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Fuel-efficiency technology trend assessment for LDVs in China: Hybrids and electrification

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1 Background

Fuel-consumption standards drive down China's use of fuel by the on-road sector and encourage the uptake of advanced vehicle-efficiency technologies. Understanding the need for a policy roadmap and long-term strategies to provide certainty for long-term fuel consumption, technology advancement, and potential compliance costs for manufacturers, China is looking ahead to advance post-2020 standards for light-duty vehicles.

In its "Made in China 2025" strategic initiative (MIIT, 2015), China set a 2025 fleet efficiency target of 4 L/100 km for passenger cars, a 20% decrease from the 2020 target of 5 L/100 km. In the Technology Roadmap for Energy Saving and New Energy Vehicles published by the Society of Automotive Engineers of China (SAE China, 2016), a 2030 fleet efficiency target of 3.2 L/100 km was set. To evaluate whether and how these targets can be met, it is essential to understand what technologies will be available within the 2020–2030 timeframe and what the costs of applying those technologies in the Chinese market will be.

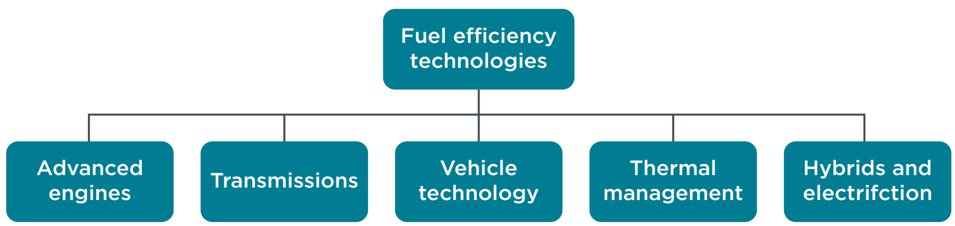

Figure 1 Categorization of fuel-efficiency technologies in the working paper

This series of technical working papers aims to provide a comprehensive understanding of the current availability, effectiveness, and future market penetration of key fuel-efficiency technologies that manufacturers are likely to use in China by 2030. This information enables a more accurate, China-specific understanding of future technology pathways.

We group technologies into several categories: advanced engine, transmission, vehicle technologies, thermal management, and hybrids and electrification (Figure 1). The specific technologies we considered include those that are available today and others that are under development and expected to be in production in the next 5–10 years.

This research relies on information from publicly available sources, third-party databases, and information from the participating partners. Our approach includes:

- A detailed literature survey, including both Chinese and global regulatory documents, official announcements, and industry and academic reports.
- Analysis of databases from Polk and Segment Y.

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- Conversations with manufacturers, tier one suppliers, research entities, and domestic and international experts.

For each key technology, we discuss how it reduces passenger-car fuel consumption, its effectiveness in reducing fuel consumption, and its current level of application or potential application in the China market. Wherever applicable, we compare technology trends in China with those in the United States and the European Union to reflect potential technology pathways in the long term.

This working paper assesses technology progress and new developments in hybrid and electric vehicles.

Table 1 Comparison of characteristics of internal combustion engine vehicles and electrified vehicles

		ICE vehicle	Mild HEV	Full HEV	PHEV	BEV
Components	ICE + fuel tank	Yes	Yes	Yes	Yes	No
	12-volt battery	Yes	Yes	Yes	Yes	Yes
	Motor/generator + higher voltage traction battery (24V and above)	No	Yes	Yes	Yes	Yes
Functions	Start-stop	Possible	Yes	Yes	Yes	Yes
	Regenerative braking	Minor	Yes	Yes	Yes	Yes
	Electric power assist	No	Yes	Yes	Yes	Yes
	All-electric drive	No	No	Yes[a]	Yes	Yes
	Plug-in	No	No	No	Yes	Yes
Electrification degree of powertrain system		–	Very low	Low	High	100%

[a] Full HEVs can be driven in all-electric mode but for limited periods of time and at limited speeds.

2 Introduction

Partly or fully electrifying a vehicle powertrain system can effectively reduce fuel consumption or even cut it to zero. These technologies are known as hybrid powertrain systems or electric drive systems. Table 1 compares the major components and functions of four types of vehicles with electrified powertrain systems, using internal combustion engine (ICE) vehicles as reference. The electrification degree of a powertrain system increases from mild hybrid electric vehicle (HEV) to full hybrid electric vehicle to plug-in hybrid electric vehicle (PHEV) to battery electric vehicle (BEV).

A 2015 study by the China Automotive Technology and Research Center (CATARC) indicated that fuel-saving potential and added technology cost rise with the electrification degree of the powertrain system (Zhao, Wang, Yu, & Ren, 2015). The most basic form of electrification, mild HEV, can achieve a 10% fuel saving with an added technology cost of 5,000 yuan, based on a mid-size car. Comparatively, the ultimate form of electrification, BEV, can eliminate 100% of direct fuel consumption at a cost of 25,000–58,000 yuan.

ICE vehicles with stop-start and regenerative braking functions such as Mazda vehicles with i-ELOOP technology are sometimes referred to as micro HEVs. However, they are not treated as a form of electrification in this working paper because they do not have an electric motor to assist with vehicle propulsion. For these micro HEVs, the ICE is the only power source of the wheels. Their low-voltage batteries can be used only to power basic accessories such as computers, lights, windows, and entertainment system. To provide power to the drivetrain, a higher-power traction battery pack and an electric motor are required. We regard stop-start and regenerative braking as advanced engine technologies and discuss them in the working paper on advanced engine technology in this series.

3 Hybrid electric vehicles

HEVs feature hybrid powertrain systems that combine a conventional ICE system with an electric drive system. The hybrid system enables HEVs to achieve fuel savings in a variety of ways. These include capturing and reusing energy normally lost to the brakes, or regenerative braking; maintaining performance while using a smaller, more-efficient engine; shutting off the engine at idle and at very low load conditions, cutting fuel consumption to zero; and enabling the engine to run at lower speeds where it is more efficient. Other fuel-saving measures are replacing the alternator with more-efficient motor/generator systems; replacing less-efficient mechanical water and oil pumps with electrical pumps that operate only when needed; and supplying the large amounts of electrical power required by automated safety features, heated seats, dynamic chassis control, and other power-hungry components of modern cars (German, 2015).

A full HEV can be driven by only the ICE, only the electric motor, or a combination of the two. With a mild HEV, the electric motor can assist the ICE to power the drivetrain but is not used to drive the wheels on its own. In other words, a mild HEV cannot run on only its electric motor.

Based on the configuration of the hybrid system, HEVs can be classified into series hybrids, parallel hybrids, and series/parallel hybrids. In a series hybrid, only the electric motor can drive the wheels, using power from either or both the traction battery and a generator run by the ICE. The proportions of power coming from the traction battery and the ICE/generator are controlled by the vehicle's computer. Since the ICE is not mechanically connected to the wheels, it can be operated at its optimum settings all the time. Typically, a series hybrid is equipped with a larger traction battery plus a smaller ICE and tends to be more efficient at low speeds such as in city driving.

In a parallel hybrid, the ICE and the electric motor can individually supply power to the drivetrain. Depending on the power needs, the computer directs the ICE and the electric motor to power the wheels either independently or simultaneously. A parallel hybrid is usually equipped with a larger ICE plus a smaller traction battery and tends to be more efficient at high speeds such as in highway driving because of the direct connection from the engine to the transmission. Parallel hybrids can be further divided into belt-driven starter/generator (BSG), integrated starter/generator (ISG), and P2 systems. A BSG system replaces the conventional starter with a high-powered electric motor that is connected to the engine shaft by a high-tension belt. An ISG system combines the conventional starter and generator into a single machine that is fitted directly to the engine crankshaft. The generator/starter of both BSG and ISG can work in both directions to capture braking energy, or to provide power assist to the engine. A P2 system is just an ISG with an additional clutch between the engine and the motor and is so called because it is a parallel hybrid with two clutches.

Series/parallel hybrids combine the benefits of series and parallel configurations. A planetary gear or a clutch pack is used to control whether the ICE is connected to the drivetrain. When the ICE is engaged, it can turn the wheels directly with power assist from the electric motor in the parallel mode. When the ICE is disconnected from the wheels, it runs the generator to power the electric motor, which directly drives the vehicle in the series mode. This complex architecture enables greater efficiency in real time but with a relatively higher cost. Currently available series/parallel hybrid systems can be further subdivided into the sophisticated power-split hybrid system, mainly used by Toyota, Ford, and GM, and the relatively simpler two-motor system, mainly used by Honda and SAIC. The features of these two types of series/parallel hybrid systems will be introduced in detail in the following section.

It should be noted that vehicles with series or series/parallel configurations are all full HEVs because their electric motors have the ability to drive the vehicle on its own. However, vehicles with a parallel configuration can be either mild or full HEVs, depending on whether the electric motor is used to power the wheels independently.

3.1 CURRENT STATUS

HEVs are not classified as new-energy vehicles[1] (NEVs) by the Chinese government and thus do not enjoy the same set of fiscal and administrative incentives as BEVs and PHEVs do. These include national purchase subsidies, local purchase subsidies, vehicle registration privileges,[2] and road access privileges. This makes HEVs relatively uncompetitive with BEVs and PHEVs. The market penetration of HEVs in China's new passenger vehicle fleet was 0.06% in 2015 and 0.33% in 2016 (Northeast Securities, 2017). By comparison, in 2014 HEVs accounted for about 20% of new vehicles sold in Japan (German, 2015) and 2.6% of new vehicles sold in the United States (EPA, 2018). In 2017, the market share of HEVs in China increased to 0.71% (Automotive Data Center of CATARC, 2018), higher than the 0.45% penetration of subsidized PHEVs.

As in other countries, HEVs were introduced into China earlier than BEVs and PHEVs. Toyota offered its second-generation Prius HEV in China

1 According to the Chinese government, new-energy vehicles include BEVs, PHEVs, and fuel cell electric vehicles (FCVs).

2 Tianjin and Guangzhou offer vehicle registration privileges to HEVs, an important incentive to boost local HEV sales. In 2017, Tianjin and Guangzhou were the two cities with the largest HEV sales in China. Comparatively, more cities offer vehicle registration privileges to NEVs, including Shanghai, Beijing, Shenzhen, Guangzhou, Tianjin, Hangzhou, and Guiyang.

as early as 2005. The FAW-Toyota joint venture handled assembly and marketing of the Prius in China. However, because all the major parts were imported, the Prius price was as high as 300,000 yuan per vehicle, which significantly reduced its cost-competitiveness. From 2005 to 2009, cumulative sales of the Prius in China were only 3,500 (Wen, 2016). In 2009, Toyota stopped production of the Prius in China.

The year 2015 was a new start for China's HEV market as Toyota localized production of three popular HEV models, including the Corolla, the Levin,[3] and the Camry. This led to a significant cost reduction for Toyota hybrids in China and greatly expanded China's HEV market. That year, total sales of HEVs in China exceeded 10,000 for the first time. Camry topped the list with 6,755 sales.

In 2016, the number of domestically produced HEV models sold in China increased from four to 12, of which 11 were made by joint ventures. The Chang'an Eado mild hybrid was the first and only hybrid model developed by an independent automaker at that time; however, it sold only six units that year. In 2016, sales of HEVs in China reached 80,988. The Corolla replaced the Camry to become the best-selling

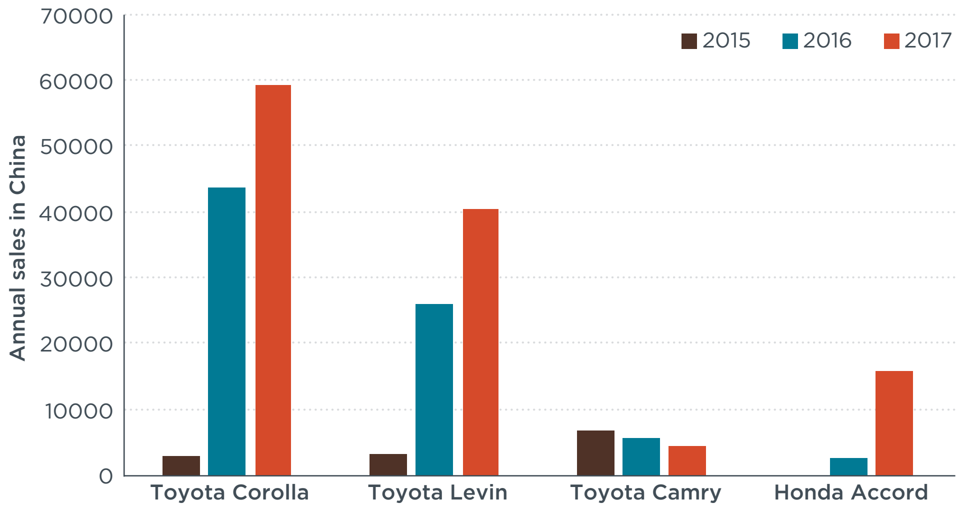

Figure 2 Annual sales of four top-selling HEVs in China in 2015–2017

HEV, with deliveries of 43,593, followed by the Levin, the Camry, and the Honda Accord. Though Hyundai/Kia, GM, and Ford also introduced HEV models to China, Japanese brands still dominated China's HEV market with a market share of 97% in 2016.

In 2017, China's HEV market continued expanding, achieving sales of 176,036 (Automotive Data Center of CATARC, 2018). Sales of Japanese models exceeded 160,000 in 2017, with the Corolla continuing to rank first with sales of 59,400. Figure 2 shows sales of the Corolla, the Levin, the Camry, and the Accord in China in 2015–2017 (Northeast Securities, 2017; Li, 2018; Sohu Auto, 2018).

By the end of 2017, there were 17 domestically made HEV models available in the Chinese market, still many fewer than ICE vehicles, BEVs, and PHEVs. Just two of the 17 were developed by China's independent automakers, including the Chang'an Eado HEV and the JAC Refine M4 HEV, both of which are 48V mild HEVs. The 15 other models are produced by joint ventures. Table 2 compares the major specifications of hybrid systems, engines, transmissions, electric motors, and traction batteries of each model with its fuel consumption value under the New European Driving Cycle (NEDC) and the manufacturer's suggested retail price (MSRP). It should be noted that the Toyota Prius currently available in China is the discontinued 2012 Prius model produced by FAW-Toyota. Newer Prius models equipped with a more-advanced hybrid system has not yet been introduced to China.

3 There are two Chinese versions of the 11th-generation Toyota Corolla. The first version is produced by FAW-Toyota and is called the Corolla while the second version is produced by GAC-Toyota and is called the Levin.

Table 2 Technical information on domestic HEVs available in the Chinese market[a]

		Hybrid system			Engine								Motor		Battery			
OEM	**Model**	**Name**	**Config**	**Degree**	**Air intake**	**Fuel supply**	**Cylinder number**	**Disp (L)**	**Power (kW)**	**Torque (N·m)**	**Unique tech**	**Transmission**	**Power (kW)**	**Torque (N.M)**	**Type**	**Capacity (kWh)**	**FC (NEDC, L/100km)**	**Base MSRP (thousand yuan)**
FAW Toyota (joint venture)	**2017 Toyota Corolla**	HSD	Series/parallel (input power-split)	Full	Naturally aspirated	MPI	4	1.8	73	142	VVT-i Atkinson cycle	E-CVT	53	207	Ni-MH	1.8	4.2	139.8
FAW Toyota (joint venture)	**2012 Toyota Prius**	HSD	Series/parallel (input power-split)	Full	Naturally aspirated	MPI	4	1.8	73	142	VVT-i Atkinson cycle	E-CVT	60	207	Ni-MH	1.31	4.3	229.8
GAC Toyota (joint venture)	**2017 Toyota Levin**	HSD	Series/parallel (input power-split)	Full	Naturally aspirated	MPI	4	1.8	73	142	VVT-i Atkinson cycle	E-CVT	53	207	Ni-MH	1.31	4.2	139.8
GAC Toyota (joint venture)	**2018 Toyota Camry**	HSD	Series/parallel (input power-split)	Full	Naturally aspirated	P-DI	4	2.5	131	221	VVT-iE Atkinson cycle	E-CVT	88	202	Ni-MH	1.6	4.1	239.8
GAC Honda (joint venture)	**2016 Honda Accord**	i-MMD	Series/parallel (two-motor system)	Full	Naturally aspirated	MPI	4	2.0	107	175	i-VTEC Atkinson cycle	E-CVT	135	315	Li-ion	1.3	4.2	239.8
Dongfeng Honda (joint venture)	**2017 Honda Spirior**	i-MMD	Series/parallel (two-motor system)	Full	Naturally aspirated	MPI	4	2.0	107	175	i-VTEC Atkinson cycle	E-CVT	135	315	Li-ion	1.3	4.2	249.9
Dongfeng Honda (joint venture)	**2017 Honda CR-V**	i-MMD	Series/parallel (two-motor system)	Full	Naturally aspirated	MPI	4	2.0	107	175	i-VTEC Atkinson cycle	E-CVT	135	315	Li-ion	1.3	4.8	219.8
Dongfeng Nissan (joint venture)	**2017 Nissan Murano**	Intelligent Dual Clutch Control	Parallel (P2)	Mild	Supercharged	MPI	4	2.5	180	330	CVTC	CVT	15	160	Li-ion	0.6	8.2	297.8
SAIC GM (joint venture)	**2017 Buick Regal**	Voltec	Series/parallel (input power split)	Full	Naturally aspirated	GDI	4	1.8	94	175	–	E-CVT	114	415	Li-ion	1.5	4.3	229.8
SAIC GM (joint venture)	**2016/2018 Buick LaCrosse**	Voltec	Series/parallel (input power split)	Full	Naturally aspirated	GDI	4	1.8	94	175	–	E-CVT	114	415	Li-ion	1.5	4.7	275.8
SAIC GM (joint venture)	**2017/2018 Chevrolet Malibu XL**	Voltec	Series/parallel (input power split)	Full	Naturally aspirated	GDI	4	1.8	94	175	–	E-CVT	114	415	Li-ion	1.5	4.3	239.9
SAIC GM (joint venture)	**2018 Cadillac XT5**	eAssist	Parallel (BSG)	Mild	Turbocharged	GDI	4	2.0	198	400	–	9AT	6.6	49	Li-ion	0.45	7.9	379.9
Chang'an Ford (joint venture)	**2017 Ford Mondeo**	Ford's hybrid system	Series/parallel (input power-split)	Full	Naturally aspirated	MPI	4	2.0	105	175	Atkinson cycle	E-CVT	92	228	Li-ion	1.4	4.2	259.8
Beijing Hyundai (joint venture)	**2016 Hyundai Sonata 9**	TMED	Parallel (P2)	Full	Naturally aspirated	GDI	4	2.0	115	189	Atkinson cycle	6AT	38	205	Li-ion polymer	1.62	4.8	209.8
Dongfeng Yueda Kia (joint venture)	**2016 Kia K5**	TMED	Parallel (P2)	Full	Naturally aspirated	GDI	4	2.0	115	189	Atkinson cycle	6AT	38	205	Li-ion polymer	1.62	4.8	199.8
Chang'an (independent brand)	**2016 Chang'an Eado**	Hybrid 48V (48V+ISG)	Parallel	Mild	Naturally aspirated	MPI	4	1.6	92	160	DVVT	5MT	11.5	50	Li-ion	0.384	5.9	86.9
JAC (independent brand)	**2018 Refine M4**	Hyboost (48V+BSG)	Parallel	Mild	Turbocharged	GDI	4	1.5	128	251	–	6MT	12	55	Li-ion	0.384	8.0	129.8

Note: Data and information in this table are derived from Auto Home, 2018a.

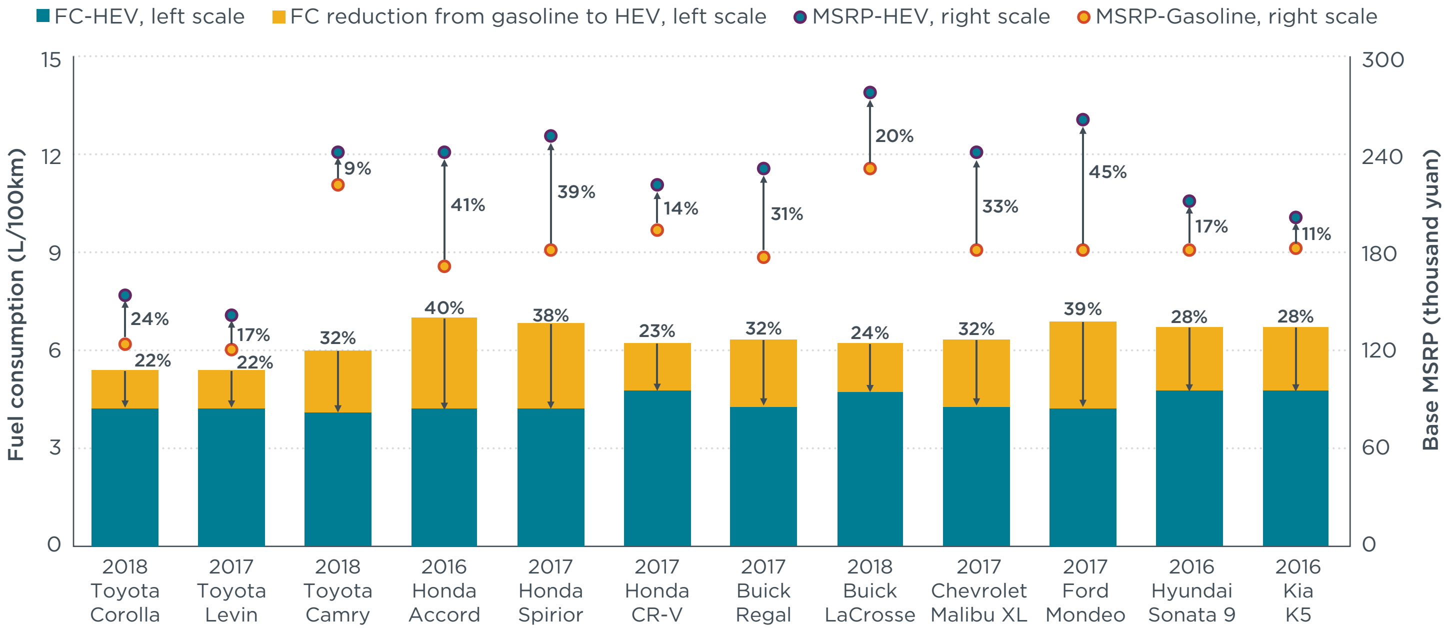

Figure 3 Fuel consumptions and MSRPs of full HEV models sold in China and their corresponding gasoline counterparts

3.1.1 Full HEVs

Most of the domestic hybrid models sold in China are full HEVs. Figure 6 compares the fuel consumption and base MSRP of each full HEV model sold in China with its gasoline counterpart. Four principles were used to choose the gasoline counterpart for each full HEV model: (1) same model, (2) same model year, (3) similar performance, and (4) best efficiency. The Prius is not included in this figure because it does not have a gasoline counterpart for comparison. In general, the fuel consumption of full HEVs under the NEDC is 22%–40% lower than the gasoline counterparts, with an average value of 30%. It should be noted that the gasoline counterparts of these full HEVs performed well in fuel efficiency by using various advanced engine, transmission, thermal management, and lightweighting technologies. The tradeoff for fuel saving is increased cost. As shown in Figure 3, the MSRP of full HEVs is 9%–45% higher than that of the corresponding gasoline vehicle. Reducing cost is still of great importance to increase the popularity of full HEVs. One of the key factors resulting in the leading sales of the Toyota Corolla and Levin in China is their successful cost control. As can be seen in the figure, the MSRPs of these two models are much lower than those of competitors.

The first and most famous full hybrid system in the world is the Toyota Hybrid System, which was renamed the Hybrid Synergy Drive (HSD) when the Prius was redesigned for the second U.S. generation in 2003. The HSD system is a power-split series/parallel hybrid system, which uses a planetary gear to adjust and blend the amount of power from the ICE and traction motor, based on the exact needs of the driving wheels. The HSD transmission, called e-CVT, performs similarly to a conventional continuously variable transmission (CVT), continuously adjusting the effective gear ratio between the ICE and the wheels to keep the ICE working at the most efficient speed, especially when the wheels increase rotational speed during acceleration. The ICE employed by the HSD system is a high-efficiency Atkinson cycle engine, paired with Toyota's advanced VVT-i or VVT-iE technology. The Atkinson cycle engine enables an increased expansion ratio and reduces waste heat through a high compression ratio, leading to thermal efficiency as high as 41% (Hayashi, 2016). The HSD system is now used by Toyota and Lexus for all of their hybrid models, including the Toyota Corolla, the Levin, and the Camry currently sold in China. Compared with their gasoline counterparts, these three full HEV models can achieve fuel savings of 22%–32%.

Other vehicles using a power-split series/parallel hybrid system in China include the Buick Regal, Buick LaCrosse, and Chevrolet Malibu XL produced by SAIC-GM, as well as the Ford Mondeo produced by Chang'an Ford. GM and Ford's hybrid systems are basically the same as Toyota's HSD system, though somewhat different in architecture. As shown in Figure 3, they can achieve fuel savings of 24%–39%.

Honda followed its own technological path and developed a two-motor series/parallel hybrid system and called it Intelligent Multi-Mode Drive (i-MMD). One motor propels the wheels while the other works as a generator. An electronic clutch pack is used to realize the shift among engine-drive mode, hybrid-drive mode, and electric-drive mode. In the engine-drive mode, usually during medium-to-high-speed cruising, the clutch system connects the ICE—operating in its most economical range—directly to the drivetrain to propel the wheels. In the hybrid-drive mode, the clutch disconnects the ICE from the drivetrain. The wheels are driven by the propulsion motor, using power from the traction battery and the generator run by the ICE. In this mode, the ICE does not response to vehicle speed changes and always works at its most efficient speed. In the electric-drive mode, the ICE is off while the propulsion motor drives the vehicle using electric energy from the traction battery. It should be noted that similarly to the HSD system, the i-MMD system also employs an Atkinson cycle engine paired with Honda's i-VTEC technology, achieving thermal efficiency as high as 38.9%.[4] The i-MMD system is normally used in Honda's mid-range hybrid models. The Honda Accord, Spirior, and CR-V sold in China are all equipped with the i-MMD system and can reduce fuel consumption by 23%–40% compared with their gasoline counterparts.

4 This is the thermal efficiency of the Atkinson cycle engine on the 2017 Honda Accord, which is currently sold in China. The newest Honda Atkinson cycle has achieved thermal efficiency of 40%, according to "2018 Honda Accord Hybrid features third-generation MMD two-motor system; no heavy rare-earth metals in motors," Green Car Congress, accessed October 5, 2017, http://www.greencarcongress.com/2017/10/20171005-accord.html.

The hybrid system used by Hyundai/Kia is typically a P2 system, which is much simpler than the two series/parallel systems and allows the use of a single, smaller electric motor instead of the two large motors required for the series/parallel systems. It replaces the traditional torque converter with a transmission-mounted electrical device (TMED), which consists of a single electric motor and two clutches, one between the Atkinson cycle engine and the motor and the other between the motor and the drivetrain. The two clutches allow the power from the ICE or the electric motor or both to pass through the 6-speed automatic transmission (Erjavec, 2012). Depending on power needs, the computer controls the clutches and determines the proportions of power coming from the ICE and the motor to achieve the best efficiency. The Hyundai Sonata 9 and Kia K5 sold in China use this TMED system, both with a fuel-saving benefit of 28%.

In addition to the engine, motor, and transmission, the traction battery is a key component of a hybrid system. Only Toyota HEVs still use the traditional Ni-MH batteries. The other major automakers all equip their HEVs with the more-advanced lithium-ion batteries, whose specific energy and power density are both higher than those of Ni-MH batteries. The battery capacity of non-plug-in HEVs is usually much smaller than that of PHEVs and BEVs because they cannot be recharged using energy from external sources. As listed in Table 2, the battery capacity of the 13 full HEV models sold in China ranges from 1.3 kWh to 1.8 kWh.

3.1.2 Mild HEVs

Compared with full HEVs, mild HEVs use a simpler parallel hybrid configuration, a smaller traction battery, and a less-powerful electric motor. Therefore, their fuel saving potential and added cost are relatively lower. ITB estimated that in general 24V–86V mild hybrids can achieve a 7%–15% fuel-consumption benefit.

To take the GM Cadillac XT5 as an example, it is equipped with GM's eAssist system, which is essentially an 86V BSG system. It replaces the conventional alternator with a higher-power electric motor and a high-tension belt drive that can work both directions to provide power assist to the ICE and to better capture regerative braking energy (German, 2015). However, the maximum power of the BSG is limited by the belt, and belt drives are not as efficient as gear drives. For example, the eAssist system has only a 0.45 kWh traction battery and 6.6 kW electric motor and does not have the ability to realize all-electric drive. Compared with the gasoline version Cadillac XT5, this mild hybrid version can reduce fuel consumption by 9.5% with a 5.6% increase in MSRP.

Other mild HEV models sold in China include the Nissan Murano, Chang'an Eado, and JAC Refine M4. It is worth mentioning that the Chang'an Eado HEV, launched in November 2016, was the first mass-produced 48V mild hybrid in the world (BusinessWire, 2017).

In general, the fuel consumption of mild HEVs on the NEDC is 3.3%–14.9% lower than that of their gasoline counterparts, with an average value of 12%. These fuel-saving benefits are achieved at a cost of a 0%–24.7% increase in MSRP, with an average value of 9.5%.

3.2 FURTHER DEVELOPMENT PATHWAYS

The Chinese government regards powertrain hybridization as an important technology to help achieve the existing 2020 fuel consumption target of 5 L/100 km, as well as the under-discussed fuel-consumption targets of 4 L/100 km in 2025 and 3.2 L/100 km in 2030. China's goal is to increase the penetration of HEVs in China's new passenger vehicle fleet from the current level of less than 1% to 8% in 2020, 20% in 2025, and 25% in 2030 (SAE China, 2016). Clearly, there is a long way to go.

Joint ventures, especially with Japanese automakers, dominate China's HEV market. However, some independent domestic manufacturers have already made significant progress on full hybrid system development. Corun, a major battery supplier of Toyota, has developed a full hybrid system called the China Hybrid System (CHS). This system is largely similar to Toyota's HSD. They both have a power-split series/parallel configuration. A major difference is that the CHS adopts dual planetary gear sets rather than the HSD's single planetary gear set. The CHS has been applied in the Geely Emgrand EC7 HEV. Compared with its gasoline counterpart, this full HEV model is reported to achieve fuel savings of 35%, reaching fuel consumption of 4.9 L/100 km (Wang, 2016). While Geely demonstrated the vehicle in December 2016, it has not yet gone on sale. In addition to technical issues, a major reason is high cost reflecting the more complex mechanical design. Clearly, domestic independent manufacturers must make significant progress on cost control to compete.

Another promising direction is 48V mild hybrid systems. These systems achieve additional cost reductions by staying below the lethal limit of about 60V, without significant reductions in efficiency compared with higher voltage mild hybrids. ITB estimates that in 2022, 48V mild hybrids will cost about 30% as much as strong hybrid powertrains with about 30% of the benefit. It will cost $800 to achieve 9% fuel savings or $1,350 to achieve 15% in 2022.

Major global suppliers such as Bosch, Continental, Valeo, and Delphi are all collaborating with auto giants on the development of 48V hybrids. Continental, one of the most active players, achieved mass production of its first 48V drive system in 2016, which was used in the Renault Scenic Hybrid Assist model (Continental, 2016). Continental has plans to introduce its 48V technology to the Chinese market.

Domestic and international battery suppliers are also actively developing 48V batteries. These include Contemporary Amperex Technology (CATL), Tianjin Lishen, China Aviation Lithium Battery, Chaowei, Johnson Controls, Hitachi, SAFT, and A123. For example, 48V lithium batteries developed by Tianjin Lishen are expected to achieve a power density of 5,000 W/kg by 2020, more than twice the 2,000 W/kg density of the current 48V lithium-ion battery produced by A123 (Gao Gong Lithium Battery, 2017).

Some 48V mild hybrid models have already entered the market. In 2016, Chang'an launched the Eado HEV, the world's first mass-produced 48V mild hybrid model. Another well-known example is the 48V hybrid Golf launched by Volkswagen in 2017 with a fuel consumption of 4.0 L/100 km. International auto giants including Audi, Renault, Daimler, Volkswagen, Fiat-Chrysler, Ford, GM, Hyundai, and Kia are all actively developing 48V hybrid models. For example, the U.S. 2019 full-size Ram pickup truck will have a standard 48V hybrid system on the base V6 engine. Domestic independent manufacturers, such as Geely, FAW, BYD, and GWM have also confirmed that they will introduce 48V hybrid systems (Gao Gong Lithium Battery, 2017). In May 2018, the Geely Bo Rui GE 48V mild hybrid officially went on sale (Zhang, 2018b). It employs a BSG system to realize fuel consumption of 5.8 L/100 km, 15% lower than the non-hybrid version (Tan, 2018).

4 Battery electric vehicles

BEVs cut direct fuel consumption to zero by completely replacing the conventional ICE powertrain system with an electric drive system comprising electric motor/generator and high-voltage traction battery. BEVs' traction battery packs are recharged by plugging them into the grid. Compared with powertrain hybridization, the transition from an ICE system to electric drive is more revolutionary because the energy sources to power vehicles are changed entirely.

4.1 CURRENT STATUS

In the past several years, China's powerful combination of favorable government policies and subsidies has made its BEV market the world's fastest-growing and largest (He, Jin, Cui, & Zhou, 2018). As shown in Figure 4, China's BEV penetration increased gradually from 0.2% in 2014 to 0.7% in 2015, 1.1% in 2016, and 1.9% in 2017 (China Association of Automobile Manufacturers, 2015–2018). BEV sales in China reached a record 468,000 in 2017, accounting for 58% of the global BEV market (China Association of Automobile Manufacturers, 2018; EV-Volumes, 2018).

Domestic independent automakers dominate China's BEV market. In 2017, all of the 10 best-selling BEV models in China were produced by domestic independent automakers. Sales by model are shown in Figure 5. The BAIC EC series ranked first, with sales of 78,765 (Gao Gong Industry Research Institute, 2018). Foreign brands lag far behind as significant government subsidies have favored domestic BEV models for nearly a decade (Cui et al., 2017).

Despite the rapid increase in BEV sales, market penetration was still minuscule at 1.9% in 2017. BEV technology is far from mature. Automakers and policymakers still face major challenges in increasing range, lowering cost, reducing charging time, and expanding availability of public charging.

Electric range is one of the biggest concerns of potential BEV owners. A survey by China's State Information Center showed that 24.2% of respondents gave up on buying BEVs because of the limited range of available products. The survey found that 80.2% of Chinese consumers expected an electric range of 400 km (249 miles) for BEVs (Guo, 2018). So far only a few vehicles have hit that goal, though manufacturers are pressing to get new models over that hurdle.

In the past several years, automakers have substantially increased the range of their BEVs. Figure 6 shows the 2014–2018 gains in range of several representative BEV models in China. For all the auto shown, the range is given as the NEDC test cycle range. Some leading models have already become more competitive on range. For example, Geely's 2018 Emgrand EV450 model and BYD's 2018 Qin EV450 model both achieve an electric range of 400 km (Zhou, 2018; Yao, 2018), matching consumer expectations based on the government survey. The new version of the BYD e6 SUV expanded its electric

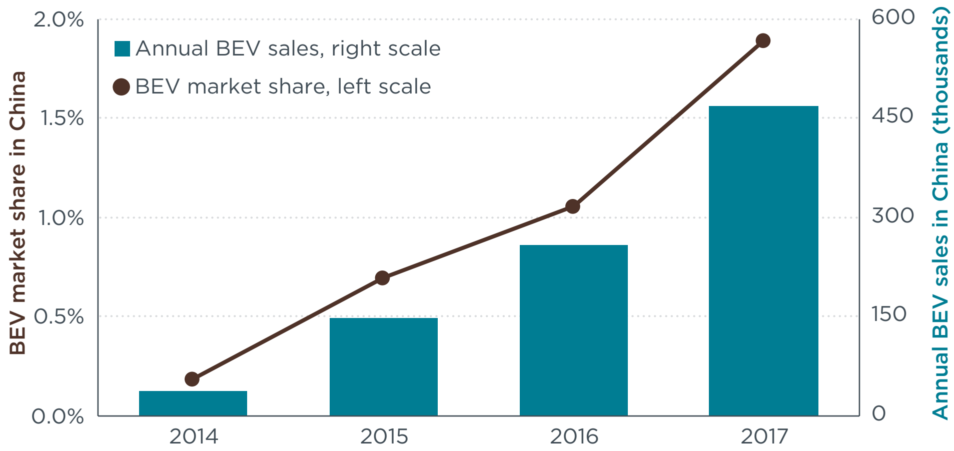

Figure 4 Annual sales and market share of BEVs in China from 2014 to 2017

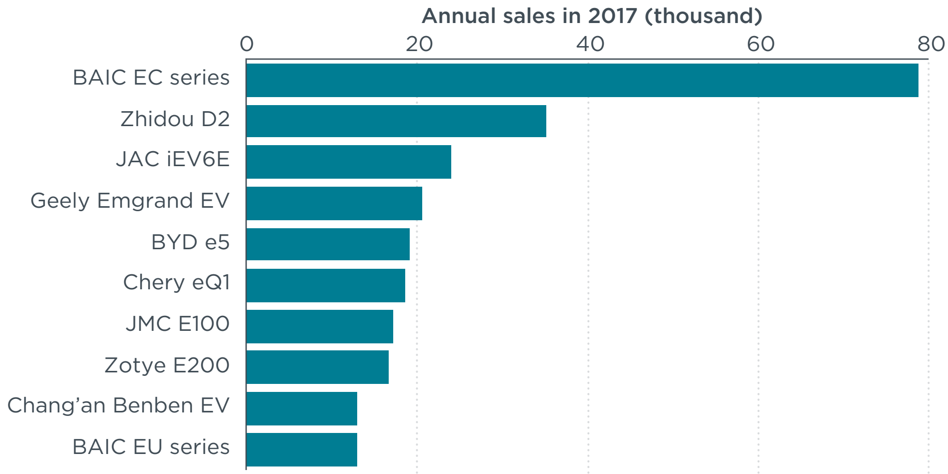

Figure 5 Annual sales of the 10 best-selling BEVs in China in 2017

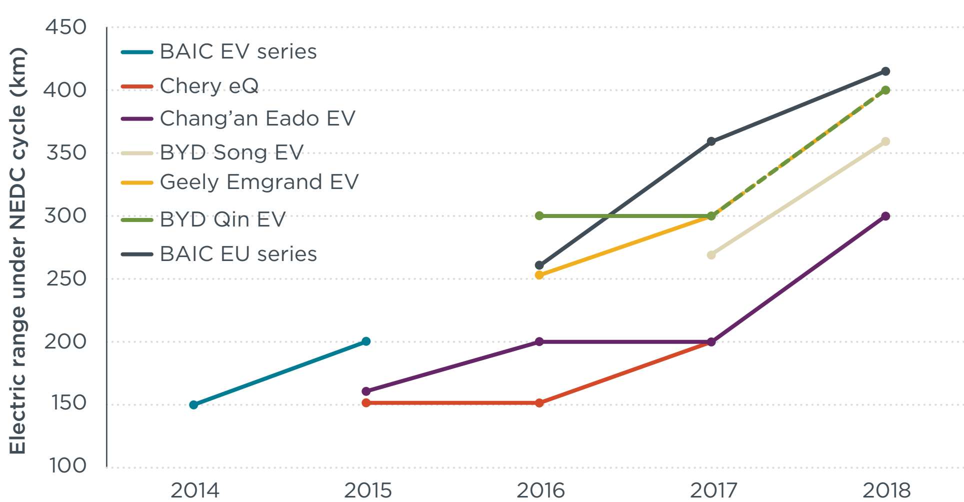

Figure 6 Electric range changes of representative BEV models in China

range from 400 km to 450 km (Sun, 2017a). BAIC's new EU5 R500 and R550 models, which debuted in April 2018, offered ranges of 416 km for the R500 and 450 km for the R550 (Auto Home, 2018b).

For comparison, the range value for the 2018 Tesla model S is 438 km; for the Tesla model X, 383 km; for the Chevrolet Bolt EV, 383 km; for the BMW i3 EV, 271 km; and for the Nissan Leaf, 243 km, based on EPA data. However, the EPA test cycle is different from the NEDC used by China, and the results differ for the two cycles. The Chevrolet Bolt EV, for example, scores a range of 520 km on the NEDC but just 383 km on the EPA cycle. In Europe, the NEDC has already been replaced by the Worldwide Harmonized Light Vehicles Test Cycle (WLTC), which is more representative of real-world driving.

Theoretically, there are two appoaches for extending electric range. One is to increase battery capacity, and the other is to reduce energy consumption. Figure 7 and Figure 8 display battery capacity and energy consumption changes for the same set of BEV models as in Figure 6. The energy consumption of each model is calculated by dividing battery capacity by electric range. The figures clearly show trends of increasing battery capacity and reducing energy consumption. Automakers are thus using both approaches.

To increase battery capacity and decrease energy consumption at the same time, the key is to improve the specific energy of the traction battery pack as measured in Wh/kg. For example, to raise battery capacity from 47.5 kWh to 60.4 kWh while

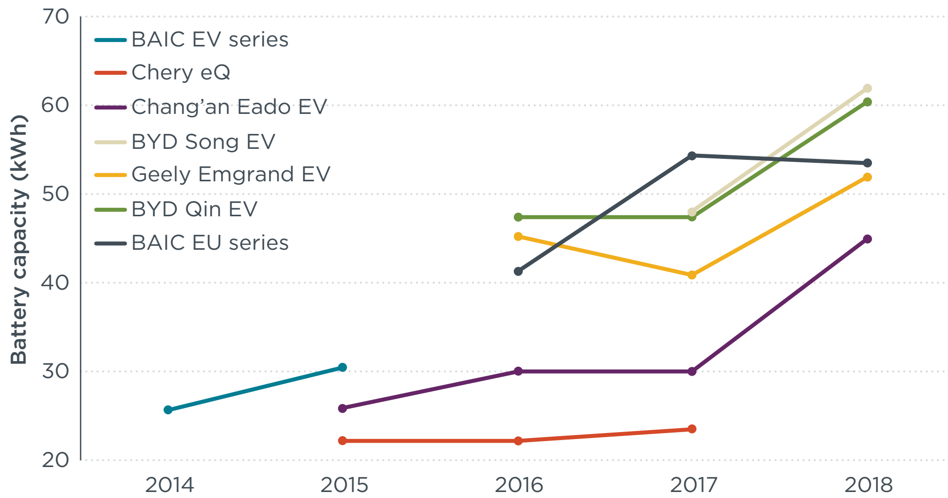

Figure 7 Battery capacity changes of representative BEV models in China

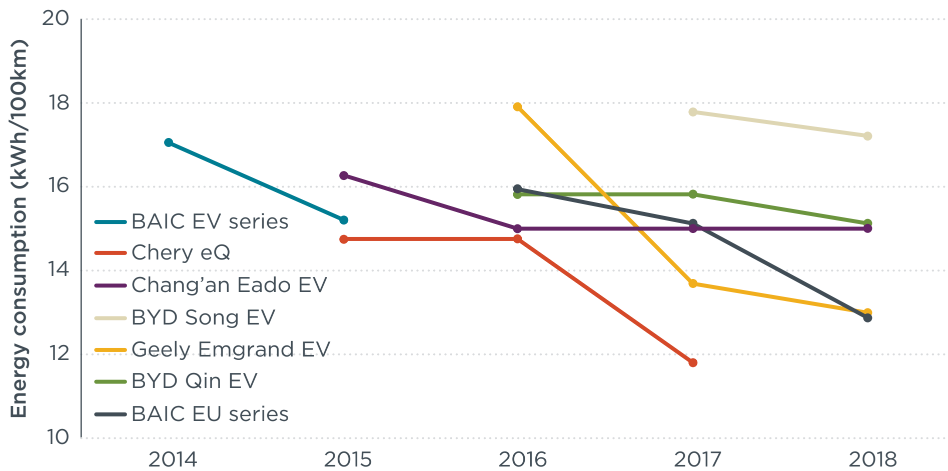

Figure 8 Energy consumption changes of representative BEV models in China

reducing energy consumption from 15.8 kWh/100 km to 15.1 kWh/100 km, the BYD Qin EV replaced its lithium ferrous phosphate (LFP) battery pack with a ternary lithium-ion battery pack. The change raised the vehicle battery pack's specific energy from 100 Wh/kg to more than 140 Wh/kg (Zhidian Auto, 2018b). Besides the application of high-specific-energy battery, the lightweighting of other vehicle components as well as improvements in motors and inverters also play an important role in extending the vehicle's range.

In addition to electric range, price is a big concern of potential BEV owners. Figure 9 compares the MSRPs of representative BEV models and their gasoline counterparts. All the MSRP values are for base models. Clearly, BEVs are still two to three times more expensive than equivalent ICE vehicles, mainly because of the high cost of traction batteries. The rapid increase in China's BEV sales to a great extent is attributable to the fiscal subsidy programs of the Chinese government, which significantly reduce the consumer purchase cost. However, the government has announced that the national fiscal subsidy program will come to an end in 2021 (Ministry of Finance of China, 2016). According to a survey jointly conducted by domestic and international research institutes in 2017, more than half of consumers[5] will give up on buying electric vehicles if the current fiscal subsidy program is phased out (Yu, 2017). To enable BEVs to be truly competitive with ICE vehicles, a significant cost reduction is indispensable.

Automakers know this better than anyone else. They continue trying to reduce the cost of BEVs. In the past several years, many BEV models have achieved an increase in performance and a decrease in MSRP at the same time. For example, compared with the Chang'an Eado EV sold in 2015, the 2018 model had an electric range 88% greater and a price 18% lower. Such changes are helping to reduce the cost disadvantage for BEVs compared with ICE vehicles.

For BEVs, the most important component is undoubtedly the traction battery pack, which has crucial impacts on the vehicle's curb weight, electric range, energy consumption, and cost. To take the Tesla Model S 85 as an example, 30% of the vehicle weight and 40% of the vehicle cost are attributable to the traction battery pack (Hao, Cheng, Liu, & Zhao, 2017). Generally speaking, the key for making the revolutionary transition from ICE vehicles to BEVs will be making a breakthrough on traction battery technology, especially a significant improvement in battery specific energy and a substantial reduction in battery cost.

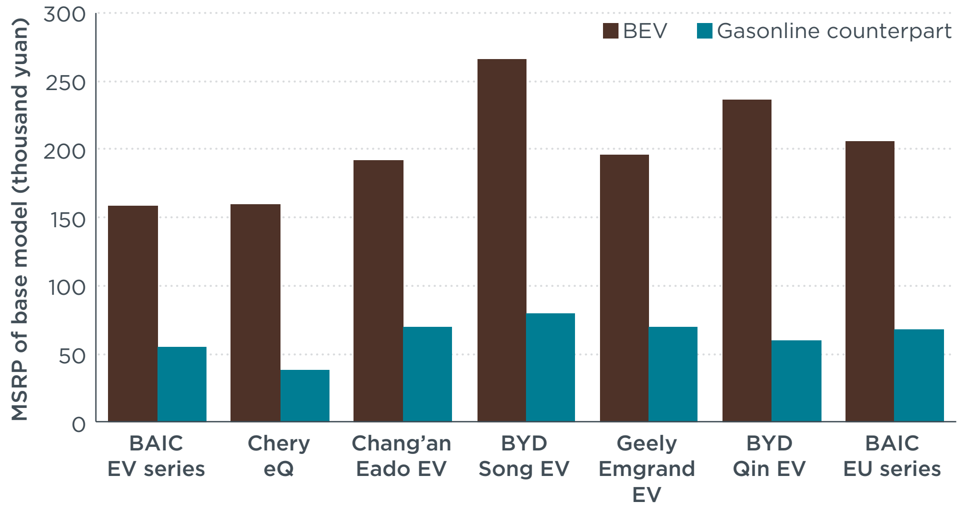

Figure 9 Base MSRPs of representative BEV models and their gasoline counterparts

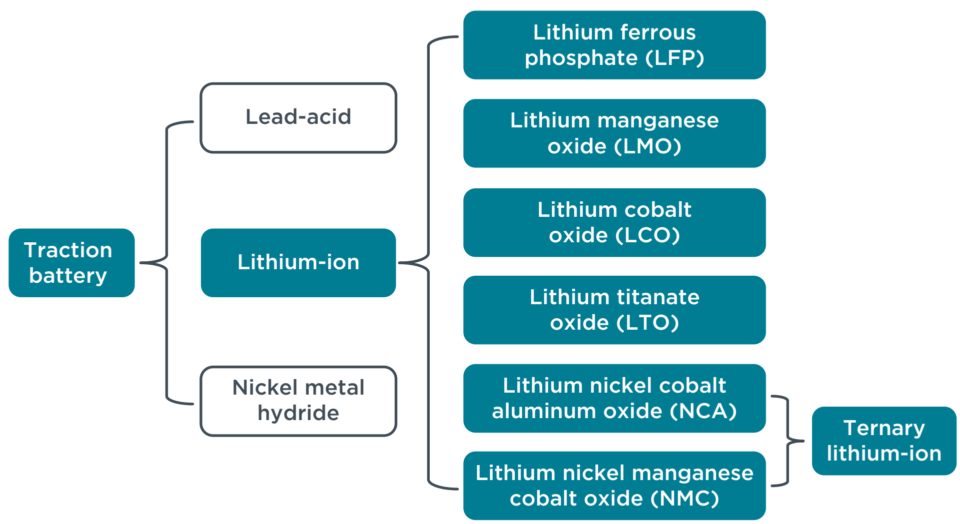

Figure 10 Major types of vehicle traction batteries

As shown in Figure 10, rechargeable traction batteries mainly include lead-acid batteries, nickel metal hydride (Ni-MH) batteries, and lithium-ion batteries. Lead-acid and Ni-MH technologies are more mature than lithium-ion technology. However, neither of them can effectively increase the electric range of BEVs because of limited specific energy and have been phased out in recent years. Lithium-ion batteries, with unexpectedly rapid technical progress, have come to dominate the market. In 2017, all the BEV traction batteries in China were lithium-ion batteries (Liu, 2018).

5 Consumers from Chengdu, Wuhan, Shijiazhuang, and Linyi participated in this survey.

Based on the cathode material, common lithium-ion traction batteries are divided into lithium ferrous phosphate (LFP), lithium manganese oxide (LMO), lithium cobalt oxide (LCO), lithium titanate oxide (LTO), lithium nickel cobalt aluminum oxide (NCA), and lithium nickel manganese cobalt oxide (NMC) batteries. The last two types are called ternary lithium-ion batteries in China. Table 3 compares the key properties of these six types of lithium-ion batteries, including specific energy, life cycle, safety including risk of fire, and cost (Battery University, 2018; Auto Refer, 2018). The most commonly used anode material for lithium-ion batteries is graphite.

LMO was the first commercially used cathode material because of its low cost; however, it is constrained by limited specific energy and limited lifetime. The Nissan Leaf is a representative BEV model using an LMO battery.

LCO, another old cathode material, has a medium performance in specific energy, lifetime, and cost. Its biggest disadvantage is low safety.

LFP has excellent lifetime and safety properties. Its cost is not high, either. However, LFP does not have a specific energy as high as ternary cathode materials, which makes it less competitive as almost all automakers expect greater range for BEVs. BYD has been a firm supporter of LFP for a long time. Most of its BEV models are powered by in-house LFP batteries. However, in December 2017, BYD announced that all its BEV models except the BYD e6 SUV would switch to ternary lithium-ion batteries in 2018 (Zhou, 2017a).

NMC is a combination of LMO, LCO, and nickel. Characterized by high specific energy and long lifetime, NMC has been increasingly popular in the traction battery market. Its major drawback is high cost. As a ternary material, NMC's properties are determined by the exact mixture of nickel, manganese, and cobalt. The current trend is to use a nickel-rich NMC material because of its better performance in improving specific energy and reducing cost. In the past several years, the mainstream mixture of nickel, manganese, and cobalt of the NMC cathode material has been gradually changed from 1:1:1 to 5:3:2, to 6:2:2, and then to 8:1:1.

NCA is a relatively new cathode material. NCA also belongs to the ternary materials category and delivers high specific energy. However, it is not very stable thermally, which means low safety (Berckmans et al., 2017).

LTO has distinct advantages such as long lifetime and superior safety performance. Those are the main reasons it has a niche in China's battery electric bus market. However, it is still not a commonly used cathode material in China's battery electric passenger car fleet because of its low specific energy and high cost.

Table 4 lists battery type, battery capacity, and electric range of the 10 best-selling BEV models in China in 2017. Only the JAC iEV6E, the BYD e5, and the JMC E100 used LFP batteries. All the others were equipped with ternary lithium-ion batteries.

Table 3 Key properties of different types of lithium-ion batteries

Cathode material	Specific energy	Life cycle	Safety (Thermal stability)	Cost
LFP	Medium	High	High	Medium
LMO	Low	Low	Medium	Low
LCO	Medium	Medium	Low	Medium
LTO	Low	High	High	High
NCA	High	Medium	Low	High
NMC	High	High	Medium	High

Table 4 Battery specifications of selected battery electric vehicle models

Model	Battery type	Battery capacity (kWh)	Electric range (km)
BAIC EC series	Ternary lithium-ion	20.3/20.5	156/162
Zhidou D2	Ternary lithium-ion	18	155
JAC iEV6E	LFP	19.66/22	156/170
Geely Emgrand EV	Ternary lithium-ion	41	300
BYD e5	LFP	43	305
Chery eQ1	Ternary lithium-ion	18.2	151
JMC E100	LFP	15	152
Zotye E200	Ternary lithium-ion	24.5	155
Chang'an Benben EV	Ternary lithium-ion	23.2/27.5	180/210
BAIC EU series	Ternary lithium-ion	41.4/54.4	260/360

Note: Data and information in this table are derived from Auto Home, 2018a.

As shown in Figure 11, ternary lithium-ion batteries dominated China's BEV market in 2017, with a total installed capacity of 9.02 GWh and a market share of 74.4%. Major ternary lithium-ion battery suppliers included CATL, Waltmal, BAK, Farasis, BYD, Jiangsu Zhihang New Energy, Tianjin Lishen, and EVE. LFP ranked second with a total installed capacity of 2.88 GWh and a market share of 23.7%. Major LFP battery suppliers included CATL, BYD, Guoxuan High Tech, National Battery, Tianjin Lishen, and EVE. Compared with ternary lithium-ion and LFP batteries, the market share of LMO batteries was negligible in 2017 (Liu, 2018).

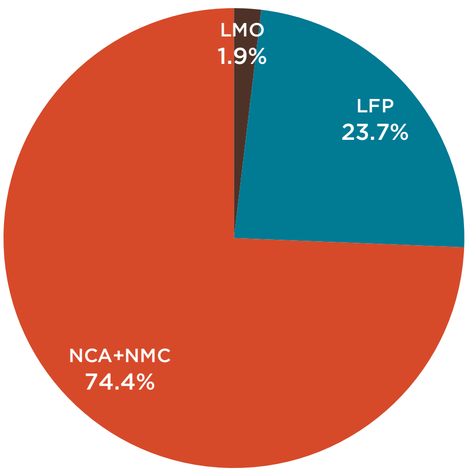

Figure 11 Market share of different types of BEV traction batteries in China in 2017 (in terms of installed capacity)

In general, the technical progress of traction batteries in China has been rapid in the past decade, reflecting the development of lithium-ion battery technology. As shown in Figure 12,[6] the specific energy of traction battery packs has been increasing. By the end of 2017, the specific energy of LFP battery packs reached 130 Wh/kg with a cell-level value of 160 Wh/kg. The specific energy of ternary lithium-ion battery packs is even higher, reaching 150 Wh/kg with a cell-level value of 240 Wh/kg (Zhang, 2018a). At the same time, the cost of traction battery packs has been decreasing. By the end of 2017, the cost of LFP battery packs declined to 1.45 yuan/Wh. The ternary lithium-ion battery pack is even cheaper, achieving a record low cost of 1.4 yuan/Wh (Liu, 2018).

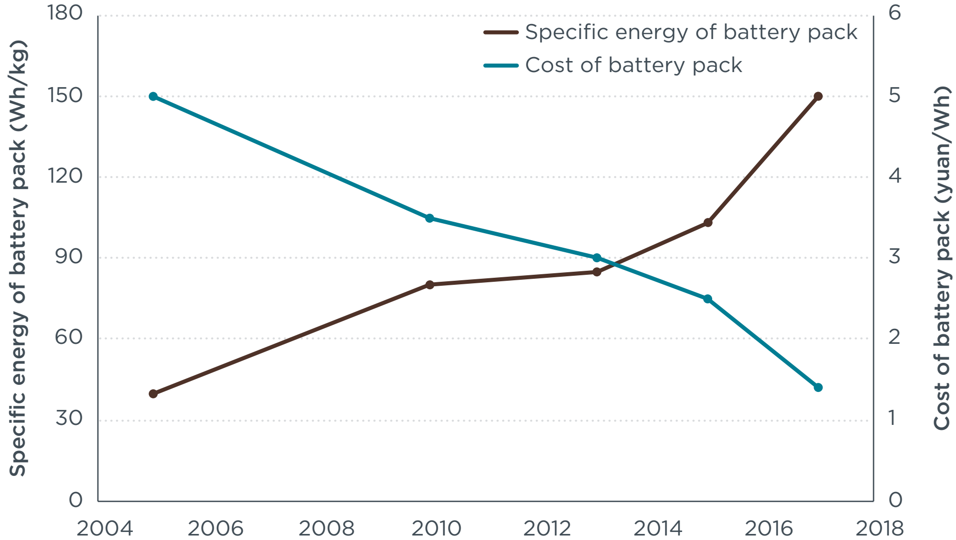

Figure 12 Changes of specific energy and cost of traction battery pack in China from 2005 to 2017

In addition to the need for a breakthrough on traction battery pack technology, the refinement of other vehicle components including electric motor, electronic control system, and thermal management system is also of significant importance to improving the performance, cost-competitiveness, and market penetration of BEVs. We do not discuss each technology in detail in this paper.

4.2 FURTHER DEVELOPMENT PATHWAYS

In 2017, China issued the final rule of its landmark NEV mandate policy, requiring all automakers selling passenger vehicles in China to produce a certain number of new-energy vehicles each year starting in 2018. For each automaker, the exact NEV production requirement is determined by its conventional passenger vehicle production and the performance of its NEV products on major technical parameters such as electric range and energy consumption (ICCT, 2018). BEVs, as a major type of NEV, will undoubtedly increase market penetration in the future, though the Chinese national government will no longer offer fiscal subsidies beginning in 2021. China's goal is to increase the penetration of BEVs and PHEVs in China's new vehicle fleet to 7%–10% in 2020, 15%–20% in 2025 and 40%–50% in 2030[7] (Society of Automotive Engineers China, 2016). The international consulting company Roland Berger estimated that 29%–47% of China's new passenger vehicle sales will be electric cars in 2030, compared with 8%–20% in the United States and 20%–32% in Europe (Roland Berger, 2018). The most aggressive prediction comes from the Energy Research

6 Data source: Presentations of Professor Ouyang Minggao, Executive Vice President of China EV100, at the 2017 and 2018 China EV100 Annual Summit.

7 New-energy commercial vehicles such as buses, coaches, trucks, and vocational vehicles are also included here.

Table 5 Summary of development goals for NEVs by automaker

	Automaker	Development goals on NEV
Domestic	BAIC (Sun, 2017b)	Annual NEV sales reaching 500,000 (independent brands only) in 2020
	BYD (Yi, 2017a)	Annual NEV sales reaching 200,000 in 2018
	Chery (Marklines, 2017)	Annual NEV sales reaching 200,000 in 2020
	Dongfeng (Wu, 2017)	Annual NEV sales reaching 300,000 in 2020
	Geely (Gan, 2017)	BEVs accounting for 35% of Geely annual sales, with PHEVs and HEVs accounting for 65% in 2020
	Chang'an (Wang, 2015)	Cumulative NEV sales reaching 400,000 in 2020 Launching 21 new BEV models and 12 new PHEV models by 2025 Discontinuing ICE vehicles in 2025
	GAC (Wang, 2017a)	Annual NEV sales reaching 200,000 in 2020
	SAIC (Wang, 2017b)	Annual NEV sales reaching 600,000 (200,000 independent brands, 400,000 joint venture brands) in 2020
	JAC (Zhang, 2017)	Cumulative NEV sales reaching 200,000 in 2020 NEVs accounting for 30% of JAC annual sales in 2025
	Lifan (Ya, 2015)	Launching 21 new BEV/PHEV models by 2020 Cumulative NEV sales reaching 500,000 in 2020
	Zotye (Huang, 2017)	NEVs accounting for 60% of annual sales in 2020
Foreign	GM (Bai, 2017)	Launching 10 BEV/PHEV models in China by 2020 Annual BEV/PHEV sales in China reaching 150,000 in 2020 and 500,000 in 2025
	Ford (Lin, 2016; Yuan, 2018)	Lauching 15 new NEV models in China by 2025 NEVs accounting for 10%–25% of Ford's global annual sales in 2020
	VW (Chen and Zhang, 2017; Yi, 2017b; Zhang, 2018c; Yang, 2017)	Launching 50 NEV models in China by 2025 Annual NEV sales in China reaching 400,000 in 2020 and 1.5 million in 2025 Launching 80 NEV models (50 BEVs, 30 PHEVs) globally by 2025 Annual NEV sales globally reaching 2 million–3 million in 2025
	Daimler (Deng, 2017; Yang, 2017)	Achieving BEV model localization in China in 2020 NEVs accounting for 15%–25% of Daimler global sales in 2025
	BMW (Niu, 2017; Yang, 2017)	Launching 25 NEV models, including 12 BEV models and 13 PHEV models, globally by 2025 NEVs accounting for 15%–25% of BMW global annual sales in 2025
	Hyundai/Kia (Zhu, 2017)	Launching 26 new NEV models globally by 2020 Annual NEV sales reaching 300,000 globally in 2020
	Toyota (Diao, 2017; Zhou, 2017b)	Launching BEV models in China, Japan, India, United States, Europe starting in 2020 Launching at least 10 BEV models globally by 2025 Annual EV sales reaching 5.5 million in 2030 Annual BEV/FCV sales reaching 1 million globally in 2030 Discontinuing ICE vehicles in 2050 (70% HEV/PHEV, 30% BEV/FCV)
	Honda (Du, 2017; Pei, 2017)	Launching battery electric SUV models in China in 2018 BEV/PHEV/HEV/FCV accounting for 2/3 of Honda annual sales in Europe in 2025
	Nissan (Kang, 2017; Yang, 2018)	Launching 20 EV models in China from 2018 to 2023 Zero emission vehicles accounting for 20% of Nissan vehicle sales in Europe by 2020

Note: In this table, the NEV development goals of some automakers include not only new-energy passenger vehicles, but also new-energy commercial vehicles such as buses, coaches, trucks, and vocational vehicles.

Institute of China's National Development and Reform Commission, indicating that all new passenger vehicles sold in China in 2025 will be BEVs (Cui and Zhang, 2017).

No matter which projection turns out to be closest, the trend toward NEVs is irreversible in China and globally. Domestic and foreign automakers have launched aggressive NEV development plans for the next decade. Table 5 summarizes the specific goals of major automakers based on their public announcements. Domestic players, which have achieved great success in the past several years, hope to maintain their lead. More than 10 domestic companies have already set ambitious NEV targets for 2018–2025. Foreign auto giants are stepping up the pace to seize NEV market in China and globally. Clearly, the competition in China's NEV market will intensify in coming years, which will lead to faster technology upgrades of NEV products and further speed the transition to a zero-emission vehicle fleet.

The key to realizing such goals is making a breakthrough in traction battery technology. Currently, the pack-level specific energy of traction batteries used in BEVs in China is 150 Wh/kg and the cost is 1.4 yuan/Wh. As shown in Figure 13, China's goal is to increase the pack-level battery specific energy of traction battery to 250 Wh/kg in 2020, 280 Wh/kg in 2025, and 300 Wh/kg in 2030. At the same time, China aims to reduce battery cost to 1 yuan/Wh in 2020, 0.9 yuan/Wh in 2025, and 0.8 yuan/Wh in 2030 (SAE China, 2016). The ICCT has conducted a comprehensive analysis of battery costs and future cost-reduction potential based on information from the best available bottom-up engineering analyses. The results indicate that on average for high-volume battery suppliers, battery costs will decline from $255/kWh (1.64 yuan/Wh) in

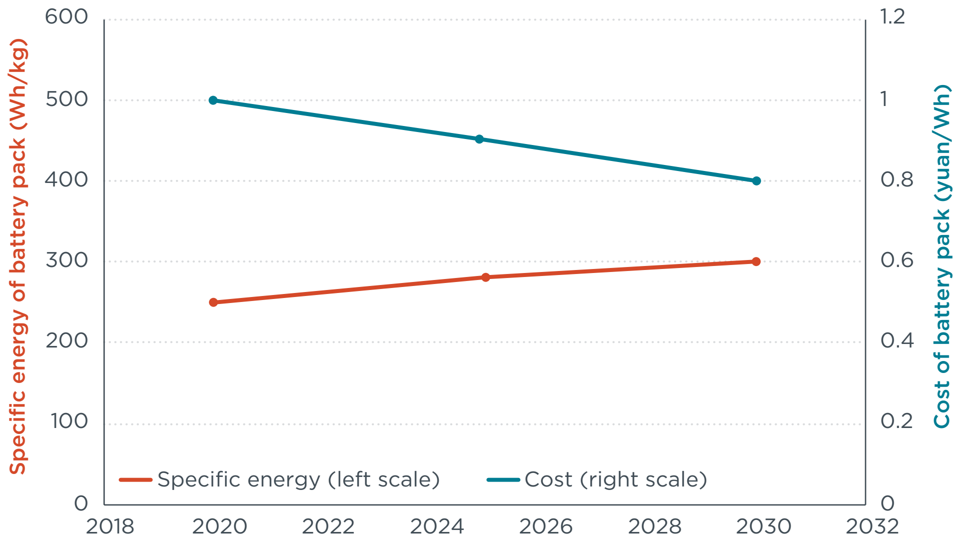

Figure 13 Targets of specific energy and cost of traction battery pack in BEVs in China 2020–2030

2016 to $195/kWh (1.25 yuan/Wh) in 2020 to around $150/kWh (0.96 yuan/Wh) in 2025 (Slowik, Pavlenco, & Lutsey, 2016).[8] Low and mid-range BEVs will become cost-competitive in China around 2021–2025 while long-range BEVs will take a few years more (Slowik & Lutsey, 2016).

The next-generation traction battery is already on the way. CATL, Tianjin Lishen, and Guoxuan High Tech have made significant improvements in high-specific-energy traction battery development. They all chose a nickel-rich NMC cathode material and a silicon carbide anode material. Their current prototypes have already achieved a specific energy of 300 Wh/kg at the cell level and 200 Wh/kg–210 Wh/kg at the pack level, though they still face some safety problems (Ouyang, 2018). Mature products are expected to debut before 2020.

To further improve the cell-level specific energy from 300 Wh/kg to 400 Wh/kg, a practical approach is to use a lithium-rich manganese-based layered oxide cathode with high specific capacity. Peking University and the Institute of Physics of the Chinese Academy of Sciences have made great progress in this field.

To achieve the more ambious cell-level specific energy target of 500 Wh/kg in 2030, a promising method may be to change the electrolyte from liquid-state to solid-state. CATL, Ningbo Material Technology and Engineering Institute, and some other research institutes in China have started developing mass-produced solid-state batteries. Solid-state batteries have a chance to reach a record-high specific energy and at the same time effectively address the safety issues faced by the current lithium-ion batteries with liquid-state electrolyte.

5 Plug-in hybrid electric vehicles

A PHEV is a full hybrid electric vehicle whose traction battery pack can be recharged by plugging it into the grid. PHEVs still have both the ICE powertrain system and the electric drive system and can be driven by the

8 Based on the June 10, 2018, exchange rate of $1 to 6.41 yuan.

electric motor independently. Based on the configuration of the hybrid system, PHEVs can also be classified into series hybrids, parallel hybrids, and series/parallel hybrids. In particular, PHEVs with a series hybrid system are also called extended-range electric vehicles. In contrast with conventional HEVs, PHEVs can obtain a significant amount of the energy required to recharge traction batteries from the grid instead of relying only on energy from the ICE/generator system and regenerative braking. This enables PHEVs to have a larger traction battery pack and to run in all-electic mode for a longer distance, thus leading to larger fuel savings.

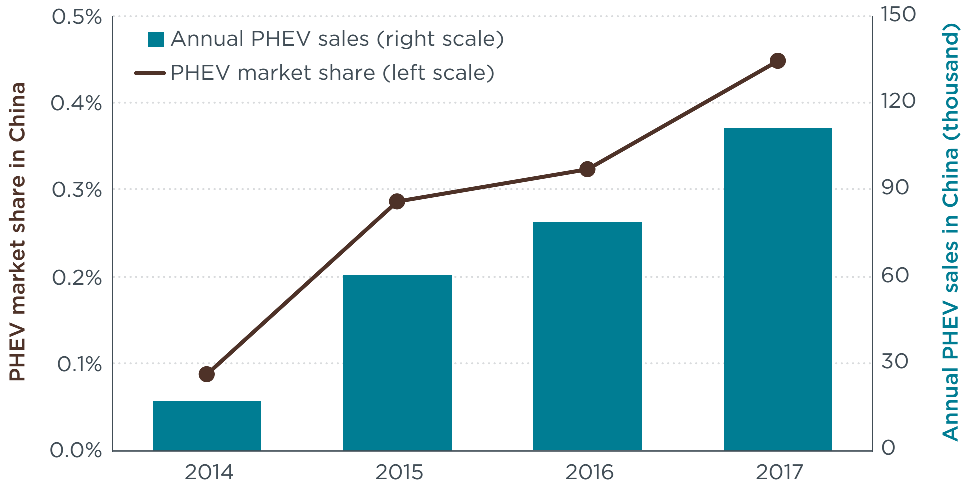

Figure 14 Annual sales and market share of PHEVs in China from 2014 to 2017

5.1 CURRENT STATUS

Similarly to BEVs, PHEVs have been strongly promoted by government fiscal and administrative incentives over the past several years (He et al., 2018). In 2017, PHEV sales in China reached a record 111,000, accounting for 27% of the global market. That same year, PHEV market share in China's passenger vehicle fleet climbed to 0.45%, eight times higher than the 2014 value, as shown in Figure 14 (China Association of Automobile Manufacturers, 2015–2018; EV-Volumes, 2018).

China's PHEV market is also dominated by domestic automakers. According to the China Passenger Car Association, the nine best-selling PHEV models in 2017 were produced by domestic independent automakers. The only foreign brand in the top 10 was the Buick Velite 5, a rebadged version of the Chevrolet Volt produced by SAIC-GM. Figure 15 provides annual sales and market share of the top five PHEV models in 2017 (Zhidian Auto, 2018a). These five all come from either BYD or SAIC, accounting for 85.3% of China's 2017 PHEV sales. The BYD Song DM ranked first with sales of 30,911 and a market share of 27.8%. Clearly, the competition pattern in China's PHEV market is much simpler than that of the BEV market, with BYD and SAIC dominant.

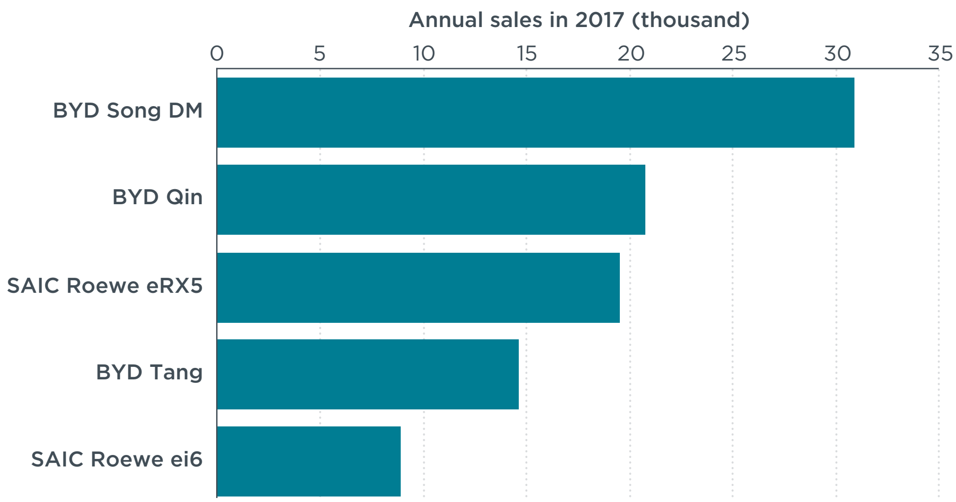

Figure 15 Annual sales of the five best-selling PHEV models in China in 2017

Figure 16 compares the fuel consumption of five typical PHEV models sold in China with that of their gasoline

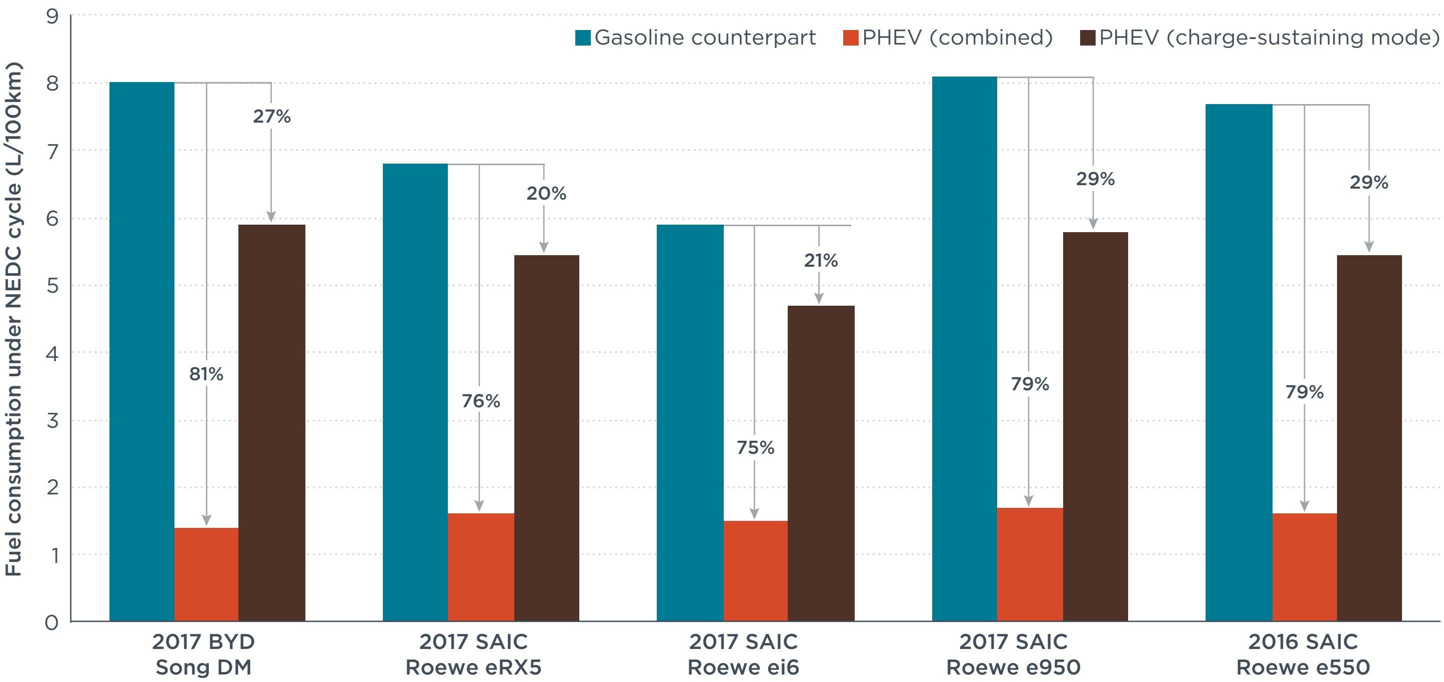

Figure 16 Fuel consumptions of typical PHEV models sold in China and their gasoline counterparts

counterparts. As with the analysis of HEVs, four principles were used to choose the gasoline counterpart for each PHEV model, including (1) same model, (2) same model year, (3) similar performance, and (4) best efficiency. In general, the fuel consumption of these PHEV models on the NEDC is 75%–81% lower than that of their gasoline counterparts, with an average value of 78%. These huge fuel savings mostly reflect the zero fuel consumption of vehicles in charge-depleting or all-electric drive mode. If the owners do not charge their PHEVs in time, the vehicles will operate in charge-sustaining or hybrid mode. As can be seen in Figure 16, the fuel saving of PHEVs in charge-sustaining mode is only 20%–29%, with an average of 25%. That is lower than the average 30% fuel saving of full HEVs currently on the Chinese market. In addition, it should be noted that the gasoline counterparts of these PHEV models are not as advanced in fuel-efficiency technologies as the gasoline counterparts of the full HEV models shown in Figure 6. Thus, an apples-to-apples comparison would show that the advantage of full HEV models in fuel-saving potential over PHEV models in hybrid mode is even higher.

In Europe, the United States, and Japan, PHEV models are usually developed based on existing full HEV models, which have already been equipped with many advanced fuel-efficiency technologies. Therefore, these PHEV models perform very well in fuel efficiency even if they are operated in charge-sustaining mode only. In China, however, the situation is quite different. Many PHEV models are developed directly based on low-tech gasoline vehicles. Their hybrid systems are not as advanced as the leading foreign brands. Thus, these PHEV models do not perform well enough in fuel efficiency in charge-sustaining mode.

As with BEVs, price is a major concern of potential PHEV owners. Figure 17 compares the MSRPs of representative PHEV models sold in China with those of their gasoline counterparts. In general, PHEV MSRPs are still 1.5 to 2.2 times the price of equivalent ICE vehicles. To enable PHEVs to be truly competitive with ICE vehicles, a significant cost reduction is indispensable, especially given the phase-out of China's national NEV subsidies.

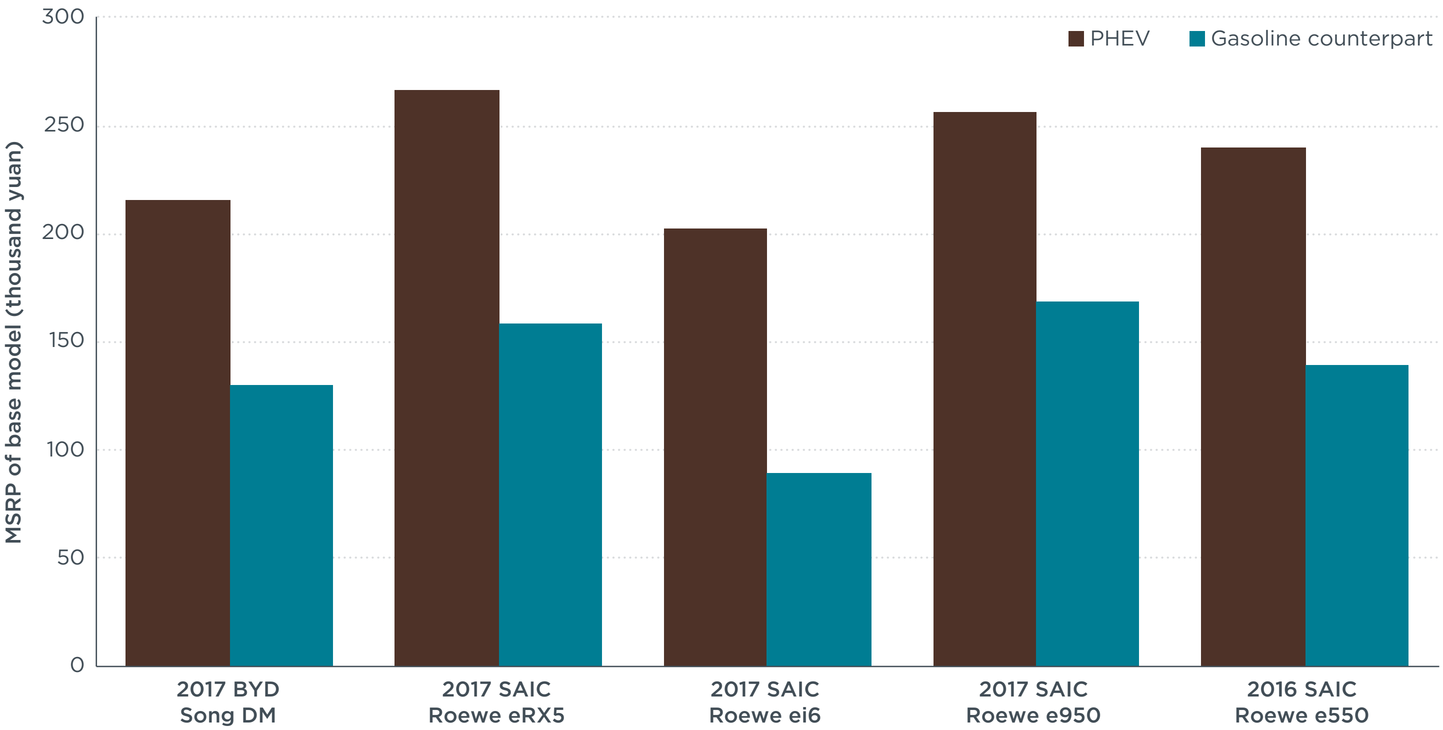

Figure 17 MSRPs of typical PHEV models sold in China and their gasoline counterparts

Table 6 Traction battery characteristics of five best-selling PHEV models in China

Model	Battery type	Battery capacity (kWh)	Electric range (km)
BYD Song DM	Ternary lithium-ion	16.9	80
BYD Qin	Ternary lithium-ion	13/18	80/100
SAIC Roewe eRX5	Ternary lithium-ion	12	60
BYD Tang	Ternary lithium-ion	16.6/20	80/100
SAIC Roewe ei6	Ternary lithium-ion	9.1	53

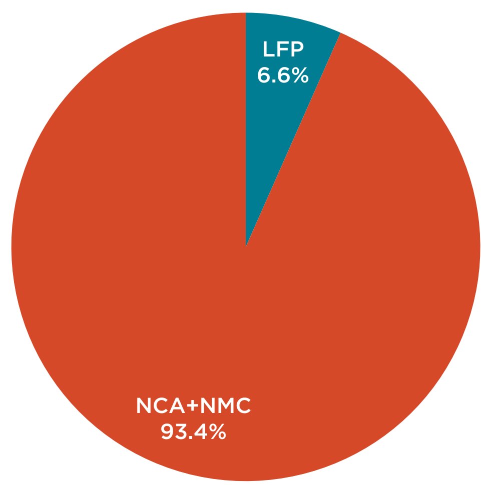

Figure 18 Market share of different types of PHEV traction batteries in China in 2017 (in terms of installed capacity)

Traction battery packs play an essential role in PHEV powertrain systems. Table 6 lists the battery type, battery capacity, and electric range of the five best-selling PHEV models in China. All of these models adopt ternary lithium-ion batteries. Their battery capacity is typically lower than that of BEVs but higher than for non-plug-in HEVs, ranging from 9.1 kWh to 20 kWh. The resulting electric range falls between 53 km and 100 km.

Figure 18 shows the market share of different types of traction batteries in China's PHEV market in 2017. Ternary lithium-ion batteries were dominant with a total installed capacity of 1.41 GWh and a market share of 93.4%. Major ternary lithium-ion battery suppliers included CATL, Waltmal, BAK, Farasis, BYD, Jiangsu Zhihang New Energy, Tianjin Lishen, and EVE. Compared with ternary lithium-ion batteries, the penetration of LFP was much lower. In 2017, the total installed capacity of LFP batteries was only 0.1 GWh, with a market share of 6.6%. BYD has long been a strong supporter of LFP. Most of its PHEV models are powered by self-produced LFP batteries. However, in December 2017, BYD announced that all PHEV models would switch to ternary lithium-ion batteries in 2018 (Zhou, 2017a). Major LFP battery suppliers in China include CATL, BYD, Guoxuan High Tech, National Battery, Tianjin Lishen, and EVE.

5.2 FURTHER DEVELOPMENT PATHWAYS

With the government's newly released NEV mandate policy, both domestic and foreign automakers have started to adjust their product plans, highlighting the development and marketing of NEV models. PHEVs as a major NEV category are projected to gain higher penetration in China's passenger vehicle fleet, especially before a significant improvement of China's public charger availability.

Competition in China's PHEV market will undoubtedly intensify. The national fiscal subsidy program, which favors domestic PHEV models, will be phased out in 2021. At the same time, driven by the recently released NEV mandate policy, more and more foreign-brand PHEV models that perform well in both charge-depleting mode and charge-sustaining mode will be introduced to the Chinese market. This intensified competition will lead to faster technology upgrades of PHEV products and further increase the PHEV market share in China.

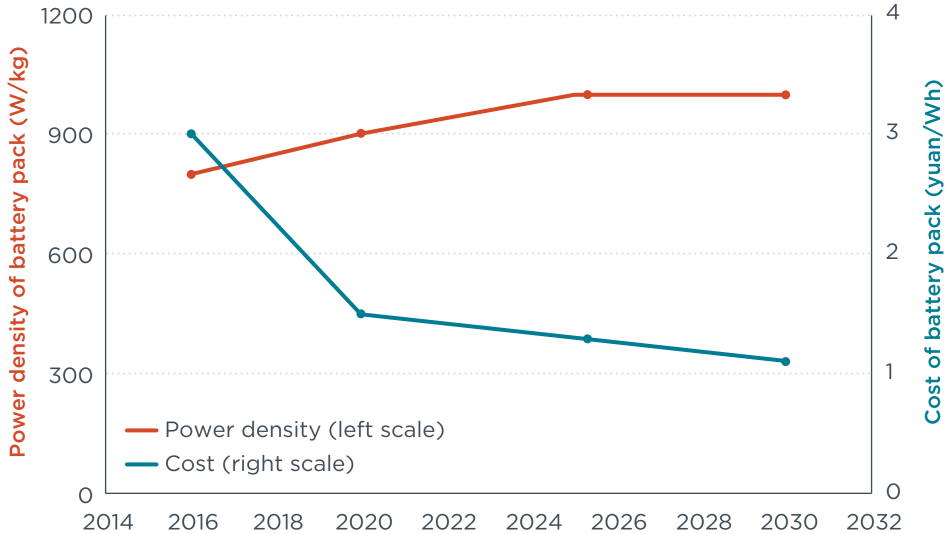

Figure 19 Targets of power density and cost of PHEV traction battery pack in China in 2020–2030

Technically, a breakthrough on traction battery technology is key. The main technical parameters of traction batteries in PHEVs include power density, specific energy, and cost. The current pack-level power density of PHEV traction batteries in China is 800 W/kg; specific energy, 70 Wh/kg; and cost, 3 yuan/Wh (Hao et al., 2017). As shown in Figure 19 (SAE China, 2016), China's goal is to increase the pack-level battery power density to 900 W/kg in 2020 and 1,000 W/kg in 2025. This target is conservative compared with Japan's target of 2,500 W/kg in 2020. The pack-level battery-specific energy is targeted to increase to 120 Wh/kg in 2020, 150 Wh/kg in 2025, and 180 Wh/kg in 2030. At the same time, the pack-level battery cost is targeted to decline to 1.5 yuan/Wh in 2020, 1.3 yuan/Wh in 2025, and 1.1 yuan/Wh in 2030.

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