EAHE model in IDA ICE was developed from IDA Tunnel, which has been validated and successfully implemented in numerous practical projects [40,41].

The assumptions in EAHE model are as follows [42].

- The cross-sectional shape of the ground duct was approximated as circular and uniform.
- Temperature fields were calculated with one-dimensional heat transfer.
- The boundary condition for the ground surface was defined using hourly fluctuations in ambient air temperature, which were also equal to the inlet air temperature.

The superposition process involved combining the external temperature fields generated by undisturbed ground, geothermal effects, and neighboring ducts along with their respective contributions. The total field was subsequently created by summing the external temperature fields and the internal temperature field of the ground duct. A one-year dynamic startup period was implemented due to the inclusion of ground with significant thermal mass in the EAHE model.

This study aims to evaluate the cost efficiency and environmental impacts of different ventilation scenarios. To achieve this, energy simulations were conducted with IDA ICE rather than employing detailed computational fluid dynamics (CFD) modeling. The

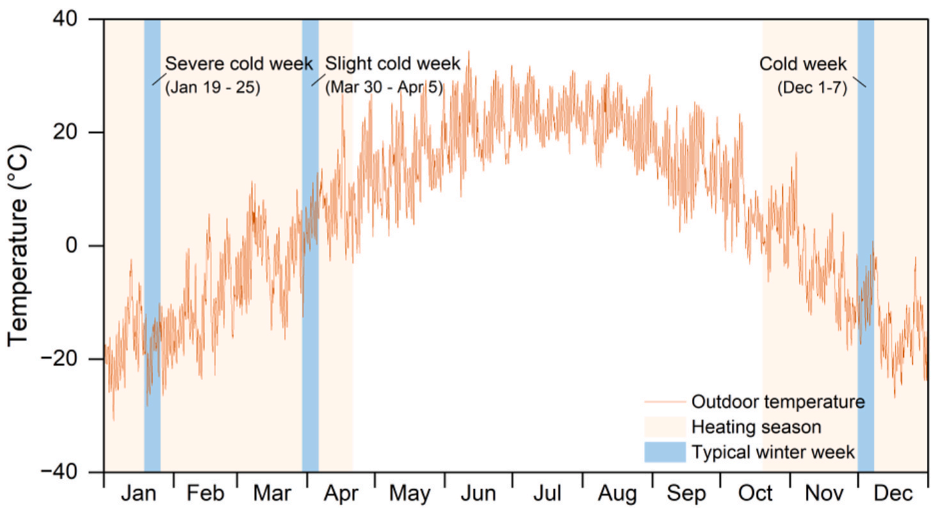

Fig. 4. Outdoor temperature profile and typical winter weeks of Harbin.

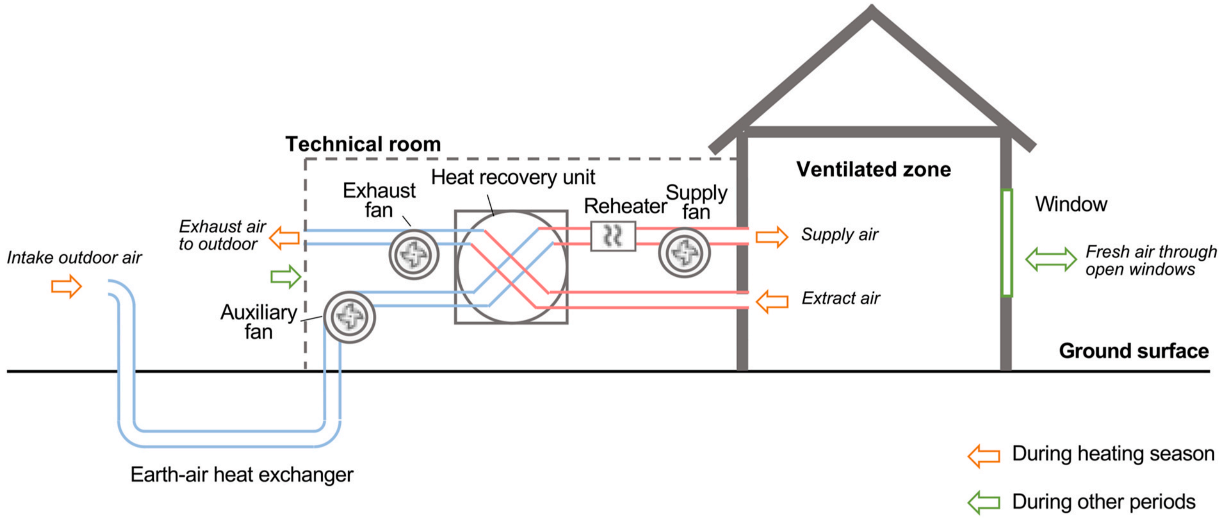

Fig. 5. Schematic of a ventilation system with EAHE and heat recovery.

Table 4
Parameters of ventilation components.

Component	Parameter	Value
EAHE	Duct diameter, m	0.08
	Duct length, m	10–100
	Thermal conductivity of duct, W/m K	0.21
	Duct spacing, m	1.5
	Burial depth, m	3
HR	Supply air temperature efficiency, %	83
Fan	Fan efficiency, %	60
	Specific fan power, kW/m^3/s	1.62
	Pressure loss in ground duct with length of 10–100 m, Pa	49–460

simulations assumed fully mixed ventilated zones with predefined airflow rates. The influence of specific supply and exhaust air outlet locations on pollutant removal effectiveness was not taken into account in the analysis.

2.3. Case design and evaluation

2.3.1. Case design

In order to evaluate the performance of each ventilation component individually as well as their combined performance, eight ventilation system cases were simulated, as summarized in Table 5. There were two reference cases applying the original natural ventilation strategy. One reference case retained the original coal-based heating system (Ref. NVc), with the heating setpoint in the

Table 5
Properties of comparison cases.

Cases	Heating system [a]	Additional radiators [b]	Heating setpoint	Ventilation type	With HR?	With EAHE?
Ref. NVc	Original	No	14 °C	Natural	No	No
Ref. NV	Renovated	Yes	17 °C/14 °C [c]	Natural	No	No
EX	Renovated	Yes	17 °C/14 °C	Exhaust	No	No
BV-H	Renovated	Yes	17 °C/14 °C	Balanced [d]	Yes	No
BV-E-H	Renovated	Yes	17 °C/14 °C	Balanced	Yes	Yes
BV-E	Renovated	Yes	17 °C/14 °C	Balanced	No	Yes
EX-21/17	Renovated	Yes	21 °C/17 °C	Exhaust	No	No
BV-E-H-21/17	Renovated	Yes	21 °C/17 °C	Balanced	Yes	Yes

[a] The "original" heating system refers to the coal boiler and Kang used in the reference model. The "renovated" heating system refers to the proposed biomass pellet boiler.
[b] "Additional radiators" are installed in auxiliary rooms (storage and kitchen) for heating purposes.
[c] 17 °C and 14 °C are the heating setpoint of bedrooms and auxiliary rooms, respectively.
[d] Ventilation setpoint is 16 °C in all balanced ventilation scenarios.

bedrooms maintained at 14 °C to meet the standard requirements for rural houses [31]. The other reference case applied a new biomass-based heating system (Ref. NV). The heating setpoint in the bedrooms was increased to 17 °C, aligning with the thermal neutral temperature preferred by local rural residents [33]. The heating setpoint in the auxiliary rooms (kitchen and storage) was set at 14 °C, which still met the standard requirements.

All the renovation cases adopted the same heating system renovation as Ref. NV. EX refers to the case applied a mechanical exhaust ventilation system. The mechanical balanced ventilation system with heat recovery was simulated both with (BV-E-H) or without EAHE (BV-H). BV-E represents the case applying a mechanical balanced ventilation with EAHE but without heat recovery. EX-21/17 and BV-E-H-21/17 share the same ventilation settings as EX and BV-E-H, but the heating setpoints for bedrooms and auxiliary rooms increased to 21 °C and 17 °C, respectively.

2.3.2. Evaluation methods

To quantify the performance of each ventilation case, two primary evaluation methods were employed: an economic method, such as the net present value of life-cycle cost (NPV of LCC), and an environmental method, such as CO_2 emissions of delivered energy consumption.

The NPV of LCC is defined as the total cost of the ventilation system renovation (EAHE design) or includes both the new ventilation and renovated heating system (for comparison across all cases) during a specific life-cycle period of 20 years:

$$LCC_{20a} = \sum I_{tot} + \sum MR_a \times \frac{1-(1+r)^{-n}}{r} + \sum R_a \times \frac{1}{(1+r)^{k_i}} + \sum E_a \times \frac{1-(1+r_e)^{-n}}{r_e}$$

where: LCC_{20a} is the NPV of LCC during a 20-year life-cycle period, CNY; $\sum I_{tot}$ is the total investment cost of renovation measure, CNY; $\sum MR_a$ is the annual maintenance and repair cost, CNY; $\sum R_a$ is the renewal cost, CNY; $\sum E_a$ is the annual energy cost; r is the real interest rate; n is the selected life-cycle period; k_i is the year from the start of the life-cycle period when a renewal measure is conducted; r_e is the escalated real interest rate. The nominal interest rate used in the calculation is 4.75 %/a [43]. The escalation rate of energy price is +0.8 %/a [44]. Table 6 lists the investment, maintenance and renewal costs for the renovation measures applied in all simulation cases.

The CO_2 emissions of delivered energy were calculated as the sum of CO_2 emissions from various energy carriers. The emission factors of biomass pellet and electricity in China are 295 kg CO_2/MWh and 584 kg CO_2/MWh [45,46]. However, as more renewable energy is integrated into the grid, the emission factor of electricity is gradually decreasing. An additional analysis was conducted to examine a potential future scenario involving low-carbon emission factors, using the dynamic emission factors of Finnish grid [47].

In EAHE design, the NPV of LCC considered only the costs associated with ventilation system renovation, and the CO_2 emissions were calculated solely for the energy delivered to the ventilation system. In the comparison of all cases, the NPV of LCC included the costs for both new ventilation system and new heating system, while CO_2 emission calculations accounted for the delivered energy consumption of the whole building.

In EAHE design, the technique for order of preference by similarity to ideal solution (TOPSIS) was used as a decision-making method to determine the optimal length of ground duct in cases involving EAHE (BV-E-H and BV-E). Recognized for its robust mathematical foundation, simplicity and ease of application, TOPSIS has been extensively applied in addressing multi-objective decision-making problems within the domain of building design and renovation [48]. TOPSIS defines the optimal solution as the one closest to the positive ideal solution and furthest from the negative ideal solution (see Fig. 6), resulting in the highest ranking among the normalized performance scores of all alternatives. More mathematical details about TOPSIS method are available in Ref. [49]. The positive ideal solution in this study corresponded to the minimum values of LCC and CO_2 emissions. The weights of two objectives were

Table 6
Cost data of heating and ventilation renovation measures.

System	Component	Cost
EAHE	EAHE material cost (duct, direct connectors, bends, air intake terminal), CNY[a]	130–1140[b]
	Earthwork cost, CNY	420–8755[b]
	Installation fee, CNY	300
	Annual maintenance cost, CNY/a	30
Balanced ventilation	AHU (HR, reheater and fans), CNY	3960–3975[b]
	Accessories (terminals and indoor pipes), CNY	155
	Installation fee of ventilation system, CNY	2000
	Annual maintenance cost, CNY/a	20
Exhaust ventilation	Fans, CNY	660
	Accessories (terminals and indoor pipes), CNY	90
	Installation fee, CNY	1000
Heating system	Biomass pellet boiler, CNY	2500
	Accessories (water-based radiators, pipes, temperature control valves), CNY	620
	Installation fee, CNY	1000
	Renewal cost of biomass pellet boiler, CNY	2500
	Renewal cost of original coal boiler, CNY	1500

[a] 1 CNY = 0.13 EUR (03/2024).
[b] Cost range is related to the ground duct length (10–100m).

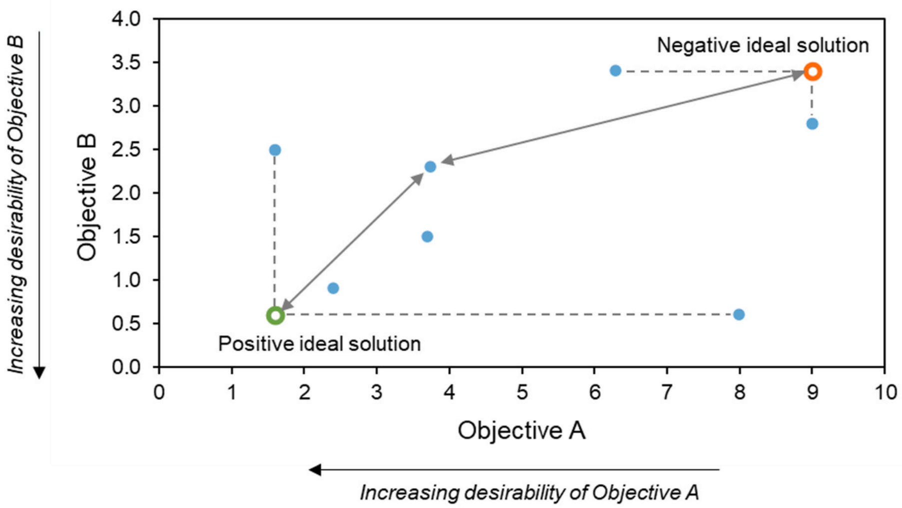

Fig. 6. Basic concept of TOPSIS.

assigned equal values of 0.5. Cases with different duct lengths were ranked based on their overall performance scores, and the length with the highest ranking was selected.

3. Results

The results section is structured into three parts. Section 3.1 first presents a multi-objective EAHE design to identify the optimal ground duct length for the balanced ventilation cases involving EAHE. Section 3.2 compares balanced ventilation cases through analyzing the ventilation power profiles during the heating season and the heating energy ratios under different weather conditions. Section 3.3 examines reference cases with a natural ventilation strategy and renovation cases with mechanical ventilation systems, focusing on LCC, CO_2 emissions, and indoor air quality.

3.1. EAHE design

The reference case during this EAHE design stage was defined as a mechanical balanced ventilation system with heat recovery but without EAHE (BV-H). Other analyzed cases applied mechanical balanced ventilation with both heat recovery and EAHE (BV-E-H), with ground duct lengths ranging from 10 m to 100 m. Two metrics were considered: the NPV of LCC of the ventilation system and the CO_2 emissions of delivered ventilation energy consumption. TOPSIS was utilized to identify the most suitable ground duct length.

Fig. 7 illustrates the metric comparison and the overall performance score for each case. It is demonstrated in Fig. 7 (a) that cases with a duct length of up to 70 m consistently achieve a lower LCC compared to the reference case, primarily due to significant reductions in energy costs. The minimum LCC occurs at a duct length of 20 m, resulting in a significant 23 % reduction in LCC. As the length increases, the investment cost also rises, while the impact on reducing energy costs becomes less apparent. When the length exceeds 70 m, the LCC surpasses that of the reference case. Fig. 7 (b) reveals that all duct lengths from 10 m to 100 m contribute to reductions in CO_2 emissions. Among all cases, the 50 m duct stands out for achieving a 57 % reduction in CO_2 emission compared to the reference case. It is noteworthy that as duct length increases, there is a corresponding rise in fan electricity consumption; however, the energy-saving effect on the reheater becomes less pronounced. Consequently, when the duct length exceeds 50m, CO_2 emissions begin to rise. The overall performance scores for various cases were computed using the TOPSIS method. Fig. 7 (c) indicates that the optimal length is 30 m, which is subsequently employed in BV-E-H and BV-E for further analysis and evaluation.

3.2. Comparison among balanced ventilation cases

Fig. 8 presents the hourly heating power profile of ventilation components in BV-E-H, along with the temperature profile of supply air during the heating season. BV-E-H is equipped with a mechanical balanced ventilation system as well as both EAHE and heat recovery. A ground duct length of 30 m was used in this EAHE, as determined in Section 3.1. The supply air temperature was observed to range from −3 °C to 11 °C after passing through the EAHE. Subsequently, as the supply air undergoes heat recovery process, its temperature stabilizes and increases to a range of 9 °C–16 °C. There remains a slight gap between the ventilation setpoint of 16 °C and the supply air temperature after heat recovery, indicating that additional heating is required from the reheater. The heating power profile reveals that the EAHE occasionally has a heating power below 0, indicating periods when it cools the supply air and heats the ground during the heating season. This behavior deviates from the original intention of system operation. The EAHE achieves a maximum heating power of 793W, which coincides with the occurrence of the lowest outdoor temperature. Another notable

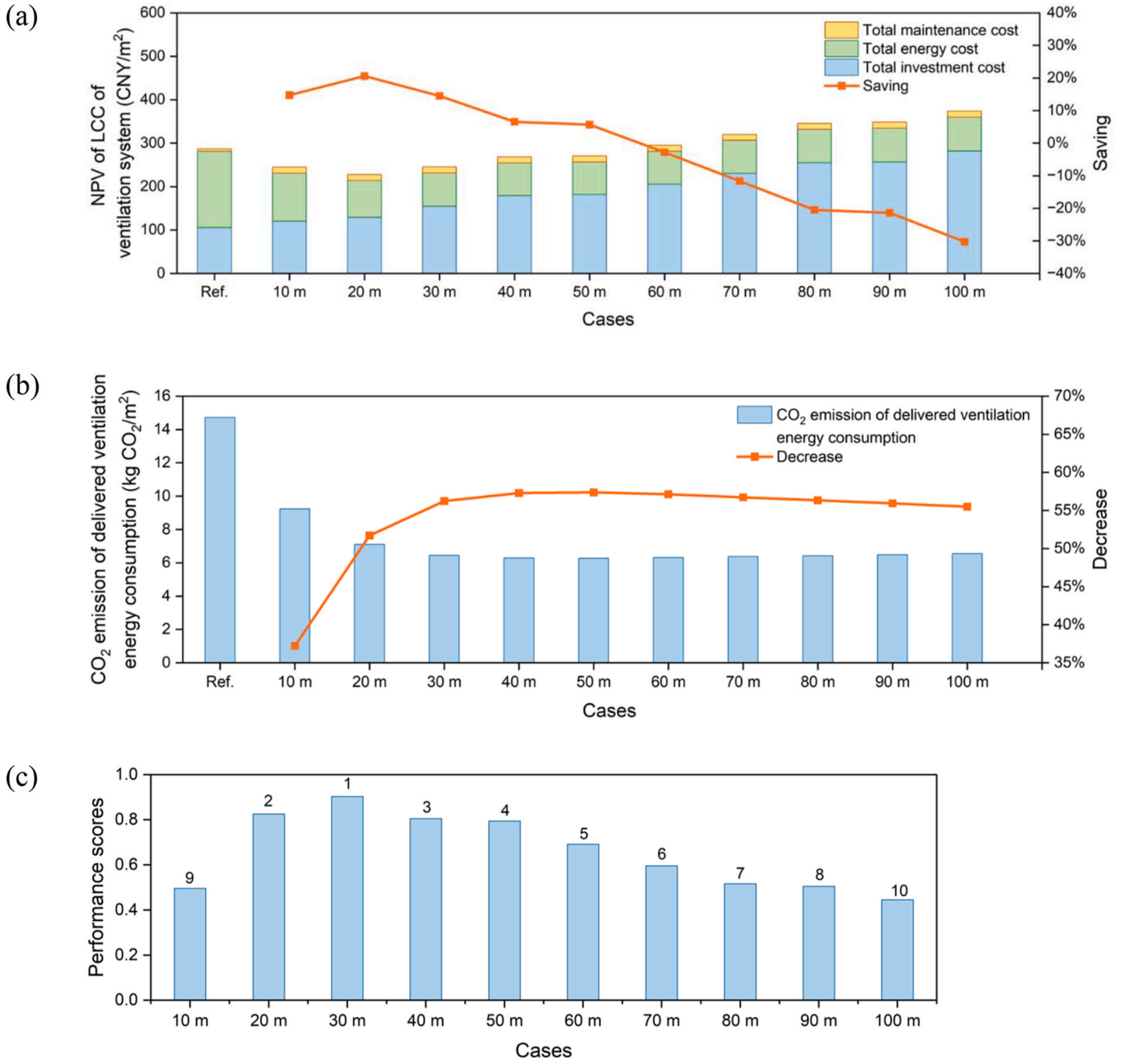

Fig. 7. (a) NPV of LCC of ventilation system, (b) CO_2 emission of annual delivered ventilation energy consumption and (c) performance scores of different duct lengths.

observation is the pronounced inverse correlation between the heating power of the EAHE and outdoor temperature. This correlation indicates that EAHE has the capability to provide more heat to the supply air when the outdoor temperature is lower. However, the heating power of the heat recovery and reheater remains relatively stable, showing minimal impact from outdoor temperature fluctuations.

Fig. 9 compares the ventilation power duration curves of three balanced ventilation cases. In the balanced ventilation system with both EAHE and heat recovery (BV-E-H), EAHE serves a heating purpose for 79 % of the time during the heating season. When compared to the typical heat recovery ventilation system (BV-H), EAHE significantly reduces the maximum heating capacity of the reheater from 882 W to 166 W, an 81 % reduction. In the absence of heat recovery (BV-E), the reheater's maximum capacity is 513 W, which is 42 % lower than that observed in the heat recovery ventilation system (BV-H). In the heat recovery ventilation system (BV-H), the heat recovery power remains relatively constant for a specific duration. This behavior is attributed to the operation of the defrost protection, which adjusts the heat recovery power to maintain the exhaust air outlet temperature of heat recovery above the defrost limit threshold (1 °C).

Besides, Fig. 9 provides insights into the ventilation heating energy of each case. The cross-sectional areas between the duration curves and the horizontal axis at zero represent the heating and cooling energies. When an EAHE is incorporated into the heat recovery ventilation system, the heating energy required from the reheater reduces by 64 % (844 kWh), while the recovered heating energy

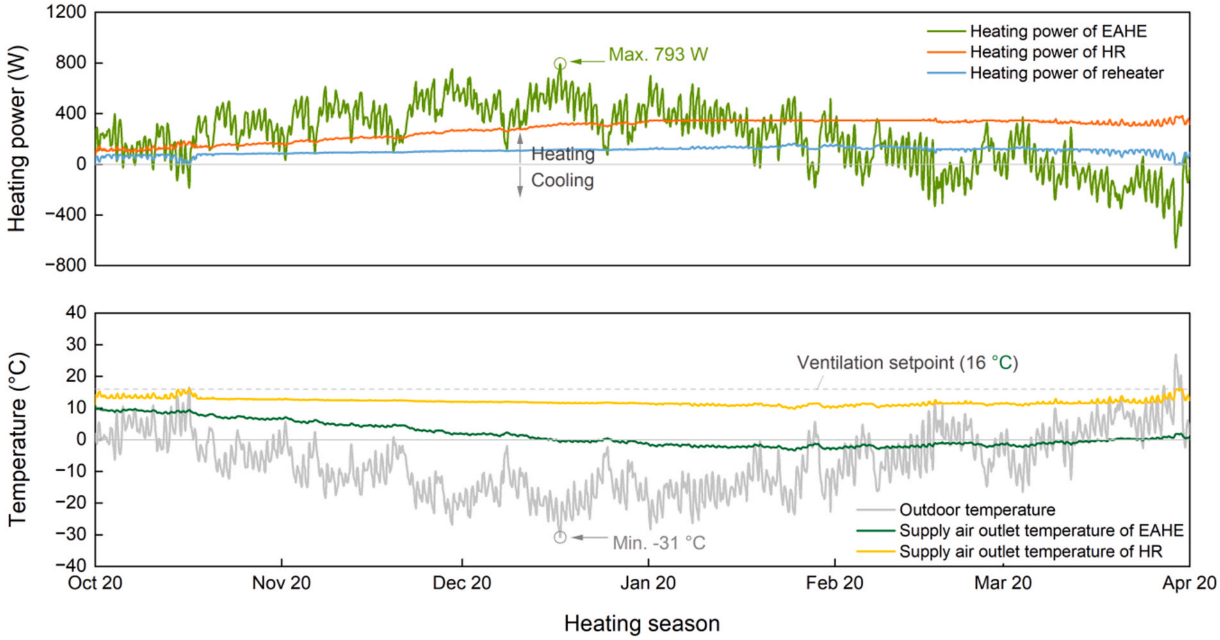

Fig. 8. Heating power profile of ventilation system versus outdoor temperature during heating season (BV-E-H).

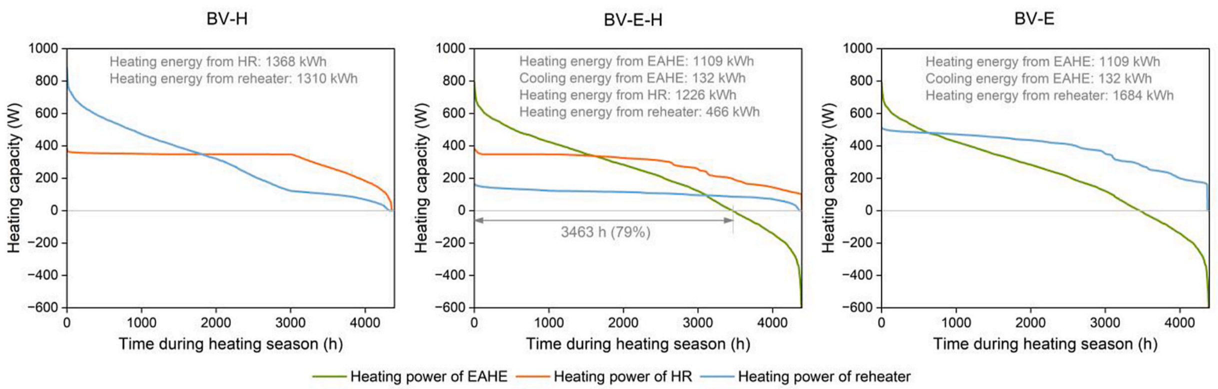

Fig. 9. Ventilation heating power duration curves and heating and cooling energies during heating season (cases with balanced ventilation system).

from the heat recovery unit is decreased by 142 kWh. The cooling energy from EAHE is 132 kWh, which leads to the extra heating demand for heat recovery and reheater.

Fig. 10 presents the heating energy ratio of ventilation components under various weather conditions and throughout the entire heating season. It analyzes the heating supply contribution of EAHE, heat recovery and reheater across three balanced ventilation cases. During a slight cold week, in the ventilation configuration integrating both EAHE and heat recovery (BV-E-H), heat recovery predominantly supplies 71 % of the heating energy. Conversely, EAHE contributes only 5 % of the heating energy, while its cooling energy accounts for 20 % of the total ventilation heating energy. The remaining heating energy is provided by the reheater. In contrast, during colder periods, including cold and severe cold weeks, the combined operation of EAHE and heat recovery (BV-E-H) leads to enhanced utilization of heat extracted from the ground and exhaust air, while reducing the reheater's heating energy ratio. Furthermore, in the balanced ventilation configuration featuring only EAHE without heat recovery (BV-E), the proportion of heating energy from the reheater is lower than that of the case relying solely on heat recovery without EAHE (BV-H). It is also noteworthy that, under colder conditions, EAHE does not cool the supply air anymore.

When examining the entire heating season, it is evident that in the ventilation case combining both EAHE and heat recovery (BV-E-H), EAHE contributes 40 % of the total ventilation heating energy. Heat recovery efficiently extracts heat from the exhaust air, constituting 44 %, while the remaining 17 % is supplied by the reheater. However, EAHE's cooling function still contributes 5 % to the total heating energy, thereby increasing the heating energy demand for heat recovery and reheater. To address this issue, certain methods, such as implementing a bypass system, need to be employed to eliminate the excess heating requirements. In the ventilation

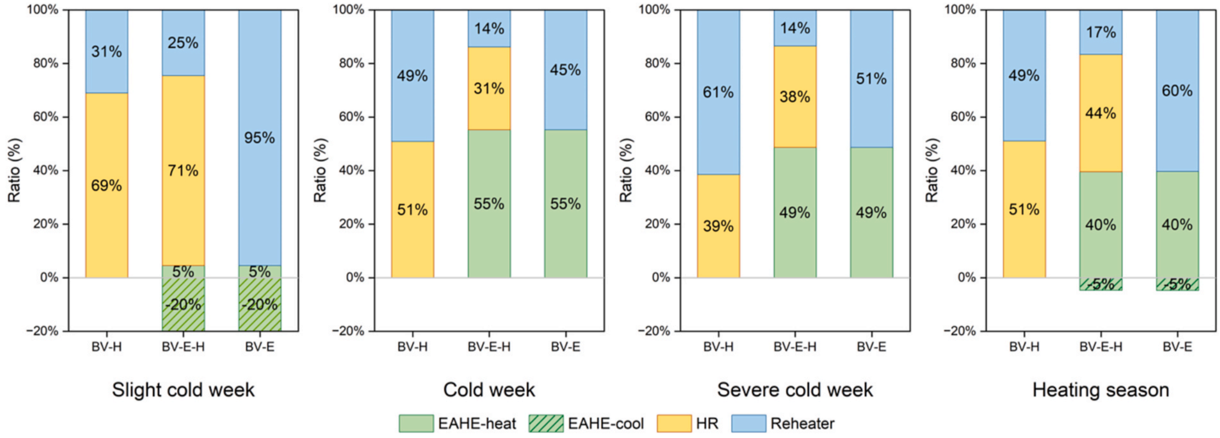

Fig. 10. Ventilation heating energy ratios during typical winter weeks and whole heating season (cases with balanced ventilation system).

configuration featuring only EAHE (BV-E), the heating energy ratio attributed to EAHE is 40 %, which is lower than that of heat recovery in the heat recovery ventilation system (BV-H). This observation suggests that if these two preheating methods are applied independently, the proportion of heat retrieved from the exhaust air exceeds that absorbed from the ground duct, resulting in lower heating energy from reheater.

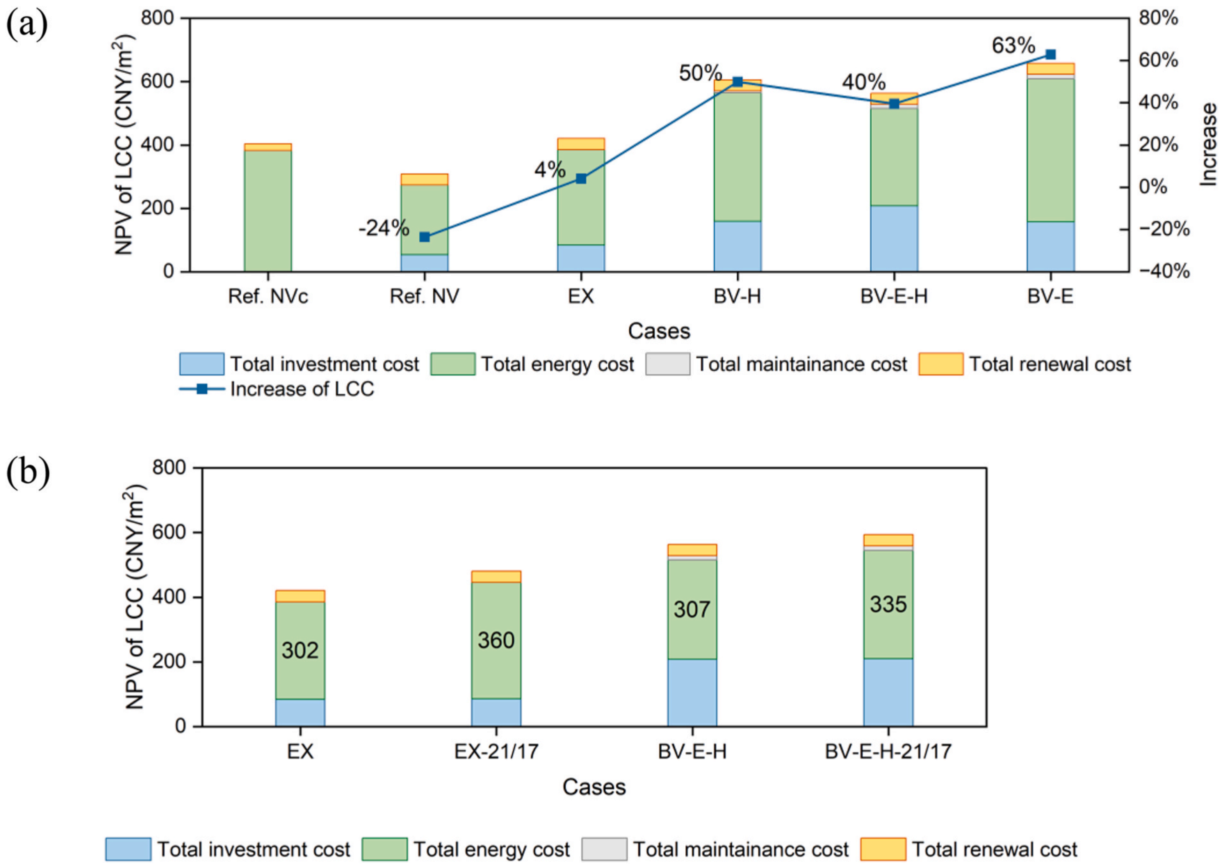

Fig. 11. (a) Building's LCC with original heating setpoints, (b) Building's LCC comparison between cases EX and BV-E-H with different heating setpoints.

3.3. Comparison between reference and renovation cases

Fig. 11 (a) illustrates the NPV of LCC for heating and ventilation renovations across both reference and renovation cases. Two reference cases were considered, both employing a natural ventilation strategy. One maintained the original coal-based heating system and original heating setpoints (Ref. NVc), while the other adopted a renovated biomass-based heating system with elevated heating setpoints (Ref. NV).

Notably, Ref. NV demonstrates a noteworthy 24 % reduction in LCC solely through the implementation of a heating system renovation. However, when both heating and ventilation renovation are applied in the renovation cases, the LCC values for all renovation cases surpass those of the reference cases. Additionally, among the renovation cases, the mechanical exhaust ventilation system (EX) exhibits a more pronounced advantage, achieving a LCC of 420 CNY/m^2. The system integrating both EAHE and heat recovery (BV-E-H) stands out among the balanced ventilation cases, displaying a LCC of 563 CNY/m^2.

Fig. 11 (b) explores the effects of higher exhaust air temperature on the outcomes of LCC. The current heating setpoints for bedrooms and auxiliary rooms were set at 17 °C and 14 °C, respectively. Thus, the exhaust air temperature from auxiliary rooms was limited to only 14 °C, exerting a certain constraint on heat recovery efficiency. When the heating setpoints were increased to 21 °C and 17 °C for bedrooms and auxiliary rooms, it is observed that the LCC for both EX and BV-E-H cases experiences an increment due to higher heating demands. EX continues to maintain a lower LCC compared to BV-E-H. However, the total energy cost of BV-E-H rises to 335 CNY/m^2, which is actually lower than that of EX (360 CNY/m^2). This highlights the subtle interaction between heating setpoints and their corresponding LCC results.

Fig. 12 (a) presents the annual CO_2 emissions from delivered energy consumption for the entire building. Among all renovation cases, BV-E-H has the lowest CO_2 emissions at 44 kg CO_2/m^2, followed by EX at 50 kg CO_2/m^2. While BV-H and BV-E do not demonstrate clear advantages, primarily due to the significant emissions associated with their electricity consumption. An additional analysis evaluated a potential future scenario that involves low-carbon emission factors, which undertook the dynamic emission factors of Finnish grid. Fig. 12 (b) shows that with a reduced emission factor for electricity, all three balanced ventilation cases achieve lower CO_2 emissions compared to EX and Ref. NVc, indicating their potential environmental advantages.

Table 7 presents the indoor air situation for each case during the heating season, evaluated by the average ventilation air change rate of the entire building. In the absence of a mechanical ventilation system, both Ref. NVc and Ref. NV have very low ventilation air change rates, which falls considerably below the standard requirements of 0.5/h [31]. Ref. NV has an even lower ventilation air change

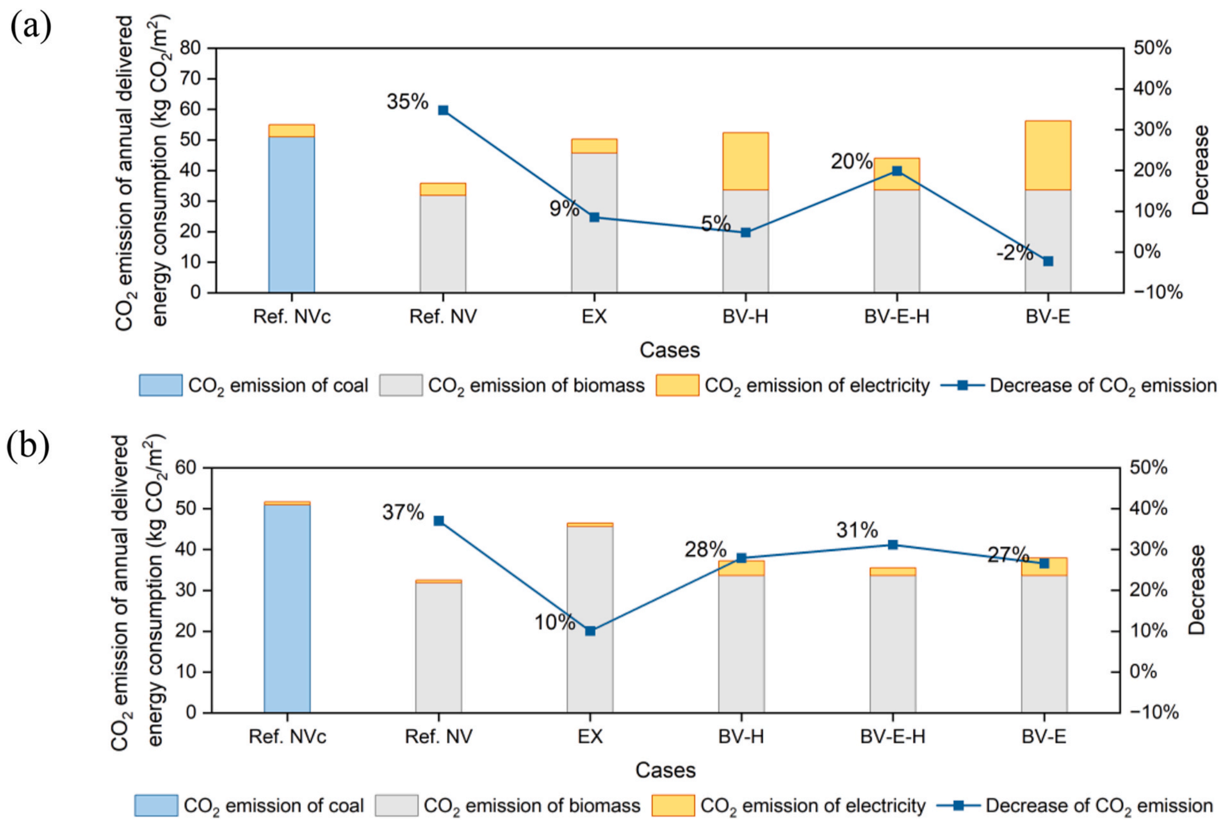

Fig. 12. Annual CO_2 emissions of building delivered energy consumption with (a) current and (b) future lower-carbon emission factor for electricity.

Table 7
Average ventilation air change rate of whole building during heating season.

Cases	Ref. NVc[a]	Ref. NV	EX	BV-H	BV-E-H	BV-E
Ventilation rate, 1/h	0.14[b]	0.08[b]	0.54	0.54	0.54	0.54

[a] Only this case uses heating system with coal boiler and Kang. Other cases use heating system with biomass boiler.
[b] The value does not fulfill the standard requirements of 0.5/h.

rate than Ref. NVc due to the reduced leaks and expanded space volume after removing Kang from the bedroom during the heating system renovation. However, introducing an exhaust or balanced ventilation system leads to a substantial improvement in indoor air quality, as evidenced by higher ventilation air change rates.

4. Discussion

In total, this study examined four mechanical ventilation systems designed for Chinese detached rural houses in severe cold climate. These systems were evaluated from both economic and environmental perspectives and compared to the reference natural-ventilated case.

The optimization of EAHE system indicates that a ground duct length of 30 m is deemed appropriate for detached rural houses in the specified area. Extending beyond this length allows the EAHE to extract more heat from the ground, further reducing the heating demand for heat recovery and reheater. However, it is also important to consider the potential disadvantages of longer pipes, such as increased pressure drop leading to higher fan power consumption and the significantly higher excavation costs. Besides, this optimal length depends closely on local weather conditions and soil properties, as well as other variables such as burial depth, duct diameter, and air change rate, which were predetermined based on empirical values and specification requirements. Lapertot et al. [50] performed a sensitivity analysis on a heat recovery ventilation system with EAHE under French climate, identifying parameters that significantly impact the system's COP. These parameters include duct diameter, duct length, burial depth, air change rate, and ventilation setpoint temperature. Incorporating these design variables into a multi-variable, multi-objective optimization becomes imperative, if a more nuanced and refined EAHE system design with optimal outcomes is wanted.

Upon integrating EAHE into the heat recovery balanced ventilation system (BV-E-H), EAHE contributes 40 % of total heating energy throughout the heating season, reducing the proportion of heating energy supplied by reheater from 49 % to 17 %. Despite these promising results, opportunities for further improvement remain exist. Since approximately 21 % of the heating season is characterized by a phenomenon where EAHE lowers the supply air temperature instead of raising it, leading to cooling energy that accounts for 5 % of the total heating energy. This occurrence is typically observed in slight cold weather conditions with rising outdoor temperatures and becomes more pronounced towards the end of the heating season. The possible explanation is related to the delayed thermal response of the ground. Towards to the end of the heating season, as outdoor temperature begins to increase, the soil exhibits a slower rate of temperature increase. Additionally, as the soil has already released heat to supply air previously, its temperature tends to be lower than that of the surrounding undisturbed soil. When warm supply air flows into the duct, its heat is transferred to the duct wall and surrounding soil. The lost heat necessitates compensation through the heat recovery and reheater, thereby augmenting unnecessary ventilation heating demand. To address this issue, it is recommended to incorporate a bypass system into the EAHE. When the supply air temperature at outlet of EAHE is lower than that at inlet, the EAHE system should be deactivated, allowing the supply air to bypass the EAHE and directly enter the heat recovery. This bypass mechanism provides a more effective utilization of the ventilation system, especially in situations where the EAHE system might unintentionally cool the supply air. Furthermore, in instances where no bypass system is integrated into the EAHE, condensed water in the ground duct should be drained regularly. The hydrophobic properties of the PVC material utilized for the ground duct facilitate effective drainage of condensed droplets, minimizing the likelihood of mold formation within the EAHE system [51].

In addition, a comparison of different weather conditions reveals that the EAHE system is notably well-suited for cold or severe cold climates. In regions with relatively mild winter temperatures, the capacity of EAHE to warm up the incoming air is considerably limited. These findings align with the conclusions drawn by Li et al. [52], who suggest applying the EAHE system in regions with a substantial temperature difference between winter and summer. Hollmuller et al. [53] similarly reported that in central European climates, the preheating capability of EAHE is less competitive due to the narrow disparity between outdoor air temperature and the upper limit of heated air temperature, based on meteorological annual average temperature.

The comparative analysis of renovation ventilation cases reveals that incorporating an EAHE into the heat recovery balanced ventilation system (BV-E-H) provides benefits in both LCC and CO_2 emission. Compared to the heat recovery balanced ventilation system (BV-H), the composite ventilation system (BV-E-H) reduces the maximum heating power of reheater and the runtime for heat recovery defrost protection procedures. These findings contradict to those derived from Chlela et al. [54], who reported that in French climate, balanced ventilation with heat recovery alone is more effective than combining an additional EAHE, primarily due to the marginal heat gain from EAHE. The observed difference in results may be attributed to the fact that the current study area experiences lower winter temperatures compared to the cities in France examined by Chlela et al. In extremely cold conditions, the performance of heat recovery is significantly hindered due to frequent defrost operations. Conversely, EAHE performs better during colder periods and helps protect the heat recovery unit from freezing. Regarding the balanced ventilation system equipped solely with EAHE (BV-E), although its initial investment cost is lower than that of the heat recovery ventilation system (BV-H), the preheating contribution of EAHE to the supply air is less substantial than that achieved by heat recovery alone. Consequently, the total energy consumption is higher, leading to increased LCC and CO_2 emissions in comparison.

Practical implementation of mechanical ventilation systems in rural houses should consider both cost-effectiveness and environmental impacts. The subsequent recommendations outline the optimal systems for various priorities and scenarios. If pursuing cost-effectiveness, the recommended order is as follows: (1) mechanical exhaust ventilation system (EX), (2) mechanical balanced ventilation system with both EAHE and heat recovery (BV-E-H), (3) heat recovery balanced ventilation system (BV-H), and (4) balanced ventilation system with EAHE solely (BV-E). However, if occupants elevate demands for indoor temperature, such as a higher heating setpoint of 21 °C for residential buildings in Nordic countries, the energy cost of the balanced ventilation system with EAHE and heat recovery (BV-E-H) may become more favorable than exhaust ventilation system (EX). This shift occurs because higher heating setpoint temperature increases the temperature of exhaust air, thereby enhancing the heat recovery's performance. Notably, the LCC of all the renovation cases surpass those of reference cases, which indicates that, from an economic perspective, it is not effective to adopt mechanical ventilation systems in detached rural houses if compared with original natural ventilation strategy. However, the ventilation air change rate is obviously increased when mechanical ventilation systems are utilized. Previous studies have shown that improving air change rate can effectively remove air pollution, leading to better indoor air quality and reduced risks of associated diseases [55]. Therefore, despite the economic challenges, there remain compelling reasons to apply mechanical ventilation in these houses with inadequate ventilation.

When prioritizing the reduction of CO_2 emissions, the recommended order of mechanical ventilation systems changes to: (1) mechanical balanced ventilation system with both EAHE and heat recovery (BV-E-H), (2) mechanical exhaust ventilation system (EX), (3) heat recovery balanced ventilation system (BV-H), (4) balanced ventilation system with EAHE solely (BV-E). With the anticipated decarbonization of the power grid, balanced ventilation systems are expected to outperform exhaust ventilation system in reducing CO_2 emission and further enhancing their long-term environmental benefits.

The horizontal single-layer serpentine layout applied in this study allows for the installation of a lengthy duct within a compact trench. This configuration only needs a shallow burial depth, facilitating cost control and mitigating construction complexity compared to a multi-layer layout [56]. Although a horizontal arrangement needs a larger land area, this poses minimal challenges for detached rural houses with spacious yards. Therefore, vertical or multi-layer layouts were excluded in this study. It is pertinent to note that implementing EAHE systems in urban contexts requires careful consideration of land area limitations, where alternative configurations, such as vertical layouts, may prove more suitable and efficient [57].

The ventilation system cases in this study assume continuous operation during the heating season. One reason for this choice is that local occupants are accustomed to natural ventilation during the non-heating season, which adequately fulfills the air change requirements. Supplementary air is only required during the heating season. Moreover, given that the ground duct is buried in shallow soil, the soil temperature rises again through solar radiation when the EAHE system is not in use. In the second year of operation, the average temperature of the supply air leaving EAHE decreases marginally by only 0.1 °C, with the average heating capacity dropping by 4 W compared to the first year. However, for longer-term operation, it is recommended to activate the EAHE combined ventilation system periodically in hot summer. During this operation, as warm outdoor air enters the ground duct, heat is transferred to the duct wall and surrounding soil, effectively charging the ground. This strategic use not only cools and dehumidifies the room but also supplements the ground with stored heat, which is then released during the next heating season [52].

5. Conclusions

Indoor air quality is closely tied to the well-being of occupants, while natural ventilation in Chinese rural houses in severe cold climate often fails to meet the air change requirements during the long and harsh winters. This study addresses this challenge by evaluating four different mechanical ventilation systems designed with energy-saving features, including heat recovery units and earth-air heat exchangers. The novelty of this study lies in its comprehensive approach to identifying the optimal ventilation solution for this building type under severe cold conditions. The feasibility of integrating various heat exchangers was evaluated in terms of their effectiveness, environmental benefits, and life cycle economic performance. Additionally, the sensitivity of the proposed mechanical ventilation options to future factor changes in thermal comfort and environmental impacts was analyzed, providing valuable insights for sustainable and adaptable ventilation system design.

The integration of an earth-air heat exchanger into a balanced ventilation system offers substantial advantages, including an 81 % reduction in the reheater's maximum heating power of the reheater and a 64 % decrease in its heating energy consumption. Notably, the effectiveness of the earth-air heat exchanger is particularly pronounced under colder weather conditions. An examination of the heating season reveals a distribution of heating energy, with earth-air heat exchanger, heat recovery and reheater contributing 40 %, 44 % and 17 %, respectively.

Among the evaluated mechanical ventilation strategies, the exhaust ventilation system emerges as the most cost-effective option, with a life cycle cost of 420 CNY/m^2. However, when occupants demand higher indoor temperatures, a mechanical balanced ventilation system incorporating both earth-air heat exchanger and heat recovery demonstrate lower energy costs compared to the exhaust ventilation system. From an environmental perspective, this integrated ventilation system achieves the lowest emissions at 44 $kg\ CO_2/m^2$. Besides, with the ongoing decarbonization of the power grid, the advantages of the three balanced ventilation systems are expected to become increasingly pronounced, ultimately surpassing the performance of the exhaust ventilation system.

These findings fulfill the research aim outlined in this paper and bridge the existing gaps in assessing the energy-saving potentials of combining heat recovery and earth-air heat exchanger for rural houses facing extreme climatic conditions. Besides, this study provides a valuable reference for decision-makers by offering practical recommendations for mechanical ventilation applications. It also contributes to addressing the pressing challenges of energy crisis, environmental sustainability, and occupant well-being, particularly in the context of residential building renovations in severe cold climate.

Future research could involve improving earth-air heat exchanger effectiveness through implementing control methods for an additional bypass system that enables automatic switching between different operation strategies. Additional research could also examine the possibilities of enhancing earth-air heat exchanger design through multi-variable, multi-objective optimization.

CRediT authorship contribution statement

Xinyi Hu: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Juha Jokisalo:** Writing – review & editing, Validation, Software, Methodology, Conceptualization. **Risto Kosonen:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Matti Lehtonen:** Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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