Book

Sustainable transport solutions : low-carbon buses in the People's Republic of China

SUSTAINABLE TRANSPORT SOLUTIONS

Low-Carbon Buses in the People's Republic of China

NOVEMBER 2018

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ADB

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ISBN 978-92-9261-414-0 (print), 978-92-9261-415-7 (electronic)
Publication Stock No. TCS189646-2
DOI: http://dx.doi.org/10.22617/TCS189646-2

Notes:
In this publication, "$" refers to United States dollars.
ADB recognizes "China" as the People's Republic of China.
Corrigenda to ADB publications may be found at http://www.adb.org/publications/corrigenda.

Cover design by Jasper Lauzon.

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Foreword

Recent rapid growth in urban population and incomes in the People's Republic of China (PRC) has led to high car ownership, congestion, and air pollution. National and local governments have made the promotion of public transport a strategic priority, and increased efforts to provide flexible, low-cost, and efficient bus transport. Many cities have set ambitious targets for replacing and adding to existing bus fleets, and some have provided subsidies to bus operators to partly offset the high up-front capital costs of new vehicles. Recent severe air pollution events in the northern PRC are adding greater urgency to the replacement of older diesel bus fleets and the adoption of clean bus technology.

The Clean Bus Leasing (CBL) Program is an Asian Development Bank loan to the PRC to accelerate the deployment and diffusion of low-carbon buses (LCBs) and new energy buses. ADB's technical assistance project, Improving Clean Bus Operations and Management, was prepared to support the CBL for vehicle choice and for monitoring the operational performance of LCBs deployed. LCBs, which include hybrid, plug-in hybrid, and different types of electric buses, have been promoted widely in cities in the PRC; as of the end of 2017, more than 350,000 electric and plug-in hybrid buses were plying the streets of cities in the PRC.

The PRC has taken the lead in the deployment of LCBs and is moving toward full electrification of bus services. This publication presents the real-world performance data of different types of LCBs collected from 16 cities in the PRC. The study also discusses their environmental and financial impacts, as well as policies used in the promotion of LCBs in the PRC.

This publication is a result of extensive consultations with stakeholders and firsthand review of LCBs in the PRC. The findings are being used in designing two of the LCB-related projects that ADB is supporting in the PRC. The insights and recommendations presented here can be used by policy makers, bus company managers, and local governments who are interested in promoting LCBs, designing appropriate support policies, and choosing the appropriate bus type for their cities.

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Acknowledgments

This publication was based on the Global Environment Facility-financed technical assistance (TA) project of the Asian Development Bank (ADB), Improving Clean Bus Operations and Management. Susan Lim and Gloria Gerilla-Teknomo led and managed the TA. Robert Guild, former director, Transport and Communications Division, East Asia Department, ADB provided overall guidance and supervision.

The team of experts who prepared the TA report are Jürg Grütter (team leader), Alain Frecon, Agostinho Ferreira, Liyuan Gong, Li Song, Jian Wang, Li Liu, Yang Xinzheng, and Gao Huanan. We would like to express our sincere gratitude to the Transport Services Division, Ministry of Transport, Government of the People's Republic of China, for their support and guidance.

Special thanks to the peer reviewers Frederic Asseline, principal climate change specialist; Alfredo Bano, evaluation specialist; Manohari Gunawardhena, investment specialist; and Ki-joon Kim, principal transport specialist, ADB.

Currency Equivalents

(as of July 2018)

Currency Unit	–	Chinese yuan (CNY)
CNY1.00	=	$0.147
$1.00	=	CNY6.78

Abbreviations

ADB	Asian Development Bank
BEB	battery electric bus
BRT	bus rapid transit
CAPEX	capital expenditure
CN	national emission standard
CNG	compressed natural gas
FTA	Federal Transit Administration
GHG	greenhouse gas
GPS	global positioning system
GWP	global warming potential
ICCT	International Council on Clean Transportation
IPCC	Intergovernmental Panel on Climate Change
LCB	low-carbon bus
LNG	liquefied natural gas
LPG	liquefied petroleum gas
NEV	new energy vehicle
OPEX	operational expenditure
PM	particulate matter
PRC	People's Republic of China
SOC	state of charge
TCO	total cost of ownership
TTW	tank-to-wheel
UNFCCC	United Nations Framework Convention on Climate Change
WTW	well-to-wheel
WTT	well-to-tank

Weights and Measures

dB	decibel
gCO_2e/km	gram of carbon dioxide equivalent emission per kilometer
$kgCO_2e$	kilogram of carbon dioxide equivalent emission
kg	kilogram
km	kilometer
kW	kilowatt
kWh	kilowatt-hour
m	meter
MJ	megajoule

Executive Summary

Background

Urban air pollution and greenhouse gas (GHG) emissions constitute some of the world's most pressing environmental problems. Air quality is a growing concern in many urban environments, and has direct health impacts for residents.

Low-emission buses can help solve part of this problem. Low-carbon buses (LCBs), which include hybrid, plug-in hybrid, and different types of electric buses, have been promoted widely in cities in the People's Republic of China (PRC); as of the end of 2017, around 380,000 electric and plug-in hybrid buses were plying the streets of cities in the PRC. This report summarizes the experience of 16 cities in the PRC with an urban bus fleet of 70,000 units, and includes performance data on around 20,000 LCBs, of which nearly 10,000 are pure electric vehicles. The objective of this report is to show real world performance data on LCBs in the PRC, their environmental and financial impact, as well as policies used to promote LCBs. The report will help other cities and countries interested in promoting LCBs develop a realistic environmental and financial impact analysis, design appropriate support policies, and learn from experiences gained in the PRC.

Most cities in the PRC use natural gas buses. Fossil fuel-powered units comply with the national emission standards CN IV or CN V, which are largely equivalent to the European Union standard for the same category. The large majority of hybrid buses used in cities are standard 10–12 meter (m) buses, while 60% of battery electric buses (BEBs) are 6–8 m units and very few units are 14 m or articulated buses. BEBs are mostly used on shorter routes with less passenger demand compared with conventional buses. As of 2018, many cities in the PRC have stopped purchasing conventional fossil fuel-powered buses. The current fleet is composed of around 40% LCBs, of which around half are pure electric buses. Most cities are targeting a 100% LCB fleet within the next 2–3 years and many have as their goal a pure electric fleet by 2021. This publication presents the real-world performance data of different types of LCBs collected from 16 cities in the PRC and may not fully reflect the average national situation.

Low-Carbon Bus Technologies

Hybrid buses are a proven and reliable technology, and are also extensively used outside the PRC. They are available in all sizes and all fuel combinations (e.g., diesel–hybrid or gas–hybrid). In cities in the PRC, they save around 20% of fuel on average with an incremental 20% investment cost that is recovered from energy savings during the lifetime of the vehicle. Hybrids are basically used as intermediate technology toward full electrification, especially for larger buses and on long routes with a high passenger demand.

Plug-in hybrid buses are very popular in the PRC due to the phaseout of subsidies for standard hybrids. The main technical difference between plug-in hybrids and standard hybrids is that the former can be charged directly at the grid. However, operators in cities in the PRC never charge their plug-in hybrids at the grid due to their small battery size and the operational complexity of charging them. Thus, bus operators use them in the same manner as standard hybrids. In this context, plug-in hybrids have the same environmental and financial impact as a standard hybrid, while costing 20% more without subsidy. Therefore, the purchase of plug-in hybrid buses is not generally recommended due to their incremental cost and their limited additional value compared with standard hybrids.

Multiple types of electric buses are available in the PRC, including BEBs charged only overnight, BEBs charged overnight and fast charged during the day, opportunity charge electric buses charged at the end of routes or at stops along the route, and electric trolleybuses which can also operate without overhead wiring. The chosen system configuration influences the quantity of batteries onboard the bus (and therefore also its price), the charging infrastructure, the electricity price (which is dependent on when the bus was charged, and which power has been installed for chargers), and the operational management of buses. BEBs are best used on short- to medium-distance routes with buses up to 12 m, while opportunity charge systems and trolleybuses are best on heavy-demand and long routes with articulated buses.

Among the cities surveyed by the project team, the battery packs of BEBs are on average 210 kilowatt-hours (kWh) for 10–12 m buses (going as low as 100 kWh) and 120 kWh for 8 m buses. The approach generally used toward charging BEBs is overnight charging plus one or various fast charges of 15–30 minutes during the day using high-powered chargers of 150–400 kilowatts (kW). Battery-swap facilities have been abandoned due to very high costs. Opportunity charge systems have been installed in only a few cities and on selected routes. Electric trolleybuses with an autonomy range of 30–50 kilometers without overhead wiring are used in some cities, especially on bus rapid transit routes. Most battery manufacturers guarantee a battery state of charge of 80% for 8 years. Buses in the PRC are often replaced after 8 years, i.e., battery replacement coincides with bus renewal.

Bus operators need to optimize the electric bus system configuration for types of electric bus technologies, battery size, and charging technology. Parameters such as route distance, electric bus performance in the summer with air-conditioning usage, battery reserve rates, and battery capacity decline over time need to be taken into account to determine battery sizes of buses under different charging regimes. The optimal system configuration will depend on technical and route criteria, electricity prices including consumption and power charges, charging infrastructure, bus costs, and system flexibility and complexity. Choosing the most effective and cost-efficient electric bus is a far more complex procedure than choosing a diesel or gas bus, and most cities in the PRC have not realized this process in a stringent manner. This has basically resulted in buses with too small battery packs, and a larger number of BEBs than would have been required if system configuration had been done adequately.

Environmental Impact

Natural gas buses use around 17% more energy in terms of megajoules per kilometer than diesel units while electric buses use four times less energy than fossil fuel-powered units—clearly showing the efficiency of electric traction. Natural gas buses have no advantage compared to diesel units concerning well-to-wheel (WTW) GHG emissions. Fuel-cell hydrogen-powered vehicles have significantly higher WTW GHG emissions than diesel or natural gas buses in the PRC due to high electricity usage for hydrogen production using electrolysis or fossil gas if gasification is employed to produce hydrogen. Hybrid and plug-in hybrid buses save on average 20% fuel. BEBs are very sensitive to the usage of air-conditioning at high temperatures or heating during winter, which can result in a 50% increase in electricity consumption.

Electric vehicles have zero direct emissions. Considering GHGs, however, it is irrelevant if emissions are caused at the exhaust pipe or upstream due to energy production and transport/transmission. Electricity production in the PRC is still dominated by fossil-fueled power plants, resulting in an average national grid factor of 0.69 kilogram of carbon dioxide emission per kWh. Even with this fossil fuel-dominated grid, electric buses still reduce direct plus indirect or WTW GHG emissions by 30%–40%. However, the impact would be much larger if electricity would be produced primarily by renewables. Therefore, greening the grid is imperative in order to reap the GHG potential of electric buses. Even taking into account bus and battery manufacturing and disposal, electric buses still have significantly lower life cycle GHG emissions than conventional units, not least because they have a longer technical life span compared with conventional buses, and their batteries can be reused in stationary applications.

Local environmental impacts, including air pollution and noise impacts of electric buses, are important and very positive. However, in absolute terms, electric buses have a diminishing advantage as stringent emission standards also result in very low emissions of air pollutants (including nitrogen oxides and particulate matter) for fossil-powered buses. Therefore, electric buses only make a significant contribution toward improved air quality in countries and cities with vehicle emission standards Euro 4 or lower; in other countries, their contribution toward improving air quality is not decisive.

Financial Impact

Investment costs for buses vary between cities depending on bus specifications. Gas-powered buses have, on average, an incremental cost of less than 10% compared with diesel units. Hybrid buses result in an additional investment of 20%–25%; plug-in hybrids, 40%–50%; and BEBs, 100%–150%, compared with conventional fossil fuel units. However, subsidies as of 2016 fully cover all incremental costs of LCBs, and make their purchase less expensive than conventional buses.

The average investment cost for chargers is $150 per kW of power. Investment in electric charging infrastructure, including auxiliary electric equipment such as transformers, can amount to around $300–$350 per kW. In most cities, the charging infrastructure is financed, owned, and operated by third parties, which levy an average service fee of $0.05–$0.08 per kWh.

LCBs have higher investment costs but lower operational expenditures due to lower energy costs and, in the case of BEBs, lower maintenance costs. However, BEBs have a 20% higher tire usage which accounts for around 40% of the total bus maintenance costs. Conventional and hybrid units are within a comparable range of the total cost of ownership (TCO). In the PRC, BEBs have around 30% higher TCOs compared with conventional buses. The TCO of

BEBs would be comparable with conventional units if they were operated for 16 years, instead of 8 years (i.e., two battery cycles). Expected future oil price increases and lower battery costs (resulting in lower electric bus costs) will also help to reduce this gap and make electric buses financially competitive with conventional units.

Low-Carbon Bus Policies

LCBs have been promoted in the PRC since 2009 by the national, provincial, and city authorities through up-front purchase subsidies, which makes it cheaper to purchase LCBs than diesel or gas buses of the same size. These subsidies have resulted in a large uptake of hybrid and electric buses. Similar policies are found in many other countries. It has allowed for the breakthrough of the technology, and has effectively eliminated the barrier toward adoption of LCBs by bus operators. Subsidies are gradually being phased out (e.g., hybrids are no longer subsidized), and the target is to fully phase out subsidies by 2021 in the PRC.

Currently, subsidies are related to the length of the bus, electric driving range, bus efficiency, and bus technology used (e.g., whether it is opportunity charged or fast charged). However, subsidies are not technology- and size-neutral, and smaller buses with an intermediate battery pack are favored.

A series of interim rules put forward in February 2018 hold electric vehicle manufacturers responsible for the recovery of electric vehicle batteries. They are required to set up recycling channels and service outlets where old batteries can be collected, stored, and transferred to specialty recyclers. Together with battery makers and their sales units, electric vehicle manufacturers must also set up a "traceability" system that enables the identification of owners of discarded batteries. Battery makers are also encouraged to adopt standardized and easily dismantled product designs to help automate the recycling process. They must also provide technical training for vehicle makers to store and dismantle old batteries.

Future Challenges

As various cities in the PRC move toward full electrification of the bus fleet, they also face the following challenges: electrification of larger buses, identification of the appropriate bus and charging technology, usage of BEBs on longer routes, identification of the optimal battery pack on buses, and optimization of charging and bus technology to reduce energy costs.

Electric buses have a positive impact on reducing GHG emissions even in the context of a fossil fuel-dominated grid. However, further emission reductions in the PRC will only be possible if electricity production makes a greater shift toward renewables.

The subsidy for plug-in hybrids has not resulted in the desired environmental impact as plug-ins are not charged at the grid due to technical and operational issues. A further incentive of hybrid or plug-in hybrids is not recommended since hybrids are cost-effective, and favoring plug-in hybrids is not an effective policy.

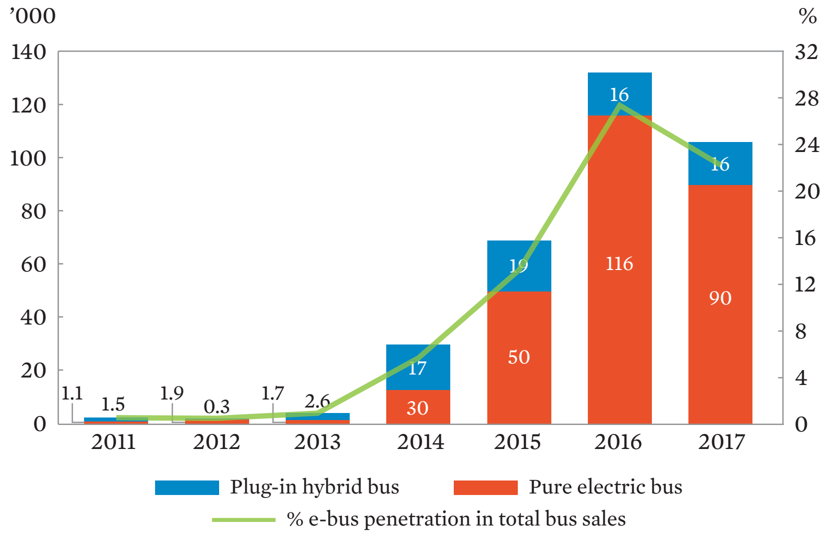
The BEB up-front subsidy policy has resulted in a large uptake of electric buses in the PRC. It has allowed for the breakthrough of the technology, and has effectively eliminated the barrier toward the adoption of electric buses by operators. With the incremental costs of BEBs slowly dropping, subsidy levels can be lowered.

The current policy is not technology- and size-neutral, but favors smaller buses with moderate to large battery sets. This can result in suboptimal technology and bus choice by bus operators. Also, high up-front subsidies potentially lead to a too large fleet and an underutilization of units, as reflected in BEBs in cities in the PRC running at only 50% of the average mileage of conventional buses. A more effective incentive scheme would be related to passenger per kilometer performance by electric buses as technology-, size-, and system-neutral, and incentivizing the use of electric buses in an adequate and cost-effective manner.

I. Introduction

Urban air pollution and greenhouse gas (GHG) emissions constitute some of the most pressing environmental problems. Air quality is a growing concern in many urban environments, and has direct health impacts for residents. Low-emission buses can help solve part of this problem. Low-carbon buses (LCBs), including hybrid, plug-in hybrid, and different types of electric buses (battery electric buses or BEBs, electric buses using opportunity charge systems, and electric trolleybuses) have been widely promoted in cities in the People's Republic of China (PRC).[1] In 2017, there were around 385,000 electric buses on the roads globally,[2] with 99% of the total located in the PRC.[3] In that same year, electric and plug-in hybrid buses made up 17% of the total bus fleet and 22% of total bus sales in the PRC (Figure 1).

Figure 1: Electric Bus Sales and Share of Total Bus Sales



Source: Bloomberg New Energy Finance. 2018. *Electric Buses in Cities: Driving Towards Cleaner Air and Lower CO_2*. https://data.bloomberglp.com/bnef/sites/14/2018/05/Electric-Buses-in-Cities-Report-BNEF-C40-Citi.pdf.

1 The term "new energy buses" is used in the PRC for plug-in hybrids, electric, and fuel cell buses.

2 Figure includes pure electric buses and plug-in hybrids.

3 Bloomberg New Energy Finance. 2018. *Electric Buses in Cities: Driving Towards Cleaner Air and Lower CO_2*. https://data.bloomberglp.com/bnef/sites/14/2018/05/Electric-Buses-in-Cities-Report-BNEF-C40-Citi.pdf.

In 2017, sales of BEBs dropped by 20% due to reduced national, provincial, and local governments' subsidies for new energy buses and tightened regulations concerning subsidy disbursements.

Therefore, the PRC has a unique experience with the operation of LCBs, their performance and impact, as well as challenges. This report summarizes the experience of 16 cities in the PRC with an urban bus fleet of 70,000 units in total, including performance data on around 20,000 LCBs, of which nearly 10,000 are pure electric vehicles. Data on LCBs is compared with data on conventional natural gas and diesel vehicles operating in the same city and on similar routes.[4]

The objective of this report is to show real world performance data on LCBs in the PRC, their environmental impact, financial performance, operational risks, and other issues. It also assesses policies used to promote LCBs in the PRC, and the critical points when moving toward 100% electrified bus operations. The report allows other cities and countries interested in promoting LCBs to realize a realistic environmental and financial impact analysis, design appropriate support policies, and learn from experiences gained in the PRC. The unique feature of the report is that its conclusions and recommendations are the results of actual performance data based on very large operational LCB fleets. Data was collected and analyzed in 2017 and 2018.

The report is structured as follows:

(i) Chapter II reviews the different LCB technologies.
(ii) Chapter III assesses the environmental impact of LCBs.
(iii) Chapter IV shows the financial performance of LCBs.
(iv) Chapter V describes the current LCB policy.
(v) Chapter VI looks at the challenges to moving toward a full electrification of bus operations.
(vi) Chapter VII draws conclusions and develops recommendations for LCB deployment.

The report also includes appendixes that describe the methodological approach used in further detail as well as provide additional data.

[4] The cities included in this study are Baoding, Beijing, Changde, Fuzhou, Guangzhou, Hengyang, Jinan, Linyi, Shanghai, Tengzhou, Tianjin, Xiangtan, Yan'an, Yangzhou, Yanzhou, and Zhunyi. For some cities (Beijing, Guangzhou, and Shanghai), data is based on one of various city bus operators. Additionally, some data from Zhengzhou was also considered.

II. Low-Carbon Bus Technologies

A. Overview

This report on low-carbon buses (LCBs) discusses hybrid, plug-in hybrid, and full electric buses, (i.e., new bus technologies which potentially reduce greenhouse gas [GHG] emissions).

Biofuel-powered buses were not included in this analysis as the bus technology itself is a conventional diesel or gas engine. Their environmental impact is purely related to fuel and depends on upstream emissions caused by the production of the biofuel, including land use change impacts.

Gas buses are considered as conventional units as they are purely fossil fuel-powered. Depending on the environmental standard, their pollution levels can be significantly lower than diesel buses, but their GHG impact is comparable with diesel units when taking into consideration the methane slip and upstream emissions related to fuel extraction, processing, and transport (see Chapter III for a comparison of the environmental impact of bus technologies).

A fuel cell electric vehicle uses a hydrogen fuel cell as the power source for the drive wheels, sometimes augmented with batteries or a supercapacitor. Like battery electric vehicles, these vehicles have zero tailpipe emissions, but potentially have emissions from the production and distribution of hydrogen. Hydrogen can be produced from various sources, including fossil fuels, biomass, and electrolysis of water with electricity. The environmental impact and energy efficiency of hydrogen depend on how it is produced. The most common forms are:

(i) **Natural gas reforming.** Synthesis gas, a mixture of hydrogen, carbon monoxide, and a small amount of carbon dioxide, is created by reacting natural gas with steam at a high temperature. Carbon monoxide is reacted with water to produce additional hydrogen. This method is the cheapest, most efficient, and most common.

(ii) **Electrolysis.** An electric current divides water into hydrogen and oxygen. Power-to-hydrogen projects are taking off, where excess renewable electricity, when it is available, is used to make hydrogen through electrolysis. Typically, in electrolysis, around 50 kilowatt-hours (kWh) of electricity are required to produce 1 kilogram (kg) of hydrogen.[5]

The average hydrogen consumption of buses[6] will result in 3–4 times more total electricity consumption than that of pure electric units, e.g., a 12 meter (m) hydrogen bus uses around

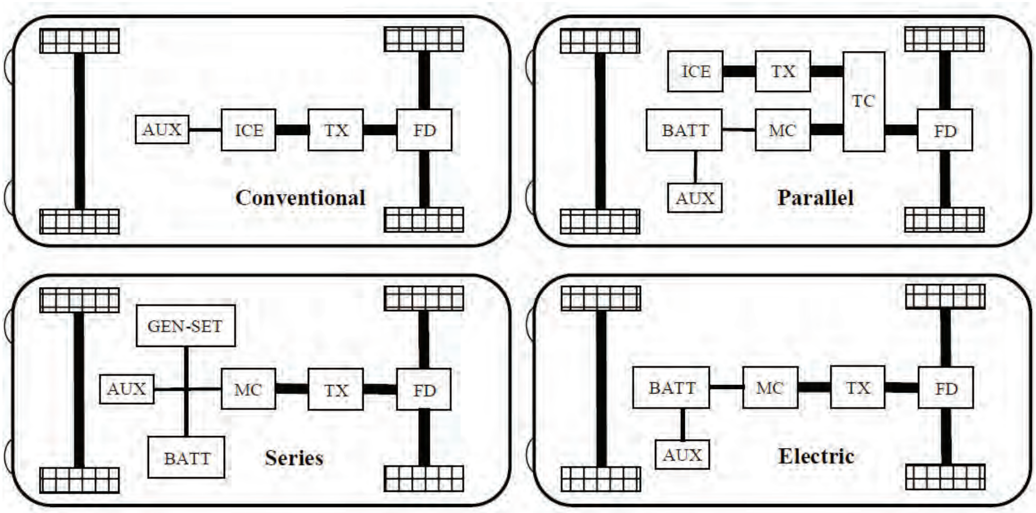
[5] F. Büchi, Paul Scherrer Institute. 2016. Trends und Potenziale der Brennstoffzellen-Entwicklung. Presentation at EMPA Akademie, Dübendorf. 26 January.

[6] Around 8 kg/100 km for a 12 m standard urban bus. See Clean Hydrogen in European Cities. 2016. London hydrogen buses and the Clean Hydrogen in European Cities Project. Presentation realized at All-Energy, May; and D. Wei. 2018. Sinohytec. Presentation realized at Urban Zero Emission Transportation Forum Beijing, 28 May.

4 kWh/km of electricity (including the production of hydrogen from electrolysis) compared to around 1–1.5 kWh/km for a battery electric bus (BEB). Thus, the resulting GHG well-to-wheel (WTW) emissions of hydrogen buses are far higher than those of diesel or gas units in the PRC, which have a largely fossil fuel grid. For a 12 m fuel cell bus in the PRC, WTW GHG emissions are in the order of 2,800 grams of carbon dioxide equivalent emission per kilometer (gCO_{2e}/km)[7] compared with 800 gCO_{2e}/km for an electric bus, and 1,100–1,200 gCO_{2e}/km for a fossil fuel unit.[8] Therefore, hydrogen buses have not been included in this report based on their negative GHG impact in the case of the PRC and the lack of practical experience with such units within the cities surveyed.

Figure 2 shows a system diagram comparing conventional with hybrid and electric buses.

Figure 2: System Diagram for Conventional, Hybrid, and Electric Buses



AUX = auxiliaries, BATT = battery, FD = final drive, GEN-SET = engine-generator, ICE = internal combustion engine, MC = motor/controller, TC = torque coupler, TX = transmission, conventional = standard diesel bus, electric = battery electric bus, parallel = parallel hybrid system, series = serial hybrid system.

Source: A. Lajunen. 2012. Evaluation of Battery Requirements for Hybrid and Electric City Buses. *World Electric Vehicle Journal*. Vol. 5.

B. Hybrid and Plug-in Hybrid Buses

Basically, types of hybrids include series and parallel hybrids as well as "mild" hybrids that use systems such as flywheels to recover braking energy. Fuel efficiency gains in hybrids are basically due to regenerative braking, shutting off the internal combustion engine during idling, and having two sources of onboard power, allowing the engine to operate at near peak efficiency more often. Reduced energy usage results in a proportional reduction of GHG emissions and of local pollutants. In terms of noise emissions, when leaving the bus stop,

[7] With the average grid factor of 0.7 kilogram of carbon dioxide equivalent emission per kilowatt-hour ($kgCO_{2e}$/kWh).

[8] All results based on WTW calculations; see for details Chapter III.C.2.

hybrid buses have approximately 3 decibels less noise compared with a diesel bus.[9] Multiple cities in the PRC have been operating diesel, compressed natural gas (CNG), liquefied natural gas (LNG), and liquefied petroleum gas (LPG)[10] hybrids for many years, where most of the units are 10–12 m buses. However, 8 m, 14 m, and 18 m hybrids are also plying the streets.

Plug-in hybrids have a larger battery than standard hybrids, and these can also be charged from an external power source. The key application of this is that they have the ability to run in an all-electric mode part of the time. The distance the bus can run on electric mode depends upon the characteristics of the route, charging frequency, and energy systems configuration. Standard or conventional hybrids run mostly on supercapacitors, while plug-in hybrids run on batteries.[11]

Thousands of plug-in hybrids in all sizes and with all types of fuel are operating in the PRC.[12] Operators no longer purchase conventional hybrids, only plug-in hybrids because only the latter qualify for subsidies. These plug-in hybrids are basically 10–12 m units with a 25 kWh battery. Recently, a few cities have received models with a larger battery size (40 kWh). Cities in the PRC generally use plug-in hybrids without charging them at the grid. (The following chapters discuss further the impacts and the reasons for this operation mode.)

10-meter, 18-meter, and 14-meter hybrid buses in Hengyang and Zhengzhou, People's Republic of China.
Source: Asian Development Bank.

C. Full Electric Buses

1. Typologies

The core components of electric vehicles are the powertrain, battery, and charging system. The battery set is obviously a key component for the electric vehicle range. However, there are different combinations of charging systems and battery packs, including direct overhead charging, opportunity fast and ultrafast charging, slow and fast charging, and battery-swap. The charging system and battery set configuration have large technical and financial implications (Figure 3).

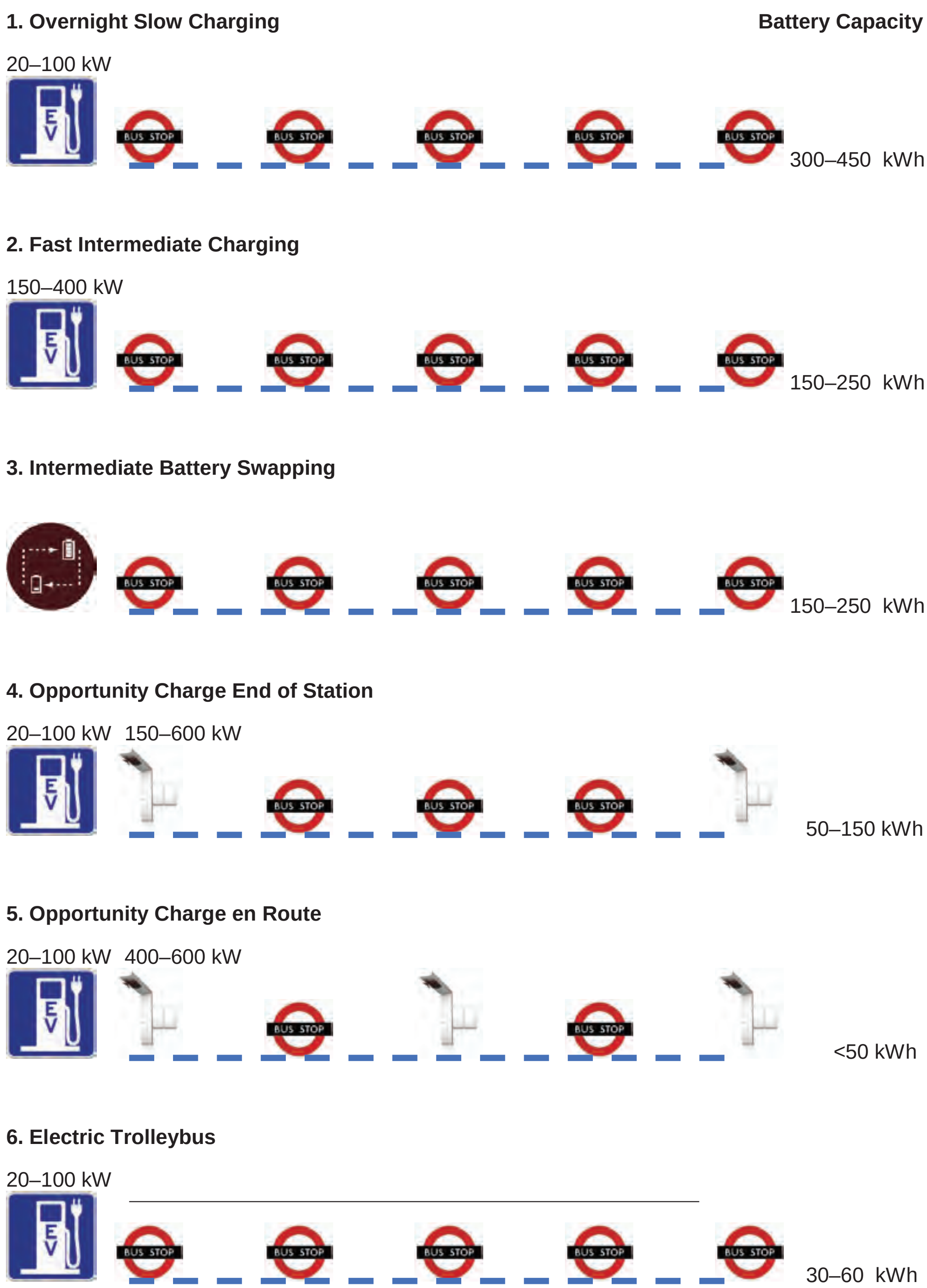
[9] Clean Fleets. 2014. *Clean Buses—Experiences with Fuel and Technology Options*. http://www.clean-fleets.eu/fileadmin/files/Clean_Buses_-_Experiences_with_Fuel_and_Technology_Options_2.1.pdf, p. 27; see also M. Faltenbacher. 2011. Abschlussbericht Plattform Innovative Antriebe Bus (Auftraggeber Bundesministerium für Verkehr, Bau und Stadtentwicklung), p. 71.

[10] Used in Guangzhou, PRC.

[11] Capacitors act as an energy store, like batteries. Classic capacitors can release a charge very quickly because they are electrostatic. Batteries rely on a chemical process, which evolves more slowly (i.e., batteries have a higher energy density, while capacitors can have a higher power density).

[12] Outside the PRC, large hybrid bus fleets composed of hundreds of units are operating in New York; London; and Bogota, Colombia.

Figure 3: Typologies of Full Electric Buses
(battery capacity for a standard 12-meter bus)



kW = kilowatt, kWh = kilowatt-hour.
Source: Asian Development Bank.

2 Battery Electric Buses

Characteristics of Battery Electric Buses

Large numbers of BEBs of multiple brands are operated in cities in the PRC. Many cities initiate electric bus operations with small 6–8 m BEBs and then progress to 10–12 m units. Some cities also manage electric double-deckers and 14 m electric buses. Generally, cities in the PRC do not realize pilots with small numbers of buses, but start operations with at least 50–100 units.

E-bus manufacturers in the PRC dominate the global market in terms of units sold. The top five manufacturers in terms of units sold in 2016[13] were Yutong with 19% of the market share in the PRC, followed by BYD, Zhontong, Nanjing Jinlong, and Zhuhai Yinlong.[14] Cities frequently buy from local manufacturers because provincial or city subsidies are linked to local manufacturers; also, it makes for simpler and faster maintenance and repair of units.

(From top left clockwise): Battery electric buses in Beijing, Jinan, Guangzhou, and Tianjin, People's Republic of China.

Source: Asian Development Bank.

Table 1 shows the average battery size of different BEBs as used predominantly in cities in the PRC. There is a large variety of battery capacities, and average battery capacities are relatively low due to buses running predominantly on shorter routes. Generally, bus operators in the PRC do not optimize the battery capacity of buses relative to route requirements or cost.

[13] Total production of all manufacturers is around 116,000 units.

[14] Bloomberg New Energy Finance, p. 6.

Table 1: Average Battery Size of Battery Electric Buses in the People's Republic of China

Bus Length	6 Meters	8 Meters	10–12 Meters
Battery capacity	60–140 kWh with majority 60 kWh	90–240 kWh with majority 120 kWh	100–330 kWh with majority 210 kWh

kWh = kilowatt-hour.

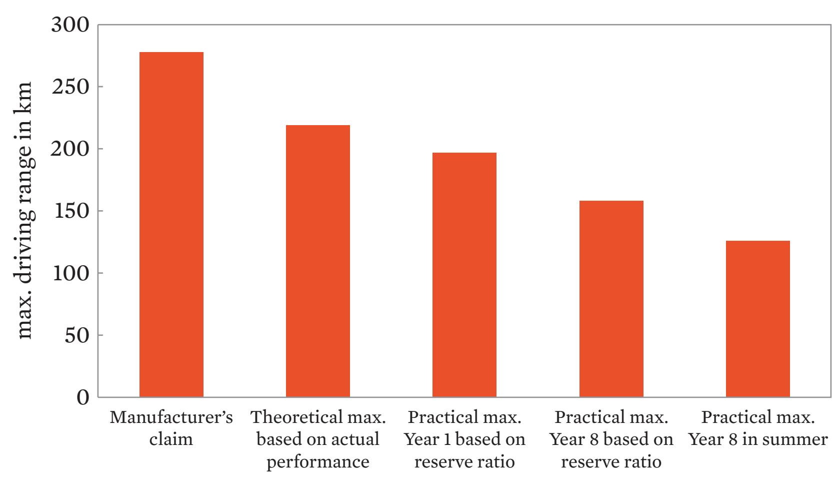
Source: Asian Development Bank, based on data on cities in the People's Republic of China.

No operator has made any recent reports on significant safety issues with batteries and overheating. In the early years, although some buses caught fire due to the batteries overheating, this problem now very seldom occurs, and not more frequently than with conventional fossil fuel-powered buses. Cases where batteries overheated, resulting in damage or even fires, are clearly limited to only a few occasions.

Driving Range of Battery Electric Buses

The electric driving range is an important criterion when determining BEB specifications. The simplified calculation of a battery pack divided by average electricity consumption can result, thereby, in misleading driving range expectations as Figure 4 shows.

Figure 4: Driving Range of Battery Electric Buses



BEB = battery electric bus, km = kilometer, kWh = kilowatt-hour, m = meter, max = maximum, SOC = state of charge.

Note: This shows the maximum driving range of 12 m BEBs with a 250 kWh battery pack, based on the average electricity usage of 12 m BEBs of 1.14 kWh, manufacturer-claimed performance rate of 0.9 kWh/km, summer energy usage of an additional 25% to the average, 80% SOC of batteries in year 8, and 10% minimum reserve ratio (for operational safety reasons).

Source: Asian Development Bank.

While manufacturers claim a driving range of 280 km with a battery pack of 250 kWh, the actual operational range is often only 200 km in year 1 (less during summer months), and can drop to 130 km in year 8 during summer. This means that the bus will not be able to operate on the routes as expected or will require more frequent recharging during the day, which might not be operationally feasible. The actual driving range and the claimed theoretical driving range can be a factor of 2 apart due to:

(i) The real-world performance of BEBs is worse than that claimed by manufacturers.
(ii) The required reserve ratio is at least 10%, as the bus cannot be operated until the battery is drained. Also, many buses are equipped with a low precision state of charge (SOC) indicator for drivers, making it risky to continue operations with low SOC levels.
(iii) The SOC of the battery drops over time. As of 2018, manufacturers typically guarantee a SOC of 80% in year 8 (i.e., in year 8, the batteries will be able to retain 80% of original energy amount even if fully loaded).
(iv) BEBs use significantly more energy when air-conditioning or heating is turned on or under extreme driving conditions (steep gradients, high speed). The difference between energy usage with and without air-conditioning can be 30%–40%. The operator will want to provide the same level of service when the air-conditioning is used and, therefore, must realize calculations not based on average energy consumption levels but based on the highest expected levels for the summer or winter months.

Therefore, to purchase the most appropriate BEBs, the bus operator must determine the working day average mileage per bus, the energy usage in summer or winter, include a reserve ratio and a lower SOC of the battery in 5–8 years, and then calculate the minimum required battery pack. At the next stage, the operator can then decide if buses should be charged only during the night or equipped with smaller battery sets, but with intermediate fast charging. However, the majority of cities in the PRC do not realize such a systematic procedure to determine the BEB configuration, but rely on recommendations of bus manufacturers, which are influenced by subsidy policies. In many cases, the result is that BEBs with too small battery sets require more frequent intermediate charging, causing potential operational disruptions, and many cities end up operating 20%–30% more electric buses than the number of conventional units used on the same route to cope with a reduced driving range.

Charging Facilities

Today, most cities employ a mixture of slow charging at night with one or various fast charges during the day. Since 2012, battery swap stations were established in various cities, including Beijing, Jinan, Tianjin, and Zhengzhou. Instead of charging the batteries in the bus, the batteries are removed by robots and replaced with new units in a process that takes around 10–20 minutes. Battery swap stations are very expensive and few in number, buses must return to the stations, systems are not standardized, and, thus, operators are locked-in with certain bus types and manufacturers, and a large amount of batteries is required.[15] Therefore, cities have abandoned this approach in favor of fast-charging systems that have lower investment and operating costs, and are far more flexible.

[15] Both the bus as well as the battery swap station need to have batteries.

Battery swap station in Zhengzhou, People's Republic of China.
Source: Asian Development Bank.

Many cities not only fast charge BEBs during the day, but also at night as they lack space to charge at their depots; thus, they charge the buses in rotation at special charging facilities. Charging at night is predominantly due to a night tariff that is, on average, 50% lower than the off-peak, and 70% lower than the peak tariff. Charging stations are mostly owned and operated by third parties that demand a service fee from bus operators.

Typically, slow chargers have a power rating of 50–100 kW, and fast chargers 150–400 kW, with the majority being between 100–200 kW, which allows buses to be recharged in 15–30 minutes.[16] Chargers normally come with two nozzles that are used either for the same bus or for two different units. Also, many chargers have a variable power output, and some automatically recognize the bus being charged and are able to deliver the correct power level. Generally, buses are charged manually, unlike in Europe where some operators opt for automated night charging using pantographs, thus saving on staff. Moreover, opportunity or end-of-route inductive charging or with the use of pantographs is popular in Europe, while such systems are rare in the PRC.

Chargers for battery electric buses in Tianjin (left) and Zhunyi (right), People's Republic of China.
Source: Asian Development Bank.

[16] Most buses enter charging stations during the day with a 30%–40% SOC and leave stations with a 80%–90% SOC.

There are many variations to the number of buses per charger, depending on the charging power used and the battery capacity of buses. The range is from 1.5 buses up to 10 buses per charger. However, most cities use a bus–charger relation of around three buses per charger. Using 400 kW chargers instead of 100 kW reduces the charging time by a factor of 4 and, thus, can considerably increase the number of buses per charger. However, it will also require moving buses around more as the charging sites can only be used as parking spaces for the charging period.

3. Opportunity Charge Systems

An opportunity charge system is a special form of fast or ultrafast charging that takes place at the end of the route or at regular bus stops along the route. Plug-in hybrids as well as BEBs can be used with such systems. Buses can be equipped with minimal batteries or capacitors. More infrastructure investment is required with such systems, while capital expenditure (CAPEX) on buses is reduced because fewer batteries are required. It also resolves the issue of driving range. However, the system reduces operational flexibility, as buses need to operate on equipped routes. Opportunity charge systems are not yet widely used in the PRC, and are far more popular in Europe. They are an interesting option for routes with a heavy demand such as bus rapid transit (BRT) routes, especially those where large buses operate.

Opportunity Charging End-of-Route

Fast charging can either be done manually or with pantographs at the end of the route typically with the use of 150–400 kW chargers. Basically, the reasons for using pantographs instead of manual charging are to save on staff costs and to simplify operations.

Since early 2018, Shanghai has operated on a 20 km BRT route an opportunity charge system with 25 12 m and 10 18 m BEBs with four 350 kW chargers with pantographs at one end of the route. The 12 m buses have 110 kWh batteries onboard, while the 18 m units have 140 kWh batteries onboard, which allow them to operate 2–3 turnarounds prior to recharging at the end of the route. Opportunity charge buses have one-third of the standard battery size compared with standard BEBs of the same size operated by the same company.

The city of Hengyang installed six fast chargers with a power capacity of 360 kW serving 8–10 m buses at the starting point of various bus routes. Each charger has two nozzles allowing for, in total, 12 buses to be charged simultaneously while awaiting their next deployment. Charging is done manually, and charging posts are around 20 m before the departure station.

Charging station end-of-route for battery electric buses in the city of Hengyang, People's Republic of China.
Source: Asian Development Bank

Opportunity Charge En Route

Opportunity charge en route systems charge buses at various bus stops inductively or through pantographs while taking on new passengers. Ultrafast high-powered charging occurs with chargers having up to 600 kW and charging times of 10–40 seconds. Systems are operated with 12 m as well as 18 m buses, with some systems charging buses equipped with supercapacitors and driving ranges of 5–10 km (i.e., charging is performed every second or third station such as with the system in the city of Ningbo). Supercapacitors can receive up to a million charges even under high temperatures, thus making their lifetime significantly longer than that of batteries.

Since 2010, Shanghai has operated an opportunity charge system with around 200 12 m buses. While charging is possible at most of the stations, in practice it was observed that buses basically charge at the end of the route. Intermediate stations are often blocked with cars or people and the stopping time to pick up passengers is often less than 15 seconds, thus charging the bus is not possible. The original buses only had supercapacitors and had operational problems due to the issues described above; the newer buses have supercapacitors as well as batteries onboard, giving them more flexibility on when to charge.

Many en route opportunity charge systems are being established in Europe with large buses (articulated and bi-articulated units) on high-frequency routes with a high passenger demand (e.g., Geneva and Nantes).

Opportunity charge system for battery electric buses in Shanghai, People's Republic of China.
Source: Asian Development Bank.

4. Electric Trolleybuses

Trolleybuses operate as 12 m and 18 m units in various cities. Without catenaries, they have a limited range of operation; but these can be expanded with the battery incorporated in the trolleybus. Electric trolleybuses typically have batteries of 40–120 kWh, allowing for an autonomy range of 20–50 km without a catenary.

12-meter trolleybuses in the cities of Beijing and Jinan, People's Republic of China.
Source: Asian Development Bank.

Various cities in the PRC, including Shanghai and Jinan, are constructing new trolleybus lines. The advantage of trolleybuses is that they do not have problems with range or issues with steep slopes, nor are they affected by very cold or very hot climates. They have a long life span, lighter, and more passenger space due to the small battery pack onboard. Also, modern systems do not require overhead wiring along the entire route, making systems less expensive and more flexible. However, there are significant infrastructure costs for the installation of overhead wires and required electric systems, which can range from $0.7 million to $1.7 million per km.

5. System Choice for Electric Buses

Choosing the best system depends on electricity and demand charge prices (including the difference between night, peak, and off-peak fees); vehicle and battery prices; cost of charging infrastructure; and characteristics specific to the route including daily mileage, bus size, bus frequency, and passenger demand. However, note the following general observations concerning the deployment of electric buses:

(i) BEBs with overnight charging plus fast day charging for units running on longer routes are good solutions for small and standard buses up to 12 m operating on routes with low to medium passenger demand.
(ii) Opportunity charge and trolleybus systems are good solutions for BRT routes operating with large units and at high frequencies. On such routes, a large amount of buses can use the same infrastructure, making this approach less costly.
(iii) Battery swap facilities are not recommended solutions due to their high cost and system rigidity.

Table 2 summarizes the pros and cons of different charging technologies.

Table 2: Charging Systems and Battery Packs of Electric Vehicles

Charging System	Advantages	Disadvantages
Overhead wiring (trolleybus)	Minimum battery amount on vehicle thus reducing vehicle weight, space required for batteries, and vehicle cost. Simple battery management system.	High infrastructure cost and limited route flexibility; electricity cost can be higher due to peak and off-peak day electricity consumption; high power requirements on the electric grid and high demand charge.[a]
Opportunity charging including ultrafast charging	Small to minimum battery amount on vehicle thus reducing vehicle weight, space required for batteries, and vehicle cost.	High infrastructure cost and limited route flexibility; electricity cost can be higher due to peak and off-peak day electricity consumption; high power requirements on the electric grid and high demand charge, but this can eventually be avoided with peak shaving.[b]
Fast charging	Increased vehicle range with lower battery quantity, thus reducing vehicle weight and cost.	Increased investment in chargers; higher electricity consumption charges are due to usage of day electricity; potentially high electricity demand charge.
Slow overnight charging	Minimum investment in charging, simple to manage, and usage of low-cost night electricity.	If this is the only charging approach used, then the vehicle will require a large battery set to have sufficient driving range, making the vehicle costly and heavy.
Battery swap	Less battery requirements on the bus if sufficient battery swap stations are available nearby.	Requires costly infrastructure and a larger amount of batteries in total; limited flexibility as battery swap systems are tied to vehicle brands.

[a] A demand charge is a fee based on the highest rate, measured in kilowatt, at which electricity is drawn during any 15- to 30-minute interval in the monthly billing period. This is separate from the charge paid for the actual energy consumed, which is measured in kilowatt-hour.

[b] On-site batteries can charge and discharge using direct current and connect to the grid through a large inverter. They can then charge from the grid at times when costs are lower, store the power, and release it when demand is higher. Through this, they can also level out the power demand posed on the grid and reduce the demand charge.

Source: Asian Development Bank.

6. Summary Comparison of Low-Carbon Bus Technologies

Table 3 lists the main advantages and disadvantages of LCB technologies.

Table 3: Technology Comparison of Low-Carbon Buses

LCB Type	Advantages	Disadvantages	Application
Hybrids	Proven and highly reliable technology; low incremental cost; 20% energy savings and lower emissions	Limited environmental impact; two traction technologies onboard	Intermediate technology toward full electrification, especially for large buses and very long routes
Plug-in hybrids	If recharged, the electric drive range can be up to 60%, thus resulting in significant environmental gains	Operationally complex to recharge; high incremental cost of buses; in practice, limited advantages compared with the hybrid bus	Not recommended in general as it has limited environmental gains with high incremental costs
BEBs with overnight charging	Simple operations; good reliability; high environmental impact; low electricity cost	Large incremental bus cost; requires very large battery sets for buses longer than 12 m and buses operating on long routes	Buses up to 12 m operating on short and standard routes
BEBs with overnight, plus fast day charging	Good reliability; high environmental impact; lower incremental cost than BEBs with pure overnight charging	Operationally more complex compared to only night charging; higher electricity cost compared with BEBs that require pure overnight charging	Buses up to 12 m operating on short and standard routes
Opportunity-charged electric buses	Automated charging; option to use very large buses with very small battery sets; lower investment cost in buses compared with BEBs	Limited experience with systems; higher investment costs in charging infrastructure; higher electricity price than for overnight-charged BEBs	12 m and larger buses operating on routes with a high passenger demand and frequency
Electric trolleybus	Proven and reliable system, lower investment cost in buses compared with BEBs	Some systems do not connect buses automatically and quickly to overhead wires, making them cumbersome; high infrastructure cost	12 m and larger buses operating on routes with high passenger demand and frequency

BEB = battery electric bus, LBC = low-carbon buses, m = meter.

Source: Asian Development Bank.

III. Environmental Performance of Low-Carbon Buses

A. Introduction

Emissions considered in this report are basically tailpipe emissions (direct or tank-to-wheel [TTW] emissions) and energy usage-related indirect emissions (well-to-tank [WTT] emissions). Black carbon emissions are included under indirect emissions. Upstream and downstream emissions caused by the manufacture of buses and their components, including batteries, as well as non-combustion-related emissions, are briefly discussed below.

Vehicle and Component Missions

Estimates of greenhouse gas (GHG) emissions caused by the production of batteries vary considerably with values ranging from 56 $kgCO_{2e}$/kWh to 494 $kgCO_{2e}$/kWh, with an average of 110 $kgCO_{2e}$/kWh.[17] Thus, a battery electric bus (BEB) with a battery set of 210 kilowatt-hours (kWh) would have additional indirect emissions of around 48 gCO_{2e}/km. The relevance of GHG emissions caused by battery production, and their impact when comparing electric versus diesel buses, are reduced by the fact that batteries can be used for stationary applications after terminating their useful life span on buses and that BEBs have a longer technical life span than fossil fuel buses due to less vibrations and moving parts. Figure 5 compares the life cycle emissions of a diesel bus, and a BEB, clearly showing that, while battery and vehicle production-related emissions are important, they are far lower than operational emissions. Thus, electric units clearly have lower total life cycle emissions than diesel units.

Non-Combustion Emissions of Local Pollutants

Buses not only have combustion emissions but also particulate matter (PM) emissions from brake, tire, and particle resuspension. Measurements of PM_{10} in the city of Zurich, Switzerland in 2007, for example, showed that PM emissions from heavy-duty vehicles in urban areas were 16% brake-related, 53% resuspension-related, and only 31% combustion-related.[18] In urban settings, measurements made by the Transport Research Laboratory,[19] the California Environmental Protection Agency Air Resources Board,[20] and the European Environment

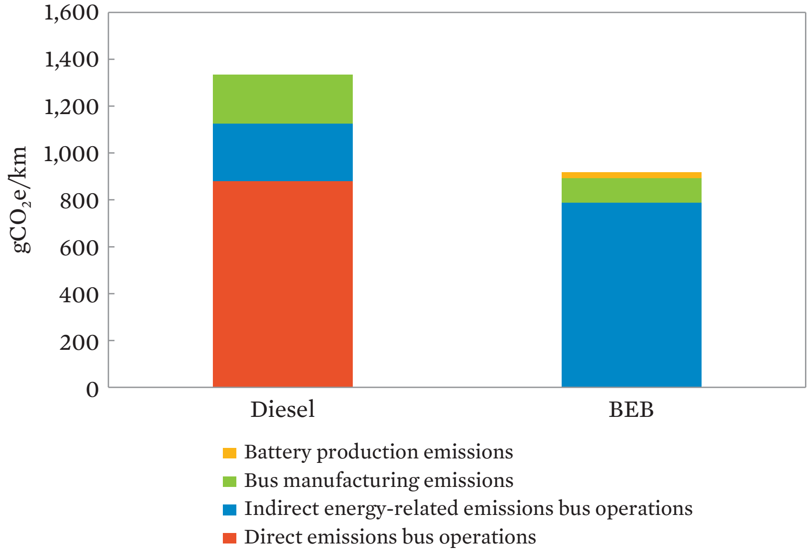
[17] International Council on Clean Transportation. 2018. *Effects of Battery Manufacturing on Electric Vehicle Life Cycle Greenhouse Gas Emissions*. https://www.theicct.org/publications/EV-battery-manufacturing-emissions.

[18] Bundesamt für Umwelt (BAFU). 2009. *PM-10 Emissionsfaktoren von Abriebspartikeln des Strassenverkehrs (APART)*. http://www.transport-research.info/sites/default/files/project/documents/20150710_141622_66365_priloha_radek_1052.pdf.

[19] Transport Research Laboratory. 2014. Briefing Paper on Non-Exhaust Particulate Emissions from Road Transport. http://www.lowemissionstrategies.org/downloads/Jan15/Non_Exhaust_Particles11.pdf.

[20] California Environmental Protection Agency Air Resources Board (CARB). 2015. EMFAC 2014 Volume III—Technical Documentation. https://www.arb.ca.gov/msei/downloads/emfac2014/emfac2014-vol3-technical-documentation-052015.pdf.

Figure 5: Life Cycle Emissions for Diesel Buses versus Battery Electric Buses



BEB = battery electric bus, CN = China national emission standard, gCO_{2e}/km = gram of carbon dioxide equivalent per km, km = kilometer, kWh = kilowatt-hour, l = liter, tCO_{2e} = tons of carbon dioxide equivalent.

Notes: For a standard urban 12-meter bus in the People's Republic of China.

Diesel bus 33 l/100 km CN V standard; BEB 1.14 kWh/km; grid factor 0.69 $kgCO_2/kWh$; 60,000 km per annum; indirect emissions also include black carbon; 8 years life span for diesel and 16 years for BEB; batteries 8 years life span; battery usage on stationary applications another 8 years; vehicle manufacturing 100 tCO_{2e} based on Ecoinvent and Mobitool; battery production 0.23gCO_{2e}/kWh; battery size 210 kWh.

Source: Asian Development Bank.

Agency[21] all estimate that $PM_{2.5}$ emissions from braking and tires of heavy-duty vehicles, which comply with the European emission standard Euro IV, Euro V, or Euro VI, are higher than emissions resulting from combustion. However, no data comparing non-combustion emissions of LCBs with conventional units are available. Presumably, LCBs have lower brake abrasion emissions due to the usage of regenerative braking, but have higher tire-based emissions (especially BEBs have a higher tire usage) and potentially have a slightly higher resuspension emission level due to increased vehicle weight. Cumulatively, LCBs are expected to have lower non-combustion emissions due to the dominance of brake abrasion emissions.

B. Energy Usage of Low-Carbon Buses

Energy usage per bus for all cities was recorded for the entire year 2016. All buses used air-conditioning; in some cities, heating was used during winter. Table 4 shows the median consumption values for different bus sizes and fuel types. The numbers are based on at least 500 buses for each size and the technology used.

[21] European Monitoring and Evaluation Programme/European Environment Agency. 2016. *Corinair Emission Inventory Guidebook*. https://www.eea.europa.eu/publications/emep-eea-guidebook-2016.

Table 4: Energy Usage of Buses, 2016

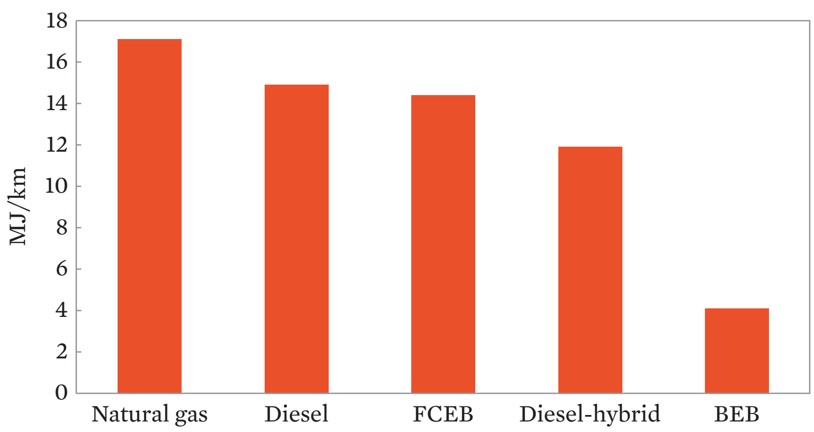
Bus Technology	Unit	Bus Length					
		6 m	8 m	10 m	12 m	14 m	18 m
Diesel	l/100 km	15	23	32	33	45	49
Natural gas[a]	kg/100 km	17	24	28	28	41	46
Trolleybus	kWh/km	n.a.	n.a.	n.a.	1.26	n.a.	n.a.
BEB	kWh/km	0.56	0.65	0.80	1.14	n.a.	n.a.

BEB = battery electric bus; kWh = kilowatt-hour; km = kilometer; kg = kilogram; l = liter; m = meter; n.a. = not applicable, i.e., no vehicles of this size and technology operate in the cities studied.

[a] Includes compressed natural gas and liquefied natural gas buses.

Source: Asian Development Bank, based on data of bus operators in cities in the People's Republic of China.

Figure 6: Energy Usage of Standard Urban 10–12 Meter Buses, 2016
(MJ/km)



BEB = battery electric bus, FCEB = fuel cell electric bus, km = kilometer, m = meter, MJ = megajoule.

Note: Fuel consumption values are based on average consumption values in cities in the People's Republic of China.

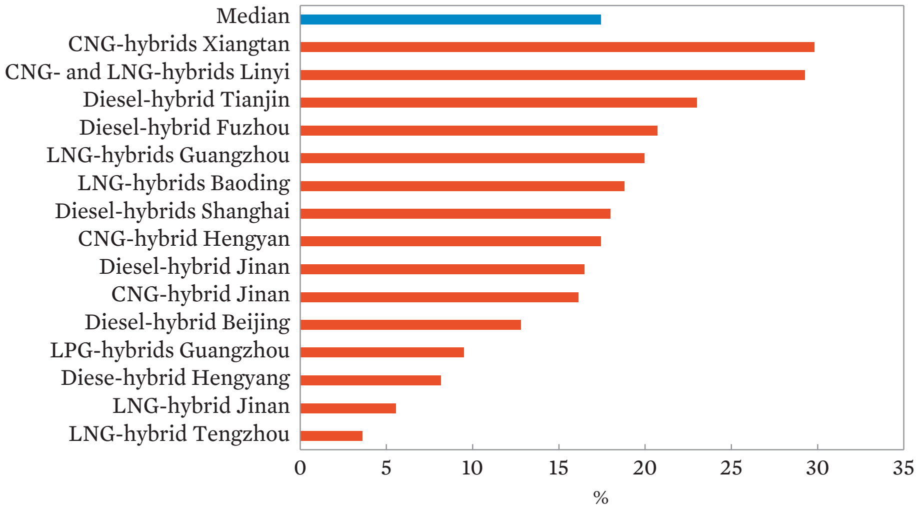
Source: Asian Development Bank.

The relation between cities with the lowest average fuel consumption figures and the highest consumption figures is around a factor of 1.5. Figure 6 shows the relation of energy usage to the different fuel types expressed in megajoule (MJ) for standard 10–12 m buses (the most used bus size type in the PRC). Natural gas buses use around 17% more energy than diesel units. Fossil fuel units use four times more energy than electric buses, which clearly shows the efficiency of electric traction.

Figure 7 shows the energy savings attributed to the usage of hybrid buses. The comparison base is a hybrid bus with the same fuel-conventional unit of the same size (i.e., a diesel-hybrid is compared with a diesel bus; a compressed natural gas (CNG)-hybrid is compared with a CNG bus, etc.) and operating on comparable routes. On average, savings of 17% are achieved in cities in the PRC with rates varying from 4% to 30%. No difference in savings of hybrids

Figure 7: Energy Savings of Hybrid Buses

(%)



CNG = compressed natural gas, LNG = liquefied natural gas, LPG = liquefied petroleum gas.

Note: Comparison of hybrid buses of the same size, same fuel conventional buses operating in the same city on comparable routes; minimum fleet size per city of 100 hybrids operating during a minimum period of 12 months.

Source: Asian Development Bank.

between hybrid fuel types [diesel-hybrid, CNG-hybrid, liquefied natural gas (LNG)-hybrid and liquefied petroleum gas (LPG)-hybrid] could be identified.

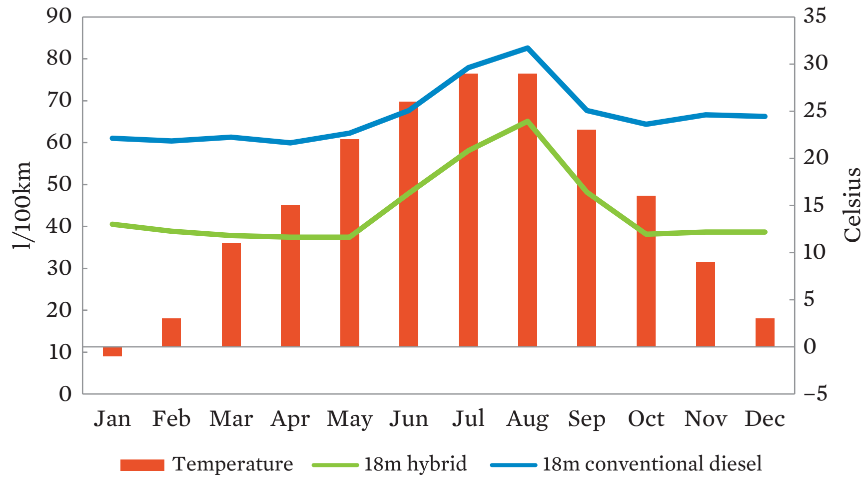
Measurements conducted in other cities with hybrid buses reveal slightly higher average savings with cities in Switzerland and Bogota, Colombia having an average savings of 20%–25%, while London, which uses double-deckers, had an energy savings of 35%–40%.[22]

Cities in the PRC use plug-in hybrids in large numbers. Unlike plug-in buses, standard hybrid buses are no longer subsidized, which means plug-in buses are less expensive than standard hybrids. However, no city regularly charges plug-in hybrid buses, i.e., they are used in the same manner as conventional hybrid units and, therefore, do not also have additional savings. The reason for this, as given by operators, is the small battery size of plug-in hybrid buses (in general, a 25 kWh battery for a 10–12 m bus) with the bus arriving at the depot with a half-full battery (due to brake energy recovery), operational complexities, and lack of chargers.

The energy consumption of hybrid buses as well as BEBs is sensitive to gradients, high load, and very low or very high temperatures that require cooling or heating. Electricity consumption in summer months can be 50% higher than during moderate temperature months (Figures 8 and 9), which affects the range of BEBs.

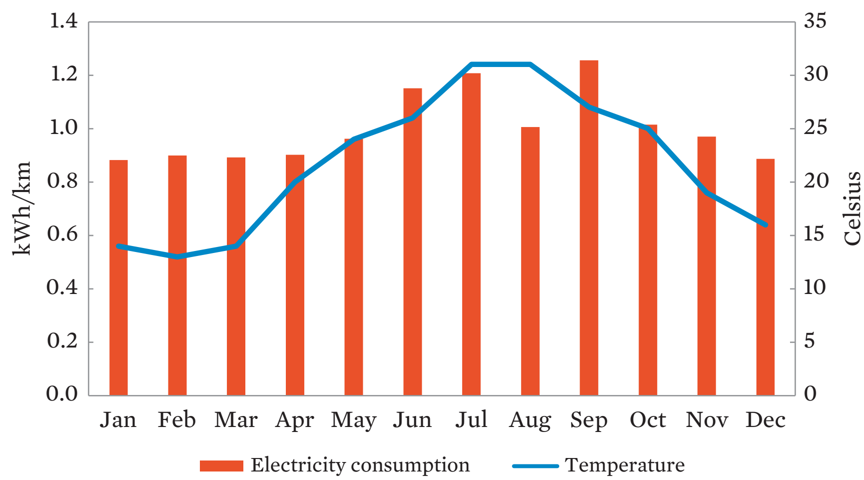
[22] Based on data from bus operators in the PRC.

Figure 8: Effect of Ambient Temperature on the Fuel Usage of Diesel and Diesel-Hybrid Buses



km = kilometer, l = liter, m = meter.
Notes: Based on the ambient temperature in Zhengzhou, People's Republic of China.
Source: Asian Development Bank.

Figure 9: Effect of Ambient Temperature on the Electricity Consumption of Battery Electric Buses



km = kilometer, kWh = kilowatt-hour.
Notes: Based on the ambient temperature in Fuzhou, People's Republic of China.
Source: Asian Development Bank.

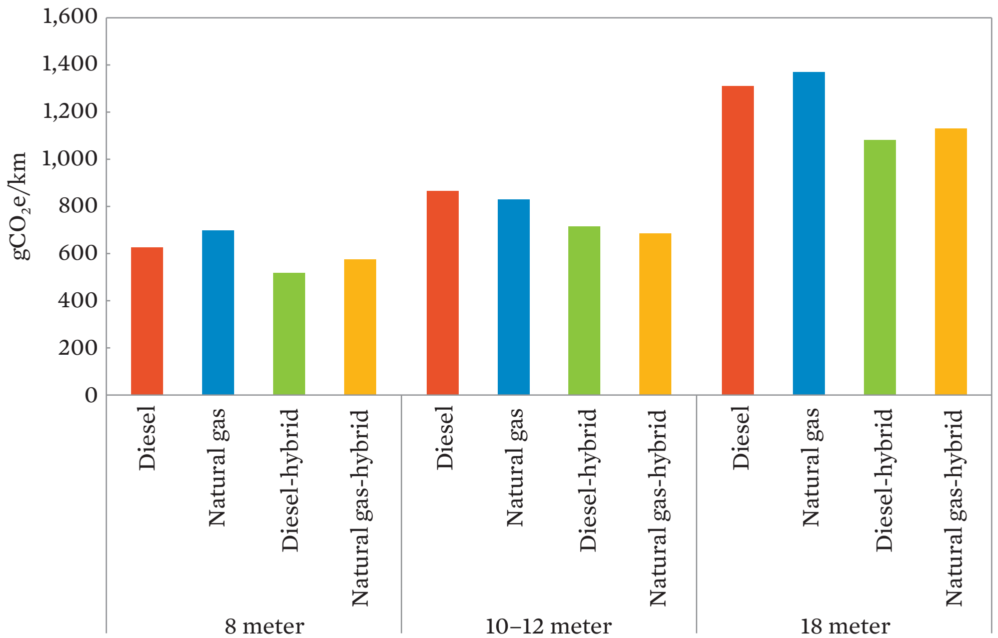
C. Global Warming Impact of Low-Carbon Buses

1. Direct Greenhouse Gas Emissions

Direct or tank-to-wheel (TTW) GHG emissions include only combustion-related exhaust emissions. Therefore, electric units have zero emissions. Methane slip within the bus is also included as direct emissions of natural gas-powered buses. Figure 10 compares the average GHG TTW emissions of buses operating in cities in the PRC.

Figure 10: Average Tank-to-Wheel Greenhouse Gas Emissions from Urban Buses, 2016

(gCO_2e/km)



gCO_{2e} = gram of carbon dioxide equivalent, km = kilometer.
Note: Surveyed cities have no 18-meter electric buses.
Source: Asian Development Bank, based on data from operators in cities in the People's Republic of China.

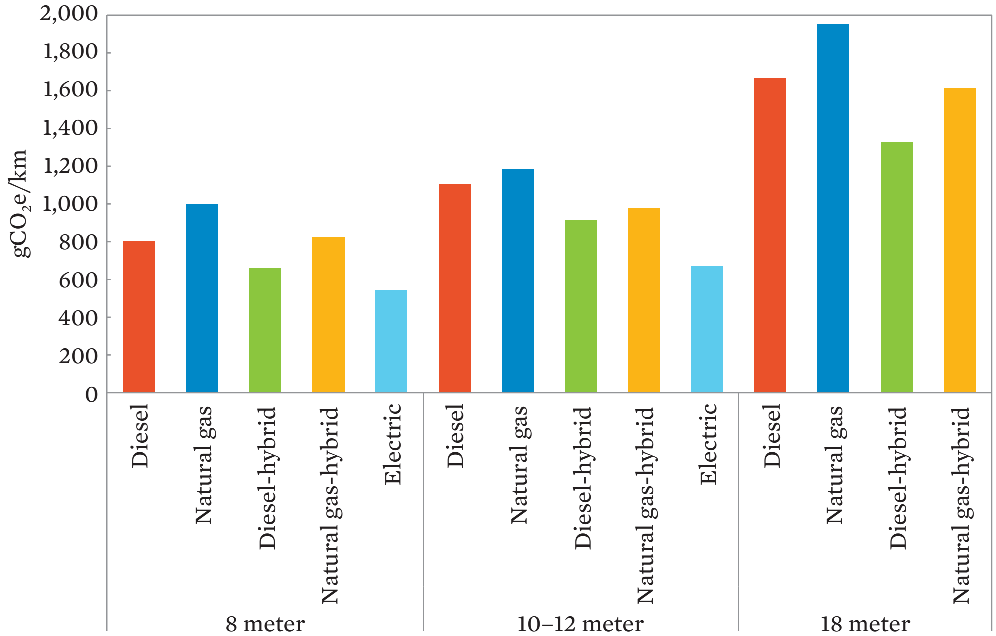
Gas and diesel buses have comparable TTW emissions. Hybrid units have around 20% lower TTW GHG emissions than conventional units. Electric buses have zero TTW emissions.

2. Direct and Indirect Greenhouse Gas Emissions

Indirect or well-to-tank (WTT) emissions are caused by fuel extraction, refinery and transport for fossil fuels and electricity production, as well as by transmission and electricity distribution losses. Also included are upstream methane slip and black carbon-related emissions based on an average vehicle emission standard of CN V. The carbon emission factor of the grid is calculated based on the net energy production (total production minus energy losses) and the total GHG emissions for electricity production. The average grid factor used in the PRC is 0.69 kgCO_{2e}/kWh.[23] Figure 11 compares well-to-wheel (WTW) GHG emissions of buses in cities in the PRC.

Figure 11: Average Well-to-Wheel Greenhouse Gas Emissions from Urban Buses, 2016

(gCO_2e/km)



gCO_{2e} = gram carbon dioxide equivalent, km = kilometer.

Note: Surveyed cities have no 18-meter electric buses.

Source: Asian Development Bank, based on data from operators in cities in the People's Republic of China.

Table 5 shows the annual average GHG emissions in tons of CO_{2e} per bus size and technology TTW as well as WTW, based on the average distance driven of buses in the PRC for each size category.

Compared to fossil fuel units, electric buses still reduce GHG emissions, even if indirect emissions are included, by around 30%–40%. Greening of the grid is imperative to further reduce GHG emissions of buses in the PRC. The GHG impact of electric buses will always largely depend on the electric grid. While electric buses will reduce GHG impacts in most of

[23] Institute for Global Environmental Studies (IGES). 2018. *IGES List of Grid Emission Factors*. Based on data provided by the National Development and Reform Commission for the year 2015 with calculations performed by the Institute for Global Environmental Strategies IGES for the year 2013. https://pub.iges.or.jp/pub/list-grid-emission-factor.

Table 5: Annual Average Greenhouse Gas Emissions per Bus (tCO_2e)

Bus Size	Bus Technology	TTW GHG Emissions	WTW GHG Emissions
8 meter	Diesel	28	35
	Natural gas	31	44
	Diesel-hybrid	23	29
	Natural gas-hybrid	25	36
	Electric	0	24
10–12 meter	Diesel	48	62
	Natural gas	46	66
	Diesel-hybrid	40	51
	Natural gas-hybrid	38	55
	Electric	0	38
18 meter	Diesel	80	102
	Natural gas	83	119
	Diesel-hybrid	66	81
	Natural gas-hybrid	69	98

GHG = greenhouse gas, tCO_{2e} = ton of carbon dioxide equivalent, TTW = tank-to-wheel, WTW = well-to-wheel.
Note: Based on annual mileage of 44,000 kilometers for 8 meter buses, 56,000 kilometers for 10–12 meter buses and 61,000 kilometers for 18 meter buses.
Source: Asian Development Bank, based on data from operators in cities in the People's Republic of China.

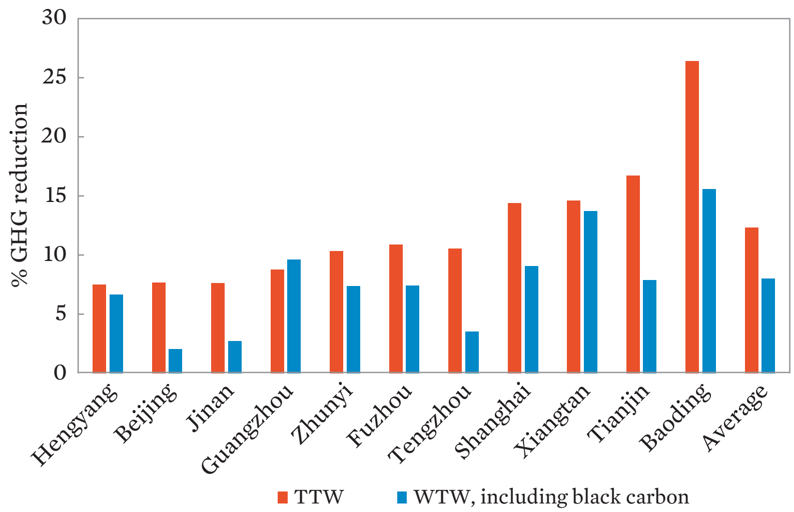
the grids, even if these are carbon-intensive, the impact is much higher the greener the grid. Countries with zero-emission grids, such as Bhutan, the Lao People's Democratic Republic, or Nepal, achieved the highest impact, with e-buses having zero emission in these countries.

3. Impact of Greenhouse Gas Emissions on Cities in the People's Republic of China

In 2016, the GHG impact of LCB usage was monitored in a sampling of cities in the PRC. On average, cities could reduce their GHG emissions by 8% (WTW) to 12% (TTW) with the usage of LCBs, with the city of Baoding having the highest percentage in reduction impact (Figure 12).

The GHG reduction impact of 8%–12% is significantly lower than the share of LCB buses due to LCBs having lower-than-average mileage and having, on average, smaller units that transport fewer passengers. While the average share of LCBs in cities in the PRC was 40% of buses, the share of bus-kilometer driven was only 28% (because LCBs are used on shorter routes) and the GHG reduction was only 8% (due to indirect emissions, limited GHG reductions of hybrids, and use of smaller-than-average LCBs). Even with 100%-electric fleets, GHG emissions will only be reduced by around 30% as long as the electric grid is not any greener.

Figure 12: Reductions in Greenhouse Gas Emissions due to Deployment of Low-Carbon Buses, 2016
(% of total bus emissions per operator)



GHG = greenhouse gas, TTW = tank-to-wheel, WTW = well-to-wheel.
Source: Asian Development Bank.

D. Local Environmental Impact of Low-Carbon Buses

Most cities in the PRC use gas buses. In general, diesel and gas units comply with the emission standard CN IV or CN V (i.e, $PM_{2.5}$ and NO_x emissions are already low). The following graph compares the tailpipe emissions of a standard 12 m urban bus relative to the emission standard.

Using natural gas buses has considerably reduced NO_x as well as $PM_{2.5}$ emissions. While electric buses are still better, the absolute impact is not that large when compared with the purchase of new diesel, gas, and electric buses. However, compared with the existing fleet, which is still significantly composed of CN IV and partially CN III units, the impact is still important. In the cities that were monitored for the study, the quantified and monetized value of the reduced local pollution was of similar importance as the GHG impact of buses.[24]

In terms of noise emissions, hybrid buses have approximately 3 decibels (dB) less noise compared with a diesel bus.[25] Electric buses result in a noise reduction of around 10 dB.[26] The effects of noise on health and the economy are significant.[27]

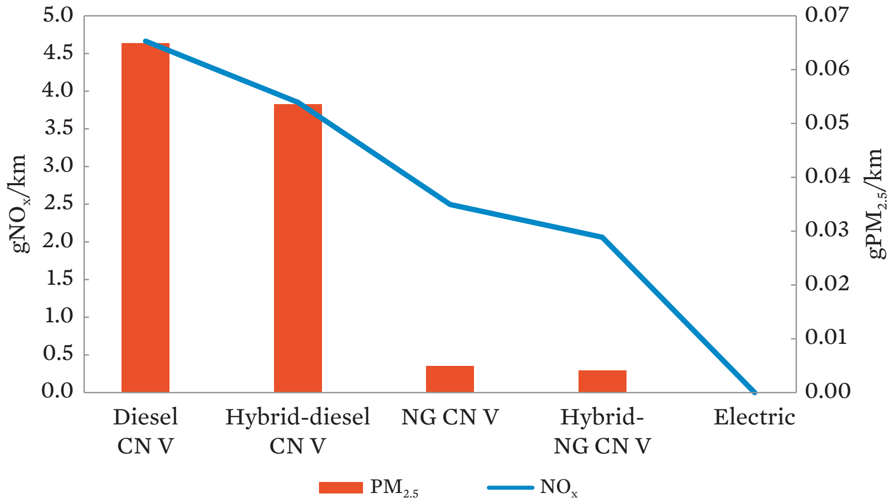
[24] International Monetary Fund. 2014. Values for the PRC were used on the economic cost per ton of pollutant.

[25] Clean Fleets. 2014. *Clean Buses—Experiences with Fuel and Technology Options*. http://www.clean-fleets.eu/fileadmin/files/Clean_Buses_-_Experiences_with_Fuel_and_Technology_Options_2.1.pdf or M. Faltenbacher et. al. 2011. *Abschlussbericht Plattform Innovative Antriebe Bus (Auftraggeber Bundesministerium für Verkehr, Bau und Stadtentwicklung)*. https://www.tib.eu/de/suchen/id/TIBKAT%3A68402764X/Plattform-Innovative-Antriebe-Bus-Abschlussbericht/.

[26] ABB, TOSA: *Die emissionsfreie Alternative für den Stadtverkeh*r. http://new.abb.com/future/de/tosa; A comparative measurement of a Euro VI diesel bus in Germany with a BEB revealed a difference of 16 dB when departing from the bus stop and 8 dB for bus transit. http://news.emove360.com/public-comparison-e-bus-much-quieter/?lang=e.

[27] See, e.g., VTPI. 2017. *Transportation Cost and Benefit Analysis II—Noise Costs*. https://www.vtpi.org/tca/tca0511.pdf.

Figure 13: Emissions of Standard Urban Buses



CN V = Chinese national emission standard V, gCO$_{2e}$ = gram carbon dioxide equivalent, km = kilometer, NG = natural gas, NO$_x$ = nitrogen oxide, PM = particulate matter.

Note: Left scale and orange curve are for NO$_x$; right scale and blue columns are for PM$_{2.5}$ emissions.

Source: Asian Development Bank.

E. Environmental Conclusions

Hybrid buses reduce energy consumption and emissions by around 20% and, theoretically, plug-in hybrids could reduce them further. In practice, however, the experience of cities in the PRC is that plug-in hybrids are not recharged at the grid due to operational complexity and too small battery sets used on the buses. Thus, the environmental impact of plug-in hybrids is the same as that for standard hybrid buses.

The GHG impact of electric buses depends largely on the electric grid, i.e., the share of electricity produced by renewables. Even in fossil fuel-dominated grids, electric buses will still reduce GHG emissions, even taking into account the life cycle emission; however, the impact is much larger when electricity is produced primarily by renewables. Therefore, greening the grid is imperative to reap the GHG potential of electric buses.

Local environmental impacts, including air pollution and noise impacts of electric buses, are important. However, they are diminishing as stringent emission standards of fossil fuel buses also result in very low emissions of air pollutants, including NO$_x$ and PM. Therefore, electric buses will basically make an important contribution toward improved air quality in countries and cities with vehicle emission standards Euro 4 or lower, while their contribution toward improving air quality in other countries will not be decisive.

IV. Financial Performance of Low-Carbon Buses

A. Bus and Infrastructure Investment Costs

Table 6 gives an overview of the capital expenditure (CAPEX) of low-carbon buses (LCBs) versus conventional units of the same size (total cost without subsidies) in cities in the PRC.

Table 6: Capital Expenditure for Low-Carbon Buses versus Conventional Buses ($)

Bus Technology	8 Meter Bus	10–12 Meter Bus
Diesel	59,000	94,000
Natural gas	63,000	102,000
Diesel plug-in hybrid	n.a.	136,000
Natural gas plug-in hybrid	n.a.	138,000
BEB	114,000	250,000

BEB = battery electric bus, n.a. = not applicable, CN V = Chinese national emission standard V.

Note: Diesel and natural gas buses CN V; plug-in hybrids with 25 kilowatt-hour battery.

Source: Asian Development Bank, based on averages of cities in the People's Republic of China.

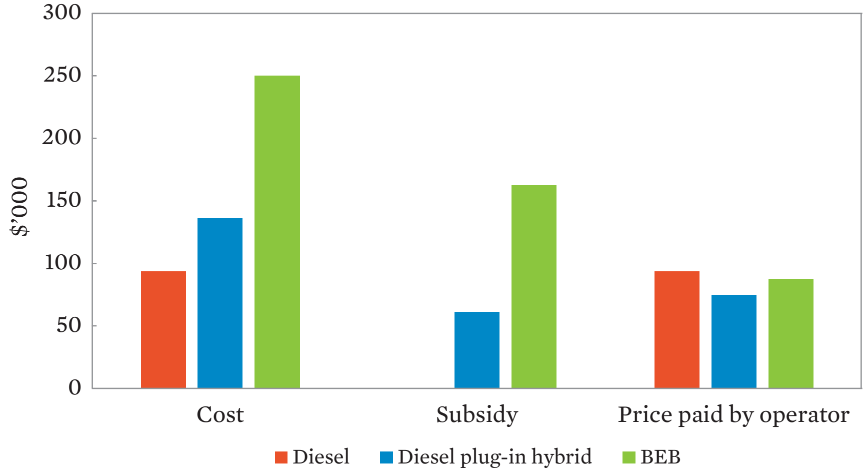
No data on 14 m or 18 m buses has been included as only few cities use them and in very limited numbers. Plug-in hybrids have an incremental cost of 40% on average compared with the same-size, same-fuel conventional units. Compared with conventional fossil fuel units, BEBs have an incremental cost by a factor of 2 to 2.5. Bus costs for buses of the same size, technology, and fuel vary by a factor of 2 between cities, depending on the quantities purchased, brand, and bus specifications (e.g., air-conditioners, low-floor entry).

Subsidies paid out for LCBs by the national, provincial, and city governments result in lower purchase prices for LCBs than conventional fossil fuel units. Additionally, LCBs have lower operating costs, making them very attractive investments for bus operators in the PRC. Figure 14 shows the full price and the actual price paid for a hybrid and a BEB version of a bus of the same size.

Most manufacturers guarantee their batteries for 8 years with a state of charge (SOC) of 80%.[28] Buses in the PRC are often replaced after 8 years (i.e., battery replacement coincides with bus replacement). However, electric buses could be used much longer as they have a technical life span that is longer than conventional buses due to having fewer parts and

[28] In some cities, 70%.

Figure 14: Comparison of Capital Expenditure for Buses With and Without Subsidies
($)



BEB = battery electric bus, CN V = Chinese national emission standard V.

Note: 12-meter standard bus with air-conditioning and one-step entry; diesel version emission standard CN V.

Source: Asian Development Bank.

vibrations compared with fossil fuel units. They could be operated without any problems for 15–20 years.[29] This would also improve resource efficiency and reduce life cycle of greenhouse (GHG) emissions. Using a BEB for 16 years requires a replacement investment for batteries in year 8. As of April 2018, bus batteries were being sold at $350/kWh. Expectations are that prices will drop annually by 10%–15% in the next few years.[30] Thus, for example, replacing a 250 kWh battery set after 8 years will result in an approximate investment of only $30,000.

The average cost of chargers is around $150/kW per charger plus $150/kW for the electric equipment, which includes transformers, grid connection, and construction. The life span of chargers is 20 years. Most of the charging systems in the PRC are financed and operated by third parties although some transport operators have also invested in their own infrastructure. Typically, the service charge for financing the charging infrastructure and servicing the chargers, as levied by charging companies, is around $0.07–$0.10 per kWh. This corresponds to around 50% of the total electricity cost paid by operators.

[29] Other countries, such as Switzerland, use electric trolleybuses for 20 years on average.

[30] Based on projections of the United States Department of Energy (US DOE) based on studies realized by Bloomberg New Energy Finance, Total Battery Consulting, Clean Energy Manufacturing Analysis Center, and Roland Berger; US DOE. *Cost and Price Metrics for Automotive Lithium-Ion Batteries*. https://energy.gov/sites/prod/files/2017/02/f34/67089%20EERE%20LIB%20cost%20vs%20price%20metrics%20r9.pdf.

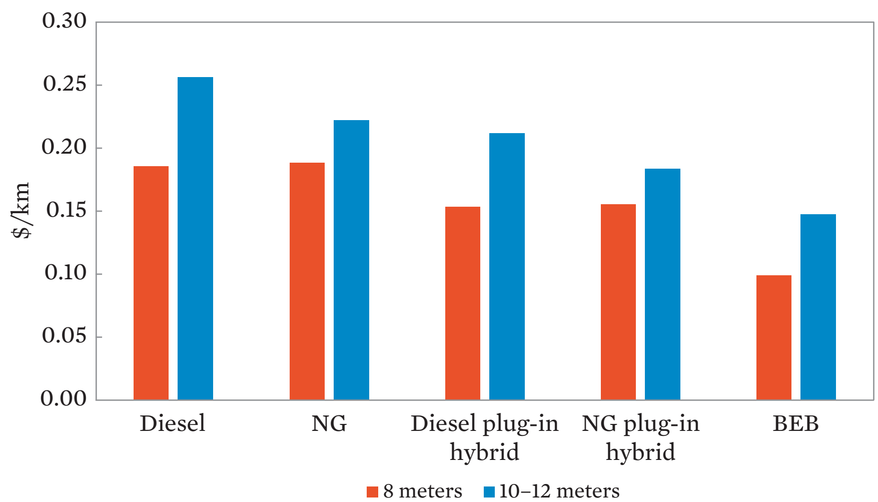
B. Operational Costs

The operational expenditures (OPEX) of buses basically include energy and maintenance costs. Insurance and tax costs are not differentiated relative to bus technologies in the PRC because buses cost the same for operators regardless of technology. OPEX costs such as bus drivers and bus dispatch are not considered because they are not related to the bus technology.

Energy Costs

Figure 15 compares the average energy costs per kilometer for different bus technologies. On average, BEBs have around 50% of the energy cost of diesel units. This includes both electricity costs and service charge (i.e., investment, maintenance, and operation of chargers).

Figure 15: Energy Cost of Urban Buses
($/km)



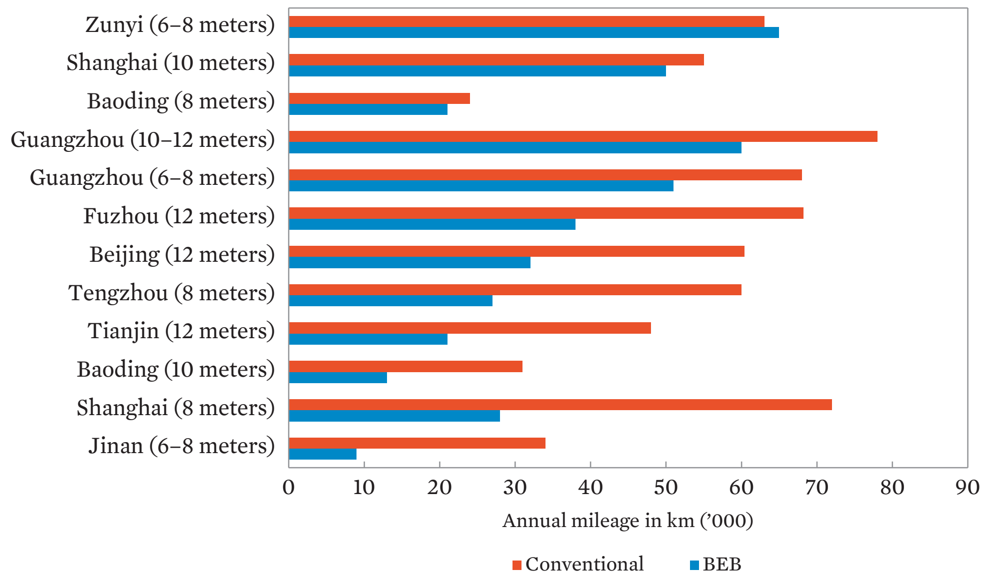
BEB = battery elective bus; km = kilometer; m = meter; NG = natural gas

Note: Average energy prices of $0.85/liter of diesel; $0.80/kg of NG; $0.15/kWh.

Source: Asian Development Bank, based on the average of cities in the People's Republic of China.

Absolute energy savings depend on the savings per unit of distance, the annual average mileage, and the commercial life span of buses. Cities in the PRC currently do not distinguish between bus technologies concerning their commercial life span (i.e., fossil fuel buses are used for the same amount of years as LCBs). In terms of bus mileage, hybrid buses are run on comparable routes to conventional buses and have similar mileage. BEBs are currently deployed on shorter routes (Figure 16).

Figure 16: Annual Bus Mileage of Battery Electric Buses versus Conventional Buses (km)



BEB = battery electric bus, km = kilometer, m = meter.
Source: Asian Development Bank.

On average, BEBs have 50% of the average mileage of conventional buses of the same size. However, this situation is changing with the increasing number of BEBs in fleets deployed on comparable routes as conventional buses.

Maintenance Costs

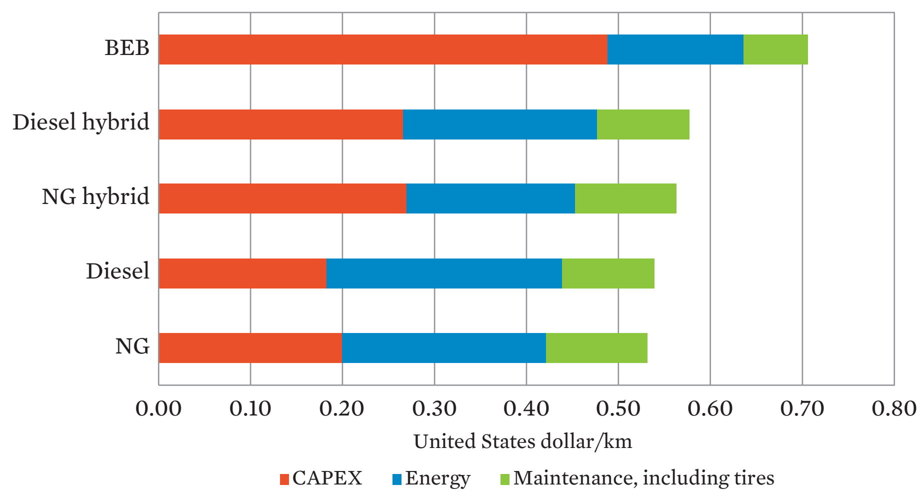
Maintenance costs for hybrids and plug-in hybrids are comparable with conventional units. Operators experience lower general maintenance costs (e.g., filters and oils) and lower brake system costs (due to regenerative braking systems) for hybrids but additional costs due to the electric system, which also has expensive spare parts.

In all cities, the bus manufacturer performs maintenance on the BEB electric components, including the batteries and the battery management system, with bus operators only conducting general and daily maintenance. BEBs have lower general maintenance costs due to having fewer components, no oil and engine filter exchanges, and lower brake pad usage, but have an increased tire usage and higher staff and spare parts costs. The maintenance of the electric parts requires different and higher trained staff which is more expensive. BEBs consume around 20% more tires compared with conventional units. Higher tire usage is attributed to the higher weight of BEBs and their sharper acceleration and braking related to the regenerative braking system. Tires are a very important cost factor, and typically account for around 40% of total maintenance costs, while oils, lubricants, and general maintenance account for around 60%. Comparing buses of the same age and size, BEBs have around 70%–90% of total maintenance costs, including tires.

Total Cost of Ownership

This study calculates the average total cost of ownership (TCO) of different technology buses, based on the average CAPEX and annual energy and maintenance cost. The calculation is performed for the standard 8 years that a bus is used commercially in most cities in the PRC. No fuel price increases have been factored into the calculations. As calculated, the TCO only includes, under OPEX, the energy and maintenance costs, including tires. Other OPEX costs (e.g. parking space, driver, overhead, bus dispatch, cleaning of buses, insurance, taxes, bus repairs, and bodywork) are not included as they are similar for all technology types. Figure 17 compares TCOs with different bus technologies.

Figure 17: Total Cost of Ownership for Different Bus Technologies ($/km)



BEB = battery electric bus, CAPEX = capital expenditure, km = kilometer, NG = natural gas, OPEX = operational expenditure.

Source: Asian Development Bank, based on the average CAPEX and OPEX costs in cities in the People's Republic of China.

Conventional and hybrid units are all within a comparable range of TCO, with hybrids 5%–7% more expensive than same-fuel conventional units. Using the CAPEX of hybrids instead of plug-in hybrids, the TCO of hybrids would be lower than of conventional units. As previously discussed, in general, plug-in hybrids in the PRC are not charged and, therefore, have the same energy savings as standard hybrids, while costing around $20,000 more for a 10–12 m unit.

Even assuming that they have the same average mileage as that of conventional buses, BEBs still have around 30% higher TCOs than conventional buses. In the PRC, subsidies are required to equalize costs between electric and conventional buses. For other countries, the differential TCO between electric and conventional buses could be smaller or bigger.

The main parameters, which influence the relative profitability of electric versus conventional units and which differ greatly from country to country, are as follows:

(i) **Energy prices, including diesel or gas price and electricity price**. Price increases of fossil fuels make electric buses more attractive.
(ii) **Lifetime mileage of buses**. In cities in the PRC, while buses are used only for 600,000–700,000 km on average, in many cities worldwide the average is 1 million–1.2 million km. The longer the lifetime mileage, the more profitable electric buses are due to lower operational costs. If e-buses are used for a longer period than conventional units, they will also be able to improve their relative profitability.

The TCO of electric buses will improve as battery prices are dropping sharply (Chapter IV.A.) resulting in lower bus costs. The reduction in battery costs could be equivalent to one-third of the current total subsidy received by e-buses as of 2020–2021. However, to make e-buses financially equivalent or more profitable than conventional units without any subsidy, the lifetime of e-buses will need to be expanded from the current average of 8 years to around 15 years.[31] Batteries would need to be replaced after 8 years. Then, buses can be used for another 7-8 years. Using e-buses for 15 years with a total mileage of 1 million–1.2 million km is technically feasible and is the current practice worldwide by most bus operators for all types of buses. E-buses suffer less vibrations and stress on components and, therefore, have an even longer life span than conventional units. Expanding the life span of buses not only makes financial sense but is also environmentally beneficial as materials and resources are used over a longer period.[32]

C. Risks and Indirect Costs for Low-Carbon Buses

In many cities, LCBs have comparable bus availability rates with that of conventional units. However, in some cities, BEBs have higher failure rates, with some cities reporting a 10%–30% higher failure and breakdown rate than conventional buses. Most reported failures are due to batteries and the battery management system, and occur primarily in the summer when batteries are under increased stress due to high air-conditioning usage. This results in lower bus availability rates and the need for a larger bus reserve fleet. Some of the main issues resulting in lower bus availability rates is the lack of qualified maintenance, the lack of spare parts as the result of too many different types of BEBs, and the low quality of some brands of buses.

In general, hybrids and plug-in hybrids have a comparable passenger capacity with that of conventional buses. However, many manufactures of BEBs put some batteries inside the bus, thereby reducing the available space for passengers. With some BEBs, the problem can also be of battery weight because of the installation of large battery packs (typically, 100 kWh of batteries means 1 ton of weight). This can result in a high axle weight, and restrictions on

[31] Using e-buses for, e.g., 10–12 years makes limited sense as costly batteries have a life span of 8 years and require replacement after this time. Thereafter, using the bus for only the potential life span of the batteries would not be optimal under financial and environmental criteria.
[32] In the case of fossil buses, a rapid replacement has its advantages as new buses have lower pollution levels. However, for e-buses, this is not the case as their combustion emissions are already zero.

the number of passengers that can be loaded.[33] It is not uncommon to have BEBs with 20% less passenger capacity compared with conventional units of the same size. Bus operators manage this problem by purchasing larger units (e.g., a 10 m unit instead of an 8 m bus) or by increasing their bus fleet by up to 20%.[34] However, the problem of reduced passenger capacity is related to the bus brand chosen, and newer models face this issue less often compared with older BEBs.

D. Financial Conclusions

Hybrid buses cost around 20% more, plug in-hybrids 40% more, and electric buses 100%– 150% more than a conventional diesel or natural gas bus of the same size. This incremental investment is recovered from hybrids due to their lower energy usage. Plug-in hybrids used without charging, like they do in the PRC, do not recover the incremental investment.

Electric buses have lower energy costs and slightly lower maintenance costs. Compared with conventional buses, they have also a longer technical life span (except for their batteries which need to be replaced after around 8 years). TCO can be lower for electric buses than for fossil fuel units if diesel or natural gas prices are high, electricity costs low, buses are used with a high mileage, and electric buses are operated for more years than conventional buses. However, in the context of cities in the PRC, the TCO of electric buses is still significantly higher than that of conventional units, thus also requiring future subsidies. Expected future fuel price increases and lower battery costs (resulting in lower electric bus costs) will reduce this gap and make electric buses financially competitive.

33 This problem does not arise frequently in the PRC as most operators chose buses with a small battery pack, recharging them during the day.

34 Operators prefer not to purchase BEBs that are 14 m or longer, which are more expensive.

V. Low-Carbon Bus Promotion Policies

New energy vehicles (NEVs) have been promoted in the PRC since 2009 by government bodies at different levels including the National Development and Reform Commission, the Ministry of Finance, the Ministry of Industry and Information Technology, the Ministry of Transport, the National Government Offices Administration, and the National Energy Administration. The support system exists on the national, provincial, and city levels, and is embedded in a macro-level policy, including as elements of strategic industrial planning, energy planning, environmental protection, and research and development. Buses are not the only NEVs promoted; they also include trucks, taxis, government vehicles, and private vehicles. NEV promotion policies are based on environmental protection and emission reduction, energy policies, as well as industrial policies to promote the domestic vehicle industry in a strategic manner.

Incentives for new energy bus deployment have been in place since 2009:[35]

(i) 2009–2012: The first economic incentive policy document was released along with the "Ten Cities, Thousands of Vehicles" demonstration program in 2009.[36] Hybrid, electric, and fuel cell hydrogen buses were included in this phase. Subsidies were given directly to bus manufacturers which subtracted them from the final selling price to operators.

(ii) 2013–2015: The central government released the second phase of e-bus subsidy policies.[37] The major change was that the government excluded hybrids since 2013 from receiving subsidies. Also, starting from 2013, cities could receive subsidies for the charging infrastructure.

(iii) Since 2013, the central government has been providing subsidies directly to pilot cities to develop the charging infrastructure for e-buses.

(iv) 2016–2020: The central government released the third phase of subsidy policies for e-buses.[38]

(v) 2017–2020: The central government released an updated e-bus subsidy policy including a cut in the level of e-bus and charging infrastructure subsidies. Also, the central government introduced operational subsidies to transit operators, and reduced diesel subsidies to encourage the operation of electric buses.

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[35] S. Sun and GIZ. 2018. *Trends and Challenges in Electric-bus Development in China*. http://www.sustainabletransport.org/archives/5770.

[36] Government of the People's Republic of China, Ministry of Finance. *2009. About Developing Energy-Saving and New Energy Vehicles*. (in Chinese) http://www.mof.gov.cn/zhengwuxinxi/caizhengwengao/2009niancaizhengbuwengao/caizhengwengao2009dierqi/200904/t20090413_132178.html.

[37] Government of the People's Republic of China. 2013. Circular on the Continuation of the Promotion and Application of New Energy Vehicles. (in Chinese) http://www.gov.cn/zwgk/2013-09/17/content_2490108.htm.

[38] Government of the People's Republic of China, Ministry of Finance. 2015. Notice on the financial support policy for the Ministry of Finance of the People's Republic of China. (in Chinese). http://jjs.mof.gov.cn/zhengwuxinxi/zhengcefagui/201504/t20150429_1224515.html.

National industrial policies that promote NEVs include the establishment of regulations and standards for such vehicles, specifically for batteries. Special importance was given to a battery recycling policy. These regulations allow for a standardization of products and ensure quality, thereby also giving the customer confidence and promoting the establishment of sustainable modes of production and products. Tax preferences for NEVs include fee waivers, purchase tax exemption, consumption tax exemption, and reduced or no tax rates on key vehicle components. Also, the PRC has innovative policies, which include targeting resources for research and development to projects related to NEVs. Infrastructure support policies include grid construction and transformation, and the establishment of charging infrastructure for NEVs.

Policies to promote the use of NEVs are basically subsidies. Subsidies are differentiated between types and categories of vehicles and technologies (hybrids, plug-in hybrids, pure electric, fuel cell). Subsidies are gradually phased out by reducing subsidy levels, excluding certain technologies from subsidies (e.g., hybrid buses are no longer subsidized, but plug-in hybrids continue being promoted), and tightening requirements (e.g., concerning an increase required electric drive range). The next section discusses the criteria for LCB subsidies in the PRC.

A. Low-Carbon Bus Incentive Scheme in the People's Republic of China

LCB subsidies for the period 2016–2020 are related to the following criteria (Appendix 2 for more details):[39]

(i) **Bus size.** Smaller buses (e.g., a 6–8 m bus receives only 50% of subsidies of a standard 10–12 m bus, while a 14 m or double-decker receives 20% higher subsidies than a standard unit).
(ii) **Pure electric drive range.** A bus with a pure electric drive range of above 250 km receives 40%–50% more subsidies than a bus with an electric drive range between 100–150 km.
(iii) **Bus efficiency.** The more efficient the bus in terms of energy consumption per net load (kWh/ton-km), the higher the subsidy level. The subsidy difference between the lowest defined efficiency category and the highest one is nearly a factor of 2.
(iv) **Technology.** Subsidies are given for battery electric buses, plug-in hybrid buses,[40] ultrafast charging electric buses, and electric trolleybuses.

Since January 2017, a distinction has also been made relative to the speed of charging, with higher subsidies given if batteries can be charged at a shorter time. The government has gradually reduced subsidies on LCBs and will further reduce incentives in 2019–2020. After 2020, all subsidies on LCBs will be phased out.

[39] Government of the People's Republic of China, Ministry of Finance. 2015. Notice on the Financial Support Policy for the Promotion and Application of New Energy Vehicles in 2016–2020; and Government of the People's Republic of China, Ministry of Finance. 2016. Notice on Adjusting the Financial Subsidy Policy for the Promotion and Application of New Energy Vehicle. http://jjs.mof.gov.cn/zhengwuxinxi/tongzhigonggao/201612/t20161229_2508628.html.

[40] Distinguishing for specific energy or gravimetric energy density in the watt-hour per kilogram (Wh/kg) of the battery and for bus size.

Two factors that also explain the types of e-buses used in the PRC are as follows:

(i) Buses longer than 12 m receive only 20% higher subsidies than 10–12 m units. However, he average cost of 18 m buses is 2.5 times higher than that of a 10–12 m bus. This means that BEBs larger than 12 m remain significantly more expensive than conventional units, while standard-sized and smaller BEBs are at cost level or cheaper than conventional units. This creates a disincentive to purchase articulated 18 m BEBs. The result is a large fleet of 10–12 m BEBs and some cities, such as Guangzhou, are replacing articulated conventional buses with 12 m BEBs. However, larger units are more efficient per passenger per km in terms of energy usage and emissions. Thus, the policy not only prevents the bus industry in the PRC from gaining more experience with electric 18 m units, but also reduces transport efficiency at the city level.

(ii) Trolleybuses receive fewer subsidies than BEBs, as their pure electric drive range is lower. It makes no sense to equip a trolleybus with a huge electric drive range as they operate mostly with catenaries. Therefore, the policy favors certain electric drive technologies, which makes limited sense from an environmental perspective.

Subsidies are given on national as well as on provincial and city levels, depending on the local policies. In 2009, the national subsidy was given to 25 cities; in 2013, the subsidy was extended to 99 cities; and, since 2016, it is available nationwide. In 2017, there were around 380,000 electric buses operating in the PRC[41] clearly showing the positive impact of these policies. Next to subsidies, finance providers to bus operating companies are also important to overcome cash flow constraints of bus operators.

B. Battery Policies

In January 2016, the National Development and Reform Commission, the Ministry of Industry and Information Technology, the Ministry of Environment Protection, the Ministry of Commerce, and the General Administration of Quality Supervision Inspection and Quarantine established the recycling policies for electric vehicle batteries. A series of interim rules put forward in February 2018 hold electric vehicle manufacturers responsible for the recovery of NEV batteries. They are required to set up recycling channels and service outlets where old batteries can be collected, stored, and transferred to specialist recyclers. Together with battery makers and their sales units, electric vehicle manufacturers must also set up a "traceability" system that will enable the identification of owners of discarded batteries. The battery makers are also encouraged to adopt standardized and easily dismantled product designs to help automate the recycling process. They must also provide technical training for vehicle makers on how to store and dismantle old batteries.

[41] Bloomberg New Energy Finance. 2018; includes pure electric buses and plug-in hybrids.

C. Incentive Schemes of Other Countries

In all countries where LCBs have achieved a penetration level which goes beyond pilot schemes, subsidy policies have been put in place. The magnitude of subsidies is comparable with the ones offered in the PRC. Subsidies are basically up-front purchase subsidies covering incremental costs of LCBs as well as related charging infrastructure. In general, while subsidies are given to operators and not manufacturers, the impact is comparable as operators in all countries prefer locally manufactured units and, in the case of the United States, for example, subsidies are only given to buses manufactured in the country under its "Buy America" program. The following gives an overview of some of the policies applied in different countries.

Germany

The scheme set up by the Government of Germany with a budget of €70 million supports public transport operators from 2018 to 2021 to cover incremental investments costs of electric and plug-in-hybrid buses compared with conventional diesel units, as well as the construction of the related electric-charging infrastructure required for the operation of these buses. Bus operators can claim up to 80% of the additional cost of their investment if they acquire five or more all-electric buses, including the cost of charging infrastructure as well as training and new service centers. Support is linked to the requirement that electric and plug-in hybrid buses shall be operated with electricity from renewable sources. The European Union Commission concluded that the environmental benefits of the scheme outweigh any potential distortion of competition brought about by the public financing and has approved it under the European Union state aid rules.

United Kingdom

The £30 million United Kingdom Low Emission Bus Scheme was launched in 2015 by the Office of Low Emission Vehicles under its £500m budget from 2015 to 2020 to support the purchase of low-emission vehicles across England and Wales. This scheme replaces an earlier low-carbon emission bus or Green Bus Fund established in 2009 which, in its four rounds from 2009 to 2013, financed more than 1,200 LCBs (basically hybrids). Of the 1,200 buses financed by this scheme, around 60% were double-deckers and 40% single-deckers; 89% of buses were hybrids, 7% biogas, and 4% pure electric buses. Total funding used for the four rounds was £89 million or around £72,000 per bus. The fund operates as a Challenge Fund, which is a competitive financing facility to disburse, in this case, public sector funds for incentive-driven solutions providing the smallest possible financial contribution to a given goal, making it less risky for private operators. In the low-emission bus, a maximum of 90% of the cost difference between a zero-emission and a conventional bus is paid. Additionally, the Bus Service Operators Grant was reformed in April 2009 to encourage improvements in fleet fuel efficiency and provide a level playing field for low-carbon emission buses. The grant introduces an incentive of an additional payment of six pence for each km that operators gain with LCBs. Transport Scotland has a similar fund (Scottish Green Bus Fund) that offers a maximum 80% of price differentials between an LCB and a diesel equivalent.

United States

The United States has a very limited number of electric buses (around 300 of 65,000 units are electric). However, it provides for federal grants to support the purchase of electric buses. The United States Department of Transportation's Federal Transit Administration (FTA) provides for a total of $55 million with grants tied to the purchase of United States-made zero-emission buses. With the new administration in 2017, a $284 million grant program was started for the purchase of so-called clean diesel buses, as well as zero-emission buses with a federal share of costs of up to 90%. The FTA requires that all capital procurements meet FTA's "Buy America" requirements, which demands that all manufactured products be produced in the United States.

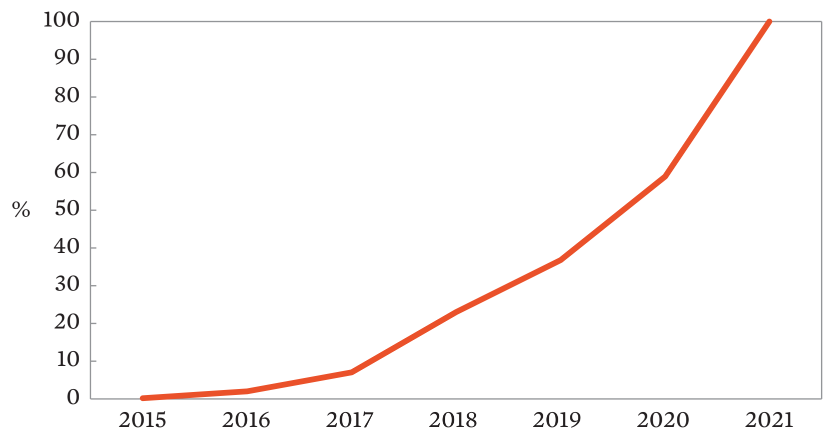
VI. Challenges for the Future

A. Full Electrification of Fleets

1. Electrification Trend in Cities

Various cities in the PRC are moving toward full electrification of or have already fully electrified their bus fleet (Figure 18).

Figure 18: Share of Electric Buses of Bus Company 2 in Guangzhou, People's Republic of China
(%)



Source: Asian Development Bank.

The Bus Company 2 of Guangzhou started in 2015 with 28 battery electric buses (BEBs) while operating a total fleet of around 13,000 buses; it operated 1,000 BEBs in 2017, had more than 3,000 units in 2018, and plan to be 100% electric by 2021. Many other cities have comparable plans with the goal to fully electrify their bus fleet in the next 5 years.

Challenges associated with a full electrification of bus fleets include the following:

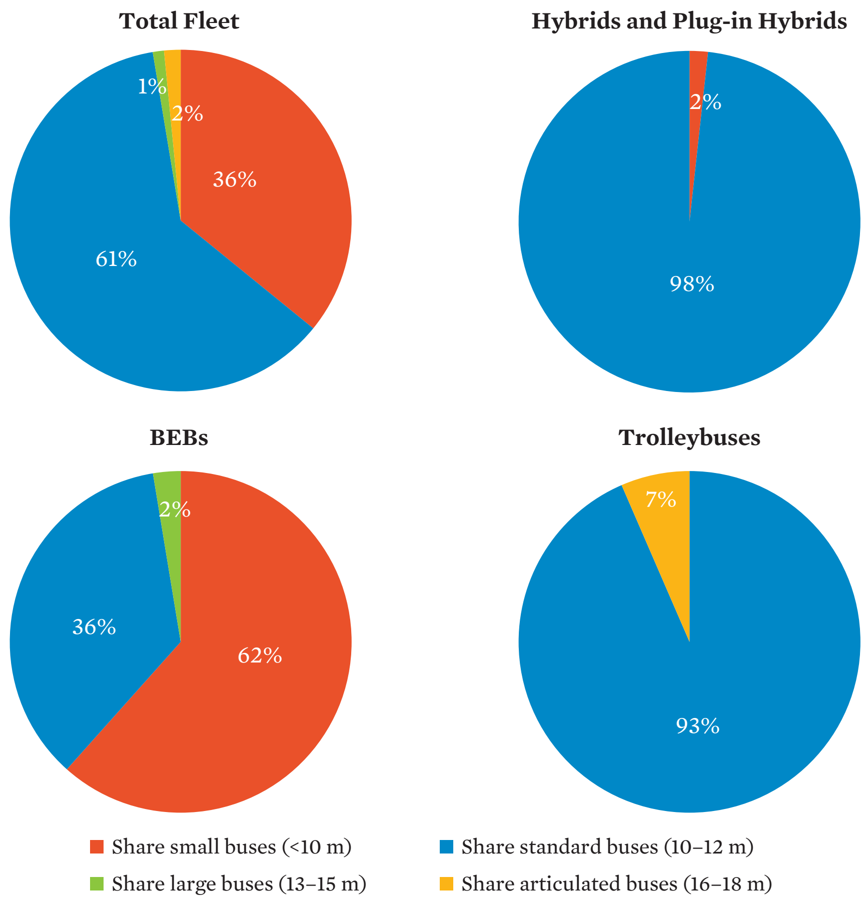
(i) Currently, electric buses are basically composed of smaller units. With full electrification, larger buses, including potentially articulated units, will have to be purchased, which would require identification of the appropriate bus and charging technology.

(ii) Currently, electric buses are used on shorter routes with less passenger demand. With full electrification, BEBs will be used on longer and more demanding routes, which would require a good determination of the optimal battery pack size on buses.
(iii) Currently, electric buses have not been optimized for costs. With full electrification and increased demands on lowering operational costs, the electric bus fleet will need to be optimized as to charging and bus technology to reduce energy costs.

2. Electric Bus Size and Technology Options

Bus fleets in typical cities in the PRC are composed of around 60% standard 10–12 m buses and 40% units smaller than 10 m. Only few cities operate fleets of three-axle 14 m buses, including double-deckers and articulated 18 m units (Figure 19). Hybrids are basically 10–12 m units, trolleybuses are to a large majority also 12 m units, with some articulated 18 m buses. On the other hand, BEBs are more than 60% small buses with only 40% being 10–12 m units, and 14 m double-decker units only in Beijing.

Figure 19: Average Bus Size of Fleets



BEB = battery electric bus, m = meter.
Source: Asian Development Bank, based on data on cities in the People's Republic of China.

It is clear that, for a full electrification of the bus fleet, the share of larger BEBs will need to be increased. Also, options for electric units larger than 12 m need to be assessed. Options available include BEBs with multiple fast day charging, opportunity charge en route, or electric trolleybuses.

18 m BEBs with slow charging at night require a very large battery set, making them heavy and costly. Therefore, this is not considered a practical solution. 18 m units often have a higher mileage due to operating on bus-only lanes and, therefore, require multiple charges. Operationally, this can be performed best at the end of routes either manually or automatically with pantographs. Such systems are currently being implemented in various cities in Europe, while only a few are operational in the PRC (e.g., in Shanghai with 10 articulated buses plus a larger number of standard 12 m units). The advantage of such systems is that buses do not need to return to bus depots for charging. Basically, the system works well for bus rapid transit (BRT) and high-frequency routes where large buses are more efficient. Pantograph or automated charging has the advantage of cost savings of staff.

Superfast charging can also be made at intermediate stations. However, this requires high-power chargers (400–600 kW) as charging time should be less than 20 seconds (equivalent to the average waiting time at stations). Such systems with 18 m articulated and 24–26 m double articulated buses operate in Nantes, France and in Geneva, Switzerland. Compared with end-of-route charging, the advantage of superfast charging is that buses require fewer batteries (lower cost), and do not require standstill times plus additional space at the end of the route. Charging facilities are integrated into stations with charging times of 10–30 seconds, while passengers board and deboard the bus, i.e., bus frequencies can be very high with a minimum bus reserve requirement due to charging. Systems can be less expensive than "opportunity charge end of route" or trolleybus systems. They are basically apt for BRT routes running on high frequencies with large buses. In the PRC, only a few pilot systems with opportunity charge at stations and 18 m buses have been established (e.g., in Ningbo).

Electric trolleybuses with an autonomy range of 30–50 km without overhead wire operate in various cities in the PRC as 12 m or 18 m units. The advantage is that only a small battery is onboard the bus (30–60 kWh for an 18 m bus). The disadvantage is a limited flexibility of operations, significant infrastructure costs ($0.6 million–$1.7 million per km), and high maintenance costs of the overhead wiring. Also, visual pollution through overhead wires might be an issue. However, the technology is proven and used worldwide in many cities.

Which system is the best will depend on the route characteristics, bus frequency, and available space and infrastructure. However, opportunity charge systems either en route or end of route tend to have significantly lower infrastructure investment costs, less maintenance problems, and result in higher operational flexibility. This is deemed to be the best available technology and solution as of today, especially for heavy passenger demand routes.

3. Determination of Optimal Battery Pack Size for Battery Electric Buses

With current average battery capacities, an expansion to 100% of the fleets into BEBs will be tricky, as BEBs will also be used on longer routes. Optimizing the battery size of buses is an important issue in this context. At the moment, this is only done in very few cities and only by the largest operators.

The range of a BEB is an important parameter. The optimal battery capacity will depend on

(i) daily distance driven,
(ii) energy usage per unit of distance,
(iii) reserve rate state of charge (SOC),
(iv) SOC over time,
(v) type of charging,
(vi) electricity cost relative to time period of the day, and
(vii) battery cost.

Daily distance driven. This depends on the routes of the BEB and the frequencies.

Energy usage. The energy usage of BEBs can vary considerably, depending on routes, drivers, climate, and traffic conditions. The core factors that will significantly increase the energy usage of BEBs are high usage of air-conditioning or heating, and steep gradients of roads. Air-conditioning and heating can result in 50% higher energy usage, while steep gradients will also significantly increase the electricity consumption. The battery capacity required must be determined based on the energy usage during air-conditioning or heating usage, not as the average during the year, to avoid operational problems during hot summer or cold winter months. Claims of energy efficiency of BEBs made by manufacturers tend to be very optimistic and not in accordance with actual monitored performance levels.

Reserve state of charge. Batteries often require a minimum SOC of 10%–15% to prevent damage and to maintain their warranty. In addition, the bus must also be operated with a reserve to prevent units from being stranded en route due to lack of electricity. Therefore, the battery size must take into account a minimum reserve ratio of 10%. In practice, most BEBs in cities in the PRC currently return to charging prior to reaching 20%–30% of SOC. This is also due to the limited reliability of onboard equipment showing the SOC of batteries.

State of charge degradation. Battery SOC deteriorates significantly over time. The manufacturer's indicated maximum range is potentially correct in the first year of operation, but not in the fifth or eighth year when batteries have a much lower SOC. Generally, bus and battery manufacturers in the PRC today guarantee a SOC of 80% in year 8 and, typically, in year 5, batteries will have a SOC of 85%. This means that the vehicle driving range with fully loaded batteries will be 15% less in year 5 compared with year 1. Buses need to be able to cover their intended route in year 5 or later and, therefore, the original battery package must also be sufficient for later years.

Type of charging. Buses charged during the night will require a larger set of batteries. Buses with fast charging during the day can have smaller sets of batteries. If a too small battery set is determined, BEBs with night charging will have to be fast-charged additionally during the day, which technically might not be feasible if the bus is not also designed for fast charging, while BEBs with intermediate fast charging might need to be charged more frequently. Both solutions might cause operational difficulties, showing the importance of defining the battery pack correctly up-front.

Price of electricity and batteries. Next to technical and operational criteria, financial aspects define which battery pack to choose. As of April 2018, bus batteries cost around $350/kWh. Therefore, more batteries mean additional bus costs. However, the night tariff for electricity is lower, which favors night charging over intermediate fast charging and, therefore, higher battery packs.

Actual driving range. While manufacturers might claim a driving range of 280 km with a 210 kWh battery pack, the actual operational range can be as low as 130 km in year 8 during the summer. Thus, the bus will require more frequent recharging during the day, which might be operationally complex. Alternative solutions are

(i) purchase buses with higher battery capacity (eventually for use only for longer routes);
(ii) use new buses with a higher SOC rate predominantly on longer routes and older units with lower SOC rates on shorter routes;
(iii) reduce air-conditioning usage in summer; and
(iv) purchase additional buses (i.e., one conventional bus is replaced by more than one BEB).

Using older units on shorter routes and new units on longer routes is considered a cost-effective solution. Still, BEBs should be able to comply with their maximum range intended until at least year 5. BEBs need not be designed for the longest routes but for ranges, which allow them to operate with one recharge during the day on 70%–80% of the routes.[42] For longer routes, two recharges per day can be realized. Table 7 shows an estimated minimum battery size for 8 m and 10–12 m BEBs, depending on the charging structure chosen for a daily mileage of 200 km for 6–8 m buses and 230 km for 10–12 m buses, which corresponds to the average daily mileage of longer routes in cities in the PRC.

Based on the current efficiency of BEBs and one recharging per day, the battery pack for 6–8 m buses will require a minimum size of around 1 kWh per daily average km driven if only charged during the night, and 0.6 kWh per daily average kilometer if charged during the night and once daily. For 10–12 m buses, the values are around 2 kWh/km if only charged at night, and around 1.1 kWh/km if also charged once daily.

[42] Recharging during the day can augment the dead mileage and result in operational difficulties and, therefore, should be minimized except on routes equipped with opportunity charge systems.

Table 7: Proposed Battery Configuration for Battery Electric Buses

Bus Size	Overnight Charging Only	Overnight and 1-Day Charging	Comment
6–8 m with 200 km daily	210 kWh	120 kWh	Both solutions are possible; however, for smaller buses, a 210 kWh battery pack might be too large and costly. The majority of 6–8 m BEBs currently in use in cities in the PRC have a battery pack of around 120 kWh (i.e., require one daily charge at minimum).
10–12 m with 230 km daily	430 kWh	240 kWh	Both solutions are possible; however, 10–12 m buses currently in usage in the PRC have battery packs of less than 310 kWh with an average of 210 kWh (i.e., require one to two charges during the day).

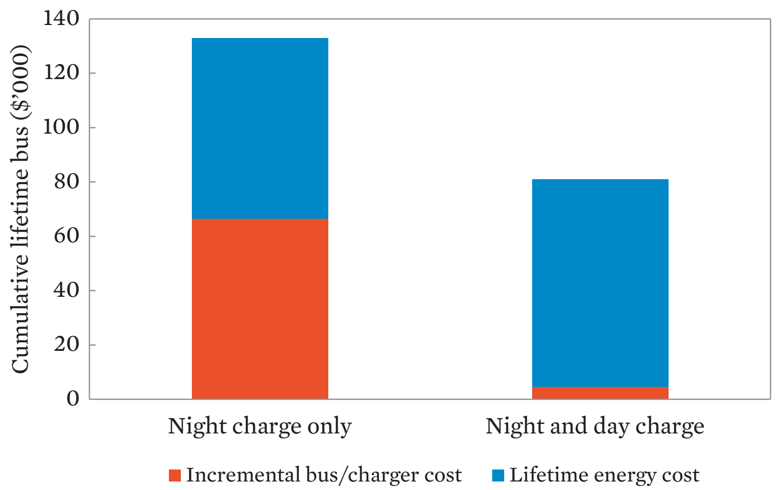
kWh = kilowatt-hour, km = kilometer, m = meter, PRC = People's Republic of China.

Source: Asian Development Bank.

4. Optimization of Charging Systems

BEB savings will depend largely on the price of electricity, with prices varying by a factor of 2 between cities in the PRC. Average prices, including the service fee, are from $0.11/kWh to $0.20/kWh. Buses are seldom charged during peak hours as all buses operate during that time. On average, the difference between the night and the off-peak day charge is $0.05/kWh. Figure 20 compares the costs of using a 10–12 m bus with a 430 kWh battery pack and overnight charging versus a 240 kWh battery pack and day plus night charging.

Figure 20: Comparison of the Costs of Night Charging versus Night and Day Charging on the Commercial Life Span of Buses



km = kilometer, kWh = kilowatt hour, m = meter, PRC = People's Republic of China.

Notes: Based on average night/off-peak day electricity charges in the PRC; average electricity consumption of a 12 m bus; 60,000 km annual mileage and 8-year life span; no discounting; bus with only night charge with a 430 kWh battery; bus with day plus night charge with a 240 kWh battery pack; average battery and charger costs of cities in the PRC.

Source: Asian Development Bank.

The average price difference of $0.05/kWh between night and off-peak day electricity is not sufficient to pay for the additional cost of a larger bus battery pack at current price levels. The better financial strategies in the PRC are to limit the battery size of buses and to realize one or various additional charges during the day.

B. Challenges for Low-Carbon Bus Support Policies

Plug-in Hybrids

With very few exceptions, plug-in hybrids are not charged. This means that they are operated like standard hybrids and their fuel usage is like those of standard hybrids. The bus is equipped with technology allowing charging from the grid, which is not used. This is due to the small average battery sizes of plug-in hybrids used in cities in the PRC (on average, 25 kWh for a 10–12 m bus), a lack of chargers, and the operational complexity of charging plug-ins, including lack of space. Also, cost savings for the operator are small due to relatively high electricity prices and low fossil fuel prices.[43] Plug-in hybrids are purchased instead of hybrids because subsidies are currently only given for plug-in hybrids. However, on average, 10–12 m plug-in hybrid bus costs around $20,000 or 20% more than a standard hybrid bus. If not recharged from the grid, the plug-in has no advantage at all over a standard hybrid, i.e., the additional investment results in no additional benefits. In the last 4 years, the government has subsidized around 70,000 plug-in hybrid buses. Promoting plug-in buses instead of standard hybrid buses has cost the government around $1.4 billion additional funds without any additional environmental or cost benefits, i.e., these resources could have been saved.

Battery Electric Buses Subsidies

As in many countries, up-front BEB subsidies have been very effective in convincing bus operators to purchase electric buses. BEBs have a lower purchase cost than conventional buses, while also having lower energy and maintenance costs. Subsidies are higher than the actual incremental cost of BEBs based on TCO. However, this is justified, as BEBs are riskier for bus operators due to the novelty of the technology and unknown actual operational costs. However, with operators having managed larger fleets of BEBs for the past few years, this risk has been reduced and subsidy levels can now be lowered. Subsidy levels, which go beyond the required incremental cost level, might only increase the profits of bus manufacturers or might result in purchasing a too large fleet of buses, i.e., a waste of financial resources. The policy of the government to start with high subsidy levels, and then gradually reducing them, is thus considered appropriate.

More problematic are some subsidy components of BEBs, which result in certain technologies or bus types being preferred:

(i) Buses longer than 12 m only receive 20% more subsidies than a standard size bus, even though a full 18 m electric bus will cost around twice that of a 10–12 m BEB. This policy clearly favors smaller buses. Subsidy levels for BEBs should reflect this,

[43] With current electricity and fossil fuel prices, and with the current battery size of plug-in hybrids, the operator will save around CNY10–CNY15 by charging the plug-in during the night, i.e., energy savings are insignificant and do not warrant the additional operational effort of charging these buses.

and be far higher for 14 m and 18 m buses to make electric units in this segment similarly attractive.

(ii) Subsidies are related to the pure electric drive range. While this approach is understood to prevent buses with very small battery sets from receiving subsidies, this can result in non-optimal configurations of buses with large battery sets instead of buses with fewer batteries that are recharged during the day. It also discourages the use of opportunity charge systems, including ultrafast charging systems or electric trolleybuses.

Up-front CAPEX subsidies are simple and send clear signals to bus operators, which also make these subsidies effective in encouraging the quick uptake of electric buses. However, as they are tied to certain bus types and technology approaches, they can result in the purchase of suboptimal bus types and bus sizes, and favor certain approaches to bus electrification. Once the initial hurdle of managing a substantial electric bus fleet has been overcome, a more effective and efficient approach might be to relate subsidies to electric bus usage, i.e., pay operational subsidies for the use of e-buses related to actual e-bus passenger per km driven.[44] Such a subsidy system would be technology- and size-neutral. Some provinces and cities, such as Guangzhou, are discussing how to establish annual subsides relative to the distance driven by e-buses. This would be a step in the right direction. Subsidy systems based on the indicator passenger–kilometer can be established, based on various simple-to-measure parameters:

(i) Distance driven is monitored through global positioning system (GPS) and an average 50% occupation rate of the maximum bus capacity to determine for each bus the passenger–kilometer realized. Payment of operators based on distance driven using GPS data is standard in the industry and used by many BRT systems. Using a default number of passengers per bus allows for differentiation of payment based on bus size, and is a simple approach to calculate payments relative to the actual bus performance. This approach is simple and does not require further equipment on buses, and fully complies with the objective to have subsidy payments relative to bus performance.[45]

(ii) A more sophisticated approach is to use passenger data electronic ticketing information, thereby determining for each bus the number of passengers transported and the average trip distance resulting directly in passenger–kilometer data. However, if tariffs are not distance-based, then trip distance might not be able to determine with electronic ticketing.

(iii) Usage of automated passenger counting equipment on buses in counting the number of passengers boarding and deboarding the bus at each station, thereby determining the average occupation rate of the bus. This information is combined with the bus distance driven derived from the GPS. Automated passenger counting equipment today have a precision level over 95%, and thus gives an accurate statement of the number of passengers onboard a bus at any time. This would be the most precise measurement, but does require automated passenger counting equipment on buses.

[44] Relating the subsidy to passenger per kilometer and not only to bus per kilometer avoids favoring smaller buses. Theoretically, passenger per kilometer can be calculated, for example, based on 50% of the maximum passenger capacity multiplied with the annual distance driven.

[45] Using as indicator distance driven only would favor smaller buses relative to larger units.

C. Conclusions Concerning Future Challenges

Many cities in the PRC will have full electric bus fleets in the next few years. To avoid inflating their bus fleet and bus costs considerably, this will require using larger electric buses and optimizing the bus battery pack and charging technology, including the potential use of trolleybus systems or opportunity charge systems on demanding routes.

The subsidy for plug-in hybrids has not resulted in the desired environmental impact, as plug-ins are not charged at the grid due to technical and operational issues. A further subsidy for hybrid or plug-in hybrids is not recommended as hybrids are cost-effective, and favoring plug-in hybrids is not an effective policy.

The BEB up-front subsidy policy has resulted in a large uptake of electric buses in the PRC. It has allowed for the breakthrough of the technology, and has effectively eliminated the barrier to adoption of electric buses by operators. With the costs of BEBs falling incrementally, subsidy levels can be lowered.

The current subsidy policy is not size- and technology-neutral, but favors smaller buses with moderate to large battery sets. This can result in suboptimal technology and bus choice by bus operators. Switching from up-front investment subsidies toward operational subsidies related to bus passenger per kilometer would be technology-neutral, and reward efficient operators of e-buses.

VII. Conclusions and Recommendations

Based on actual performance data on very large operational low-carbon buses (LCBs), experience of 16 cities in the People's Republic of China (PRC) with an urban bus fleet of 70,000 units in total, data was collected and analyzed in 2017 and 2018. Fossil-fueled, hybrid, plug-in hybrid, and battery electric buses (BEBs) were compared on their environmental and financial impacts; and also, various promotion policies implemented by the PRC for LCBs were discussed.

On the environment side, the greenhouse gas (GHG) impact of LCBs is basically limited by the high carbon factor of electricity production in the PRC. There, hybrids use around 20% less energy and reduce GHG emissions in an equivalent manner, while electric buses use one-fourth of energy of fossil fuel buses and reduce around 30%–40% of well-to-wheel GHG emissions. Thus, BEBs clearly have a positive impact on reducing GHG missions even in the context of a fossil fuel-dominated grid. However, further reductions in the PRC will only be possible if the electricity production shifts more toward renewables.

BEBs have zero local emissions and reduce noise pollution significantly. However, the newest emission standards applied in the PRC have reduced this impact of electric buses as modern fossil fuel buses also have very low emission levels.

On the financial side, in the PRC, the total cost of ownership (TCO) of hybrid buses are comparable with conventional units, while electric buses still have significantly higher TCOs. The incremental capital expenditure investment cannot be recovered even with lower energy and maintenance costs for BEBs. This situation can change in the future with fossil fuel price increases, lower battery costs, and if BEBs are used more intensively and for longer periods. Therefore, the gradual reduction of subsidies for electric buses is justified.

Bus operators need to optimize the electric bus system configuration for types of electric bus technologies, battery size, and charging technology. Parameters (e.g., route distance, electric bus performance in summer using air-conditioning, battery reserve rates, and battery capacity decline over time) need to be taken into account to determine the battery sizes of buses under different charging regimes. The optimal system configuration will depend on technical and route criteria, electricity prices, and bus costs. In general, pure BEBs are best used for smaller and medium-sized units operating shorter routes with intermediate fast charging for buses operating longer routes, while bus routes with high frequencies and high passenger demand are best operated by opportunity charge systems and electric trolleybuses.

On the policy side, the PRC, as in many other countries, has various incentives to encourage the uptake of LCBs. Currently, the PRC subsidizes LCBs upfront, which invited an uptake of LCBs by bus operators as hybrid and electric units cost less to purchase than diesel or gas buses, while having lower operational costs. Plug-in hybrids are widely used in the PRC and, recently, cities have only purchased plug-in hybrids instead of standard hybrids as the latter are no longer subsidized. However, with very few exceptions, plug-in hybrids are not recharged at the grid because they only have a small battery onboard and due to operational complexity. Thus, in practice, significantly more expensive plug-in hybrid buses operate like a standard hybrid unit, but only with the benefits of standard hybrids. As plug-in hybrids cost around 20% more than standard hybrid buses, this is not an efficient use of resources.

As current subsidies unduly prefer smaller BEBs, and those with a specific battery set buses longer than 12 m, opportunity charge systems, and trolleybuses do not have the same advantages. Therefore, the subsidy policy may result in a suboptimal system choice with lower environmental impact and higher costs. Also, high up-front subsidies potentially lead to very large fleet and an underutilization of units as reflected in BEBs running in cities with only 50% of the average mileage of conventional buses. A more effective subsidy scheme should be related to passenger per kilometer performance by electric buses, thus being technology-, size-, and system-neutral.

The PRC has vast experience in successfully operating LCBs. Many cities are moving toward full electrification of bus services, and current policies and available electric bus technologies allow them to take this step. Hybrid buses have been used in the PRC as well as in other countries for heavier routes and larger buses, and basically as an intermediate step toward full electrification. In the case of the PRC, plug-in hybrids have not resulted in additional benefits compared with hybrids, as operators do not charge them at the grid. Today, the pathway of conventional buses to hybrids to plug-in hybrids to BEBs is not necessarily the optimal path for any given city. For other countries and cities, moving directly from conventional buses to electric buses can be feasible as reliable electric technologies are already available for all types of routes and buses.

APPENDIX 1

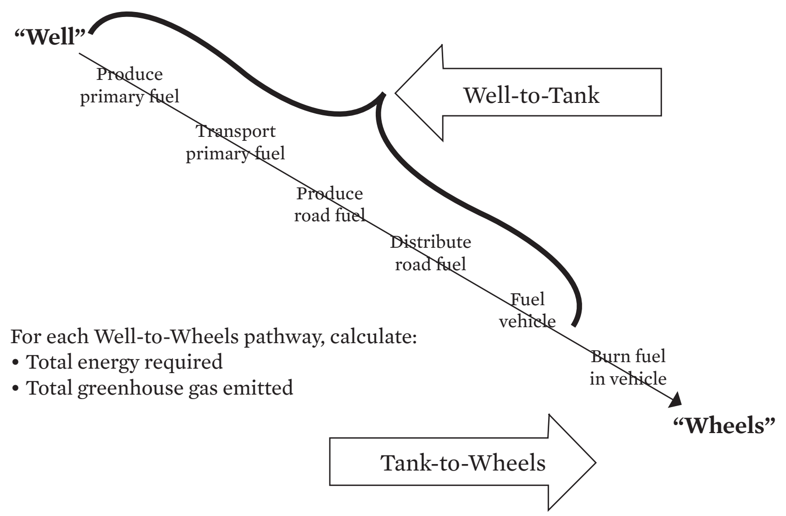
Methodological Aspects

Hybrid and plug-in hybrid buses considered in this study include diesel-hybrids, compressed natural gas hybrids, liquefied natural gas hybrids, and liquefied petroleum gas hybrids. Bus sizes included in this study are 6 meters (m), 8 m, 10 m, 12 m, 14 m, and 18 m units.[1] Bus units with length of 14 meters also include double-deckers. Data on the performance, energy usage, and distance driven by each bus was collected every month from January to December 2016. Additionally, data was collected per bus category and technology on investment cost, charging structure and cost, energy usage and cost, maintenance cost (separated per item), bus availability, and fault rates per technology.

Emissions included in this report are as follows:

(i) Greenhouse gas (GHG) emissions, including direct (tank-to-wheel) and indirect emissions (well-to-tank). Black carbon is included within indirect emissions.
(ii) Local pollutants, including particulate matter ($PM_{2.5}$) and nitrogen oxide (NO_X) resulting as tailpipe emissions from internal combustion engines.

Figure A1: Tank-to-Wheel, Well-to-Tank, and Well-to-Wheels



Source: European Commission. 2016. *Well-to-Wheels Analyses*. https://ec.europa.eu/jrc/en/jec/activities/wtw.

[1] Units with length of 6 meters (m) cover buses that are 5.1–7 m in size; 8 m units, those that are 7.1–9 m in size; 10 m units, those that are 9.1–11 m in size; 12 m units, those that are 11.1–13 m in size; 14 m units, those that are 13.1–15 m in size; and 18 m units those that are larger than 15.1 m.

Direct Greenhouse Gas Emissions (Tank-to-Wheel)

The GHGs included under the United Nations Framework Convention on Climate Change (UNFCCC) are carbon dioxide (CO_2), methane (CH_4), nitrous oxides (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), sulfur hexafluoride (SF_6) and trifluoride nitrogen (NF_3). Those that are relevant for the transport sector are CO_2, CH_4, and N_20. However, according to UNFCCC methodologies for determining emissions from the transport sector, N_2O emissions are very marginal. Therefore, the only GHG emissions included in this study are CO_2 and CH_4.[2] CO_2 emissions are determined based on energy consumption, according to the Intergovernmental Panel on Climate Change (IPCC) methodology (2006), which is also used in all approved UNFCCC methodologies:

$$E_{CO_2,C} = FC_x \times NCV_x \times EF_{CO_2,x}$$

where:

$E_{CO_2,C}$ CO_2 emissions due to combustion
FC_x consumption of fuel type x
NCV_x net calorific value of fuel type x
$EF_{CO_2,x}$ CO_2 emission factor of fuel type x

Direct GHG emissions also include methane slip for gaseous vehicles. Methane slip is determined based on the average reported values of the International Council on Clean Transportation, which summarizes different sources. Leakage of unburned methane is important due to the high global warming potential (GWP) of CH_4.[3] "Direct" methane slip is caused in the crankcase and exhaust pipe of a vehicle, and "indirect" methane slip is caused by leaks in the gas pumps and wells.[4]

Indirect Greenhouse Gas Emissions (Well-to-Wheel)

The most important indirect emission is due to electricity production, including transmission and distribution losses. Electricity-based emissions are based on the combined margin approach used by the UNFCCC for climate change projects. These are separated in various grid regions of the People's Republic of China (PRC). The calculations in this report took into account the unweighted average of the grid in the PRC.

Indirect emissions also include well-to-tank emissions of fossil fuels. Based on the UNFCCC, a standard markup factor per fossil fuel type is used to estimate the GHG emissions caused upstream by fossil fuel extraction, refinery, and transport.

[2] IPPC. 2006. *Fifth Assessment Report*. Chapter 3. https://www.ipcc.ch/report/ar5/.

[3] For a discussion of GWP, see, e.g., IPCC Fourth Assessment Report: Climate Change 2007, Climate Change 2007: Working Group I: The Physical Science Basis. https://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html,

[4] International Council on Clean Transportation (ICCT). 2015. Assessment of Heavy Duty Natural Gas Vehicles Emissions: Implications and Policy Recommendations. Table 4. https://www.theicct.org/publications/assessment-heavy-duty-natural-gas-vehicle-emissions-implications-and-policy,

Table A1.1: Grid Factors

Regional Grid	Covered Region	Grid Factor in $kgCO_{2e}/kWh$
North China Grid	Beijing, Tianjin, Hebei, Shanxi, Shandong, and Inner Mongolia	0.76
Northeast China Power Grid	Liaoning, Jilin, and Heilongjiang	0.78
East China Grid	Shanghai, Jiangsu, Zhejiang, Anhui, and Fujian	0.70
Central China Power Grid	Henan, Hubei, Hunan, Jiangxi, Sichuan, and Chongqing	0.65
Northwest China Power Grid	Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang Uygur	0.63
Southern China Power Grid	Guangdong, Jiangxi, Yunnan, Guizhou, and Hainan	0.63
Unweighted average		**0.69**

$kgCO_{2e}/kWh$ = kilogram carbon dioxide equivalent per kilowatt-hour.

Source: Institute for Global Environmental Strategies. 2019. IGES List of Grid Emission Factors. https://pub.iges.or.jp/pub/list-grid-emission-factor; calculated by IGES using data from the People's Republic of China, National Development and Reform Commission 2015 Report; factor based on data year 2013.

Black Carbon

Increased particle emissions result not only in worsening air quality, but also in higher black carbon emissions. A scientific assessment of black carbon emissions and impacts found that these are second to CO_2 in terms of climate forcing. On average, black carbon is 2,700 times more effective on a mass-equivalent basis than CO_2 in causing climate impacts within 20 years, and 900 times more effective within 100 years.[5] Black carbon is part of particulate matter (PM) from diesel engines. The GHG impact of black carbon is determined based on the mass of $PM_{2.5}$ emissions (using the European emission model COPERT),[6] the fraction of black carbon in $PM_{2.5}$ and the GWP_{100} of black carbon.

Local Pollutants

Local pollutants considered, due to their impact on local air quality, are $PM_{2.5}$ and NO_x. Only combustion-related emissions are included. For example, particle emissions caused by tires or brakes are not considered. Pollutants are determined based on the emission category of the vehicle using COPERT.[7]

[5] Bond et al. 2013. Bounding the Role of Black Carbon in the Climate System: A Scientific Assessment. *Journal of Geophysical Research*. doi:10.1002/jgrd.50171 or World Bank. 2014. *Reducing Black Carbon Emissions from Diesel Vehicles: Impacts, Control Strategies, and Cost-Benefit Analysis*. http://documents.worldbank.org/curated/en/329901468151500078/Reducing-black-carbon-emissions-from-diesel-vehicles-impacts-control-strategies-and-cost-benefit-analysis.

[6] For a discussion of COPERT, see http://emisia.com/products/copert.

[7] European Environment Agency. 2016. Road Vehicle Tyre and Brake Wear; Tier 2 approach (i.e., not considering speed, load factor, or gradient).

Since January 2015, all heavy-duty vehicles in the PRC must comply with the China National emission standard IV (equivalent to Euro IV), and since January 2017, all public transport buses must comply with the China National emission standard V.

Summary Default Values

Table A1.2 summarizes default values used within this report for calculating the environmental impact of LCBs.

Table A1.2: Default Values for Calculating the Environmental Impact of Low-Carbon Buses

Parameter	Description	Value	Source
$NCV_{D,NG}$	Net Calorific Value of diesel/ natural gas	Diesel: 43.0 MJ/kg NG: 48.0 MJ/kg	IPCC, 2006, Table 1.2
$EF_{CO2,D/NG}$	CO_2 Emission Factor of diesel /natural gas	Diesel: 74.1 gCO_2/MJ NG: 56.1 gCO_2/MJ	IPCC, 2006, Table 1.4
GWP_{100} of black carbon	Global warming potential 100 years of black carbon	900	IPCC, 2013, Table 8A
GWP_{100} of CH_4	Global warming potential 100 years of methane	28	IPCC, 2013, Table 8A
WTT $MF_{D/CNG/LNG}$	WTT mark-up factor for diesel, CNG, and LNG	Diesel: 23% CNG: 18% LNG: 29%	UNFCC, 2014, table 3
Methane slip $NG_{TTW/WTW}$	Methane slip as % of NG consumption TTW and WTW	TTW: 1.1% WTW: 2.3%	ICCT, 2015, Table 4

CNG = compressed natural gas, CH_4 = methane, CO_2 = carbon dioxide, EFCO2,x = CO2 emission factor of fuel type x, GWP = global warming potential, ICCT = International Council on Clean Transportation, IPCC = Intergovernmental Panel on Climate Change, kg = kilogram, LNG = liquefied natural gas, MF = mark-up factor, MJ = megajoule, NCVx = net calorific value of fuel type x, NG = natural gas, TTW = tank-to-wheel, UNFCC = United Nations Framework Convention on Climate Change, WTT = well-to-tank, WTW = well-to-wheel.

Sources: International Council on Clean Transportation (ICCT). 2015. *Assessment of Heavy Duty Natural Gas Vehicles Emissions: Implications and Policy Recommendations*. https://www.theicct.org/publications/assessment-heavy-duty-natural-gas-vehicle-emissions-implications-and-policy; Intergovernmental Panel on Climate Change (IPPC). 2006. IPCC *Guidelines for National Greenhouse Gas Inventories*. https://www.ipcc-nggip.iges.or.jp/public/2006gl/; IPCC. 2013. *Fifth Assessment Report (AR5)*. https://www.ipcc.ch/report/ar5/; and UNFCCC. 2014. *CDM Methodological Tool: Upstream Leakage Emissions Associated with Fossil Fuel Usage. Version 2.0*. https://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-15-v2.0.pdf.

APPENDIX 2

Low-Carbon Bus Incentive Schemes

The subsidy is based on 10–12 meter (m) bus as a standard vehicle. The subsidy level of pure electric buses of other lengths can be calculated relative to the 10–12 m bus based on the actual bus length and the energy consumption. A bus with a length of less than 6 m is given 0.2 times the subsidy of a standard vehicle, a bus between 6–8 m is given 0.5 times the subsidy, a bus between 8–10 m is given 0.8 times the subsidy, and double-deckers or longer buses are given 1.2 times the subsidy.

Table A2: Subsidy Level of Buses
(CNY10,000/bus)

Vehicle type	Energy Consumption per Unit Carrying Mass E_{kg} in Wh/km.kg	Standard Vehicle (10–12 m bus)					
		Electric Driving Range (constant velocity method, km)					
		6–19	20–49	50–99	100–149	150–249	≥250
Pure electric bus	$E_{kg} < 0.25$	20	26	30	35	42	50
	$0.25 \le E_{kg} < 0.35$	20	24	28	32	38	48
	$0.35 \le E_{kg} < 0.5$	18	22	24	28	34	42
	$0.5 \le E_{kg} < 0.6$	16	18	20	25	30	36
	$0.6 \le E_{kg} < 0.7$	12	14	16	20	24	30
Plug-in hybrid passenger bus		/	/	20	23	25	

/ = not applicable, CNY = Chinese yuan, E_{kg} = energy consumption per kilogram, kg = kilogram, km = kilometer, m = meter.

Example: 10–12 m bus with electric drive range of 120 km and an E_{kg} of 0.4 receives a subsidy of CNY280,000; an electric bus with the same drive range and same E_{kg} but with a size of 7 m would receive a subsidy of CNY140,000.

Source: Ministry of Finance, People's Republic of China.

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Sustainable Transport Solutions

Low-Carbon Buses in the People's Republic of China

This publication discusses the real-world performance data of low-carbon buses in the People's Republic of China. It also reviews the environmental and financial impacts, as well as the policies used to promote them. The People's Republic of China has taken the lead in the deployment of low-carbon buses and is moving toward full electrification to address climate change and reduce greenhouse gas emissions. Data and information in this publication can benefit countries interested in promoting low-carbon buses to design appropriate climate change policies.

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