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Greenhouse gas emissions reduction potential of CO_2-based mobile air conditioning systems in China's electric bus fleets

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Introduction

Mobile air conditioning (MAC) systems are an essential component of motor vehicles because they promote passenger comfort. In recent years, almost all new passenger cars and buses sold in China were equipped with MAC systems; these systems were also increasingly included on new trucks, and the penetration rate reached approximately 90% in 2020 (Yang et al., 2022). Given this widespread adoption, it is important to understand and mitigate the environmental impact of MAC systems in China, especially in regions where extensive heating and/or cooling are required.

The International Energy Agency estimated that in 2015, global greenhouse gas (GHG) emissions from MAC systems were around 420 million tonnes of carbon dioxide equivalent (CO_2e), or more than 1% of global energy-related CO_2 emissions (International Energy Agency [IEA], 2019). A more recent study found that MAC systems accounted for about 6% of global transport-related CO_2 emissions in 2021 (Tiseo, 2023). A thorough evaluation of the environmental impacts of MAC systems is thus also of global concern.

MAC systems release GHGs in two ways: direct and indirect emissions. Direct emissions happen when the refrigerant evaporates or leaks during vehicle assembly, maintenance, and operation, and during disposal and recycling. Indirect emissions are the result of the MAC system's energy consumption during vehicle operation. On average, indirect emissions are almost 70% of the GHG emissions from MACs (IEA, 2019). The emergence of new refrigerants in recent decades is expected to support the improvement of MAC systems. These new refrigerants include CO_2 in the form of R-744, which has a 100-year global warming potential (GWP) of 1, and HFO-1234yf, with a 100-year GWP of less than 1. The GWP of currently applied refrigerants—such as R-134a, with a 100-year GWP

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of 1,430—is much higher. Nevertheless, the transition to newer refrigerants in China is challenging in part because of patent restrictions. Patents on HFO-1234yf products such as Chemours' Opteon™ YF and Honeywell's Solstice® yf significantly increase their cost in China and are a barrier to widespread application (Mao, 2023; Mao et al., 2022).

A prior study, Mao et al. (2022), detailed the results of surveys and interviews conducted with bus manufacturers and MAC system suppliers in China, and explored both the energy performance of MAC systems in electric buses and the potential of deploying new refrigerants to improve environmental performance. Building from that, this paper uses real-world data collected from electric buses operating in three representative cities in China in 2022 to examine the energy consumption of MAC systems. We then use a simulation model to examine the GHG reduction potential of CO_2-based MAC systems in electric buses based on different scenarios of deployment across China.

Methodology

Data collection

Real-world data was collected from three cities in different regions of China that have different climates: Tianjin, Guilin, and Sanya (Figure 1). Tianjin is located in the north of China so vehicle cabins require a lot of heat during winter. Guilin is a popular tourist destination in southwestern China that has mountainous terrain, mild temperatures, and a humid climate throughout the year; real-world data regarding the electric bus cooling needs in Guilin was collected during the summer. Sanya has a tropical, humid climate all year round.

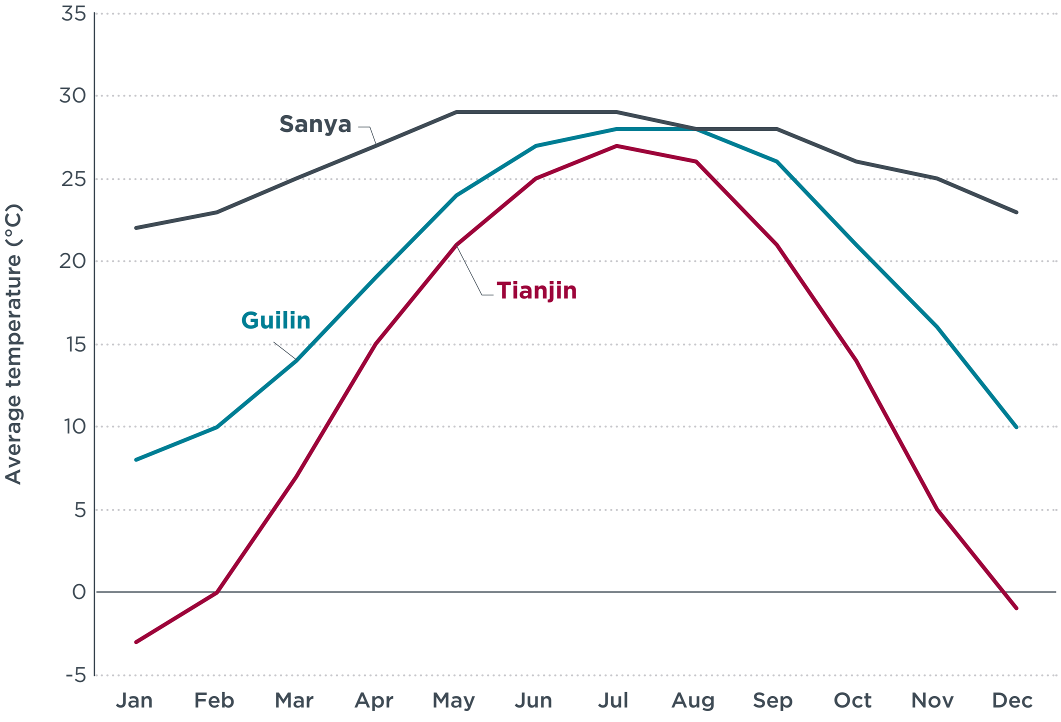

Figure 1. Temperature patterns in the selected cities in 2022 (Weather Spark, 2023a, 2023b, 2023c)

We selected three different electric bus models, each with the same general vehicle specifications and similar cabin sizes and gross vehicle weights. The cabin AC systems used in our testing were all provided by Songz, a popular AC system supplier in China. Refrigerants R-410A and R-407C were used on the sample electric buses (the same refrigerants that the buses use in daily operations). The specifications of the vehicles and AC systems are listed in Table 1.

Figure 2. Location of selected cities and type of data analyzed

Table 1. Specifications of bus models and MAC systems tested

Vehicle specifications			
Testing site	Tianjin	Sanya	Guilin
Bus maker	Tianjin Jinma	BYD	Higer
Nominal battery capacity (kWh)	384	253	138
Cabin dimension (mm)	12,000*2,550*3,360	10,690*2,500*3,530	10,490*2,480*3,060
Wheelbase (mm)	6,100	5,250	5,700
Total bus energy consumption (kWh/100 km)	113	70	68
Window dimensions (m^2) (including front, rear, and side windows)	35.8	27.7	26
Doors	2	2	2
Passenger capacity	81	48	84
Gross vehicle weight (tonnes)	18	18	16.5
MAC system specifications			
MAC technology	Heat pump + positive temperature coefficient (PTC) heater	Single-cooled air conditioner	Heat pump
Supplier	Songz	Songz	Songz
Refrigerant	R410A	R410A	R407C
Max air mass flow rate (m^3/h)	6,000	4,500	4,500
Max power – heat pump (kW)	9	9	9.5
Max power – PTC (kW)	12 + 1 (windshield defrosting)	—	—
Voltage (V)	24	24	24

For more details about the measures used to collect real-world data, please refer to Appendix A. Additionally, the detailed real-world test results of power demand from the MAC systems of electric buses in the three regions are in Appendix B.

The coefficient of performance, or COP, is a key measure of the conversion of input energy to cooling and heating power. Various COP values were used in our model to calculate the total energy of MAC systems over a year and the resultant potential for decarbonization (Figure 3). The COP curves for refrigerants R410A and R407C were derived from real-world tests. Due to the lack of data availability, the COP curve of refrigerant CO_2 was derived from publicly available data from the literature (Song, Lu, Lei, Cai, et al., 2021; Song, Lu, Lei, Wang, et al., 2021; H. Wang et al., 2022) and from a survey of bus manufacturers.

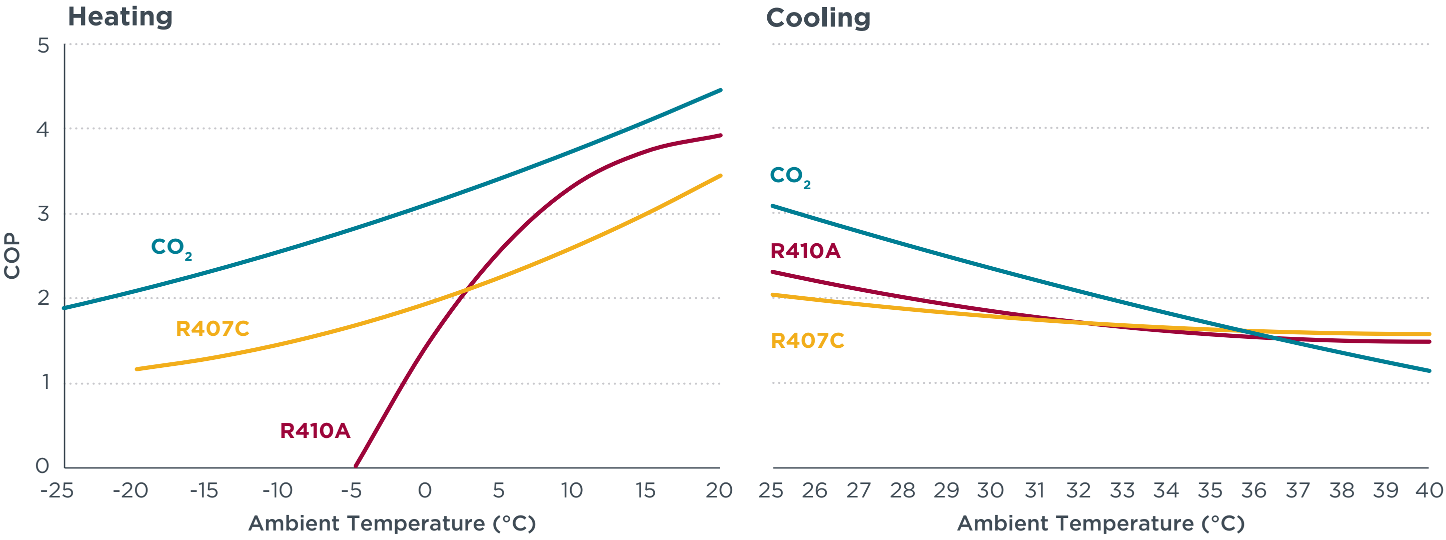

Figure 3. System COP curves for refrigerants R410A and R407C derived from real-world testing data and, for CO_2, derived from literature. The higher the COP, the greater the efficiency during heat exchange, making the MAC system more energy efficient.

Model configuration

We framed an energy model of a vehicle and MAC system using the Amesim simulation platform developed by Siemens, and it is illustrated in Figure 4. The real-world testing data served to calibrate key parameters of the model, including the control strategy (the on-off controller) and the derived COP values. Our simulation followed the control strategy described in Table 2.

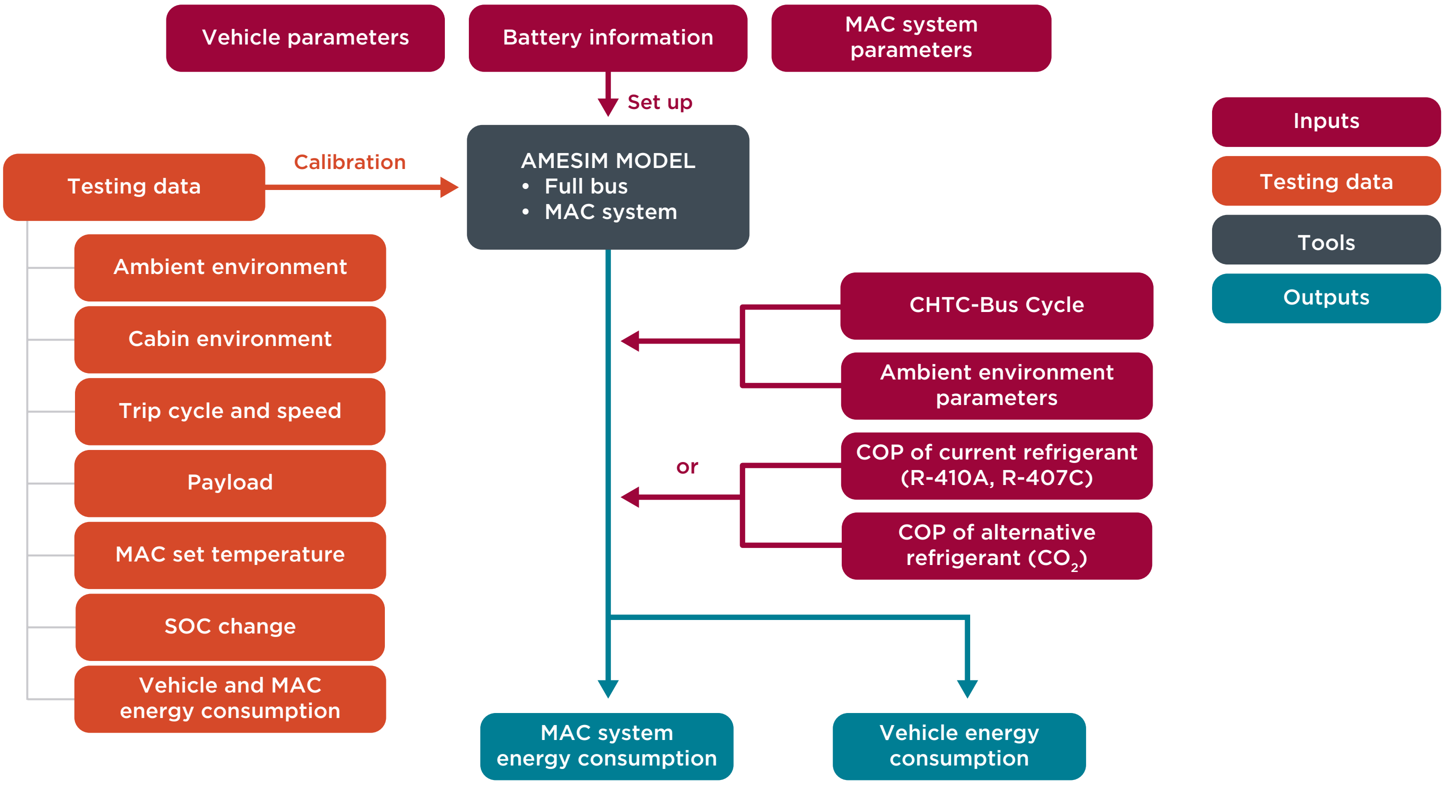

Figure 4. Mechanism of simulation in the model used in this study.

Table 2. Control strategy in simulation

	Ambient temperature (°C)	MAC set temperature (°C)
Heating	Lower than -10	16
	-10 to 0	17
	0 to 5	18
	5 to 15	20
	15 to 20	25
Cooling	25 to 36	26
	Higher than 35	28

Simulated power demand of a CO_2-based MAC system

The model shows that CO_2-based systems reduce MAC energy consumption compared with R410A- and R407C-based systems when used for heating (Figure 5). The power demand of a CO_2-based system is estimated to be 18.1 kW at -10 °C, 21% lower than the demand of an R407C-based system. Additionally, a CO_2-based MAC system performs well in a broader range of cold temperatures than the other systems and that reduces GHG emissions from auxiliary heating facilities as well. Our survey of local operators for this study found that auxiliary heating facilities are typically on board electric buses that operate in cold regions. A diesel-fueled PTC heater is generally applied as a substitute for an R410A-based heat pump when the ambient temperature is -5 °C and below.[1] Our simulation showed the diesel-fueled PTC heater increases the total power of the MAC system by approximately 14.5 kW at -10 °C. Meanwhile, a CO_2-based system can still be functional when the ambient temperature drops to as low as -20 °C or -25 °C (Song et al., 2021; X. Wang et al., 2023) and no auxiliary heating facilities are required.

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[1] A positive temperature coefficient heater, also known as a self-regulating heater, is an electrical resistance heater with resistance increasing by temperature.

In moderate ambient temperatures between 15 °C and 25 °C, the power demand for heating and cooling plummets and the average power demand from the MAC system is negligible, about 0.4 kW. Results also show that CO_2-based MAC systems reduce GHG emissions from cooling, but with constraints. In ambient temperatures under 35 °C, CO_2-based systems produce fewer GHG emissions than R407C- and R410A-based systems, but CO_2-based systems are inferior in terms of energy efficiency when the ambient temperature is higher than 35 °C. This is due to the physical properties of refrigerant CO_2, which cannot be liquefied above the critical temperature point (Linde GmbH, n.d.). In the extremely high ambient temperature of 40 °C, our estimates show that CO_2-based MAC systems are 28% and 34% less energy efficient than R410A- and R407C-based MAC systems (Figure 5).

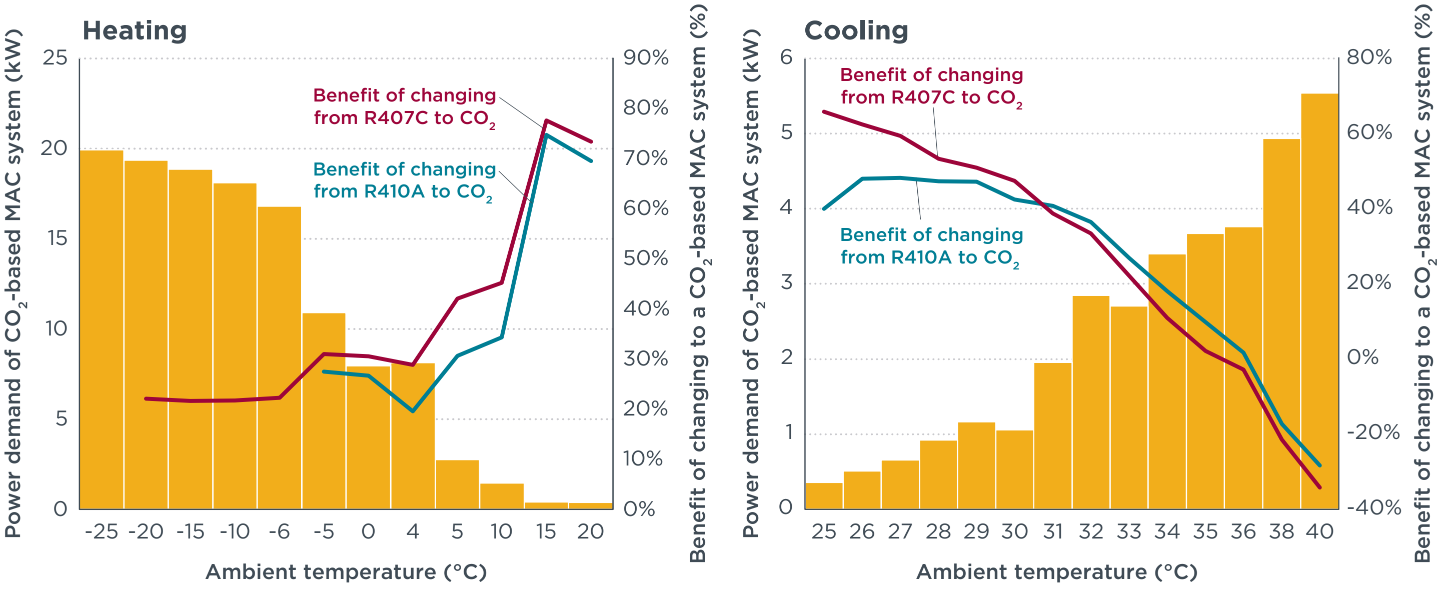

Figure 5. Simulated power demand of a CO_2-based MAC system (bars) and its decarbonization benefits compared to R410A and R407C systems (curves)

Appendix C contains more information about the power demands of MAC systems with various refrigerants on a typical 11 m long electric city transit bus operating in temperatures from -25 °C to 40 °C.

GHG emissions reduction potential based on regional promotion of CO_2-based systems

In this section, we consider the different climate patterns and geographical characteristics across China and estimate the potential GHG reduction benefits of CO_2-based MAC systems in electric bus fleets under different deployment scenarios. Figure 6 illustrates the scenarios to promote CO_2 technology in electric bus fleets in China. The scenarios are constructed based on temperature patterns in winter, as the MAC CO_2 technology provides more GHG emissions reduction benefits when used for heating. The scenarios are as follows:

» Scenario 1: 100% adoption of CO_2-based MAC systems in regions I, II, III, IV, and V

» Scenario 2: 100% adoption of CO_2-based MAC systems in regions I, II, III, IV, V, and VI

» Scenario 3: 100% adoption of CO_2-based MAC systems in all regions

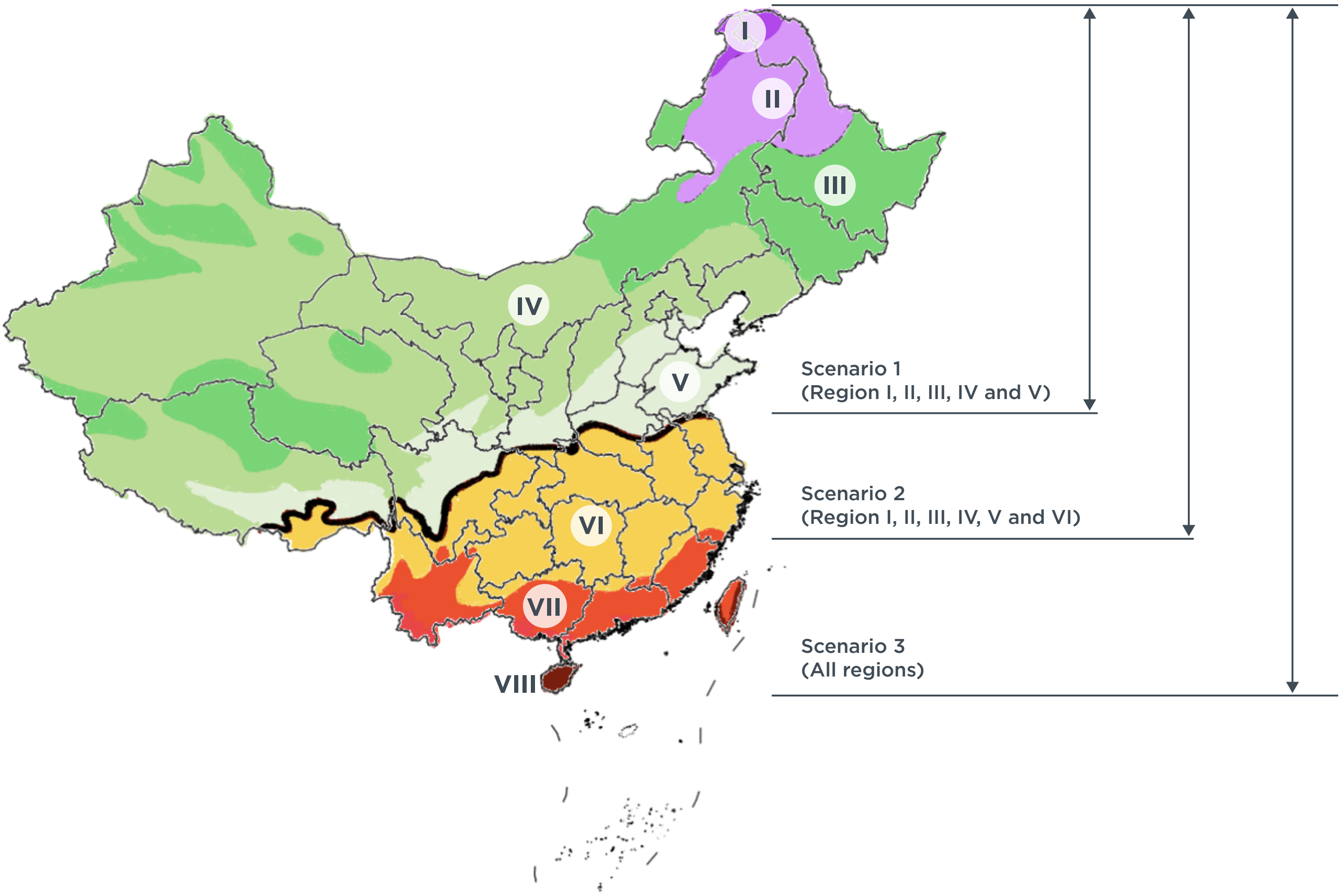

Figure 6. Scenarios of CO_2 MAC technology promotion generated by the authors using the geographical and climate information summarized by Xu (2017)

Several assumptions underpin this analysis. First, we adopted the same distribution of electric bus sales as in 2022, and all city-level sales data was aggregated to the regional level (listed in Table 3). Because China's electric bus market has been booming for years and most cities in China have adopted electric buses, the market structure is quickly consolidating around this technology (Mao et al., 2023). As a result, we assumed no major changes in the market shares between regions. Second, as there is little public information about the market share of refrigerants in buses, we interviewed experts to help understand. Based on our interviews, we assumed the market shares of R407C and R410A are each 50% in the current electric bus market and expect that CO_2-based technology could become the prevailing technology on electric buses in the coming years. Third, we assumed the bus models tested in this study are representative models of electric buses in China in terms of vehicle and MAC specifications, driving patterns, and more. A typical electric bus was assumed to operate for 60,000 km per year (Ministry of Ecology and Environment [MEE], 2015) and the CO_2 emissions rate from the grid electricity used to charge the battery was assumed as 0.5703 t CO_2/MWh (MEE, 2023). This study only focuses on the decarbonization potential of CO_2-based MAC systems during the promotion period.[2] Once the new technology is fully deployed, the total decarbonization effects can only be projected by considering the fleet size of electric buses, and such projections are beyond the scope of this study. Leakage is the source of direct GHG emissions from the electric bus fleet and we assumed that

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[2] The promotion period refers to the period during which the buses with current refrigerants are replaced by ones with CO_2-based systems.

the leakage rate of a typical electric bus is 20 g per year, based on a survey (China Automotive Technology and Research Center, 2022).

Table 3. Market shares of electric bus by region in 2022

Regions	I	II	III	IV	V	VI	VII	VIII
Percentage of electric bus sales	0.01	0.28	4.79	11.45	18.07	51.91	12.82	0.67

We found that a CO_2-based MAC system can save up to 99.9% of direct GHG emissions compared to currently deployed refrigerants, considering the high GWP values of R407C (GWP_{100yr} = 1,700) and R410A (GWP_{100yr} = 2,088). CO_2 is the only refrigerant applied in the CO_2-based system and it has a GWP value of 1 (Department of Climate Change, Energy, the Environment and Water, 2021; Mao et al., 2022).

Figure 7 illustrates the total GHG emissions reduction potential from the entire electric bus fleet compared with current technologies and the direct (leakage) and indirect (energy-saving) emissions benefits; a summary table with details of GHG reduction potential by scenario is in Appendix D. The simulation shows that 2.1% of total GHG emissions can be reduced by adopting CO_2-based MAC systems in Regions I to VI throughout the year. We estimate that greater decarbonization benefits can be realized if CO_2-based MAC systems are deployed in all regions of China: 5.5% of total GHG emissions can be saved from electric bus fleets every year. A total of 33,181 tonnes of CO_2e would be avoided by promoting of CO_2-based MAC systems in electric bus fleets across China for each year during the promotion period we modeled.

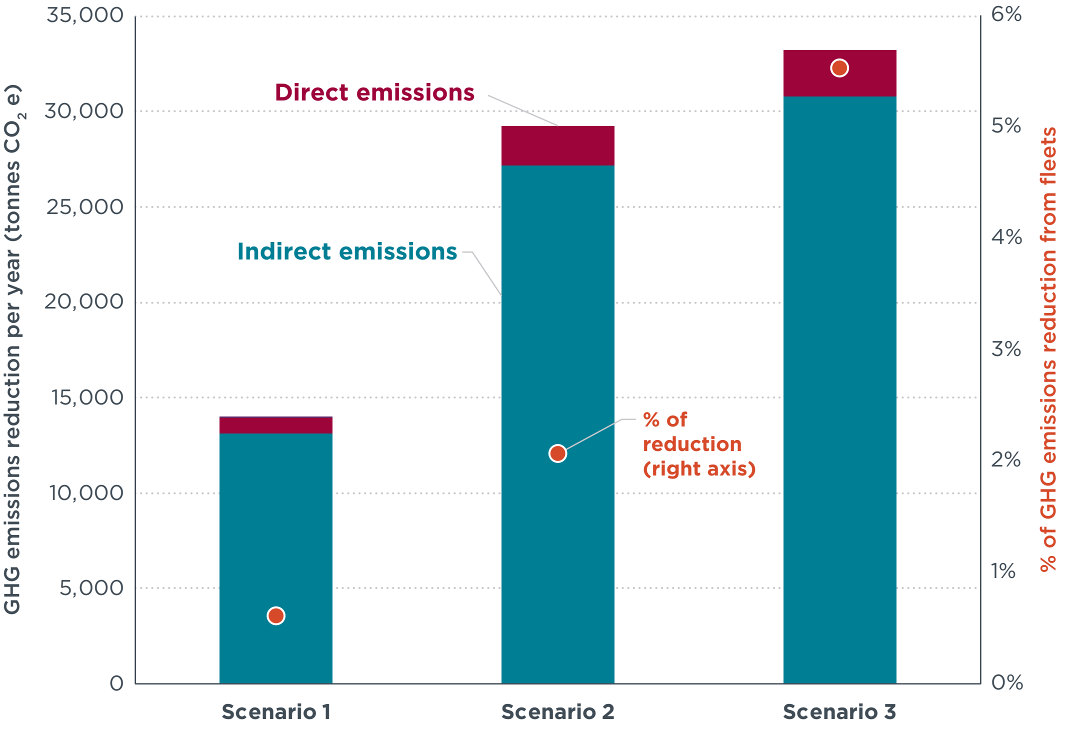

Figure 7. GHG emissions reductions by scenario

Conclusion and suggestions for policy

This paper showed that CO_2-based MAC technologies have the potential to decrease the total energy consumption of electric buses. We used an Amesim simulation model to estimate the GHG emissions reduction potential and found that deployment of CO_2-based MAC systems can avoid up to about 5.5% of the total GHG emissions from China's electric bus fleet every year, depending on geographic coverage. A few recommendations for China stem from this work:

- ***For the central government:*** **Consider including the energy performance of MAC systems in the vehicle type-approval procedure**. At present, China does not explicitly regulate the energy performance of MAC systems on electric buses. The energy performance of MAC systems is significantly impacted by working conditions such as temperature and humidity and this study found that MAC systems can consume up to 55% of the total energy consumption of electric buses (Appendix C). While this energy-intensive component is not well covered and reflected in the type-approval test procedure, the procedure underestimates the energy consumption of electric buses in hot and cold climates. Including MAC systems in the procedure can provide more accurate estimates of real-world energy consumption and range for fleet operators.
- ***For the central government:*** **Reward high-efficiency MAC systems with extra credits in the upcoming commercial vehicle carbon credit system**. A new credit system for new energy commercial vehicles, including electric buses, is expected to be proposed in the coming years and is a good opportunity to promote high-efficiency MAC systems by awarding them extra credits. Fleet operators and manufacturers that apply high-efficiency MAC systems can compensate for the extra costs by selling the credits to others. In earlier studies, the ICCT summarized information about different credit frameworks for vehicles in different markets (Yang, 2023; Yang et al., 2022). One of the most critical lessons learned from international practices is that the MAC credit system should be flexible and dynamic enough to evolve with technological progress. Fewer credits should be granted over time, and as the alternate refrigerants are applied more widely.
- ***For local authorities:*** **Investigate the cost-effectiveness of CO_2-based MAC systems at the province and city levels**. Electric buses with CO_2-based MAC systems can at present be more expensive than currently dominant technologies because of the need to retrofit the vehicle and update the structure of tubes, sensors, and controllers. This study found that cold regions benefit from CO_2-based systems in terms of GHG reduction potential, but we did not consider cost feasibility. Local fleet operators would likely want to consider the cost-effectiveness of CO_2-based MAC systems in real-world operations.
- ***For fleet operators:*** **Realizing the full GHG emissions reduction potential of a CO_2-based MAC system requires good driving habits and teaching drivers about energy-efficient driving**. The configuration of the MAC system, including how the cabin temperature is set, impacts the real-world energy consumption of electric buses. Fleet operators and industry associations could organize training for drivers to help them drive more efficiently.

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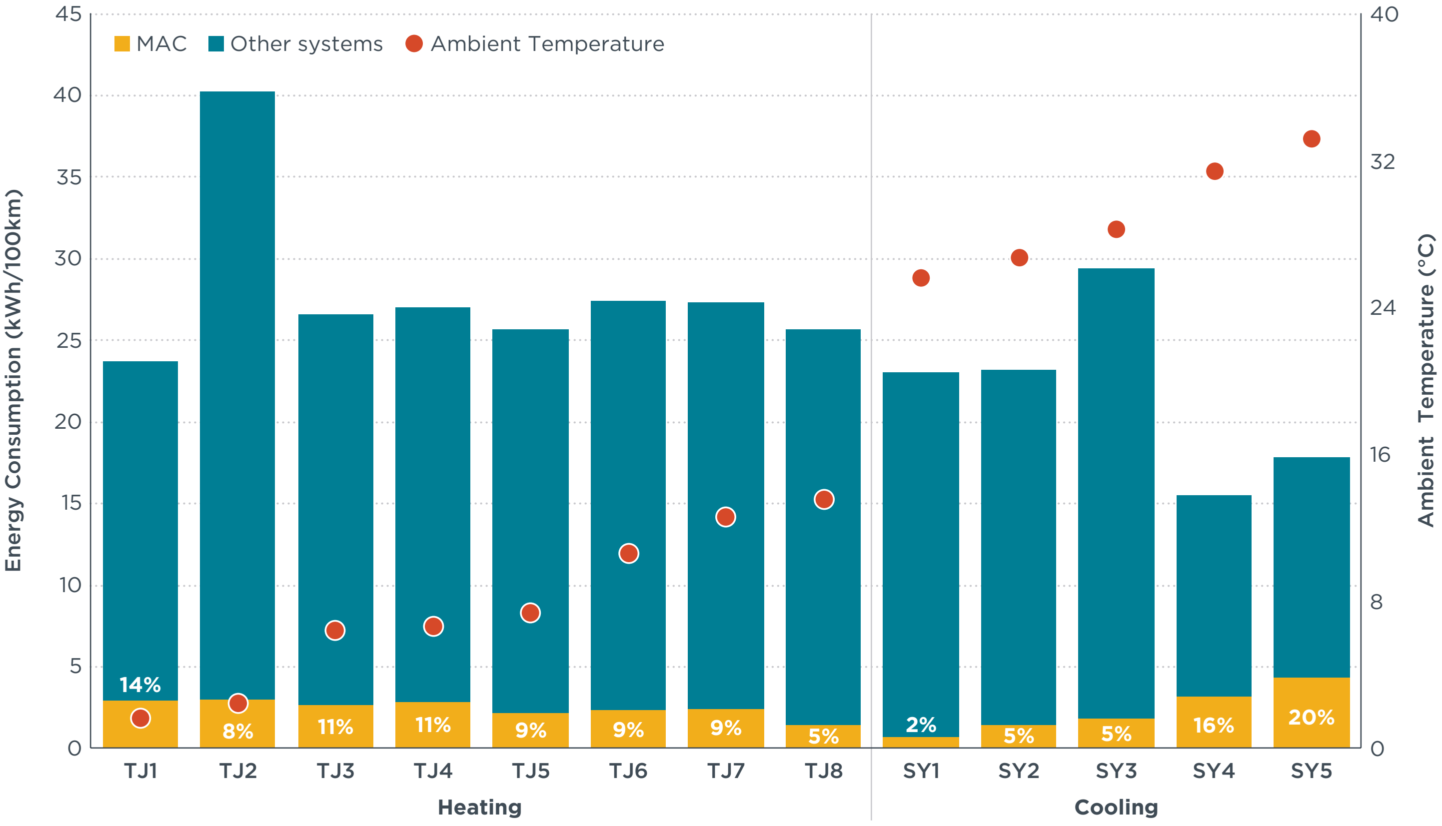
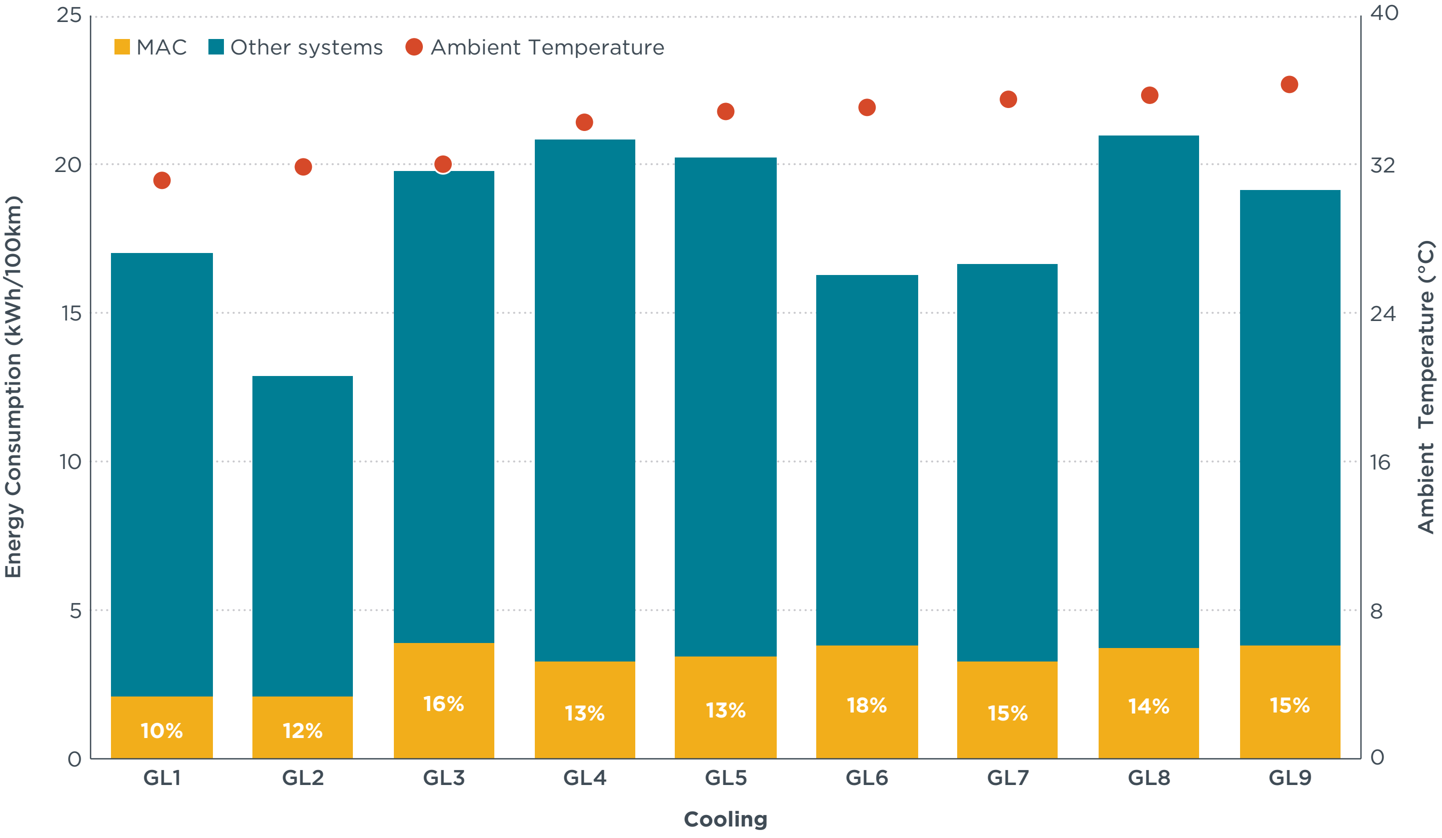
Appendix A. Details of our real-world data collection

No.	Items	Data types	Testing methods	Position of apparatus
1	Vehicle energy consumption	Voltage, current	Telematics	High-voltage cable for vehicle
2	AC system energy consumption	Voltage, current	Telematics	High-voltage cable for AC system
3	Driving	Speed, accelerator	GPS speedometer	Adhered to seat
4	Temperature	Int/exterior temperature	Digital thermometer	Adhered to seat and window
5	Cabin passengers	Door open interval	Timer	Manual
		Number of passengers	Manual counting and recording	—

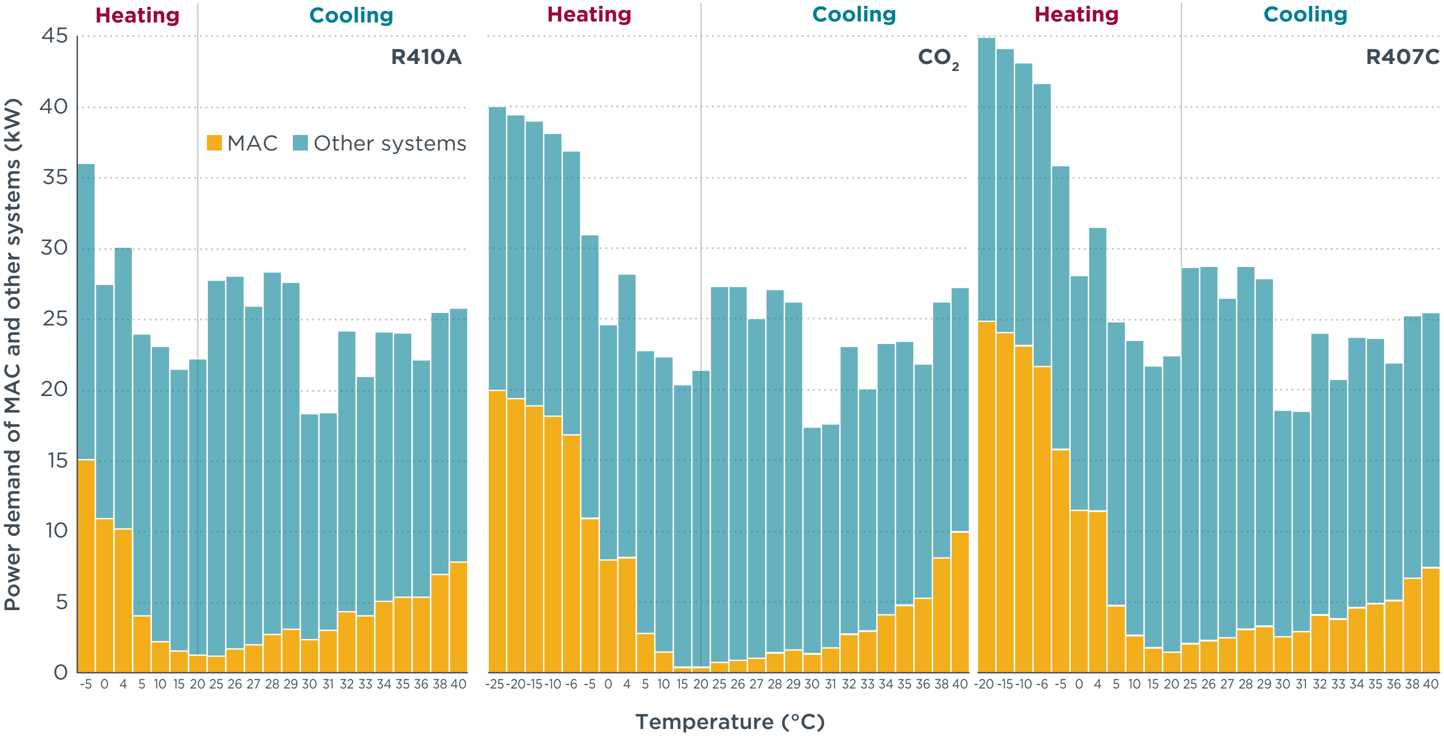
Appendix B. Real-world energy consumption of MAC systems from tests

In the figures below, each column depicts the power demand of the MAC system and other systems from one trip in one city, according to the test. For example, “TJ3” represents the third trip in Tianjin, “GL4” represents the fourth trip in Guilin and “SY5” illustrates the fifth trip in Sanya.





Appendix C. Power demand of different MAC systems by temperature



Appendix D. Details of the GHG emissions reduction potentials for each scenario

	Reduction potentials of GHG emissions from the entire bus fleet				
Scenarios	**Indirect emissions from heating (tonnes CO_2e)**	**Indirect emissions from cooling (tonnes CO_2e)**	**Direct emissions (tonnes CO_2e)**	**Total reduction (tonnes CO_2e)**	**Total reduction (%)**
Scenario 1	4,701.4	8,391.2	831.7	13,924.3	0.6%
Scenario 2	13,526.7	13,631.6	2,079.3	29,237.6	2.1%
Scenario 3	16,562.4	14,215.9	2,403.6	33,181.8	5.5%