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Original article

Life cycle climate performance of R410A and its environmentally friendly alternative working fluids in a heat pump system

Yong Zhang, Zhao Yang *, Yubo Chen, Hongxia He, Yanfeng Zhao

State Key Laboratory of Engines, School of Mechanical Engineering, Tianjin University, Tianjin 300350, China

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ABSTRACT

Heat pump technology utilizes a small amount of electricity and other energy sources to drive residential heat pump systems, achieving efficient utilization of environmental thermal energy such as air heat and geothermal energy. However, numerous scholarly investigations are available that delve into the quantitative environmental impact of heat pumps, particularly due to the utilization of high global warming potential (GWP) refrigerants. The Life Cycle Climate Performance (LCCP) method stands as a well-acknowledged method for assessing the carbon emission of heat pumps throughout their entire life, encompassing the stages from production to disposal. This paper compares the life cycle climate performance calculation results for R410A and its environmentally friendly alternative working fluids across six global cities using heat pumps as an example. From the perspective of life cycle climate performance, R32, R290, R452B, and R466A emerge as excellent candidates to replace R410A. Additionally, in countries with high emission factors, annual energy consumption becomes a crucial factor. In some countries with low emission factors, the use of R290 instead of R410A can even reduce life cycle climate performance by about 87.8%. In the future, as we contemplate the adoption of low-GWP environmentally friendly refrigerants, more efforts are required in addressing the transformation of grid emission factors and the development of efficient heat pump systems.

Introduction

In recent years, the increasingly obvious global warming caused by greenhouse gas emissions, reducing greenhouse gas emissions has become a major scientific issue of urgent global concern. Relevant studies indicate that the global warming trend is still ongoing, with multiple climate change indicators breaking observational records. In 2018, the CO_2 equivalent emissions from the global refrigeration and air conditioning sector accounted for approximately 11.8 %. The use of low-carbon solutions in heating, ventilation, and air conditioning (HVAC) systems has emerged as a critical front in the fight to mitigate greenhouse gas emissions [1].

To this end, countries and regions worldwide are adopting a series of measures, including loan repayment relief and energy efficiency funding support programs to achieve the climate goals mentioned in the Paris Agreement, reduce greenhouse gas emissions, and promote the use of heat pump products. What's more, countries worldwide have signed and enacted numerous conventions and laws to accelerate the substitution process for new low-carbon working fluids. On October 31, 2022, the United States formally joined the Kigali Amendment, becoming the 140th contracting party, committing to reduce the production and use of hydrofluorocarbons [2]. In 2021, Japan introduced the "Fluorocarbon Life Cycle Management Initiative," addressing emissions issues throughout the entire lifecycle of fluorocarbons [3]. The proposal of China's dual-carbon goals aims to achieve higher-quality sustainable development by integrating low-carbon into the whole framework of social and economic development as well as the establishment of an ecological civilization [4]. With the phasing out of hydrochlorofluorocarbons (HCFCs) and the reduction in production of hydrofluorocarbons (HFCs), the development and application of low global warming potential refrigerants are becoming increasingly urgent.

Heat pump technology utilizes a small amount of electricity and other energy sources to drive residential heat pump systems, achieving efficient utilization of environmental thermal energy such as air heat and geothermal energy. It has significant advantages in energy conservation, environmental protection, and low carbon emissions [5,6]. With the increasing awareness of green environmental protection, there is a noticeable increase in consumer preferences and demand for heat pump products. Fig. S1 shows the growth in annual sales of global building heat pumps and selected markets for 2021 and 2022. As can be seen from the figure, the global sales of heat pumps climbed by 10.6 % in

* Corresponding author.
E-mail address: zhaoyang@tju.edu.cn (Z. Yang).

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Nomenclature

Abbreviations

AEC	Annual energy consumption (kWh/year)
COP	Coefficient of performance
EOL	End of life
GEF	Grid emission factor (kg CO_2e/kWh)
GWP	Global warming potential
HCFCs	Hydrochlorofluorocarbons
HFCs	Hydrofluorocarbons
HVAC	Heating, ventilation, and air conditioning
LCA	Life cycle analysis
LCCP	Life cycle climate performance (kg CO_2e)
NBP	Normal boiling point (℃)
NIST	National Institute of Standards and Technology
ODP	Ozone depleting potential
TEWI	Total equivalent warming impact

Symbols

C	The practical charge of refrigerant (kg)
E_D	The direct emissions (kg CO_2e)
E_I	The indirect emissions (kg CO_2e)
E_{LCCP}	The sum of direct and indirect emissions (kg CO_2e)
ERD	The emission factor of refrigerant disposal (kg CO_2e/kg)
ERM	The emission factor of refrigerant manufacturing (kg CO_2e/kg)
m	The mass of the unit (kg)
MM	The gas emission factors of the material production (kg CO_2e/kg)
mr	The weight of the recycled material (kg)
P_c	Critical pressure (MPa)
R_a	Annual leakage rate (%)
R_e	End of Life Refrigerant Leakage (%)
RM	The emission factors of the recycled material (kg CO_2e/kg)
T_c	Critical temperature (℃)
T_g	Temperature glide (℃)
Y	The average lifetime of the heat pump system (year)

2022. At the same time, the sales of air-to-water heat pumps in Europe have achieved a significant increase (49.3 %) over the previous year [7].

R410A is a refrigerant mixture widely used in residential heat pumps, which is a mixture composed of R32 and R125 (50 %/50 %). Meanwhile, it is a non-azeotropic working fluid with zero ODP, safe and non-toxic, but with a significant greenhouse effect [8]. In addition, R410A is compatible with polyolefin oil and is widely used to replace R22 in residential heat pump systems [9]. However, due to the high GWP of R410A, it does not meet current environmental requirements and regulations. It is only used as a transitional substance to replace R22 [10]. As the pace of reducing high GWP refrigerants gradually accelerates, domestic and international scholars have undertaken extensive research on alternative refrigerants for R410A. Chen et al. [11] investigated the cycle performance of two low-GWP hydrofluoroolefin blends in a vapor injection system. They found the capacity of R452B and R447B decreased by 0.7–5 % and 6–15 % compared to R410A, respectively. The use of vapor injection technology can compensate for this deficiency. Shen et al. [12] conducted experimental assessments of the cycle performance of R452B and R454B in the residential split heat pumps, comparing them with R410A. It was shown that R452B and R454B served as excellent alternatives. Sieres et al. [13] analyzed the cycle performance of two low-GWP working fluids (R452B and R454B) based on the liquid-to-water heat pump. The results indicated that compared with R410A, the two types of working fluids have lower compression power and similar coefficients of performance. In addition, Mishra et al. [14] utilized exergy analysis to analyze the cycle performance parameters of five alternative refrigerants to R410A. The results indicated that among the five alternative refrigerants, the R447A system has the smallest total exergy destruction and exergy destruction ratio. Moreover, some scholars have also compared the cycle performance of R1234ze(E), R1234yf, and L-41b to R410A [15–17].

Considering the current state of research, the focus is often on comparative analysis of the cycle performance between R410A and low-GWP alternative refrigerants. The analysis of refrigerants' influence on the climate is usually limited to GWP values, but this is too restrictive. Since the current global discussion is mainly concentrated on reducing the direct contribution of working fluids to global potential values, the indirect contributions of these fluids to global potential values are often overlooked when making choices. Consequently, more comprehensive integrated assessment indicators have been developed, such as Life Cycle Analysis (LCA), Life Cycle Climate Performance (LCCP), and Total Equivalent Warming Impact (TEWI) [18–22]. TEWI only covers the carbon emissions corresponding to equipment use and does not include the carbon emissions corresponding to equipment manufacturing and disposal. Given the limitations of the TEWI evaluation metric, the United Nations Environment Programme (UNEP) has introduced the concept of LCCP to assess the influence of HVAC systems on climate throughout their entire life period (including manufacturing, operation, and disposal). This method integrating simulation software with local weather conditions and LCCP calculation tools can streamline the process of system design, especially for complex systems.

The LCCP research results of different refrigerants in different systems are shown in Table 1. According to Table 1, it can be found that the focus of LCCP research is on refrigeration and air conditioning, while there is less research on LCCP analysis for heat pump systems, and the working fluids studied are not comprehensive, especially the lack of some new heat pump alternative refrigerants such as R452B, R454B, and R466A. Therefore, this paper introduced a modular framework and a calculation tool to analyze the LCCP more comprehensively of R410A and its environmentally friendly alternative refrigerants in a heat pump system. This study is of great significance for selecting new-generation alternative refrigerants for R410A and accelerating the phase-out of high-GWP refrigerants.

Methodology

LCCP calculation

The guideline of the International Institute of Refrigeration (IIR) summarized the whole calculation process of LCCP. At present, many well-known scholars also use such a theoretical basis to calculate LCCP in different systems [23,33]. However, the LCCP tool provided by IIR couldn't be edited, couldn't define new refrigerants, and had small errors. As a result, we rebuilt the Excel-based calculation tool for LCCP, which can automatically obtain emission factors and weather data for different regions. At the same time, it integrates the function of calculating the energy consumption index of the system within the year.

Fig. S2 shows the flowchart for calculating LCCP. Among them, the energy consumption is related to the cycle performance of the system and the thermal load. The heat pump simulation is calculated using self-developed software, which has obtained software copyright in China. Fig. S3 shows part of the operating interface of the software. The compressor model of common refrigerants such as R134a, R410A, R22, and CO_2 is embedded in the software, which is based on the parameters

Table 1
Studies on the LCCP of different refrigerants in the various systems.

Item	Year	Author	Type [a]	Research object	Refrigerant	Influence factor
1	2017	Choi et al. [23]	N	Heat pump and gas boiler	R410A, R32, R290	System type, grid emission factor
2	2015	Beshr et al. [24]	N	Supermarket refrigeration systems	CO_2, N-40, L-40, R404A	System type, refrigerant charge, annual leak rate
3	2022	Panato et al. [25]	E	Refrigeration system	R410A, R452B, R454B, R32	Refrigerant type, electricity emission factor
4	2021	Wan et al. [26]	N	Unitary air-conditioners	R410A, R32, R290, R452B, R466A	Climate, refrigerants type
5	2018	Aprea et al. [27]	E	Household refrigerator	R134a, R1234yf, R1234ze(E)	Refrigerants type
6	2023	Wang et al. [28]	N	Ground source heat pump	R134a, R152a, R1234yf, R1234ze(E), R290	Refrigerant type, annual leak rate, refrigerant charge
7	2020	Maiorino et al. [29]	E	Domestic refrigerator	R134a, R152a	Refrigerant charge, grid emission factor
8	2021	Wan et al. [30]	N	Air conditioning systems	R410A, R466A, R1234yf, R32, R452B, R290	Grid emission factor, refrigerant type
9	2021	Yang et al. [31]	E	Domestic heat pumps	R410A, R32, R32/R1234yf, R32/R1234ze(E)	Operating period, refrigerants type
10	2023	Yang et al. [16]	N&E	Electric vehicle thermal management system	R134a, R1234yf, R152a, R744	Driving conditions, climate, refrigerants type, COP
11	2024	Yu et al. [32]	E	Electric vehicle heat pumps	R1234yf, CO_2, R290, CO_2/R41	Refrigerant type, grid emission factor

[a] N: Numerical study; E: Experimental study.

provided by Danfoss (Tianjin) Ltd. The heat exchanger can be designed according to the capacity. The software is linked to REFPROP 10.0a to select the latest refrigerant or create a custom refrigerant blend. By changing the environmental parameters of evaporation side and condensation measurement, we can obtain the cycle performance parameters of the system under the conditions given in AHRI Standard 210/240.

Eq. (S1) to Eq. (S3) give the main thermodynamic model, and Eq. (S4) to Eq. (S10) give the calculation details of LCCP. The calculation of direct emissions is relatively simple compared to indirect emissions. The values of parameters Y, C, R_e, and R_a can be accessed from the guideline and manufacturer. The GWP and GWP_d can be obtained through relevant reports or literature. The values of parameters RM, MM, ERM, and ERD are obtained according to the guidelines of IIR [23]. The values of AEC are calculated based on the working conditions in AHRI standard 210/240. The important input parameters for LCCP calculation are shown in Table S1.

Low GWP refrigerant selection

In the selection of a new generation of environmentally friendly refrigerants, the ideal refrigerant should meet the conditions of zero ODP, very low GWP, safety, non-toxic, excellent thermodynamic properties, and low price. However, perfect refrigerants do not exist at this stage, and the choice of a new generation of refrigerants must be balanced and compromised in all aspects. LCCP is a more reasonable method of performance evaluation because it includes both system efficiency and environmental impact.

Table S2 provides a comparison of the properties of R410A and its environmentally friendly working fluids. The composition, normal boiling point (NBP), and temperature glide (T_g) were based on the UNEP (RTOC) Assessment Report (2022). The GWP_{100} values in the table are obtained by the IPCC Sixth Assessment Report (2021). The critical temperature (T_c) and critical pressure (P_c) of the selected refrigerants were obtained by using REFPROP 10.0 [34]. The normal boiling point and critical parameters of R32, R290, R452B, R454B, and R446A are close to those of R410A, but the GWP of the alternative working fluids are significantly lower than that of R410A. In addition, the safety level is another important parameter of refrigerant. According to the ANSI/ASHRAE standard 34–2022, R32, R452B, and R454B are classified as class A2L, which have a lower flammability and lower toxicity. Because R466A contains a large proportion of non-combustible components (R125 and R13I1), it is non-combustible and classified as A1. However, R290 is classified as A3 because of its high flammability. Therefore, when the system uses R290 as refrigerant, the charge should be reduced as much as possible, and safety devices should be added to ensure safety during operation.

Additionally, it was also considered the compatibility of the alternatives with R410A operating pressures, as shown in Fig. S4. It can be seen from the figure that the saturated vapor pressure curves of R32, R452B, R454B, and R466A are relatively close to that of R410A, which indicates that the thermodynamic properties of the five working fluids tend to be consistent. The vapor pressure curve of R290 is quite different from that of R410A, but we also analyzed it because of its excellent environmental performance.

Annual energy consumption of the systems

Heat pump description

The rated capacity of the target cooling-based heat pump system is 11 kW. The system is a single-speed compressor unit with a fixed fan speed. It has a volumetric efficiency of 95 %, an isentropic efficiency of 68 %, and a mechanical efficiency of 96 %. The revolutions per minute (RPM) and displacement volume of the compressor are preset according to the capacity of the system and the type of refrigerant. Table. S3 shows the corresponding RPM, displacement volume and the charge of the various refrigerants. In the calculation process, the thermodynamic model is unchanged, but the refrigerant charge amount will be optimized in the calculation process.

Annual energy consumption and evaluation platform

AHRI 210/240 standard puts forward a method called the temperature bin method to estimate the thermal load, energy efficiency, and power consumption, which is suitable for the fixed-speed system studied in this paper. The weather data can be obtained from the National Solar Radiation Database and EnergyPlus built-in weather data [35–37]. We classify the hour-by-hour climate data of the typical meteorological year. The temperature bin method was used to evaluate the local climatic conditions. The temperature bins and corresponding hours of six cities are displayed in Table S4.

The grid emission factor was obtained from the Energy Information Administration (EIA) for residential heat pumps in different countries [38]. In this study, simulations were conducted under each bin temperature. The heat pump simulation system would return the energy consumption and refrigerant charge. These outputs were used to evaluate the LCCP. Here we refer to an Excel-based calculation tool to incorporate weather and load into the model [39].

Results and discussion

Validation of developed models

We developed the simulation models of an 11-kW and 115-kg vapor compression system with the self-developed heat pump simulation software. In order to visually compare the LCCP differences between different refrigerants, we adopted a "drop-in" approach without making any further changes to the system. This simplified approach allows for a more intuitive comparison of LCCP emissions for different refrigerants. Many scholars have used this method to compare LCCP and proved the feasibility of this method [26,27,40], so we also carried out similar simplified processing.

The capacity and COP of R410A were analyzed using the vapor compression system simulation model and compared with the existing experimental results to verify the accuracy of the simulation model. The verification results of the cooling cycle are displayed in Fig. 1. The results show that the deviation of the cooling capacity and COP between the simulation results and the experimental results is less than ± 5 %.

Cycle performance analysis

The heating and cooling load of the building is affected by the climatic conditions. Taking into account geographical location, annual cooling time, annual heating time, and grid emission factors, we selected six different cities for analysis. The outdoor dry bulb temperatures of six different cities are shown in Fig. S5. The results show that the dry bulb temperature in Inchon is the lowest, ranging from −11.8℃ to 32.7℃, while that in Phoenix is the highest, ranging from 2.2℃ to 44.4℃. The annual average temperatures of Miami, Phoenix, Tokyo, Inchon, Geneva, and Lyon are 24.5℃, 23.8℃, 13.0℃, 11.9℃, 10.4℃, and 11.8℃, respectively.

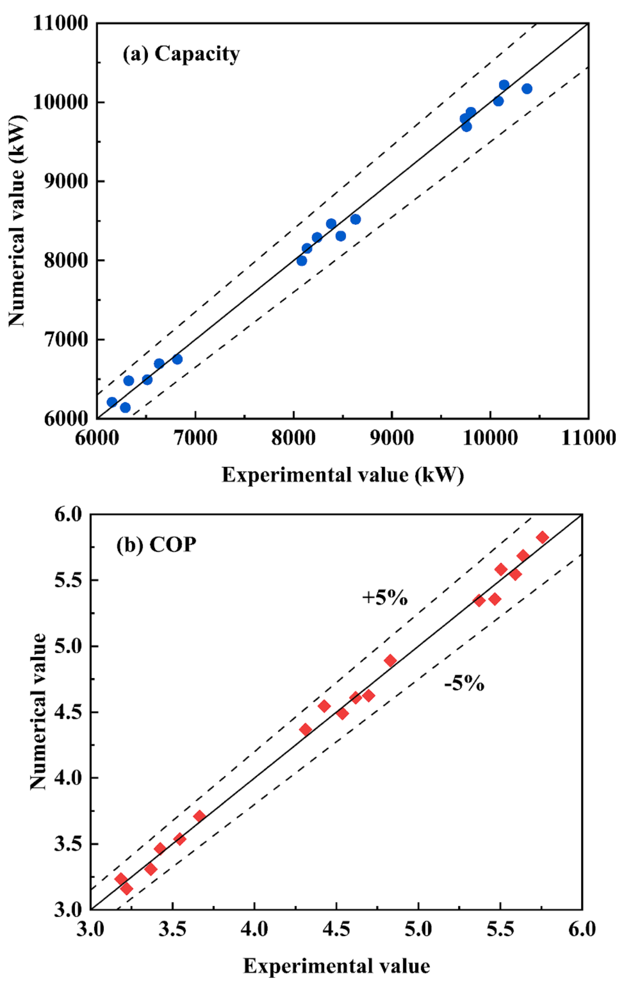

Fig. 1. Validation of the developed model [12,32].

Then, the cycle performance is calculated based on the simulation system of the heat pump within a year. Fig. S6 and Fig. S7 show the simulation results of the cycle performance for different refrigerants in Miami, including cooling seasonal total load (CSTL), heating seasonal total load (HSTL), cooling seasonal total energy (CSTE), heating seasonal total energy (HSTE), and annual energy consumption (AEC). The specific calculation formula can be expressed as Eq.(S11) to Eq.(S18). As can be seen from Fig. S6, The CSTL is similar when different refrigerants are used, but the CSTL corresponding to the alternative refrigerant is slightly greater than R410A. While the HSTL of the six refrigerants is basically the same. Fig. S7 shows a comparison of system power consumption with different refrigerants. It can be found that the HSTE corresponding to the six refrigerants is similar, mainly because the average temperature in Miami is higher, the long-term cooling is longer than the heating time, so the use of alternative refrigerants has little impact on the HSTE. Overall, the use of alternative refrigerants can reduce AEC, with the R32 and R290 systems being the most significant.

Fig. S8 shows the seasonal energy efficiency ratio (SEER), heating seasonal performance factor (HSPF), and annual performance factor (APF) for different refrigerants in Miami. It can be found that the system has a higher SEER when the new alternative refrigerant is used. However, when advantages of HSPF when the system uses R290 and R466A are not obvious. In summary, the adoption of the new alternative refrigerant has a higher APF compared to R410A.

LCCP analysis

Effect of different cities on LCCP

Fig. 2 shows the LCCP results for R410A in six cities. For Miami and Phoenix, the most emissions are due to the operating phase (cooling), which requires longer periods of cooling throughout the year because of the hot climate in these two areas. For Tokyo and Incheon, emissions from the operating phase (heating) account for the most, as the climate in these two regions is colder and requires longer heating times throughout the year. Geneva and Lyon have significantly lower emissions than the other four cities due to smaller GEFs. In summary, when the system uses R410A with a higher GWP, the direct emissions due to refrigerant leakage are the main factor affecting LCCP for Geneva and Lyon with smaller GEFs, while the energy consumption (including cooling emissions and heating emissions) due to equipment operation is the main factor affecting LCCP for the other four countries with high GEFs. This finding is consistent with the conclusion of Wan et al [26].

Effect of different refrigerants on LCCP

Fig. 3 shows the LCCP results in six cities for R410A and its alternatives (R32, R290, R452B, and R466A). The order of LCCP of the five working fluids from large to small is R410A > R466A > R452B > R32 > R290. Thus, R290, R32, R452B, and R466A are good substitutes for R410A as far as LCCP is concerned. It's worth noting that the selection of R290 as an alternative working fluid for R410A can significantly reduce emissions by about 87.8 % in Geneva. In general, the environmental benefits of replacing R410A with a lower-GWP refrigerant increase as the GEF decreases, which is similar to the findings obtained by Maiorino et al [29].

Furthermore, Fig. S9 shows the proportion of emissions of each part. For Miami, Phoenix, Tokyo, and Incheon, due to their high GEFs, the operating phase of the heat pump system accounts for the largest proportion of the life-cycle emissions, regardless of the refrigerant used. For Geneva and Lyon, when R32, R452B, and R466A are used as alternatives to R410A, the emissions due to refrigerant leakage account for the largest proportion of life-cycle emissions. When R290 is used as an alternative to R410A, the emissions due to equipment operation account

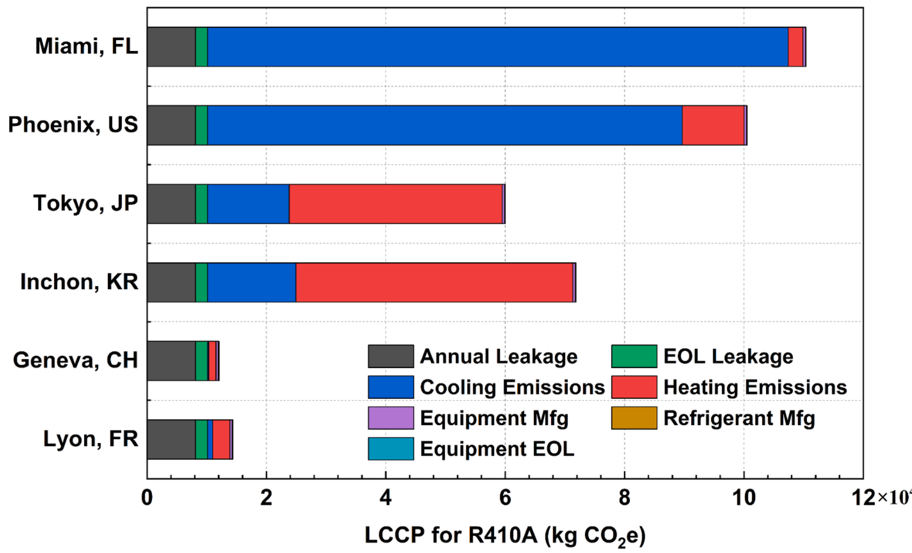

Fig. 2. Effect of different countries and regions on LCCP for R410A.

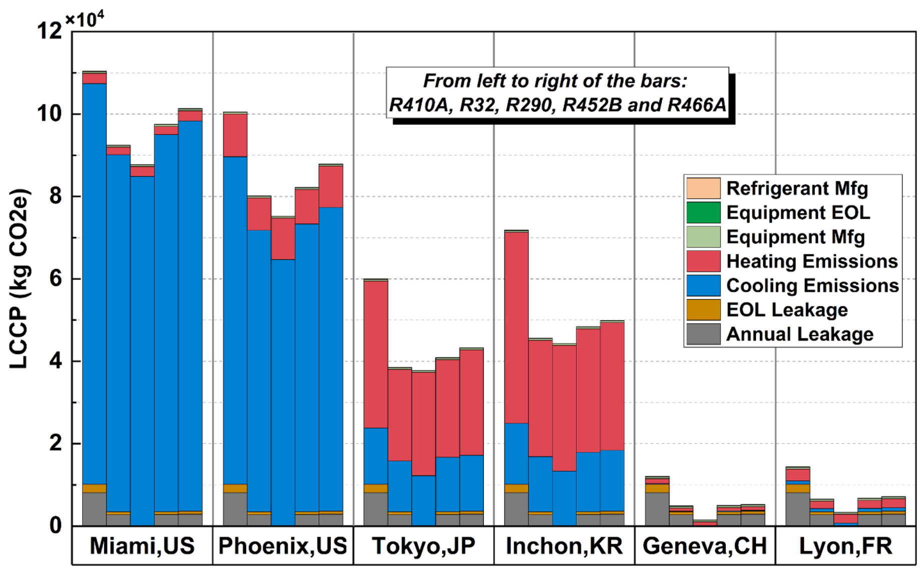

Fig. 3. Effect of different refrigerants on LCCP.

for the largest proportion of life-cycle emissions. Therefore, when using environmentally friendly refrigerants, further improvements in energy efficiency can still reduce the life-cycle emissions of the system.

Effect of refrigerant manufacturing emission rates on LCCP

For R454B, the refrigerant manufacturing emission rates have not been reported so far. Therefore, we investigated the sensitivity analysis of LCCP to different refrigerant manufacturing emissions. According to the IIR guideline, R32 and R1234yf have refrigerant manufacturing emission rates of 7.2 and 13.7 kg CO_2e/kg, respectively. Since R454B is composed of R32/R1234yf (68.9 %/31.1 %), we assume R454B has refrigerant manufacturing emissions of 5,10 and 15 kg CO_2e/kg, respectively. The LCCP calculation results of different refrigerant manufacturing emissions in 6 cities are shown in Table 2. The results show that even for Geneva and Lyon with low GEF, when the refrigerant manufacturing emissions increase from 5 to 15, the proportion of

Table 2
R454B refrigerant manufacturing emissions' effect on LCCP.

(kg CO_2e)	5 kg CO_2e/kg			10 kg CO_2e/kg			15 kg CO_2e/kg		
City	ERM	LCCP	Percentage	ERM	LCCP	Percentage	ERM	LCCP	Percentage
Miami, US	48	96092.6	0.05 %	96	96140.6	0.10 %	144	96188.6	0.15 %
Phoenix, US	48	82314.8	0.06 %	96	82362.8	0.12 %	144	82410.8	0.17 %
Tokyo, JP	48	38756.8	0.12 %	96	38804.8	0.25 %	144	38852.8	0.37 %
Inchon, KR	48	45828.3	0.10 %	96	45876.3	0.21 %	144	45924.3	0.31 %
Geneva, CH	48	3833.2	1.25 %	96	3881.2	2.47 %	144	3929.2	3.66 %
Lyon, FR	48	5561.9	0.86 %	96	5609.9	1.71 %	144	5657.9	2.55 %

refrigerant manufacturing emissions increases from 1.25 % to 3.66 % and from 0.86 % to 2.55 %, respectively. For the other four countries with high GEF, the effect of refrigerant manufacturing emission rates on the proportion of refrigerant manufacturing emissions is minimal. Thus, we can think that the refrigerant manufacture emission rate's influence on LCCP is insignificant in the calculation process.

Effect of GWP values on LCCP

The GWP of refrigerant directly affects the direct emissions of the system. To study the impact of GWP ranges on the emissions of the whole life cycle, a baseline comparison of LCCP was established by using different ranges of GWP values. We choose Miami with a higher GEF and Lyon with a lower GEF as representatives for analysis to facilitate comparison. Fig. 4 displays the total LCCP emissions for different ranges of GWP value by emissions categories. For Miami with high GEF, the total direct emissions increase as GWP increases, but emissions from energy consumption always dominate. As for Lyon with low GEF, the total direct emissions gradually increase as GWP values increase. When GWP is greater than 500, direct emissions gradually become dominant. This result is consistent with the result in Section 3.3.2.

Fig. 5 provides the percentages of the total LCCP emissions in Miami and Lyon by emissions categories. For Miami, the percentage of the energy consumption of the LCCP changes from 99.44 % for a GWP of 10 to 87.68 % for a GWP of 3,000. The end-of-life emissions of the equipment account for only about 0.01 % of total emissions. When GWP is less than 300, the direct emissions do not account for more than 1.5 % of total emissions for Miami. For Lyon, the energy consumption comprises 86.88 % for a GWP of 10 to 21.01 % for a GWP of 3,000. To sum up, while improving system energy efficiency, low-GWP alternative refrigerants should be used whenever possible. Especially for countries with low GEFs, the use of refrigerants with low GWP can effectively reduce LCCP emissions.

Effect of annual refrigerant leakage rate on LCCP

It is well known that refrigerants can leak during system operation, which will undoubtedly lead to an increase in carbon emissions. This influence is embodied in the annual leakage rate (R_a) and the emissions generated during refrigerant manufacturing. To analyze the effect of R_a

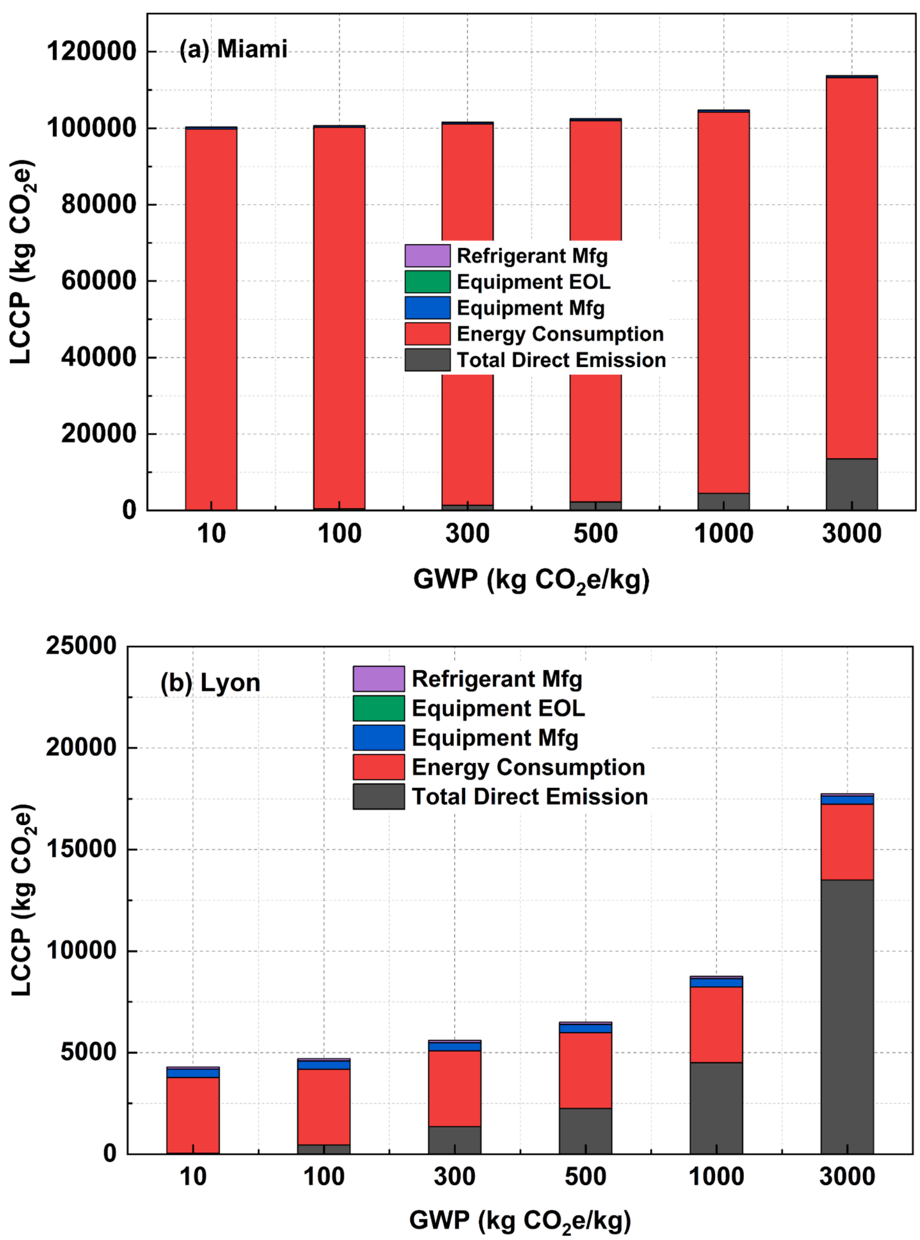

Fig. 4. Effect of sample GWP Values on LCCP in Miami (a) and Lyon (b).

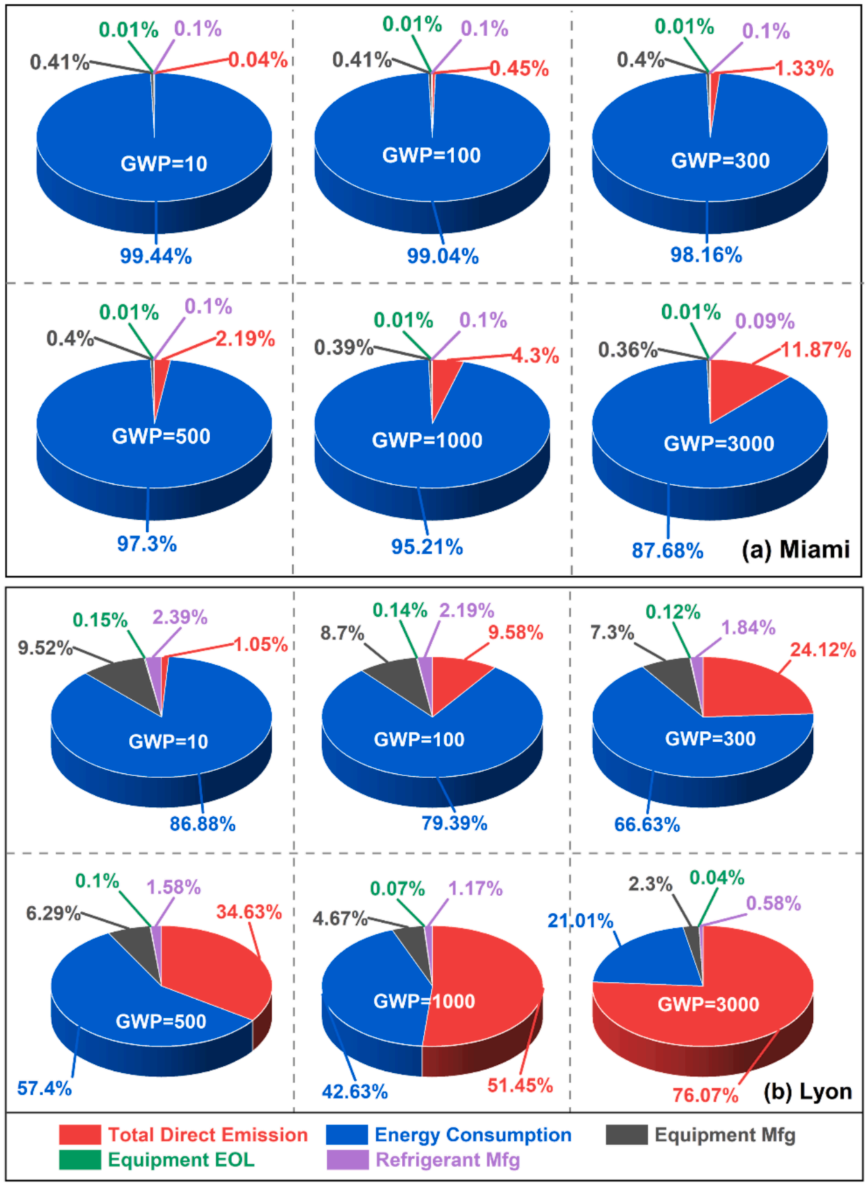

Fig. 5. GWP sensitivity study of Miami (a) and Lyon (b).

on LCCP, the parameters were analyzed with R_a ranging from 0 % to 50 % and GWP ranging from 10 to 3,000. As shown in Fig. 6, for Miami and Lyon, as R_a increases from 0 % to 50 %, total emissions for a refrigerant with a GWP of 10 increases by 931.5 kg CO2e, while total emissions for a refrigerant with a GWP of 3000 increases by 135,481.5 kg CO2e. Therefore, when high GWP refrigerants have to be used, it is crucial to ensure the tightness of the system and reduce refrigerant leakage as much as possible.

Conclusions

This paper studies the LCCP of six cities by using the simulation model of the heat pump system and the calculation tool of LCCP. The effects of important parameters on LCCP are also analyzed, and the main conclusions are as follows:

(1) When the system uses R410A with a higher GWP, in countries with higher GEFs, the impact of system efficiency on heat pump system emissions outweighs refrigerant leaks. However, for cities with lower GEF such as Geneva and Lyon, annual leaks constitute the primary factor influencing LCCP.
(2) From the perspective of LCCP, R290, R32, R452B, and R466A are all excellent alternatives for R410A. For Miami, Phoenix, Tokyo, and Incheon, due to their high GEFs, the operating phase of the heat pump system accounts for the largest proportion of the life-cycle emissions, regardless of the refrigerant used.
(3) For Geneva and Lyon, when R32, R452B, and R466A are used as alternatives to R410A, the emissions due to refrigerant leakage account for the largest proportion of life-cycle emissions. However, when R290 is used as an alternative to R410A, the emissions due to equipment operation account for the largest proportion of life-cycle emissions.
(4) The system efficiency, GWP, grid emission factor, and annual leakage rate are critical factors influencing LCCP performance. The lifetime emissions of the system can be reduced by selecting refrigerants with lower GWP, reducing the annual leakage rate of the refrigerant, using cleaner energy sources, and improving the energy efficiency of the system.

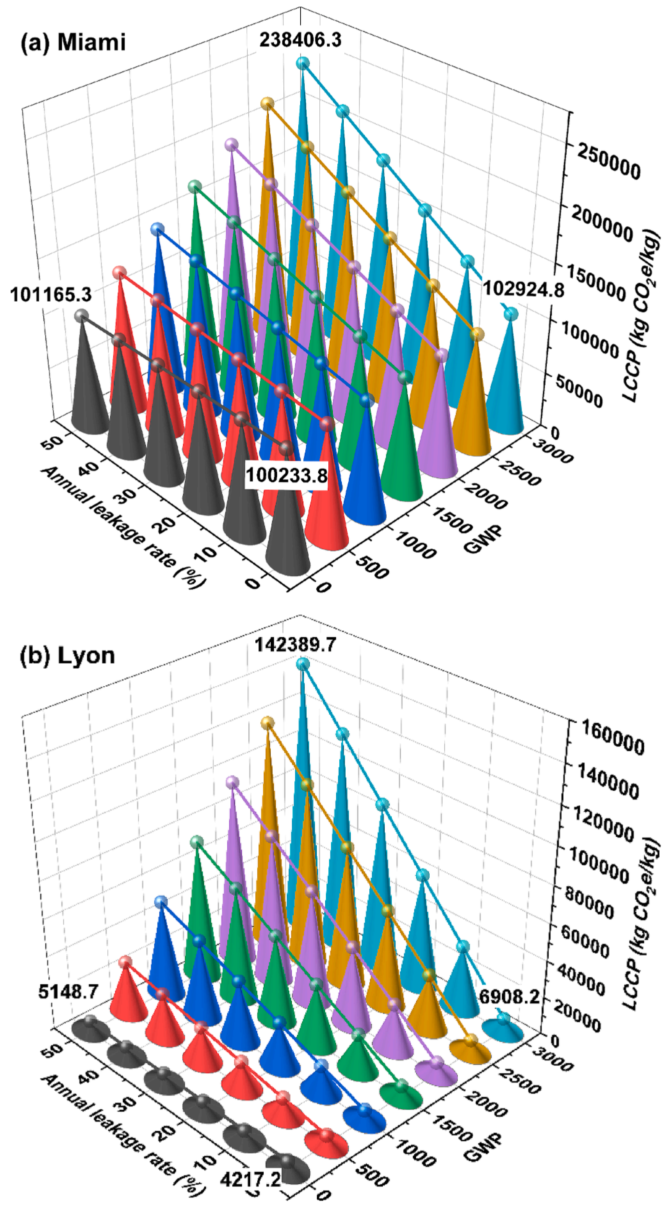

Fig. 6. Annual leakage rate sensitivity study of Miami (a) and Lyon (b).

CRediT authorship contribution statement

Yong Zhang: Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation, Conceptualization. **Zhao Yang:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Yubo Chen:** Writing – review & editing, Methodology. **Hongxia He:** Writing – review & editing. **Yanfeng Zhao:** Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seta.2024.104020.

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