WORKING PAPER 2023-31

DECEMBER 2023

Zero-emission bus and truck market in China: A 2022 update

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Introduction

Heavy-duty vehicles (HDVs) contribute significantly to greenhouse gas (GHG) emissions and air pollution in China. HDVs emitted about half of the GHG emissions across all on-road vehicles and approximately 3% of GHG emissions from all industry in China in 2019 (Ministry of Ecology and Environment, 2020). Despite advances in diesel engine emissions performance, a full transition to zero-emission heavy-duty vehicles (ZE-HDVs) will be required for China to meet its economy-wide decarbonization targets.

This paper builds upon data from our most recent market analysis, which focused on ZE-HDVs in China in 2021 (Mao et al., 2023), and here we analyze China's ZE-HDV market in 2022. We provide insights into developments in several key areas, including the application of ZE technologies across different vehicle segments and the geographic variation in ZE-HDV adoption. We also present a detailed analysis of ZE-HDV specifications, including battery suppliers, battery capacity, range, and specific energy density at the original equipment manufacturer (OEM) level. Furthermore, we track advancements in battery-swapping and fuel cell electric vehicle (FCEV) technologies. HDV registration and vehicle specification information for 2022 was drawn from ZEDATA (2022). Throughout the paper, we define HDVs as all trucks and buses with a gross vehicle weight exceeding 3.5 tonnes, battery electric vehicles (BEVs) as those that rely on plug-in chargers for recharging, and battery-swap-capable battery electric trucks (BETs) as those that use battery-swapping technology.

For years, China has been a global leader in the production and adoption of ZE-HDVs. In 2022, it was the dominant market with roughly 110,000 ZE-HDVs sold; that was about 81% of the total global market (Chu & Cui, 2023). The 2022 ZE-HDV market in China was still dominated by BEVs, which captured 96% of the market. Among BEVs, 89% were powered by charging, while the remaining 11% were battery swap capable. FCEVs remained less common but doubled their market share from 2% of total ZE truck sales in 2021 to 4% in 2022, with absolute sales surging by 144%.

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Acknowledgments: The authors thank Felipe Rodriguez, Yidan Chu, and Eamonn Mulholland of the ICCT for their generous help and valuable inputs. We also appreciate Tomas Husted's work in editing this paper. Any errors are the authors' own.

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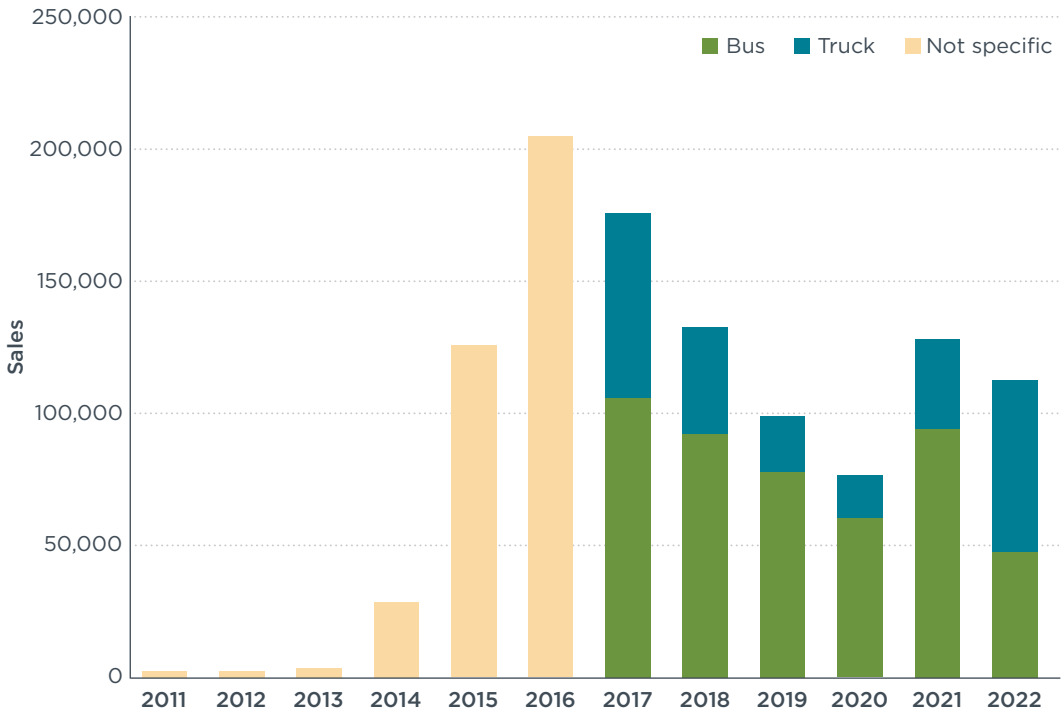
Snapshot of the ZE-HDV market in 2022

Overview

In 2022, total sales of ZE-HDVs in China decreased by 12% to 113,000 units, from 128,000 units in 2021 (Figure 1). This decline was likely due to the economic slowdown related to strict, COVID-19-related lockdowns; these disrupted economic activity in April and May, and a late-year wave of COVID infections also worsened market conditions in China. At the same time, the overall HDV market (including conventional vehicles) dropped by 51.8% in 2022 compared to 2021 (China Association of Automobile Manufacturers, 2023). This suggests that China's ZE-HDV market was more resilient during the economic turbulence than the market for conventionally powered vehicles. As a result, although the volume of ZE-HDV sales contracted in 2022, the market penetration of ZEVs in the HDV market increased to 9%. Sales of electric trucks and tractor-trailers in 2022 were almost double what they were in 2021; electric bus sales in 2022 were half of what they were in the previous year.



Note: Yellows are non-specific ZE-HDV categories for the years 2011 to 2016 due to data availability.

Figure 1. Sales of ZE-HDVs from 2011 to 2022.

Figure 2 and Figure 3 show the market share of the top 10 manufacturers in the ZE-HDV and diesel HDV markets, respectively. The top 10 manufacturers in the diesel HDV market collectively captured 76% of the market in 2022, a decrease from 85% in 2021. The ZE-HDV market was comparatively less concentrated, with the top 10 manufacturers accounting for 61% of the market in 2022, down from 70% in 2021. The leading manufacturers differed significantly between the two markets in 2022, with only Dongfeng, Foton, SAIC, and Sinotruck showing up in both top 10 lists. The top five ZE-HDV bus manufacturers in 2022 were Yutong, Kinglong, CRRC, Zhongtong, and BYD; that is largely unchanged from 2021, though CRCC surpassed Zhongtong to become the third largest manufacturer. In the truck segment, the top five also remained consistent: Dongfeng, Geely, Foton, SAIC, and Yutong. However, there were some shifts in ranking, with Geely moving ahead of Foton to become the second largest ZE-HDV truck manufacturer and SAIC outperforming Yutong to place fourth.

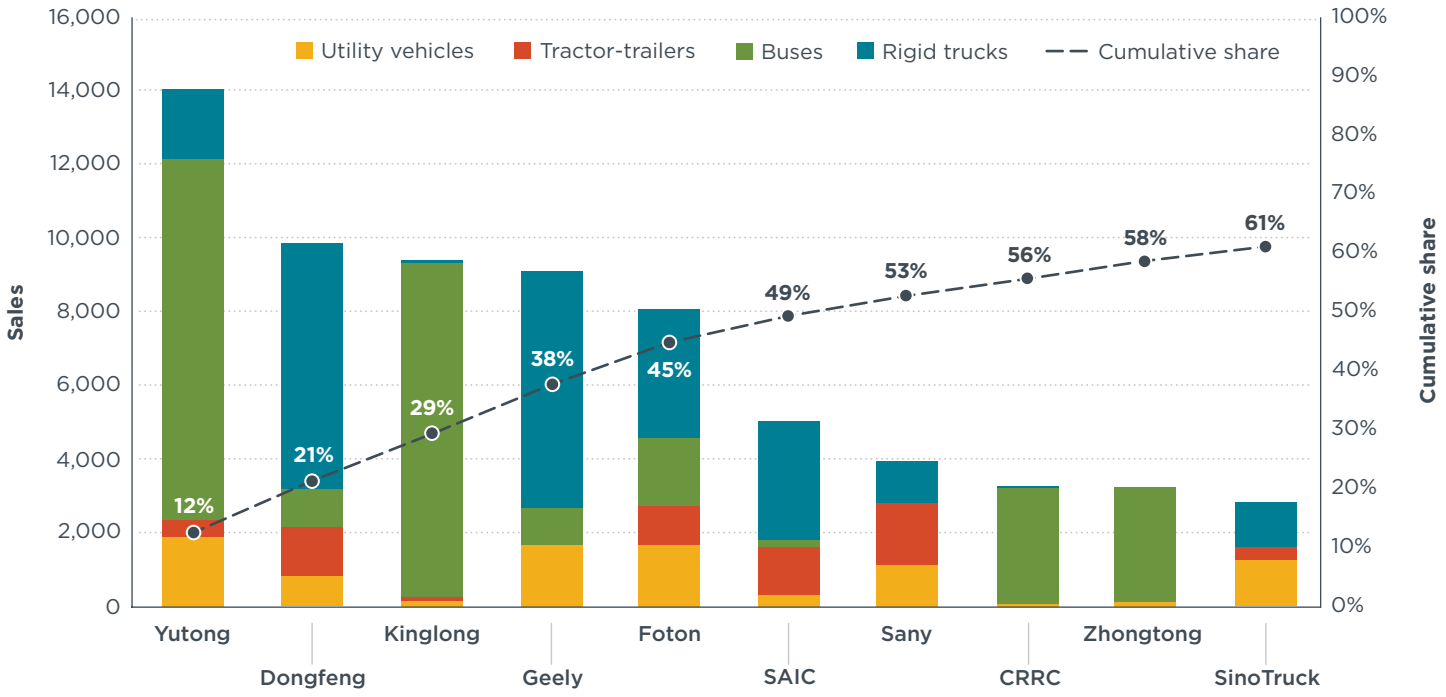


Figure 2. Top 10 ZE-HDV manufacturers in 2022.

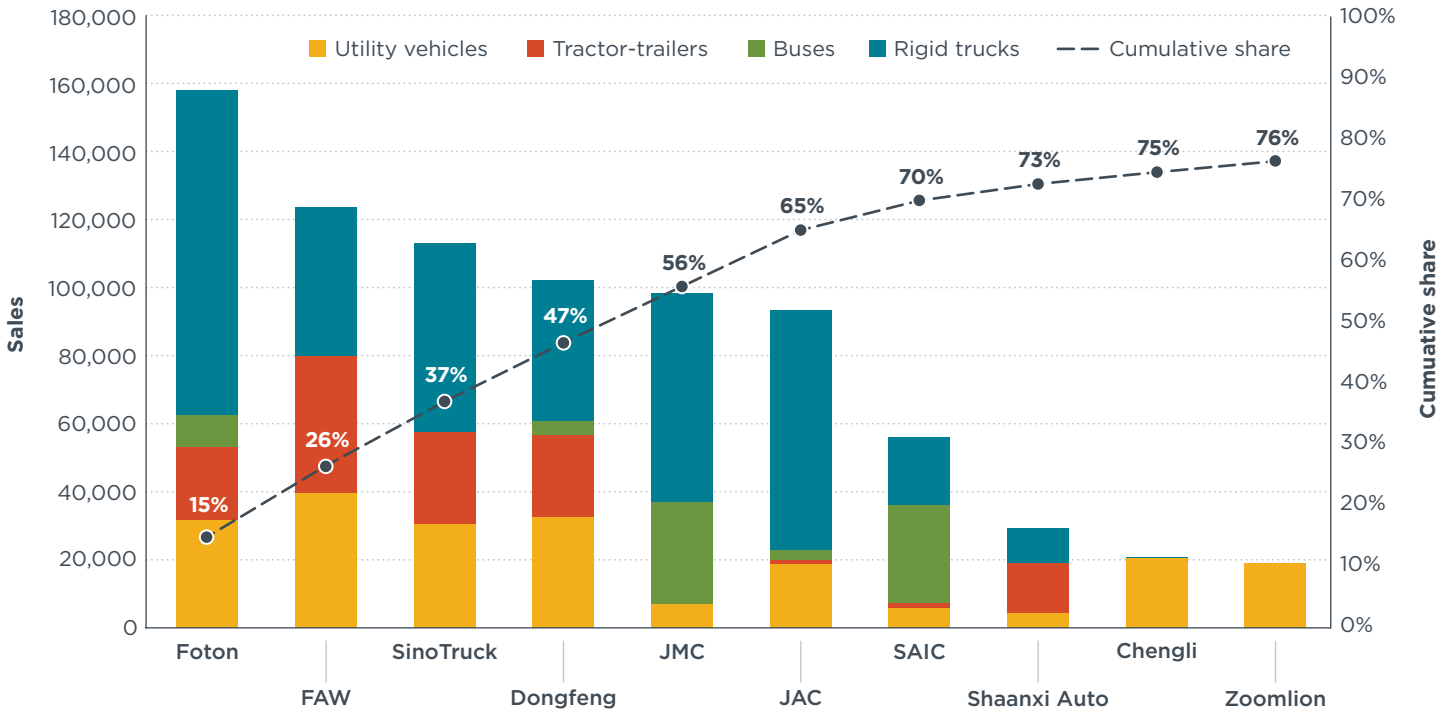
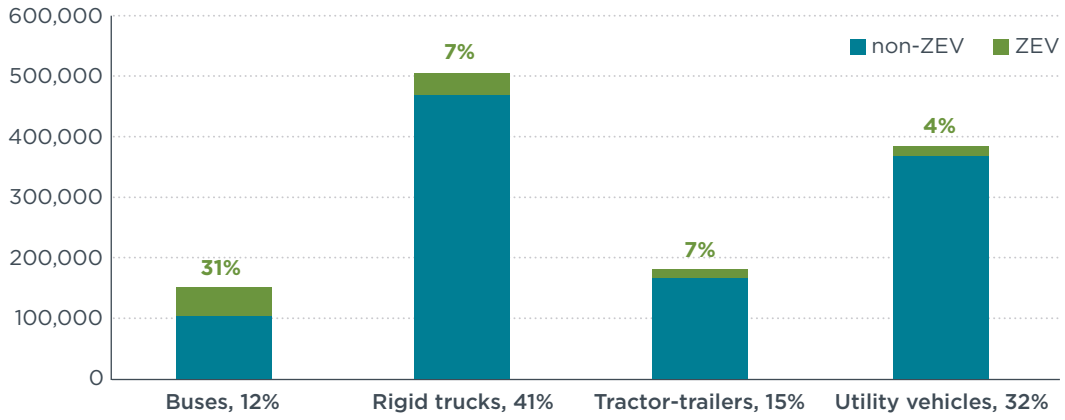


Figure 3. Top 10 diesel HDV manufacturers in 2022.

Sales by segment

Figure 4 illustrates the share of ZE-HDVs across different segments in 2022. The bus segment led with a ZE share of 31%, which was mainly due to city bus electrification efforts. Despite this significant share, buses constituted only around 12% of all HDVs sold in China in 2022. Rigid trucks and tractor-trailers each had a ZE share of 7%, while utility vehicles trailed with a 4% share.[1] Growth in the ZE rigid truck segment is particularly important for accelerating HDV electrification, as these vehicles were 41% of all HDVs sold in 2022.

1 Dump trucks were included in the rigid trucks category.



Note: The percentage value to the right of the green data bar refers to the share of ZE-HDVs within each segment. The percentage value next to the segment name refers to the segment's share of total HDVs.

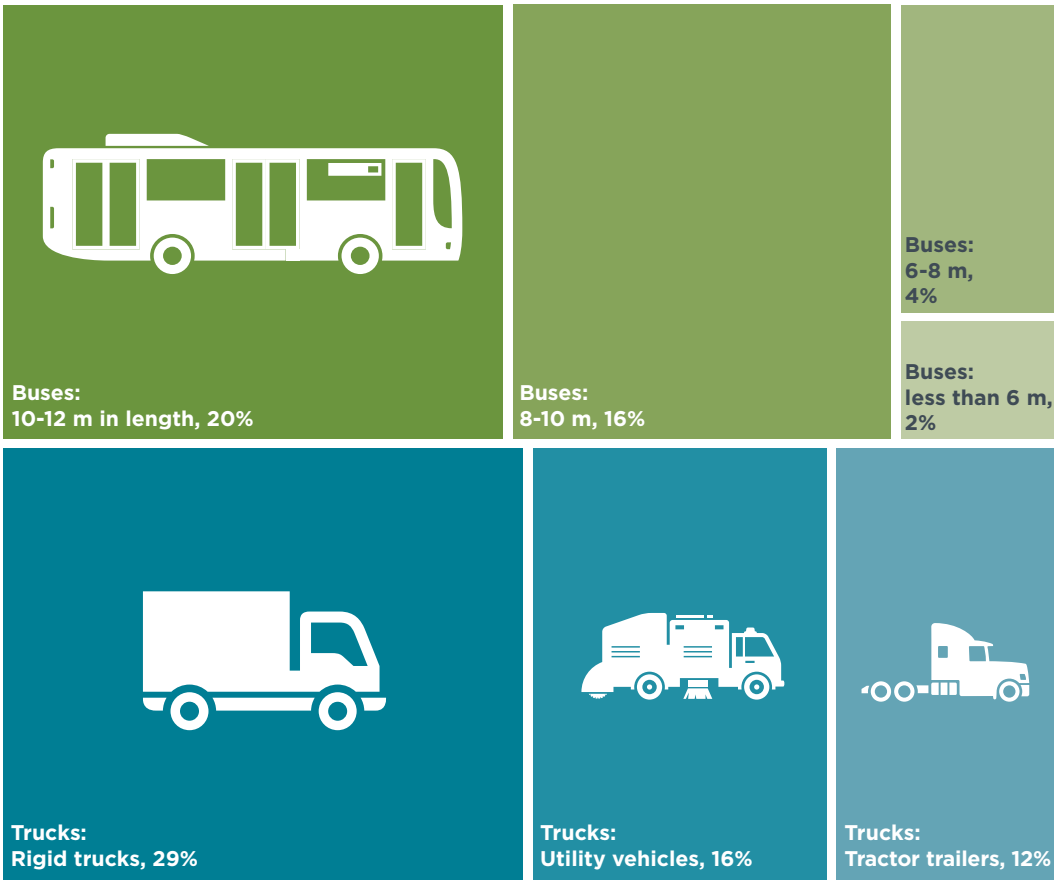
Figure 4. ZE share of HDVs by segment.

Figure 5 illustrates the composition of the 2022 ZE-HDV market by vehicle type. Buses were 42% of all ZE-HDV sales, a large drop from the previous year's 73% share. Buses between 10 m and 12 m in length were the most common bus type sold (20% of all ZE-HDV sales in 2022), followed by buses between 8 m and 10 m (16%), and buses shorter than 8 m (6%).

Trucks—including rigid trucks, tractor-trailers, and utility trucks—emerged as the largest category within the ZE-HDV market in 2022 and were 58% of all vehicles sold. This was a substantial increase from a 27% share of the overall market in 2021. Rigid trucks made up half of all truck sales and accounted for 29% of all ZE-HDV sales in 2022, up from 15% of ZE-HDV sales in 2021. Approximately 98% of rigid trucks sold in 2022 were small logistics vehicles with a gross weight of less than 4.5 tonnes; urban delivery trucks are a typical example of such vehicles, and have been the target of various government incentives and supporting policies to promote electrification (Mao et al., 2023). Mostly below 5 tonnes, urban delivery trucks can drive about 300 km to 500 km on a single charge. Electric urban delivery trucks are increasingly competitive with their diesel counterparts thanks to lower operating expenses and privileged road access in cities such as Chengdu (Mao et al., 2023; Mao & Rodríguez, 2021).

Tractor-trailers made up roughly 21% of truck sales in 2022, and their share of the overall ZE-HDV market grew significantly, from 4% of ZE-HDV sales in 2021 to 12% in 2022. The popularity of ZE tractor-trailers in China has grown for two main reasons. First, the government's "Blue Sky Campaign" has sought to urge high-polluting industries to reduce emissions. Tractor-trailers are widely used in such industries, including port logistics, steel, and mining, and have become a focus of electrification efforts due to their large emissions-reduction potential. Second, because tractor-trailers in China are primarily used for short-haul transport, battery swapping can be conveniently implemented. This approach alleviates range anxiety and eliminates the need to spend long periods charging.

The remaining 28% of the truck market, and 16% of the overall ZE-HDV market, was made up of utility trucks. Most of these trucks were designed for specific purposes, such as sanitation and refrigeration.



Note: The percentage value refers to the segment's share of total ZE-HDV sales. Figures in the graphic may not sum to 100 due to rounding.

Figure 5. Breakdown of ZE-HDVs sales by segment.

ZE technology pathways

Figure 6 depicts the technology composition of ZE-HDVs across vehicle segments from 2017 to 2022. BEVs with plug-in chargers still dominate, but their market share has been in decline since 2020 and fell to 85% of ZE-HDV sales in 2022, when 96,000 units were sold. In contrast, battery-swap-capable BETs and FCEVs have grown, reaching 12,000 and 4,600 units sold in 2022 and representing 11% and 4% of the ZE-HDV market, respectively. There was also significant growth in battery-swap-capable BETs (+8%) and FCEVs (+1%) compared to 2021.

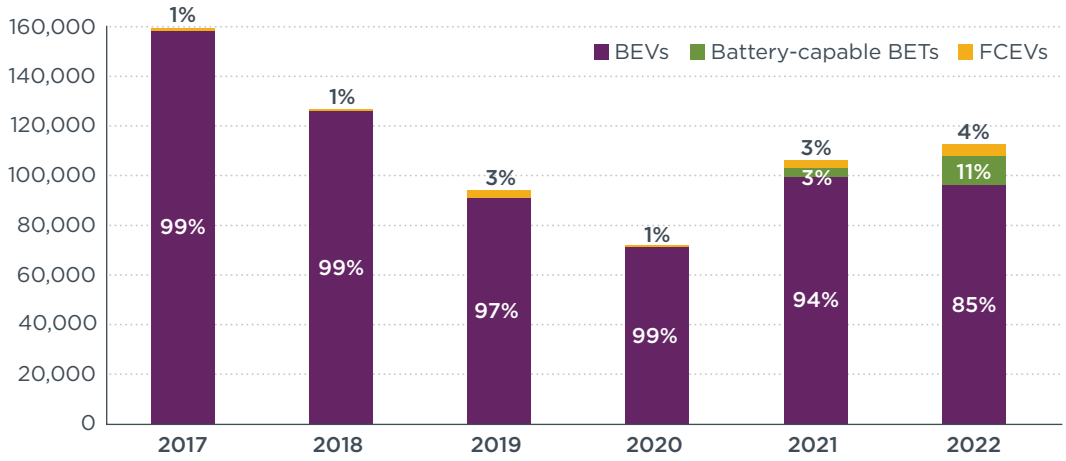


Figure 6. Market share by ZE technology, 2017–2022.

Figure 7 shows the breakdown of ZE-HDV technology by vehicle type. For buses, BEVs were the predominant technology, used for 97% of the ZE bus fleet. FCEVs accounted for the remaining 3%, and there were no battery-swap-capable ZE buses. As many major cities in China electrified their bus fleets with the support of government subsidies in past years when battery-swapping technology was less mature (Al-Alawi et al., 2022), BEVs are relatively entrenched as the primary technology pathway. This demonstrates how early technological decisions and investments can shape and potentially lock in certain technologies for the future; such decisions influence both current practices and long-term innovation and adoption trends.

Compared with buses, the rigid truck and utility vehicle segments have seen more adoption of battery-swapping and FCEV technologies, though these are still a small portion of the market. In the rigid truck segment, battery-swap-capable BETs and FCEVs are 8% and 2% of the ZE market, respectively, and in the utility vehicle segment, battery-swap-capable BETs and FCEVs are 7% and 8% of the market, respectively.

Meanwhile, most tractor-trailers have adopted battery-swapping technology, and such vehicles were 61% of the ZE tractor-trailer market in 2022. As tractor-trailers are often equipped with larger battery packs that may require 1.5 to 2 hours to charge using high-power DC fast charging—or approximately 6 to 7 hours with slow charging—battery swapping has emerged as a quicker alternative to charging (Kaiyuan Securities, 2023).

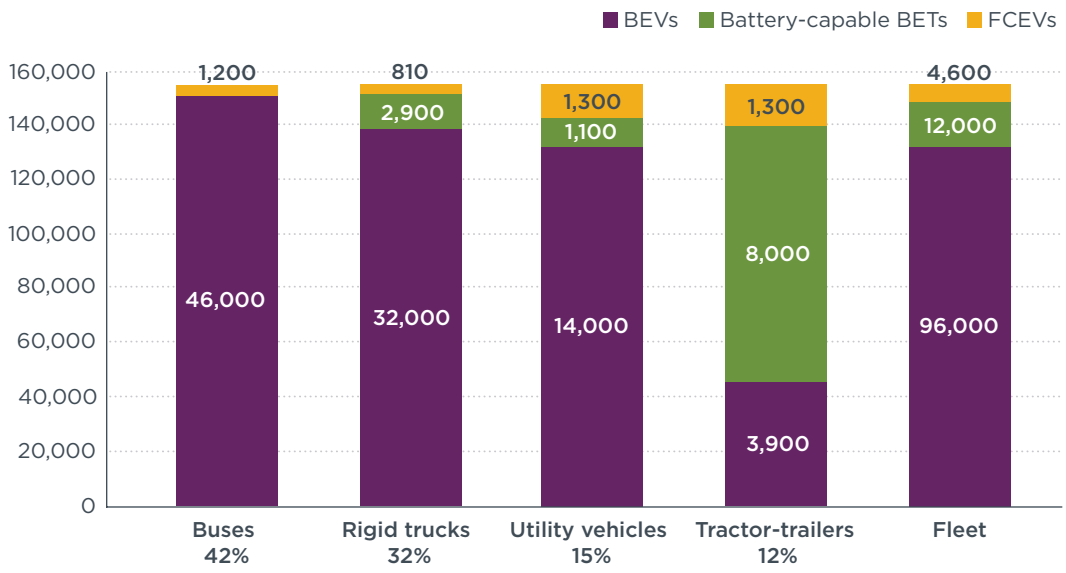


Figure 7. Market share by ZE technology in 2022.

Figure 8 and Figure 9 highlight the top cities for sales and top manufacturers of ZE technology for buses and trucks, respectively. In this context, top cities are ranked by sales of each technology in 2022. The color coding represents the type of ZE technology, with grey indicating BEVs, pink denoting battery-swap-capable BETs, and purple signifying FCEVs. The percentage displayed to the right of each data bar represents the market share of each city or manufacturer within their respective ZE technology category.

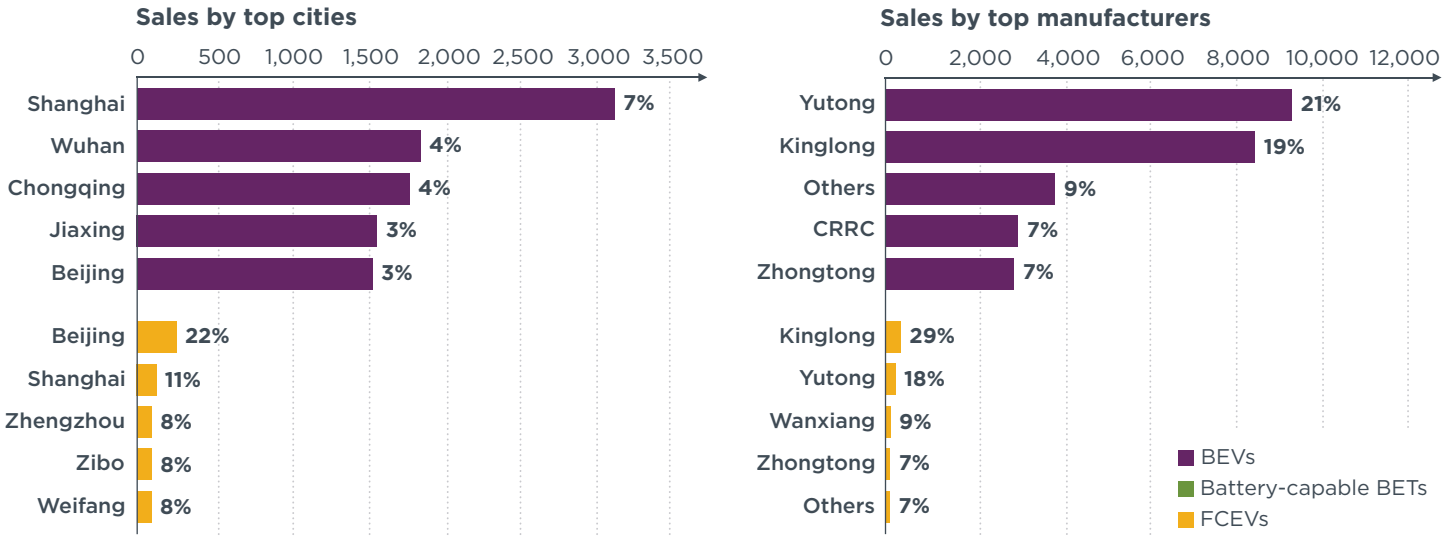


Figure 8. Top cities for sales and top manufacturers of ZEV technology in 2022, buses.

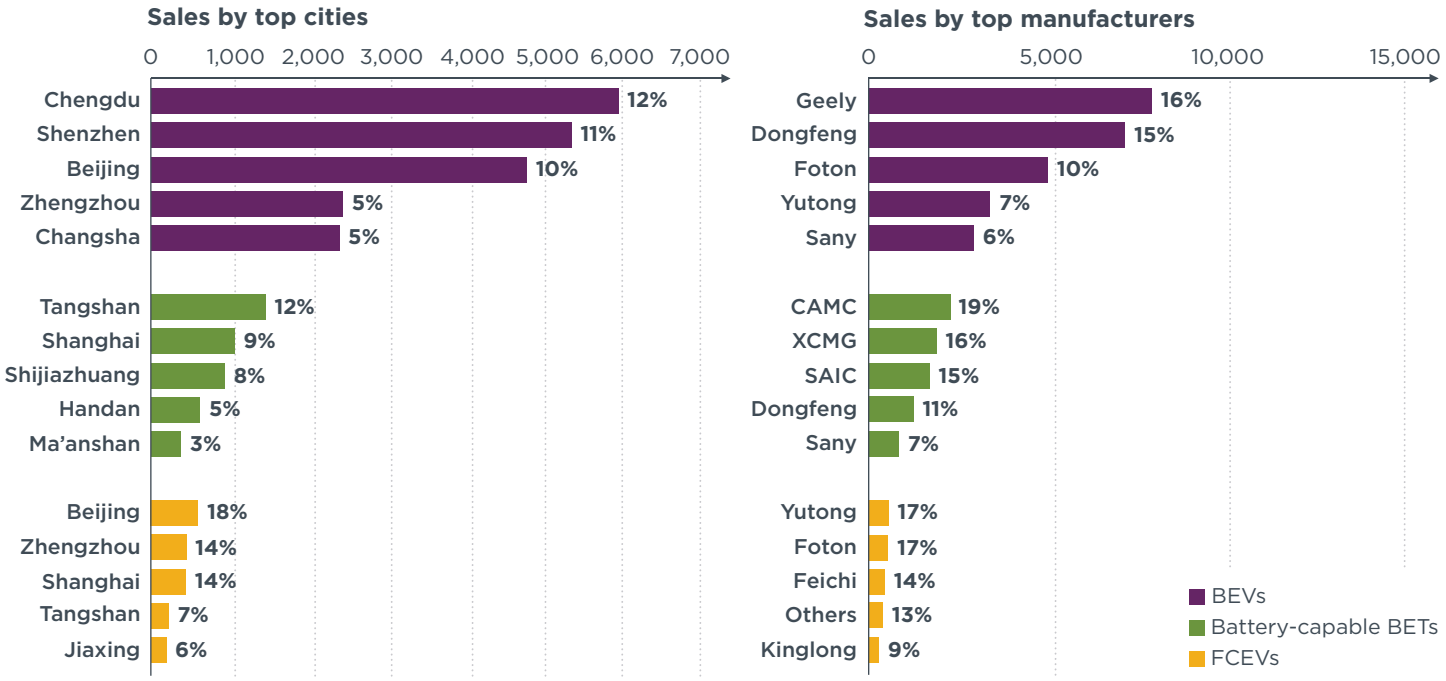


Figure 9. Top cities for sales and top manufacturers of ZEV technology in 2022, trucks.

For buses, top cities for BEVs included Shanghai, Wuhan, Chongqing, Jiaxing, and Beijing, which collectively accounted for 22% of BEVs in the bus segment. The top five manufacturers of BEV buses were Yutong, Kinglong, small OEMs ("Others" in Figure 8), CRRC, and Zhongtong, and these collectively accounted for 61% of BEV buses. The top cities for FCEV buses were Beijing, Shanghai, Zhengzhou, Zibo, and Weifang. These cities jointly represented 57% of FCEVs in the bus segment. The top five manufacturers of FCEVs buses were Kinglong, Yutong, Wanxiang, Zhongtong, and small OEMs, which collectively accounted for 70% of FCEVs in the bus segment. As noted above, there were no battery-swap-capable ZE buses sold in 2022.

Among trucks, the leading cities for BEVs were Chengdu, Shenzhen, Beijing, Zhengzhou, and Changsha. These cities collectively accounted for 43% of BEVs in the truck segment. The top five manufacturers for BEV trucks were Geely, Dongfeng, Foton, Yutong, and Sany, which together manufactured 54% of BEV trucks sold in

2022. The leading cities for battery-swap-capable BETs were Tangshan, Shanghai, Shijiazhuang, Handan, and Ma'anshan. These cities collectively accounted for 38% of battery-swap-capable BETs. The top five manufacturers for battery-swap-capable BETs were CAMC, XCMG, SAIC, Dongfeng, and Sany. These manufacturers collectively accounted for 68% of battery-swap-capable BETs. On the other hand, for FCEVs, the top cities were Beijing, Zhengzhou, Shanghai, Tangshan, and Jiaxing. These cities jointly represented 58% of FCEVs in the truck segment. The top five manufacturers for FCEV trucks were Yutong, Foton, Feichi, small OEMs ("Others" in Figure 9) and Kinglong. These manufacturers collectively accounted for 70% of FCEVs in the truck segment.

Beijing, Shanghai, and Zhengzhou are pioneers among Chinese cities in ZE-HDVs. Each of these cities ranks in the top five for at least one bus and truck ZE technology. These three cities primarily lead in FCEVs or BEVs, with the exception of Shanghai, which is ranked second for battery-swap-capable BETs among trucks. Zhengzhou is also home to the headquarters of Yutong, the largest manufacturer of new energy buses in China and globally.

Some of the cities made it to the list due to a province-level strategy. For example, Zibo and Weifang were among the top cities for FCEV buses and are actively establishing industrial clusters for fuel cells and related materials. Both cities are in Shandong province, which had a foundation in hydrogen-related technology capacity even before 2020 and is aiming to develop its hydrogen industry. The province is home to the state-owned engine manufacturer Weichai, which acquired a 19.9% stake in Canadian fuel cell developer Ballard Power Systems in 2018. Another Shandong-based private sector company, Dongyue Group, produces fuel cell membranes (International Energy Agency, 2021).

Tangshan, Shijiazhuang, Handan, and Ma'anshan have earned positions on the top cities list from their high share of battery-swap-capable BETs. These cities all have significant steel industries; as noted above, battery swapping has become a favored solution for trucks and tractors involved in bulk transport. Policy initiatives have also accelerated the adoption of this technology in these cities. For example, Tangshan is a focus city under the "Battery Swapping Pilot Program" announced by the Ministry of Industry and Information Technology of China (MIIT) in 2021; under this plan, China intends to establish over 60 battery-swapping stations and deploy 2,600 battery-swap-capable BETs by 2023 (Bureau of Industry and Information Technology of Tangshan, 2022).

Jiaxing, Wuhan, and Chongqing led for BEVs in the bus segment; all three have adopted electric buses in their public transportation systems. Meanwhile, Chengdu, Shenzhen, and Changsha led for BEV trucks. Both Chengdu and Shenzhen are actively working to electrify their heavy-duty fleets through various city-wide policies, for instance by establishing zero-emission zones and implementing bans on the operation of diesel heavy-duty trucks in downtown areas during daytime hours (Mao & Rodríguez, 2021, Shenzhen Government, 2022). In July 2022, Chengdu also issued a city-wide action plan promoting green transportation (see the next section for more detail). Changsha, for its part, is home to the headquarters of SANY Group, a company that ranks fifth in China for BEV truck production.

Among manufacturers, Yutong and Kinglong held a leading position for both buses and trucks. Both primarily produce BEVs, which comprise over 85% of their respective ZE-HDV fleets, and the two manufacturers together accounted for 40% of the market in BEVs for the bus segment in 2022. However, Yutong and Kinglong have also expanded into other emerging ZE technologies, specifically FCEVs, which now account for 6% and 7% of their ZE-HDV fleets, respectively. This effort propelled both manufacturers into the top five in the FCEV market for both buses and trucks.

Foton and Zhongtong adopted a similar strategy of investing in BEVs and FCEVs. Foton leads in the truck segment, while Zhongtong excels in the bus segment. Sany and Dongfeng, on the other hand, led in BEVs and battery-swap-capable BETs in the truck segment.

Among the rest of the manufacturers featured in the top rankings, each excelled in only one type of ZE technology. For example, Geely had a leading 16% share in the BEV truck market; notably, 99.5% of Geely's entire ZE HDV fleet consists of BEVs. Feichi stood out for investing heavily in FCEVs, which are employed in 95% of the company's ZE HDVs, making Feichi the only manufacturer to allocate more than 20% of its fleet to FCEVs. This effort enabled Feichi to capture a 14% FCEV market share in the truck segment. CAMC, XCMG, and SAIC were the top three manufacturers of battery-swap-capable BETs; within their own fleets, 84% of CAMC's ZE HDVs utilize this technology, followed closely by XCMG at 74%, and SAIC at 35%.

Geographical distribution

Figure 10 illustrates the geographical deployment in the top five cities for ZE buses, rigid trucks, and tractor-trailers registered in 2022. Shanghai, Wuhan, Beijing, Chongqing, and Chengdu are the top five cities for ZE-HDV buses, while the leading cities for ZE-HDV trucks are Beijing, Shenzhen, Chengdu, Shanghai, and Zhengzhou. There is some overlap between leading cities in the implementation of ZE buses and trucks, in part because city-level policy support can be effective at promoting both types. In July 2022, for instance, Chengdu issued a city-wide action plan promoting green transportation (Chengdu Municipal Bureau of Economic and Information Technology, 2022). The plan includes the promotion of an electrified HDV fleet, particularly for public sector vehicles such as city buses, urban logistics delivery trucks, and construction vehicles. In the case of Zhengzhou, the city government's push to electrify its HDV fleet aligns with a city-wide 5-year strategy issued in 2021 that includes the electrification of all new city buses and sanitation vehicles (Henan Development and Reform Commission, 2022). The effort not only serves the city's environmental goals but also has helped create demand for local HDV manufacturer Yutong, which was the leading ZE-HDVs manufacturer in 2022. This illustrates how the city's policy has supported both environmental goals and local industry.

The leading cities for ZE-HDV tractor-trailers—Tangshan, Shanghai, Shijiazhuang, Handan, and Ordos—reflect the influence of regulation on high-polluting manufacturers. Four of these cities are located in the province of Hebei, which is renowned for its heavy industry; that industry has rapidly transitioned to ZE-HDVs in part due to pressure from the Hebei government to achieve A-grade environmental performance for all of its steel manufacturers since 2022 (Jia & Ma, 2022). Clean transportation, including the introduction of new energy vehicles, plays a crucial role in this effort. This policy-driven initiative not only aligns with the province's environmental objectives, but also encourages businesses to adopt and invest in ZE-HDVs.

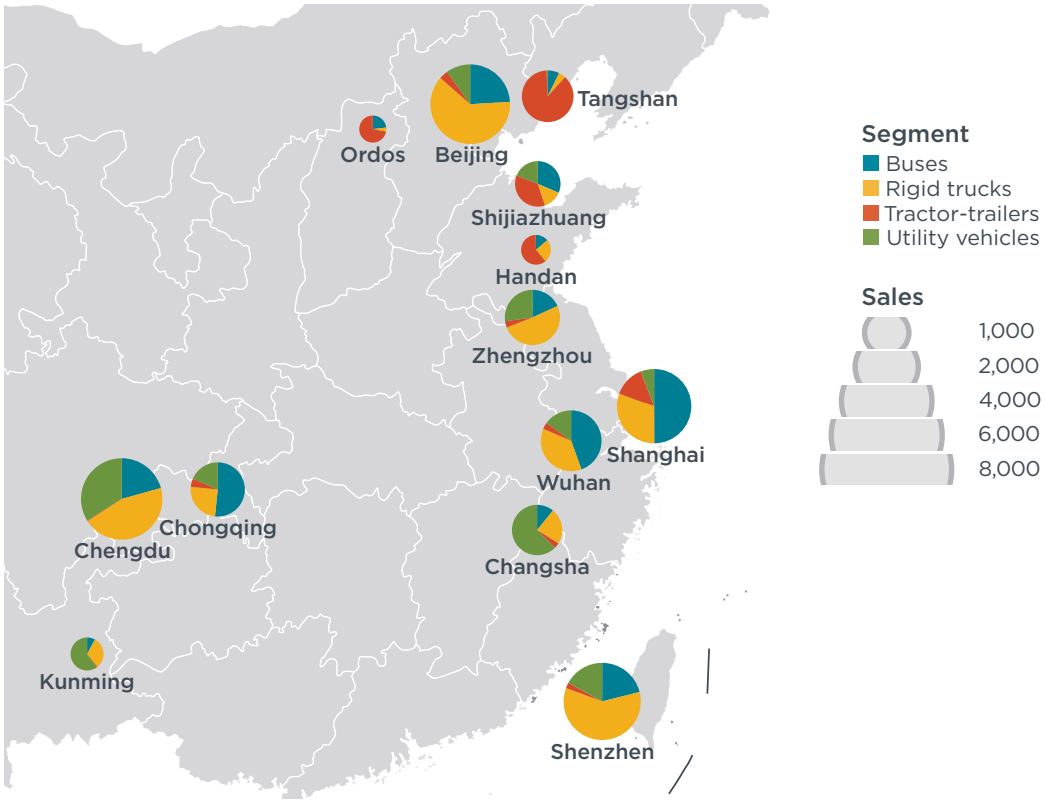


Figure 10. Geographical deployment of top five cities for each ZE-HDV segment in 2022.

OEM performance and progress on key metrics in 2022

Battery electric technology

Battery supply

Despite the COVID-19 related economic downturn in 2022, total installed battery capacity in China surged by 90.7%, according to official sources (Xinhua News, 2023). In addition, as Figure 11 shows, the battery market was more consolidated in 2022: Contemporary Amperex Technology Co. Ltd. (CATL) increased its market share in the HDV battery sector to 79% (from 55% in 2021), and Eve Energy saw a four percentage point increase to 9%. Several other battery suppliers, such as Gotion, Slanpower, and BYD, saw their market shares plummet to below 3%.

Lithium ferrophosphate (LFP) remained the dominant battery technology in the ZE-HDV industry in 2022, with 99.4% of market-wide battery capacity (Figure 12). As shown in Figure 13, 81% of this capacity was supplied by CATL. LFP is a chemical compound popular in spite of its lower specific energy than other competitors because it has strong safety performance and is low in cost (Mao et al., 2023). Nickle-manganese-cobalt (NMC) is another important battery technology for passenger vehicles in China (Jin et al., 2021), but has been almost completely abandoned for heavy trucks and buses due to rising concerns over safety and higher upfront cost (Chedongxi.com, 2020; Ma et al., 2020; Sound Group, 2018). In 2022, among major battery suppliers, only BYD still produced NMC. In August 2023, CATL launched a new "Shenxing" LFP battery with a 4C charging rate, which could significantly improve the performance of LFP batteries in terms of charging duration as compared with NMC batteries (CATL, 2023). Due to this and other factors, the leading position of LFP batteries in the HDV industry appears likely to continue.

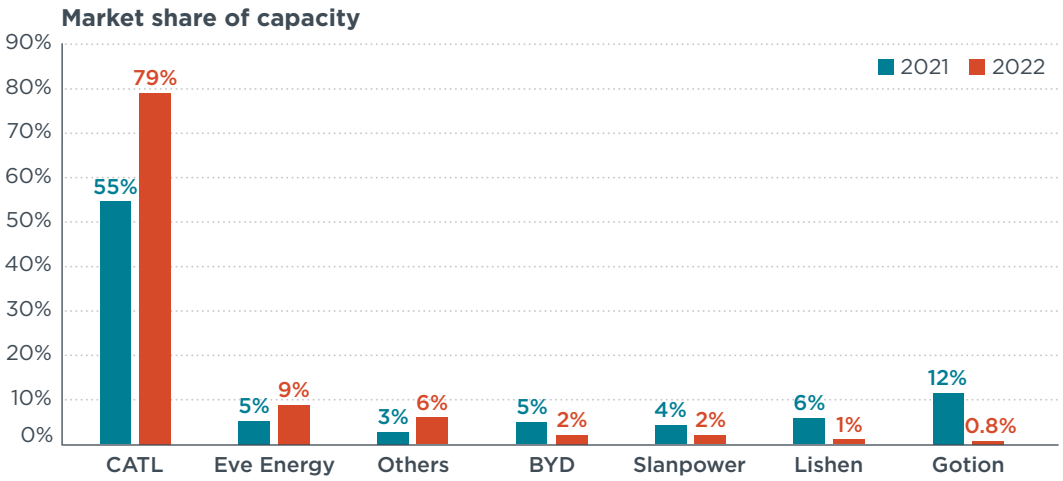


Figure 11. Market share by battery supplier in 2021 and 2022.

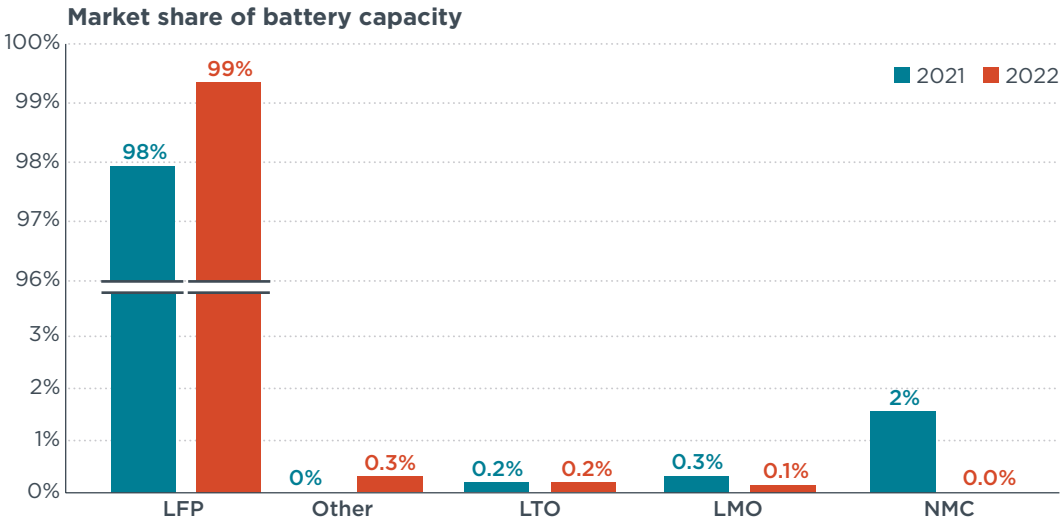


Figure 12. Market share by battery chemistry in 2021 and 2022.

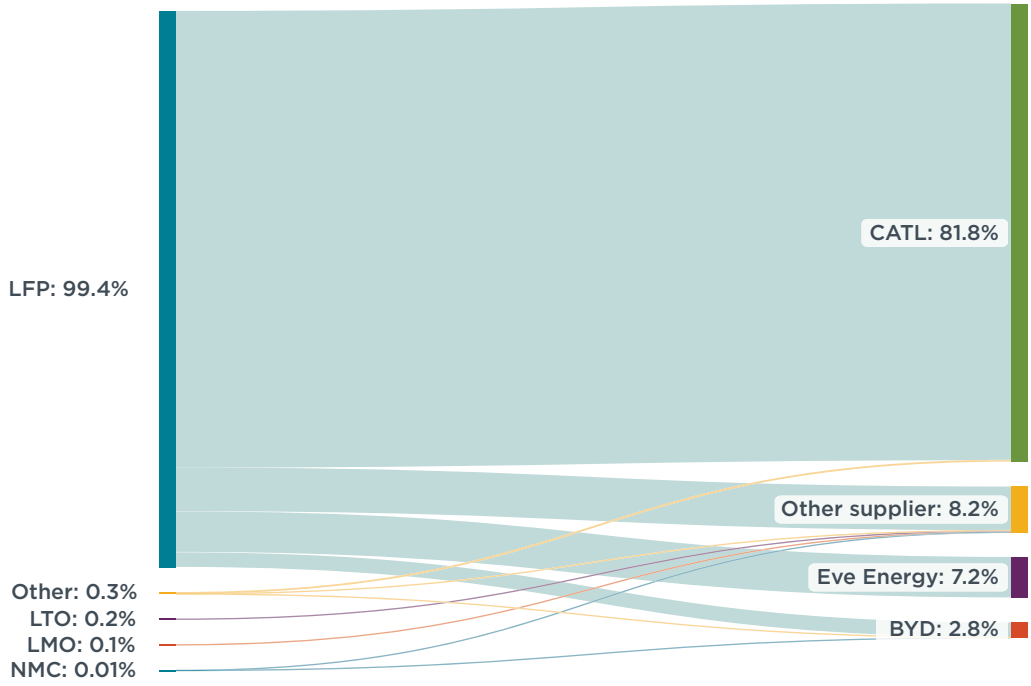
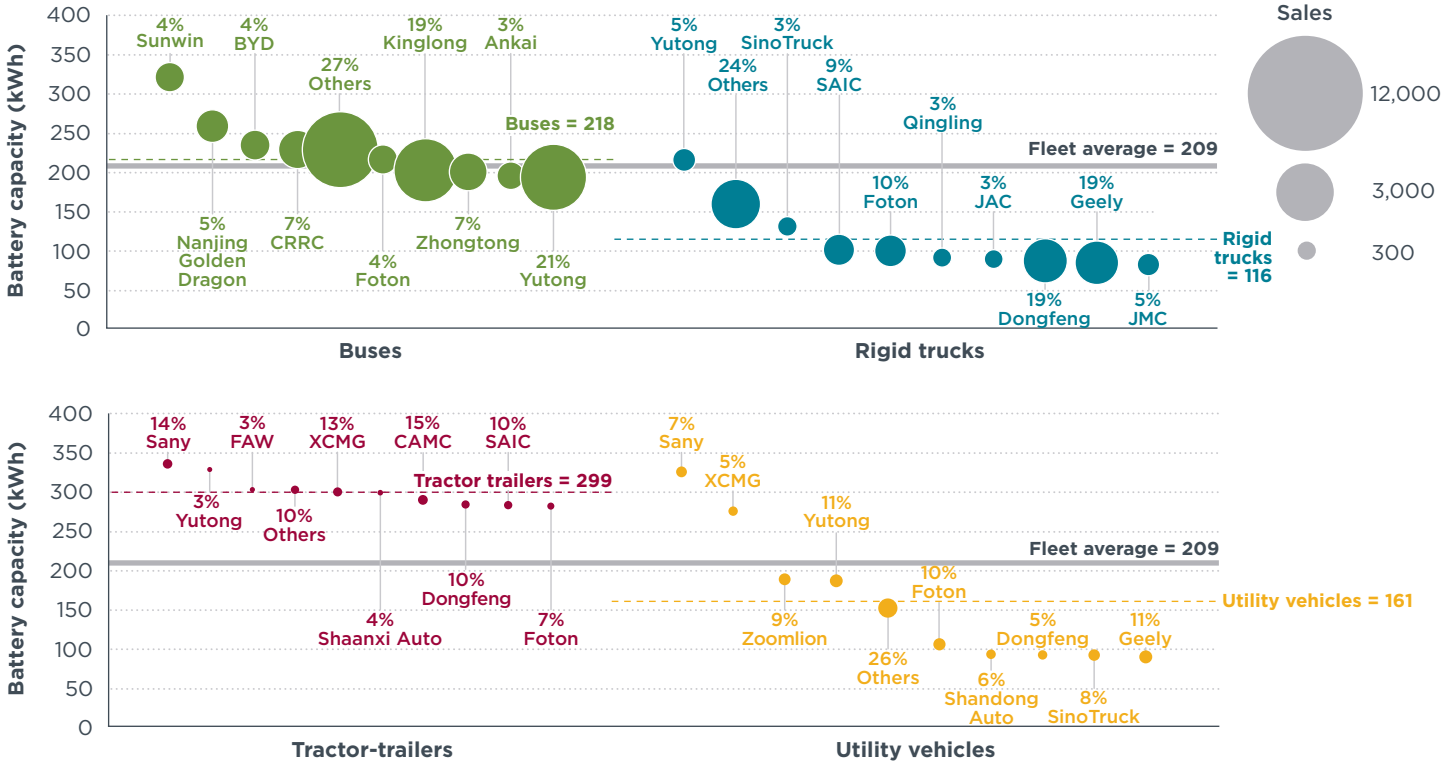


Figure 13. Battery suppliers and battery chemistry, 2022.

Battery capacity

In 2022, the average battery capacity of new ZE-HDVs China reached 209 kWh, an increase of roughly 20% from 2021. Among all ZE-HDV manufacturers, Sunwin offered the largest average battery capacity for buses, 321 kWh. Yutong offered the largest fleet-average battery capacity for trucks, 218 kWh.

Electric tractor-trailers were equipped with the largest batteries and the sales-weighted average battery capacities for tractor-trailers, buses, and trucks were 299 kWh, 218 kWh, and 116 kWh, respectively. The larger batteries offer longer driving range, but may also limit freight capacity.



Note: In the chart, green represents buses, blue signifies rigid trucks, red denotes tractor-trailers, and yellow indicates utility vehicles. The grey line represents the fleet average across all vehicle types (buses, rigid trucks, tractor-trailers, and utility vehicles). The size of each bubble corresponds to the total sales for each OEM in the respective category.

Figure 14. Average battery capacity of the top 10 BEV manufacturers in each segment, 2022.

Energy consumption and range

In 2022, new ZE-HDVs sold in China had an average energy consumption of 0.53 kWh/km. Within the same vehicle segment, the difference in energy consumption among different manufacturers was generally minimal. The exception was utility vehicles, for which the energy consumption varied more widely (Figure 15). In the bus segment, Sunwin recorded the highest fleet average energy consumption at 0.55 kWh/km. In contrast, Ankai, the most energy-efficient OEM in this segment, had an average of 0.41 kWh/km. Notably, there is a significant difference in energy consumption between segments. Tractor-trailers reached a sales-weighted average energy consumption of 1.37 kWh/km, which is 160% more than the fleet average. Meanwhile, rigid trucks and buses consumed energy below the fleet average, recording 0.36 kWh/km and 0.44 kWh/km, respectively.

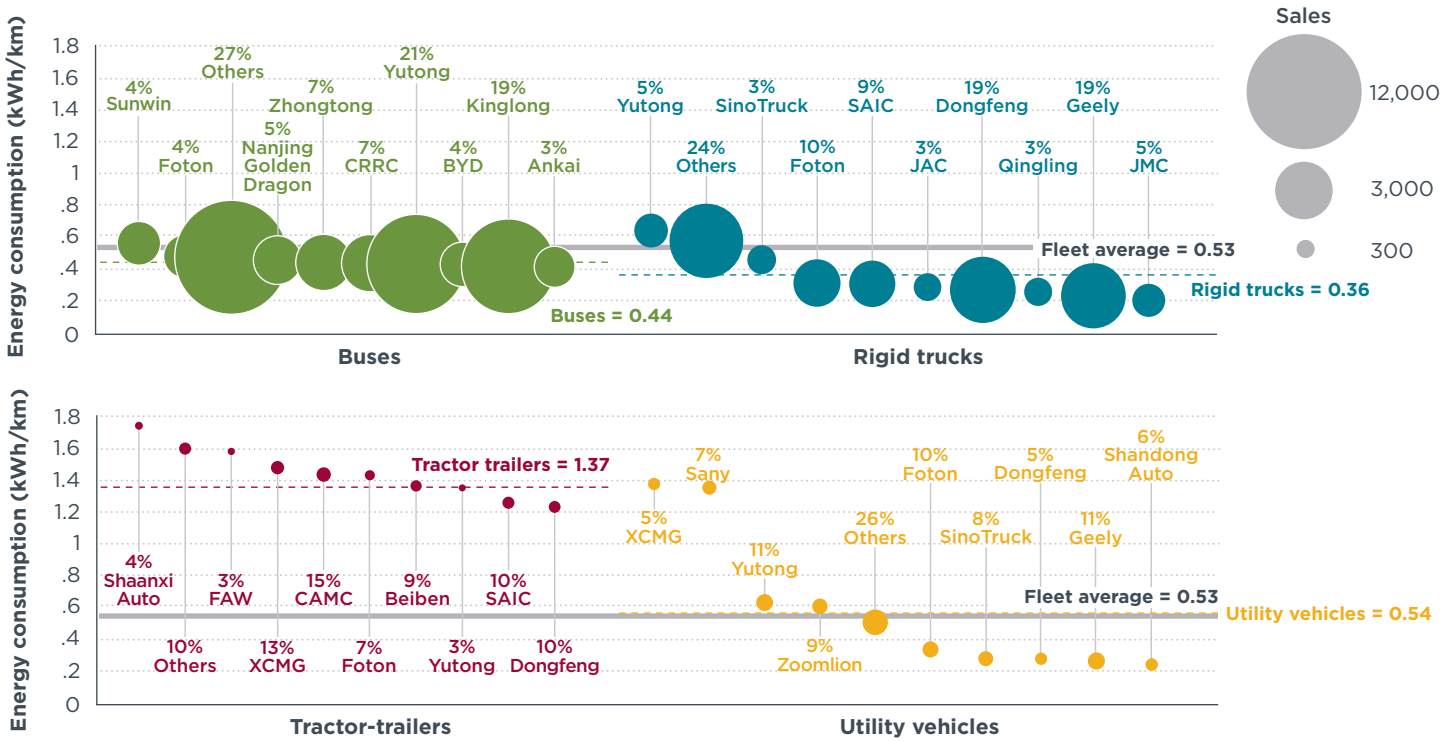


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Figure 15. Average energy consumption of the top 10 BEV manufacturers in each segment, 2022.

A major reason for the significant variation between segments is the differing weight of each vehicle type. Vehicle weight can significantly impact energy consumption (Galvin, 2022). Figure 16 examines this relationship by contrasting energy consumption patterns with the gross vehicle weight of different segments. The trend indicates that the larger the gross vehicle weight rating (GVWR), the greater the energy consumption. Tractor-trailers have the highest GVWR of all segments. Interestingly, within the tractor-trailer segment, energy consumption among OEMs ranges between 1.1 kWh/km and 1.6 kWh/km, even though they have almost identical GVWRs.

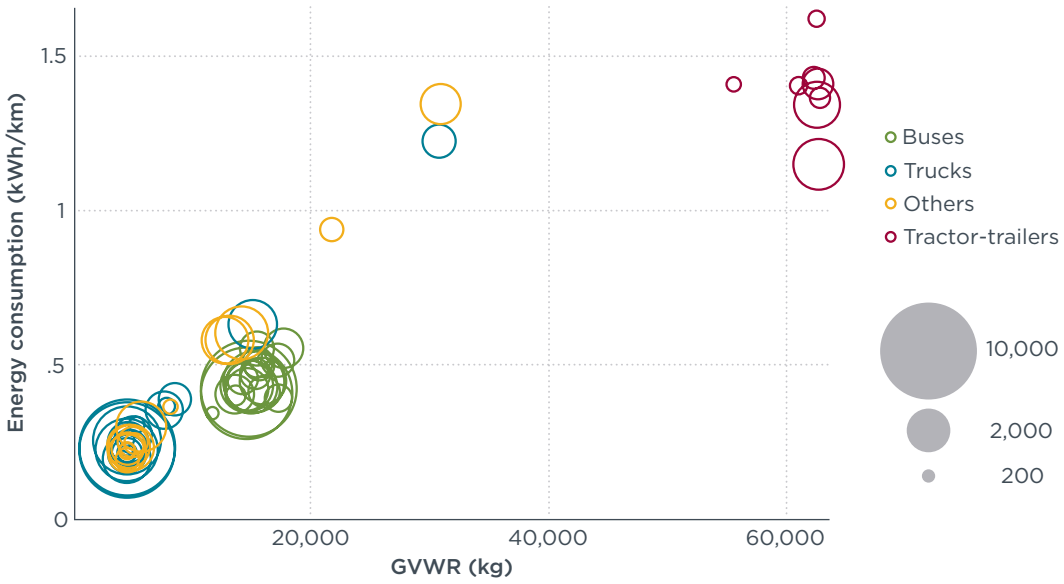
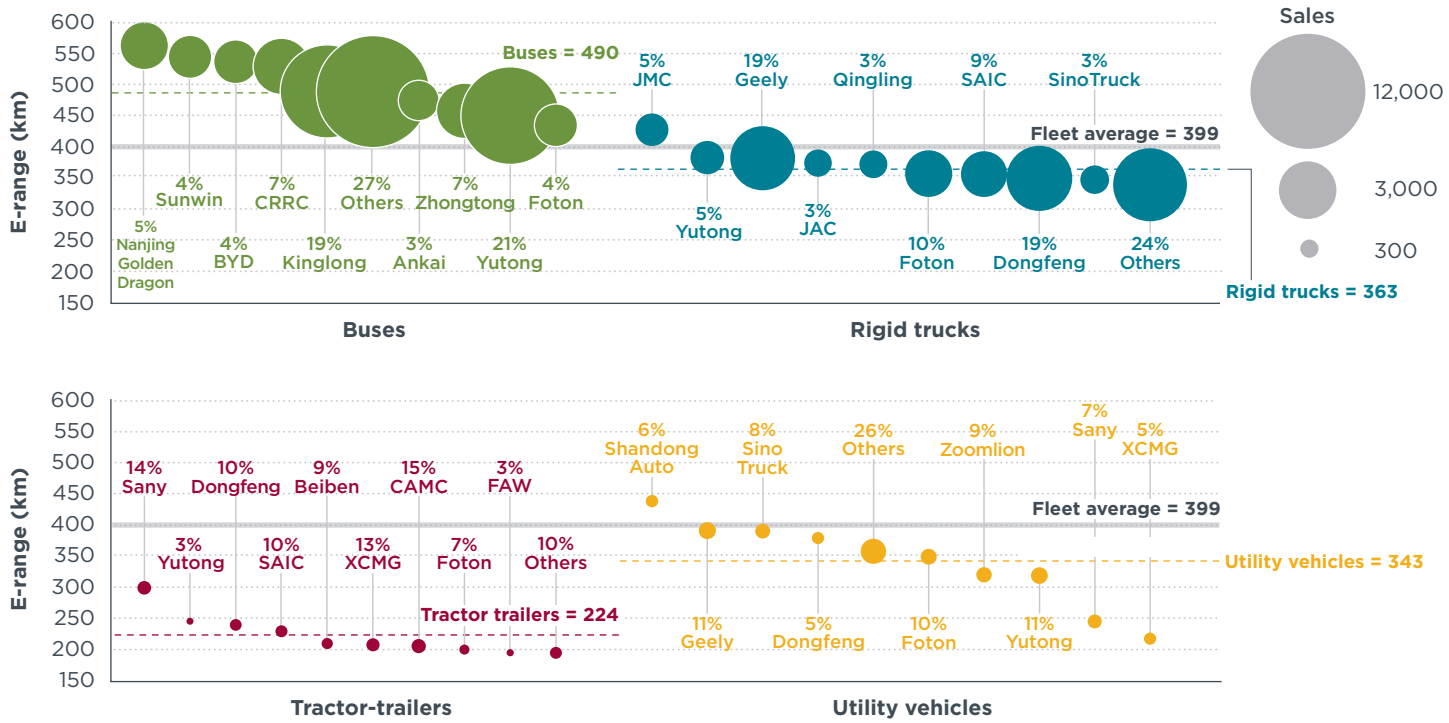


Figure 16. Average energy consumption versus GVWR for models with sales greater than 100 in 2022; bubble size indicates the total sales for each OEM.

BEV range saw a minor year-on-year decrease, from 403 km among vehicles sold in 2021 to 399 km among those sold in 2022. Driving distance varied by vehicle category (Figure 17). The vehicles with longest ranges were around 18 tonnes in GVW, and most of them were buses. Nanjing Golden Dragon, which accounted for 5% of sales in the category, had the longest range (565 km), followed by Sunwin (547 km), BYD (539 km), and CRRC (532 km). For tractor-trailers with a gross combination weight over 25 tonnes, the average range was approximately 230 km. Sany was the manufacturer to provide the longest-range tractor-trailers at 300 km, while most of other tractor-trailer manufacturers failed to reach the average electric distance of 399 km.



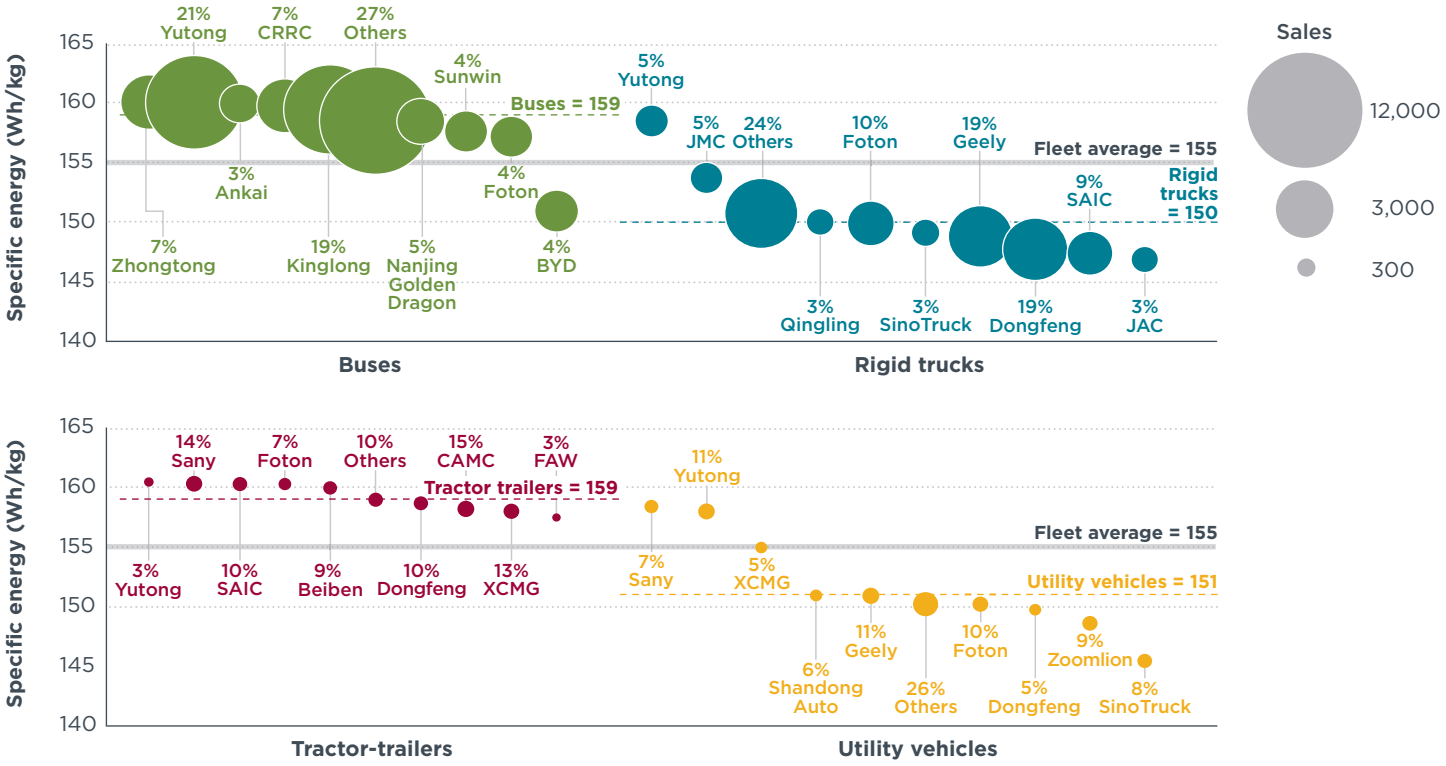
Note: In the chart, green represents buses, blue signifies rigid trucks, red denotes tractor-trailers, and yellow indicates utility vehicles. The grey line represents the fleet average across all vehicle types (buses, rigid trucks, tractor-trailers, and utility vehicles). The size of each bubble corresponds to the total sales for each OEM in the respective category.

Figure 17. Average ranges of the top 10 BEV manufacturers within each segment.

Specific energy

Specific energy is an indicator of the total energy of a battery per battery cell. The specific energy of LFP batteries sold in China increased from 132 Wh/kg in 2021 to 155 Wh/kg in 2022, amid advancements in cell-to-pack technology by CATL and the BYD Blade battery that improved the system specific energy of LFP batteries by refining the internal structure of battery modules (BYD, 2020; CATL, 2022). City bus and tractor-trailer batteries had the highest average specific energy of 159 Wh/kg. Rigid trucks and utility vehicles had a slightly lower values, 150 Wh/kg and 151 Wh/kg, respectively.

These patterns underscore a significant shift from diesel to electric trucks and buses. Electric vehicles are constructed with fewer components than internal combustion engine vehicles, and with a heightened emphasis on patented technologies. As a result, a tier-one supplier like CATL plays an increasingly important role, facilitating quicker adoption of advanced techniques and innovations with its market dominance in battery manufacturing (Park, 2021; Raftery, 2018; Tomatore, 2023; Park, 2021; Raftery, 2018; Tomatore, 2023). The technical advantage of top tier-one suppliers can be even greater with more advanced integration of key components such as battery cells and chassis.

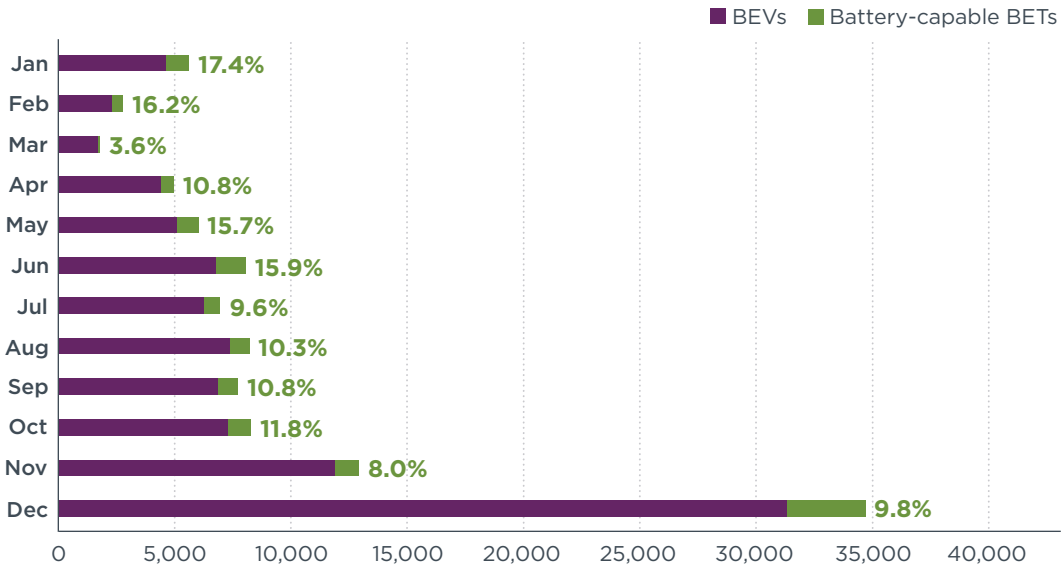


Note: In the chart, green represents buses, blue signifies rigid trucks, red denotes tractor-trailers, and yellow indicates utility vehicles. The grey line represents the fleet average across all vehicle types (buses, rigid trucks, tractor-trailers, and utility vehicles). The size of each bubble corresponds to the total sales for each OEM in the respective category.

Figure 18. Specific energy of the top 10 BEV manufacturers within each segment, 2022.

Battery-swapping technology

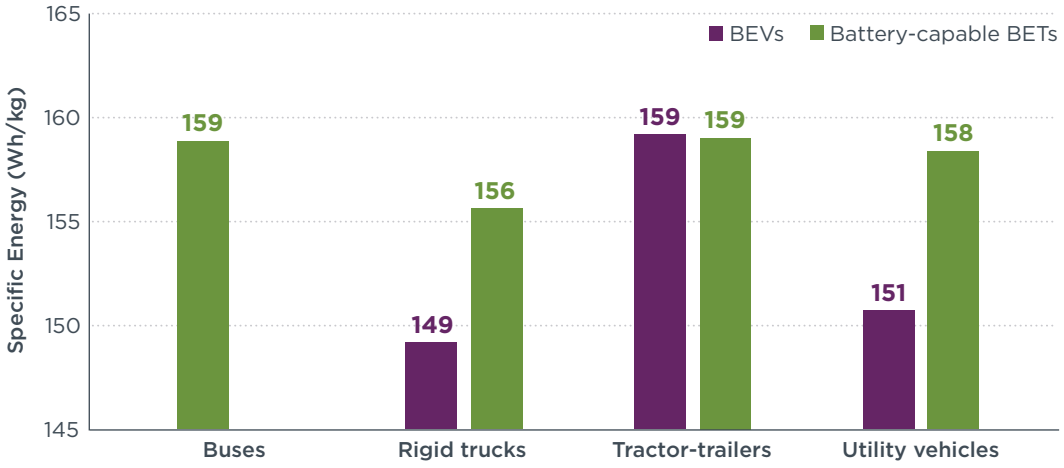
In 2022, 11% of ZE trucks or tractor-trailers sold could support battery swapping. Despite the seasonality typical of ZE-HDV sales, battery-swap-capable BETs maintained a penetration rate of at least 3.6% throughout the year in 2022 (Figure 19).



Note: In the chart, purple represents BEVs, greendenotes battery-swap-capable BETs. Percentage indicates the share of battery-swap-capable BETs among all BEVs in the HDV sector.

Figure 19. ZE-HDV sales by technology in 2022.

Figure 20 illustrates the differences in average specific energy between BEVs and battery-swap-capable BETs across various segments. As noted above, there were no battery-swap-capable vehicles in the bus segment. Battery-swap-capable BETs displayed either an equivalent or increased specific energy relative to the BEVs: Among rigid trucks and utility vehicles, battery-swap-capable BETs exhibited a specific energy that was 7 Wh/kg greater than their BEV counterparts, and among tractor-trailers, the two had identical specific energy values.

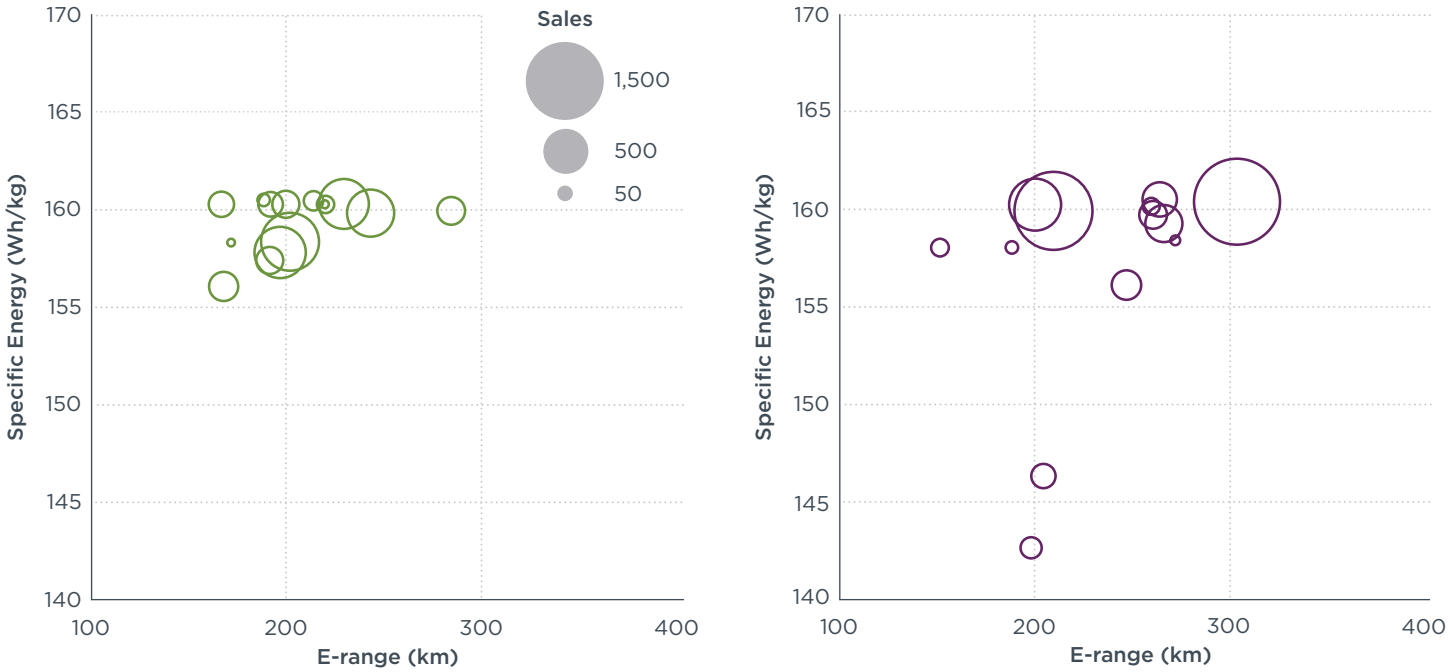


Note: In the chart, purple represents BEVs, green denotes battery-swap-capable BETs. Number above data bar indicates the specific energy in Wh/kg for each HDV segment.

Figure 20. Comparison of the specific energy of BEVs and battery-swap-capable BETs in 2022.

Figure 21 focuses on tractor-trailers—among the most prevalent and promising applications for battery-swapping technology—and presents a side-by-side comparison of fleet-average specific energy and range for major OEMs (sales weighted). Battery-

swap-capable tractor-trailers have lower range (212 km) compared with BEVs (249 km). The gap in range between battery-swap-capable BETs and BEVs was more significant for other segments, with ZE-HDVs with battery swapping generally showing shorter range than BEV counterparts. For instance, battery-swap-capable BETs sold in 2022 can drive an average of 249 km, while BEV trucks' average range is 374 km, a 33% difference.



Note: Green represents battery-swap capable BETs, purple denotes BEVs. Bubble size indicates the total sales for each OEM.

Figure 21. Specific energy versus range for both BEVs and battery-swap-capable tractor-trailers.

Fuel cell electric vehicle technology

In 2022, sales of FCEV HDVs surged by 144% relative to 2021. Of the 113,000 ZE-HDVs sold in 2022, 4,572 were FCEVs. For comparison, from 2016 to 2021, FCEV sales totaled 8,938 units (Mao & Rodríguez, 2021).

Figure 22 shows the top 10 fuel cell HDV manufacturers in China in 2022. The market concentration is relatively high, with the leading 10 manufacturers accounting for 87% of the market. Yutong, the largest producer of FCEV HDVs in 2022, accounted for 18% of the total market, producing approximately 800 vehicles.

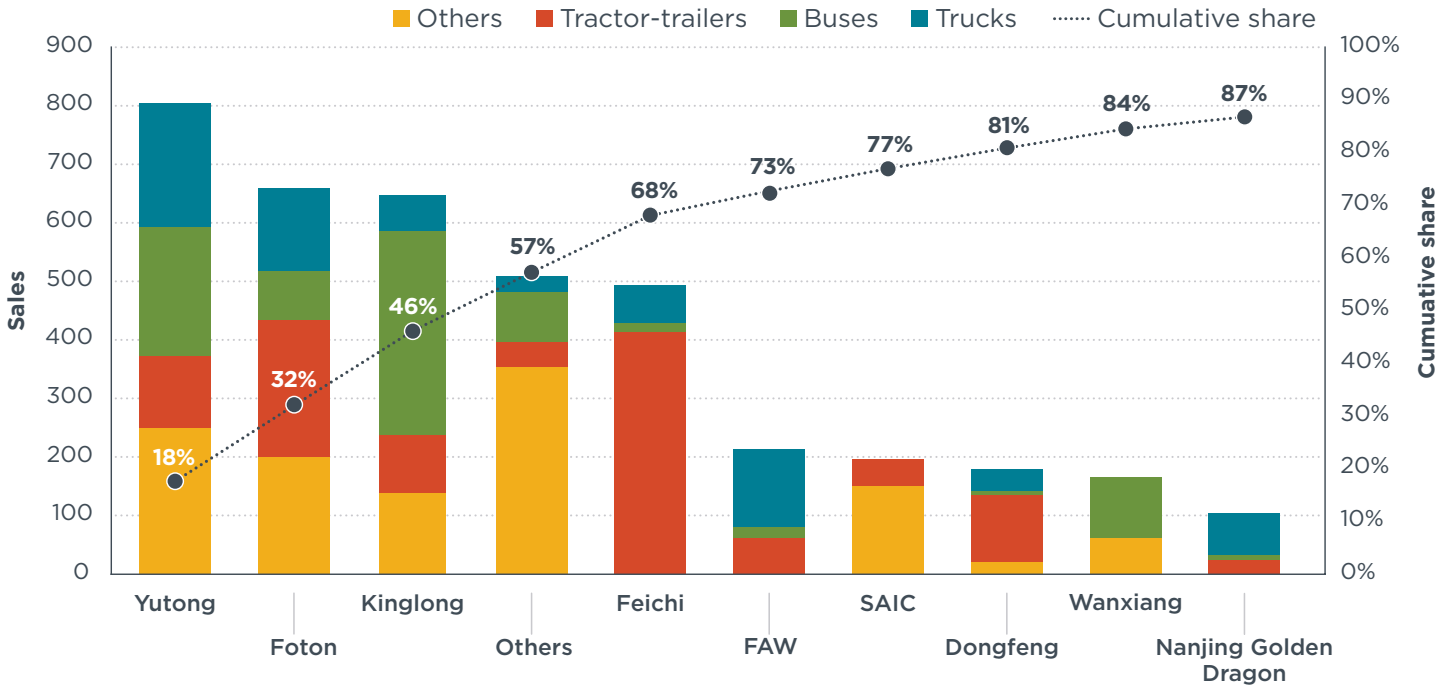


Figure 22. Top 10 FCEV manufacturers, 2022.

Despite being in its nascent stage, we anticipate the FCEV sector will gain momentum in the coming years, driven by policy support from the Chinese government and decreasing costs in fuel cell technology. Table 1 shows several notable policies that were drafted between 2020 and 2022 to promote fuel cell electric technology. These policies aim to accelerate adoption and overcome existing challenges in various ways.

Table 1. Chinese national policies to promote hydrogen fuel cell technology between 2020 and 2022.

Selected national policies to promote hydrogen fuel cell technology		
Date	**Policy**	**Objective**
August 2022	Public Consultation on Promoting the Development of the Energy Electronics Industry (Draft for Soliciting Ideas)	To focus on breakthroughs in key areas such as ultra-long-life and high-safety battery systems; large-scale, large-capacity, and efficient energy storage; mobile energy storage in transportation tools; and on accelerating the research and development of hydrogen energy storage, fuel cells, and other types of batteries.
March 2022	Key Points of Automotive Standardization Work in 2022 (issued by the National Technical Committee of Auto Standardization)	To standardize the testing methods of fuel cell engine performance and support research on standards of key system components such as on-board hydrogen systems.
March 2022	Plan on the Development of Hydrogen Energy for the 2021–2035 Period (issued by the National Development and Reform Commission)	To accelerate the innovation of proton exchange membrane fuel cell technology; develop key materials, enhance major performance indicators, and batch production capabilities; improve fuel cell reliability, stability, and durability; and support the development of new types of fuel cells and related technologies.
June 2021	Notice on Organizing the First Round of Certification for National Energy Research and Development Innovation Platforms during the 14th Five-Year Plan (issued by the National Energy Administration)	According to the notice, the certification process for national energy research and development innovation platforms should focus on key areas such as new energy-based power systems, innovative energy storage, hydrogen energy, and fuel cells.
2020	Hydrogen And Fuel Cell Vehicle Pilot City Program	To bolster hydrogen production, advance the FCEV market, and slash transport emissions. Cities wishing to participate must form clusters to promote a robust supply chain for hydrogen fuel and FCEV parts. Clusters can receive up to 1.87 billion CNY for FCEV and hydrogen development, provided they meet stringent criteria like FCEV registrations and hydrogen production standards.

Sources: Zheshang Securities (2022) and Zhou et al. (2022).

Beyond these policy initiatives, as shown in Figure 23, the cost of a fuel cell system has also decreased by 71% in the last 5 years in China, falling from 15,000 CNY/kW in 2017 to 4,400 CNY/kW in 2021. This significant reduction has made the technology more accessible and appealing for wider adoption. Initially, heavy reliance on foreign products and technology resulted in high costs during the early stages of fuel cell development in China. However, since 2017, Chinese fuel cell system manufacturers have made significant investments in research and development and that resulted in a rapid decrease in costs.

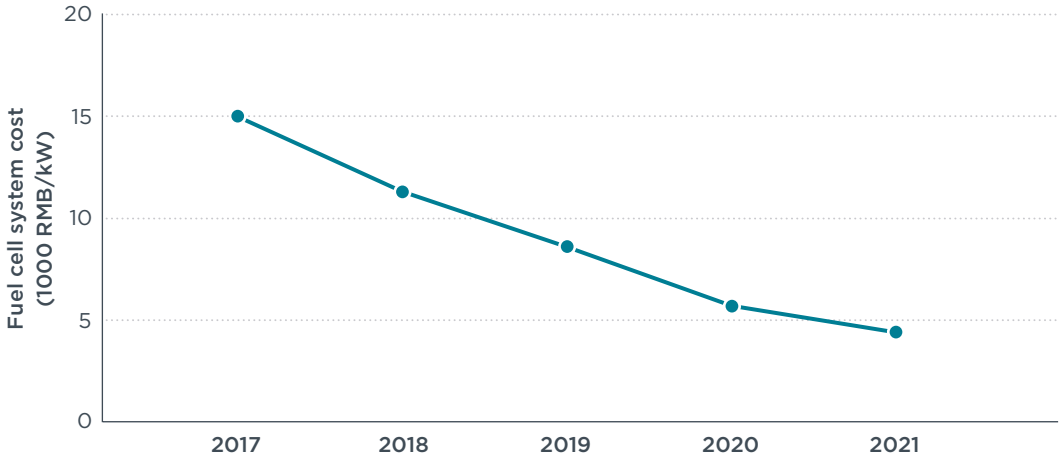


Figure 23. Fuel cell system cost from 2017 to 2021. *Source*: Liduo Data (2022).

The use of FCEVs in China is growing, but their widespread adoption faces critical challenges, particularly the lack of sufficient hydrogen refueling infrastructure. According to the government's National Development and Reform Commission (2022), China aims to have approximately 50,000 FCEVs on the road by 2025. However, as of the end of 2022, the country had built 358 hydrogen refueling stations. To meet its ambitious target, substantial investment in an extensive hydrogen refueling network is crucial.

Another obstacle for FCEVs is ensuring their environmental sustainability. The technology's success hinges on the availability and affordability of hydrogen fuel. Although 'gray' hydrogen produced from fossil fuels is cheaper and more accessible, it undermines the technology's environmental benefits. Zhou et al. (2022) found that the current subsidy design from the Hydrogen and Fuel Cell Vehicle Pilot City Program addresses only CO_2 emissions, neglecting upstream and downstream emissions. Under the program, hydrogen producers could potentially still supply high-emitting hydrogen. For example, of 11 hydrogen pathways analyzed in the study, four met the additional subsidy threshold: hydrogen produced from natural gas combined with carbon capture and storage (CCS), hydrogen derived from landfill gas, and electrolysis hydrogen using either 100% renewable electricity or grid-average electricity. However, from a life-cycle GHG emissions standpoint, hydrogen produced using grid-average electricity exhibits the highest emissions among all 11 pathways analyzed, with GHG emissions that significantly surpass those of fossil petroleum. Therefore, caution is needed when selecting a pathway for hydrogen industry development. There is an urgent need to invest in green hydrogen derived from renewable sources. Such investments are essential to increase production and reduce costs while fostering the sustainability of FCEVs.

Summary of key findings

Sales of ZE-HDVs in China declined by 12% between 2021 and 2022; sales of buses contracted to about half of their 2021 level, and sales of electric trucks expanded significantly. These different sales patterns imply a certain market saturation for electric buses and a potentially critical moment for rapid development for electric

trucks. Overall, the ZE-HDV market saw greater resilience than the market for conventionally powered HDVs against the economic downturn linked to COVID-19 lockdowns in 2022.

Additionally, the following highlights emerged from our analysis:

» China's ZE-HDV market is more diverse than the conventional HDV market in terms of manufacturer market concentration, and the share of the market controlled by the top 10 OEMs declined between 2021 and 2022 in both the conventional and ZE-HDV sectors. Yutong and Foton were the top conventional and zero-emission model manufacturers, respectively. Not all leading OEMs have leveraged their success in the conventional market to penetrate the electric market, but new players such as Geely have increased their market share through innovative investments and development strategies.

» ZE tractor-trailers grew substantially in 2022 amid government policy initiatives to clean and decarbonize key industries such as port logistics, steel, and mining.

» While BEVs remained dominant with 85% of the market, alternative technology pathways such as battery swapping and FCEVs saw modest growth in sales of 8% and 1% in 2022 over 2021. Tractor-trailers in particular stood out for their widespread adoption of battery-swapping technology; roughly 61% of ZE tractor-trailers sold in 2022 were battery-swap-capable vehicles. Cities with heavy industries such as Tangshan, Shanghai, Shijiazhuang, Handan, and Ordos have led the promotion of ZE tractor-trailers.

» CAMC, XCMG, and SAIC were leading manufacturers for battery-swapping technology.

» CATL, by far China's leading ZE-HDV battery manufacturer by capacity, gained even more market share in 2022 and reached 79% of industry battery capacity, up from 55% in 2021.

» LFP remained the dominant battery technology in the industry, accounting for 99% of market share.

» ZE-HDV battery capacity grew by roughly 20% on average between 2021 and 2022, amid a trade-off between load of battery and freight capacity.

» ZE tractor-trailers sold in 2022 had an average energy consumption of 1.4 kWh/km, far higher than the average of other vehicles, estimated at between 0.36 and 0.54 kWh/km.

» The specific energy of LFP batteries jumped from 132 Wh/kg (2021) to 155 Wh/kg (2022). Innovative battery technologies including CTP from CATL and the Blade Battery from BYD emerged to improve the system specific energy of LFP batteries.

» Fuel cell electric trucks grew considerably in 2022, with a 144% increase in total sales compared to 2021; however, fuel cell technology is still in a nascent stage of development. Looking ahead, a continued decline in the cost of hydrogen could provide momentum for further expansion of the market.

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