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Life Cycle Climate Performance Evaluation (LCCP) of Low-GWP Refrigerants for Electric Vehicle Heat Pump Towards Carbon Neutrality

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ABSTRACT

The environmental-friendly heat pump with low global warming potential (GWP) is increasingly essential for the electric vehicle (EV) to save energy consumption and extend the driving range, it is beneficial to achieve the carbon neutrality from reducing both direct and indirect carbon emissions. The long-used R134a has a great climate impact due to its high GWP, researchers have been investigating heat pump systems with low-GWP refrigerants. Previously, the life cycle climate performance (LCCP) was a widely accepted metric to evaluate the carbon footprint of mobile air conditioning systems "from cradle to grave" for the classical engine vehicle, however, such LCCP analyses about EV heat pumps can hardly be found. To facilitate the EV industry and policymakers better understand the environmental impacts of those low-GWP refrigerants, this study provided a comprehensive LCCP analysis for the EV heat pumps based on the system bench test results, local climates, local power supply characteristics, real-world driving patterns, vehicle cabin thermal sensation, and climate control load. Three low-GWP refrigerants, i.e., CO2, binary blends of CO2 and R41 (with GWP values of 49), M2 (R410A substitute with GWP values of 137), were compared against R410A and R134a. Among the selected refrigerants, CO2/R41 shows the lowest LCCP, reducing 5-42% of total emissions relative to R134a in various climates, and 1-21% less than the CO2 system.

Keywords: electric vehicle, heat pump, carbon neutrality, LCCP, low-GWP refrigerant, climate change

1. INTRODUCTION

According to statistics from ministry of industry and information technology of the people's republic of China, the total number of automobiles in China in December 2021 was 302 million, among which, the number of new energy vehicles reached 7.84 million. Most of these automobiles still used R134a refrigerant in their air-conditioning (AC) systems. The global warming potential (GWP) of R134a is 1340, which means the greenhouse effect of R134a is 1340 times higher than that of CO_2, considering China's huge number of vehicles, the direct carbon emission from the refrigerant leakage during operation, maintenance and retirement in their life cycle cannot be ignored. In addition, considering the lack of engine waste heat in new energy vehicles, the conventional AC system needs to be switched to the heat pump system in winter to meet the cabin heating demand, however, the heating capacity of R134a usually decreases dramatically under low ambient temperatures (below -5 °C), thus the heat pump needs to be used together with PTC (positive temperature coefficient) electric heating, whose energy efficiency is very low resulting in large indirect carbon emissions.

Thus, with the proposal of China's carbon neutrality target and the official entry into force of the Kigali Amendment to the Montreal Protocol, the green and efficient development of the new energy vehicle heat pump is imperative. On the one hand, it is urgent to convert the currently widely used HFC refrigerant R134a into a low greenhouse effect working fluid to reduce direct emissions; On the other hand, it never stops improving the energy efficiency of the heat pump to reduce indirect emissions. Thus, the life cycle climate performance (LCCP) criterion is necessarily adopted to comprehensively evaluate both effects, which is calculated as total equivalent CO_2 emissions generated over the system's lifetime "from cradle to grave" [1].

Previously, LCCP models have been successfully established for mobile air conditioning (MAC) systems on traditional internal combustion engine (ICE) vehicles. However, The new energy vehicle heat pump has significant differences from the mobile air conditioning systems, as illustrated in Fig.1. Intuitively, the HP system is more complex than MAC system, the ambient temperature in which the heat pump works normally needs to drop to -20 °C, since the cabin heating and cooling are provided by the same heat pump system, more heat exchangers, valves and tubes are required to implement mode switching. These differences make the LCCP developed for MAC system no longer applicable for the NEV heat pump system.

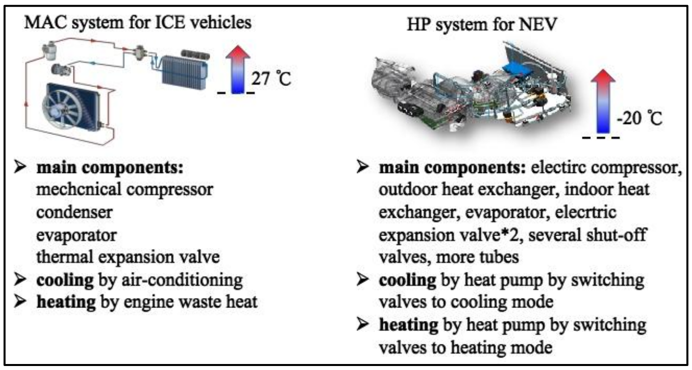

Fig. 1. Differences between conventional MAC system and NEV heat pump

The R134a alternative refrigerants are expected to show good performance under both cooling and heating mode in the heat pump system. However, up to now, there has not been a globally recognized solution because of the trade-off between environmental effect and system performance. The heating performance of R1234yf in cold climate is not satisfactory. Although CO_2 heat pump shows superior heating performance, the cooling coefficient of performance (COP) is even lower than R134a at high ambient temperature (above 35°C). Besides, the high pressure of CO_2 heat pump presents a challenge for its application. R290 has higher volumetric heating capacity and better COP performance than those of R134a, but the strong flammability restricts its use, which brings safety issues. An R410A-based heat pump system was reported and fulfilled the heating requirements for both passenger's comfort and defrosting/demising. However, the GWP of R410A is as high as 2088, which is not acceptable in terms of the environmental impact. To address the above issues, we previously proposed some other possible sloutions, such as the application of CO_2/R41 blends, which offers various performance merits and in the meanwhile reduces the system pressure compared to pure CO_2[2]. In addition, we evaluated M2 (R32/R1123/R161/R13I1 22%/30%/13%/35%) as low-GWP alternative for R410A in NEV heat pump to meet the GWP restriction[3].

Since China has the largest number of new energy vehicles in the world, thus, it is necessary to study environmental impacts of the heat pump from the perspective of life cycle and to evaluate the emission reduction potential of the available low-GWP refrigerants. However, there is still no study on the LCCP evaluation for NEV heat pump, especially analyzing the life cycle carbon emission of the available low-GWP refrigerants, which make it difficult for policy makers and the industry to determine the future choice. Thus, to fill the gap in knowledge of this research sector, this study aims to develop a comprehensive LCCP model for NEV heat pump systems, and to evaluate the environmental benefits of using low-GWP refrigerants in such systems. The model is based on the system bench test results and considers the local climates, real-world driving patterns of car owners, vehicle cabin thermal sensation and climate control load. Based on the model, the LCCP of NEV heat pump system are evaluated using low-GWP refrigerants, i.e., CO_2, M2 and CO_2/R41 blend (50%/50% mass fraction), with R134a and R410A as the baseline. The LCCP results will identify the lowest life cycle emission and give new insights of the environmental impacts of these refrigerants in the heat pump application in addition to the single indicator of GWP.

2. METHODOLOGY

2.1 LCCP calculation

LCCP quantitively estimates the equivalent CO_2 emissions caused by a refrigerant and its application in refrigeration throughout the system's service life. The total emissions, EM_{tot}, consist of direct emissions and indirect emissions, as Eq. (1) expresses:

$$EM_{total} = DEM + IEM \tag{1}$$

The direct emissions, estimated using the GWP of refrigerant and its mass emitted into the atmosphere, are defined as follows:

$$DEM = (GWP + Adp.GWP) \times (RL_{reg} + RL_{irreg} + RL_{ser} + RL_{EOL}) \tag{2}$$

where the $Adp.GWP$ measures the environmental consequence of atmosphere degradation products of the refrigerant. RL_{reg}, RL_{irreg}, RL_{ser} and RL_{EOL} are respectively refrigerant leakage through the system's hoses and joints (regular leakage), leakage caused by accidents (irregular leakage), leakage during services and leakage duet to end-of-life disposal. It is reasonable to suppose that an EV heat pump has the same refrigerant leakage rate as a conventional MAC. Therefore, these four parts of emissions refer to the existing methods developed for conventional MACs. Table 1 shows the information of studied refrigerants. The $Adp.GWP$s of R410A, M2, and CO_2/R41 are not available and are assumed as 0. The manufacturing emissions of virgin M2 and CO_2/R41 are not available and assumed to be the same as R134a.

Table 1 Refrigerant information for LCCP calculation

Refrigerant	R134a	R410A	M2	CO_2	CO_2/R41
Mass fraction (%)	100	100	100	100	50/50
GWP	1430	2088	137	1	49
Adp.GWP	1.6	-	-	0	-
Mfg. emissions ($kgCO_2 \cdot kg^{-1}$)	8	10.7	-	0.2	-
EOL emissions ($kgCO_2 \cdot kg^{-1}$)	2.1	2.1	2.1	2.1	2.1

The indirect emissions are defined as

$$IEM = EM_{Mfg} + EM_{EOL} + EM_{OT} + EM_{SO} \qquad (3)$$

where EM_{Mfg} is the emissions due to refrigerant and system components manufacturing, EM_{OT} represents the mass transportation of system onboard vehicle, EM_{EOL} denotes the end-of-life disposal of refrigerant and components, and EM_{SO} is the emissions due to system operation. Since the EM_{Mfg} emissions and EM_{EOL} are associated with industrial production and have little relation to vehicle type (electric or fuel vehicle), these two parts also refer to the existing method[1]. However, the calculation of EM_{OT} and EM_{SO} is different from the conventional one for the following reasons: (1) EVs are driven by electricity, including their climate control systems. Thus, it is electricity consumption, not fuel consumption, that contributes to the emissions; (2) Unlike the belt-driven compressor of which the speed depends on the fuel engine, the speed of the electric compressor can be controlled based on the cabin climate control load; (3) Since there is no waste heat from the fuel combustion, the EV AC system is required to provide heat for the passenger cabin in cold ambient, which also consumes electricity and should be included in the emission calculation.

EM_{OT} can be calculated by:

$$EM_{OT} = E_{ds} \times M_{sys} \times AVKT \times t_{life} \times CEF \qquad (4)$$

where E_{ds} represents the distance specific energy consumption per kilogram mass of EV, M_{sys} is the mass of air conditioning system, $AVKT$ is short for the annual vehicle kilometers traveled, t_{life} is the lifetime of the vehicle, and CEF is the grid carbon emission factor of electricity generation, or carbon intensity. The distance specific energy consumptions of the tested EV with AC off under WLTC (World-wide harmonized Light-duty Test Cycle) are 178.4 $Wh \cdot km^{-1}$ and 202.0 $Wh \cdot km^{-1}$, respectively in 25 ℃ and -7 ℃ ambient. To simplify the calculation, we adopt the mean value 190.2 $Wh \cdot km^{-1}$ in this study. In addition, the electricity consumption was found to be linearly related to vehicle mass when the mass varies within a small range. Considering the system mass is much smaller than the vehicle mass, the energy consumption by the system mass transport can be treated as proportional to its mass fraction. As a result, the E_{ds} is 190.2 $Wh \cdot km^{-1} \cdot kg^{-1}$ divided by the vehicle mass 1595 kg, and determined as 0.1192 $Wh \cdot km^{-1} \cdot kg^{-1}$. The component mass is assumed to be the same for systems with different refrigerants. The average vehicle lifetime is considered as 10 years for all studied regions.

EM_{SO} are predicted based on the energy consumption model shown in Figure 2.

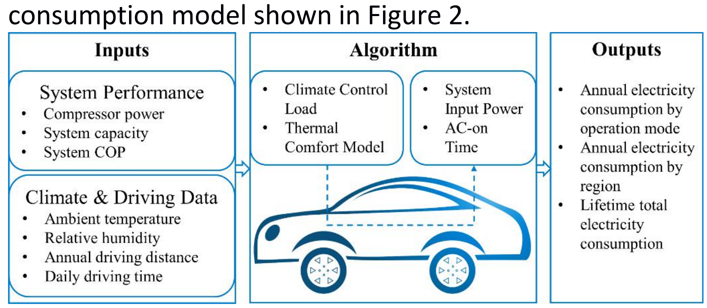

Fig. 2. Model structure of energy consumption prediction of EV climate control system

The energy consumption model requires system performances, climate and driving data as the inputs. The model outputs the annual electricity consumption for a single electric vehicle. The energy consumption algorithms are mainly referred to our previous work[4] while the system input power and the operation time are modified in this study. The model outputs the annual electricity consumption for a single electric vehicle, E determined by

$$E = \sum_{j=1}^{12} (\sum_{i=1}^{24} P_{tot,i} \times t_{i.sys-on})_j \times ND_j \qquad (5)$$

where $P_{tot,i}$ and $t_{i,sys-on}$ are respectively the system input power and operation time during a certain hour of day, and ND_j is the number of days in each month. The subscripts i and j denote respectively each hour of day (1 to 24) and each month of year (1 to 12). Therefore, emissions related to the lifetime operation is determined as follows

$$EM_{SO} = E \times t_{life} \times CEF \tag{6}$$

2.2 Data collection

Data of climate conditions are used to predict the system input power, the climate control load and the cabin thermal comfort. We select 6 cities with typical climates from both China and the US in the case study. They are moderate climates (Beijing, Shanghai and Chicago), warm climates (Guangzhou and Phoenix) and cold climate (Fargo) as Table 2 lists. The climate data sources of those cities are respectively the Chinese Standard Weather Data (CSWD) and the Typical Meteorological Year 3 (TMY3) dataset. These datasets contain long-term-averaged climate data, including hourly dry bulb temperature and relative humidity in each month.

The vehicle-use data are used to predict the system operation time. We collected on-road statistics of private vehicles in order to obtain more realistic results. Due to the relatively short history of China's motor vehicle industry and a lack of officially published driving data, the AVKT data come from the report by the Xiaoxiong Fuel Consumption, a smartphone app which enables private car owners to monitor the fuel consumption of their cars in China. The report published the AVKT data from 455,957 samples supplied by the app users across China. The information of commute by private vehicles in Chinese cities refer to a traffic analysis report published in 2019 by AutoNavi, a famous Chinese navigation service provider. The commute data were obtained based on their traffic big data which were collected through the global positioning system (GPS). In this paper, the commute data are considered as the daily driving time on workdays. The driving data for the US cities refer to the National Household Travel Survey (NHTS) 2017 dataset published by the US Department of Transportation. In this study, we use the on-road hourly car-travel pattern shown in Figure 3 to calculate the hourly distribution-weighted average driving time as follows:

$$t_i = \frac{5t_{d,wd}f_{i,wd} + 2t_{d,wk}f_{i,wk}}{7} \tag{7}$$

where t_i is the weighted average driving time within one hour, $t_{d,wd}$ and $t_{d,wk}$ are respectively the daily driving time on workdays and weekends, $f_{i,wd}$ and $f_{i,wk}$ are respectively the hourly percentage of travel on workdays and weekends, and i denotes each hour of day ranging from 1 to 24. It should be noted that the daily commute data we collected can only be regarded as the $t_{d,wd}$, but not the $t_{d,wk}$. In fact, the average daily driving distance on weekends is about 1.3 times that on workdays. Thus, we infer that average daily driving time on weekends is also 1.3 times that on workdays by supposing that the average driving speed on the road are the same for both workdays and weekends.

$$t_{d,wk} = 1.3t_{d,wd} \tag{8}$$

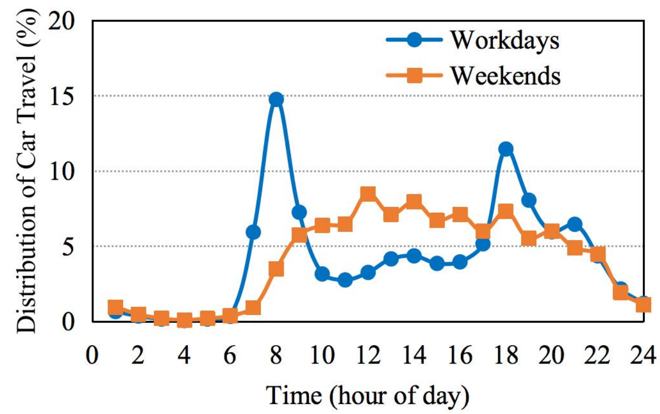

Fig. 3. Temporal distribution of private vehicle travel

The CEF data for electricity generation in China refer to the report officially published by National Development and Reform Commission, while the data for US are from the US Environmental Protection Agency. Table 2 summarizes the major data used in the LCCP calculations.

Table 2 Major data sources for LCCP calculations

City	Annual average temperature (℃)	AVKT (km)	Average daily driving time (hour)	CEF ($kgCO_2 \cdot kWh^{-1}$)
Beijing, CN	12.6	15469	1.48	0.884
Shanghai, CN	16.6	14647	1.42	0.704
Guangzhou, CN	22.2	17328	1.36	0.527
Phoenix, US	24.3	20050	1.57	0.441
Chicago, US	10.7	19635	1.15	0.371
Fargo, US	5.2	18164	1.06	0.688

2.3 Heat pump system and power consumption

The heat pump system with the studied refrigerants refer to our previous studies[2-4]. The test conditions for the cooling performance are modified from SAE J 2765. Under the heating mode, the lowest ambient temperature is -10 ℃ for R134a, R410A and M2 while the lowest temperature is -20 ℃ for CO_2 and CO_2/R41.

Both climate condition and vehicle speed affect the system performance and thus the energy consumption. To account for these effects, we first fitted the performance data under every single climate condition (ambient temperature and relative humidity) as functions of vehicle speed. Next, we obtained the drive cycle-averaged performance by calculating the time-averaged values of the performance data within the WLTC drive cycle, as Eq.(9) shows:

$$p_i = \frac{\int_0^T p_i(t)\,dt}{T} \quad (9)$$

where t is the time sequence, T is the total duration of the drive cycle and p_i is the compressor power. Then, the cycle-averaged performance data are fitted as functions of ambient temperature. The influence of relative humidity is finally taken into account by modifying the air enthalpy. Figure 4 shows the validation of the simulated COPs against the experimental results.

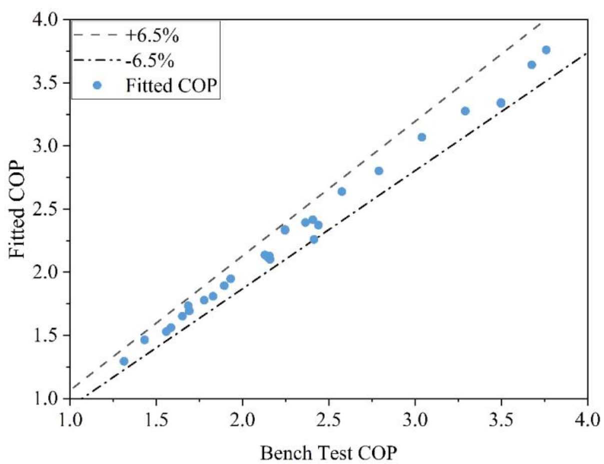

Fig. 4. Validation of developed model

We incorporate the PMV-PPD thermal comfort model into the determination of system input power and operation time. To calculate the compressor power, the operation modes needs to be first determined. The PMV (Predicted Mean Vote) index is associated with the passenger's thermal sensation and is used to judge the system operation mode (heating or cooling mode).

$$P_i = \begin{cases} P_{heating,i} & PMV < 0 \\ P_{AC,i} & PMV \geq 0 \end{cases} \quad (10)$$

where $P_{heating,i}$ and $P_{AC,i}$ are respectively the compressor power under heating and cooling mode. The subscript i is each hour of day ranging from 1 to 24.

Under the cooling mode, the effect of humidity is taken into consideration by air enthalpy modification.

$$P_{AC,i} = P_{p,AC,i} \times h_{local,i} / h_{p,i} \quad (11)$$

where $P_{p,AC,i}$ is the cooling power predicted by the performance data, $h_{p,i}$ is the evaporator inlet air enthalpy under test conditions, and $h_{local,i}$ is the local air enthalpy determined by the climate data. The input power under the heating mode is determined by the heating capacity together with the climate control load. For the heat pump, the PTC heater will operate when the heating capacity is inadequate for the heating load. Thus, the heat pump input power is calculated by:

$$P_{heating,i} = \begin{cases} P_{HP,i} + (Q_{heating,i} - Q_{HP,i})/\eta_{PTC} & Q_{heating,i} > Q_{HP,i} \\ P_{HP,i} & Q_{heating,i} \leq Q_{HP,i} \end{cases} \quad (12)$$

where $P_{HP,i}$ and $Q_{HP,i}$ are respectively the heat pump compressor power and heating capacity, $Q_{heating,i}$ is the cabin heating load, and η_{PTC} is the heating efficiency of the PTC heater, specified as 0.95 in this paper. The heating capacity is provided only by the heater in the conventional cooling system. Hence, the input power is defined as:

$$P_{heating,i} = Q_{heating,i} / \eta_{PTC} \quad (13)$$

Referring to our previous study (Zhang et al., 2017), the cabin heating load on EV consists of two main parts, namely the ambient load and the ventilation load:

$$Q_{heating} = Q_{ven} + Q_{amb} \quad (14)$$

The total system input power should include the power of fan and blower:

$$P_{tot,i} = P_i + P_{fan,i} + P_{blower,i} \quad (15)$$

The fan power $P_{fan,i}$ is usually adjusted according to compressor discharge pressure and vehicle speed. To simplify the calculation, we treated the fan and the blower power in the same way as the compressor power, that is, we use the drive cycle-averaged value.

We predict the EV heat pump system-on time based on the PPD (Predicted Percent Dissatisfied) index, which is the statistical percentage of people who will turn on the air conditioner when they feel dissatisfied with the thermal environment. Thus, the statistically averaged heat pump system-on time is calculated by multiplying the driving time and the PPD index,

$$t_{i,sys-on} = t_i \cdot PPD_i \quad (16)$$

where t_i is the hourly driving time obtained by Equation (7), and PPD_i is the hourly PPD index in the PMV-PPD algorithm.

Combining the collected data, Eq (15) and Eq (16) give the system input power and operation time.

Finally, Eq (5) and Eq (6) respectively determine the annual electricity consumption and emissions due to heat pump operation.

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3. RESULTS AND DISCUSSION

Figure 5 presents the direct and indirect emissions of heat pumps with different working fluids. The direct emissions mainly depend on the refrigerant GWP. It is noticed that the direct emissions are slightly higher in warm regions than in other regions. This is because the regular refrigerant leakage rate of MAC increases with the rise in temperature. Nevertheless, the direct emissions in different regions are still close to each other in general. This result demonstrates that lowering the refrigerant GWP is the key to reduce the direct emissions.

The indirect emissions vary with regions. The M2 heat pump generates slightly less indirect emissions than R410a but 2–27% more than R134a. This result has the same trend as the energy consumption. The CO2 heat pump shows the highest indirect emissions in all regions except in the cold climate, where the CO2 system has a relatively good heating performance and generates around 7% less indirect emissions than R134a. In warm climates, the direct emissions of the CO2/R41 heat pump are lower than CO2 by 9–23% and are close to R134a or M2. In cold climates such as Fargo, CO2/R41 shows 8% of emission reduction compared to R134a.

Although the M2 heat pump has higher indirect emissions than R134a, its total emissions are lower than R134a by 3-35% due to its decreased direct emissions. Thanks to its very low GWP, the CO2 heat pump reduces 6-27% of total emissions relative to R134a except in Shanghai. The CO2/R41 heat pump shows the lowest emissions in all studied regions, reducing the emissions by 5-42% in comparison with R134a, and by 1-21% compared to CO2.

4. CONCLUSIONS

This study establishes a comprehensive LCCP model for electric vehicle heat pump system. Based on the developed LCCP model, we evaluate the environmental impact of electric vehicle heat pumps using low-GWP refrigerants. Although M2 shows 2-27% higher indirect emissions than R134a, it reduces 90% of the direct emissions. In general, it shows 3-35% less total emissions compared to R134a for EV heat pump application. The direct emissions of the CO2 heat pump can be neglected while the CO2 system can reduce 7% of the indirect emissions only in cold climates such as Fargo. Thanks to its low direct emissions, the total LCCPs of the CO2 heat pump are reduced by 6–27% relative to R134a except in Shanghai (+20%). CO2/R41 shows the lowest LCCP among all refrigerants when applied to the EV heat pump, reducing 5-42% of total emissions relative to R134a, and 1-21% relative to CO2, depending on the climate. The results and the model presented in this study may provide guidance for LCCP-based refrigerant selection and design of EV heat pumps.

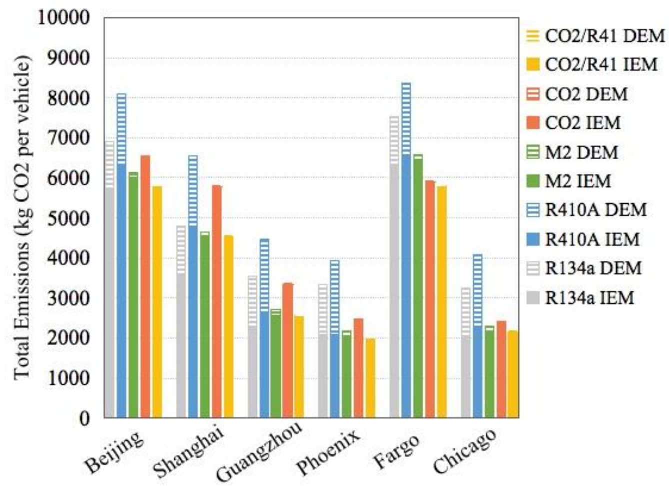

Fig. 5. Total emissions of heat pumps with various refrigerants

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