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Mobile air conditioning system series: Market status and a case study of electric buses in China

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Introduction

Policy background

Mobile air conditioning (MAC) systems worldwide have long relied on chlorofluorocarbons (CFCs) as refrigerants in their cooling cycles. Most of these CFCs are ozone-depleting substance (ODS) with very high global warming potential (GWP). Refrigerants and ODSs that have high GWP and that leak from operating systems into the atmosphere result in severe climate impacts, most notably ozone layer depletion. One example of such CFCs is dichlorodifluoromethane (R-12) which has serious ozone depleting potential (ODP). R-12 was still in operation until ~1990 in most developed countries, when it was phased out of markets by the Montreal Protocol on Substances that Deplete the Ozone Layer, also known as Montreal Protocol, which was adopted in 1987 and entered into force in 1989 (United Nations, 1987).

In response to the Montreal Protocol, MAC systems have transitioned from R-12 to R-134a worldwide, as R-134a is not an ODS and causes less climate impact than its predecessor. However, R-134a still has a relatively high GWP of 1,430 (Myhre et al., 2013), meaning that its heat-trapping power is 1430 times greater than that of CO2. For this reason, the European Union (EU) approved Directive 2006/40/EC in 2006—known as the F-gas Directive—which sets a limit on the GWP of refrigerants used in automobile applications. The limit is a GWP of 150 for MAC units installed in vehicle model year 2010 and later, and for MAC units installed in any vehicle to be sold in the European market after 2017, regardless of its model year.

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R-12 was widely used as an air-conditioning refrigerant in the Chinese automobile industry before 1994. R-12 is an ODS with ODP of 1. China banned R-12 as a refrigerant for automobile air conditioners in 2002 as an ozone layer protection measure. To date, passenger cars, trucks and buses sold in China mainly use R-134a (ODP=0) as an environmentally friendly alternative to R-12. Due to the high demand for heating in electric buses in winter, those with heat pumps may also use R-407C and R-410A as refrigerants. Passenger cars exported to Europe and the United States instead use HFO-1234yf refrigerant to meet local requirements for refrigerants with low GWP.

The 2016 Kigali Amendment to the Montreal Protocol is a significant additional regulation to curb MAC refrigerant emissions around the globe (United Nations, 2016). The Kigali Amendment calls for global collaboration to phase-down production and consumption of HFCs. To date, the HFCs being phased down have replaced 15% of the ODSs that the protocol initially targeted, while the remaining ODSs are replaced by non-fluorocarbon alternative refrigerants (Blumberg & Isenstadt, 2019). With the transition to low-GWP refrigerants and their associated MAC systems, the potential climate impact of refrigerant leakage may decline significantly in the future.

However, the energy needed to operate the MAC system is another main source of GHG emissions. The energy consumption of MAC systems is estimated to be 3–7% of total consumption with great geographical variation (Blumberg & Isenstadt, 2019; Mock, 2013; United Nations Environment Programme et al., 2005). MAC systems may account for about 20% of total energy in hot and humid climates (Papasavva et al., 2009).

For internal combustion engine vehicles, fuel consumption results directly in GHG emissions. For electric vehicles, however, GHG emissions are the result of power demand on the grid and electricity generated by fossil-fuel power plants. Battery production for long-range driving also introduces GHG emissions. Indirect GHG emissions from electric vehicles are associated with the share of electricity coming from a thermal source such as a coal-fired power plant; this indicates, conversely, that electric vehicles will be much cleaner if they are powered by renewable energy. In China, unfortunately, indirect GHG emissions will be higher than in the EU and US, as ~66% of electricity is generated from fossil-fuel sources with carbon intensity of around 0.27 kg/kWh in 2020 (Ritchie & Roser, 2020). Still, EVs in China generate emission reduction benefits compared to their combustion engine counterparts. An ICCT study found that BEVs correspond to about 34%–46% lower lifecycle GHG emissions than gasoline passenger cars (Bieker, 2021).

As the world's second largest emitter of GHGs, China is ambitiously advancing its energy saving and carbon emission targets. In 2020, China's president Xi Jinping announced that China will reach carbon peaking by 2030 and achieve carbon neutrality by 2060, which triggered a great campaign to reduce and offset carbon in the coming decades (Koty, 2021). As part of this transition, it will be critical to improve the energy efficiency of MAC systems to curb indirect GHG emissions.

The main objective of this study is to explore the market status of MAC refrigerants and to identify potential technologies for reducing energy consumption and GHG emissions from MAC systems. In this study, we review the MAC technology and market status of the EU and US and examine the status of China's MAC systems with a focus on electric buses. We conducted a series of surveys and interviews to collect firsthand information about the electric bus market in China with assistance from the consultant Automotive Data of China (Tianjin) Co., Ltd. (CATARC-ADC). We cover the mainstream technical pathways and identify the main problems the Chinese MAC industry is confronting. Additionally, we estimate the potential reduction in GHG emissions with three technologies: advanced & substitute refrigerants, waste heat recovery, and dynamic adaptation by algorithm.

Technical background: MAC technologies

Cooling air conditioner

A classic cooling air conditioner is defined as equipment whose only function is cooling; it is mostly used in passenger vehicles, trucks, and buses that have waste heat sources. The cooling air conditioner is a vapor compression refrigeration system, composed mainly of an internal heat exchanger, an external heat exchanger, high-pressure/low-pressure pipelines, compressors, receiver dryers, expansion valves, and sensors. The cooling air-conditioning refrigeration cycle includes 4 phases:

a) *Compression.* The compressor compresses the low-pressure, cool-temperature refrigerant vapor sucked in from the evaporator, turning it into high-pressure, high-temperature vapor and sending it to the condenser.

b) *Heating.* The high-pressure, high-temperature gaseous refrigerant is condensed in the condenser, and exchanges heat (exothermic) with the air outside the vehicle. After that, it is transformed into a high-temperature, high-pressure liquid refrigerant.

c) *Throttling.* The high-pressure liquid refrigerant flowing out of the condenser flows through the expansion valve and evaporates into vapor, then is sent to the evaporator.

d) *Heat absorption.* Low-pressure, low-temperature liquid refrigerant vaporizes in the evaporator, and exchanges heat (absorbing heat) with the air in the vehicle to become a low-pressure, cool-temperature gaseous refrigerant, which is absorbed in the evaporator. Finally, the refrigerant vapor loses heat and moves into the next working cycle.

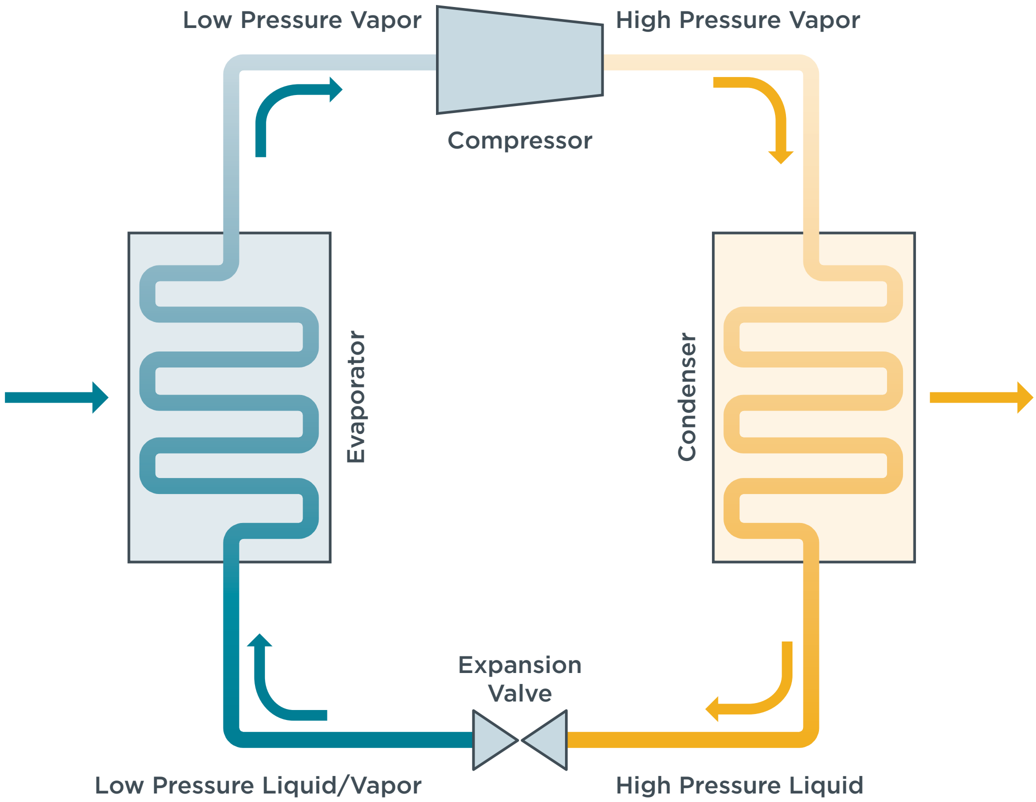
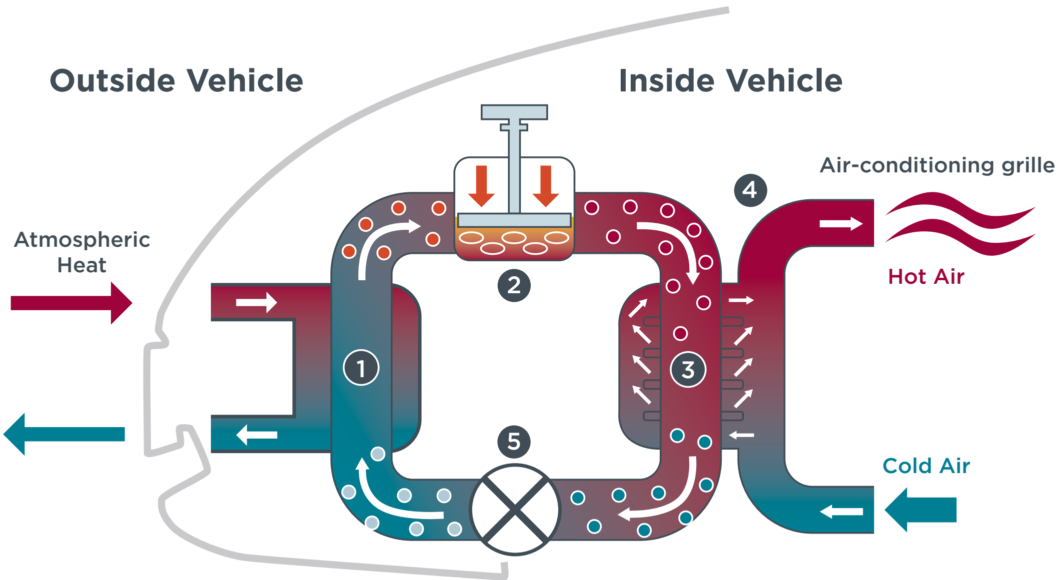


Figure 1. Mechanics of the refrigeration cycle (Super Radiator Coils, 2021)

Heat pump conditioner

Heat pump conditioners can generate heat in cold temperatures and are thus suitable for pure electric vehicles that do not have engine waste heat. Heat pump air conditioners are equipped with two modes of cooling/heating and have a more complicated structure than a cooling conditioner. The heat pump cooling cycle is identical to the cooling air conditioner. When heating, the refrigerant runs in the reverse direction through the four-way and other valves. The fan blows low-temperature air through the condenser and the air is heated. After the refrigerant comes out of the condenser, it enters the evaporator through the expansion valve. The expanded refrigerant in the evaporator exchanges heat with an external heat source, and then is sucked into the compressor again for the next cycle.



1. Heat is absorbed from atmosphere
2. Heat is compressed and turned into heating
3. Heat heats cold air in cabin and raises temperature
4. Heated air is blown into cabin
5. Decompressed heat turns into low temperature heat

Figure 2. Mechanics of the heat pump conditioning system (NISSAN MOTOR Co Ltd, n.d.)

PTC heating system

The Positive Temperature Coefficient (PTC) system generates heat through electric-heat conversion, and thus is the most widely used electric heating technology. The PTC system can be categorized into air-driven PTCs (APTC) and water-driven PTCs (WPTC). APTC is directly installed in the air-conditioner box to heat the air in the cabin directly. WPTC is usually installed outside the box and transfers heat to the cabin through media inside the box. WPTC is more popular and offers the advantages of a highly flexible design and no risk of high-voltage electricity leakage.

Fuel heater

The fuel heater generates heat for the cabin by burning fuels. Compared with the PTC system, the fuel heater only needs low-voltage battery power. Hence, a fuel heater does not affect a vehicle's driving range and battery life. However, the energy efficiency of the fuel heater is about 70%, which is lower than that of the PTC and heat pump system. The fuel heater will also produce substantial quantities of CO_2, NO_x and other pollutant emissions.

Technical background: refrigerants

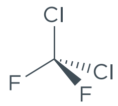
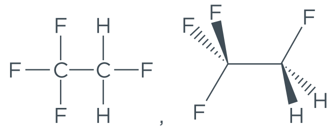
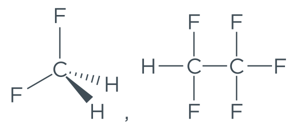
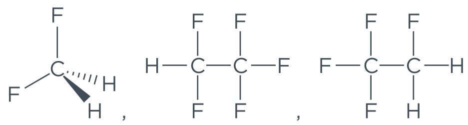
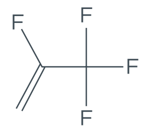
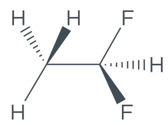
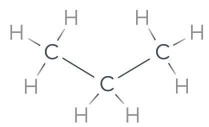
Refrigerants are evolving to be more energy efficient, safer, and less harmful to climate and the ozone layer. In recent years, some promising refrigerants with good performance on climate were invented, such as HFO-1234yf. Table 1 summarizes the properties of several representative refrigerants in use today.

R-12 is a legacy refrigerant still used in some air conditioners and refrigerators. Formally named dichlorodifluoromethane or Freon-12, R-12 is a compound with high levels of solubility and safety. It was invented and widely applied in the 20th century but was banned by most countries due to severe impacts on ozone depletion (A-GAS, n.d.).

R-134a, R-410A and R-407C are refrigerants in use that have a good safety record and zero ODP, however, each one has a GWP of more than 1000. Specifically, R-410A and R-407C are a mixture of refrigerants, each containing different shares of chemical compounds, for example, R-410A consists of 50% CH_2F_2 and 50% CHF_2CF_3, and R-407C is a compound with CH_2F_2 (23%) + CF_3CHF_2 (25%) + CF_3CH_2F (52%).

HFO-1234yf, HFC-152a, R-744 and R-290 are several promising alternative refrigerants with good performance regarding ozone layer protection and global warming mitigation. HFO-1234yf performs better than other refrigerants in terms of GWP, with a score of less than 1. However, this substance is patent-restricted and therefore insufficient to support refrigerant replacement for the entire industry in China. HFC-152a is an organofluorine compound with a GWP of less than 150; it is also used as a propellant for aerosol sprays and in gas duster products. R-290 performs well on GWP but is highly flammable and may need extra care for real-world use and storage.

Table 1. Property information of some representative refrigerants

Refrigerant	GWP-100yr	ODP	Safety	Chemical formula	Status	Structure	Sources
R-12	2400	1	A1	CCl_2F_2	Phased out		(NOAA, n.d.)
R-134a	1430	0	A1	CF_3CH_2F	Popular		(PubChem, n.d.)
R-410A	1975	0	A1	CH_2F_2(50%) + CHF_2CF_3(50%)	Popular		(ChemEurope, n.d.)
R-407C	1700	0	A1	CH_2F_2(23%) + CF_3CHF_2(25%) + CF_3CH_2F (52%)	Popular		(AGC Chemicals, n.d.)
HFO-1234yf	<1	0	A2L	$C_3H_2F_4$	Substitute		(Koban, 2009)
HFC-152a	138	0	A2	$C_2H_4F_2$	Substitute		(EPA, 2014)
R-744	1	0	A1	CO_2	Substitute	O=C=O	(EPA, 2014)
R-290	3	0	A3	C_3H_8	Substitute		(Darment, n.d.)

Literature review: Status of MAC technology in Europe and the Americas

The performance of electric buses usually declines in extreme temperatures, which place increased stress on the powertrain and increase energy demand to ensure thermal comfort in the passenger compartment and driver cabin. The driving range of an electric bus can fall by more than 45% when the ambient temperature reaches around 40°C and the bus is at full passenger occupancy (Basma et al., 2020), imposing more complications for bus operators in scheduling charging. In addition, considering global climate change and more frequent heat waves in western Europe and North America, MAC for public transport applications—and especially buses—is becoming a standard design requirement rather than an optional design choice.

The choice of the MAC technology is of great importance for bus manufacturers and operators as it has a direct impact on the total bus driving range, energy efficiency, operating costs, and maintenance costs (Göhlich et al., 2015). The main MAC technologies can be categorized into fuel-powered and electrically powered technologies. Fuel-powered technologies are the conventional air conditioning units installed in conventional buses and vehicles and are driven by the engine. Electrically-powered technologies are driven by electric motors that draw energy directly from the battery, and they are mainly installed in electric buses (Peng & Du, 2016; Suh et al., 2015). Electric MAC systems in electric buses are of two types: (1) Vapor Compression Cycles (VCC) AC units, and (2) heat pump (HP) AC units. Both technologies are mainly driven by an electric compressor but with some technical differences related to the physical properties of their refrigerants. However, the main difference between VCC AC units and HP is that the latter can be used for heating as well.

With the increase in electric bus sales in Europe, and in North and Latin America over the past 5 years, most new bus models are equipped with HP as the main MAC technology (Haddad et al., 2019). BYD group equipped their K-Series electric bus models with a variety of MAC technologies provided by Valeo (Valeo, 2017). Valeo offers several VCC AC unit and HP technologies with 2 options for working fluids: refrigerant R-134a and refrigerant R-407C. Irizar bus models (Irizar, 2021) are equipped with a HP provided by Hispacold (Hispacold, 2021), with no clear information regarding the working fluid. The eCitaro electric bus of Mercedes-Benz is equipped with a very promising CO_2-based HP (Mercedes-Benz, 2020), i.e., the working fluid is CO_2, also known as R-744, similar to the Solaris Urbino 12 electric bus (Solaris, 2021). The Volvo 7900E bus models are mainly equipped with VCC AC units, with the option to install an additional HP onboard the bus to support the VCC AC unit (Volvo, 2021). VDL declares that their Citea electric bus models (VDL, 2021) are all equipped with MAC supplied by Thermo King, mainly a VCC AC unit that operates using refrigerant R-407C (Thermo King, 2021). Alstom on the other hand equips its APTIS electric bus model with HP, with no further information on the choice of the working fluid (Alstom, 2019).

In addition, many MAC suppliers have announced plans to produce new MAC technologies that fit electric bus applications. SONGZ, a Chinese manufacturer of MAC units, has recently announced that it will supply BYD's 22-meter buses operating in Brazil with VCC AC units (GetNews, 2021). SONGZ offers a variety of VCC AC units, with the majority of their technologies using refrigerant R-134a (SONGZ, 2021). German MAC manufacturer Eberspaecher is supplying electric buses operating in Mexico and North America (Sustainable Bus, 2021) with VCC AC units that operate on refrigerant R-134a (EBERSPAECHER, 2021). Another manufacturer actively developing MAC for electric buses is Cooltek, which offers a variety of HP models that operate on refrigerant R-410a (Cooltek, 2021). Finally, German manufacturer Konvekta is investing heavily in CO_2 HPs for electric buses, further advancing the uptake of this technology in electric bus applications (Konvetca, 2021). Table 2 summarizes all MAC system information mentioned above.

Table 2. MAC supplier and technology information in the EU and US

OEM	AC supplier	AC technology	Refrigerant
BYD	Valeo	VCC/HP	R-134a/R-407C
BYD	SONGZ	VCC	R-134a
Irizar	Hispacold	HP	No information
Mercedes-benz	No information	HP	R-744
Volvo	No information	VCC + HP	No information
VDL	Thermo King	VCC	R-407C
Alstom	No information	HP	No information
Multiple	Eberspaecher	VCC	R-134a
Multiple	Cooltek	HP	R-410a
Multiple	Konvekta	HP	R-744

The technical specifications of the different MAC technologies in the EU/US and Latin American markets demonstrate that EU-based OEMs are deploying HP technologies in their electric buses, with a special focus on CO_2 as a refrigerant. This is mainly driven by European regulations regarding refrigerants in AC systems such as directive EU 2006/40 (European Commission, 2006). On the other hand, in the absence of any directives or regulations in the Latin American market, more buses are being equipped with VCC AC units that use R-134a, despite its high global warming and ozone depletion potentials.

Survey list and key topics

In this study, we conducted a survey reaching out to several Chinese OEMs and MAC suppliers about key specifications of the most representative vehicle models and MAC systems, which are listed in Table 2 and Table 3, respectively. We collected information for both passenger vehicles and buses, from which the top sellers in each segment were then selected.

SAIC, FAW, and Dongfeng are the top 3 passenger vehicle manufacturers with the highest sales in 2020; NIO is a brand-new but rapidly growing China-based OEM that makes electric passenger vehicles only. On the other hand, Yutong, BYD, Foton, and Dongfeng are representative OEMs for commercial vehicle and electric bus providers in 2020. Regarding MAC suppliers, DENSO and SONGZ are the companies interviewed for this study. These firms are key suppliers of passenger vehicles and electric buses in China, respectively.

In total, 10 questions about cooling technology performance and development were posed to the OEMs and MAC suppliers shown in Table 3. From the OEM side, we are evaluating OEM preference on type of refrigerant and its difficulty for update. For MAC suppliers, barriers on technology development, cost variance, and MAC performance are also highlighted.

Table 3. Survey list in this study

No.	Type		Name	Comment
1	OEMs/ Auto groups	Passenger vehicles	SAIC	No. 1 in sales in 2020
2			FAW	No. 2 in sales in 2020
3			Dongfeng	No. 3 in sales in 2020
4			NIO	No. 1 in sales of electric passenger vehicle in 2020
5		Buses	Yutong	No. 1 in sales of electric buses in 2020
6			BYD	No. 2 in sales of electric buses in 2020
7			CRRC	No. 3 in sales of electric buses in 2020
8			Foton	No. 2 in sales for commercial vehicles in 2020
9			Dongfeng	No. 3 in sales for commercial vehicles in 2020
10	MAC suppliers		DENSO	Prominent air conditioner supplier for passenger vehicles
11			SONGZ	Largest supplier for electric buses in China
12			Valeo	Prominent supplier for R-744 systems on electric buses

Table 4. Key topics of the survey

No.	OEMs	MAC suppliers
1	Technology pathway and share	Market share
2	Cost variation across different technologies	Cost variation across different technologies
3	COP[1] variation across different technologies	COP variation across different technologies
4	Type of refrigerant and share	Type of refrigerant and share
5	Reason for refrigerant selection	Reason for refrigerant selection
6	Refrigerant consumption and suppliers	Refrigerant consumption and sources
7	Refrigerant replacement schedule and technology preference	Research plan for conditioning technology
8	Key barriers on refrigerant replacement during use stage	Key barriers to refrigerant replacement innovation
9	Impact of price decline of HFO-1234yf on refrigerant replacement	Cooling cycles
10	Maintenance issues	Maximum cooling capacity and power

Survey findings: technology status, potential pathways for MAC system decarbonization, and challenges

GHG emissions from MAC systems include direct and indirect emissions, where direct emissions are from leakages during air-conditioning filling, operation leakage, and maintenance and scrap emissions. Indirect emissions refer to emissions that can be linked to air-conditioning component production and recovery, as well as to energy consumed during cooling/heating when MAC systems operate. Based on the responses of OEMs and MAC suppliers to the survey questions, we conclude that the energy efficiency of electric bus MAC systems can be improved by several technologies: advanced & substitute refrigerants, waste heat recovery, and dynamic adaptation by algorithm.

1 Coefficient of performance, an indicator of the energy efficiency of a MAC system.

Advanced & substitute refrigerants

Classic refrigerants may encounter several challenges in real-world use, the most outstanding of which is a work environment of extreme conditions. Advanced refrigerants are therefore developed for use in colder temperatures. According to our survey, heat pump systems with R-410A and R-407C dominate the electric bus market in China, although this technology operates under extreme conditions regularly. In general, this technology may not work below -5°C unless equipped with an auxiliary PTC heater, resulting in much higher energy consumption. Nevertheless, the use of low-GWP refrigerants with good heating performance in cold climates, such as R-744 and R-290, can significantly reduce energy consumption of electric buses. A study in a cooler region found that a heat pump system using a low GWP refrigerant can reduce energy consumption of buses by more than 50% relative to a cooling conditioner with PTC heaters (Göhlich et al., 2015), which also implies the need to develop advanced refrigerants that perform well under a wide range of working temperatures.

At present, R-744 and R-290 are used on electric buses in several cases. We collected energy efficiency indicators for both cooling (Energy Efficiency Ratio, EER) and heating (Coefficient of Performance, COP) MAC systems from 14 in-use electric bus models in China with different refrigerants. Table 4 compares the EER and COP of refrigerants at different ambient temperatures. Among all refrigerants, the heat pump system with R-744 has COP ranging from 1.8–2.3, a twofold efficiency increase when compared to a PTC heating system. However, R-744 has a lower EER, implying inferior cooling performance compared to other refrigerants. The R-290 system performs well at cold temperatures with COP ranging from 1.8 to 3.0. More attention should be paid to the safety of R-290 due to its high flammability.

Table 5. Variation of EER and COP across different refrigerants and evaporating temperatures for heat pump systems

Temperature	35°C	0°C	-10°C	-20°C
Efficiency indicator	EER (for cooling)	COP (for heating)		
R-410A	2.4	1.7	-	-
R-407C	2.3	1.7	-	-
R-290	2.3	3.0	2.5	1.8
R-744	1.8	2.5	2.1	2

Source: Choudhari & Sapali, 2017; Kalla et al., 2018

Waste heat recovery

Even though electric vehicles have no waste heat from an engine, the powertrain system can generate heat during operation. Hence, an effective way to improve performance of MAC systems onboard is by recovering waste heat from the powertrain.

Compared to conventional heat pumps, a bus's heating capacity and COP can increase by 15.8% and 5.2% respectively if a heating recovery system is also deployed onboard (Ahn et al., 2016); while 5.1% of heating capacity and 2.6% of COP improvement could be achieved through a series recovery system (Han et al., 2020). According to this survey, some Chinese companies are also developing new waste heat recovery systems, by which COP can increase by about 10% more.

At the same time, costs soar when this technology is used. We learned that system renovation and more heat exchangers are required; therefore, a 10% premium on total cost is inevitable, according to our survey.

Dynamic adaptation

In addition to updating components, the MAC system can reduce total energy consumption by 6% by adapting to different working conditions and number of passengers on board, according to two studies (He et al., 2018; Luo et al., 2018). However, this technique makes MAC systems more expensive. The system price ranges between 25,000 and 60,000 CNY for R-410A and R-407C refrigerants. Substitute systems with R-744 and R-290 are much more expensive than the existing systems due to limited supply; for example, a MAC system with R-744 is 3–5 times more expensive than a MAC system by R-410A or R-407C, according to our survey.

Main challenges

This survey suggests that China's MAC industry is still facing great challenges in refrigerant replacement and MAC energy efficiency improvement. Here we identify the challenges that China's MAC industry should address in the coming years.

Limited supply of alternative technologies with better environmental performance. Several advanced refrigerants are available in the Chinese market, but only HFO-1234yf is technically ready for real-world use with internal combustion engine vehicles. Some promising technologies such as R-744 and R-290 are moving toward mass production and further deployment.

A solid paywall of patents for promising refrigerants. HFO-1234yf has been proven to have great cooling performance and a GWP of less than 1. However, HFO-1234yf is still under the patent umbrella of Honeywell and Chemours and thus cannot be produced by Chinese suppliers. The paywall of HFO-1234yf is an obstacle to its mass deployment and Chinese suppliers may also have to pay a premium to procure the refrigerant.

Incomplete standard to support refrigerant update. Lifecycle emissions of MAC systems are highly volatile depending on ambient temperatures and working conditions. However, China has not built a complete set of standards for MAC energy consumption testing and limitation; instead, GB/T 37123-2018 stipulates the cooling/heating energy efficiency performance for several specific working conditions, but this does not cover all dimensions of on-board performance.

Methodology of this study: modified LCCP model

Life Cycle Climate Performance (LCCP) is an evaluation method for heating, ventilation, air conditioning, and refrigeration systems in terms of global warming performance over their life cycle, encompassing all direct and indirect emissions. Hence, LCCP is one of the most comprehensive methods for assessing GHG emissions and it is used in this study to estimate the GHG emissions reduction for each alternative refrigerant and MAC system.

LCCP considers both direct and indirect emissions from different stages, where direct emissions include all forms of emission due to refrigerant leakage, and indirect emissions involve emissions from manufacturing, operation, and disposal of the system. Since its development in 1999, LCCP has been integrated into a MAC lifecycle analysis model "GREEN-MAC-LCCP" (Papasavva et al., 2010) and adopted as a recommended best practice by SAE International (SAE International, 2009). However, GREEN-MAC-LCCP model does not consider electric vehicles, so in this study, we modified and built a new LCCP model specifically for electric buses. We added new parameters such as cabin volume and area, heating energy efficiency, running time for heating, emission factors for the grid, etc. Figure 3 shows the model used in this study.

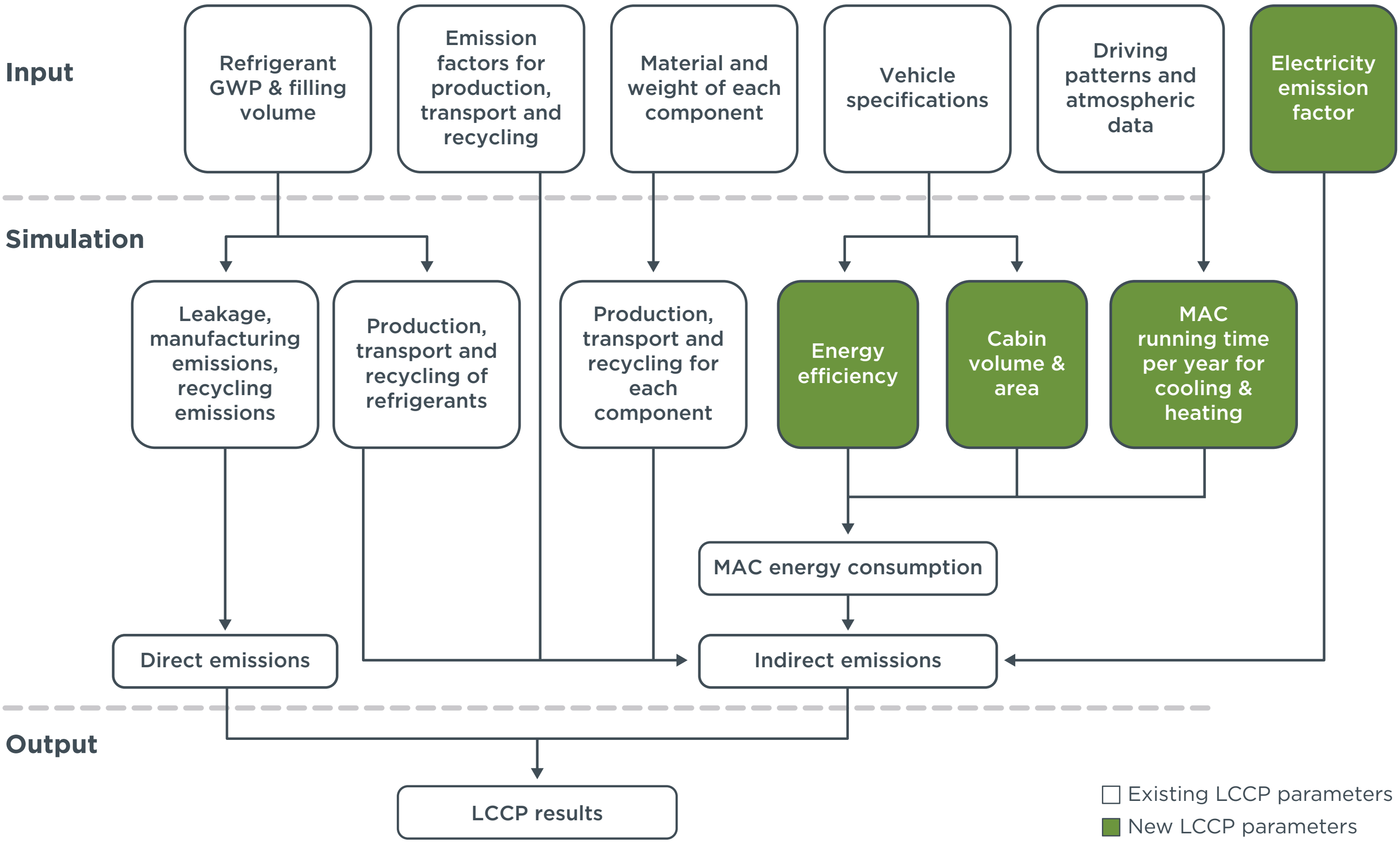


Figure 3. The flowchart of modified LCCP model in this study

Modeling results: Potential improvement of MAC systems on electric buses

To properly evaluate electric buses' GHG emission reduction potential, we applied the LCCP method to estimate emissions from refrigerant and mobile air conditioning technology. Bus chassis design has a great impact on the refrigerant filling volume and its heating capacity. Here we consider a 10-meter model as an example to illustrate the indirect GHG emissions from an on-board MAC system.

Table 6. Information collected from the survey and for simulation in this study

Body length (m)	6	8	10	12
Cabin volume (m^3)	20-30	34-38	40-56	49-63
Filling volume (kg)	2-4	4-6	6-8	8-9

Direct emissions

Table 6 summarizes the assumptions for direct GHG emissions simulation. We assumed that a typical electric bus is filled twice with refrigerants over the bus's life and that leakage occurs at a 0.5% rate per filling, as suggested by some studies (IPCC, 2019). The R-744 system normally operates under higher pressure, which generates higher leakage during use (Meszler Engineering Services, 2004). Hence, 3 maintenance interventions are assumed for the R-744 system over its lifetime. HFO-1234yf is not modeled in the simulation due to its very limited application on electric buses.

Table 7. Assumptions for direct emissions of electric bus MAC system with heat pump technology

Specifications	R-410A	R-407C	R-744	R-290
GWP	2100	1700	1	3
Initial filling (kg)[2]	6	6	3.8	1.5
Maintenance visits over the system's life	2	2	3	2
Leakage per filling (%)	0.5%	0.5%	0.5%	0.5%
Leakage per maintenance visit (%)	100	100	100	100
Leakage per disposal (%)	100	100	100	100

Modeling results show that use of R-744 and R-290 can reduce direct emissions by more than 99.9%. Direct GHG emissions from a MAC system of R-290 are lower than R-744 even though R-290 has a higher GWP. This is because R-290 has a lower volume and requires less filling. Table 7 illustrates the direct GHG emissions by refrigerants.

Table 8. Direct emissions from electric bus MAC system with heat pump technology

		Direct GHG emissions (kg CO_2e)			
		Body length			
		6m	8m	10 m	12m
Refrigerants	**R-410A**	18,995	31,658	37,990	53,819
	R-407C	15,377	25,628	30,754	43,568
	R-744	8	13	15	22
	R-290	7	11	14	19

Indirect emissions

Lifecycle indirect emissions are mainly due to energy consumption of onboard MAC system and lifecycle emissions from materials. The energy consumption of MAC systems is highly dependent on working and climatic conditions. We assumed that bus cabin heating is expected when ambient temperatures drop below 10°C and cooling is expected for ambient temperatures above 26°C. Therefore, it is also necessary to examine local conditions when evaluating the potential of electric bus energy consumption.

In this study, we selected three representative Chinese cities: Harbin (cold), Beijing (mild/cool), and Guangzhou (warm) as target cities for analysis. Table 8 illustrates the assumptions applied for simulation in each city.

Table 9. Assumption of working conditions for MAC system and electric buses

Scenarios		Harbin	Beijing	Guangzhou
Working temperature[3] by frequency of occurrence	-30°C — -20°C	6.10%	-	-
	-20°C — -10°C	18.80%	0.40%	-
	-10°C — 0°C	13.20%	18.00%	-
	0°C — 10°C	16.60%	22.40%	4.50%
	10°C — 15°C	10.30%	11.10%	13.00%
	15°C — 25°C	30%	28.80%	43.20%
	25°C — 35°C	5%	19.40%	39.30%
VKT (km)		44,900	39,400	53,800
Average speed[4] (km/h)		19.67	23.14	17.39
Grid baseline emission[5] (kgCO_2/KWh)		0.6634	0.6168	0.4512

2 A 10m length bus is assumed.

3 Calculated by average hourly temperature over 10 years for each region.

4 AutoNavi China city transportation analysis report 2018, https://finance.sina.com.cn/tech/2021-01-25/doc-ikftssap0417680.shtml

5 NCSC, http://www.ncsc.org.cn/SY/tjkhybg/202003/t20200323_770098.shtml

By simulating the MAC system performance using the assumptions above, Figure 4 shows indirect emissions of each refrigerant and technology. Note that each bar in the diagram shows the lifecycle emissions of a single on-board MAC system. In Harbin, the coldest climatic region considered in this study, heating is the main source for indirect emissions of MAC systems. MAC systems with R-290 and R-744 have superior performance over R-410A and R-407C systems by ~50%. In heating mode, the MAC system operating with R-290 reduces indirect emission by 42% relative to the popular R-410A and R-407C systems, while MAC systems operating with R-744 witness a 38% reduction as well (Figure 4). Also, waste heat recovery and dynamic adaptation help reduce the indirect MAC system emissions by 10% and 6%, respectively.

However, the pattern changes when it comes to cooling. The R-290 system works almost as efficiently as original refrigerants, although the R-744 system performs worse than R-410A and R-407C for cooling purposes. R-744 is simulated to emit about 7.0 tCO_2e and 6.6 tCO_2e with and without dynamic adaptation, respectively.

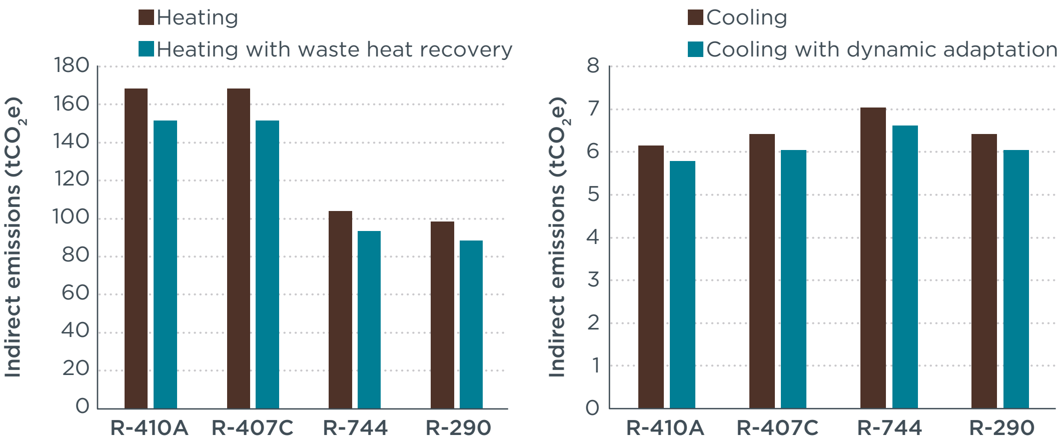


Figure 4. Potential improvement of Indirect emissions by refrigerant and technology in Harbin (cold climate)

In Beijing, heating and cooling are both important sources of indirect emissions for electric bus MAC systems. As shown in Figure 5, the R-290 system can reduce indirect emissions by almost 55% relative to R-410A and R-407C systems, while the R-744 system realizes a ~45% reduction in heating. This also implies that the alternative systems work similarly in cold and mild regions in terms of heating. On the other hand, R-744 underperforms other refrigerants for cooling purposes, with ~19 tCO_2e emitted without dynamic adaptation. The following diagram illustrates variation across different technologies and refrigerants (Figure 5).

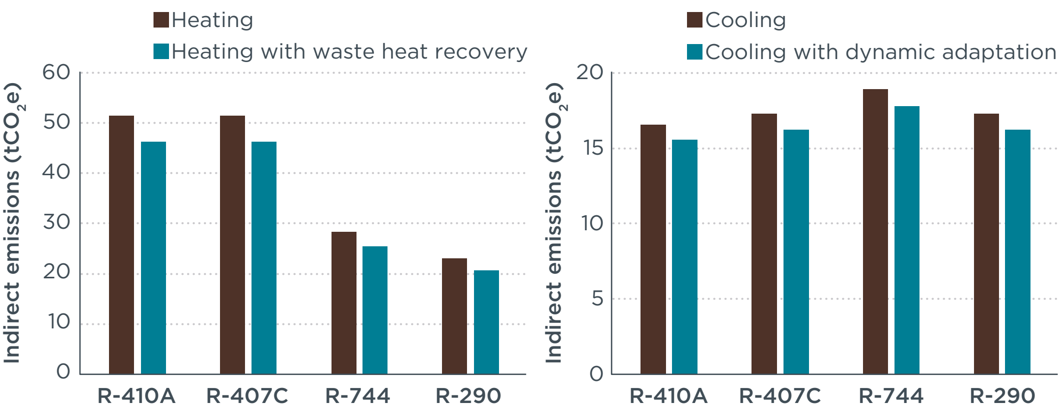


Figure 5. Potential improvement of indirect emissions by refrigerant and technology in Beijing (mild climate)

Guangzhou is a city in southern China with a warm climate, so cooling demand dominates the total energy consumption of the MAC system. Likewise, the cooling pattern of Guangzhou also shows that R-744 has the highest indirect emissions among all refrigerants investigated. The indirect emissions by R-744 MAC systems amount to about 51 tCO_2e, 10% and 14% higher than R-407C and R-410A systems.

Regarding heating, the emission reductions of alternative refrigerants lessens in hot climates, compared to cooler regions. R-744 and R-290 MAC systems record ~10% decline in indirect emissions relative to incumbent refrigerants. Figure 6 depicts the simulated indirect emissions across each refrigerant and technology.

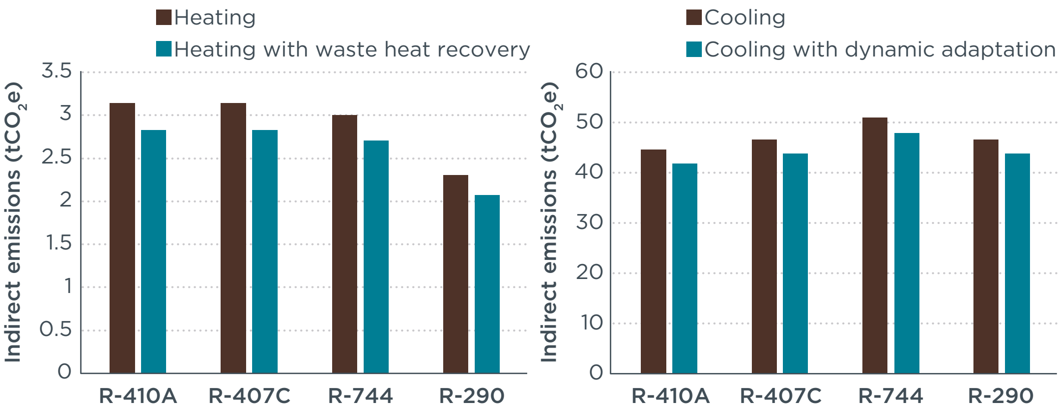


Figure 6. Potential improvement of Indirect emissions by refrigerant and technology in Guangzhou (hot climate)

Total emissions

Figure 7 illustrates the lifecycle emissions for different MAC systems and regions. The R-410A and R-407C MAC systems emit greenhouse gases ranging from 45 to 249 tCO_2e, of which direct emissions account for 13%–53% of total emissions. Greater total GHG emissions can be observed in longer bus lengths. Substitute refrigerants (R-744 and R-290) can eliminate most direct emissions and greatly reduce indirect emissions from Beijing and Harbin. For warmer regions like Guangzhou, substitute refrigerants do not perform any better than currently used refrigerants in terms of indirect emissions.

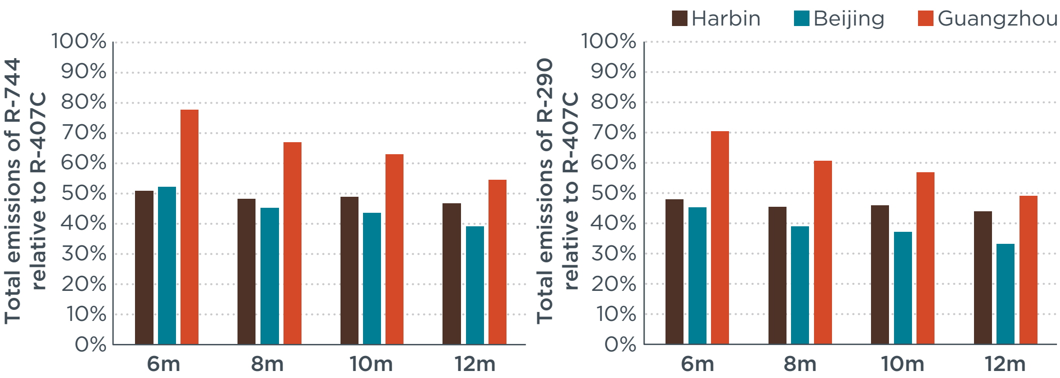


Figure 7. Total emissions of R-744 system in each region related to R-407C system

Wrap-up and key takeaways

In this study, we approached and interviewed several important manufacturers and MAC system suppliers in China. We reviewed the MAC system and refrigerant progress in the EU and US markets, and we identified the market status of China's MAC system and technology. We examined the potential technical pathways for MAC system decarbonization on electric buses. In a nutshell, we evaluated three technologies for reducing GHG emissions: applying advanced & substitute refrigerants, waste heat recovery, and dynamic adaptation.

In addition, we simulated the lifecycle GHG emissions for several MAC refrigerants and technologies used by mainstream manufacturers. Our modified LCCP model found that popular refrigerants (R-410A and R-407C) directly emit more than 15 tons CO_2e over the entire life cycle of one MAC system. We also examined the indirect emissions for 3 regions, namely Beijing (mild), Guangzhou (hot) and Harbin (cold). Even though every region has the potential to reduce GHG emissions a great deal, cities in cold areas have the greatest room for improvement. For example, in Harbin and Beijing the MAC system can typically reduce total GHG emissions by 30–127 tCO_2e per vehicle, while the MAC in Guangzhou can shed 14–47 tCO_2e

However, several questions remain. For example, is there an optimal way to reduce MAC system emissions at a reasonable cost? Are there other efficient refrigerants that can be used in China to get around the patent paywall? How can standards/guidelines be set up to control emissions from on-board MAC systems more effectively? Which combination of technologies will be most efficient for regions with different climate conditions? There is no way to answer these questions without an in-depth investigation of China's market for MAC systems and in particular, the real-world energy performance of MAC systems for different vehicle categories. In future works we will examine the potential energy consumption improvement of MAC systems from a technical and cost-effective perspective.

Appendix 1. Questionnaire for the survey

	Questions in Chinese	English translation
1	主要生产那种类型的汽车（动力类型及车型）？	What type of vehicles do you produce (by powertrain and category)?
2	主要采用哪种空调技术（空调系统+制冷剂），各类空调技术在企业内的占比大概多少?	What type of MAC technology (air conditioning system + refrigerant) do you use? What is the share of each technology?
3	选择空调技术的主要因素有哪些?	What is the key rationale behind your decision to use this MAC technology?
4	目前正在使用的空调技术的制冷/制热能效?	How efficient is your MAC system for heating and cooling?
5	R-134a、R-410A、HFO-1234yf等制冷剂主要的供货商有哪些，不同制冷剂的采购价格大概多少?	What are the main options for refrigerants such as R-134a、R-410A、HFO-1234yf? What's the range of cost for procuring these options?
6	单车制冷剂的消费量大概多少?	How much refrigerant does a typical model consume for a single filling?
7	是否有相应的替代制冷剂的偏好?	Is there a preferred substitute refrigerant?
8	汽车生命周期内需要加注几次制冷剂?	How many times is the vehicle filled over its lifetime?
9	是否要求下辖4s店回收维修过程中的制冷剂，实际回收率大概多少?	Are retailers required to recycle refrigerants? What is the recycling rate?
10	如何处置回收后的制冷剂?	How will recycled refrigerants be managed?
11	选择替代制冷剂主要考虑的因素有哪些?	What is the key rationale behind your choice of substitute refrigerant?
12	适用于电动车及传统燃油车的空调技术有哪些差异?	What different MAC technologies are used in electric vehicles and internal combustion engine vehicles?
13	是否已经开始或者计划开始研发适用于替代制冷剂的空调系统，研发及应用的难点有哪些?	Are any new MAC systems under development? What's the bottleneck for application?
14	是否针对汽车空调开展能效提升技术的研究工作，能效提升效果怎么样?	Are there any studies regarding improved energy efficiency for MAC technology?

Appendix 2. Total emissions from MAC systems of electric buses

Length	Region	Refrigerant	Emissions (tCO_2e)			Percentage improvement[6]
			Direct emissions	Indirect emissions	Total emissions	
6m	Harbin	R-410A	18.99	100.98	119.97	/
		R-407C	15.38	101.25	116.62	/
		R-744	0.01	59.30	59.31	49.15%
		R-290	0.01	55.89	55.90	52.07%
	Beijing	R-410A	18.99	45.54	64.54	/
		R-407C	15.38	46.26	61.64	/
		R-744	0.01	32.16	32.17	47.82%
		R-290	0.01	27.94	27.95	54.66%
	Guangzhou	R-410A	18.99	46.34	65.34	/
		R-407C	15.38	48.28	63.66	/
		R-744	0.01	49.41	49.41	22.37%
		R-290	0.01	44.89	44.89	29.47%
8m	Harbin	R-410A	31.66	127.52	159.18	/
		R-407C	25.63	127.79	153.41	/
		R-744	0.01	74.05	74.06	51.73%
		R-290	0.01	69.84	69.85	54.47%
	Beijing	R-410A	31.66	53.66	85.32	/
		R-407C	25.63	54.38	80.01	/
		R-744	0.01	36.18	36.19	54.76%
		R-290	0.01	31.22	31.23	60.97%
	Guangzhou	R-410A	31.66	46.84	78.50	/
		R-407C	25.63	48.77	74.40	/
		R-744	0.01	49.83	49.85	33.01%
		R-290	0.01	45.21	45.23	39.22%
10m	Harbin	R-410A	37.99	174.48	212.47	/
		R-407C	30.75	174.75	205.50	/
		R-744	0.02	100.14	100.16	51.26%
		R-290	0.01	94.53	94.55	53.99%
	Beijing	R-410A	37.99	68.02	106.01	/
		R-407C	30.75	68.74	99.49	/
		R-744	0.02	43.30	43.31	56.46%
		R-290	0.01	37.01	37.03	62.78%
	Guangzhou	R-410A	37.99	47.71	85.70	/
		R-407C	30.75	49.65	80.40	/
		R-744	0.02	50.59	50.60	37.07%
		R-290	0.01	45.79	45.81	43.03%
12m	Harbin	R-410A	53.82	195.39	249.21	/
		R-407C	43.57	195.65	239.22	/
		R-744	0.02	111.76	111.78	53.27%
		R-290	0.02	105.52	105.54	55.88%
	Beijing	R-410A	53.82	74.41	128.23	/
		R-407C	43.57	75.13	118.70	/
		R-744	0.02	46.47	46.49	60.83%
		R-290	0.02	39.59	39.61	66.63%
	Guangzhou	R-410A	53.82	48.10	101.92	/
		R-407C	43.57	50.04	93.61	/
		R-744	0.02	50.92	50.94	45.58%
		R-290	0.02	46.05	46.07	50.79%

6 Change relative to the R-407C system

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