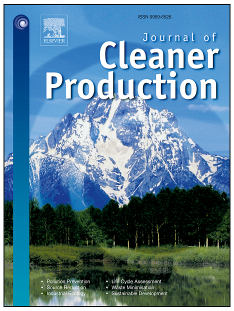

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CRediT authorship contribution statement

Li Gong: Methodology, Data curation, Writing - original draft. Zhongbin Zhang: Conceptualization, Methodology, Writing - review & editing, Supervision. Meng Chen: Formal analysis, Writing - review & editing. Steve Taylor: Supervision. Xiaolin Wang: Validation, Supervision.

Study on the carbon footprint of cold storage units using low-GWP alternative refrigerants

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Abstract：The increasing contribution of refrigeration systems to global warming has led to widespread demand for low global warming potential (GWP) refrigerants as alternatives. This paper proposed a comprehensive environmental assessment method for evaluating the carbon footprint of units charged with low-GWP refrigeration. Experimental and numerical studies were used to investigate the carbon footprint impact of using alternative refrigerants at different ambient temperatures in China. Initially, the model was validated through experimental case studies on the use stage of cold storage units. Subsequently, a comparison was made between the cooling capacity (CC) and energy efficiency ratio (EER) of cold storage units charged with different refrigerants. Additionally, the impact of alternative refrigerants in the use stage was analyzed by numerical calculations, and the adaptability of the cold storage unit to the ambient temperature and the national energy structure was also studied. The results indicate that among the four stages of the cold storage unit, the use stage is the hotspot of carbon footprint due to the large amount of energy consumption and the existence of refrigerant leakage and other behaviors. Utilizing low-GWP alternative refrigerants could significantly reduce the carbon footprint of the cold storage units' use stage by 10.56% to 16.39%, thereby lowering the whole stage carbon footprint. Furthermore, the ambient temperature and national energy structure could also effectively reduce the carbon footprint of cold storage units' whole stage by 1% to 27.17%. Furthermore, after adopting low GWP refrigerants, the life-cycle cost (LCC) of the units have also decreased by 6.1% to 12%. Taking into account both environmental impact and economic considerations, it is recommended to directly replace R404A with R448A in the units in regions where the average

ambient temperature is above 15 °C.

Key words: cold storage unit; low-GWP; R448A; carbon footprint

Acronyms

GWP	Global warming potential
CC	Cooling capacity
EER	Energy efficiency ratio
GHG	Greenhouse gas
PCMs	Phase change materials
HCFCs	Hydrochlorofluorocarbons
HFCs	Hydrofluorocarbons
T_c	Condensing temperature
T_e	Evaporating temperature
LCA	Life cycle assessment
LCC	Life-cycle cost
LCCP	Life cycle climate performance
TEWI	Total equivalent warming impact
ODP	Ozone depletion potential
TEV	Thermal expansion valve
SH	Super-heating degree
SC	Sub-cooling degree

1. Introduction

Designing energy efficient and environmentally friendly refrigeration systems is urgently needed in the face of the deterioration of the global climate (Belman-Flores et al., 2022; Koronaki et al., 2012; Kumar Singh et al., 2020). The Paris Agreement of the United Nations Framework Convention on Climate Change (Firoiu et al., 2021) established a long-term temperature target, that was, to limit the global mean temperature rise to below 2 °C (Rogelj et al., 2017), and to limit the actual temperature rise to 1.5 °C. The situation presented substantial energy-related challenges across nearly all industries (Deng et al., 2021; Evans et al., 2014; Zheng et al., 2019). Globally, the application of refrigeration has consumed 60% of the global total energy consumption (Canova et al., 2019; McLinden and Huber, 2020; Tian et al., 2019), while their greenhouse gas (GHG) emissions have accounted for approximately 1% of the total societal emissions.. In China, the refrigeration industry's indirect GHG emissions from electricity usage alone account for 9% of the country's total annual carbon emissions (China Refrigeration, 2023). Specifically, the cold storage unit, as an integral component of the continuous global cold chain (including industrial, medical, and food sectors), necessitates our focus on improving energy efficiency and reducing GHG emissions. Compared to traditional buildings, cold storage units have a greater potential for energy savings. This potential varies depending on the types and locations of the cold storage units (Evans et al., 2014; López-Belchí, 2019). Therefore, by enhancing the operational efficiency of cold storage units, not only can energy waste be reduced, but the negative environmental impact can also be significantly diminished (Rashidi et al., 2019; Soltani et al., 2020; Tartibu, 2019).

Nowadays, there is an increasing need to improve refrigeration efficiency to reduce GHG emissions while fulfilling the requirements for cold storage (Liu and Yu, 2018). Consequently, improving the efficiency of cold storage systems has become a focal point in most research endeavors (Deng et al., 2014; Lee et al., 2015). Some studies found that using inverter technology was an important means of load regulation to achieve energy-saving effects (Meraj et al., 2023; Ossorio and Navarro-Peris, 2023; Zhang et al., 2023). Some studies indicated that optimizing the charge of non-azeotropic refrigerants lowered the refrigerant charge and optimized unit performance (Hu et al., 2018; Rashidi et al., 2019; Vaitkus and Dagilis, 2014). Some studies indicated that optimizing the inertia structure of refrigeration systems significantly improved the coefficient of performance of the units (Khalili and Garousi Farshi, 2020; Nuermaimaiti et al., 2023). Additionally, numerous researchers have found that the utilization of phase change materials (PCMs) has a significant impact on the performance of cold storage units (Yan et al., 2019). For instance, incorporating fins can increase the heat transfer surface area and optimize the refrigeration unit structure in cold storage systems (Cheng and Zhai, 2018; Zhai et al., 2015). This enhancement in heat transfer and overall efficiency plays a crucial role in improving the performance of cold storage units.

Meanwhile, in pursuit of improved refrigeration efficiency and sustainable development, an increasing number of researchers have been studying refrigerant performance. Standardization plays a pivotal role in facilitating the adoption of new refrigerants, as shown in Figure 1, the Montreal Protocol aims to stop the production and use of ozone-depleting chemicals. The Kyoto Protocol states that HFCs are regulated as GHGs, with serious impacts on climate change (Ramiah et al., 2016). China' s formal acceptance of the Kigali Amendment to the Montreal Protocol in 2021 will reduce consumption of HFCs to 80% of the baseline by 2045 (UNEP, 2019). At present, many scholars are looking for suitable alternative refrigerants to reduce the use of HFCs, especially R134a/R404A/R410A, which is widely used in the field of refrigeration in China. Figure 2 shows the low GWP refrigerant substitution of these commonly used refrigerants. It can be seen from the figure that for the alternative refrigerants of R404A, the refrigerants belonging to the A1 class have a GWP value greater than 1000, and it is difficult to find a substitute with a GWP lower than 150 (except for natural refrigerants CO_2 and HCs). Although natural refrigerants have been used in some areas of the country, the refrigeration system needs to be redesigned to ensure normal operation. Some scholars have evaluated the performance of CO_2, its energy efficiency performance is lower in warm climate conditions, and more complex technologies are required to meet the demands of future carbon neutrality (Heredia-Aricapa et al., 2020; Sooben et al., 2019). During that time, the focus was on identifying substitutes that had minimal impact on the environment while still ensuring effective and efficient refrigeration systems (Tsamos et al., 2017; Baakeem et al., 2018; Sun et al., 2019). Mota-Babiloni et al. (2014) investigated six possible substitutes for R404A and showed higher cooling coefficients when simulating the basic cooling cycle of a typical grocery store operation case. Bortolini et al. (2015) discovered that non-azeotropic HFCs mixtures had emerged as medium GWP alternative refrigerants for directly replacing R404A. This finding highlighted the potential of these mixtures as suitable substitutes in refrigeration applications. Cascini et al. (2016) studied an effective alternative refrigerant solution to enhance environmental protection and improve unit efficiency. Gao et al. (2022) investigated the performance of R407A and R407F and found that they exhibit several desirable characteristics, including low GWP, high potential for performance improvement, and ease of retrofitting old equipment. Therefore, they are considered suitable commercial mid-term alternatives for medium-temperature applications. In addition, some scholars (Makhnatch et al., 2017; Petrovic et al., 2018; Mota-Babiloni et al., 2015) had found that R404A can be replaced by R448A, R449A, R450A and R455A in the future. At the same condensing temperature (T_c) or evaporating temperature (T_e), R448A as a substitute refrigerant for R404A demonstrates higher CC and lower energy consumption in a semi-hermetic reciprocating compressor. However, some scholars (Wu et al., 2020; Vaitkus and Dagilis, 2017) had only analyzed R404A alternative refrigerant (R407) from the perspective of energy efficiency, lacking a full life cycle assessment of safety, economics and environmental damage. The comprehensive environmental impact benefits of R404A alternatives could not be fully analyzed and evaluated (Zhang et al., 2022).

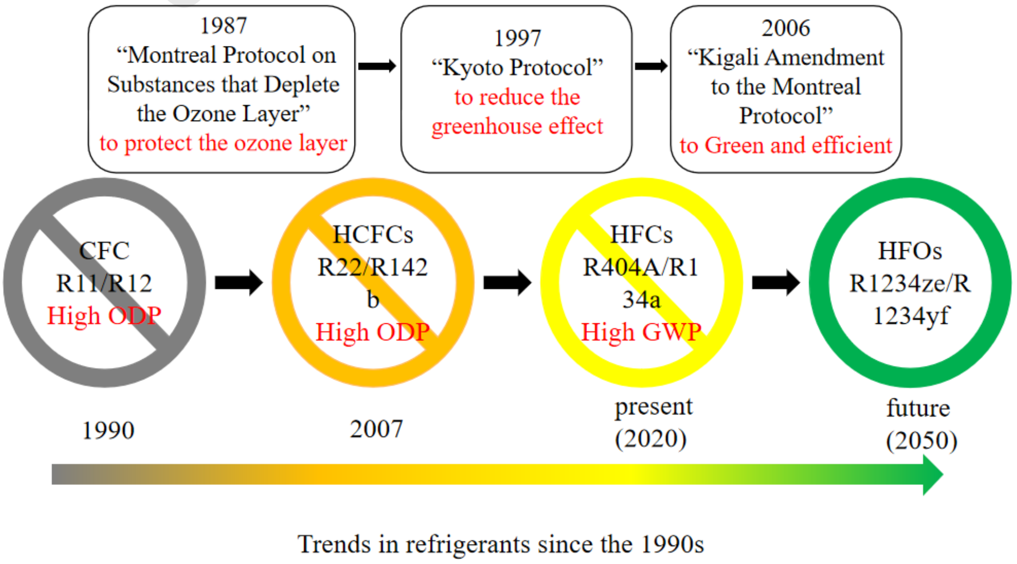


Fig. 1. Development of refrigerants since 1990's

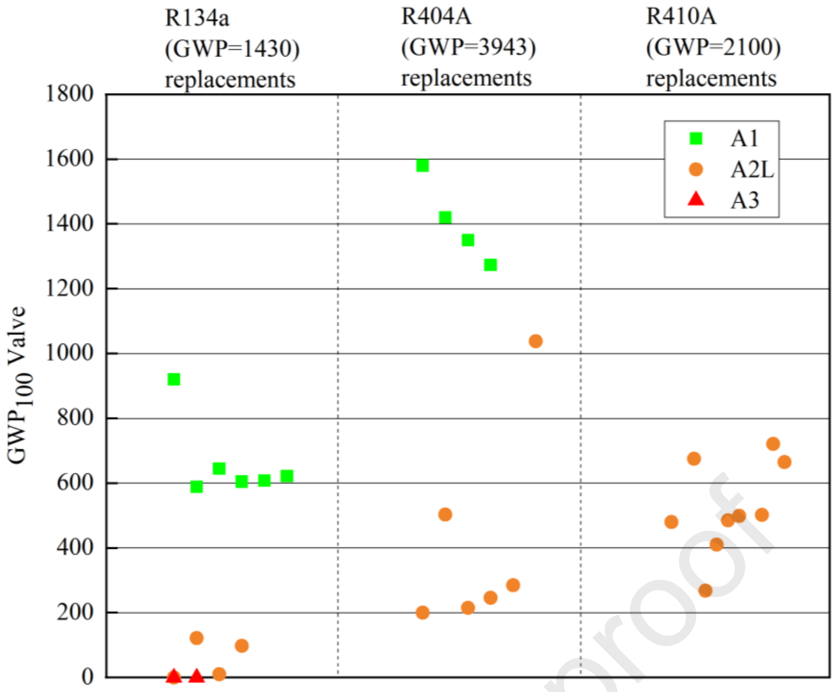


Fig. 2. Low GWP alternatives to commonly used refrigerants (K. Amrane, 2013)

Given the interrelationships among the various factors mentioned above, it is crucial to conduct multifactor analysis of the environmental impacts of cold storage units. This paper proposed a method to evaluate the environmental impact of cold storage units through carbon footprint. For environmental assessment in the refrigeration field, many scholars prefer to use life cycle assessment (LCA). Choi et al. (2021) proposed an environmental impact assessment method for household refrigerators based on life cycle climate performance (LCCP). This method reveals that the main factors influencing the lifecycle carbon emissions of refrigerators are system performance and manufacturing energy consumption. Aprea et al. (2022) studied supermarket refrigeration equipment and found that the environmental friendliness of refrigerators is often assessed using the total equivalent warming impact (TEWI) indicator. However, this indicator has limitations in terms of fixed evaluation parameters (i.e. refrigerant charge, power consumption, power emission coefficient and so on). Wang et al. (2021) combined LCA method, system dynamics method and multi-objective optimization method and proposed an optimization decision-making method for refrigerant alternatives to meet the requirements of carbon emission reduction. The study found that refrigerant substitution can provide significant environmental benefits, with a reduction in GHG intensity ranging from 64.4% to 75.5%. Based on the LCA method, Gasia et al. (2021) studied the environmental and economic impacts of newly developed refrigeration system components to optimize the energy efficiency of the refrigeration system. Wu et al. (2013) utilized two carbon footprint models to assess the vapor-compression refrigeration system and PCM-based cold storage system. The study revealed that the PCM-based cold storage system exhibited better emission reduction performance. Gao et al. (2022) compared LCCP and TEWI of cold storage units charged with R404A, R407A and R407F to propose ways to improve the performance of units. However, there is no unified quantitative standard to discuss the environmental impact of refrigeration equipment. Therefore, this study will use carbon emissions to quantify the impact of different stages of cold storage units.

This study assessed the carbon footprint generated by cold storage units under different influencing factors. By utilizing a GHG emissions model, the study evaluated the impact of three key factors: alternative refrigerants, ambient temperature, and national energy structure (China). The purpose is to evaluate the impact on GHG emissions of replacing high-GWP refrigerants with low-GWP refrigerants in cold storage, to determine the practicability of alternative refrigerants, and to provide a theoretical basis for the nationwide promotion of alternative refrigerants through regional discussions. Through the study of different ambient temperatures, it paves the way for the challenges brought about by climate change in the future. Understanding the key factors in the environmental impact of cold storage and refrigerants is critical to developing effective ideas for reducing carbon emissions and achieving environmental protection. This article establishes and calculates the GHG emission model of the four stages of cold storage, and then verify it through experimental comparison. In section 2, the carbon footprint assessment method and experimental approach are introduced. Section 3 compares the model's calculation results with the experimental test results to validate its feasibility. In section 4, the impact of alternative refrigerants, ambient temperature, and national energy structure on the carbon footprint of the cold storage unit in each stage is analyzed and compared. Finally, section 5 presents the key conclusions of this study.

2. Methodology

2.1. Theoretical calculations

In this study, the model framework focuses on assessing the impact of climate change, following the guidelines of ISO 14067 (2018) and ISO 14404-4 (2020) in the impact assessment category. The environmental impact of the cold storage refrigeration system was quantified using carbon dioxide equivalent (CO_{2eq}) as per the 100-year time frame recommended by the Intergovernmental Panel on Climate Change. The same time frame was used to calculate GHG emissions for cold storage units using different refrigerants, taking care to ensure there was no overlap between them. This method consists of four stages: objective and scope definition, model establishment, analysis and discussion, and result.

2.1.1. Objectives and scope definition

2.1.1.1. The objective of the study

The objective of the study was to investigate the carbon footprint of cold storage units by quantifying the GHG emissions that occur at each stage and using CO_{2eq} to calculate the potential contribution to climate change. To achieve this, a new GHG emissions model was proposed for cold storage units using alternative refrigerants. The model aimed to identify carbon hotspots and factors related to energy efficiency and emissions reduction, thereby supporting decision-making in the green cold chain industry.

2.1.1.2. Functional unit

The chosen functional unit was a compressor with a nominal power of 2.27kW and a CC of 4.7kW. The evaluation was carried out under subtropical monsoon climate conditions in Nanjing, located in eastern China, for a period of one year. Then, this functional unit could be applied to cold storage unit refrigeration system. This study used four different refrigerants: R404A, R407F, R407A, and R448A. R407A, R407F, and R448A are low-GWP alternatives to R404A. The main performance characteristics of the four refrigerants were presented in Table 1. Table 2 provided the relevant data on additional GHG emissions caused by cold storage units. Previous research on these three alternative refrigerants has shown that they are all good replacements for R404A, but no one has compared their environmental impacts in terms of carbon emissions specifically in the context of cold storage unit operation (Deng et al., 2021; Gao et al., 2022).

Table 1 Physical parameters of the four refrigerants

Thermodynamic characteristics	R404A	R407A	R407F	R448A
Chemical composition	R125/R143a/R134a	R125/R134a/R143a	R32/R125/R134a	R32/R125/R134a/R1234ze/R1234yf
GWP, AR5	3943	2107	1825	1273
Safety classification	A1	A1	A1	A1
Critical Temperature (℃)	72.1	82.0	82.6	83.7
Critical pressure (MPa)	3.728	4.494	4.754	4.675
Glide temperature (℃)	0.75	4.6	5.2	6.27

Table 2 The relevant data on additional GHG emissions caused by cold storage units

Parameters	R404A unit	R407A unit	R407F unit	R448A unit	Ref.
Annual refrigerant charge amount (kg)	5.57	5.57	5.26	5.26	Hu et al. (2018) and Deng et al. (2021)
Leakage rate per year (%)	5	5	5	5	Gao et al.

					(2022)
Recovery rate per year (%)	15	15	15	15	Gao et al. (2022)

2.1.1.3. System boundaries

The setting of the system boundary was used to determine the unit processes included in the carbon footprint of the cold storage unit. Figure 3 illustrates the system boundary of the model. The schematic diagram of the cold storage unit system was shown in Figure 4. For the cold storage unit, we followed the LCA methodology and include several stages, including production, assembly, use and maintenance, and recycling and disposal. GHG emissions model included both the unit itself and the refrigerant. In this study, the carbon emissions from the production of the unit's materials and the final disposal stage were not considered within our scope. Additionally, we had not taken into account the heat exchange rate of materials or the human energy input.

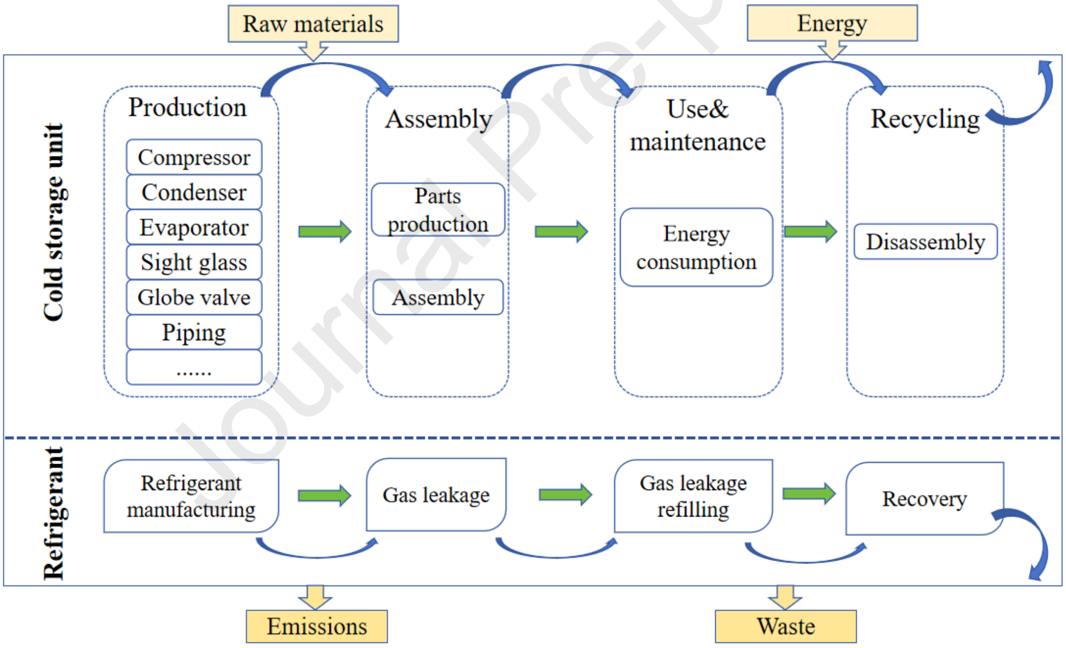


Fig. 3. The system boundary of the cold storage unit

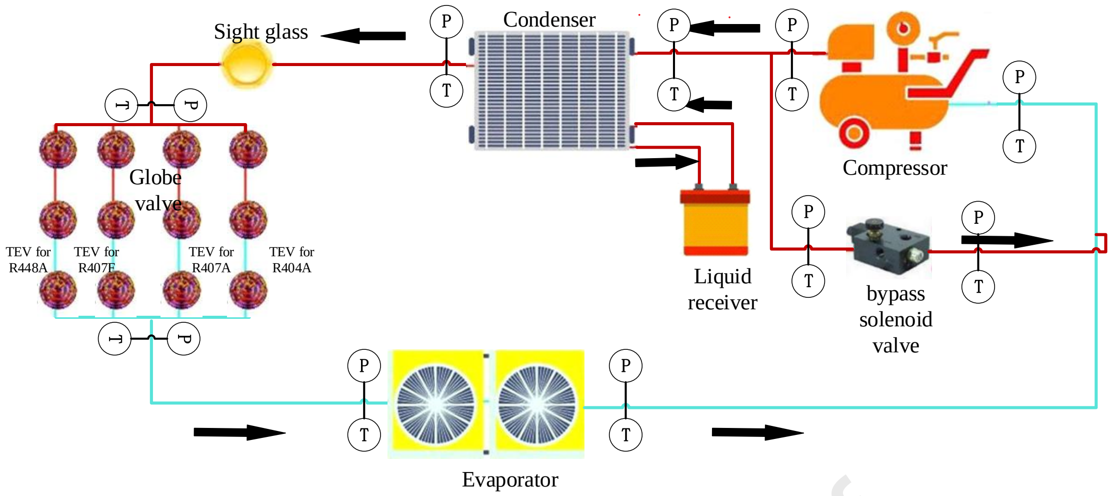


Fig. 4. Schematic diagram of the tested unit

2.1.2. Model establishment

The model primarily considered the GHG emissions of different refrigerants within the cold storage unit. Considering the life cycle perspective, it included the stages of production, assembly, use and maintenance, recovery and disposal. Given that the life cycle carbon footprint of a refrigeration system was mainly affected by electricity consumption and refrigerant leakage, impacts related to raw material extraction, processing and disposal are considered negligible. Additionally, the focus of this study was to compare the carbon footprints of cold storage units when charged with different refrigerants. Therefore, the input and disposal of raw materials for the cold storage units were treated as a contributing factor rather than calculated separately.

1. *Production stage.* The manufacturing of cold storage units and refrigerants requires the consumption of various forms of energy, which indirectly leads to GHG emissions. In this study, we assessed the production of the cold storage unit and the production of the refrigerant as separate entities to calculate their respective GHG emissions (C_{pro}). These calculations were shown in eq. (1):

$$C_{pro} = （E_{pro1}+E_{pro2}） \times \beta_v \tag{1}$$

where E_{pro1} and E_{pro2} represent the energy consumed during the production of the refrigeration unit and the refrigerant, respectively (kWh), β_v represents the carbon emissions factor of the unit (kg CO_2/kWh).

2. *Assembly stage.* This study assumed that the cold storage unit and refrigerant could be assembled after their production, without considering the energy consumption from transportation. The GHG emissions (C_{ass}) during the assembly stage were determined by the direct GHG emissions caused by refrigerant leaks during installation. The calculation of C_{ass} was given in eq. (2):

$$C_{ass} = L_{ass} \times GWP \tag{2}$$

where L_{ass} represents the amount of refrigerant leakage (kg) during the assembly process;

3. *Use and maintenance stage.* In this study, a specific cold storage unit was selected as the model. We calculated the energy consumption during the operation of the cold storage unit to determine its corresponding GHG emissions (C_{use1}), as shown in eqs. (3-9):

$$C_{use1} = E_{use} \times \beta_v \tag{3}$$

$$E_{use} = \left(\frac{\sum_i A_i Q}{\eta_e \lambda}\right) \times Y_{annual} \times Y_{life} \tag{4}$$

$$Q = m \times (h_{eo} - h_{co}) \times \eta_{com} \times \eta_{con} \times \eta_{eva} \times \eta_{valve} \tag{5}$$

$$\eta_{\text{com}} = \frac{T_{in} - T_{out}}{T_{in} - T_1} \tag{6}$$

$$\eta_{\text{con}} = \frac{T_{out-con} - T_{in-con}}{T_{c-\max} - T_{in-con}} \tag{7}$$

$$\eta_{eva} = \frac{T_{out-eva} - T_{in-eva}}{T_{e-\max} - T_{in-eva}} \tag{8}$$

$$\eta_{valve} = \frac{\Delta h_{act}}{\Delta h_1} \tag{9}$$

where A_i represents a given environmental temperature for a percentage of time within one year; Q represents the CC of the cold storage unit at the corresponding environmental temperature (kW); λ represents the coefficient of the performance of the cold storage unit; η_e represents the efficiency of the auxiliary machine; Y_{life} represents the operational lifespan of the cold storage unit, it is assumed to be 1 year in this study; Y_{annual} the working time within one year for the cold storage unit (h); m represents the mass flow rate of the refrigerant (kg/s); h_{eo} is the enthalpy at the evaporator outlet (J/kg), and h_{co} is the liquid enthalpy at the condenser outlet (J/kg); η_{com}, η_{con}, η_{eva}, and η_{valve} represent the adiabatic efficiency of the compressor, condenser efficiency, evaporator efficiency, and expansion valve efficiency, respectively. T_{in} and T_{out} are the inlet and outlet temperatures of the compressor, respectively (℃). T_1 is the theoretical isentropic compression outlet temperature. T_{in-con} and $T_{out-con}$ are the inlet and outlet temperatures of the condenser, respectively, and T_{c-max} is the theoretical maximum condensing temperature. T_{in-eva} and $T_{out-eva}$ are the inlet and outlet temperatures of the evaporator, respectively, and T_{e-max} is the theoretical maximum evaporating temperature. Δh_1 and Δh_{act} represent the theoretical isentropic enthalpy drop and the actual enthalpy drop, respectively (kJ/kg).

Additionally, during the operation and maintenance of the refrigeration unit, refrigerant leakage can occur. Therefore, the authors considered the direct GHG emissions caused by refrigerant leakage (C_{use2}), as shown in eq. (10):

$$C_{use2} = (L_{use} + L_{main}) \times Y_{life} \times GWP \tag{10}$$

where L_{use} and L_{main} represent the amount of refrigerant leakage (kg) during the use and maintenance process, respectively.

4. *Recycling stage.* During the recycling stage, the energy consumed during the recycling of the cold storage unit and refrigerant was denoted as E_{rec}. Additionally, GHG emissions occurred due to refrigerant leaks during the recovery process. Therefore, the GHG emissions (C_{rec}) in the recycling stage included two parts, and the calculation was shown in eq. (11):

$$C_{rec} = E_{rec} \times \beta_v + M_{rec} \times (1 - \propto_{rec}) \times GWP \tag{11}$$

where M_{rec} represents the remaining amount during the refrigerant recovery process (unit: kg), and $\propto_{rec}$ represents the recovery rate of refrigerant.

2.2. Experimental investigation

2.2.1. Experimental setup

The purpose of our study was to investigate the environmental impact of units charged with alternative refrigerants. In this study, the units currently in use in enterprises were selected as the experimental objects to explore the trend of the impact of alternative refrigerants on carbon footprint. This cold storage unit consists of a compression condensing unit, an air cooler, thermal expansion valve (TEV), and interconnected copper pipes. The specific specifications can be found in Table 3. The tests are performed in compliance with relevant national standards (GB/T 17758-2010, n.d.). The experiments are conducted in a humidity chamber laboratory, and calculations are performed using the air enthalpy method. The testing system consists of an air sampler, an air processing unit, and a data acquisition system. The data acquisition system is used to independently adjust T_c and T_e based on the indoor and outdoor environmental temperatures. Then, the air handling unit is employed to regulate the temperature and humidity of both the indoor and outdoor environments. It is noteworthy that R404A, R407A, R407F and R448A exhibit distinct temperature glides and require different super-heating control methods. Consequently, the temperature sensing bulbs in the TEV of the refrigeration system are regulated by a consistent expansion valve structure. Additionally, to effectively manage refrigerant charge, two shut-off valves are positioned before and after each TEV. Based on existing research, it has been found that the expansion valve of R448A can elevate the temperature to achieve the desired super-heating degree (SH) at the evaporator outlet. The input power during the testing process was recorded for comparative analysis.

Table 3 Test equipment specification

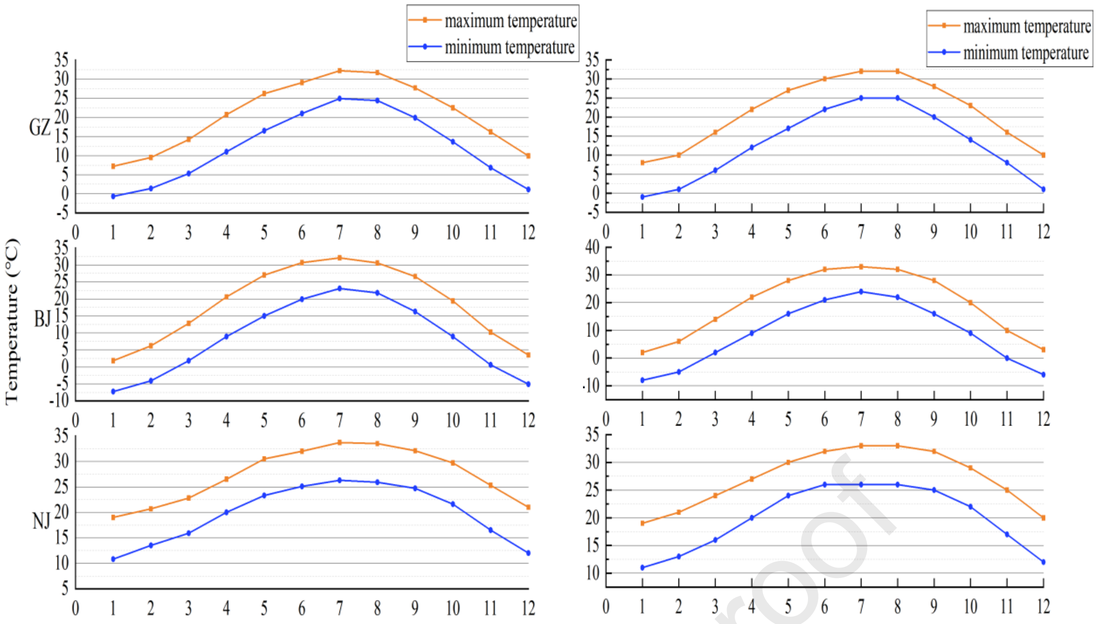
Type of equipment	Specification
compression condensing unit	2.27 kW (rated power)
accumulator	6.8 liters
air cooler	6300 m^3/h
copper pipe	9.52 mm (liquid line) 15.88 mm (gas line)
refrigerant	R404A, R407A, R407F, and R448A

2.2.2. Experimental conditions

This study selected three cities with different climate characteristics as representatives to study the changes in cold storage performance and carbon footprint under different ambient temperatures and energy structures. The comprehensive energy consumption of the three cities of Nanjing, Beijing and Guangzhou in 2022 was 37.01 million tons, 14.09 million tons and 16.42 million tons of standard coal respectively (Nanjing Bureau of Statistics, 2023; Beijing Municipal People's Government portal., 2023; Guangzhou Municipal People's Government portal, 2023). Figure 5 shows the historical climate and average monthly temperatures of Nanjing (NJ), Beijing (BJ) and Guangzhou (GZ) in the past year (China Meteorological Administration, 2023). It can be seen that the annual average temperatures of Nanjing, Beijing and Guangzhou are respectively in the range of 12.1 to 20.59 ℃, 8.32 to 18.46 ℃ and 19.63 to 27.23 ℃. Therefore, ambient conditions of 25 ℃, 15 ℃, and 10 ℃ are chosen to assess their impact on the unit's performance. Based on the national standard for cold storage facilities in China (GB/T 21363-2018, n.d.), the inside temperature selected in this experiment was 4 ℃. The specific experimental conditions are shown in Table 4.

Table 4 Experimental conditions

Ambient temperature (℃)	Inside temperature (℃)	SH (℃)	T_e (℃)
25	4	5	-7
15	4	5	-7
10	4	5	-7



(a) (b)

Fig. 5. Climatic background and temperature data of the three cities this year. (a) Climatic background: average monthly temperatures from 1981 to 2010; (b) Average monthly temperature in the past year)

In the experiment, two main performance parameters, namely CC and EER, were calculated, and the performance of the unit was analyzed. CC was calculated using equation (12), EER was calculated using equation (13).

$$Q_c = \frac{q_a\,(h_{\alpha 1} - h_{\alpha 2})}{v_n\,(1 + W_n)} \tag{12}$$

$$EER = \frac{Q_c}{P} \tag{13}$$

where Q_c represents cooling capacity (kW); h_{a1} and h_{a2} represent the evaporator return enthalpy (kJ/kg) and supplied air enthalpy (kJ/kg), respectively; q_a represents the air volume flow rate (m^3/h); V_n and W_n represents the evaporator outlet air specific volume (m^3/kg) and water content (kg/kg), respectively, P represents the input power (kW) in the medium-temperature refrigeration compression condenser unit.

2.2.3. Uncertainty analysis

The experimental apparatus and measurement methods of this study were proposed earlier. Inspection points were installed in front and back of each component, and the instrument model and accuracy were shown in Table 5. The uncertainty of the measuring instrument meets all the requirements of GB/T 17758-2010. To increase the reliability of the results, this paper characterizes the dispersion of CC and EER measurements by calculating uncertainty with formulas.

Table 5 Measurement details of the sensors

Name	Measurement range	Specifications and type	Precision
Flow meter	0.04-1.2 m^3/h	YOKOGAWA	±0.5 m^3/h
T-type thermocouple	-20 to 300 °C	VT6	±0.5 °C
Electronic scale	0-40 kg	RZ-789	±0.3 kg
Electric energy meter	0-20 kW	WT230	0.10%
Differential pressure sensor	0-0.25 MPa	EJA120	0.50%
Pressure transducers	-0.1 to 4.4 MPa	MPM480	±0.25%

Uncertainty could be divided into type A and type B. The purpose of Type A is to reduce errors caused by testing conditions and methods, while the purpose of Type B is to reduce errors caused by insufficient instrument accuracy. All the uncertainties were calculated in Eqs. (14)–(17).

$$u_A = \frac{s(X)}{\sqrt{n}} \tag{14}$$

$$s(X) = \sqrt{\frac{\sum_{i=1}^{n}(X - \bar{X})^2}{n-1}} \tag{15}$$

where *n* represents the number of test points, *s (X)* represents the standard deviation calculated by Bessel formula and u_A represents the A-type uncertainty.

$$u_B = \frac{a}{\sqrt{3}} \tag{16}$$

where *a* represents the half width of the measured possible value interval and u_B represents the B-type uncertainty.

$$u(X) = \sqrt{u_A^2(X) + u_B^2(X)} \tag{17}$$

where *u (X)* represents the composite uncertainty, i.e. the final result of uncertainty.

The calculation results show that the uncertainty of CC is within ±2.6% and the uncertainty of EER is within ±0.58%.

2.3. Economic evaluation

In this study, economic evaluation was conducted using LCC analysis, which is an economic evaluation metric. LCC metrics usually include the initial cost and operating cost of the system. Aktacir et al. (2006) research illustrates that the initial cost primarily comprises the costs associated with various unit components, equipment, parts, refrigerants and installation. The initial costs of this study are detailed in table 6. The installation cost is based on the commercial platform of a company operating refrigeration equipment in eastern China, the change of refrigerants will not significantly increase the manufacturer's production cost. So, in this study, the primary factor affecting the LCC indicator is the electricity cost for operating the cold storage unit. Therefore, the operating cost is equal to the total electricity consumption of the unit multiplied by the residential electricity price, where electricity consumption can be estimated using the 24-hour electricity consumption in the experiments and the unit's service life. In terms of operating costs, the residential electricity price is 0.6 yuan /kWh.

The calculation formula of LCC is formula (18)：

$$LCC = C_p + C_i + \sum_{t=1}^{N} \frac{C_e}{(1+r)^{t-1}} \tag{18}$$

where C_p is the procurement cost of parts and refrigerants; C_i is the installation cost; C_e is the cost of electricity consumption. The discount rate (r) is 4%, and the considered service life (N) for 10 years (Wang et al., 2019).

Table 6 Initial cost statistics of the unit refrigeration system

Unit	Initial cost (CNY)			
	R404A	R448A	R407F	R407A
Compressor condensing unit cost	3488	3488	3488	3488
Valves cost	462	524	524	524
Air cooler cost	1150	1150	1150	1150
Spare parts cost	335	335	335	335
Refrigerants cost	720	1200	980	960
Installation cost	350	350	350	350
Total cost	6505	7047	6827	6807

3. Experimental validation

To validate the accuracy of the model calculations, the outdoor ambient temperature was set at constant values of 25/15/10 ℃, and the carbon emissions caused by the operational phase of the units were measured separately after charging them with R404A/R407A/R407F/R448A. This study relies on manufacturer-provided data for calculations, without performing independent verification, as the same refrigeration unit is used in both the production and assembly stages. As for the recycling stage, the factor that causes the difference in carbon footprint is the refrigerant recovery rate, and the annual refrigerant recovery rate is provided in Table 2. The measurement errors in these three stages are small, so this study focuses only on the comparative experimental verification in the use stage. Figure 6 depicts the verification of carbon footprints of the cold storage units between experimental and model calculation results. It can be observed that the experimental results are slightly differ from the calculated results. at different elevations. This difference can be attributed to factors such as the working hours during the experiment, refrigerant charge amount, and heat sources such as lighting and human presence. Overall, the calculated results show a consistent trend with the experimental results, with a relative error of less than 5.5%. Therefore, the accuracy of the model is acceptable.

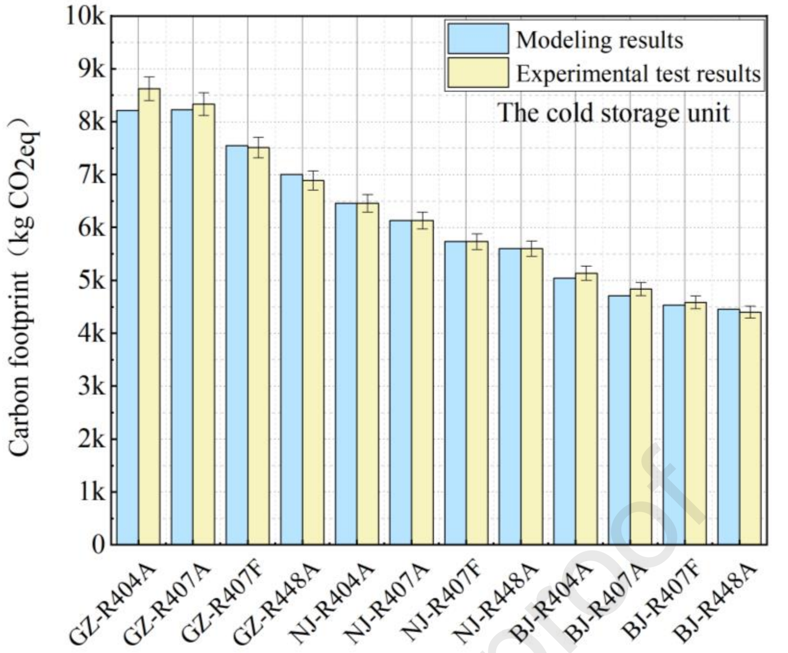


Fig. 6. Validation of C_{use1} generated by cold storage unit during the use stage

4. Results and Analysis

4.1. Experimental results and discussion

In order to present the use stage in more detail, the impact of alternative refrigerants and ambient temperature on the energy consumption generated by the operation of the cold storage unit. Based on the theoretically established model, we conducted experimental research on cold storage units using four different refrigerants under three different ambient temperature conditions. The study investigated the impact of different refrigerants and ambient temperatures on the refrigeration performance of the units.

As shown in Figure 7, the refrigeration performance of the units remains consistent under different ambient temperature conditions. The units charged with R407F outperform those charged with other refrigerants in terms of refrigeration capacity. The CC of the R448A unit is comparable to that of the R407A unit, slightly surpassing the R404A unit. However, the full potential of the R448A unit's CC may not be realized due to the mismatch between its slide temperature and the design of the expansion valve. Compared to the R404A unit, the CC of the R448A and R407A units increases by 5.3% to 7.6%, while the CC of the R407F unit increases by 11.7% to 14.4%.

The variation in EER of the units differs from that of CC. This is because the condensing pressure of the cold storage unit, which is charged with four types of refrigerants, increases with the rise in condensing temperature, leading to an increase in compression ratio. This leads to a decrease in gas transfer coefficient, resulting in a decrease in CC of the compressor. As the compression ratio increases, the input power also increases, leading to a decrease in EER. The unit charged with R448A is less affected by this phenomenon, thereby exhibiting higher EER values. Compared to the R404A unit, the R448A unit, R407F unit, and R407A unit exhibit EER improvements of 1.4% to 3.5%, 1.0% to 1.8%, and 0% to 0.7% respectively. Particularly, at an environmental temperature of 25 °C, the cold storage unit charged with R448A refrigerant has a significantly higher EER compared to the units charged with the other three refrigerants. This is because at this temperature, the R448A unit experiences higher T_c and sub-cooling degree (SC), resulting in fewer performance limitations. It can be observed that the R407F unit demonstrates significant performance advantages under lower environmental temperature conditions, followed by the R448A unit. The R448A unit exhibits notable refrigeration performance advantages under higher environmental temperatures.

In addition, when the parameter settings of the cold storage unit change, the performance of the unit will also change accordingly, but the amount of performance change depends more on the selection of refrigerant. Deng et al. (2021) compared the performance of units charged with the same refrigerant at different frequencies and found that the performance variation trend was consistent.

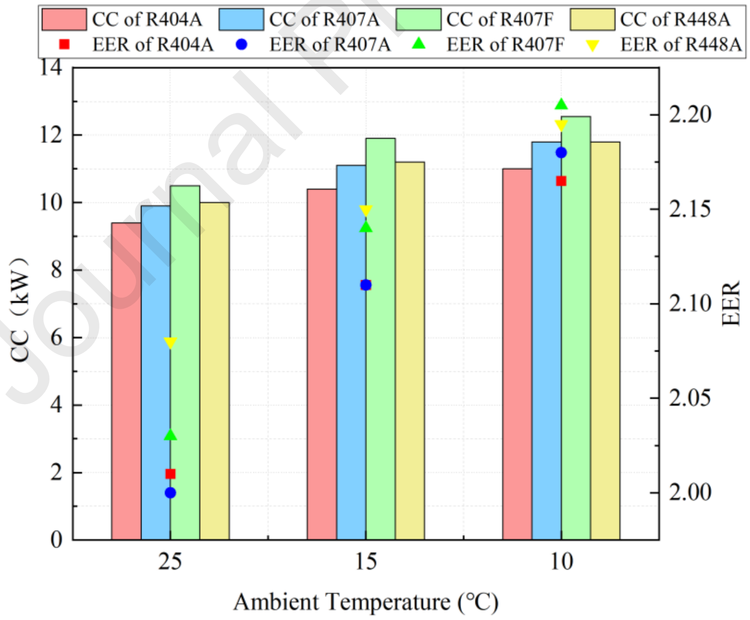


Fig. 7. CC and EER of cold storage units

4.2. Model calculation results and discussion

Based on the modeled system boundaries and selected functional units, this article provided a comparative analysis of the carbon footprints of cold storage units using R404A, R407F, R407A and R448A. In this paper, three Chinese cities with different annual mean temperature (involving three different climate types) were selected, namely, the 1-year life span of NJ (baseline), GZ and BJ. Figure 8 displayed the relative contribution of the impact of climate change in each different stage in Nanjing, which has a subtropical monsoon climate.

Cold storage units using different refrigerants contributed significantly to each stage. GHG emissions from the production stage accounted for 7% of R404A and 4% to 5% of alternative refrigerants. In addition, R404A has GHG emission of 5% in the final recovery stage and alternative refrigerants of 3% to 4%. The study found that the use stage is a major contributor to climate change. In the whole stage of cold storage units using R404A, the proportion of GHG emissions in the use and maintenance stage is as high as 87%. Since the use stage of cold storage units is more relevant than the production, assembly and recovery stages, the impact of the use stage on climate change is mainly analyzed to determine its potential GHG emission reduction opportunities and future impacts.

The use stage is primarily associated with the unit's energy efficiency and the refrigerant charge. Firstly, we placed a strong emphasis on various low-GWP alternative refrigerants. Secondly, we explored the impact of alternative refrigerants on unit efficiency. Unit efficiency is influenced by parameters such as ambient temperature, operating temperature, and refrigerant charge. In order to better investigate the effects and adaptability of low-GWP alternative refrigerants on unit efficiency, our study focused on the changes in carbon footprint when units, charged with low-GWP refrigerants, operated under varying ambient temperatures. This research aimed to understand their adaptability in different regional markets within the country.

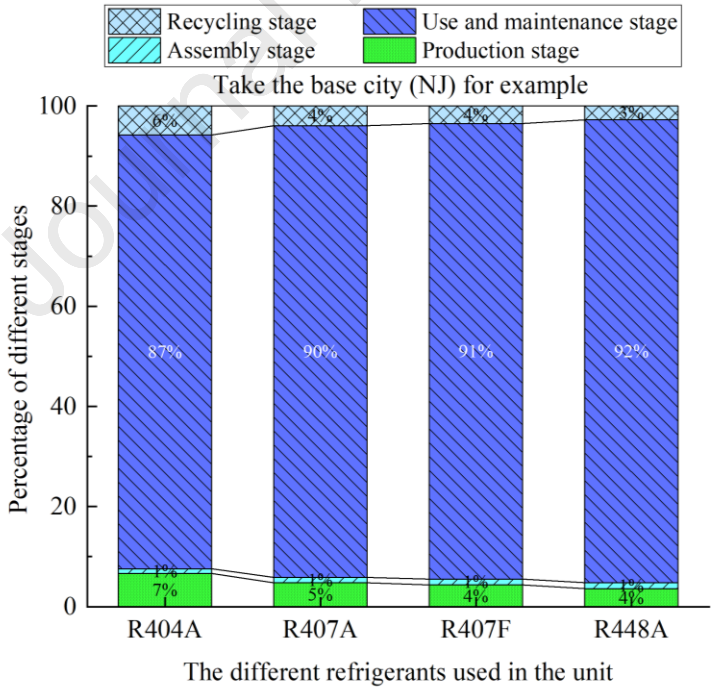


Fig. 8. Comparison the relative contribution of the cold storage unit of different refrigerants in different stages

4.2.1. GHG emissions from refrigerants

During the use stage, refrigerant leakage is observed in the refrigeration unit. The annual leakage rate of refrigerant in the investigated cold storage was determined to be 5%. Consequently, in terms of GHG emissions, the impact of refrigerant leakage on the environment should not be underestimated.

As shown in the figure 9, during the use stage of the R404A charged unit, refrigerant leakage contributes to 15% of the overall carbon emissions during this stage. Even with low-GWP refrigerant R448A, the emissions resulting from refrigerant leakage still account for 5% of the use stage emissions. Furthermore, as the unit ages or undergoes improper maintenance, the refrigerant leakage rate tends to increase over time. This demonstrates that the carbon emissions caused by refrigerant leakage should not be underestimated within the environmental impact whole stage of the unit.

As shown in the figure 10, the substitution of low-GWP refrigerants has significantly reduced GHG emissions during the use stage of this cold storage unit. The units charged with R407A, R407F, and R448A have reduced emissions by 10.56%, 14.11%, and 16.39%, respectively, compared to the unit charged with R404A. The blue dashed line in the figure represents the variation in C_{use1} caused by refrigerant leaks, while the green dashed line represents the variation in C_{use2} caused by unit energy consumption. From the graph, it is evident that the slope of the blue dashed line is steeper, indicating a more significant reduction in carbon emissions caused by refrigerant leakage after the refrigerant replacement. Therefore, directly replacing R404A with low-GWP refrigerants like R448A in existing well-established cold storage units can significantly reduce environmental damage.

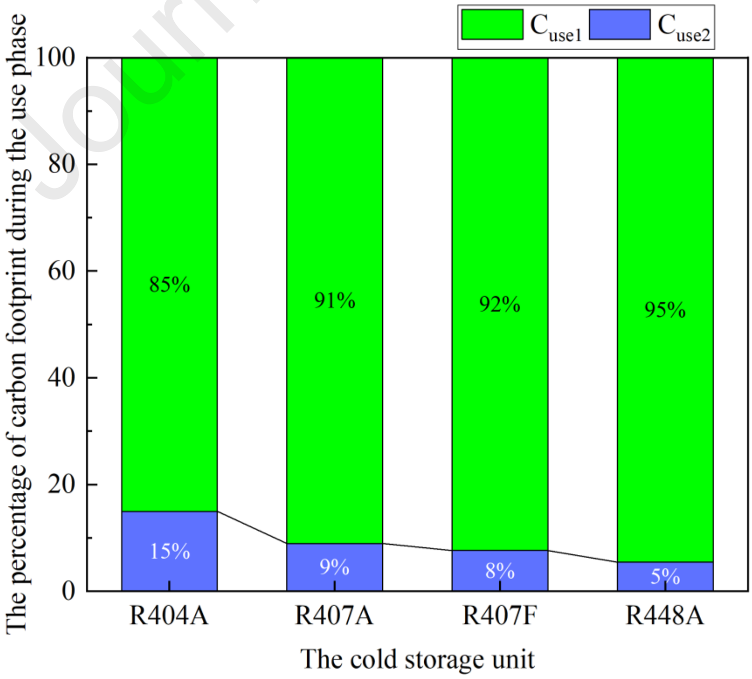


Fig. 9. Percentage breakdown of carbon footprint of cold storage unit during the use stage

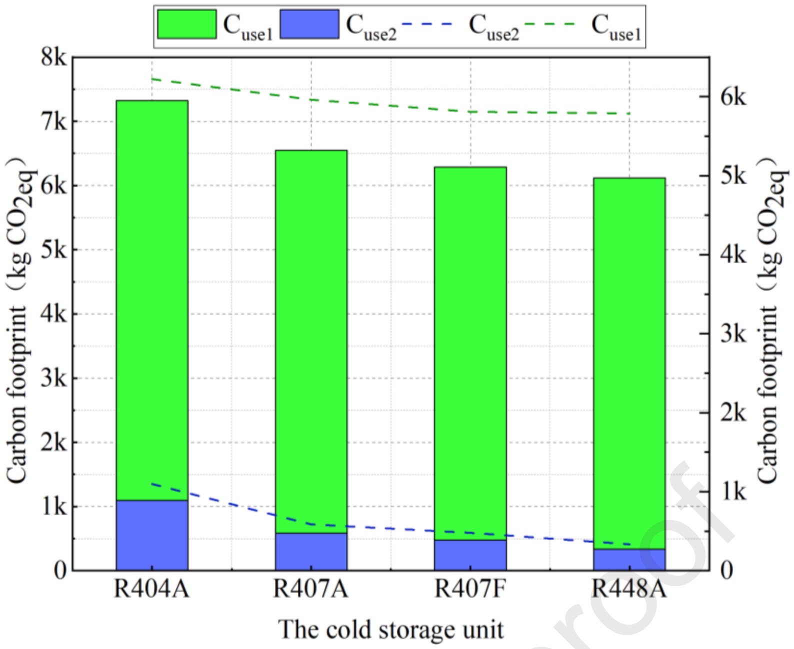


Fig. 10. Carbon footprint data graph of cold storage unit during the use stage

4.2.2. Ambient temperature

The GHG emissions of cold storage units using four different refrigerants in Guangzhou (25 °C), Nanjing (15 °C) and Beijing (10 °C) were calculated and compared, and the effects of ambient temperature on the operation of the refrigeration units were investigated. The total GHG emissions from the refrigeration units at various ambient temperatures, as well as the stage-wise breakdown, are depicted in Figure 11.

Based on the comparison of the cold storage unit charged with R404A in Nanjing, it can be observed that the carbon emission of R404A unit in Nanjing is about 8449.92 kg CO_{2eq}, which is 14.11%, 18.22% and 22.61% higher than that of the alternative refrigerant (R407A,R407F and R448A) used in the same place. Using the same refrigerant, the GHG emissions of the units are 23.57% lower than in Guangzhou and 13.99% higher than in Beijing.

At higher ambient temperatures, the CC of the units decreases, energy consumption increases, and carbon emissions increase. For instance, the GHG emission of cold storage units charged with R404A in Guangzhou were 10441.21 $kgCO_{2eq}$, which is an increase of 30.4% compared to those in Beijing. On account of Guangzhou belongs to the oceanic subtropical monsoon climate, with an annual average temperature of about 24 °C, while Beijing belongs to the warm temperate semi-humid and semi-arid monsoon climate, with an annual average ambient temperature of about 10 °C. Cold storage units in areas with high ambient temperature have long working hours and low energy efficiency.

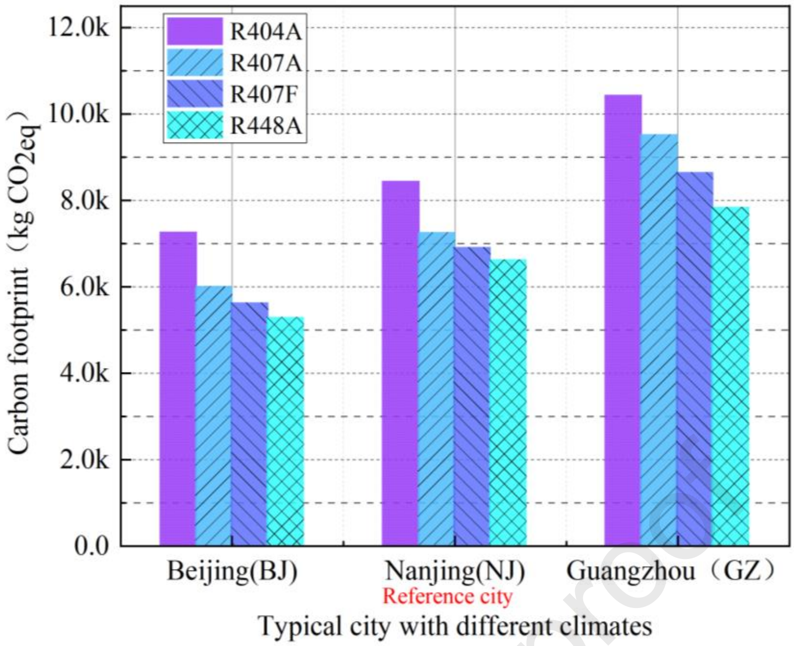


Fig. 11. Comparison of carbon footprints in the whole stage of cold storage units in different regions

4.2.3. National energy structure

As shown in Figure 12, author studied the influence of national power matrix on GHG emissions during the whole stage of cold storage units. Different carbon emission factors (0.5271/0.7035/0.8843 $kgCO_{2eq}/kWh$) in southern, eastern and northern China were used to calculate the effects of cold storage units on climate change (Ministry of Ecology and Environment of the People's Republic of China, 2020). The results show that the cold-storage unit assembly uses less than 1% of GHG emissions when using the same refrigerant, and consumes very little electricity for material production and recycling. R448A GHG emissions in southern, Eastern and North China under different carbon emission factors are 4131.97 $kgCO_{2eq}$, 4659.97 $kgCO_{2eq}$ and 4680.76 $kgCO_{2eq}$, respectively. In Beijing, where the ambient temperature is low, the cold storage units using R407A, R407F and R448A reduce the emission by 17.37%, 22.5% and 27.17% respectively compared with those using R404A. In Guangdong, they can achieve GHG reductions of 8.8%, 17.13% and 24.92%, respectively, this is because the carbon emission coefficients of electricity in the southern region can result in lower GHG emissions throughout the entire stage of the units. Comparing Figures 11 and 12, it is evident that the impact of energy structure on emissions reduction is significant. Furthermore, when the units use R448A refrigerant, it can significantly reduce GHG emissions in any region.

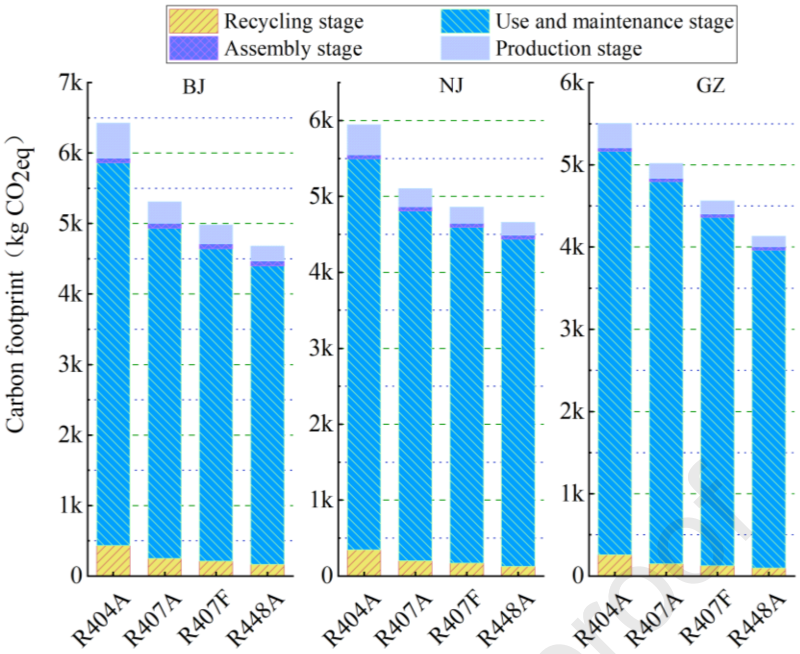


Fig. 12. The carbon footprint of the unit under different national energy structures

4.3. Sensitivity analysis

In this section, we employed sensitivity analysis to assess the robustness of our conclusions by varying key parameters within the computational model. Furthermore, we were able to derive reliable methods to reduce GHG emissions based on the results of the sensitivity analysis.

This study identified refrigerant leakage as a critical factor that influenced the carbon footprint of refrigeration systems. As demonstrated in Section 4.2.1 of this paper, the impact of using low-GWP refrigerants on C_{use2} became more pronounced compared to C_{use1}. We investigated the increase in carbon footprint during the use stage by assuming an annual refrigerant leakage rate ranging from 5% to 20%. As shown in the figure 13, the carbon footprint during the use stage increased with the rise in the annual refrigerant leakage rate. When the annual refrigerant leakage rate increased from 5% to 20%, the carbon footprint of C_{use2} reached 40% during the use stage, representing a 67.1% increase in this stage's carbon footprint. The proportion of direct emissions caused by refrigerant leakage significantly escalated, aligning with the carbon footprint attributable to energy consumption. This underscored the vital importance of using low-GWP refrigerants for environmental protection.

Future endeavors to develop ultra-low-GWP refrigerants or upgrade systems to accommodate natural refrigerants emerged as reliable approaches for reducing GHG emissions in cold storage systems.

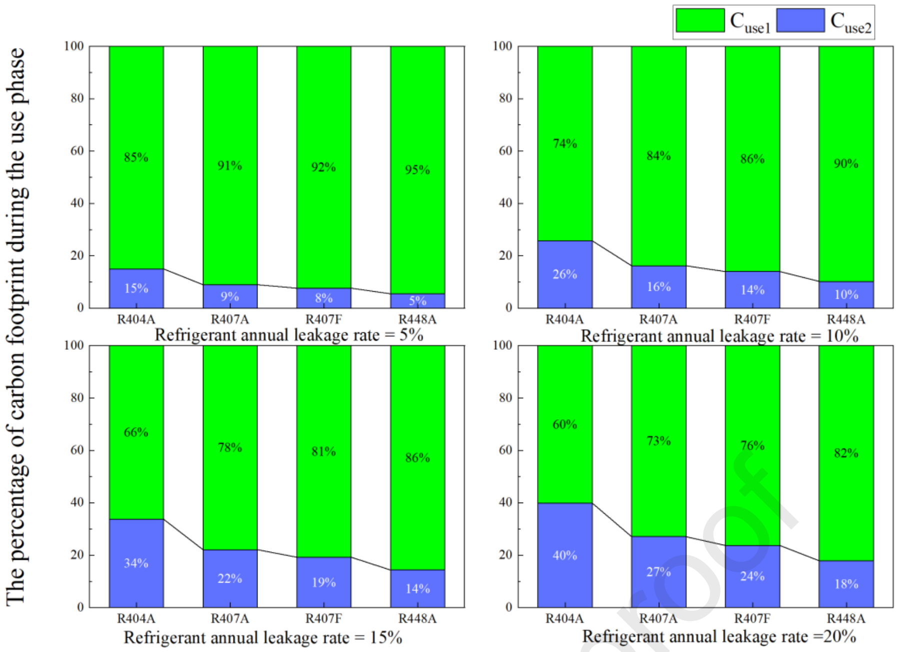


Fig. 13. Comparison of refrigerant leakage rates during the use stage

4.4. Economic performance

It can be seen from Figure 14 that the four types of units have similar costs in the first year. The payback period of the three alternative refrigerant units is about 1 year compared to the R404A unit. They have generated profits every year since then. At the end of the service life, R407A, R407F and R448A units are 6.1%, 12% and 9.9% lower than R404A units, respectively. This is attributed to the fact that the EER of the alternative refrigerant unit surpasses that of R404A, resulting in a substantial reduction in the unit's operational expenses. Although the refrigerant's initial cost may be slightly higher, both R407F and R448A have exhibited a decrease in LCC over extended periods of usage. Consequently, units employing alternative refrigerants, especially R407F and R448A, demonstrate promising economic viability.

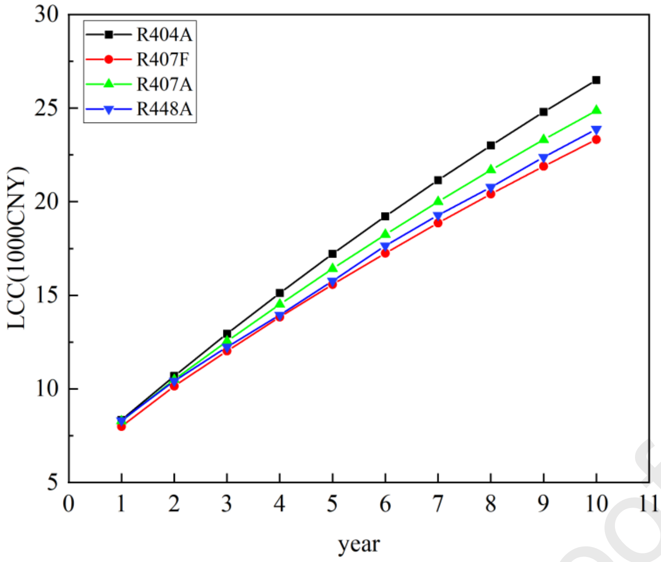


Fig. 14. Changes in LCC operating years for R404A, R407A, R407F and R448A units

4.5. Challenges and Prospects

This study was limited by the available data. Obtaining comprehensive and consistent experimental emission data was challenging for our study, so we relied on numerical models to predict emissions. Analyzing refrigerant performance under different temperature conditions is complicated because multiple factors can affect the actual situation. During actual usage, the performance of the unit is limited by phenomena such as frosting and thawing. Our research is based on model analysis, which means we have to rely on some assumptions to conduct simulations. These assumptions may introduce uncertainties in practical application. Furthermore, we have found that the choice of refrigerant is a direct contributor to greenhouse gas emissions, making refrigerant handling an important aspect of carbon footprint generation. In our study, a recovery rate of 15% was utilized. There is limited available data regarding the ease of handling these refrigerants themselves. Recent research by Ribeiro et al. (2023) suggests the feasibility of utilizing VSA processes for the recovery of R-32 rather than widespread use. It is evident that obtaining specific handling data would require more in-depth field investigations and detailed experimental data. From the study of the life cycle of the cold storage unit, increasing the quantity and quality of the refrigeration system, and the discussion of the external environment are the key requirements for increasing the reliability of the research. In addition, the use of these refrigerants should also be evaluated in terms of a wider range of impact categories (e.g., Stratospheric Ozone Depletion, Cumulative Energy Demand, among others) to identify possible trade-offs. Therefore, establishing the model should consider more available alternative refrigerants, relevant impact categories, local environments, refrigeration technology advancements, and the units themselves. Only in this way can we clearly understand the advantages of using alternative refrigerants in refrigeration systems.

In the future, our research results could pave the way for the development of more sustainable cold storage solutions. As the world pays more and more attention to energy efficiency and environmental impact, optimizing refrigeration systems using low-GWP refrigerants is the short-term development direction of future cold storage, so relatively suitable alternative refrigerants can be explored according to this method. Given the ongoing challenges posed by climate change, our research could contribute to the creation of climate-resilient cold chains. By considering the environmental performance of refrigerants under different temperature conditions, we can design systems that adapt to changing climate patterns and minimize carbon footprint.

5. Conclusion

This study investigates the impact of alternative refrigerants, ambient temperature, and national energy structure on the carbon footprint of cold storage units throughout their whole stage through experimental and numerical analysis. Experimental scenarios were designed based on specific conditions to assess the performance of cold storage units charged with different refrigerants under varying environmental temperatures, thereby validating the accuracy of the computational model. The calculated results of the model were used to determine the carbon footprint of the units under different influencing factors. The influence of refrigerant substitution, ambient temperature, and national energy structure on the carbon footprint throughout the unit's whole stage was discussed. The key findings are summarized as follows：

(1)The R407F unit performs well in terms of CC under low environmental temperature conditions. R407F may be the preferred choice in areas with consistently lower ambient temperatures. However, with the exacerbation of global warming, future environmental temperatures may rise further. Therefore, in regions with higher ambient temperatures, especially where the environmental temperature frequently exceeds 15 ℃, the R448A unit, which demonstrates excellent EER performance and has a lower direct environmental impact, may be more suitable as an alternative refrigerant.

(2)A research analysis was conducted on the four stages of cold storage units. The results indicate that the use stage of the units contributes the most to carbon emissions, followed by the production and disposal stages, while the assembly stage accounts for only 1% of the whole stage.

(3) The carbon footprint analysis of the unit's use stage shows that the carbon emissions of refrigerant leakage account for about 15% of the total emissions. Compared to units charged with R404A, units charged with R407A, R407F, and R448A show reductions in emissions by 10.56%, 14.11%, and 16.39% respectively. Therefore, the use of low-GWP refrigerants not only reduces energy consumption of the units but also effectively lowers the carbon emissions resulting from

refrigerant leakage.

(4) The study findings indicate that the GHG emissions of the cold storage units can be reduced by 1% to 27.17% due to the influence of ambient temperature and national energy structure. Lower ambient temperatures can lead to reduced energy consumption and decreased GHG emissions during the use stage of the units, thereby mitigating their environmental impact. Furthermore, changes in the national energy structure play a crucial role in promoting green and low-carbon operations, which can help alleviate the exacerbation of greenhouse effects and reduce environmental burdens. Therefore, selecting appropriate ambient temperature and national energy structure is beneficial for minimizing the environmental impact of the units.

In practical engineering, modifications can be made to the units, and the level of maintenance during operation can also impact their environmental impact. However, in this study, existing R404A units were used without considering the modification process. Further research is needed to explore materials for unit modifications and maintenance measures to mitigate the negative environmental effects.

CRediT authorship contribution statement

Li Gong: Methodology, Data curation, Writing - original draft. Zhongbin Zhang: Conceptualization, Methodology, Writing - review & editing, Supervision. Meng Chen: Formal analysis, Writing - review & editing. Steve Taylor: Supervision. Xiaolin Wang: Validation, Supervision.

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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References

Aktacir, M.A., Büyükalaca, O., Yılmaz, T., 2006. Life-cycle cost analysis for constant-air-volume and variable-air-volume air-conditioning systems. Applied Energy 83, 606–627. https://doi.org/10.1016/j.apenergy.2005.06.002

Aprea, C., Ceglia, F., Llopis, R., Maiorino, A., Marrasso, E., Petruzziello, F., Sasso, M., 2022. Expanded Total Equivalent Warming Impact analysis on experimental standalone fresh-food refrigerator. Energy Conversion and Management: X 15, 100262. https://doi.org/10.1016/j.ecmx.2022.100262

Baakeem, S.S., Orfi, J., Alabdulkarem, A., 2018. Optimization of a multistage vapor-compression refrigeration system for various refrigerants. Applied Thermal Engineering 136, 84–96. https://doi.org/10.1016/j.applthermaleng.2018.02.071

Belman-Flores, J.M., Heredia-Aricapa, Y., Pardo-Cely, D., Rodríguez-Valderrama, D.A., De Alba-Rosano, M., Silva-Romero, J.C., 2022. Experimental evaluation of R513A as a low GWP refrigerant to replace R134a in a domestic refrigerator. International Journal of Refrigeration 142, 148–155. https://doi.org/10.1016/j.ijrefrig.2022.06.019

Beijing Municipal People's Government portal, 2023. Statistical Bulletin of Beijing National Economic and Social Development in 2022. https://www.beijing.gov.cn/zhengce/zhengcefagui/202303/t20230321_2941262.html (accessed 9.9.23).

Bortolini, M., Gamberi, M., Gamberini, R., Graziani, A., Lolli, F., Regattieri, A., 2015. Retrofitting of R404a commercial refrigeration systems using R410a and R407f refrigerants. International Journal of Refrigeration 55, 142–152. https://doi.org/10.1016/j.ijrefrig.2015.02.015

Canova, A., Laudicina, G., Lazzeroni, P., Perez-Mora, N., Repetto, M., 2019. Exploitation and optimal management of free cooling for industrial refrigeration. Energy Conversion and Management 198, 111815. https://doi.org/10.1016/j.enconman.2019.111815

Cascini, A., Gamberi, M., Mora, C., Rosano, M., Bortolini, M., 2016. Comparative Carbon Footprint Assessment of commercial walk-in refrigeration systems under different use configurations. Journal of Cleaner Production 112, 3998–4011. https://doi.org/10.1016/j.jclepro.2015.08.075

China Refrigeration, 2023. Show express. https://cr-expo.com/ (accessed 11.10.23).

China Meteorological Administration, 2023. Climate background. https://weather.cma.cn/ (accessed 9.9.23).

Cheng, X., Zhai, X., 2018. Thermal performance analysis of a cascaded cold storage unit using multiple PCMs. Energy 143, 448–457. https://doi.org/10.1016/j.energy.2017.11.009

Choi, S., Jung, Y., Kim, Y., Lee, H., Hwang, Y., 2021. Environmental effect evaluation of refrigerator cycle with life cycle climate performance. International Journal of Refrigeration 122, 134–146. https://doi.org/10.1016/j.ijrefrig.2020.10.032

Deng, Q., Zhang, Z., Hu, X., 2021. Thermoeconomic and environmental analysis of an inverter cold storage unit charged R448A. Sustainable Energy Technologies and Assessments 45, 101159. https://doi.org/10.1016/j.seta.2021.101159

Deng, S., Wang, R.Z., Dai, Y.J., 2014. How to evaluate performance of net zero energy building – A literature research. Energy 71, 1–16. https://doi.org/10.1016/j.energy.2014.05.007

Evans, J.A., Foster, A.M., Huet, J.-M., Reinholdt, L., Fikiin, K., Zilio, C., Houska, M., Landfeld, A., Bond, C., Scheurs, M., van Sambeeck, T.W.M., 2014a. Specific energy consumption values for various refrigerated food cold stores. Energy and Buildings 74, 141–151. https://doi.org/10.1016/j.enbuild.2013.11.075

Evans, J.A., Hammond, E.C., Gigiel, A.J., Fostera, A.M., Reinholdt, L., Fikiin, K., Zilio, C., 2014b. Assessment of methods to reduce the energy consumption of food cold stores. Applied Thermal Engineering 62, 697–705. https://doi.org/10.1016/j.applthermaleng.2013.10.023

Firoiu, D., Ionescu, G.H., Pîrvu, R., Cismaş, L.M., Tudor, S., Patrichi, I.C., 2021. Dynamics of Implementation of SDG 7 Targets in EU Member States 5 Years after the Adoption of the Paris Agreement. Sustainability 13, 8284. https://doi.org/10.3390/su13158284

Gao, E., Zhang, Z., Deng, Q., Jing, H., Wang, X., Zhang, X., 2022. Techno-economic and environmental analysis of low-GWP alternative refrigerants in cold storage unit under year-round working conditions. International Journal of Refrigeration 134, 197–206. https://doi.org/10.1016/j.ijrefrig.2021.11.007

Gasia, J., Fabiani, C., Chàfer, M., Pisello, A.L., Manni, A., Ascani, M., Cabeza, L.F., 2021. Life cycle assessment and life cycle costing of an innovative component for refrigeration units. Journal of Cleaner Production 295, 126442. https://doi.org/10.1016/j.jclepro.2021.126442

GB/T 17758-2010, 2010, China, Unitary air conditioners, General Administration of Quality Supervision, Inspection and Quarantine of the PRC & Standardization Management Committee of the PRC.

GB/T 21363-2018, 2018, China, Positive displacement refrigerant compressor condensing unit, General Administration of Quality Supervision, Inspection and Quarantine of the PRC & Standardization Management Committee of the PRC.

Guangzhou Municipal People's Government portal, 2023. Statistical Bulletin of Guangzhou National Economic and Social Development in 2022. https://gz.gov.cn/zwgk/sjfb/tjgb/content/mpost_8922708.html (accessed 9.9.23).

Heredia-Aricapa, Y., Belman-Flores, J.M., Mota-Babiloni, A., Serrano-Arellano, J., García-Pabón, J.J., 2020. Overview of low GWP mixtures for the replacement of HFC refrigerants: R134a, R404A and R410A. International Journal of Refrigeration 111, 113–123. https://doi.org/10.1016/j.ijrefrig.2019.11.012

Hu, X., Zhang, Z., Yao, Y., Wang, Q., 2018. Non-azeotropic refrigerant charge optimization for cold storage unit based on year-round performance evaluation. Applied Thermal Engineering 139, 395–401. https://doi.org/10.1016/j.applthermaleng.2018.04.089

ISO 14044, 2020. Environmental Management - Life Cycle Assessment - Requirements and Guidelines. International Organization for Standardization (ISO), Brussels.

ISO 14067, 2018. Greenhouse Gases - Carbon Footprint of Products - Requirements and Guidelines for Quantification and Communication. International Organization for Standardization (ISO), Brussels.

K. Amrane, 2013. Overview of AHRI Research on Low-GWP Refrigerants. https://www.ahrinet.org/analytics/research/ahri-low-gwp-alternative-refrigerants-evaluation-program (accessed 1.9.23).

Khalili, S., Garousi Farshi, L., 2020. Design and performance evaluation of a double ejector boosted multi-pressure level absorption cycle for refrigeration. Sustainable Energy Technologies and Assessments 42, 100836. https://doi.org/10.1016/j.seta.2020.100836

Koronaki, I.P., Cowan, D., Maidment, G., Beerman, K., Schreurs, M., Kaar, K., Chaer, I., Gontarz, G., Christodoulaki, R.I., Cazauran, X., 2012. Refrigerant emissions and leakage prevention across Europe – Results from the RealSkillsEurope project. Energy, The 24th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy, ECOS 2011 45, 71–80. https://doi.org/10.1016/j.energy.2012.05.040

Kumar Singh, K., Kumar, R., Gupta, A., 2020. Comparative energy, exergy and economic analysis of a cascade refrigeration system incorporated with flash tank (HTC) and a flash intercooler with indirect subcooler (LTC) using natural refrigerant couples. Sustainable Energy Technologies and Assessments 39, 100716. https://doi.org/10.1016/j.seta.2020.100716

Lee, S.H., Hong, T., Piette, M.A., Taylor-Lange, S.C., 2015. Energy retrofit analysis toolkits for commercial buildings: A review. Energy 89, 1087–1100. https://doi.org/10.1016/j.energy.2015.06.112

Liu, Y., Yu, J., 2018. Performance analysis of an advanced ejector-expansion autocascade refrigeration cycle. Energy 165, 859–867. https://doi.org/10.1016/j.energy.2018.10.016

López-Belchí, A., 2019. Assessment of a mini-channel condenser at high ambient temperatures based on experimental measurements working with R134a, R513A and R1234yf. Applied Thermal Engineering 155, 341–353. https://doi.org/10.1016/j.applthermaleng.2019.04.003

Makhnatch, P., Mota-Babiloni, A., Rogstam, J., Khodabandeh, R., 2017. Retrofit of lower GWP alternative R449A into an existing R404A indirect supermarket refrigeration system. International Journal of Refrigeration 76, 184–192. https://doi.org/10.1016/j.ijrefrig.2017.02.009

McLinden, M.O., Huber, M.L., 2020. (R)Evolution of Refrigerants. J. Chem. Eng. Data 65, 4176–4193. https://doi.org/10.1021/acs.jced.0c00338

Meraj, S.T., Yu, S.S., Rahman, Md.S., Hasan, K., Hossain Lipu, M.S., Trinh, H., 2023. Energy management schemes, challenges and impacts of emerging inverter technology for renewable energy integration towards grid decarbonization. Journal of Cleaner Production 405, 137002. https://doi.org/10.1016/j.jclepro.2023.137002

Ministry of Ecology and Environment of the People's Republic of China, 2020. 2019 Annual Emission Reduction Project China Regional Power Grid Baseline Emission Factors. https://www.mee.gov.cn/ywgz/ydqhbh/wsqtkz/202012/W020201229610353340851.pdf (accessed 1.9.23).

Mota-Babiloni, A., Navarro-Esbrí, J., Peris, B., Molés, F., Verdú, G., 2015. Experimental evaluation of R448A as R404A lower-GWP alternative in refrigeration systems. Energy Conversion and Management 105, 756–762. https://doi.org/10.1016/j.enconman.2015.08.034

Nanjing Bureau of Statistics, 2023. Statistical Bulletin of Nanjing National Economic and Social Development in 2022. http://tjj.nanjing.gov.cn/bmfw/njsj/202303/t20230324_3871176.html (accessed 9.9.23).

Nuermaimaiti, W., Xuewu, L., Pengze, Y., zongrui, W., Dapeng, H., 2023. Research on Gas Wave Refrigeration Application of Full Feedback Periodic Jet Oscillator. International Journal of Refrigeration. https://doi.org/10.1016/j.ijrefrig.2023.03.024

Ossorio, R., Navarro-Peris, E., 2023. Testing of Variable-Speed Scroll Compressors and their inverters for the evaluation of compact energy consumption models. Applied Thermal Engineering 230, 120725. https://doi.org/10.1016/j.applthermaleng.2023.120725

Petrovic, Andrija, Delibasic, B., Filipovic, J., Petrovic, Aleksandar, Lomovic, M., 2018. Thermoeconomic and environmental optimization of geothermal water desalination plant with ejector refrigeration system. Energy Conversion and Management 178, 65–77. https://doi.org/10.1016/j.enconman.2018.10.035

Ramiah, V., Gangemi, M., Liu, M., 2016. Chapter 2 - Environmental Policies Post the Kyoto Protocol on Climate Change: Evidence from the US and Japan, in: Ramiah, V., Gregoriou, G.N. (Eds.), Handbook of Environmental and Sustainable Finance. Academic Press, San Diego, pp. 25–54. https://doi.org/10.1016/B978-0-12-803615-0.00002-9

Rashidi, S., Hormozi, F., Sundén, B., Mahian, O., 2019. Energy saving in thermal energy systems using dimpled surface technology – A review on mechanisms and applications. Applied Energy 250, 1491–1547. https://doi.org/10.1016/j.apenergy.2019.04.168

Ribeiro, R.PPL., Sosa, J.E., Araújo, J.M., Pereiro, A.B., Mota, J.P., 2023. Vacuum Swing Adsorption for R-32 recovery from R-410A refrigerant blend. International Journal of Refrigeration. https://doi.org/10.1016/j.ijrefrig.2023.01.020

Rogelj, J., Fricko, O., Meinshausen, M., Krey, V., Zilliacus, J.J.J., Riahi, K., 2017. Understanding the origin of Paris Agreement emission uncertainties. Nat Commun 8, 15748. https://doi.org/10.1038/ncomms15748

Soltani, M., Chahartaghi, M., Majid Hashemian, S., Faghih Shojaei, A., 2020. Technical and economic evaluations of combined cooling, heating and power (CCHP) system with gas engine in commercial cold storages. Energy Conversion and Management 214, 112877. https://doi.org/10.1016/j.enconman.2020.112877

Sooben, D., Purohit, N., Mohee, R., Meunier, F., Dasgupta, M.S., 2019. R744 refrigeration as an alternative for the supermarket sector in small tropical island developing states: The case of Mauritius. International Journal of Refrigeration 103, 264–273. https://doi.org/10.1016/j.ijrefrig.2019.03.034

Sun, Z., Wang, Q., Xie, Z., Liu, S., Su, D., Cui, Q., 2019. Energy and exergy analysis of low GWP refrigerants in cascade refrigeration system. Energy 170, 1170–1180. https://doi.org/10.1016/j.energy.2018.12.055

Tartibu, L.K., 2019. Developing more efficient travelling-wave thermo-acoustic refrigerators: A review. Sustainable Energy Technologies and Assessments 31, 102–114. https://doi.org/10.1016/j.seta.2018.12.004

Tian, S., Shao, S., Liu, B., 2019. Investigation on transient energy consumption of cold storages: Modeling and a case study. Energy 180, 1–9. https://doi.org/10.1016/j.energy.2019.04.217

Tsamos, K.M., Ge, Y.T., Santosa, Id., Tassou, S.A., Bianchi, G., Mylona, Z., 2017. Energy analysis of alternative CO2 refrigeration system configurations for retail food applications in moderate and warm climates. Energy Conversion and Management 150, 822–829. https://doi.org/10.1016/j.enconman.2017.03.020

United Nations Environment Programme (UNEP). Handbook for the Montreal Protocol on Substances that Delete the Ozone Layer Thirteenth Edition (2019), ISBN: 978-9966-076-59-5. 2019.

Vaitkus, L., Dagilis, V., 2017. Analysis of alternatives to high GWP refrigerants for eutectic refrigerating systems. International Journal of Refrigeration 76, 160–169. https://doi.org/10.1016/j.ijrefrig.2017.01.024

Vaitkus, L., Dagilis, V., 2014. Refrigerant charge reduction in low-temperature transport refrigerator with the eutectic plate evaporator. International Journal of Refrigeration 47, 46–57. https://doi.org/10.1016/j.ijrefrig.2014.07.011

Wang, H., Zhao, L., Cao, R., Zeng, W., 2021. Refrigerant alternative and optimization under the constraint of the greenhouse gas emissions reduction target. Journal of Cleaner Production 296, 126580. https://doi.org/10.1016/j.jclepro.2021.126580

Wang, Y., Liu, S., Nian, V., Li, X., Yuan, J., 2019. Life cycle cost-benefit analysis of refrigerant replacement based on experience from a supermarket project. Energy 187, 115918. https://doi.org/10.1016/j.energy.2019.115918

Wu, J., Liu, G., Marson, A., Fedele, A., Scipioni, A., Manzardo, A., 2022. Mitigating environmental burden of the refrigerated transportation sector: Carbon footprint comparisons of commonly used refrigeration systems and alternative cold storage systems. Journal of Cleaner Production 372, 133514. https://doi.org/10.1016/j.jclepro.2022.133514

Wu, S., Zhou, C., Doroodchi, E., Moghtaderi, B., 2020. Techno-economic analysis of an integrated liquid air and thermochemical energy storage system. Energy Conversion and Management 205, 112341. https://doi.org/10.1016/j.enconman.2019.112341

Wu, X., Hu, S., Mo, S., 2013. Carbon footprint model for evaluating the global warming impact of food transport refrigeration systems. Journal of Cleaner Production 54, 115–124. https://doi.org/10.1016/j.jclepro.2013.04.045

Yan, G., Liu, Y., Qian, S., Yu, J., 2019. Theoretical study on a vapor compression refrigeration system with cold storage for freezer applications. Applied Thermal Engineering 160, 114091. https://doi.org/10.1016/j.applthermaleng.2019.114091

Zhai, X.Q., Cheng, X.W., Wang, C., Wang, R.Z., 2015. Experimental investigation and performance analysis of a fin tube phase change cold storage unit for high temperature cooling application. Energy and Buildings 89, 9–17. https://doi.org/10.1016/j.enbuild.2014.12.021

Zhang, L., Yang, Z., Zhai, R., Lv, Z., Zhang, Y., Deng, Q., 2022. Flammable performance and experimental evaluation of a new blend as R404A lower-GWP alternative. International Journal of Refrigeration 135, 113–120. https://doi.org/10.1016/j.ijrefrig.2021.12.019

Zhang, S., Wang, C., Zhong, H., Zhao, Z., Feng, J., Wu, Q., Wu, J., 2023. Study on the temperature distribution of motor and inverter in an electric scroll compressor for vehicle air conditioning under refrigeration conditions. International Journal of Refrigeration. https://doi.org/10.1016/j.ijrefrig.2023.05.012

Zheng, X., Wang, R.Z., Tu, Y.D., 2019. Investigation on energy consumption of desiccant coated heat exchanger based heat pump: Limitation of adsorption heat of desiccant. Energy Conversion and Management 188, 473–479. https://doi.org/10.1016/j.enconman.2019.03.077

Highlights:

- A carbon footprint evaluation model for the units was established.
- Influencing factors of carbon footprint are studied numerically and experimentally.
- By GHG assessments, the optimal refrigerant and external conditions were determined.
- Alternative refrigerants reduce carbon emissions for cold storage units by 8.8%-24.92%.

Declaration of interests

☒ 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.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: