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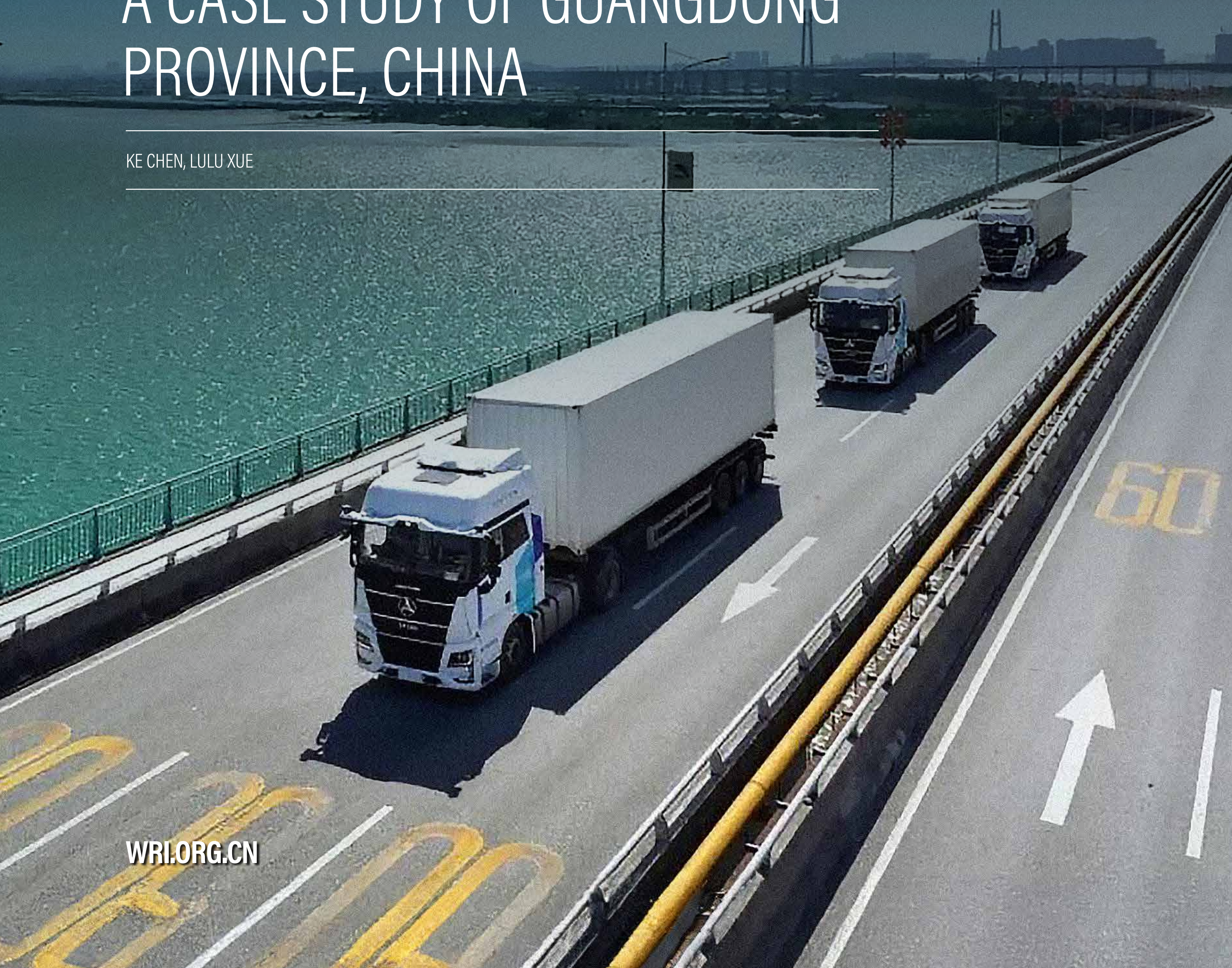
TECHNO-ECONOMIC FEASIBILITY ANALYSIS OF ZERO-EMISSION TRUCKS IN URBAN AND REGIONAL DELIVERY USE CASES: A CASE STUDY OF GUANGDONG PROVINCE, CHINA

KE CHEN, LULU XUE



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Design and Layout by: **Harry Zhang** harryzy5204@gmail.com

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EXECUTIVE SUMMARY

HIGHLIGHTS

- To tackle small fleet operators' concerns and accelerate zero-emission truck (ZET) adoption, we assessed the techno-economic feasibility of ZETs over the time frame of 2022–2030 across use cases in different model years (MYs) for Shenzhen and Foshan in Guangdong Province.
- The promotion of battery electric trucks (BET) in urban delivery, port operation, and drayage duty cycles should be prioritized because their total cost of ownership (TCO) parity with diesel trucks will be reached before MY2025, particularly with comprehensive policy incentives.
- Proposed comprehensive policies in this study are effective to move ZET TCO parity years with diesel trucks earlier than MY2025 in most use cases. BETs benefited more from the comprehensive policies in TCO parity year reduction than fuel-cell electric trucks (FCETs).
- Choosing BETs with smaller batteries, ensuring that charging facilities are sufficiently available, and adjusting operation schedules to allow for multiple within-day charges are important to reduce BETs' TCO.
- Gaps in purchase costs between ZETs and internal combustion engine vehicles (ICEVs) remain large by MY2030, although TCO parity is reached in most use cases. Therefore, financing mechanisms like leasing are essential to ease ZETs' up-front cost burdens.
- Given the day-to-day operational variability of small fleet operators, it is critical to design BETs to ensure operational flexibility, cost effectiveness, and mass production.

About this report

To reduce carbon and air pollutant emissions, promoting ZETs—referring to battery electric trucks and fuel-cell electric trucks—is important (Xue and Liu 2022). Unlike buses and private cars, the trucking industry is dominated by small- and medium-sized enterprises (SMEs) in China (TUC 2022a). Currently, ZETs in Chinese cities were primarily adopted by large fleet operators that were less cost-sensitive. Now, to further promote ZETs, addressing the demand side, particularly more cost-conscious and less technology-savvy SMEs' concerns, is critical for ZETs' future uptake. From the demand perspective, small fleet operators are often concerned about the following issues related to ZET transition: (1) whether the operation of ZETs is technologically feasible where range constraints or payload loss can be avoided; (2) whether purchase cost gaps between ZETs and ICEVs are acceptably small; and (3) whether TCO parity with equivalent ICE trucks can be reached (Tol et al. 2022).

To tackle demand-side concerns and ramp up ZET adoption, it is important to understand the current operational and cost challenges of ZETs, what interventions are effective in overcoming the challenges, and which use case and zero-emission technology to prioritize and when.

To address the questions mentioned earlier, this study chooses one of China's front-runner regions of ZET transition, Guangdong Province, as an example. To reduce the data collection efforts, we choose the cities of Shenzhen and Foshan in Guangdong for in-depth analysis. The two cities are not only leading ZET transitions in Guangdong, but also set ambitious goals for ZET adoption.

We assessed the techno-economic feasibility of ZETs over the time frame of 2022–2030 across different use cases and MYs. The base year is set to 2022 where the most recent data are available. The analysis was carried out for 14 localized use cases:

- Five truck segments, including delivery vans, 4.5-t (ton) light-duty trucks (LDTs), 18-t straight trucks, 31-t dump trucks, and 42-t tractor trailers.
- Four duty cycles, namely, urban delivery (UD), regional delivery (RD), port operation (PO), and drayage duty cycles (DDC).
- Two types of goods transported, including light cargo and heavy cargo.

In this study, the techno-economic feasibility of ZETs is assessed in different use cases, based on three variables essential for small fleet operators to decide if ZET transition is feasible (Hunter et al. 2021; Tol et al. 2022):

- ZETs' operational feasibility. In this study, operational feasibility is evaluated by the

sizes of key components for ZETs, including energy storage capacities, peak power outputs, and curb weights, to meet the ranges and wheel power demands in different use cases during MY2022 and MY2030. The resulting component sizing is useful to find the proper ZET models for the given use case that can come at a reasonable cost and meet the day-to-day operational requirements.

- Differences of purchase costs between ZETs and ICEVs. Here, ZETs' purchase costs are projected based on the technology progress of key components (such as battery packs, electric drives, fuel cell (FC) systems, and hydrogen storage tanks) characterized by the learning curve outlined by Yelle (1979) in which the reduction in unit costs of each key component is a function of accumulated production volumes. We further employed existing literature and market predictions to validate and adjust the projections.

- TCO gaps between ZETs and ICEVs. TCO was evaluated by adding up the capital, operation, and maintenance expenditure of the vehicles; the mid-life replacement costs of key components (such as battery packs); and the opportunity costs of the loss in ZETs' payload capacity. Due to limited data availability, costs such as vehicle residual values and refueling labor costs are not considered in this study.

The use cases with near-term opportunities for ZET transition are identified, based on ZETs' TCO parity years with ICEVs. Further, we evaluate the possible roles played by different interventions—including technological development, policy incentives, operational improvements, and business models—in affecting the previously mentioned decision variables and in accelerating the achievement or advances of TCO parity years relative to diesel trucks. Further, we used an example to illustrate if the conclusions could be applied to other cities and discussed the caveats and uncertainties of the analysis.

Research findings

A. Without ZET incentives, BET promotion in PO, DDC, and urban delivery (UD) could be prioritized, given that the TCO parity with ICE trucks in these use cases will be reached earlier than other use cases.

1. BETs, except for dump trucks, have TCO cost advantages in PO, DDC, and UD in absence of ZET incentives. In these use cases, BETs will reach TCO parity relative to ICEV counterparts before MY2027. This is because BETs are much more energy efficient than ICEVs in PO and UD by taking advantage of frequent stop-and-goes to recoup energies from regenerative braking. By contrast, battery electric dump trucks are less cost advantageous, because of the prominent payload loss issue. Particularly in two instances:

- Battery-electric 42-t tractor trailers in PO, DDC, and UD will reach TCO parity with diesel tractor trailers before MY2025, representing one of the most promising truck segments to be electrified at the moment. This is because: (1) BET tractor trailers in Shenzhen and Foshan mostly carry lightweight goods and (2) operational optimization measures taken by fleet operators in DDC—including using small battery capacities to fulfill the operation and matching BET configurations with charging facility availability—are helpful for BET to reach TCO parity early, relative to diesel trucks.

- Battery-electric 4.5-t LDTs and straight trucks in UD will reach TCO parity relative to their diesel counterparts by MY2027. Particularly, when carrying lightweight goods, both vehicle segments have achieved cost parity now (MY2022–2023), whereas when transporting heavy goods, the parity years will be postponed to MY2025–2027 after being penalized for the payload losses.

By contrast, FCETs' TCO are lower than BETs in RD. In RD, ZETs' TCO cost parity relative to ICEVs will be achieved around MY2028–2030, much later than UD. BETs are less cost advantageous in RD because: (1) ICEVs are relatively more energy-efficient for high-speed highway driving than urban driving; (2) for simplicity, this study does not differentiate FCETs' energy efficiency between UD and RD; therefore, we may have given FCETs more cost advantages in RD.

Figure ES-1 | ZET TCO parity relative to ICEVs for all use cases

● BET ▲ FCET (hybrid) ● FCET (H_2-only)

VEHICLE	DUTY CYCLE	CARGO TYPE	DAILY VKT (KM)	2022	2023	2024	2025	2026	2027	2028	2029	2030	Above 2030
4.5-t LDT	UD	Light goods	200	BET									FCET (hybrid), FCET (H_2-only)
			300	BET							FCET (hybrid)	FCET (H_2-only)	
		Heavy goods	200				BET						FCET (hybrid), FCET (H_2-only)
			300						BET			FCET (hybrid), FCET (H_2-only)	
	RD	Light goods	300					BET				FCET (hybrid)	FCET (H_2-only)
			400					BET			FCET (hybrid)	FCET (H_2-only)	
			500					BET		FCET (hybrid)	FCET (H_2-only)		
		Heavy goods	300										BET, FCET (hybrid), FCET (H_2-only)
			400									FCET (hybrid), FCET (H_2-only)	BET
			500								FCET (hybrid)	FCET (H_2-only)	BET
18-t straight truck	UD	Light goods	200		BET								FCET (hybrid), FCET (H_2-only)
			300		BET						FCET (hybrid), FCET (H_2-only)		
		Heavy goods	200				BET				FCET (hybrid)	FCET (H_2-only)	
			300				BET		FCET (hybrid)	FCET (H_2-only)			
	RD	Light goods	300									FCET (hybrid), FCET (H_2-only)	BET
			400								FCET (hybrid), FCET (H_2-only)	BET	
			500							FCET (hybrid)	FCET (H_2-only)	BET	
		Heavy goods	300								FCET (hybrid), FCET (H_2-only)		BET
			400							FCET (hybrid), FCET (H_2-only)			BET
			500						FCET (hybrid)	FCET (H_2-only)			BET
31-t dump truck	UD	Heavy goods	200								BET		FCET (hybrid), FCET (H_2-only)
			300								FCET (hybrid)	BET, FCET (H_2-only)	
42-t tractor trailer	PO_TRIP	Light goods	200	BET									
			300	BET									
	PO_DVKT		200	BET				FCET (hybrid)	FCET (H_2-only)				
			300	BET			FCET (hybrid)	FCET (H_2-only)					
	DDC_TRIP		200										BET
			300				BET						
			400	BET									
			500				BET						
	DDC_DVKT		200										BET, FCET (hybrid), FCET (H_2-only)
			300									FCET (hybrid), FCET (H_2-only)	BET
			400								FCET (hybrid), FCET (H_2-only)		BET
			500							FCET (hybrid)	FCET (H_2-only)		BET
	UD		200			BET					FCET (hybrid)	FCET (H_2-only)	
			300		BET					FCET (hybrid), FCET (H_2-only)			
	RD		300									FCET (hybrid), FCET (H_2-only)	BET
			400								FCET (hybrid), FCET (H_2-only)		BET
			500							FCET (hybrid)	FCET (H_2-only)		BET

Note: This study assumes that the useful life of the 31-t dump truck is five years and that of other vehicle segments are six years based on Pers. Comm. (2023a).

Abbreviations: TCO=total cost of ownership; BET=battery electric truck; FCET=fuel cell electric truck; ICEV=internal combustion engine vehicle; H_2-only=hydrogen-only mode; hybrid=hybrid mode; VKT=vehicle kilometers traveled; UD=urban delivery; RD=regional delivery; PO_TRIP=port operation (using the trip distance method); PO_DVKT=port operation (using the daily VKT method); DDC_TRIP=drayage duty cycle (using the trip distance method); DDC_DVKT=drayage duty cycle (using the daily VKT method).

Source: WRI authors' calculation.

2. Changes in energy prices will greatly affect ZETs' parity years with ICE trucks in some use cases. The previously mentioned conclusion on TCO parity years is valid when the diesel price is at the 2022 level of 8.1 Chinese Yuan (CNY)/liter and the charging cost is fixed at 1.2 CNY/kWh. If diesel prices drop to the 2019 and 2021 average price of 6.5 CNY/L, and charging costs rises to 1.4 CNY/kWh and above (due to widespread adoption of ultra-fast chargers), battery electric trucks will achieve TCO parity with diesel trucks at a much later time for 42-t tractor trailers in DDC (parity year=~MY2030) and 18-t ton straight trucks in UD with light goods transportation (parity year=~MY2030). Similarly, for FCETs, if the diesel prices remain at the 2022 level, the break-even green hydrogen price in MY2030 is around 30 CNY/kg. However, if the diesel prices drop to the 2021 average price, FCETs are unlikely to achieve TCO parity with diesel trucks at any time before MY2030.

Therefore, **with lower diesel prices, removal of diesel subsidies (Black et al. 2023), increased taxes on diesel prices (OECD 2022), or alternative energy incentives (on electricity and hydrogen) should be considered,** to maintain the cost competitiveness of ZETs.

B. Comprehensive policies are effective to move ZET TCO parity years with ICE trucks earlier, especially for BETs. In this study, we focus on the comprehensive (national and local) policies the impacts of which on TCO can be quantified under this study's TCO methodology framework, including purchase subsidy, tax exemption, energy (electricity/hydrogen fuel) incentives, carbon pricing on conventional fuels, road access privileges, reduction of expressway road tolls, increases of maximum authorized weights of ZETs (also known as ZET weight allowance), and financing cost reductions.

1. There is no silver bullet. Comprehensive policy incentives are more effective to bringing forward ZETs' TCO parity years to an earlier date than single measures. BETs' TCO parity years benefit more from the proposed comprehensive policies in this study. Under the combination of the proposed policies in this study (without a BET purchase subsidy), BETs will reach TCO parity with diesel counterparts in most use cases before MY2025, zero to nine years earlier than the case without policy incentives. By contrast, even with greater amounts of subsidies (including an FCET purchase subsidy), FCETs will reach TCO parity with diesel counterparts before MY2028, three to six years earlier than the case without policy incentives. Overall, with the eight proposed policy incentives, the TCO parity years of BETs are zero to six years earlier than FCETs in most use cases, making BETs the most cost-competitive ZET option.

2. The impacts of policies on ZETs' TCO parity years and TCO reduction are use-case-specific. ZETs benefit from the proposed policies of tax exemption, energy incentives, road access privileges, reduction of expressway road tolls, financing cost reduction, and increases of maximum authorized vehicle weights in this study in TCO reduction. The improvement in cost parity is not significant when applying the carbon pricing measure due to China's current low carbon prices. Specifically,

- the proposed purchase and ownership tax exemption and energy incentives are essential to bridge the TCO gaps between ZETs and ICEVs, for most use cases;
- road access privileges for ZETs are more effective in RD and DDC because we assume that the policy works on vehicle kilometers traveled (VKTs), and both use cases have long VKTs;
- the reduction of expressway road tolls is more influential for 42-ton tractor trailers' RD and DDC because the two use cases have large shares of VKTs on expressways and high toll rates;
- the ZET weight allowance is useful for heavy goods transportation; and
- the financing cost reduction is conducive to moving forward TCO parity years in UD.

3. The FCET purchase subsidy analyzed in this study is found to be one of the most influential policy interventions for FCETs' TCO reduction; but governments

should refrain from using large purchase subsidies to boost ZET adoption to avoid oversupply of truck capacities in the market. With the purchase subsidy assumed in this study, FCETs' time to TCO parity is reduced by zero to two years for all use cases, achieving TCO parity with its diesel counterpart by MY2026–2030. Of note, considering that large public subsidies to promote ZETs would distort the market supply of truck capacities and reduce ZETs' cost competitiveness (Pers. Comm. 2023a), governments should refrain from using large purchase subsidies to stimulate ZET adoption. Instead, scrappage subsidies or other non-subsidy measures such as road access privileges offer viable alternatives.

Figure ES-2 | **ZET TCO parity relative to ICEVs with policy incentives**

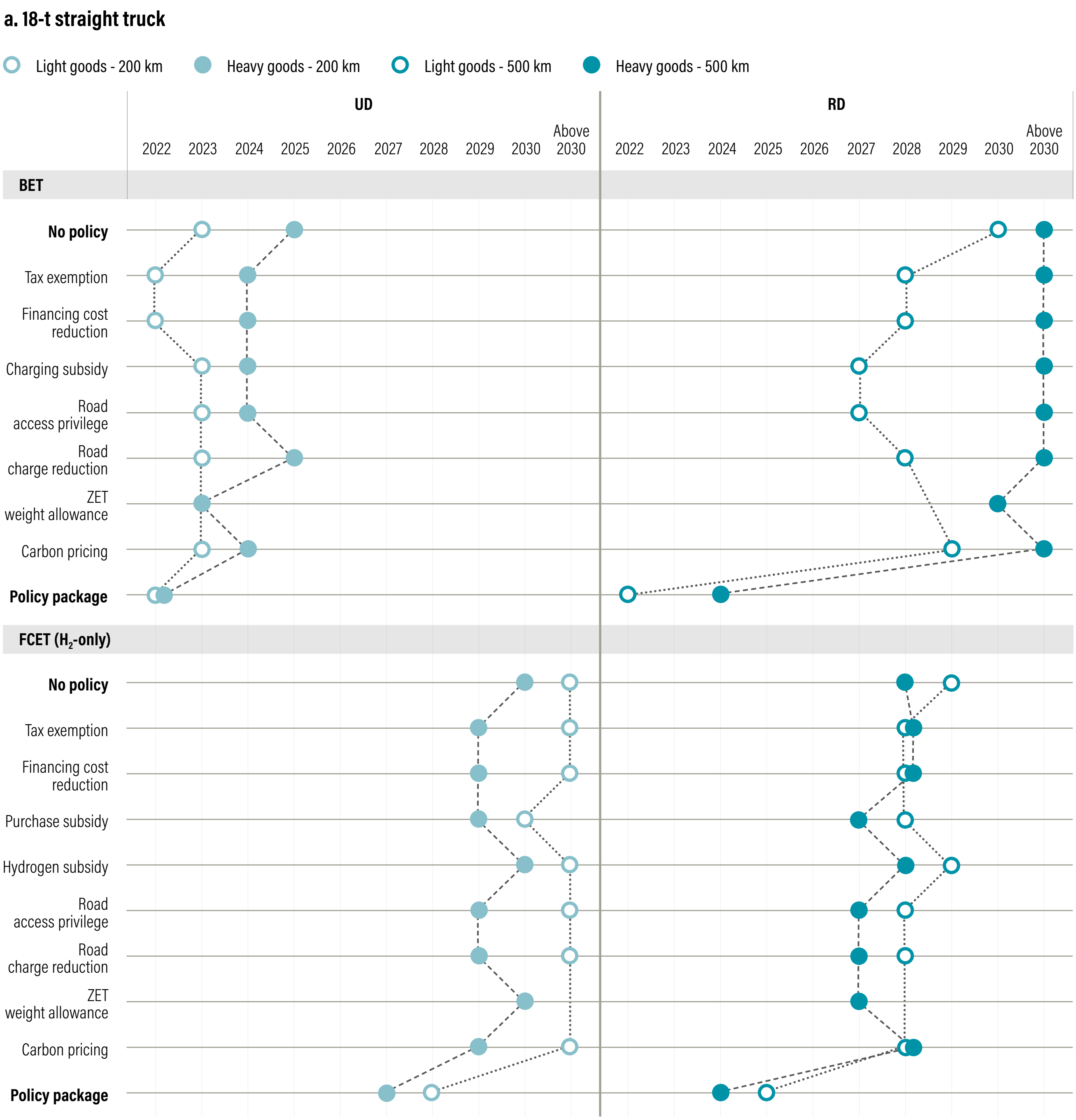


Figure ES-2 | **ZET TCO parity relative to ICEVs with policy incentives (cont.)**

b. 31-t dump truck

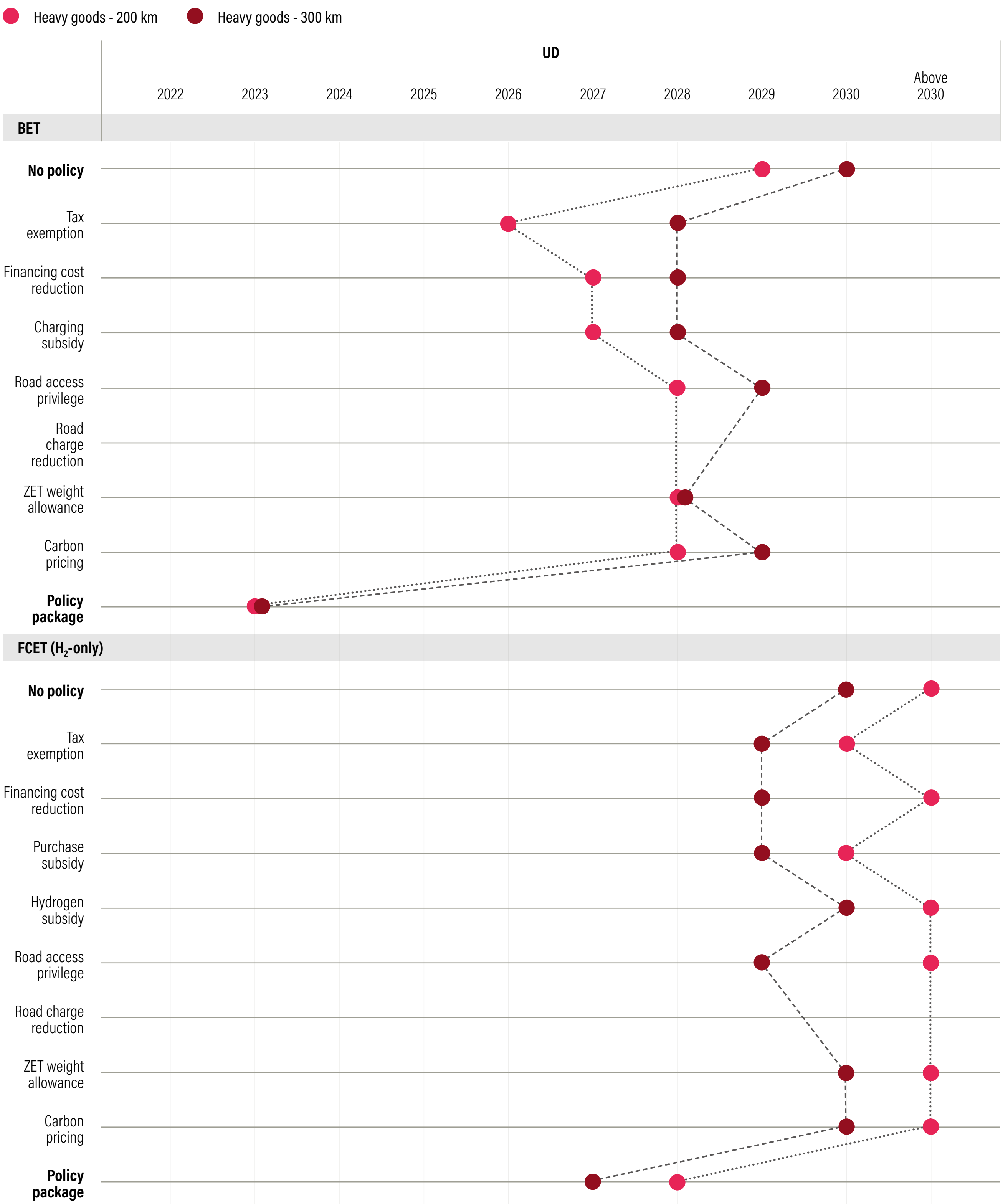
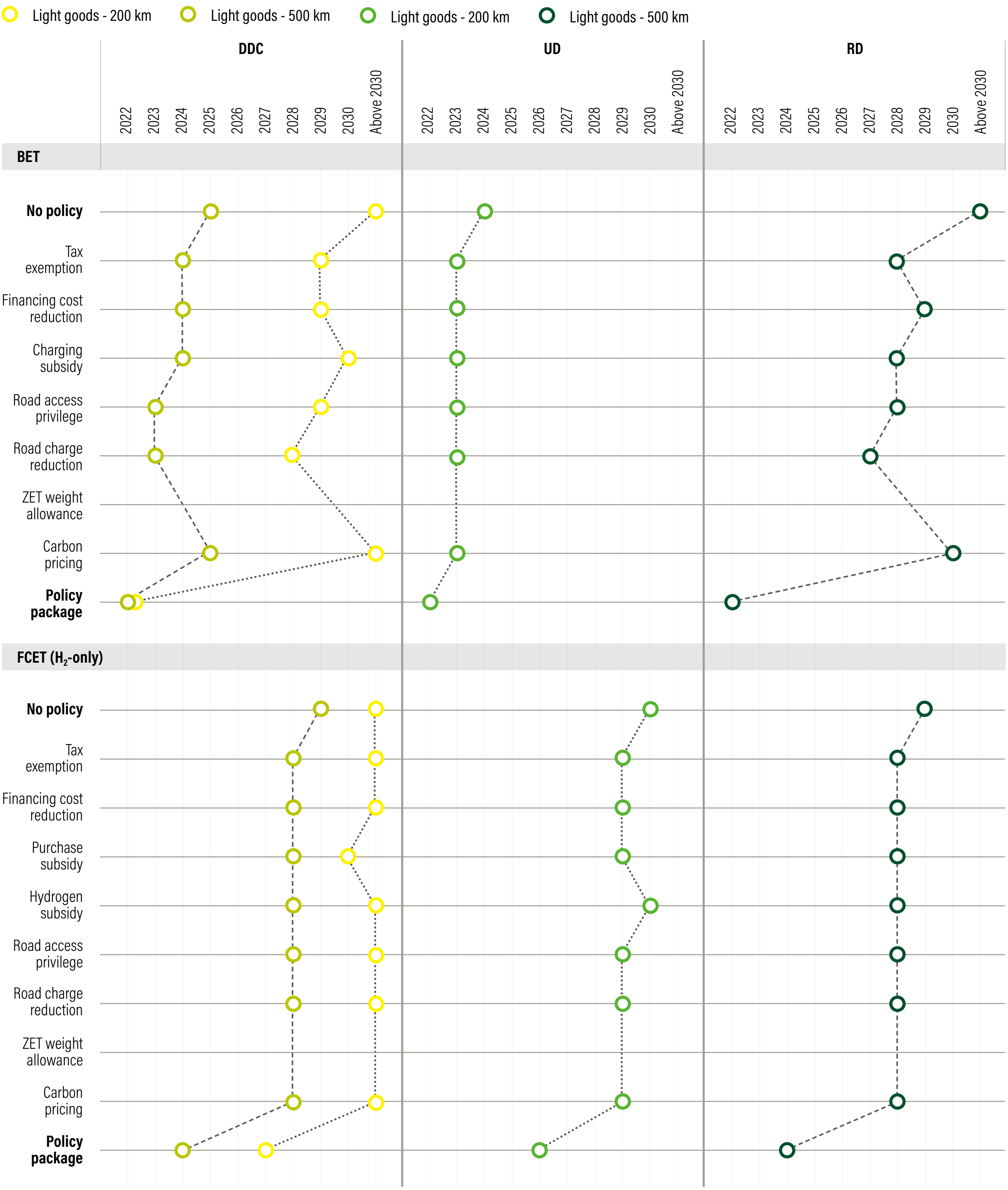


Figure ES-2 | **ZET TCO parity relative to ICEVs with policy incentives (cont.)**

c. 42-t tractor trailer



Note: For a 42-t tractor trailer, DDC denotes the DDC_TRIP use cases for BETs and the DDC_DVKT use cases for FCETs.

Source: WRI authors' calculation.

C. Apart from policies, financing mechanisms, operational optimization, and technology improvements are also essential to accelerate the adoption of ZETs.

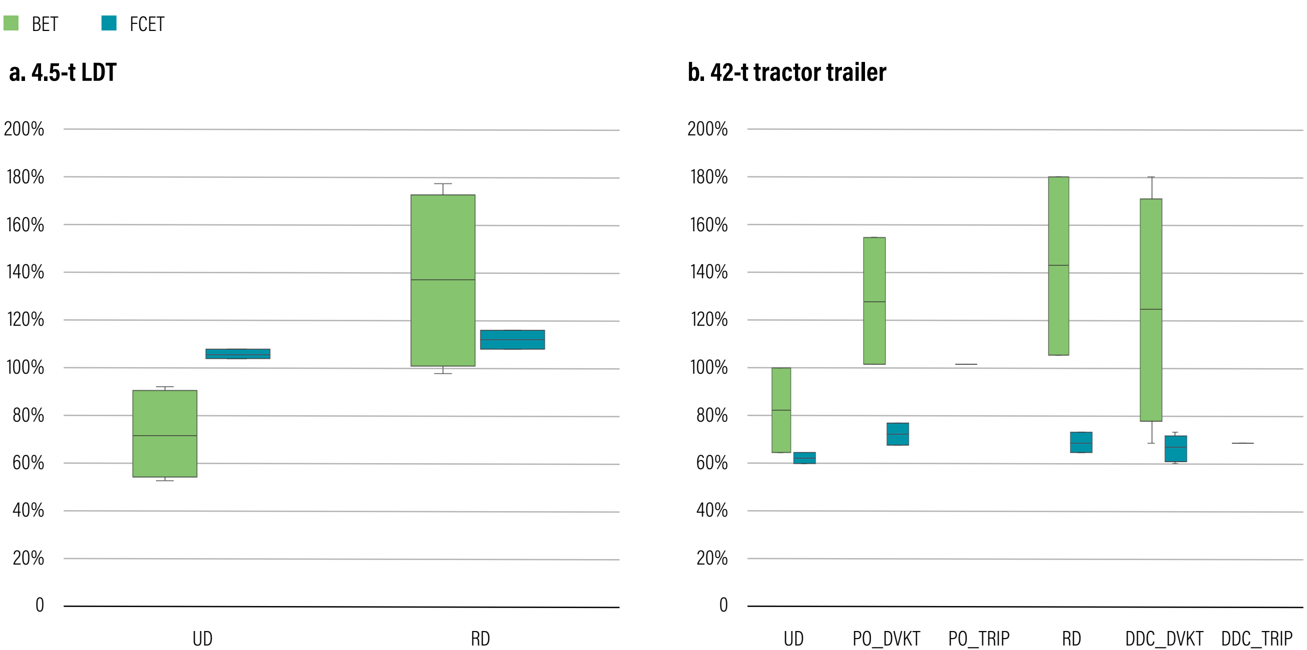
1. Financing mechanisms are essential to ease ZETs' up-front purchase costs. Although the TCO parity with ICE trucks is reached in most use cases by MY2030, tremendous gaps in purchase costs between ZETs and ICEVs remain. By MY2030, the purchase costs of ZETs are still 53 to 322 percent higher than those of ICEVs in all use cases examined by this study.

To ease fleet operators' burden on costly up-front expenses of ZETs—particularly for small fleet operators—and allocate the risks of ZET transition to appropriate stakeholders, it is necessary for private and public players to take actions, including reducing the minimum down payment requirements on ZET loans; encouraging ZET leasing or battery swapping; unlocking green finance (through reduced interested rates and extended repayment terms) and blended finance for ZET financing; and providing tax benefits, flexible depreciation, or first loss guarantees for new business models.

2. Operational optimization is a necessary measure to reduce costs and improve operational feasibility. As in the case of DDC, choosing BETs with smaller batteries, ensuring charging facilities are sufficiently available, and adjusting operation schedules to allow BETs for more than one charge a day are important to reduce BETs' TCO.

For this type of operation to work, it is crucial to have: (1) broad availability of (ultra)-fast charging facilities, parking spaces, and grid capacities at the DDC's customer locations (Kotz et al. 2022); and (2) BETs' operation schedules that allow for sufficient charging time windows—for example, timing charging with loading (or unloading) of trucks or break times of drivers.

Figure ES-3 | **Percentage differences in purchase costs between ZETs and ICEVs for MY2030**



Note: The percentage represents the difference in the purchase costs between ZETs and comparable ICEVs divided by the purchase costs of ICEVs, that is, (ZET-ICEV)/ICEV. Zero percent indicates no difference between the purchase costs of ZETs and ICEVs. No purchase subsidy or tax is considered for the purchase costs.

Abbreviations: BET=battery electric truck; FCET=fuel cell electric truck; ICEV=internal combustion engine vehicle; VKT=vehicle kilometers traveled; UD=urban delivery; RD=regional delivery; PO_TRIP=port operation (using the trip distance method); DDC_DVKT=drayage duty cycle (using the daily VKT method); DDC_TRIP=drayage duty cycle (using the trip distance method).

Source: WRI authors' calculation.

3. Accelerating technology developments is essential to reduce ZET's TCO and move its parity years to an earlier date. Battery cost reduction, vehicle energy-efficiency improvement, and battery energy density increases are critical for reducing BETs' TCO, while the cost reduction of the FC systems and green hydrogen prices are essential to bring down FCETs' TCO (FC system costs are more influential for UD, while hydrogen prices are more important for RD).

4. It is important to design BETs with flexibility. Significant variations in BET battery capacities exist. For example, even within the same-use case, the differences in battery capacities of BETs examined in this study could vary by 51 kWh to 322 kWh in MY2025. Given the day-to-day operational variability of small fleet operators, designing a broadly applicable BET that is capable of meeting the majority operation (in terms of ranges) in an often-applied use case is critical. This means both Original Equipment Manufacturers (OEMs) and fleet operators should have a thorough understanding of existing diesel fleets' daily mileage profiles.

D. Data-driven and multi-dimensional policymaking is necessary.

1. Data on ZETs' energy efficiency and existing diesel truck fleets' mileage are important to improve the TCO estimation and to inform policymaking. Energy efficiency would greatly affect ZETs' parity years and determine which use case to prioritize ZET promotion. Further, truck fleets' mileage profiles are also critical to the design of broadly applicable ZETs. Therefore, it is important for governments to gather ZETs' real-world energy-efficiency and ICEVs' mileage data by use case and share among key stakeholders, such as OEMs.

2. Fleet operators in reality would also take multiple factors into consideration, such as the safety and security of ZETs, shippers' requirements, market demands and profitability, and customers' awareness of the recent development of ZETs when deciding if ZET transition is feasible (QTLC and MOV3MENT 2022). Therefore, **it is also necessary to go beyond the policies examined in this study to consider more policy options,** such as enhancing ZETs' fire safety, enforcing air pollution prevention policies, improving ZETs' residual values, and organizing public education campaigns (particularly for small fleet operators).

E. The conclusions from the study would be applicable to cities with similar use case characteristics, including truck segment deployed, type of goods transported, driving cycles, and ambient temperature. **Cities with different characteristics should be cautious when applying this study's conclusions.** For example, a 49-ton BET100 tractor trailer in Tangshan's DDC had reached TCO parity with its diesel counterpart in MY2022, earlier than Shenzhen examined in this study. This is because tractor trailers in Tangshan do not require large battery capacities (trip distances within 100 km) and have a large proportion of the daily VKTs performed near docks or in the urban environment (Mao et al. 2023).

Figure ES-4 | **ZETs' TCO parity years relative to ICE trucks for the DDC use case in Shenzhen and Tangshan**

● BET ▲ FCET (hybrid) ● FCET (H_2-only)

VEHICLE	DUTY CYCLE	CARGO TYPE	DAILY VKT (KM)	2022	2023	2024	2025	2026	2027	2028	2029	2030	Above 2030
49-t tractor trailer (Tangshan)	DDC_TRIP	Heavy goods	200				BET						
			300	BET									
			400	BET									
			500	BET									
	DDC_DVKT		200				BET					FCET (hybrid), FCET (H_2-only)	
			300					BET				FCET (hybrid), FCET (H_2-only)	
			400						BET			FCET (hybrid), FCET (H_2-only)	
			500							BET		FCET (hybrid), FCET (H_2-only)	
42-t tractor trailer (Shenzhen)	DDC_TRIP	Light goods	200										BET
			300				BET						
			400	BET									
			500				BET						
	DDC_DVKT		200										BET, FCET (hybrid), FCET (H_2-only)
			300									FCET (hybrid), FCET (H_2-only)	BET
			400								FCET (hybrid), FCET (H_2-only)		BET
			500							FCET (hybrid)	FCET (H_2-only)		BET

Note: This study assumes that the trip distance for Tangshan's DDC use case is 100 km, while that for Shenzhen is 200 km. Further, the energy consumption of a MY2022 49-t diesel tractor trailer is 64L/100 km, a BET is 230kWh/100 km, and an FCET is 18kg/100 km.

Abbreviations: BET=battery electric truck; FCET=fuel cell electric truck; ICEV=internal combustion engine vehicle; DDC_TRIP=drayage duty cycle (using the trip distance method).

Source: WRI authors' calculation.

CCINN
廣御點
百年手艺打造一席茶点
本座三樓
订座电话
020-88503633
3F
电话:3699 8848
旺角冰室
旺角冰室
城市
专业植发找雍禾

SECTION 1

INTRODUCTION

Addressing the demand side, particularly cost-conscious and less technology-savvy SMEs' concerns, is critical for ZET's future uptake. The study aims to tackle the research questions that what ZET operational feasibility, purchase costs, and TCO challenges are confronted by fleet operators (particularly, SMEs) now; what interventions are effective in overcoming the challenges; and what roles would different interventions play.

Trucks represented 52, 84, and 91 percent of road transport-related CO_2, NOx, and PM emissions in China in 2020 (Xue and Liu 2022; MEE 2021). Promoting ZETs—referring to battery electric trucks and fuel-cell electric trucks—is important to reduce carbon and air pollutant emissions (Xue and Liu 2022).

Unlike buses and private cars, the trucking industry in China is dominated by SMEs, including affiliated individuals and self-employed individuals (TUC 2022a). In 2020, these SMEs represented around 75 percent of China's fleet operators, referred to as carriers, own-account third-party logistic providers, and own-account shippers in this study. Seventy-eight percent of these individuals had an annual income at about China's average level in 2020 (97,379 CNY) (SINOIOV and Chang'an University 2022). By contrast, the median income for tractor trailer drivers in the United States was US $47,130, 38 percent higher than the US average income in 2020 (USBLS 2020; USCB 2020). In the past, ZETs in Chinese cities were primarily adopted by large fleet operators that were less cost-sensitive. Now, to further promote ZETs, addressing the demand side, particularly more cost-conscious and less technology-savvy SMEs' concerns, is critical for ZET's future uptake.

From the demand perspective, small fleet operators are often concerned about the following aspects for ZET transition: (1) whether the operation of ZETs is technologically feasible where range constraints or payload loss can be avoided; (2) whether purchase cost gaps between ZETs and ICEVs are acceptably small; and (3) whether TCO parity with equivalent ICE trucks can be reached (Tol et al. 2022).

To tackle the previously mentioned concerns, it is important to understand what ZET operational feasibility, purchase costs, and TCO challenges are confronted by fleet operators now; what interventions are effective in overcoming the challenges; and what roles would different interventions play.

- Policy incentives: Although policy incentives are effective to incentivize ZET adoption, with the complete phase-out of national new energy vehicle (NEV)[1] purchase subsidies, China lacks policy incentives to bridge the cost gaps between ZETs and ICEVs. Lingering questions remain as to what policies would be needed to maintain the rapid growth of ZETs.

- Technology improvements: Current zero-emission technologies encounter technical issues in many use cases, such as high costs, range constraints, payload loss, peak power deficiency, and long downtime due to prolonged charging or maintenance time, compared with their ICEV equivalents (QTLC and MOV3MENT 2022). When and to what degree technological advances would resolve ZETs' techno-economic challenges remain unanswered.

- Business models and operational optimization: Despite current technological challenges and lack of policy incentives, battery swapping and leasing of ZETs have pushed ZET adoption in China (Shen and Mao 2023; Z. Wang et al. 2020). For example, the annual sales of battery-swapping heavy-duty trucks (HDTs) in 2022 reached 12,431, higher than battery electric HDTs (Sohu 2023). The

model of battery swapping works because fleet operators only pay for the vehicle body without batteries, and the locations of battery swapping stations are coordinated with truck operation schedules (Ren et al. 2024). In the future as technologies develop, whether operational improvements and business models would still be useful would need investigation.

Adding to the complexity is the wide variety of truck use cases awaiting ZET transition, and policymakers (and fleet operators) remain unclear about which use-case and zero-emission technology to prioritize. For example, the Shenzhen government offered an 800,000 CNY purchase subsidy per vehicle to facilitate the adoption of 4,200 battery-electric dump trucks in 2019, about one third of the city's dump truck fleet (NEICV 2022). However, the effort was deemed unsuccessful partly due to the high costs associated with battery-electric dump trucks (Pers. Comm. 2023a). Now, rather than electrifying the rest of the dump truck fleet, the Shenzhen government has changed the focus to tractor trailers operated in the seaport (Shenzhen MTB 2021).

To address the questions raised earlier, this study uses one of China's frontrunner regions of ZET transition, Guangdong province, as an example, to tackle the following questions:

- What are the current challenges with ZET adoption?
- In the near term, which vehicle segment and use case should be prioritized and at what time?
- Which zero-emission technology to transition to?
- What interventions would be helpful to overcome ZETs' techno-economic challenges?
- Would Guangdong's findings be applicable to other Chinese regions?

Guangdong has been leading China's ZET adoption for years. From 2019 to 2022, its new ZET sales ranked the first among 31 Chinese provinces in China (Niu et al. 2023). To reduce

the data collection efforts, we chose the cities of Shenzhen and Foshan for in-depth analysis. Among 21 cities in Guangdong, the two cities accounted for 27 percent of the province's LDT stocks and 30 percent of HDT stocks in 2021 (Guangdong Stats 2023). Guangdong also established ambitious goals for ZET transition: Shenzhen aims to reach 80 percent NEVs in new sales of urban delivery LDTs and 100 percent NEVs or clean energy vehicles[2] in the fleet of tractor trailers operated in Shenzhen Port by 2025 (MIIT et al. 2023; Shenzhen MEEB 2022). As the leading city of Guangdong FCEV city cluster, Foshan (and the Guangdong City Cluster) aims to adopt 10,000 FCEVs by 2025 (Guangdong DRC et al. 2022).

Since Guangdong is spearheading ZET transition in emerging use cases, its experiences shed light on the ZET transition in other Chinese regions. This study also examined whether Guangdong's findings would be applicable to other Chinese regions.

Table 1 | **Current policy incentives for ZET adoption at the national level and in Shenzhen and Foshan**

	BATTERY ELECTRIC DELIVERY VAN	BATTERY ELECTRIC LDT	BATTERY ELECTRIC HDT	FC ELECTRIC TRUCK
National incentives				
Purchase and ownership tax exemption	ZETs are exempted from the purchase tax until the end of 2025 and will receive a 50% tax waiver during 2026 and 2027; ZETs are exempted from ownership tax (MOF, STA, and MIIT 2023, 2018)			
Purchase subsidy	X	X	X	3000 CNY/kW based on rated power of FC systems (capped at 110kW) (Guangdong DRC et al. 2022)
Alternative energy subsidy	Demand charges waived for ZETs (State Council 2023)			3-12 CNY/kg hydrogen (MOF, MIIT, MOST, NDRC, and NEA 2020)
Local incentives: Shenzhen				
Purchase subsidy (or scrappage scheme)	X	X	50,000-70,000 CNY/vehicle to scrap diesel tractors and replace with ZETs at Shenzhen Port (Shenzhen MTB 2023).	
Operation subsidy	X	X	5,000 CNY/month for BETs and 3,000 CNY/month for FCETs, for tractor trailers operated in Shenzhen Port (Shenzhen MTB 2023).	
Alternative energy subsidy		X		Preferential electricity rates for electrolysis (Shenzhen DRC 2022)
Road access privilege	The city introduced 16 zero-emission freight zones in the city centers that ban the access of diesel LDTs from entering throughout the day. Further, it grants access to new-energy light- and medium-duty trucks to enter some areas within the city but forbids diesel trucks from entering at a particular time of a day (Shenzhen PSB 2022, 2023a, 2023b, 2023c) (see Appendix A).			
Local incentives: Foshan				
Scrappage scheme	X	X	X	30,000-70,000 CNY/vehicle (Foshan Nanhai Government 2021).
Operation subsidy	0.2-0.4 CNY/km (capped at 30,000 km per year) (Foshan MTB 2022)	0.6 CNY/km (capped at 30,000 km per year) (Foshan MTB 2022)	X	1.5 CNY/km for LDTs (capped at 50,000 km per year) (Foshan MTB 2022)
Alternative energy subsidy		X		18 CNY/kg hydrogen (Foshan Nanhai Government 2022)
Road access privilege	The city introduced four zero-emission freight zones in the city center that ban the access of diesel trucks (some zones also banned diesel HDTs) from entering throughout the day. Further, it grants access to new-energy light- and medium-duty trucks to enter some areas within the city but forbids diesel trucks from entering at a particular time of day. FC LDTs and construction trucks are allowed to enter Nanhai District throughout the day, while the diesel equivalents are banned from access throughout the day (Foshan MEEB and Foshan PSB 2022; Foshan Nanhai Government 2021) (see Appendix A).			

Notes: The purchase subsidy is the lump sum of national and local purchase subsidies of the Guangdong FCEV City Cluster. X=no policies.

Source: WRI authors' summary.


西
华穗路
Huasui Rd
广州大道中
Guangzhou Ave M
华夏路(南)
Huaxia Rd (S)
华夏路(北)
Huaxia Rd (N)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SECTION 2

RESEARCH METHODOLOGY

This section outlines the methods to quantify three decision variables that are important for ZET transition across 14 use cases, including operational feasibility, purchase cost gaps between ZETs and ICEVs, and TCO parity years with ICE trucks. It further elaborates the method to evaluate how different interventions—including technological development, policy incentives, operational improvements, and financing mechanisms— would affect the three decision variables, particularly in facilitating the achievement of TCO parity years relative to diesel trucks.

We assessed the techno-economic feasibility of ZETs over the time frame of 2022–2030 across use cases in different MYs for Shenzhen and Foshan.

The scope of analysis and the methodology framework are summarized as follows:

- Time frame: The base year of this study is set to 2022, when the most recent data are available. The MY is set to MY2022–2030, since we focus on near-term solutions, and near-term projections are relatively more accurate than long-term projections.

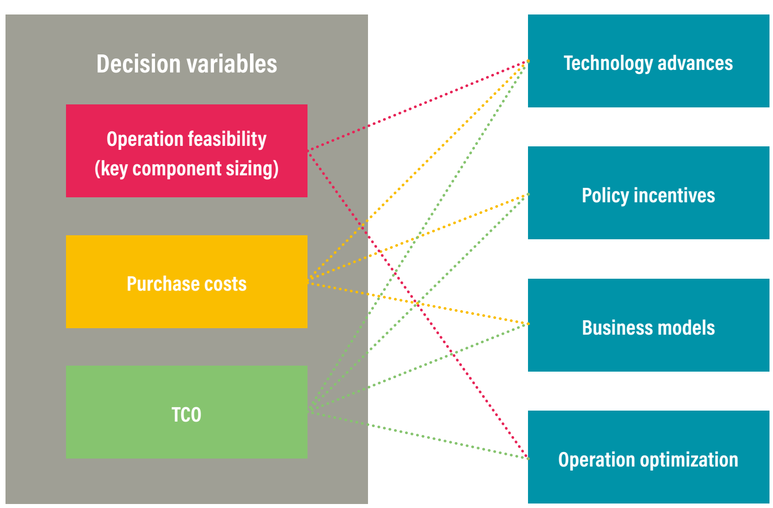
- Alternative fuels or powertrains: Given that limited public resources should be prioritized, only zero-emission and ICE powertrains are considered. Other alternative powertrains, such as plug-in hybrid electric vehicles and natural gas or low-carbon fuel powered internal combustion engines are not covered, due to lack of data or limited applications in Guangdong.

- Techno-economic analysis: This study focuses on quantifying the decision variables that are important for small fleet operators to support ZET transition, including operational feasibility of ZETs, purchase cost gaps between ZETs and ICEVs, and TCO parity with ICE trucks (Tol et al. 2022). Other decision variables that are difficult to quantify, such as vehicle fire safety, are not covered.

  Following the existing literature's practices (Basma et al. 2023; CARB 2019; Hunter et al. 2021; Mao et al. 2021; Tol et al. 2022), the use cases with near-term opportunities for ZET transition are identified, based on ZETs' TCO parity years with ICEVs. Further, we evaluate the possible roles played by different interventions—including technological development, policy incentives, operational improvements, and financing mechanisms—in affecting the previously mentioned decision variables, particularly the roles they played to facilitate the achievement or advances of TCO parity years relative to diesel trucks. Other interventions, such as shippers' requirements that are not readily quantifiable and have limited impacts, are not examined. Further, we used an example to illustrate if the conclusions would be applied to other cities and discussed the caveats and uncertainties of the analysis.

- Data sources: Data used to perform the above analysis include the authors' extensive interviews with key local stakeholders in Shenzhen and Foshan (see Appendix B); a literature review of future technology and cost projections, status quo, and best practices on ZET promotion; and a policy document review

Figure 1 | **Relationship among the four types of interventions and fleet operators' decision variables**



Source: WRI Authors.

of domestic and international policies and mainstreamed ZET make-and-models.

The detailed methods and data sources for techno-economic analysis are explained as follows:

2.1 Definition of use cases

The techno-economic analysis is performed for each use case. In this study, use cases are characterized by factors relevant to ZETs' operational feasibility and cost competitiveness, including vehicle segments, types of goods transported, and duty cycles. We identified prevailing truck use cases in Shenzhen and Foshan, using the following methods

Truck segments: Based on statistical yearbooks, the 2022 Catalogue of New Energy Vehicle Models Exempt from Vehicle Purchase Tax (hereinafter referred to as "NEV Catalogue") (MIIT 2022), and Pers. Comm. (2023a), the analysis selected truck segments that are common in Shenzhen and Foshan (see Table 2). Truck segments with limited

Table 2 | **Truck classification and shares of truck stocks in Shenzhen and Foshan in 2022**

<table>
<tr><th></th><th>GVW/GCW</th><th>SHARE OF TRUCK STOCK IN SHENZHEN IN 2022</th><th>SHARE OF TRUCK STOCK IN FOSHAN IN 2022</th><th>NUMBER OF ZET MODELS IN 2022 NEV CATALOGUE</th><th>THIS STUDY</th></tr>
<tr><td colspan="6">Mini truck</td></tr>
<tr><td>Regular truck</td><td>GVW≤1.8t</td><td rowspan="2">0.2%</td><td rowspan="2">0.05%</td><td>X</td><td rowspan="2">(Few stocks)</td></tr>
<tr><td>Refrigerated truck</td><td>GVW≤1.8t</td><td>X</td></tr>
<tr><td colspan="6">Light-duty truck</td></tr>
<tr><td>Vans</td><td>1.8t<GVW<4.5t</td><td rowspan="4">75%</td><td rowspan="4">78%</td><td>X</td><td>√</td></tr>
<tr><td>Regular truck</td><td>4.2t<GVW<4.5t</td><td>372</td><td>√</td></tr>
<tr><td>Refrigerated truck</td><td>2.2t<GVW<4.5t</td><td>47</td><td>(Few stocks)</td></tr>
<tr><td>Dump truck</td><td>2.2t<GVW<4.5t</td><td>1</td><td>(Few stocks and limited ZET models)</td></tr>
<tr><td colspan="6">Medium-duty truck</td></tr>
<tr><td>Straight truck</td><td>4.5t≤GVW<12t</td><td rowspan="3">2%</td><td rowspan="3">4%</td><td>14</td><td rowspan="3">(Few stocks and limited ZET models)</td></tr>
<tr><td>Refrigerated truck</td><td>4.5t≤GVW<12t</td><td>11</td></tr>
<tr><td>Dump truck</td><td>4.5t≤GVW<12t</td><td>5</td></tr>
<tr><td colspan="6">Heavy-duty truck</td></tr>
<tr><td>Straight truck</td><td>12t≤GVW≤31t</td><td rowspan="4">23%</td><td rowspan="4">18%</td><td>25</td><td>√</td></tr>
<tr><td>Tractor trailer</td><td>31t≤GCW≤49t</td><td>192</td><td>√</td></tr>
<tr><td>Dump truck</td><td>16t≤GVW≤31t</td><td>126</td><td>√</td></tr>
<tr><td>Refrigerated truck</td><td>14t≤GVW≤31t</td><td>10</td><td>(Few stocks and limited ZET models)</td></tr>
</table>

Note: X=Exclusion from the analysis.

Abbreviations: GVW=gross vehicle weight; GCW=gross combined weight; t=ton.

Sources: WRI authors' summary based on Guangdong Stats 2023, MIIT 2022, Pers. Comm. 2023a, and SAC/TC576 2019.

real-world applications and few ZET make-and-model availability, such as refrigerated trucks and medium-duty trucks, are not covered.

Duty cycles and daily vehicle kilometers traveled (VKTs): The study identifies four duty cycles that are typical in Shenzhen and Foshan, including UD, RD, PO, and DDC, based on Pers. Comm. (2023a). Long-haul duty cycles defined as daily VKTs over 500 km in this study are not included because 90 percent of vehicles' daily VKTs are within 500 km in Shenzhen and Foshan (Pers. Comm. 2023a).

Typical examples of duty cycles collected based on Pers. Comm. (2023a) are shown in Table 3. For example, Shenzhen has approximately 23,000 drayage tractors serving its Port—the third largest container port in China (Xinhua Finance 2023)—that are mainly consist of 4×2 tractors with 3-axle container semi-trailers (gross combined weight [GCW]=42 tons) (Pers. Comm.

Table 3 | **Typical duty cycles and truck models in Shenzhen and Foshan**

DUTY CYCLE	VEHICLE CATEGORY	CARGO TYPE	DESCRIPTION OF THE DUTY CYCLE
UD	Delivery van	Parcel delivery (light goods)	Last-mile delivery: • Round-trip distance: 30–100 km • Round trips per day: 2–4 • Daily VKTs: 60–200 km
	4.5-t LDT	Parcel delivery (light goods)	Delivery between distribution centers within a city: • Round-trip distance: 50–80 km • Round trips per day: 2–4 • Daily VKTs: 100–300 km
		Beverage transportation (heavy goods)	Delivery between warehouses and grocery stores within a city: • Round-trip distance: 40–200 km • Round trips per day: 1 (milk run) • Daily VKTs: 40–200km
	31-t dump truck	Construction materials/ waste (heavy goods)	Construction sites to ports (to be shipped to surrounding cities) or recycling sites within a city or dump sites at city periphery: • Round-trip distance: 60–80 km • Round trips per day: 2–3 • Daily VKTs: 120–240 km
RD	18-t straight truck/ 42-t tractor trailer	Parcel delivery (light goods)	Intercity delivery (for example, between distribution centers in Foshan and Guangzhou): • Round-trip distance: 150–200 km • Round trips per day: 2 • Daily VKTs: 300–400 km
		Beverage transportation (heavy goods)	Intercity delivery between factories and warehouses: • Round-trip distance: 150–200 km • Round trips per day: 2 • Daily VKTs: 300–400 km
PO	42-t tractor trailer	Containers (light goods)	Transportation of containers between docks and container storage yards: • Operating at low speeds for 17 hours per day, with long idling hours and frequent stop-and-goes • Daily VKTs: 120–240 km
DDC	42-t tractor trailer	Containers (light goods)	Intra and intercity transportation between ports and warehouses: • Round-trip distance: 200–400 km • Round trips per day: 1–1.5 • Daily VKTs: 200–500 km

Note: A 4.5-t LDT refers to light duty trucks with gross vehicle weights of 4.490–4.495 tons. The 18-t straight truck and 31-t dump truck, respectively, indicate straight trucks of 18 tons gross vehicle weight and dump trucks of 31 tons gross vehicle weight, respectively. A 42-t tractor trailer means tractor trailers with gross combined weights of 42 tons.

Abbreviations: LDT=light duty truck. UD=urban delivery; RD=regional delivery; DDC=drayage duty cycle; PO=port operation.

Source: Authors' summary based on Pers. Comm. 2023a (see Appendix B).

2023a). Because 76 percent of containers at this export-oriented port are sourced from neighboring cities like Dongguan and Huizhou, the one-way trip length of the drayage tractors is up to 200 km (Wang et al. 2024). Further, since the port's appointment system allows for one booking per truck per day, the tractor trailer could make one to one-and-a-half round trips a day (NEICV 2022) with the daily VKTs of DDC between 200 and 500 km (Pers. Comm. 2023a).

The ZET configurations and TCO estimations are highly sensitive to daily and annual VKTs. In this study, the daily VKTs of UD are capped at 300 km, while the lower bound of daily VKTs for RD is set to 300 km (up to 500 km), based on Pers. Comm. (2023a). Within the same use case, vehicle attributes and costs of ZETs are analyzed at a 100km-daily VKT interval (such as BET200 and BET300), to capture VKTs' impacts on ZETs' TCO. The annual operating days and useful years for each use case were collected based on Pers. Comm. (2023a). It is assumed that trucks' annual VKTs will not decline by age, and ZETs and ICEVs have the same annual VKTs and useful years.

Types of goods transported: Although ZETs tend to "volume out" when transporting light volumetric goods, there are still many occasions in Guangdong where trucks will "weigh out." For example, the freight volumes in Guangdong in 2019 primarily consisted of heavy goods like building materials and cement (32.7 percent), due to high infrastructure investment demands (Lin et al. 2021). On the other hand, Guangdong also has relatively large shares of light goods in freight volumes, particularly in container ports (Lin et al. 2021). This explains the reason for the widespread adoption of 42-t tractor trailers in PO and DDC, instead of 49-t tractor trailers.

This study considers two types of goods—light cargos and heavy cargos. Cargos with freight densities[3] smaller than 210 kg/m^3 (such as small household appliances) are classified as light cargos; those with freight densities equal to or greater than 210 kg/m^3 (such as coal and beverages) are treated as heavy cargos (CATARC 2017). For heavy cargo transportation, ZETs will move the cargo up to the gross vehicle weight (GVW) but have payload capacity loss, while ZETs will be volumed out (that is, reaching the volumetric capacity of the vehicles) before weighing out for light cargo transportation; so no payload capacity loss will be incurred.

Figure 2 | **Breakdown of freight volumes in China and major regions in 2019**

CARGO TYPE	NATION	JING-JIN-JI REGION	JIANGSU-ZHEJIANG-SHANGHAI	GUANGDONG	PEARL RIVER DELTA REGION
Coal-related products	12.6%	21.0%	2.0%	2.4%	2.2%
Metal and mines	7.1%	16.3%	3.4%	1.7%	1.3%
Building materials and cement	38.7%	24.9%	35.3%	43.6%	32.7%
Machineries	6.7%	6.0%	13.3%	8.2%	11.5%
Light industrial products	7.9%	5.8%	14.5%	14.1%	18.4%
Fresh food	5.9%	5.7%	2.6%	2.9%	2.4%
Others	21.1%	20.3%	28.9%	27.1%	31.5%
Total	100%	100%	100%	100%	100%

Note: Red indicates high freight volumes in the region. Green denotes low freight volumes in the region.

Source: Lin et al. 2021.

Table 4 | **Use cases covered in this study**

NO.	VEHICLE	DUTY CYCLE	CARGO TYPE	DAILY VKTS	ANNUAL OPERATING DAYS AND USEFUL YEARS	ANNUAL VKTS
1	Delivery van	UD	Light & heavy goods	200 and 300 km	310 days 6 years	62,000-93,000 km
2-3	4.5-t LDT	UD	Light & heavy goods	200 and 300 km	310 days 6 years	62,000-93,000 km
4-5		RD	Light & heavy goods	300, 400, and 500 km		93,000-155,000 km
6	31-t dump truck	UD	Heavy goods	200 and 300 km	270 days 5 years	54,000-81,000 km
7-8	18-t straight truck	UD	Light & heavy goods	200 and 300 km	320 days 6 years	64,000-96,000 km
9-10		RD	Light & heavy goods	300, 400, and 500 km		96,000-160,000 km
11	42-t tractor trailer	UD	Light goods	200 and 300 km	310 days 6 years	62,000-93,000 km
12		PO	Light goods	200 and 300 km		62,000-93,000 km
13		DDC	Light goods	200, 300, 400, and 500 km		62,000-155,000 km
14		RD	Light goods	300, 400, and 500 km		93,000-155,000 km

Note: Use cases with daily VKTs within 100 km (BET100 and FCET100) are excluded for analysis because there are few operation limitations with the use cases.

Abbreviations: LDT=light-duty trucks; UD=urban delivery; RD=regional delivery; PO=port operation; DDC=drayage duty cycle; VKT=vehicle kilometres traveled.

Source: Authors' summary based on Pers. Comm. 2023a (see Appendix B).

Taken together, the study constructs 14 use cases for analysis (Table 4). They cover five truck segments, including delivery vans, 4.5-t light-duty trucks (LDT), 18-t straight trucks, 31-t dump trucks, and 42-t tractor trailers; four duty cycles, namely, UD, RD, PO, and DDC; and two types of goods transported—light goods and heavy goods.

2.2 Method of ZETs' key component sizing

Transitioning from ICEVs to ZETs is deemed feasible if operational limitations such as range constraints, peak power deficiency, or payload losses can be overcome (Hunter et al. 2021). Therefore, this study focuses on resizing key components of ZETs, including energy storage capacities, peak power outputs, and curb weights, that are crucial to addressing some of the key operational limitations of ZETs. Due to limited data available, charging time lost is not considered and will be included in future research.

Here, the current component sizing of ZETs as of 2022 is drawn from the 2022 NEV Catalogue (MIIT 2022) and Pers. Comm. (2023a), using the most common ZET models (the median values). The analysis for 2022 aims to identify the operational limits with current ZET models across use cases.

In the future, with technological progress and operational optimization, this study assumes that ZETs' key components will be able to meet the ranges and peak wheel powers in different use cases during MY2022 and MY2030, based on common practices adopted in existing literature (Hunter et al. 2021; Mao et al. 2021). The resulting component sizing is to find the ZET models for different use cases that can come at a reasonable cost and meet day-to-day operational requirements. It is noteworthy that in this study, MY2022 ZETs differs from the ZETs in 2022 in that MY2022 ZETs are assumed to meet the range and power requirements of all the use cases (including RD), whereas the real-world ZETs in 2022 do not necessarily satisfy all the operational requirements.

Energy storage of ZETs

The capacities of energy storages (such as battery capacity and hydrogen storage) for MY2022–MY2030 ZETs were estimated based on VKTs and ZETs' energy efficiency as indicated in Equation 1:

$$E_{u,t} = \frac{VKT_u \times EE_{u,t}}{100 \times DoD} \qquad \text{(Equation 1)}$$

Where:

$E_{u,t}$ represents the nominal battery capacity or hydrogen storage capacity (kWh or kg).
VKT_u is the daily or trip VKT, which is examined at a 100 km interval within the range of each use case (such as BET200 and BET300 for UD).
$EE_{u,t}$ is the energy efficiency of BETs or FCETs (kWh/100 km or kg/100 km).
DoD is the depth of discharge of batteries (%) for BETs. This study assumes 80% (Mao et al. 2021; Nykvist and Olsson 2021; Phadke et al. 2021; Wu et al. 2015; Zhao et al. 2018), or usable capacity (%) of hydrogen storage systems for FCETs. This study assumes 85% for FCETs (Danebergs 2019).
u represents use case, and t is model year.

Operation optimization and technology improvements are instrumental in reducing the required energy storage capacities of ZETs:

From the operation perspective, trucks' operation schedules and the availability of charging/refueling facilities can affect BETs' VKTs and hence battery capacities.

Two ways to configure ZETs' energy storage capacities are possible: (1) Sizing energy storage capacities based on daily VKTs. This assumes that ZETs are charged or refueled on a daily basis. For BETs, it would be charged overnight at depots. (2) Sizing energy storage capacities based on trip (or tour) distances. This applies to BETs because they sometimes need to be charged more than once a day. In addition to overnight charging, the vehicles are also charged between trips, upon loading or unloading, or between shifts. This also means the optimization of trucks' operation to coordinate with charging time as well as the availability of ultra-fast chargers (and land spaces) when the opportunity charging is needed. The choice of methods leads to different energy storage capacities and charging technologies. For example, using the "daily VKT" method, a BET200 can fulfill daily VKTs within 200 km, while switching to the "trip distance" method, a BET200 can achieve 500 km daily VKTs. To support the latter, ultra-fast charging or battery swapping could be deployed (IEA 2023b).

This study adopts two methods to configure battery capacities for BETs: the "daily VKT" method for UD and RD (see the section on definition of use cases for the values of daily VKTs), and both the "daily VKT" method and the "trip distance" method for PO and DDC (using the daily VKTs specified in that section and the trip distances explained in the section on results from MY2022 to MY2030). The rationale for the method selection is explained in that section.

For FCETs, the on-board hydrogen storage system is sized based on the daily VKTs[4] (using the daily VKTs specified in the section on definition of use cases). Although FCETs could be refueled every few days, to reduce the costs of hydrogen storage systems, this study assumes that hydrogen refueling stations are available and that FCETs are refueled on a daily basis.

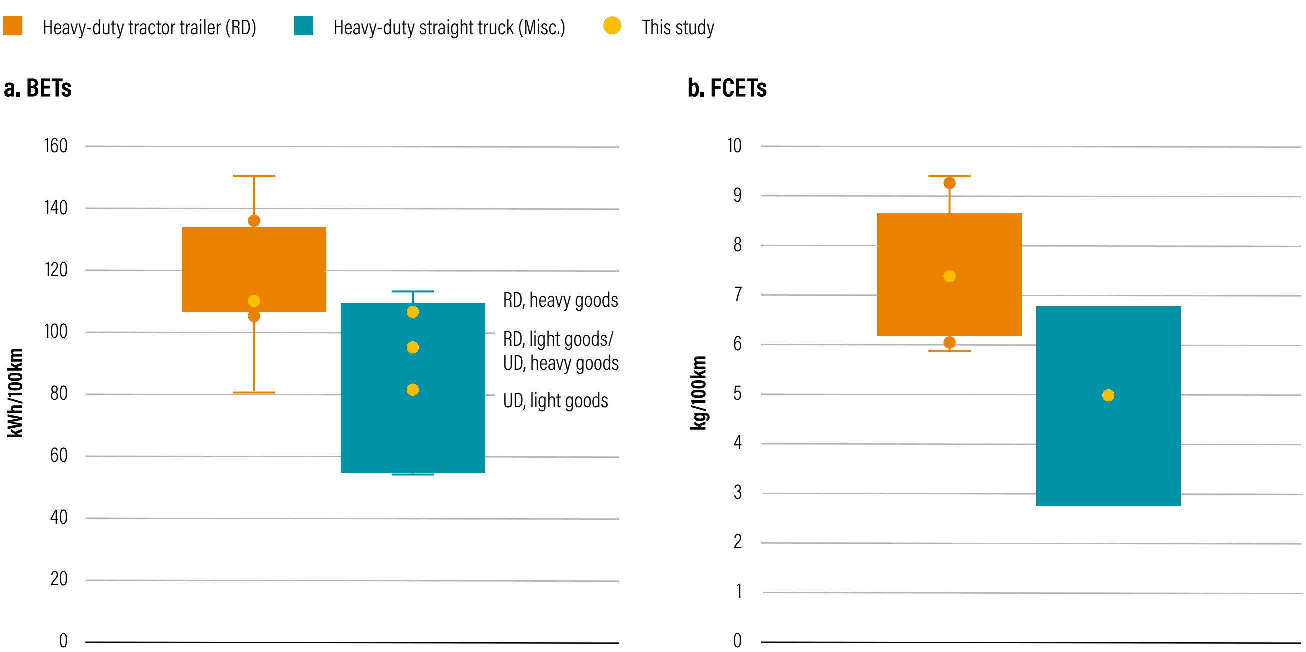
From the technological perspective, ZETs' energy efficiency (used interchangeably with energy consumption) improvements also affect energy storage capacities; therefore, it is important to accurately determine the energy consumption of each powertrain.

To capture the real-world energy efficiency for ICEVs, BETs, and FCETs, we collected the energy efficiency data for the current use cases in 2022, based on fleet operators' interviews (Pers. Comm. 2023a) (see Appendix B). We further projected and validated the energy efficiency during MY2022 and MY2030 based on a literature review and cross verification using energy-efficiency ratios (EERs) (see Table 5).

Here, for same vehicle segment, the real-world energy consumption is differentiated by travel patterns between urban and highway travel and payloads between light goods transportation and heavy goods transportation. For example, we assume in 2022, a battery-electric 42-t tractor trailers' energy consumption is approximately 110 kWh/100 km in UD and 118 kWh/ 100km in RD (on highways) based on 2023 ZET pilots in Shenzhen (Pers. Comm. 2023a). With heavy goods transportation, we assumed LDTs experience 3 to 5 percent energy consumption increases, while HDTs witness 13 to 18 percent increases in energy consumption for UD and RD, respectively (Alonso-Villar et al. 2023). The energy consumption of ICEVs and ZETs of PO comes directly from the interviews of fleet operators in Shenzhen Port (Pers. Comm. 2023a) (see Appendix B).

The future energy consumption projections of ZETs are based on a literature review, while those of ICEVs are assumed to be fixed to the 2022 level. The future energy consumption of ZETs during MY2022 and MY2030 is estimated and validated through a literature review and the EER values. For example, Figure 3 shows that the projected energy consumption for 42-t tractor trailers and 18-t straight trucks in MY2030 falls within a reasonable range of energy consumption in existing literature. Considering that energy efficiency from existing literature may not be comparable since the values are highly sensitive to speeds and truck models, we also use vehicle EERs to verify future energy consumption of ZETs. The EER is the ratio of energy used to power an ICEV divided by the energy used to power a ZET over the same drive cycle. Because a larger EER implies greater efficiency advantages of ZETs such as BETs in UD and PO, we adjusted ZETs' future energy consumption to ensure that the EER is within a reasonable range (CARB 2018).

Figure 3 | **Projected vehicle energy efficiency of BETs and FCETs in MY2030 in this study and existing literature**



Note: Although this study focuses on 18-t straight trucks and 42-t tractor trailers and distinguishes the use cases by types of goods transported, the literature may not do so. Therefore, we compared the energy consumption from the same truck category and similar duty cycles.

Abbreviations: BET=battery electric truck; FCET=fuel cell electric truck; UD=urban delivery; RD=regional delivery; Misc.= miscellaneous.

Sources: WRI authors' summary of Basma et al. 2023; Burke and Sinha 2020; Burnham et al. 2021; CARB 2019; Hunter et al. 2021; Mao et al. 2021; Rout et al. 2022; Ruf et al. 2020; Tol et al. 2022; Transport and Environment 2021.

Table 5 | **EER comparisons across use cases for BETs and FCETs**

USE CASE	CARGO TYPE	BET		FCET	
		MY2022	MY2030	MY2022	MY2030
4.5-t LDT					
UD	Light goods	3.2	3.7	1.6	2.0
	Heavy goods	3.1	3.6	1.7	2.0
RD	Light goods	2.6	2.9	1.5	1.8
	Heavy goods	2.6	2.9	1.5	1.8
18-t straight truck					
UD	Light goods	2.9	3.1	1.4	1.5
	Heavy goods	2.9	3.1	1.6	1.8
RD	Light goods	2.3	2.4	1.3	1.4
	Heavy goods	2.3	2.5	1.4	1.6
31-t dump truck					
UD	Heavy goods	2.9	3.1	1.5	1.6
42-t tractor trailer					
PO	Light goods	4.0	4.2	1.7	1.8
UD	Light goods	2.9	3.1	1.5	1.6
RD	Light goods	2.3	2.5	1.3	1.4
DDC	Light goods	2.3	2.5	1.3	1.4

Abbreviations: BET=battery electric truck; FCET=fuel cell electric truck; UD=urban delivery; RD=regional delivery; DDC=drayage duty cycle; PO=port operation; EER=energy efficiency ratio.

Sources: WRI authors' calculation and summary based on Burke and Sinha 2020; Burnham et al. 2021; CARB 2019; Gilleon et al. 2022; Giuliano et al. 2021; Hunter et al. 2021; Kotz et al. 2022; Lane et al. 2022; Mao et al. 2021; Rout et al. 2022; Ruf et al. 2020; Sato et al. 2022; Tol et al. 2022; Transport and Environment 2021.

Peak power outputs

In this study, ZETs are modeled using electric drives and electrical components that are in keeping with existing ICEVs' power output during MY2022 and MY2030.

Noteworthy is that the power of FC systems important to FCETs' TCO varies significantly by configuration. There are two types of FCET configurations (Marcinkoski et al. 2016; Zhao et al. 2018): One configuration is the plug-in hybrid system, where the FCET carries a large battery pack and operates as a plug-in hybrid FC vehicle. The rated power of an FC system is sized based on the average power output, and the battery pack complements the FC system to supply the peak power demand. In addition to providing peak power, the battery could also act as a range extender where FCETs can either draw the energy from the FC system or be charged directly from the power grid. The other configuration is an FC-dominant system in which the FC system is used to provide energy, and the battery pack is only used to provide peak power (and restore energy from regenerative braking).

The plug-in hybrid configuration prevails in China's market today and will remain to dominate the short haul or regional haul applications in the near future because the FC system with low power output (currently about 110 kW for FC-HDTs in China) is technologically proven and commercially affordable (Zhao et al. 2018; Pers. Comm. 2023c). Therefore, this study assumes that FCETs will continue using the hybrid configuration during MY2022 and MY2030: For HDTs, a 100 kWh battery with 2 C-rate[5] is chosen to supply the peak power while the FC system provides continuously average power output. For LDT, a 30 kWh battery with 1 C-rate is used. The battery capacities for LDTs and HDTs are standardized for FCETs as of 2022, based on our analysis of the NEV Catalogue (MIIT 2022). The power for the FC system is derived by deducting the peak wheel power by the battery power. It should be pointed out that this configuration of FCETs may not be optimized. Future studies are needed to reduce unnecessary battery capacities while meeting the peak power demands of all use cases.

Curb weights and payload loss of ZETs

Growing battery capacities, hydrogen storage capacities, and FC systems' power would lead to the increases in ZETs' curb weights and dimensions and losses in ZETs' payload and volume capacities, compared with ICEV equivalents (Basma et al. 2023; Rout et al. 2022) . In this study, we focus on payload loss and leave the issue of volume loss for future analysis.

The payload loss of MY2022–2030 ZETs is calculated and projected for the use cases of heavy goods transportation. Here, the calculation is carried out by subtracting the diesel powertrain's weight from a comparable ICEV and adding key components:

- Battery packs, electric drives (including electric motors, inverters, and transmissions), and auxiliary components for BETs;
- FC systems (including balance of plant), hydrogen storage systems, battery packs, electric drives (e-drives), and auxiliary components for FCETs.

The assumptions and data sources for the current and future weights of the key components for ZETs are listed in Table 6. For example, the future weight of battery packs is determined by the energy density and capacities of battery packs.[6] Since currently 90 percent of new-energy commercial vehicles in China use lithium-iron-phosphate (LFP) batteries (CALB 2022), the energy density of 160 Wh/kg for LFP battery packs was used for 2022, based on this study's estimation of the median value for BET models published in the 2022 NEV Catalogue (MIIT 2022). In the future, with the use of new materials (such as solid-state batteries) and optimized battery packaging, batteries will have higher densities, lower costs, better safety, and longer cycle life (Berckmans et al. 2017; EC 2021). The study takes a chemistry-neutral approach and only assumes battery performance parameters, regardless of the technology adopted. For the performance parameter of battery packs' energy densities, we assume that the value will increase to 238 Wh/kg in 2030, a 49 percent increase from the 2022 level (Qiu et al. 2021). Based on the assumptions, for a 42-t BET500 tractor trailer operating in RD, the battery pack would weigh up to 4.6 tons in MY2022 and 2.9 tons in MY2030.

To validate the above weight-related assumptions, we also benchmarked the estimated curb weights of MY2022 ZETs with comparable ZETs in the NEV Catalogue of 2022 (MIIT 2022). The difference in curb weights was between 0 and 2 percent, demonstrating that the method we used is robust.

Table 6 | **The assumptions on the weights and costs of ZETs' key components**

WEIGHTS				COSTS			
INDICATOR	**MY2022**	**MY2030**	**DATA SOURCES**	**INDICATOR**	**MY2022**	**MY2030**	**DATA SOURCES**
Diesel powertrain [a] and glider [b]							
Diesel powertrain weight (kg)	300-2000 (Vary by truck segment)	Same as MY2022	**MY2022** estimate is based on Pers. Comm. (2023c) for LDTs and Mao et al. (2021) for HDTs	**Glider cost (CNY)**	60% of ICEVs' vehicle costs	Same as MY2022	**MY2022** estimate is based on Macquarie (2021).
Battery pack [c]							
Energy density (pack level) (Wh/kg)	160	238 (+49%)	**MY2022** estimate is the median value of the NEV Catalogue in 2022 (MIIT 2022); **MY2030** projection is based on Qiu et al. (2021). The improvement is resulting from using new cathode and anode materials and optimizing battery packaging (Berckmans et al. 2017; EC 2021).	**Battery cost (pack level) (CNY/kWh)**	930	680 (-27%)	**MY2022** estimate is based on the Technology Roadmap for Energy Saving and New Energy Vehicles 2.0 (hereinafter referred to as "the road map") (China SAE 2021); **MY2030** projection is based on a learning rate of 12% (Hsieh et al. 2019), and cumulative production from Xue and Liu (2022). The projection is validated by China SAE (2024). The cost reduction is a result of new materials, improved battery packaging, and integration (Sharpe and Basma 2022).
E-drive [d]							
E-drive weight (kg/kW)	Vary by truck segment	Vary by truck segment (-20%)	**MY2022** estimate is based on Pers. Comm. (2023c); **MY2030** declination relative to MY2022 is based on the road map (China SAE 2021) The improvement is a result of better integration of powertrain components and the use of lightweight materials (EUCAR 2019).	**E-drive cost (CNY/kW)**	430	296 (-32%)	**My2022** estimate is adapted from ICCT (Mao et al. 2021); **MY2030** projection is based on a learning rate of 15% (Qiu et al. 2021) and the cumulative production from Xue and Liu (2022). The projection is validated by Mao et al. (2021). The cost reduction is a result of better integration, system simplification, and economies of scale (U.S. DRIVE 2017a).
FC system [e]							
FC system's specific power (W/kg)	600	900 (+50%)	**MY2022** estimate and **MY2030** projection are based on Pers. Comm. (2023c). The improvement is attributed to technology advances in components (such as membrane and catalyst) and optimized system design (APCUK and Austin Power 2022; U.S. DRIVE 2017b).	**FC system cost (CNY / kW)**	4,120	891 (-78%)	**MY2022** estimate is based on Sinosynergy (2022); **MY2030** projection is based on a learning rate of 20% (Ajanovic and Haas 2018; IEA 2015) and the cumulative production of FCEVs from the road map (China SAE 2021). The projection is around the median value of the forecasts in the existing literature (see Figure 4). The cost reduction is attributed to higher power density, lower catalyst loading, and manufacturing improvements (DOE 2023)

Table 6 | **The assumptions on the weights and costs of ZETs' key components (cont.)**

WEIGHTS				COSTS			
INDICATOR	MY2022	MY2030	DATA SOURCES	INDICATOR	MY2022	MY2030	DATA SOURCES
Hydrogen storage system [f]							
Gravimetric capacity	4.5%	6.5% (+43%)	**MY2022** estimate is based on authors' interview (Pers. Comm. 2023c); **MY2030** projection is based on the road map (China SAE 2021) The improvement is driven by the deployment of Type IV tanks and liquid hydrogen (Cheng et al. 2024).	**Hydrogen storage system cost (CNY/ kg H_2)**	4,000	1560 (-61%)	**MY2022** estimate is based on the road map (China SAE 2021); **MY2030** estimate is based on a learning rate of 15% (Qiu et al. 2021) and the cumulative production of FCEVs from the road map (China SAE 2021). The projection is validated by China SAE (2024). The cost reduction is mainly driven by economies of scale and increased adoption of automation (Hydrogen Council 2020).
Auxiliary components							
Weight (kg)	Vary by truck segment	Vary by truck segment	The weight is validated by the curb weight of vehicles and the weight of other key components.	**Cost (CNY/kW)**	486 (OBC); 389 (DC/DC converter)	Same as MY2022	**MY2022** estimate of on-board charger (OBC) is based on Mao et al. (2021), and DC/DC converter is based on Nair et al. (2022).

Note: [a] Diesel powertrains include major components such as engine, gearbox, fuel tank, and exhaust after-treatment. For simplicity, we do not consider the evolution of diesel powertrains; therefore, the weights of diesel trucks are kept constant during MY2022 and MY2030.
[b] Glider includes truck cabins and chassis. Its cost is estimated by deducting truck prices by the cost of diesel powertrain. This study assumes glider costs are the same for ICEVs, BETs, and FCETs.
[c] Battery packs include cells, battery management systems, thermal management systems, and battery packaging. We assume that BETs and FCETs adopt the same type of battery packs, thereby having the same energy density for battery packs.
[d] E-drives consist of electric motors, inverters, and transmissions. The weights of e-drives are estimated and scaled to different truck segments based on motor power.
[e] FC systems are composed of FC stacks, balance of plant, and DC/DC. Weights of FC systems are determined by their specific powers.
[f] Hydrogen storage systems include hydrogen storage tanks, valves, and sensors. The weight of the systems depends on their gravimetric capacity, defined as "the usable quantity of hydrogen in the storage system divided by the total mass of the storage system" (USDOE n.d.).

Sources: WRI authors' summary based on APCUK and Austin Power 2022; Berckmans et al. 2017; Cheng et al. 2024; China SAE 2021, 2024; EC 2021; EUCAR 2019; Hsieh et al. 2019; Hydrogen Council 2020; IEA 2015; Macquarie 2021; Mao et al. 2021; MIIT 2022; Nair et al. 2022; Pers. Comm. 2023c; Qiu et al. 2021; Sharpe and Basma 2022; Sinosynergy 2022; USDOE 2023; U.S. DRIVE 2017a, 2017b; and , Xue and Liu 2022.

2.3 Method of purchase cost estimation

Fleet operators would also be willing to switch to ZETs if: (1) the up-front purchase costs of ZETs are affordable; or (2) financing mechanisms exist to reduce fleet operators' up-front capital expenses and allocate the risks to appropriate parties other than fleet operators.

Technology progress plays a critical role in bringing down the costs: ZETs are expected to experience significant technological advances that result in lower purchase costs. In this study, the estimation of ZETs' purchase costs (interchangeably with vehicle prices) during MY2022 and MY2030 was based on a bottom-up method that used the estimated direct manufacturing costs

(DMCs) of major ZET components, the indirect cost multiplier (ICM), and value-added tax (VAT) (see Equation 2). For simplicity, the purchase costs of ICEVs are assumed to be the same over the next decade.

Financing mechanisms also have a bearing on ZETs' purchase costs. Even when TCO parity with diesel equivalents is reached, fleet operators may struggle to buy a ZET, particularly for small fleet operators with limited profit margins and creditworthiness (CFLP 2022). Therefore, the role played by different financing mechanisms to ease ZETs' capital costs is discussed. However, due to limited data availability, we do not evaluate the impact on TCO of different financing mechanisms.

$$Vehicle_{u,t} = Glider_u + DMC_{u,t} \times (1+ICM\%) \times (1+VAT\%)$$

$$\begin{aligned} DMC_{BET,u,t} = {} & Battery\ cost_t \times E_{u,t} \\ & + Electric\ drive\ cost_t \times rated\ power_{u,t} \\ & + Other\ electrical\ component\ cost_u \end{aligned}$$

$$\begin{aligned} DMC_{FCET,u,t} = {} & Fuel\ cell\ system\ cost_t \times rated\ power_{u,t} \\ & + Hydrogen\ storage\ cost_t \times E_{u,t} \\ & + Electric\ drive\ cost_t \times rated\ power_{u,t} \\ & + Other\ electrical\ components\ cost_u \end{aligned}$$

(Equation 2)

Where:

$Vehicle_{u,t}$ is the vehicle purchase cost (CNY).
$Glider_u$ is the glider cost (CNY).
$DMC_{u,t}$ is the direct manufacturing cost (without gliders) of BETs and FCETs (CNY).
ICM is the indirect cost multiplier (%).
VAT is the value-added tax rate of 13% (MOF et al. 2019).
u represents the use case, and *t* is the model year.
$E_{u,t}$ represents the nominal battery capacity or hydrogen storage capacity (kWh or kg) (see the section on "Energy storage of ZETs" for the calculation method and data sources).
$Battery\ cost_t$, $Electric\ drive\ cost_t$, $Fuel\ cell\ system\ cost_t$, $Hydrogen\ storage\ cost_t$ is the unit cost of battery, e-drive, FC system, and hydrogen storage system (CNY/kWh or CNY/kW or CNY/kW or CNY/kg) (see Table 6 for data sources).
$rated\ power_{u,t}$ represents the rated power of an e-drive or FC system (kW).
$Other\ electrical\ components\ cost_u$ is the cost of other electrical components, for example, on-board charger (OBC) and DC/DC converter (CNY).[7]

The assumptions on how technology advances would drive down DMCs and relevant data sources are listed in Table 6. It is worth noting that in this study, to reflect technology progress and scales of economies, DMCs of key components such as the battery pack, e-drive, FC system, and hydrogen storage system are captured by the learning curves that describe the reduction in unit costs of each key component as a function of accumulated production volumes. We further employed existing literature and market predictions to validate and adjust the projections. In this study, the learning rates of the unit cost for each key component were taken from existing literature. For example, this method was applied to estimate the unit cost of battery packs. The cost of LFT battery packs in 2022 was about 930 CNY/kWh (China SAE 2021), which is 20 percent cheaper than nickel-cobalt batteries (BNEF 2022). Using a 12 percent learning rate to project (Hsieh et al. 2019), the cost of battery packs would drop to 680 CNY/kWh by 2030, a 27 percent reduction from the 2022 level. Our prediction is in the middle of the forecasts made by existing studies, about the same level as the predictions in *Technology Roadmap for Carbon Neutrality of Commercial Vehicles* 1.0 (China SAE 2024) and the U.S. Environmental Protection Agency's Phase 3 Greenhouse Gas Emissions Standards for Heavy-duty vehicles (USEPA 2024) (see Figure 4).

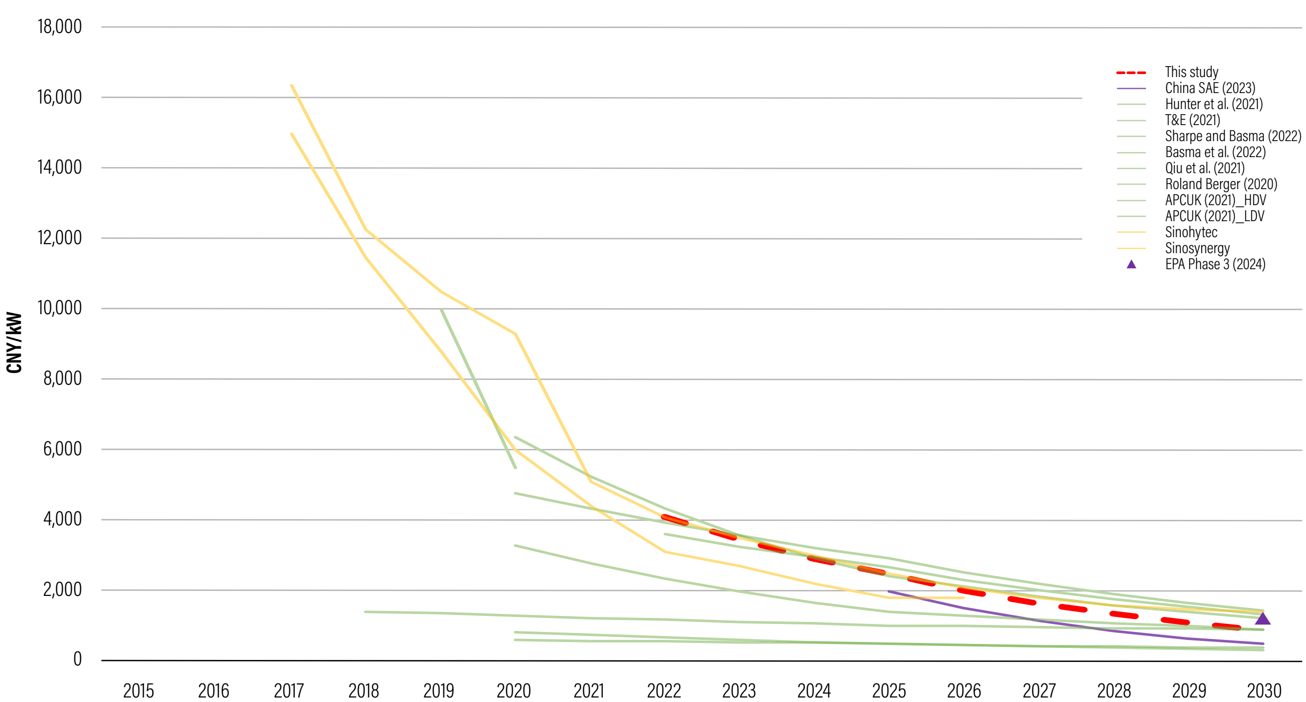
ICM represents the indirect costs of vehicle prices, such as research and development expenses and profit markups. The values of ICM vary substantially by country and technology and could span from 2 to 45 percent (Rogozhin et al. 2010). Considering limited profit markups of ZET OEMs in China (FitchRatings 2022), this study adopts a 16 percent ICM (Orient Securities 2019) and assumes that it will not decline during MY2022 and MY2030.

The estimated vehicle prices of MY2022 ZETs were validated against the manufacturer's suggested retail prices of comparable ZETs sold in Shenzhen and Foshan[8] (Pers. Comm. 2023b). The cost difference is within 10 percent and is deemed insignificant.

Figure 4 | **Projections of selected ZET key component costs**

a. Battery pack

b. FC system



Note: Red represents this study's prediction, while green and yellow denote the academic and corporate projections, respectively. Purple indicates the targets set by government agencies and industrial associations.

Abbreviations: FC=fuel cell; HDV=heavy-duty vehicles; LDV=light-duty vehicles.

Source: WRI authors' summary.

2.4 Method of TCO estimation

Apart from operational feasibility and purchase costs, whether TCO parity with equivalent ICE trucks is reached is another important criterion for fleet operators to decide on ZET transition. Building on key component sizing and purchase costs, this study further estimates ZETs' TCO for each vehicle segment and use case from MY2022 to MY2030.

TCO is assessed from the perspective of end users, rather than that of society; therefore, policy influences such as taxes and subsidies are considered, in addition to technology progress and operational improvements. The results are used to address: (1) which use case to prioritize ZET transition, at which year, and which zero-emission technology to transition to, and (2) how technological leapfrogs, operational improvement, and policy incentives would be helpful to achieve or advance the TCO parity years relative to ICE trucks.

Further, given that trucking industry is highly fragmented in China and characterized by many small fleet operators and self-employed truck drivers (TUC 2022a), TCO is estimated from SMEs' perspective: (1) The purchase costs in this study are the prices for small purchases, rather than the bulk procurement prices, (2) financing costs and insurance are set on the high end to capture the high-risk premiums associated with SMEs (CFLP 2022). Last, because in China the first owners dominate the market—fleet operators seldom consider the second and third life sale of used trucks (Mihelic et al. 2020)—this study adopts the first owners' TCO.

TCO estimated in this study are in the form of net present values. Because private entities generally use a higher discount rate while public entities use a lower discount rate (CARB 2019), this study employs a discount rate of 7 percent (Basma et al. 2023; Hunter et al. 2021; Meszler et al. 2019). Noteworthy is that this study differs from the existing literature (CATARC 2022; Mao et al. 2021) on the estimation of China ZETs' TCO in that we quantify costs associated with payload losses and midlife replacement costs of key components. Specifically, the costs evaluated in this study include direct costs (such as purchase costs, operation and maintenance costs, and the midlife replacement costs for key components) and opportunity costs including potential lost payload capacity (see Equation 3 and the following explanations on data sources). Other costs, such as vehicle residual values and refueling labor costs, are not considered due to limited data availability.

$$\begin{aligned} TCO_{p,u,t} &= CAPEX_{p,u,t}+OPEX_{p,u,t}+Key\ component\ replacement_{p,u,t}+Payload_{p,u,t} \\ &= CAPEX_{p,u,t}+\textstyle\sum_{i}^{N}\left[OPEX_{p,u,t,i}/(1+r)^{i-1}\right] +Key\ component\ replacement_{p,u,t} +Payload_{p,u,t} \end{aligned} \quad \text{(Equation 3)}$$

Where:

$CAPEX_{p,u,t}$ represents the capital expenditure, which covers vehicle purchase cost, purchase tax, and financing cost (CNY).

$OPEX_{p,u,t}$ represents operating expenses, which include energy, road charge, maintenance, insurance, and ownership taxes in this study (CNY).

$Key\ component\ replacement_{p,u,t}$ is the cost to replace ZETs' key components, such as batteries or the FC system (CNY). (See the section on "Method to calculate the replacement costs of key components" for calculation methods and data sources.)

$Payload_{p,u,t}$ is the payload loss cost of ZETs (CNY). (See the section on "Method to monetize ZET payload loss" for calculation method and data sources.)

p represents different powertrains, u is the use case, t is the model year, i is the year since the vehicle was purchased, N is the useful life, and r is the discount rate.

Table 7 | **Cost elements considered in this study and existing literature**

COST BREAKDOWNS		COMMON FOR TCO ESTIMATION	EXISTING LITERATURE	SCOPE OF THIS STUDY
$CAPEX_{p,u,t}$	$Vehicle_{p,u,t}$	Yes	All literature reviewed by this study considers the cost elements.	√
	$Financing_{p,u,t}$	Yes		√
	$Purchase\ tax_{p,u,t}$	Yes		√
$OPEX_{p,u,t}$	$Energy_{p,u,t}$	Yes		√
	$Road\ charge_{u,t}$	Yes		√
	$Maintenance_{p,u,t}$	Yes		√
	$Insurance_{p,u,t}$	Yes		√
	$Ownership\ tax_{u,t}$	Yes		√
	Refueling labor cost	No	Hunter et al. (2021)	×
	Residual value	Yes	Ruf et al. (2020), CARB (2019), Basma et al. (2023), Mao et al. (2021)	×
$Key\ component\ replacement_{p,u,t}$		No	CARB (2019); Rout et al. (2022)	√
$Payload_{ZET,u,t}$		No	Tol et al. (2022), Hunter et al. (2021)	√
$Useful\ life_{u}\ (N)$		Yes	All literature reviewed by this study considers the cost elements.	√
Discount rate (r)		Yes		√
$Annual\ kilometer\ traveled_{u}$		Yes		√

Note: p represents different powertrains, u is the use case, and t is the model year.

Sources: Authors' review of existing literature on ZET TCO estimation, including Basma et al. 2021, 2023; Burnham et al. 2021; CARB 2019; CATARC 2022; Chen and Melaina 2019; Danebergs 2019; Hao et al. 2020, 2022; Hunter et al. 2021; Kast et al. 2017; König et al. 2021; Mao et al. 2021; Marcinkoski et al. 2016; Niu et al. 2023; Ouyang et al. 2021; Phadke et al. 2021; Qiu et al. 2021; Rout et al. 2022; Ruf et al. 2020; Sharpe and Basma 2022; Tol et al. 2022; Transport and Environment 2021; Van Velzen et al. 2019; Wu et al. 2015; and Xie et al. 2023.

Method to monetize ZET payload loss

Fleet operators interviewed by this study indicate that ZETs' payload loss leads to lost revenues (or customer losses) that would equate to high costs. Therefore, it is crucial to reflect payload loss in ZETs' TCO.

Hunter et al. (2021) proposed four approaches to quantify the monetary impacts of ZETs' payload loss on fleet operators, which are adapted by this study into: (1) buying additional trucks, (2) renting additional trucks, (3) making additional trips, and (4) hiring other fleets to fulfill the runs.

This study chooses the third method where ZETs make additional trips to compensate for the payload loss, since it is a cheap and feasible option for small fleet operators (Hunter et al. 2021). Further, given that trucks are not always fully loaded, ratios of empty running in vehicle-kilometers (27–36 percent) by truck segments are applied (TUC 2022b) to the additional trips/mileages to compensate the payload loss.

$$Payload_{u,t} = \left[\frac{PC_{ICEV}}{PC_{ZET}} \times (1\text{-}M_u) + M_u\text{-}1 \right] \times (Energy_{u,t} + Road\ charge_{u,t} + Maintenance_{u,t}) \quad \text{(Equation 4)}$$

Where:

$Payload_{u,t}$ represents the payload loss cost of ZETs (CNY).

PC_{ICEV} is the payload capacity of ICEVs (kg); PC_{ZET} is the payload capacity of ZETs (kg). (See the section on "Curb weights and payload losses of ZETs" for calculation methods and data sources.)

M_u is the proportion of empty running (%) (TUC 2022b).

$Energy_{u,t}$, $Road\ charge_{u,t}$ and $Maintenance_{u,t}$ is the energy, road charge, and maintenance costs of ZETs (CNY). (See the section on "Method of the calculation and forecasting of other costs" for calculation methods and data sources.)

u is the use case.

t is the model year.

Method to calculate the replacement costs of key components

Because major propulsion or energy storage of trucks is expensive and has limited durability, costly replacement expenses should be taken into consideration.

Determining whether key components will be replaced, and which parties will be responsible for the expenses are crucial to estimate the replacement costs. Given that diesel trucks have a relatively short useful life in China (five to six years in this study), this study does not consider midlife rebuilding of diesel trucks. For BETs, OEMs in China are required to provide a warranty of five years or up to 200,000 km (MOF et al. 2018), shorter than the useful years (five to six years) and cumulative mileages (250,000–900,000 km) of BETs investigated in this study; therefore, battery replacements are anticipated. Conversely, although FC stack refurbishment or replacement is also expected, in a buyers' market for FCETs, OEMs and FC system integrators in China would often take on the responsibility to reinforce their competitiveness (Pers. Comm. 2023c). Therefore, for FCETs, this study does not count the replacement costs to end users' TCO.

For BETs' battery replacement, this study uses 3,000–4,000 Equivalent Full Cycles (EFCs) as the threshold for battery replacement, since research shows that LFP cells can sustain 3,000–4,000 EFCs if ambient temperatures and charging C-rates are mild (Jenu et al. 2018, 2022; Xue et al. 2020). The use cases meet the weather and C-rate condition, and in most use cases with one to two charges per day, the EFCs of BETs (1,440–2,880 for 80 percent DoD) are insufficient to trigger battery replacement. Only when BETs are charged over two charges per day[9] are battery replacements called for. For simplicity, in this study, the battery replacement costs are the battery pack costs when BETs are purchased[10].

Method of calculating and forecasting other costs

Energy costs are estimated by multiplying energy efficiency with energy prices. In this study, the energy prices (including diesel prices, charging costs, and hydrogen prices) are assumed as follows:

- The cost of charging hinges on charging infrastructure delivery mechanisms and local electricity tariffs. For electricity tariffs, both Shenzhen and Foshan adopt time-varying rates with demand charges waived for ZETs (Guangdong DRC 2018). For charging infrastructure delivery mechanisms, the study considers the most common case for public chargers in China where a private third-party invests in charging facilities (and possibly grid upgrades). To obtain a representative charging cost, we randomly selected 50 public charging stations in Shenzhen and Foshan and documented their charging costs by different times of a day (TELD n.d.). The average charging costs of 1.2 CNY/kWh (including utility tariffs and charging infrastructure investments) is obtained and validated by Pers. Comm. (2023a). This average cost is used to simulate ZETs' TCO during MY2022 and MY2030.[11]

- The study assumes that the investments on hydrogen refueling infrastructure and other relevant infrastructure are recouped by at-pump hydrogen prices. In Guangdong Province, at-pump grey hydrogen prices in 2022 were between 55 and 70 CNY/kg (Pers. Comm. 2023a); therefore, 55 CNY/kg is adopted for 2022. The study assumes that by 2030, hydrogen will be all sourced from renewable energy. The 2030 green hydrogen prices are set to 30 CNY/kg, with less than 15 CNY/kg for hydrogen production (BNEF 2023; IEA 2023a; IRENA 2021; RMI 2022; WEF 2023), around 5 CNY/kg for storage and transportation (WEF 2023; Zhang and Jiang 2023), and an additional 10 CNY/kg for dispensing[12] (WEF 2023).

- Guangdong's diesel oil was averaged at 8.1 CNY/L in 2022 (Eastmoney 2022). This value is used for estimating diesel trucks' TCO in the next decade.

Because of the plug-in hybrid design, FCETs can operate in two modes that are characterized by different energy costs (Pers. Comm. 2023c): the hydrogen-only mode or the hybrid mode. In the hydrogen-only mode, FCETs only draw energy from hydrogen tanks; therefore, the energy costs are solely hydrogen costs. In the hybrid mode, FCETs draw energy from both hydrogen tanks and batteries, and the energy costs are the combination of hydrogen and electricity costs. This study estimated the TCO of both modes, and when using the hybrid mode, we assumed that FCETs would exhaust the energy from batteries in everyday operation.

Maintenance costs and insurance costs are either distance-based or annual-based and vary by truck segment and powertrain in this study. Both data are collected based on the authors' interviews. Although ZETs' current maintenance costs are higher than ICEVs in some circumstances (Pers. Comm. 2023a), in the future, their maintenance costs will fall below ICEVs when the technologies become proven (Burnham et al. 2021). In this study, the maintenance costs used are based on Pers. Comm. (2023a; 2023b). To reflect the future trend, we keep the surveyed ZETs' maintenance costs when they are lower than ICEVs. Unlike maintenance costs, due to high costs to repair damaged parts and lack of data on ZETs' risk profiles (CARB 2021a), ZETs' insurance rates are generally 2,000–10,000 CNY higher than their ICEV counterparts (Pers. Comm. 2023a).

Road tolls of expressways and taxes are listed in Tables 8 and 9.

Financing costs are calculated based on purchase costs. We only estimate trucks' financing costs based on bank loans, considering that loans are common for truck financing in China. This study follows China's current regulation and sets the down payments for truck loans to 30 percent of diesel truck prices and 25 percent of ZET prices (PBC and CBIRC 2017). An interest rate of 10 percent for small fleet operators is adopted with three-year loan periods (Pers. Comm. 2023b).

Noteworthy is that these costs (except for hydrogen prices) or rates are not assumed to change over time. Considering that energy costs make up a significant portion of ZETs' TCO and energy prices fluctuate over time (NDRC 2021), we also performed a sensitivity analysis to evaluate how our conclusions on TCO parity with diesel trucks would vary by energy price.

Table 8 | **Maintenance costs, insurance costs, and taxes for ICEVs, BETs, and FCETs**

VEHICLE	TECHNOLOGY	MAINTENANCE (CNY/100KM)	INSURANCE (CNY/YEAR)	OWNERSHIP TAX (CNY/TONNE/YEAR)	PURCHASE TAX (%)
4.5-t LDT	ICE truck	20	13,000	16	Vehicle price / (1 + VAT%) × 10%
	BET	18	16,000		
	FCET	18	20,000		
18-t straight truck	ICE truck	67	17,500		
	BET	50	24,000		
	FCET	50	24,000		
31-t dump truck	ICE truck	70	20,000		
	BET	65	30,000		
	FCET	65	30,000		
42-t tractor trailer	ICE truck	67	20,000		
	BET	50	30,000		
	FCET	50	30,000		
Data sources		Authors' interview (Pers. Comm. 2023a; 2023b)		Guangdong's Vehicle and Vessel Tax (Guangdong Government 2022)	China Vehicle Purchase Tax Law (NPC 2018)

Note: Ownership tax for the trailer unit is not included in the table.

Source: WRI authors' summary.

Table 9 | **Road tolls for ICEVs, BETs, and FCETs in Guangdong Province**

VEHICLE	AXLE NUMBER	DUTY CYCLE	TOLL RATE (CNY/KM)	PROPORTION OF VKTS ON EX-PRESSWAYS (%)
4.5-t LDT	2	UD	0.52	20%
		RD		40%
18-t straight truck	2	UD	1.09	20%
		RD		50%
31-t dump truck	4	UD	1.95	0%
42-t tractor trailer	5	UD	2.01	20%
		RD		60%
		DDC		60%
Data sources			*Guangdong Tolled Roads' Charge Standard* (Guangdong DOT 2020)	*Fuel Consumption Test Methods for Heavy-duty Commercial Vehicles (GB 27840-2011)* (AQSIQ and SAC 2011)

Note: Tolls do not vary by vehicles' powertrain.

Source: WRI authors' summary.

Policy effects: Given that policies are effective in closing ZETs' TCO gaps with ICEVs, current and future policy effects on ZETs' TCO reduction are evaluated.

Based on government policy documents and literature review, this study enumerates current and future policies at the disposal of national and local governments to close the TCO gaps between ZETs and ICEVs. The policies are categorized into financial incentives, regulations, and infrastructure safeguards. Not all the policies were evaluated for the TCO impacts. We focus on national and local policies the impacts of which on TCO can be quantified under this study's TCO methodology framework. Based on the criteria, eight policies were selected, including purchase subsidy, tax exemption, energy (electricity/hydrogen fuel) incentives, carbon pricing on conventional fuels, road access privileges, reduction of expressway road tolls, ZET weight allowance, and financing cost reduction.

Here, we only investigate the eight proposed policies' impacts on ZETs' TCO parity years with ICEVs and do not quantify government expenditure in ZET promotion or future ZET market shares resulting from the policies. To quantify the policies' TCO impacts, the proposed eight policies were formulated from 2022 to 2030 in China (and Guangdong)'s context, with the guiding principle to reduce government expenditures on ZET promotion. Further, except for subsidies, the degree of policy interventions for BETs and FCETs is set to be identical so as to compare the varying impacts of the same policy on the TCO of BETs and FCETs. Considering that FCETs are at the early stage of promotion, FCETs' subsidies, including the purchase subsidy and (green) hydrogen fuel incentive, were set to be higher than BETs.


EVER LAWFUL
MAERSK
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HAMBURG SÜD
EVERGREEN
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COPIAPO
MONROVIA
Safmarine

SECTION 3

RESEARCH RESULTS

This section reveals the ZET component sizes, purchase costs, and TCO across 14 use cases from 2022 to 2030 in Guangdong. We further explored: (1) future component sizing of ZETs to meet day-to-day operational variability of small fleet operators; (2) purchase costs of ZETs and the need for financing mechanisms; (3) TCO parity years relative to ICEVs and their sensitivity to different energy efficiency and energy prices; (4) the roles played by technological development, policy incentives, and operational improvements in advancing TCO parity years relative to ICEVs; and (5) applicability of this study's conclusions to other Chinese regions.

3.1 Results for 2022

ZET attributes and applications in 2022

Based on this study's analysis of mainstreamed ZET models in China using the NEV Catalogue of 2022 (MIIT 2022), it appears that although ZET models in 2022 can meet some use cases' operation requirements, they still have range, payload, and peak power inadequacies in other use cases:

- Ranges

BETs in UD of short daily VKTs can be electrified. In the real world, with this range limitation, some fleet operators would change operation to deploy BETs in routes with short daily mileages, while using diesel trucks for long mileages (such as 200 to approximately 300 km); the other fleet operators would achieve a full electric fleet in UD but sacrifice one-on-one replacement with the diesel fleet—that is, additional BETs are needed to meet the same operational requirement as the diesel fleet (Pers. Comm. 2023a).

FCETs' actual ranges are longer than BETs; they can meet all the range requirements of UD but still have few limitations with RD characterized by long daily VKTs. For example, FC 4.5-t LDTs have a maximum range of 348 km, falling short of meeting the RD use cases with 350 to approximately 500 km daily VKTs.

- Payload loss

Because most ZETs in 2022 were non-native ZETs that use existing platforms from ICEVs,[13] their configurations were not optimized (Pers. Comm. 2023c), thereby facing outstanding payload loss issues. Among all vehicle segments, 4.5-t LDTs are more sensitive to payload loss problems than HDTs: Zero-emission LDTs' payload capacities could be reduced by 26 to 42 percent, compared to the ICE LDTs. The degree of payload loss is the largest for FC electric LDTs, with the payload capacity about half of that for an ICE LDT. As ZETs' GVW increase, the payload loss problem become less significant. For example, zero-emission straight trucks' payload capacities are 15 percent smaller than diesel straight trucks, while zero-emission tractor trailers' maximum payloads were only 5% less than the diesel tractor trailers.

- Peak motor powers

Most ZETs in 2022 can meet the peak power demands of all use cases, except for FC dump trucks. Since the purchase subsidy of national

Table 10 | **Zero-emission truck technical configurations in 2022**

		BET					FCET					
	GVW/GCW (kg)	Nominal battery capacity (kWh)	Rated/peak motor power (kW)	Payload capacity (kg)[a]	Actual AER (km)[b]	Applications	H_2 storage (kg)	Nominal battery capacity (kWh)	Rated power of FC system (kW)	Payload capacity (kg)[a]	Actual range (km)[b]	Applications
Delivery van	3,495 (4×2)	42~50	30/60	960~1,315	161~186	Partial UD	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
LDT	4,495 (4×2)	81	60/120	1,251 **(-26%)**	185~196	UD	9	30	84	978 **(-42%)**	Approx. 348	UD and partial RD
Straight truck	18,000 (4×2)	247	90/171	7,927 **(-15%)**	195~228	UD	30	105	102	7,952 **(-15%)**	Approx. 464	UD and partial RD
Dump truck	31,000 (8×4)	423	270/405	12,230 **(-20%)**	Approx. 200	UD	40	127	110	13,193 **(-14%)**	Approx. 358	UD
Tractor trailer[c]	42,000 (4×2)	282	250/360	25,257 **(-5%)**	134~205	UD, partial DDC, and PO	36	100	110	25,489 **(-4%)**	255~471	UD, PO, and partial RD and DDC

Notes: [a] Percentage in parentheses indicates the percent of maximum payload loss in terms of a comparable diesel truck.
[b] The actual AER of BET is calculated based on the battery capacity, DoD, and energy efficiency; actual range of FCET is calculated based on hydrogen storage capacities, usable capacities of hydrogen storage systems, and energy efficiency using the hydrogen-only mode.
[c] The technology deployed for BET tractor trailers in Shenzhen's real-world application (that is, port operation) is battery swapping trucks.

Abbreviations: GVW=gross vehicle weight; GCW=gross combined weight; BET=battery electric truck; FCET=fuel cell electric truck; H_2=hydrogen; LDT=light-duty truck; AER=all electric range; UD=urban delivery; RD=regional delivery; DDC=drayage duty cycle; PO=port operation; approx.= approximately; N.A.=not applicable.

Sources: Authors' summary based on Pers. Comm. (2023a) (see Appendix B) and NEV Catalogue (MIIT 2022).

FCEV City Cluster Demonstration Program is correlated with the rated powers of FC systems with the upper limit of 110 kW (Guangdong DRC et al. 2022), the FC systems are sized not to exceed 110 kW to maximize subsidy proceeds and minimize R&D investments. Therefore, a dump truck with a 2C, 127-kWh battery and a 110-kW FC system can achieve a 364-kW peak motor power, which is insufficient to satisfy the power demand if the vehicle climbs with a full load in construction or dumping sites.

Purchase costs and TCO for 2022

Based on publicly available data from online dealer platforms and authors' interviews, this study roughly calculates the purchase costs differences between ZETs and ICEVs in 2022 (the same specifications in Table 10). The results show that if purchased directly, ZETs are more expensive than ICEVs. FCETs are particularly more expensive, with the purchase costs 272–482 percent higher than ICEVs, while BETs are 58–113 percent higher than ICEVs. Further, with innovative business models, such as battery swapping, the purchase costs of battery electric tractor trailers—that is, vehicle bodies without the batteries—are almost the same as their diesel counterparts (Qi 2022).

We further calculated ZETs' TCO as of 2022 ZETs for UD, PO, and DDC (with a daily VKT of 200 km). Considering that current ZETs are inadequate to meet the range requirements in RD, their TCOs are not quantified. The influences from existing city-specific ZET incentives on TCO are considered.

For BETs, their TCO was cheaper than ICEVs in UD and PO when transporting lightweight goods, while they are more expensive than ICEVs when transporting heavy goods in UD. On the contrary, even when accounting for the purchase and operational subsidies from the Guangdong FCEV City Cluster, the TCO of FCETs in 2022 was still 55,000–600,000 CNY higher than ICEVs (except for PO). This is because of the expensive purchase cost of FCETs, high hydrogen prices (55 CNY/kg) and payload losses owing to the non-native design of FCETs; and limited amounts of local FCEV City Cluster subsidies in Guangdong Province (Figures 5, 6, and 7). For example, a 31-t FC dump truck

in Beijing's Daxing district can receive about 2 million CNY in national, municipal, and district-level subsidies (Beijing Daxing Government 2022; Beijing MEITB 2022), 150 percent higher than it is in Foshan, Guangdong; therefore, in Beijing Daxing district, the TCO of FC dump trucks was 650,000 CNY lower than their diesel counterparts in 2022 (see Figure 6).

The following points are worth noting:

- First, Shenzhen and Foshan governments' BET subsidies were applied to the use cases that nearly reach TCO parity, such as 4.5-t LDTs in UD, or had achieved the TCO parity, such as 42-t tractor trailers in PO. The operation subsidies (about 54,000 CNY per vehicle) in Foshan were conducive to bridge battery-electric LDTs' TCO gaps with ICEVs, especially in UD heavy goods transportation. The purchase subsidies (50,000–70,000 CNY per vehicle) in Shenzhen to battery-electric tractor trailers in PO primarily served to reduce the purchase costs, given that battery-electric tractor trailers had already achieved TCO parity with their diesel equivalents in PO.

- Second, although TCO parity with diesel trucks had been reached for battery electric 18-t straight trucks and 42-t tractor trailers in UD with light goods shipments, their real-world applications are limited in Shenzhen and Foshan (Pers. Comm. 2023a). This could be attributed to the limited availability of ZET make-and-models (MIIT 2022) or deployment of the same truck in multiple use cases (such as RD), where ZETs still have technological or economical limitations.

Table 11 | **TCO gaps between ZET trucks and ICEV trucks for 2022 with policy incentives**

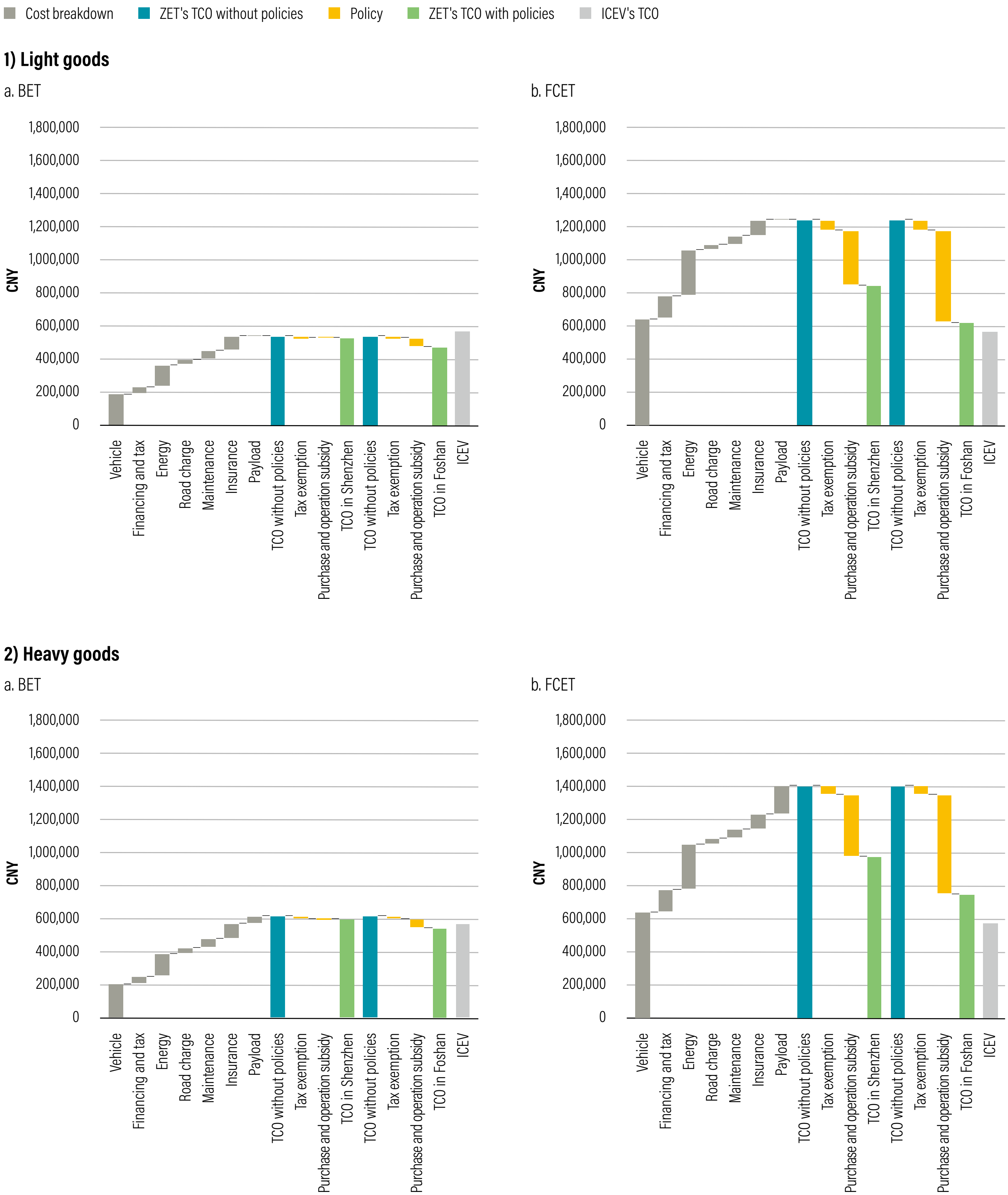
USE CASE	CARGO TYPE	DIFFERENCES BETWEEN BET TCO AND ICEV TCO (CNY)		DIFFERENCES BETWEEN FCET TCO AND ICEV TCO (CNY)	
		SHENZHEN	FOSHAN	SHENZHEN	FOSHAN[c]
Delivery van					
UD	Misc. goods	-65,703 **(-19%)**	-83,703 **(-24%)**	N.A.	N.A.
4.5-t LDT					
UD	Light goods	-43,572 **(-8%)**	-97,572 **(-17%)**	279,989 **(49%)**	54,989 **(10%)**
	Heavy goods	24,051 **(4%)**	-29,949 **(-5%)**	403,833 **(70%)**	178,833 **(31%)**
18-t straight truck					
UD	Light goods	-6,157 **(-1%)**	-6,157 **(-1%)**	478,911 **(40%)**	448,911 **(38%)**
	Heavy goods	32,327 **(3%)**	32,327 **(3%)**	462,616 **(36%)**	432,616 **(33%)**
31-t dump truck					
UD	Heavy goods	238,931 **(15%)**	238,931 **(15%)**	574,447 **(36%)**	504,447 **(32%)**
42-t tractor trailer					
UD	Light goods	11,234 **(1%)**	-11,234 **(1%)**	476,719 **(30%)**	406,719 **(26%)**
PO	Light goods	-392,009 **(-17%)**	-142,009 **(-6%)**	-11,606 **(-1%)**	166,394 **(7%)**
DDC	Light goods	202,150 **(12%)**	202,150 **(12%)**	596,407 **(35%)**	596,407 **(35%)**

Notes: [a] TCO gaps are the TCO differences between ZETs and their ICEV counterparts. Percentage in parentheses indicates the percent of TCO gaps relative to the ICEV counterparts.
[b] Based on Pers. Comm. (2023a), it assumes that the daily VKT across all use cases is 200 km and the useful life of all vehicles is six years, except for dump trucks, which is five years.
[c] Foshan doesn't have any seaport; this study uses other Chinese port cities to replace Foshan when calculating the TCO for PO and DDC so as to reflect the case without city-specific ZET incentive policies.

Abbreviations: BET=battery electric truck; FCET=fuel cell electric truck; UD=urban delivery; RD=regional delivery; DDC=drayage duty cycle; PO=port operation; TCO=total cost of ownership; Misc.= miscellaneous; N.A.=not applicable.

Sources: WRI authors' calculation.

Figure 5 | **TCO of a 4.5-t LDT for the urban delivery use cases in 2022 in Shenzhen and Foshan**

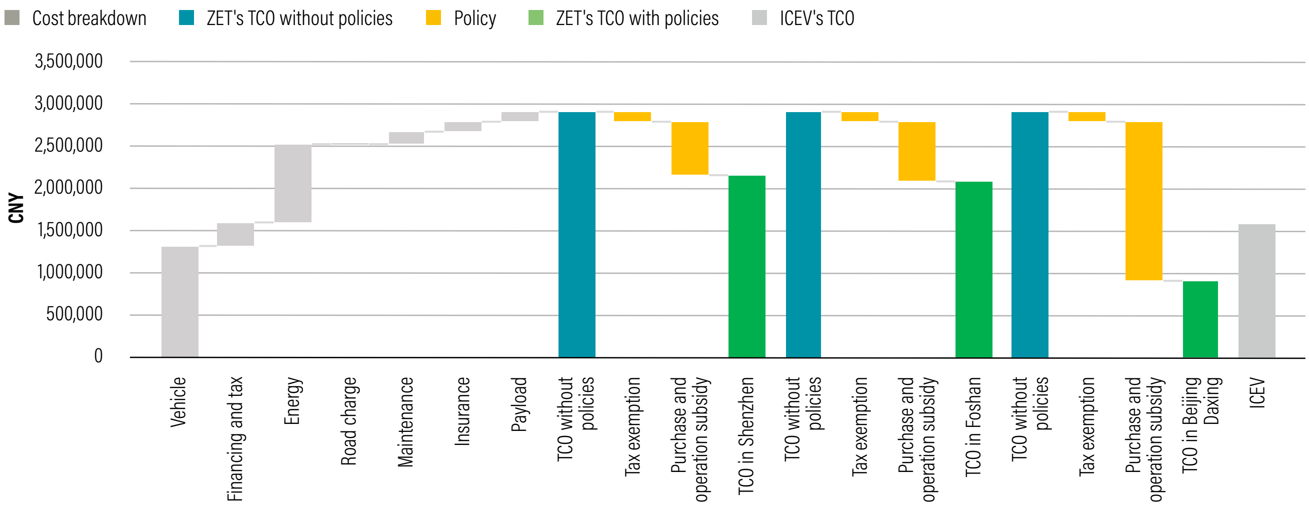


Notes: This figure assumes that the daily VKTs across all use cases are 200 km and that the useful life of LDTs is six years (Pers. Comm. 2023a).

Abbreviations: BET=battery electric truck; FCET=fuel cell electric truck; ICEV=internal combustion engine vehicle.

Source: WRI authors' calculation.

Figure 6 | **TCO of a 31-t FC dump truck in the urban delivery use case in 2022 in Shenzhen, Foshan, and the Daxing District of Beijing**

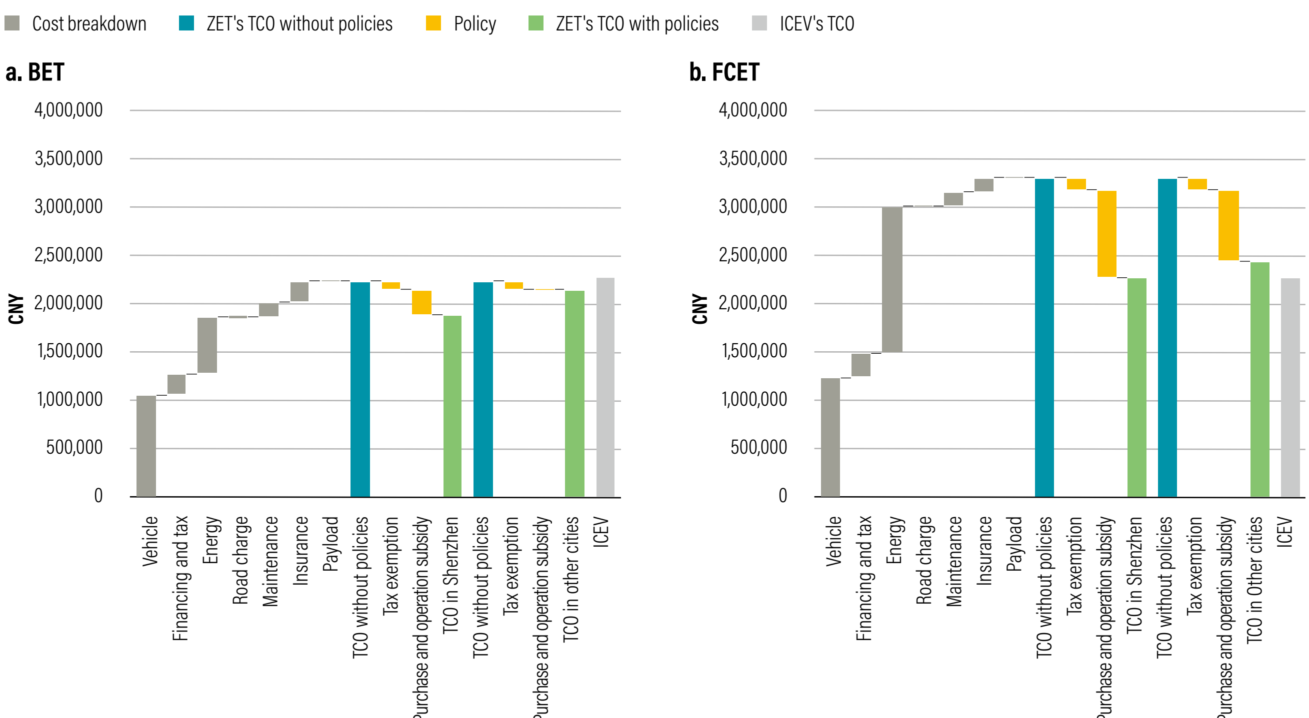


Notes: This figure assumes that the daily VKTs across all use cases are 200 km and the useful life of the 31-t dump truck is five years (Pers. Comm. 2023a).

Abbreviations: BET=battery electric truck; FCET=fuel cell electric truck; ICEV=internal combustion engine vehicle.

Source: WRI authors' calculation.

Figure 7 | **TCO of a 42-t tractor trailer for the port operation use case in 2022 in Shenzhen and other Chinese cities**



Notes: This figure assumes that the daily VKTs across all use cases are 200km and the useful life of the 42-t tractor trailers are six years (Pers. Comm. 2023a).

Abbreviations: BET=battery electric truck; FCET=fuel cell electric truck; ICEV=internal combustion engine vehicle.

Source: WRI authors' calculation.

3.2 Results from MY2022 to MY2030

ZET component sizing during MY2022 and MY2030

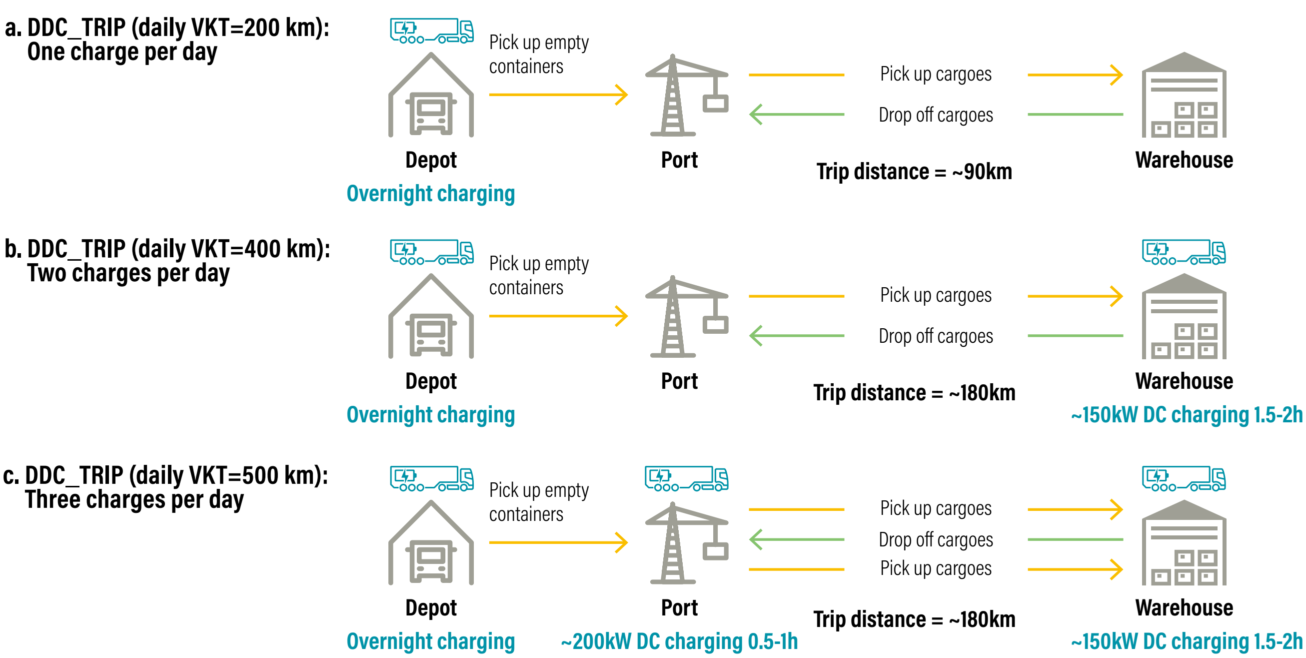
Based on the section, "Method of estimating ZETs' key component sizing," this section estimates the sizing of key components—including nominal battery capacities, FC systems' power, and hydrogen storage capacities to meet the ranges and peak wheel power demands for all use cases during MY2022 and MY2030, with the consideration of technological progress and operational optimization.

BET component sizing: increases in battery capacities leading to payload loss

In 2022, BETs can only meet some UD's range requirements. Therefore, for BETs to meet the range requirements for all use cases during MY2022 and MY2030, battery capacities of BETs need to increase.

As outlined in the section, "Method of estimating ZETs' key component sizing," two methods are available to configure BETs' battery capacities. This study adopts the "daily VKT" method for UD and RD because it is difficult to optimize operation in short time periods with highly variable destinations, uncertain operation schedules, and limited charging infrastructure availability in large geographic coverage. However, for PO and DDC, both the "daily VKT" and "trip distance" methods are considered. The "trip distance" method is feasible because operation of BETs can be improved with predictable destinations and operation schedules, return-to-base operation, as well as relatively small geographic coverage. Particularly, if fast-charging facilities can be installed at customers' warehouses, a battery electric tractor trailer with a 200 km range in DDC can achieve 400 km daily VKTs, with one daytime charge at customers' sites during the 1.5-hour dwell period for loading containers. Further, if fast-charging facilities can be installed at both port terminals (or parking spaces near terminals) and customers' warehouses, the same BET could reach 500 km daily VKTs in DDC, with two daytime charges per day (see Figure 8). This study assumes that when using the "trip distance" method in PO and DDC, the range of BETs is 200 km. This is a reasonable value considering that most tractor trailers serving the port have a trip distance up to 200 km (Wang et al. 2024).

Figure 8 | **Operation and charging schemes for a battery-electric tractor trailer in DDC_TRIP with a 200 km range (BET200)**



Source: Authors' summary based on Pers. Comm. (2023a) (see Appendix B).

The analysis yielded the following results:

In UD and RD that employ the "daily VKT" method, battery capacities are expected to increase substantially from the 2022 level, particularly for RD. The nominal battery capacity of a 4.5-t LDT will rise from 81 kWh in 2022 to 148–255 kWh to meet RD's range requirements by MY2025, an increase of 83–215 percent from the 2022 level, while in UD, 88–139-kWh nominal battery capacity will be sufficient by MY2025, an increase of 8–71 percent from 2022.

The rise in battery capacities comes at the cost of increased payload loss in some use cases where the increase in battery capacities outweighs the improvements on battery energy densities and vehicles' energy efficiency. The payload loss problem is particularly significant for battery electric LDTs in RD. For a MY2025 battery-electric LDT in RD (with 148–255 kWh battery capacity), its payload capacity will shrink by 36 to 69 percent relative to an ICE LDT. BETs' payload loss problem will be alleviated as the BETs' GVW increases. For a MY2025 42-t battery-electric tractor trailer in RD, its payload capacity will only be reduced by 3 to 8 percent, compared to the diesel equivalent.

In the PO and DDC use cases, employing the "daily VKT" method and the "trip distance" method to configure BETs lead to different battery capacities and payload loss. Taking DDC for example, using the "trip distance" method, the 288 kWh battery capacity of a MY2025 42-t tractor trailer is sufficient to fulfill 300 to 500 km daily VKTs, compared to 432–720 kWh battery capacities using the "daily VKT" method. With a smaller battery pack (288 kWh), the BET will have no payload loss by MY2025, using the "trip distance" method.

Figure 9 | **Nominal battery capacities for MY2025 and MY2030**

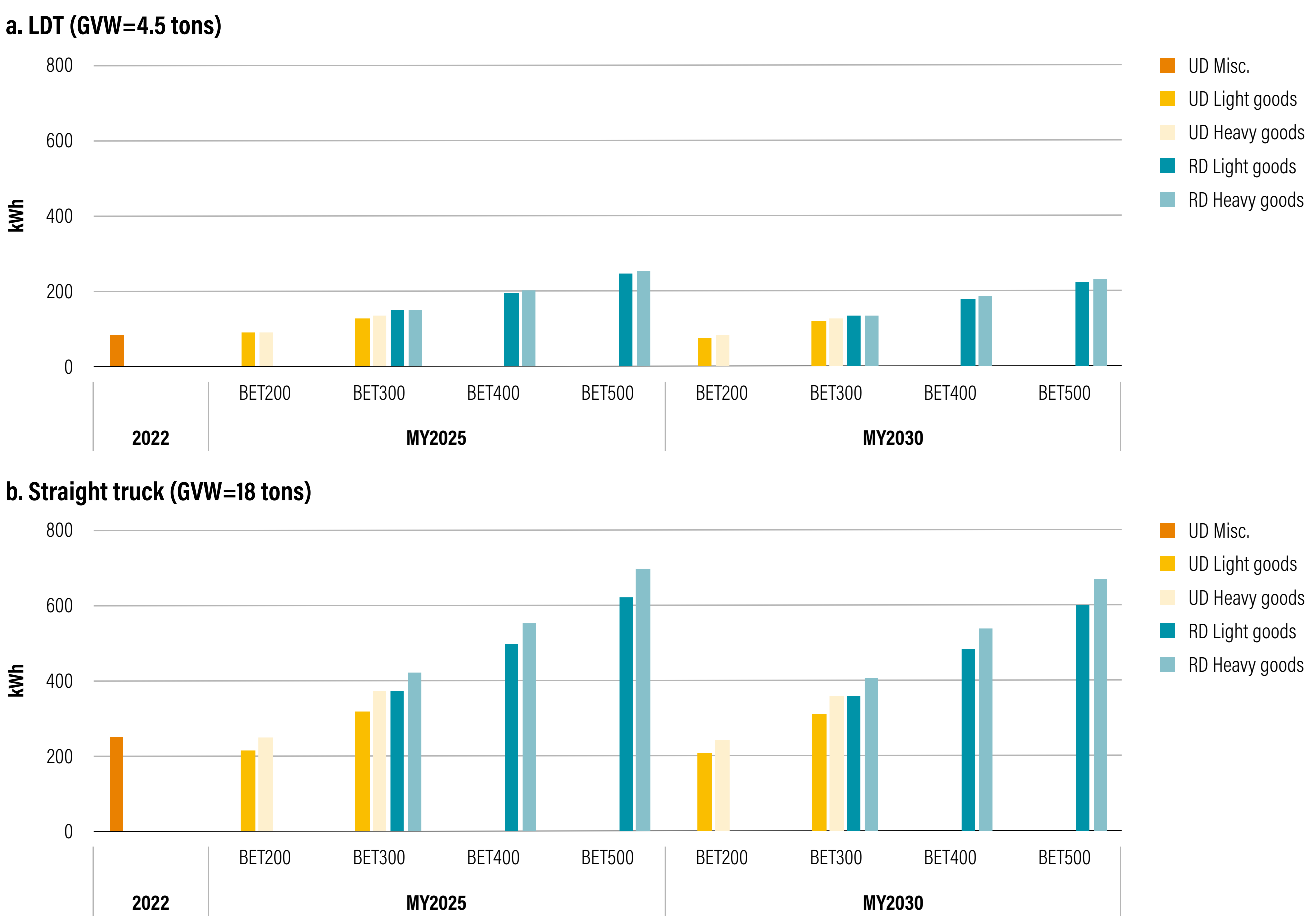
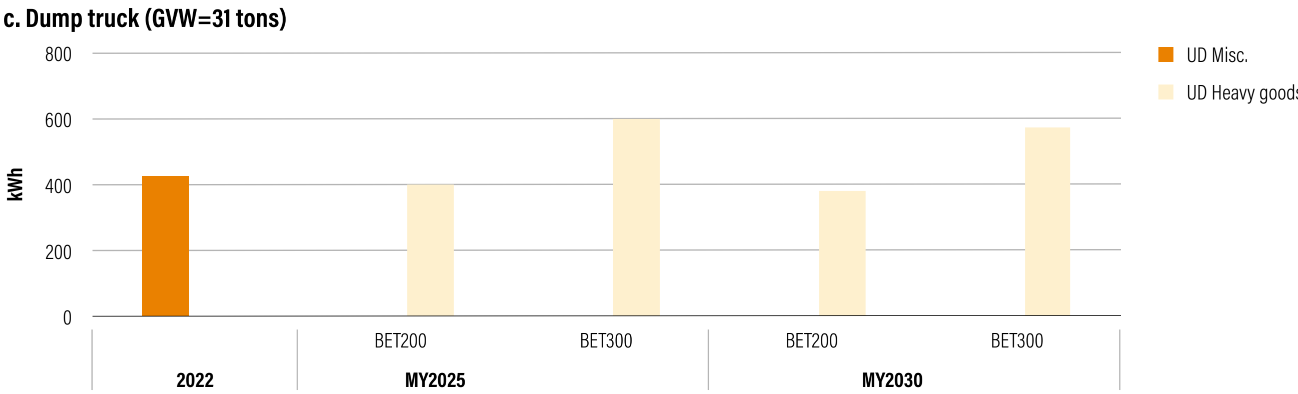
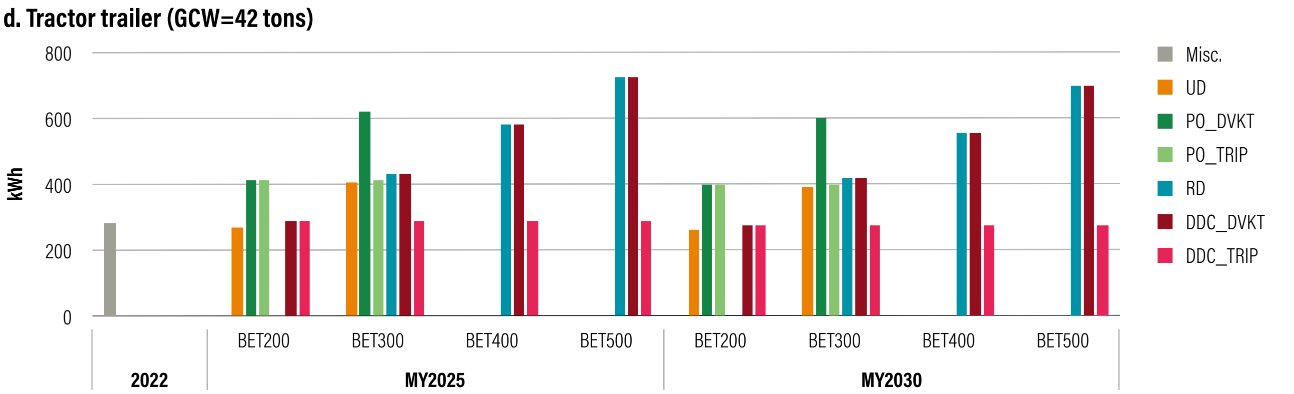


Figure 9 | **Nominal battery capacities for MY2025 and MY2030 (cont.)**





	MY2025		MY2030	
	DIFFERENCES WITH 2022[a]	DIFFERENCES WITHIN THE USE CASES (KWH)	DIFFERENCES WITH 2022[a]	DIFFERENCES WITHIN THE USE CASES (KWH)
LDT				
UD	8%~71%	51	-1%~57%	47
RD	83%~215%	107	67%~189%	98
Straight truck				
UD	-15%~51%	160	-17%~46%	156
RD	51%~181%	322	46%~172%	311
Dump truck				
UD	-5%~42%	201	-9%~36%	192
Tractor trailer				
UD	-4%~43%	135	-8%~38%	130
RD	53%~155%	288	47%~145%	277
PO_DVKT	46%~119%	206	41%~111%	198
PO_TRIP	46%	0	41%	0
DDC_DVKT	2%~155%	432	-2%~145%	415
DDC_TRIP	2%	0	-2%	0

Notes: [a] The percent of "differences with 2022" indicate the differences of the nominal battery capacities for MY2025 and MY2030 BETs with the 2022 BETs.
[b] For DDC_TRIP and PO_TRIP, the maximum trip distance is fixed at 200 km; therefore, the battery capacities are sized based on the 200 km actual all-electric range.

Abbreviations: BET=battery electric truck; UD=urban delivery; RD=regional delivery; PO_DVKT=port operation (using the "daily VKT" method); PO_TRIP=port operation (using the "trip distance" method); DDC_DVKT=drayage duty cycle (using the "daily VKT" method); DDC_TRIP=drayage duty cycle (using the "trip distance" method); Misc.= miscellaneous.

Source: WRI authors' calculation.

Figure 10 | **Losses of maximum payloads of BETs compared to ICEVs for MY2025 and MY2030**

Abbreviations: BET=battery electric truck; UD=urban delivery; RD=regional delivery; PO_DVKT=port operation (using the "daily VKT" method); PO_TRIP=port operation (using the "trip distance" method); DDC_DVKT=drayage duty cycle (using the "daily VKT" method); DDC_TRIP=drayage duty cycle (using the "trip distance" method); Misc.= miscellaneous.

Source: WRI authors' calculation.

FCET component sizing: few increases on hydrogen storage and limited payload loss

MY2022 FCETs had already met the range requirements of some RD use cases; therefore, differing from BETs, FCETs' on-board hydrogen storage system would need few increases to meet all use-case requirements during MY2022–MY2030. For example, by MY2025, hydrogen storage needs to increase by 2–34 percent to meet the range requirements across all use cases. The increases are only considerable for 4.5-t LDTs in RD; the hydrogen storage capacities should increase from 9 kg in 2022 to 12 kg in MY2025 to support 500 km daily VKTs (a 34 percent increase). However, the increases in hydrogen storage capacities are insignificant for other truck segments. For example, for 18-t straight trucks in RD, the hydrogen storage capacities only need to increase from 30 kg to 31 kg to meet 500-km daily VKTs (a 4 percent increase).

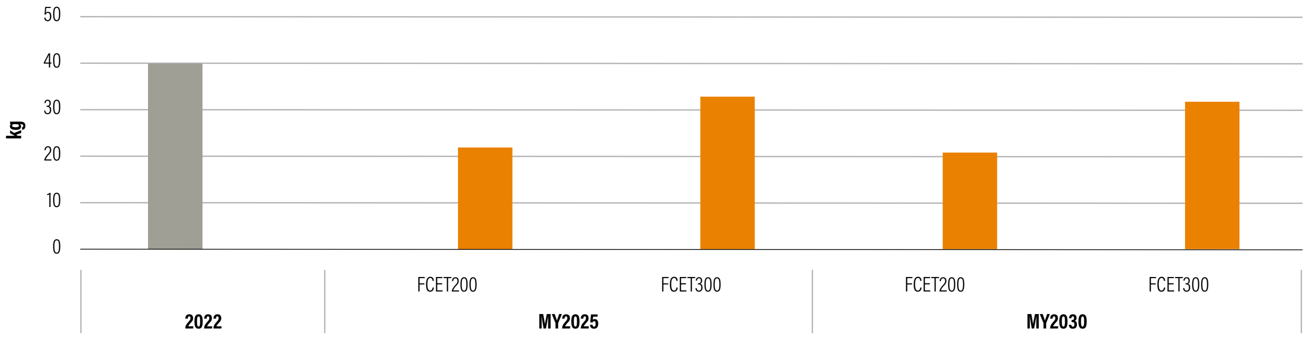
Apart from hydrogen storage, the FC systems' power should also be raised, particularly for FC dump trucks. We assume during MY2022 and MY2030, FC dump trucks still carry a 2C, 127 kWh battery, and the fuel cell system's power would increase from 110 kW to 151 kW to meet the 405 kW peak power needs for all the use cases and model years.

Unlike BETs, the increases in hydrogen storage capacities and FC systems' power result in limited payload loss of FCETs. Because of better integration of powertrain components (that is, features of native electric vehicles) (Mauro Erriquez et al. 2017), the usage of lightweight structural materials, improvements in battery energy density and hydrogen storage's gravimetric capacities, FCETs' payload loss reduces rapidly. Although LDTs in RD remain to have the largest payload loss, the payload capacity of a MY2030 LDT reduces by 8–14 percent relative to ICEVs, a great improvement from 2022's 42 percent. By MY2030, FCETs' payload loss problem will be eliminated for FCET HDTs, as in the case of dump trucks and 42-t tractor trailers.

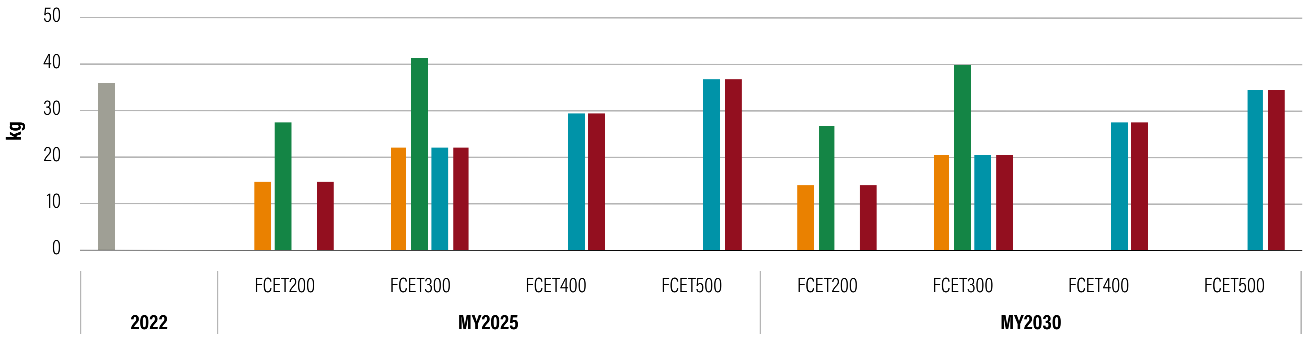
Figure 11 | **Sizes of on-board hydrogen storage for FCETs in MY2025 and MY2030**

Figure 11 | **Sizes of on-board hydrogen storage for FCETs in MY2025 and MY2030 (cont.)**

c. Dump truck (GVW=31 tons)



d. Tractor trailer (GCW=42 tons)



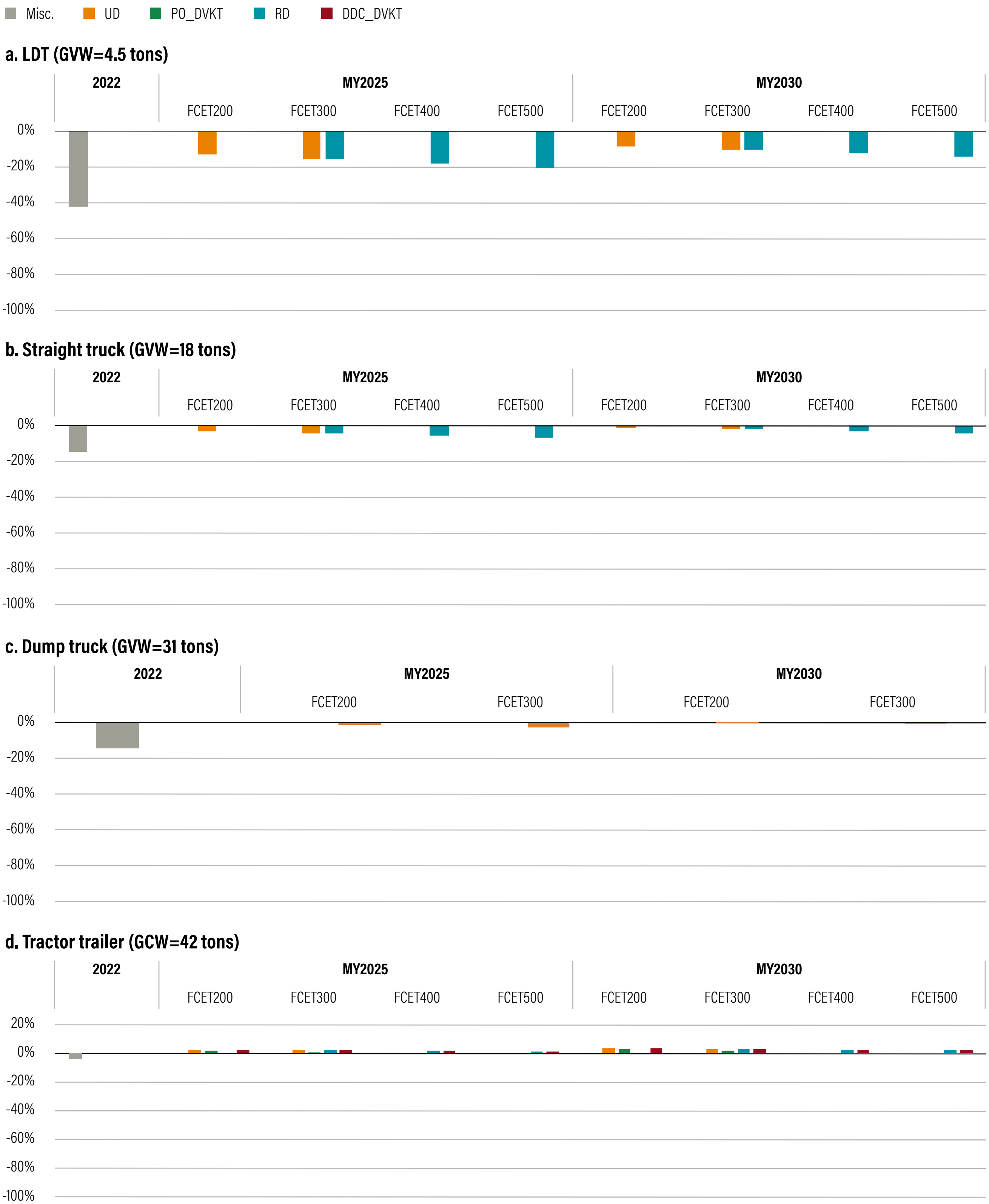
	MY2025		MY2030	
	DIFFERENCES WITH 2022[a]	DIFFERENCES WITHIN THE USE CASES (KG)	DIFFERENCES WITH 2022[a]	DIFFERENCES WITHIN THE USE CASES (KG)
LDT				
UD	-46%~-20%	2.4	-53%~-29%	2.2
RD	-31%~34%	4.8	-29%~18%	4.2
Straight truck				
UD	-59%~-38%	6.2	-61%~-42%	5.8
RD	-38%~4%	12.4	-42%~-3%	11.7
Dump truck				
UD	-45%~-18%	11.0	-47%~-21%	10.6
Tractor trailer				
UD	-59%~-39%	7.4	-62%~-43%	6.9
PO_DVKT	-23%~15%	13.8	-26%~11%	13.4
RD	-39%~2%	14.7	-4%~-43%	13.8
DDC_DVKT	-59%~2%	22.1	-62%~-4%	20.7

Notes: [a] The percentage of "differences with 2022" indicate the differences of the on-board hydrogen storage for MY2025 and MY2030 FCETs with the 2022 FCETs.

Abbreviations: FCET=fuel cell electric truck; UD=urban delivery; RD=regional delivery; DDC_DVKT=drayage duty cycle (using the "daily VKT" method); PO_DVKT=port operation (using the "daily VKT" method); Misc.= miscellaneous.

Source: WRI authors' calculation.

Figure 12 | Losses of payload capacities of FCETs compared to ICEVs for MY2025 and MY2030



Abbreviations: FCET=fuel cell electric truck; UD=urban delivery; RD=regional delivery; DDC_DVKT=drayage duty cycle (using the "daily VKT" method); PO_DVKT=port operation (using the "daily VKT" method); Misc.= miscellaneous.

Source: WRI authors' calculation.

Designing ZETs (BETs) with flexibility will be necessary during MY2022 and MY2030

We further evaluate the differences in ZET configurations within and across use cases during MY2022 and MY2030. The results illustrate significant variations in ZET component sizes exist, particularly for BETs (Figures 9 and 11). Even within the same-use case, the differences in battery capacities of BETs examined in this study could vary from 51 kWh to 322 kWh in MY2025. The variation is particularly significant in RD. For example, the battery capacities of an 18-t straight truck in RD—including BET300, BET400, and BET500—differ by 322 kWh in MY2025, while the differences are less significant for FC 18-t straight trucks. The capacities of hydrogen storage only vary by 16 kg. Further, considering that trucks are often deployed across use cases (such as UD and RD) with day-to-day variability in VKTs and types of goods transported (TUC 2022b), the differences in BET configurations are even larger. For example, the battery capacities of 18-t straight trucks in UD (BET200) and RD (BET500) would differ by 388–453 kWh during MY2022 and MY2030.

The large variations of BET configurations pose challenges to both OEMs and fleet operators to produce or purchase fitting BET models. Two solutions to the challenges exist (Tol et al. 2022; Tetra Tech and GNA 2022):

- Designing a broadly applicable BET that is capable of meeting the majority of operation in one often-applied use case. This solution will create volumes for the mass production of ZETs with the same specifications and lower the manufacturing costs for OEMs. However, it would raise the purchase costs and TCO of ZETs for fleet operators due to larger batteries and greater payload loss.

- Purpose-building a BET for a sub-use case. Compared with a broadly applicable BET, the purpose-built BET will offer fleet operators with a lower price but limited operational flexibility. Further, it may compromise the ability of OEMs to mass manufacture ZETs.

To accommodate SMEs' needs for operation flexibility, designing broadly applicable BETs is recommended. BETs that are purpose-built to specific use cases suit large fleet operators who often have long-term contracts with customers and accumulate rich experiences in vehicle dispatching. However, the solution would be infeasible for small fleet operators who often live on the spot market with uncertain customer bases (and possibly operate across multiple use cases) and have limited numbers of vehicles to dispatch. To design broadly applicable BETs, governments play an important role in collecting statistics on the daily mileage of existing truck fleets and sharing that information with major industrial stakeholders like OEMs.

ZET Purchase cost projections from MY2022 to MY2030

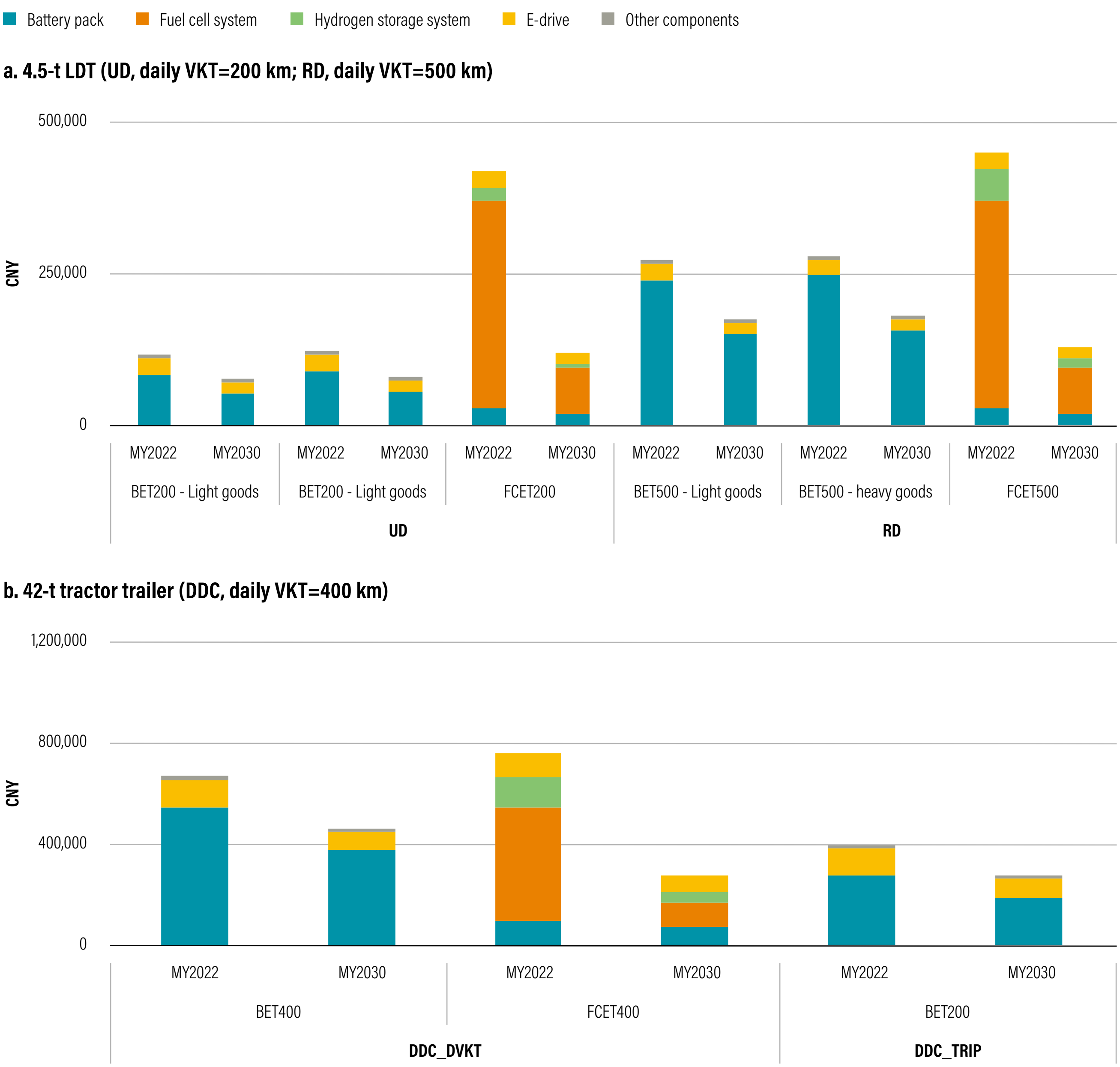
We estimated ZETs' purchase costs during MY2022 and MY2030 with the following results:

ZETs' purchase costs drop rapidly during MY2022 and MY2030. Compared to MY2022, the purchase costs of ZETs in MY2030 decline by 22 to 64 percent.

The purchase costs of FCETs decline more rapidly than BETs: FCETs' purchase costs drop by 53 to 64 percent between MY2022 and MY2030, whereas those of BETs reduce by 22 to 30 percent during the same period. By MY2030, FCETs are a cheaper ZET option to buy in most use cases (except for 4.5-t LDTs in UD). The rapid decline in FCETs' purchase costs is due to the assumed rapid cost reduction of the most expensive component of FCETs: the FC systems (75–80 percent reduction during MY2022 and MY2030) in this study, and the plug-in hybrid design of FCET that helps diminishing power requirements from the FC systems.

Second, despite the rapid reduction in ZETs' purchase costs, the purchase costs of ZETs are still higher than ICEVs during MY2022 and MY2030. For example, by MY2030, the purchase costs of ZETs are still 53 to 322 percent more expensive than ICEVs in all use cases examined by this study. The wide purchase cost gaps between ZETs and ICEVs could be partly attributed to the low vehicle prices of diesel trucks in China. The manufacturer's suggested retail price (MSRP) of a diesel 42-t tractor unit[14] was about

Figure 13 | **DMCs for ZETs in selected use cases in MY2022 and MY2030**

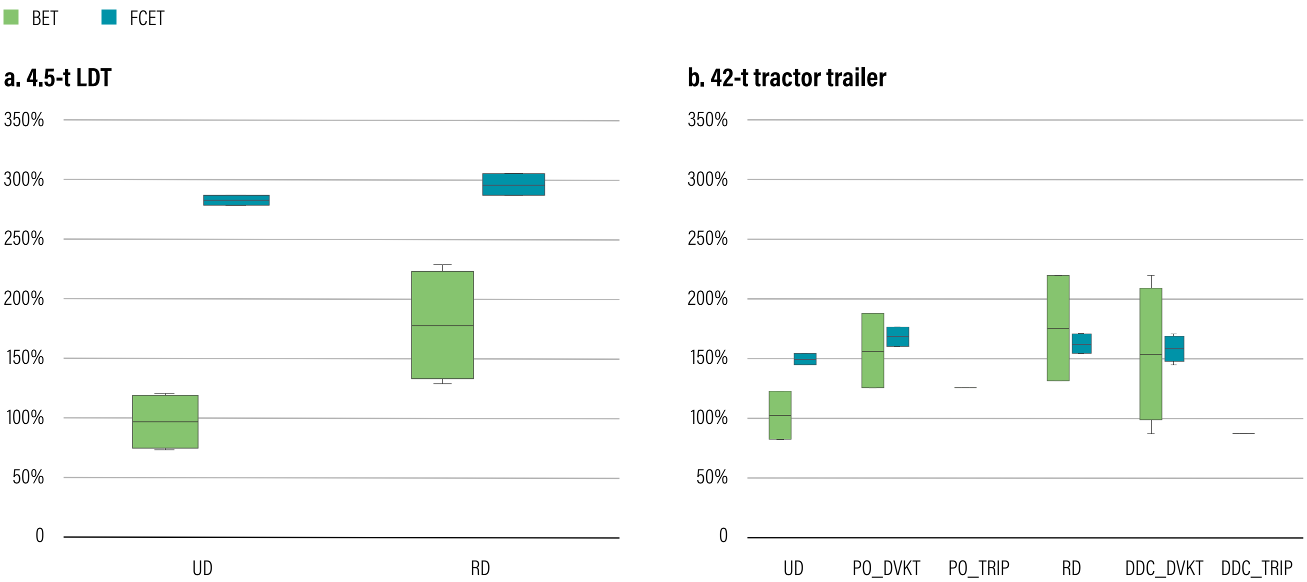


Abbreviations: BET=battery electric truck; FCET=fuel cell electric truck; ICEV=internal combustion engine vehicle; UD=urban delivery; RD=regional delivery; DDC_DVKT=drayage duty cycle (using the "daily VKT" method); DDC_TRIP=drayage duty cycle (using the "trip distance" method).

Source: WRI authors' calculation.

330,000 CNY in 2022, only one third of the MSRP of a Class 8 diesel tractor unit in the United States (Xie et al. 2023).[15] Therefore, although the purchase cost of a MY2030 battery-electric 42-t tractor in DDC_DVKT (BET200) is approximately 560,000 CNY, much cheaper than the cost of a comparable diesel tractor in the United States, the BET is still twice the purchase cost of the diesel counterpart in China. The case is the same for FCETs: Although FCETs' vehicle prices are cheaper than BETs in most use cases, they are still 60 to 140 percent higher than their diesel counterparts by MY2030.

Figure 14 | Percentage differences in purchase costs between ZETs and ICEVs in MY2025

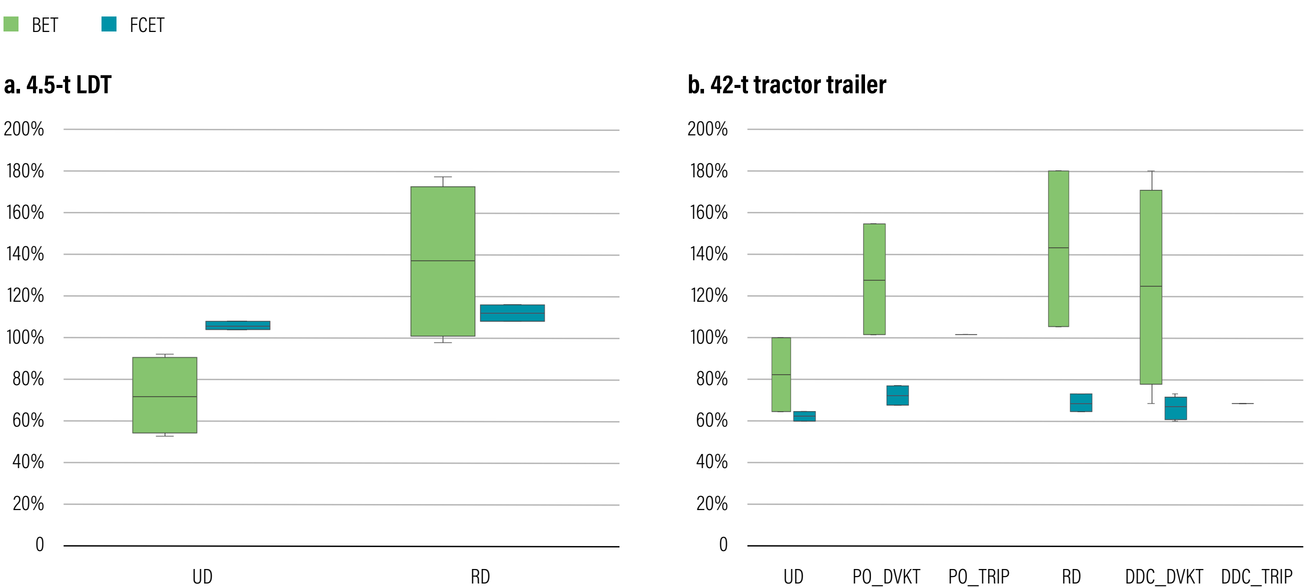


Notes: The percentage represents the difference in purchase costs between ZETs and comparable ICEVs divided by the purchase costs of ICEVs, that is, (ZET-ICEV)/ICEV. Zero percent indicates no difference between the purchase costs of ZETs and ICEVs. No purchase subsidy or tax is considered for the purchase costs.

Abbreviations: BET=battery electric truck; FCET=fuel cell electric truck; ICEV=internal combustion engine vehicle; UD=urban delivery; RD=regional delivery; PO_TRIP=port operation (using the "trip distance" method); DDC_DVKT=drayage duty cycle (using the "daily VKT" method); DDC_TRIP=drayage duty cycle (using the "trip distance" method).

Source: WRI authors' calculation.

Figure 15 | Percentage differences in purchase costs between ZETs and ICEVs in MY2030



Notes: The percentage represents the difference in purchase costs between ZETs and comparable ICEVs divided by the purchase costs of ICEVs, that is, (ZET-ICEV)/ICEV. Zero percent indicates no difference between the purchase costs of ZETs and ICEVs. No purchase subsidy or tax is considered for the purchase costs.

Abbreviations: BET=battery electric truck; FCET=fuel cell electric truck; ICEV=internal combustion engine vehicle; UD=urban delivery; RD=regional delivery; PO_TRIP=port operation (using the "trip distance" method); DDC_DVKT=drayage duty cycle (using the "daily VKT" method); DDC_TRIP=drayage duty cycle (using the "trip distance" method).

Source: WRI authors' calculation.

To ease the costly up-front burdens of buying a ZET, particularly for small fleet operators, and to allocate the risks of the ZET transition to appropriate stakeholders, it is necessary for private and public entities to take concerted efforts. Although ZET purchase subsidies offer a possible solution to reducing the up-front costs, more financially sustainable solutions, such as innovative business models, are needed:

- Leasing or battery swapping: In the leasing model, fleet operators only pay a monthly lease or per-km payment to use the vehicle. In the battery swapping model, fleet operators only pay for the vehicle body without batteries, while battery swapping station operators (such as utilities and battery pack manufacturers) own the batteries and collect an extra service surcharge for battery swapping.

  Although the leasing and battery swapping models have been commonly practiced in China (Shen and Mao 2023; Z. Wang et al. 2020), their application has been restricted to a few use cases and regions. For example, leasing is commonly seen for 4.5-t battery-electric LDTs and FC-trucks in Guangdong Province, and battery swapping is widely used for battery-electric tractor trailers in short-haul use cases (Shen and Mao 2023; Z. Wang et al. 2020).

  To further accelerate the adoption of ZETs, measures should be taken by governments, financial institutions, and investors to facilitate the adoption of these innovative business models. These measures include but are not limited to green finance for ZETs through interest rate discounts and extended repayment terms, blended finance, tax benefits and flexible depreciation for leasing, and first loss guarantees to hedge against general or specific risks associated with ZETs (such as vehicle failure and residential value risk) (Sankar et al. 2022; Kok et al. 2023; Coyne et al. 2023).

- Reduction of loan down payments: To promote ZETs, financial regulators in China could also consider reducing the minimum down payment requirements for ZETs. At present, PBC and CBIRC (2017) regulates that the down payment for truck loans be no less than 30 percent of diesel truck prices and 25 percent of ZET prices. Although this regulation has already provided ZETs with advantages in up-front costs relative to ICEVs, the down payment for ZETs is still much higher than for their diesel counterparts. For example, the down payment for a MY2025 42-t BET200 tractor in DDC would be approximately 56,000 CNY higher than that for a diesel tractor. However, if financial regulators in China could further reduce ZETs' minimum down payment requirements from 25 to 20 percent, the down payment for the MY2030 42-t BET200 tractor would be only 25,000 CNY higher than that for its diesel equivalent.

TCO projections for MY2025 and MY2030

TCO parity years between ZETs and ICEVs are achieved earlier in UD, PO, and DDC without ZET incentives

We further projected ZETs' TCO without any ZET policy incentives for all powertrains and across all use cases during MY2022 and MY2030, to analyze when ZETs would achieve TCO parity relative to ICEVs and which zero-emission technologies would be more cost effective. Because FCETs can operate in the hydrogen-only mode or the hybrid mode, TCO for both modes was calculated and compared.

The TCO results show that without policy interventions, TCO parity relative to ICEVs is mainly achieved during this decade. However, in different use cases, the parity years and cost-effective zero-emission powertrains vary greatly.

- In UD, PO, and DDC, BETs of all the vehicle segments, except for the dump truck, will reach TCO parity relative with ICEV counterparts by MY2022–2027, much earlier than FCETs.

  Battery-electric 4.5-t LDTs and straight trucks in UD will reach TCO parity relative to their diesel counterparts by

MY2022–2027. The wide range of parity years is attributed to different types of goods transported: When carrying lightweight goods, both vehicle segments will achieve cost parity recently (MY2022-2023), whereas when transporting heavy goods, the parity years will be postponed to MY2025-2027 after being penalized for the payload losses.

Battery-electric 42-t tractor trailers in PO, DDC, and UD will become more cost-effective than diesel tractor trailers recently (MY2022–2025), representing one of the most promising truck segments to be electrified at the moment. In addition, their cost advantage relative to diesel counterparts will reach ~300,000 CNY by MY2030. This is because: 1) Battery-electric tractor trailers in Shenzhen and Foshan mostly carry lightweight goods; 2) using the "trip distance" method to size the batteries in the DDC use case leads to smaller batteries and lower TCO (see explanations below).

Battery-electric 31-t dump trucks will reach TCO parity relative to their diesel counterparts by MY2029-2030, about the same years as FC dump trucks. However, because of the large payload loss associated with BET300 dump trucks, they are more expensive compared to FC dump trucks. In MY2030, the TCO of a BET300 dump truck is about 50,000-100,000 CNY higher than an FC dump truck.

- For RD, TCO cost parity relative to ICEVs will be achieved around MY2028-2030 for most truck segments, much later than UD. Further, the cost-effective technology of RD is different from UD.

Battery-electric 4.5-t LDTs in RD exhibit a wide range of parity years relative to ICEVs, depending on the types of goods transported. When carrying lightweight goods, it can achieve TCO parity around MY2026, with BETs as a cost-effective option; when transporting heavy goods, the 4.5-t LDT will achieve TCO parity after MY2030 with FCETs as a cheaper option because of fewer payload losses of FCETs compared to BETs. Therefore, FCETs are more flexible and economical in RD if the LDT carries miscellaneous goods.

FC 18-t straight trucks and 42-t tractor-trailers in RD witness a significant TCO reduction and will reach cost parity by MY2028–2030, earlier than BETs. Further, the TCO of FCETs that operate in the hybrid mode is about 30,000–40,000 CNY lower than FCETs that operate in the hydrogen-only mode, thereby reaching parity about one year earlier. In contrast to FCETs, BETs in RD are more costly: The TCO of battery-electric tractor trailers and straight trucks is 7,000–650,000 CNY higher than FCETs in MY2030. This is because BET are less energy-efficient in RD than UD (Al-Wreikat, Serrano, and Sodré 2021; Singer et al. 2023) and this study does not differentiate FCETs' energy efficiency between UD and RD. Therefore, we may give FCETs more cost advantages in RD.

Figure 16 | **ZET TCO parity relative to ICEVs for all use cases**

● BET ▲ FCET (hybrid) ● FCET (H_2-only)

VEHICLE	DUTY CYCLE	CARGO TYPE	DAILY VKT (KM)	2022	2023	2024	2025	2026	2027	2028	2029	2030	Above 2030
4.5-t LDT	UD	Light goods	200	BET									FCET (hybrid), FCET (H_2-only)
			300	BET							FCET (hybrid)	FCET (H_2-only)	
		Heavy goods	200				BET						FCET (hybrid), FCET (H_2-only)
			300						BET			FCET (hybrid), FCET (H_2-only)	
	RD	Light goods	300					BET				FCET (hybrid)	FCET (H_2-only)
			400					BET			FCET (hybrid)	FCET (H_2-only)	
			500					BET		FCET (hybrid)	FCET (H_2-only)		
		Heavy goods	300										BET, FCET (hybrid), FCET (H_2-only)
			400									FCET (hybrid), FCET (H_2-only)	BET
			500								FCET (hybrid)	FCET (H_2-only)	BET
18-t straight truck	UD	Light goods	200		BET								FCET (hybrid), FCET (H_2-only)
			300		BET						FCET (hybrid), FCET (H_2-only)		
		Heavy goods	200				BET				FCET (hybrid)	FCET (H_2-only)	
			300				BET		FCET (hybrid)	FCET (H_2-only)			
	RD	Light goods	300									FCET (hybrid), FCET (H_2-only)	BET
			400								FCET (hybrid), FCET (H_2-only)	BET	
			500							FCET (hybrid)	FCET (H_2-only)	BET	
		Heavy goods	300								FCET (hybrid), FCET (H_2-only)		BET
			400							FCET (hybrid), FCET (H_2-only)			BET
			500						FCET (hybrid)	FCET (H_2-only)			BET
31-t dump truck	UD	Heavy goods	200								BET		FCET (hybrid), FCET (H_2-only)
			300								FCET (hybrid)	BET, FCET (H_2-only)	
42-t tractor trailer	PO_TRIP	Light goods	200	BET									
			300	BET									
	PO_DVKT		200	BET				FCET (hybrid)	FCET (H_2-only)				
			300	BET			FCET (hybrid)	FCET (H_2-only)					
	DDC_TRIP		200										BET
			300				BET						
			400	BET									
			500				BET						
	DDC_DVKT		200										BET, FCET (hybrid), FCET (H_2-only)
			300									FCET (hybrid), FCET (H_2-only)	BET
			400								FCET (hybrid), FCET (H_2-only)		BET
			500							FCET (hybrid)	FCET (H_2-only)		BET
	UD		200			BET					FCET (hybrid)	FCET (H_2-only)	
			300		BET					FCET (hybrid), FCET (H_2-only)			
	RD		300									FCET (hybrid), FCET (H_2-only)	BET
			400								FCET (hybrid), FCET (H_2-only)		BET
			500							FCET (hybrid)	FCET (H_2-only)		BET

Note: This study assumes that the useful life of the 31-t dump truck is five years and that of other vehicle segments are six years based on Pers. Comm. (2023a).

Abbreviations: TCO=total cost of ownership; BET=battery electric truck; FCET=fuel cell electric truck; ICEV=internal combustion engine vehicle; H_2-only=hydrogen-only mode; hybrid=hybrid mode; VKT=vehicle kilometers traveled; UD=urban delivery; RD=regional delivery; PO_TRIP=port operation (using the trip distance method); PO_DVKT=port operation (using the daily VKT method); DDC_TRIP=drayage duty cycle (using the trip distance method); DDC_DVKT=drayage duty cycle (using the daily VKT method).

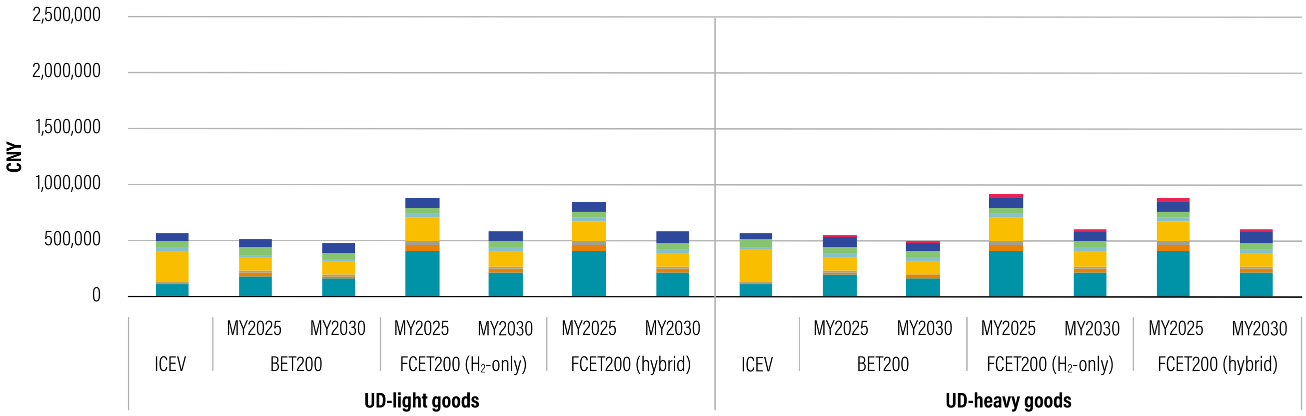
Source: WRI authors' calculation.

Figure 17 | **TCO breakdowns of battery-electric and FC- LDTs, straight truck, dump truck, and tractor trailer in different use cases in MY2025 and MY2030**

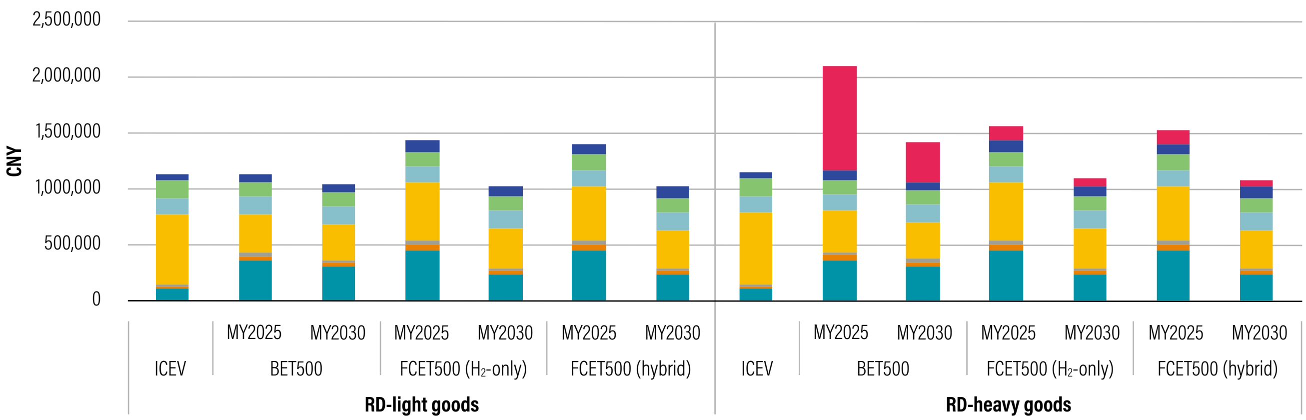
Vehicle   Financing   Tax   Energy   Road charge   Maintenance   Insurance   Payload

1). 4.5-t LDT

a. UD (daily VKT=200 km)



b. RD (daily VKT=500 km)



2) 18-t straight truck

a. UD (daily VKT=200 km)

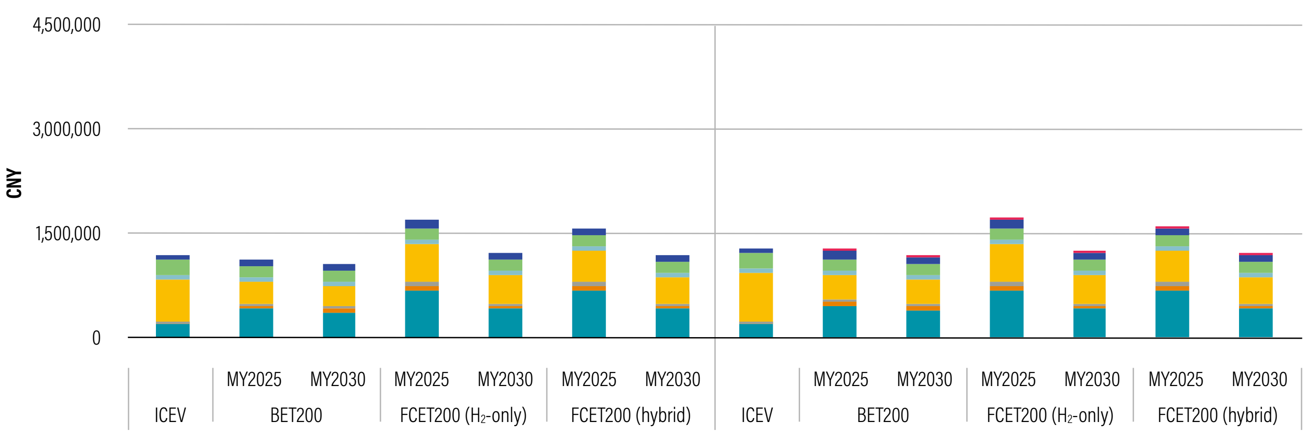
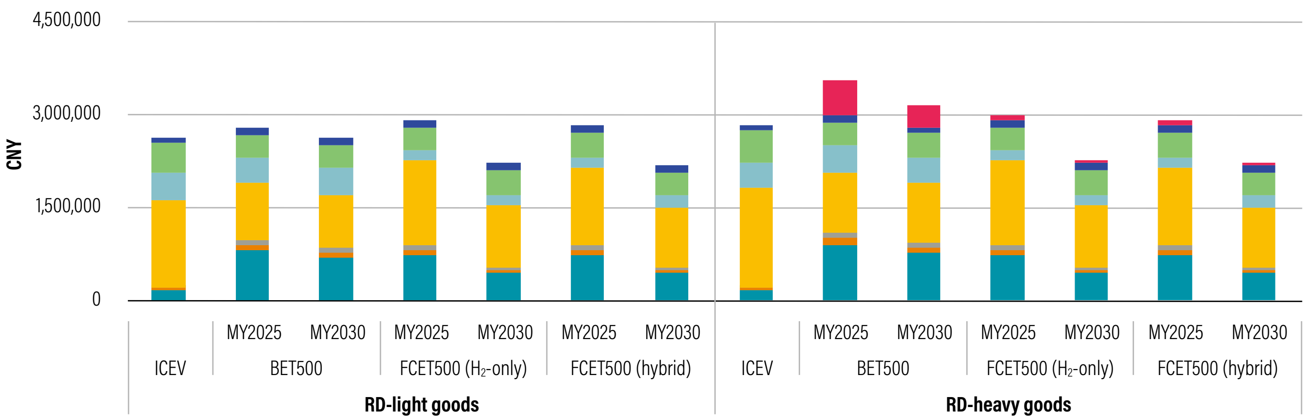


Figure 17 | **TCO breakdowns of battery-electric and FC- LDTs, straight truck, dump truck, and tractor trailer in different use cases in MY2025 and MY2030 (cont.)**

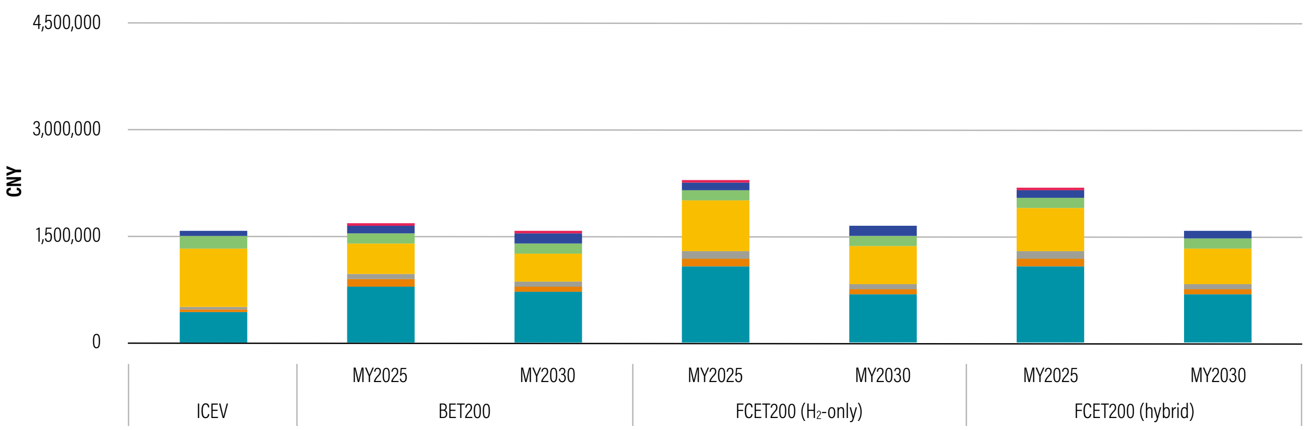
Vehicle | Financing | Tax | Energy | Road charge | Maintenance | Insurance | Payload

b. RD (daily VKT=500 km)



3) 31-t dump truck

a. UD (daily VKT=200 km)



4) 42-t tractor trailer

a. PO_TRIP (daily VKT=200 km), UD (daily VKT=200 km), and DDC_TRIP (daily VKT= 400 km)

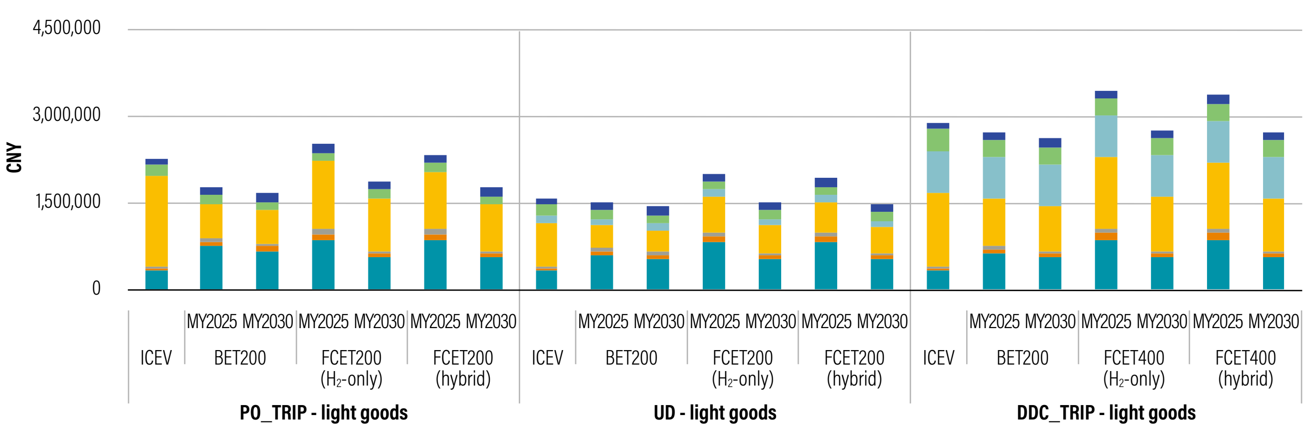
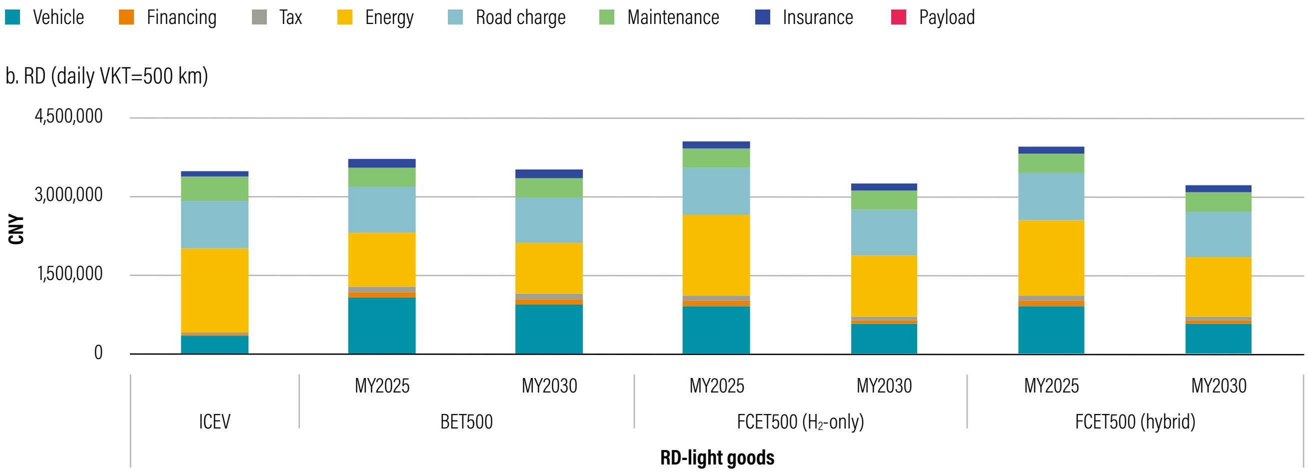


Figure 17 | **TCO breakdowns of battery-electric and FC- LDTs, straight truck, dump truck, and tractor trailer in different use cases in MY2025 and MY2030 (cont.)**



Notes: This study assumes that the useful life of the 31-t dump truck is five years and that of other vehicle segments is six years (Pers. Comm. 2023a).

Abbreviations: TCO=total cost of ownership; BET=battery electric truck; FCET=fuel cell electric truck; ICEV=internal combustion engine vehicle; H_2-only=hydrogen-only mode; hybrid=hybrid mode. UD=urban delivery; RD=regional delivery; PO_TRIP=port operation (using the "trip distance" method); DDC_TRIP=drayage duty cycle (using the "trip distance" method).

Source: WRI authors' calculation.

TCO parity years between ZETs and ICEVs are sensitive to energy efficiency and energy prices

Because energy cost savings are one major contributor for ZETs to achieve TCO parity early (particularly for light good transportation, energy cost savings contribute to 18–53 percent of ZETs' TCO reduction), the relative energy efficiency of ZETs to ICEVs (that is, EER) and energy prices per each unit of energy consumed (including diesel prices, charging costs, and hydrogen prices) will affect when ZETs would reach parity with ICEVs.

Using 42-t tractor trailers (light goods transportation) as an example, we calculated TCO gaps between ZETs and ICEVs resulting from different EERs and explored the relationship with EER and TCO gaps (and parity years). The method can also reveal the sensitivity of ZET TCO gaps (and parity years) to energy efficiency, considering that ZETs' energy efficiency varies greatly by driving cycles and technology improvements (Al-Wreikat, Serrano, and Sodré 2021). For simplicity, the TCO of FCETs in the hydrogen-only mode was used.

The results show that ZETs tend to reach TCO parity earlier when EER is higher:

- For BETs, in the use cases where EER value is high—that is ZETs are more efficient, such as PO (EER=4.0) and UD (EER=3.0)—BETs reach TCO parity earlier (MY2022–2024) than in other use cases, such as RD. This is because BETs are comparatively more efficient in PO and UD where they can take advantage of frequent stop-and-goes to recoup energies from regenerative braking, but ICEVs' fuel consumption is the highest in the very drive cycle. On the other hand, in RD, diesel trucks are typically more efficient during sustained high-speed highway driving when they can stay closer to the optimal engine speed, while battery-electric tractor trailers are less efficient (CARB 2018). In this case, the EER value is low (2.4), and BETs will achieve cost parity at a much later time (after MY2030).

- A similar trend is observed for FCETs. FC tractor trailers achieve TCO parity relative to their diesel counterparts earlier (MY2026–2027) in PO than they are in UD and RD (MY2028–2030), since the EER value is higher (EER=1.7) in PO than it is in UD and RD (EER=1.3-1.5).[16]

Figure 18 | Relationship between EERs and TCO gaps of ZETs and ICEVs in MY2025: An example of a 42-t tractor trailer

a. Battery-electric 42-t tractor trailer

EER ⩾ 2.7 PO_DVKT UD RD

L/100km \ kWh/100km	100	110	120	130	140	150	160	170
70	-1,547,846	-1,448,701	-1,349,556	-1,250,412	-1,151,267	-1,052,122	-952,978	-853,833
65	-1,368,314	-1,269,169	-1,170,025	-1,070,880	-971,735	-872,591	-773,446	-674,301
60	-1,188,782	-1,089,637	-990,493	-891,348	-792,204	-693,059	-593,914	-494,770
55	-1,009,250	-910,106	-810,961	-711,816	-612,672	-513,527	-414,383	-315,238
50	-829,719	-730,574	-631,429	-532,285	-433,140	-333,995	-234,851	-135,706
45	-650,187	-551,042	-451,898	-352,753	-253,608	-154,464	-55,319	43,826
40	-470,655	-371,511	-272,366	-173,221	-74,077	25,068	124,213	223,357
35	-291,124	-191,979	-92,834	6,310	105,455	204,600	303,744	402,889
30	-111,592	-12,447	86,697	185,842	284,987	384,131	483,276	582,421
25	67,940	167,085	266,229	365,374	464,518	563,663	662,808	761,952

b. Fuel cell 42-t tractor trailer

EER ⩾ 1.8 PO_DVKT UD RD

L/100km \ kg/100km	5	6	7	8	9	10	11	12
70	-1,190,355	-1,023,656	-856,958	-690,260	-523,562	-356,863	-190,165	-23,467
65	-1,010,823	-844,125	-677,426	-510,728	-344,030	-177,332	-10,633	156,065
60	-831,291	-664,593	-497,895	-331,196	-164,498	2,200	168,898	335,597
55	-651,759	-485,061	-318,363	-151,665	15,034	181,732	348,430	515,128
50	-472,228	-305,529	-138,831	27,867	194,565	361,264	527,962	694,660
45	-292,696	-125,998	40,701	207,399	374,097	540,795	707,494	874,192
40	-113,164	53,534	220,232	386,931	553,629	720,327	887,025	1,053,723
35	66,368	233,066	399,764	566,462	733,160	899,859	1,066,557	1,233,255
30	245,899	412,597	579,296	745,994	912,692	1,079,390	1,246,089	1,412,787
25	425,431	592,129	758,827	925,526	1,092,224	1,258,922	1,425,620	1,592,319

Notes: We assume that the daily VKTs across all use cases in the chart are 300 km. The useful life of tractor trailer is six years (Pers. Comm. 2023a). The TCO of FCETs reflects the hydrogen-only mode.

Abbreviations: EER=energy efficiency ratio; UD=urban delivery; RD=regional delivery; PO_DVKT=port operation (using the "daily VKT" method); TCO=total cost of ownership.

Source: WRI authors' calculation.

We then calculated the sensitivity to different energy prices (including diesel prices, charging costs, and hydrogen prices) of TCO gaps and parity years between ZETs and ICEVs. The previous analysis assumes that future electricity and diesel prices will remain fixed to 2022 average levels, and green hydrogen prices will drop to 30 CNY/kg by 2030. However, due to demand and supply fluctuations (Ma et al. 2022), increases in infrastructure investments with widespread adoption of rapid chargers (IEA n.d.), and changes in utilization rates of infrastructure (He 2021), energy prices are volatile.

Our analysis shows that changes in energy prices will affect ZETs' parity years with diesel trucks in some use cases.

For BETs, under the current diesel prices, the breakeven charging costs in MY2025 range from 1.3 CNY/kWh to above 1.8 CNY/kWh in the use cases where BETs are the lowest-cost option such as PO, UD, and DDC. If diesel prices drop from the current 8.1 CNY/L to 6.5 CNY/L—2019 and 2021's average prices (Eastmoney 2022)—charging costs should decline substantially to 0.9 CNY/kWh-1.5 CNY/kWh for BETs in the previously mentioned use cases to reach TCO parity before MY2025 (Figure 19). However, if diesel prices drop from the current 8.1 CNY/L to 6.5 CNY/L, and charging costs rise from 1.2 CNY/kWh to 1.4 CNY/kWh, BETs will achieve TCO parity with diesel trucks at a much later time for 42-t tractor trailers in DDC_TRIP (parity year=~MY2030) and 18-t straight trucks in UD with light goods transportation (parity year=~MY2030).

For FCETs, under current diesel prices, the breakeven green hydrogen prices in MY2030 vary by use case from below 20 CNY/kg to 40 CNY/kg (Figure 20). However, in the use cases where FC trucks are the lowest cost option such as RD, breakeven green hydrogen prices are expected to be around 30 CNY/kg. If diesel prices drop to 2020's average level of 6.5 CNY/L, FCETs will achieve TCO parity with diesel trucks before MY2030 only when hydrogen prices decline to 20 CNY/kg-25 CNY/kg.

Figure 19 | **BETs' TCO parity years relative to ICEVs with different diesel prices and charging costs in selected use cases**

a. 42-t tractor trailer in PO_TRIP (daily VKT=200 km)

Diesel price (CNY/L) \ Electricity price (CNY/kWh)	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8
9.00	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022
8.75	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022
8.50	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022
8.25	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022
8.00	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022
7.75	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2023
7.50	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2023	2024
7.25	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2023	2024	2025
7.00	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2023	2024	2025	2026
6.75	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2023	2024	2025	2026	2028
6.50	2022	2022	2022	2022	2022	2022	2022	2022	2022	2023	2024	2025	2026	2028	2030
6.25	2022	2022	2022	2022	2022	2022	2022	2022	2023	2024	2025	2026	2028	2030	>2030
6.00	2022	2022	2022	2022	2022	2022	2022	2023	2024	2025	2026	2028	2030	>2030	>2030
5.75	2022	2022	2022	2022	2022	2022	2023	2024	2025	2026	2028	2030	>2030	>2030	>2030
5.50	2022	2022	2022	2022	2022	2023	2024	2025	2026	2028	2030	>2030	>2030	>2030	>2030
5.25	2022	2022	2022	2022	2023	2024	2025	2026	2028	2030	>2030	>2030	>2030	>2030	>2030
5.00	2022	2022	2022	2023	2024	2025	2026	2028	2030	>2030	>2030	>2030	>2030	>2030	>2030

Electricity price (CNY/kWh)

Figure 19 | BETs' TCO parity years relative to ICEVs with different diesel prices and charging costs in selected use cases (cont.)

b. 42-t tractor trailer in DDC_TRIP (daily VKT=400 km)

Diesel price (CNY/L)	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8
9.00	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2023	2024	2026	2029
8.75	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2024	2025	2028	>2030
8.50	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2023	2025	2027	2030	>2030
8.25	2022	2022	2022	2022	2022	2022	2022	2022	2022	2023	2024	2026	2028	>2030	>2030
8.00	2022	2022	2022	2022	2022	2022	2022	2022	2022	2023	2025	2027	2030	>2030	>2030
7.75	2022	2022	2022	2022	2022	2022	2022	2022	2023	2024	2026	>2030	>2030	>2030	>2030
7.50	2022	2022	2022	2022	2022	2022	2022	2022	2024	2025	2028	>2030	>2030	>2030	>2030
7.25	2022	2022	2022	2022	2022	2022	2022	2023	2024	2027	2030	>2030	>2030	>2030	>2030
7.00	2022	2022	2022	2022	2022	2022	2022	2024	2026	2028	>2030	>2030	>2030	>2030	>2030
6.75	2022	2022	2022	2022	2022	2022	2023	2025	2027	2030	>2030	>2030	>2030	>2030	>2030
6.50	2022	2022	2022	2022	2022	2023	2024	2026	2029	>2030	>2030	>2030	>2030	>2030	>2030
6.25	2022	2022	2022	2022	2022	2023	2025	2028	>2030	>2030	>2030	>2030	>2030	>2030	>2030
6.00	2022	2022	2022	2022	2023	2024	2026	2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
5.75	2022	2022	2022	2022	2024	2025	2028	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
5.50	2022	2022	2022	2023	2025	2027	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
5.25	2022	2022	2022	2024	2026	2029	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
5.00	2022	2022	2023	2025	2028	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030

Electricity price (CNY/kWh)

c. 18-t straight truck in UD (daily VKT=200 km; light goods transportation)

Diesel price (CNY/L)	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8
9.00	2022	2022	2022	2022	2022	2022	2022	2022	2022	2022	2023	2024	2025	2026	2027
8.75	2022	2022	2022	2022	2022	2022	2022	2022	2022	2023	2023	2024	2025	2027	2029
8.50	2022	2022	2022	2022	2022	2022	2022	2022	2023	2023	2024	2025	2026	2028	2030
8.25	2022	2022	2022	2022	2022	2022	2022	2022	2023	2024	2025	2026	2028	2030	>2030
8.00	2022	2022	2022	2022	2022	2022	2022	2023	2024	2025	2026	2027	2029	>2030	>2030
7.75	2022	2022	2022	2022	2022	2022	2023	2023	2024	2025	2027	2029	>2030	>2030	>2030
7.50	2022	2022	2022	2022	2022	2023	2023	2024	2025	2026	2028	2030	>2030	>2030	>2030
7.25	2022	2022	2022	2022	2022	2023	2024	2025	2026	2028	2030	>2030	>2030	>2030	>2030
7.00	2022	2022	2022	2022	2023	2024	2024	2026	2027	2029	>2030	>2030	>2030	>2030	>2030
6.75	2022	2022	2022	2023	2023	2024	2025	2027	2029	>2030	>2030	>2030	>2030	>2030	>2030
6.50	2022	2022	2022	2023	2024	2025	2026	2028	>2030	>2030	>2030	>2030	>2030	>2030	>2030
6.25	2022	2022	2023	2024	2025	2026	2028	2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
6.00	2022	2023	2023	2024	2026	2027	2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
5.75	2023	2023	2024	2025	2027	2029	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
5.50	2023	2024	2025	2026	2028	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
5.25	2024	2025	2026	2028	2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
5.00	2024	2026	2027	2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030

Electricity price (CNY/kWh)

Notes: This study assumes that the useful life of tractor trailers and straight trucks is six years (Pers. Comm. 2023a). Green denotes ZETs' parity year relative to ICEVs in 2022; yellow and orange in 2023–2029; and red in 2030 or later.

Abbreviations: TCO=total cost of ownership; BET=battery electric truck; ICEV=internal combustion engine vehicle; UD=urban delivery; PO_TRIP=port operation (using the "trip distance" method); DDC_TRIP=drayage duty cycle (using the "trip distance" method).

Source: WRI authors' calculation.

Figure 20 | **FCETs' TCO parity years relative to ICEVs with different diesel prices and hydrogen prices in selected use cases**

a. 4.5-t LDT in RD (daily VKT=500 km; heavy goods transportation)

Diesel price (CNY/L)									
9.00	2027	2028	2029	2030	>2030	>2030	>2030	>2030	>2030
8.75	2027	2028	2029	>2030	>2030	>2030	>2030	>2030	>2030
8.50	2027	2028	2030	>2030	>2030	>2030	>2030	>2030	>2030
8.25	2027	2029	2030	>2030	>2030	>2030	>2030	>2030	>2030
8.00	2028	2029	2030	>2030	>2030	>2030	>2030	>2030	>2030
7.75	2028	2029	>2030	>2030	>2030	>2030	>2030	>2030	>2030
7.50	2028	2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
7.25	2029	2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
7.00	2029	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
6.75	2029	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
6.50	2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
6.25	2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
6.00	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
5.75	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
5.50	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
5.25	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
5.00	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
	20	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**

Hydrogen price (CNY/kg)

b. 42-t tractor trailer in RD (daily VKT=500 km)

Diesel price (CNY/L)									
9.00	2024	2025	2027	2030	>2030	>2030	>2030	>2030	>2030
8.75	2024	2026	2028	2030	>2030	>2030	>2030	>2030	>2030
8.50	2024	2026	2028	>2030	>2030	>2030	>2030	>2030	>2030
8.25	2025	2026	2029	>2030	>2030	>2030	>2030	>2030	>2030
8.00	2025	2027	2029	>2030	>2030	>2030	>2030	>2030	>2030
7.75	2025	2027	2030	>2030	>2030	>2030	>2030	>2030	>2030
7.50	2026	2028	>2030	>2030	>2030	>2030	>2030	>2030	>2030
7.25	2026	2028	>2030	>2030	>2030	>2030	>2030	>2030	>2030
7.00	2027	2029	>2030	>2030	>2030	>2030	>2030	>2030	>2030
6.75	2027	2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
6.50	2028	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
6.25	2028	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
6.00	2029	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
5.75	2029	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
5.50	2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
5.25	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
5.00	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
	20	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**

Hydrogen price (CNY/kg)

Figure 20 | **FCETs' TCO parity years relative to ICEVs with different diesel prices and hydrogen prices in selected use cases (cont.)**

c. 18-t straight truck in RD (daily VKT=500 km; heavy goods transportation)

Diesel price (CNY/L) \ Hydrogen price (CNY/kg)	20	25	30	35	40	45	50	55	60
9.00	2024	2025	2026	2028	>2030	>2030	>2030	>2030	>2030
8.75	2024	2025	2027	2029	>2030	>2030	>2030	>2030	>2030
8.50	2024	2025	2027	2029	>2030	>2030	>2030	>2030	>2030
8.25	2024	2026	2028	2030	>2030	>2030	>2030	>2030	>2030
8.00	2025	2026	2028	>2030	>2030	>2030	>2030	>2030	>2030
7.75	2025	2027	2029	>2030	>2030	>2030	>2030	>2030	>2030
7.50	2025	2027	2029	>2030	>2030	>2030	>2030	>2030	>2030
7.25	2026	2027	2030	>2030	>2030	>2030	>2030	>2030	>2030
7.00	2026	2028	>2030	>2030	>2030	>2030	>2030	>2030	>2030
6.75	2026	2029	>2030	>2030	>2030	>2030	>2030	>2030	>2030
6.50	2027	2029	>2030	>2030	>2030	>2030	>2030	>2030	>2030
6.25	2027	2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
6.00	2028	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
5.75	2029	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
5.50	2029	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
5.25	2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030
5.00	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030	>2030

Notes: This study assumes that the useful life of tractor trailers and straight trucks is six years (Pers. Comm. 2023a). The TCO of FCETs reflects the hydrogen-only mode. Unlike the previous analysis, for simplicity of the sensitivity analysis, prices of green hydrogen are fixed throughout the FCETs' useful life. Green denotes ZETs' parity year relative to ICEVs in 2024–2026; yellow and orange in 2027–2029; and red in 2030 or later.

Abbreviations: TCO=total cost of ownership; FCET=fuel cell electric truck; ICEV=internal combustion engine vehicle; RD= regional delivery.

Source: WRI authors' calculation.

Operational optimization and technology leapfrogs are essential for ZETs to achieve TCO parity early

Without policy incentives, the driving forces for the decline in TCO could be attributed to operational optimization and technology advances.

First, optimization measures taken by fleet operators, including matching BET configurations with charging facility availability and improving operational efficiency, are important for ZETs to reach TCO parity relative to diesel trucks early.

Our analysis shows that choosing BETs with smaller batteries, ensuring that charging facilities are sufficiently available, and adjusting operation schedules to allow BETs more than one charge a day are important in reducing BETs' TCO. This is especially the case for the PO and DDC use cases. For example, in DDC, if fleet operators choose a 288-kWh MY2025 battery-electric tractor trailer with a 200 km range (BET200) to perform 200–500 km daily VKTs, the BET200's vehicle price would be 300,000–440,000 CNY lower than the BET400 or BET500's price (with 576–720 kWh battery capacities). Therefore, BET200 is likely to reach TCO parity with diesel trucks earlier (parity year=MY2022–2025) than BET400 or BET500 (parity year=after MY2030).

In this case, rapid charging at customer locations (or employing the battery-swapping model) is necessary. Although frequent high-power charging of BETs (two to three charges per day) would lead to costly midlife battery replacement and increased energy costs (for BETs to charge at peak hours and higher power rates), these expenses will be offset by cheaper BET prices as a result of small battery capacities (Figure 21). To make this type of operation a reality, it is crucial to have: (1) broad availability of (ultra)-

fast charging facilities, parking spaces, and grid capacities at customer locations (Kotz et al. 2022) and (2) BETs operation schedules that allow for sufficient charging time windows—for example, timing charging with loading (or unloading) of trucks or break times of drivers.

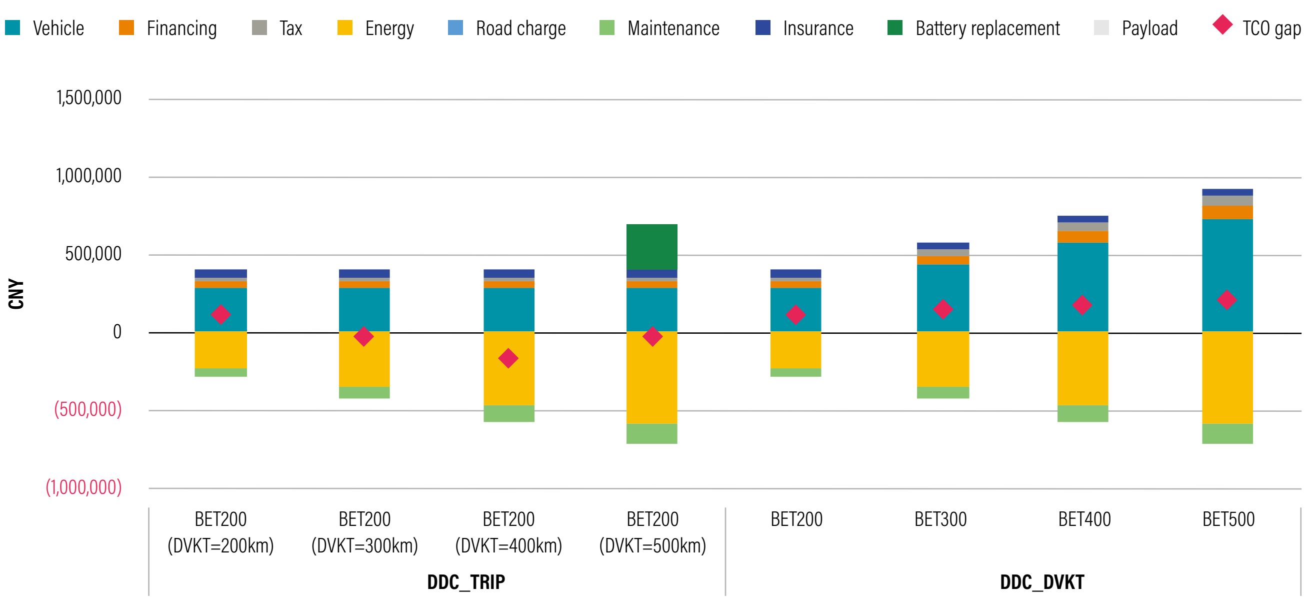
The other important operational aspect is operational efficiency improvement. Because BETs' energy costs are lower than ICEVs, the longer daily VKTs of BETs, the fewer TCO gaps between BETs and ICEVs. This explains why in DDC_TRIP with a 200-km daily VKT, the TCO of a battery-electric 42-t tractor trailer is still 100,000 CNY and 20,000 CNY higher than the diesel equivalent in MY2025 and MY2030, respectively.

Trucks often do not have sufficiently long daily VKTs because of inefficient operation by fleet operators or excessive supply of truck capacity resulting from soft demand or large public subsidies (Pers. Comm. 2023a). To enhance vehicle utilization and avoid market oversupply, fleet operators should optimize fleet asset management, route planning, and dispatch operations (Mišić et al. 2022), while governments should refrain from using large amounts of purchase subsidies to boost ZEV supplies.

Second, accelerating technology developments in key ZET components is essential to reduce ZETs' TCO and move its parity years to an earlier date. The following analysis shows the modelled percentage reduction in TCO from MY2022 through MY2030 due to technology improvements (Figure 22) with the results as follows:

For BETs, the largest TCO reduction comes from: (1) a drop in battery costs; (2) improvements in vehicle energy efficiency (like using more efficient thermal management, active aerodynamic, low rolling resistance tires, and light weighting) (National Petroleum Council 2012; Yang 2018); and (3) the reduction of payload losses from battery energy density improvement, better integration of powertrain components, and the usage of lightweight structural materials (EUCAR 2019).

Figure 21 | **TCO gaps between BETs and ICEVs for 42-t tractor trailers in the DDC_TRIP and DDC_DVKT in MY2025**



Notes: Abbreviations: TCO=total cost of ownership; BET=battery electric truck; ICEV=internal combustion engine vehicle; DDC_TRIP=drayage duty cycle (using the "trip distance" method); DDC_DVKT=drayage duty cycle (using the "daily VKT" method); DVKT=daily vehicle kilometer traveled..

Source: WRI authors' calculation.

Technology contributors to BETs' TCO reduction vary by use case, particularly with the type of cargo transported. For example, for light goods transportation, battery costs and energy efficiency are determining factors, contributing to a 46–65 percent and 18–42 percent BETs' TCO reduction during MY2022 and MY2030, respectively. However, for heavy goods transportation, battery energy density improvement is more significant, responsible for 12 to 78 percent of BETs' TCO reduction. Because in the real world small fleet operators transport assorted cargos, battery costs, energy efficiency, and battery energy density all play integral roles when it comes to technology-driven cost reduction.

For FCETs, the largest TCO reduction is attributed to the cost reduction of the FC systems and the decline of green hydrogen prices (due to the lower cost of renewable energy and more efficient and cost-effective electrolyzers (IRENA 2020). Technology contributors to FCETs' TCO reduction also vary significantly by use case. For UD, fuel cell system cost is the most influential parameter, accounting for 50–70 percent of FCETs' TCO reduction during MY2022 and MY2030; whereas for RD, hydrogen prices will play a more important role, contributing to 16–40 percent of FCETs' TCO reduction, and the cost-reduction contribution of hydrogen prices grows as FCETs' daily VKTs increase.

Figure 22 | **Contributions of technology improvements to ZET TCO reduction between MY2022 and MY2030 in selected use cases**

a. BET

VEHICLE	CARGO TYPE	TECHNOLOGY IMPROVEMENTS	UD		RD		DDC_TRIP	
			200 km	300 km	300 km	500 km	200 km	500 km
4.5-t LDT	Light goods	Battery cost (CNY/kWh)	46%	48%	49%	51%	N.A.	
		E-drive cost (CNY/kW)	17%	12%	11%	7%		
		Energy efficiency (kWh/100km)	37%	40%	40%	42%		
	Heavy goods	Battery cost (CNY/kWh)	29%	21%	17%	1%	N.A.	
		E-drive cost (CNY/kW)	10%	5%	4%	0%		
		Energy efficiency (kWh/100km)	28%	23%	20%	9%		
		Battery energy density (Wh/kg)	24%	40%	47%	78%		
		Lightweighting	10%	12%	12%	12%		
18-t straight truck	Light goods	Battery cost (CNY/kWh)	56%	60%	62%	65%	N.A.	
		E-drive cost (CNY/kW)	22%	16%	14%	9%		
		Energy efficiency (kWh/100km)	22%	24%	24%	26%		
	Heavy goods	Battery cost (CNY/kWh)	42%	39%	36%	24%	N.A.	
		E-drive cost (CNY/kW)	14%	9%	7%	3%		
		Energy efficiency (kWh/100km)	18%	18%	16%	13%		
		Battery energy density (Wh/kg)	12%	20%	25%	43%		
		Lightweighting	13%	14%	16%	17%		
42-t tractor trailer	Light goods	Battery cost (CNY/kWh)	54%	60%	58%	63%	53%	58%
		E-drive cost (CNY/kW)	28%	20%	19%	12%	26%	15%
		Energy efficiency (kWh/100km)	18%	20%	23%	25%	21%	27%

Figure 22 | **Contributions of technology improvements to ZET TCO reduction between MY2022 and MY2030 in selected use cases (cont.)**

b. FCET

VEHICLE	CARGO TYPE	TECHNOLOGY IMPROVEMENTS	UD 200 km	RD 500 km
4.5-t LDT	Light goods	FC system cost (CNY/kW)	70%	51%
		Hydrogen storage cost (CNY/kg)	3%	6%
		Battery cost (CNY/kWh)	2%	1%
		E-drive cost (CNY/kW)	2%	2%
		Energy efficiency (kg/100km)	9%	16%
		Hydrogen fuel price (CNY/kg)	14%	24%
	Heavy goods	FC system cost (CNY/kW)	58%	33%
		Hydrogen storage cost (CNY/kg)	3%	4%
		Battery cost (CNY/kWh)	2%	1%
		E-drive cost (CNY/kW)	2%	1%
		Energy efficiency (kg/100km)	10%	16%
		Hydrogen fuel price (CNY/kg)	15%	25%
		Hydrogen storage gravimetric capacity (wt%)	1%	4%
		FC system specific power (W/kg)	1%	2%
		Battery energy density (Wh/kg)	1%	2%
		Lightweighting	7%	12%
18-t straight truck	Light goods	FC system cost (CNY/kW)	55%	35%
		Hydrogen storage cost (CNY/kg)	5%	8%
		Battery cost (CNY/kWh)	4%	3%
		E-drive cost (CNY/kW)	4%	2%
		Energy efficiency (kg/100km)	8%	12%
		Hydrogen fuel price (CNY/kg)	25%	39%
	Heavy goods	FC system cost (CNY/kW)	50%	30%
		Hydrogen storage cost (CNY/kg)	5%	7%
		Battery cost (CNY/kWh)	4%	2%
		E-drive cost (CNY/kW)	3%	2%
		Energy efficiency (kg/100km)	8%	12%
		Hydrogen fuel price (CNY/kg)	25%	38%
		Hydrogen storage gravimetric capacity (wt%)	1%	2%
		FC system specific power (W/kg)	0%	0%
		Battery energy density (Wh/kg)	1%	2%
		Lightweighting	3%	5%
42-t tractor trailer	Light goods	FC system cost (CNY/kW)	53%	33%
		Hydrogen storage cost (CNY/kg)	6%	9%
		Battery cost (CNY/kWh)	4%	2%
		E-drive cost (CNY/kW)	5%	3%
		Energy efficiency (kg/100km)	8%	13%
		Hydrogen fuel price (CNY/kg)	25%	40%

Note: The text highlighted in blue denotes the technical parameters that are included in "reduction of payload losses."

Abbreviations: BET=battery electric truck; FCET=fuel cell electric truck; ICEV=internal combustion engine vehicle; UD=urban delivery; N.A.=not applicable.

Source: WRI authors' calculation.

BETs' TCO parity is likely to be advanced to MY2022-2025 with a suite of ZET incentives

Apart from operation and technology improvements, policy incentives are important to reduce ZETs' TCO. Based on literature review (C40 2020; Concept Consulting Group 2022; WEF 2021), this study enumerates policies at the disposal of national and local governments to accelerate the deployment of ZETs, including financial incentives, regulations, and infrastructure safeguards.

We choose to focus on eight types of policies the impacts of which on TCO can be quantified under this study's TCO methodology framework. The eight policies were formulated in the China (and Guangdong)'s context, with the aim to reduce government expenditure on ZET promotion. The assumptions for the eight policies during 2022 and 2030 are listed as follows:

- **Purchase subsidies:** China has phased out NEVs' purchase subsidies since 2023 and only offered the FCEV City Cluster subsidies in five city clusters (MOF et al. 2020; 2021). This study considers no purchase incentives for BETs during 2022 and 2030. Considering that the TCO of FCETs remains high, we assume future Guangdong City Cluster's FCEV purchase subsidies will be reduced to 20 percent of the 2022 level during MY2022 and MY2030. Based on the projected power ratings of the FC systems (see the section, "Results from MY2022 to MY2030"), FCETs will receive 50,400–90,000 CNY purchase subsidies per vehicle, representing 11–22 percent of FCETs' purchase costs in MY2030.

- **Tax benefits:** At present, diesel trucks in China are subject to a purchase tax (10 percent tax rate) and an ownership tax (tax rates vary by city). However, ZETs are exempted from the purchase tax until the end of 2025 and will receive a 50 percent tax waiver during 2026 and 2027, and the ownership tax will continue to be fully waived (MOF et al. 2018; 2023). This study assumes that both taxes will be fully waived for ZETs from 2026 onward.

- **Incentives on alternative fuels and charging or refueling infrastructure expansion:** Currently, China has waived demand charges for ZET charging and offered various subsidies on energy prices and the construction and operation of charging or refueling infrastructure. For example, Fujian and Jiangsu provinces provided 0.1–0.3 CNY/kWh subsidies for ZETs that charge on public chargers, and the City of Foshan offers 18 CNY/kg subsidies on hydrogen prices (Changzhou Government 2024; Foshan Nanhai Government 2022; Fujian DRC et al. 2022). Henan Province offered grants to cover 40 percent of charging equipment capital investments for public charging stations (Henan Government 2020). This study assumes that in addition to waiving demand charges, local governments will offer 0.1 CNY/kWh incentives on BETs charging. Further, 1 to 20 CNY/kg incentives on green hydrogen are also considered in this study to keep the prices of green hydrogen within 30 CNY/kg during 2023 and 2030—a target set by the Guangdong FCEV City Cluster (Guangdong DRC et al. 2022).

- **Carbon pricing on conventional fuels:** At present, China does not have carbon pricing on transportation fuels. In this study, we assume that a carbon tax will be imposed on tailpipe carbon emissions from diesel trucks. The rate is set at the 2022 average price of the Guangdong Emission Trading Scheme (ETS) (80 CNY/ton CO_2),[17] which is 45 percent higher than the carbon price of China's national ETS in 2022 (Jinan University 2022).

- **Reduction of expressway road tolls:** Distance-based road tolls are common for expressways in China (Guangdong DOT 2020). To incentivize the adoption of ZETs, some regions in China have offered ZETs with reduced toll rates. For example, Gansu Province waived 15 percent tolls for NEVs traveling along expressways within the province; Tianjin went further to exempt 100 percent of road tolls for zero-emission tractor trailers serving Tianjin seaport (i.e., the DDC use case) (Gansu DOT et al. 2021; Tianjin MTC and Tianjin DRC 2021). Considering that road charges are widely used for recovering expressway capital, operation, and maintenance costs in China (Reja et al. 2013), this study assumes only a modest reduction of 15 percent in expressway tolls for ZETs to ensure sustainable financing of highway operation and maintenance.

- **Road access privilege:** To curb traffic congestion, trucks face stringent access restrictions in Chinese cities. For example, in Shenzhen, some expressways ban drayage HDTs, including zero-emission HDTs, from access (see Appendix A). To grant access privilege to ZETs, some cities relax the access restrictions for ZETs while maintaining the restrictions for diesel trucks. This measure would lead to detours of ICE trucks that equate to reduced daily VKTs for ZETs, or longer operating hours and increased earnings for ZETs. To quantify the benefits of the measure, this study takes a simplified approach and only examines the VKTs that were reduced, compared to ICE trucks. Based on our estimation, the relaxation of expressway access for zero-emission drayage trucks in Shenzhen would lead to a 4–6 percent daily VKT reduction, compared to their diesel counterparts. A 5 percent daily VKT reduction is assumed for the following analysis.

- **ZET weight allowance:** The EU's Weights and Dimensions Directive (EU 2019) provides ZETs with an additional weight of 2 tons compared to a reference diesel truck, up to 42-t GVW, and a proposal to grant a 4-ton additional weight allowance is under discussion (Soone 2023). China does not yet have additional weight allowances for ZETs; only a few provinces such as Henan allow trucks, including both ZETs and ICEVs, to be exempt from overloading penalties if exceeding the maximum GVW (or GCW) by 10 percent (Henan People's Congress 2023). Here, we assume that the national government will grant an additional 500-kg weight allowance for LDTs and an additional 2-t allowance for HDTs, provided that the increases in ZETs' GVW will not exceed the vehicles' maximum axle loads.

- **Financing cost reduction:** Financing a truck instead of directly purchasing the vehicle is common in China. The loan interest rates vary with the sizes of fleet operators and their creditworthiness. Large fleet operators have lower annual interest rates (around 4 to 7 percent), while small fleet operators and self-employed individual truck drivers would face higher annual interest rates (7–10 percent) for the three year-loan period (Pers. Comm. 2023b). This study assumes that the national government allows small operators to buy ZETs at the loan prime rate of 4.2 percent (Bank of China n.d.), reduced from 10 percent used in the previous analysis.

Table 12 | **Policy incentives to bridge ZETs and ICEVs' TCO gaps in China's context**

MEASURES			SELECTED GLOBAL CASES	NATIONAL GOVERNMENT	LOCAL GOVERNMENT	INDUSTRY
Supply side	Financial incentives	ZET mandate	▪ **California:** ZEV sales of 40% (tractors), 55% (Class 2b-3 truck), 75% (Class 4-8 straight trucks), and 100% (drayage trucks) by 2035 (CARB 2021b, "Advanced Clean Trucks"; CARB 2023, "Advanced Clean Fleets"). ▪ **EU:** 100% CO_2 emissions reduction for new vans from 2035 onwards (EU 2023b) and proposed targets for new heavy-duty vehicles in 2030 (-45%), 2035 (-65%), and 2040 (-90%) (EU 2023a). ▪ **China:** none for truck segments.	○		
		Research and development	▪ **EU:** Zero Emission Freight EcoSystem in Horizon Europe (ZEFES n.d.). ▪ **China:** National Key R&D Program of China (HTRDC n.d.).	√	√	√

Table 12 | **Policy incentives to bridge ZETs and ICEVs' TCO gaps in China's context (cont.)**

MEASURES			SELECTED GLOBAL CASES	NATIONAL GOVERNMENT	LOCAL GOVERNMENT	INDUSTRY
Demand side	**Financial incentives**	Purchase subsidies (or scrappage scheme)	▪ **California:** up to $200,000 vouchers for terminal tractors (CARB n.d., "Clean Off-Road Equipment Vouchers"). ▪ **Germany:** 80% of the ZET price difference with diesel counterparts (BALM 2022). ▪ **China:** none, except for FCEV subsidies in five FCEV city clusters (MOF et al. 2020; 2021).	√	√	
		Tax benefits	▪ **US:** clean vehicle tax credit of up to $40,000 (USDOT n.d., " Commercial Clean Vehicle Credit"). ▪ **Germany:** non-hybrid electric cars exempt from motor vehicle tax (German Bundestag 2012). ▪ **China:** ZEVs are exempted from the purchase tax until the end of 2025 and will receive a 50% tax waiver during 2026 and 2027; ZETs are exempted from vehicle ownership tax (MOF et al. 2018; 2023).	√		
		Carbon pricing on conventional fuels	▪ **California:** emission-based credit for transportation fuel (CARB n.d., "Low Carbon Fuel Standard"). ▪ **China:** no carbon pricing on conventional fuels.	○	○	
		Reduction of expressways' tolls	▪ **Germany:** ZEVs exempt from tolls. ▪ **China:** Some regions in China have provided ZETs with 15-100% road toll reduction (Gansu DOT et al. 2021; Tianjin MTC and Tianjin DRC 2021).		√	
		Innovative business model	▪ **Industry:** Lease of battery electric trucks in U.S. (Penske 2023) and a pay-per-use model to rent hydrogen fuel cell trucks in Switzerland and Germany (Hyundai n.d.; Shell Corporation 2023). ▪ **China:** The national government rolled out the "NEV Battery Swapping Mode Application and Demonstration" program (MIIT 2021).	√	√	√
		Operational efficiency improvements	▪ **Industry:** delivery route optimization for Électricité de France (AnyLogic n.d.).			√
		Residual value guarantee	▪ **US:** Used clean vehicles can receive 30% of the sale price up to $4,000 (USDOT n.d., "Used Clean Vehicle Credit") ▪ **Industry (China):** DST Electric Vehicle Rental provided residual value guarantees for certain ZET models (Evpartner 2023).	○	○	√
		Financing cost reduction	▪ **California:** Access to low-cost capital through loan loss reserve for small businesses (CARB n.d., "Zero-Emission Truck Loan Pilot Project").	○	○	

Table 12 | **Policy incentives to bridge ZETs and ICEVs' TCO gaps in China's context (cont.)**

MEASURES			SELECTED GLOBAL CASES	NATIONAL GOVERNMENT	LOCAL GOVERNMENT	INDUSTRY
Demand side	Regulations	Road access privilege	▪ **US and EU:** Zero-emission freight zones were introduced in Los Angeles, Santa Monica, Rotterdam, Amsterdam, Oslo, and other cities (Xue et al. 2023). ▪ **China:** Relaxed the road access restrictions for ZETs (Xue et al. 2023).		√	
		ZET weight allowance	▪ **EU:** 2 tons additional weight for ZETs (or GCW) (EU 2019) and proposed 4 tons additional weight for long-haul transportation. ▪ **U.S.:** 2,000 pounds additional weight (California Constitution 2019). ▪ China: None.	○	○	
	Infrastructure safeguards	Incentives to alternative fuels and charging/refueling infrastructure expansion	▪ **US:** grants to deploy charging and fueling infrastructure dedicated to heavy-duty ZEVs along highways (FHWA 2024; USEPA 2022). ▪ **China:** Waived demand charges (State Council 2023); purchase and operation subsidies to charging/refueling infrastructure (Henan Government 2020; Otog Government 2023).	√	√	
		Distribution and consolidation centers	▪ **Rotterdam:** Optimization of the locations of distribution and consolidation centers to improve operational efficiency and reduce emissions (City of Rotterdam 2020). ▪ **China:** Cities such as Foshan and Suzhou planned new logistic hubs in the city centers to improve logistical efficiency (JLL 2021)		√	√

Notes: The table shows the policy-making jurisdictions in China's context. Green indicates that the TCO impacts of the policy incentives were quantitatively evaluated in this study. The letter "○" denotes the policy or measure has not yet been taken by relevant stakeholders in China. "√" denotes the policy or measure has been taken by relevant stakeholders in China.

Sources: WRI authors' summary based on C40 2020; Concept Consulting Group 2022; WEF 2021.

The results:

Comprehensive policy incentives (that is, the previously mentioned eight policies combined) are more effective in bringing forward ZETs' TCO parity years to an earlier date than single measures. These benefits are more significant for BETs. Under the combination of the eight policies, BETs will reach TCO parity with their diesel counterparts in the most-use cases by MY2022–2025, zero to nine years earlier than the case without policy incentives. By contrast, even with greater amounts of subsidies (particularly the purchase subsidy), FCETs will reach TCO parity with diesel counterparts by MY2022–2028, three to six years earlier than the case without policy incentives. Overall, with the eight proposed policy incentives, the TCO parity years of BETs are zero to six years earlier than FCETs in most use cases (except for a 4.5-t BET500 LDT when transporting heavy goods), making BETs the most cost competitive ZET option. For example, without policy incentives, the TCO parity point of FC 18-t straight trucks in RD is earlier than the BET equivalent. However, with the comprehensive policy incentives, the TCO parity point of battery electric 18-t straight trucks in RD is moved to MY2022–2024, surpassing FC 18-t straight trucks' parity point of MY2024–2027.

For BETs, the proposed policies exert varying degrees of impact on BETs' TCO parity years across different use cases. Based on this study's policy assumption, BETs benefit most from tax exemption, electricity incentives, road access privileges, reduction of expressway tolls ZET weight allowances, and reductions on financing costs in reducing the TCO parity years. Nonetheless, the improvement in cost parity is not significant when applying the proposed carbon-pricing measure, because of low carbon prices in Guangdong. Six assumed policies are more influential:

- Tax exemption and electricity incentives for BETs are found to be essential to bridge the TCO gaps between BETs and ICEVs for all use cases. Compared to the case without incentives, BETs' TCO parity point will be reduced by zero to three years with tax exemption or electricity incentives. Tax exemption is particularly useful for battery-electric HDTs, such as 18-t straight trucks (in RD light goods transportation), 31-t dump trucks, and 42-t tractor trailer (in RD). An approximately 100,000 CNY tax deduction per vehicle is sufficient to bridge the TCO gaps and move the TCO parity point of BETs (MY2026–2028) two to three years earlier than the case without incentives.

- Financing cost reductions is particularly effective in reducing TCO parity years in UD, where with the proposed policy, BETs' time to TCO parity will be reduced by zero to two years.

- Road access privileges for BETs are more effective in use cases of long daily VKTs and large shares of operating expenses, such as RD and DDC, because this study assumes that the policy works on VKTs. With road access privileges, the TCO parity years of battery-electric 42-t tractor trailers will be reduced by three years in RD.

- Reduction of expressway tolls is more influential for 42-t tractor trailers operating in RD and DDC because 42-t tractor trailers in the two use cases have large shares of VKTs on expressways and high toll rates. Road charges represent around 18 to 27 percent of battery-electric 42-t tractor trailers' TCO in RD and DDC, making the two use cases most easily affected by the measure of road toll reduction. As a result, the time for battery-electric 42-t tractor trailers to achieve TCO parity is moved zero to four years earlier, compared to the case without incentives.

- ZET weight allowance is useful for heavy goods transportation, reducing the BETs parity points by zero to four years in these use cases. Although the measure fails to move the TCO parity years of some heavy-goods use cases before MY2030 (such as 18-t BET500 straight trucks and 4.5-t BET500 LDTs in RD), it is the most effective approach to TCO reduction for the heavy-goods use cases. For example, with the 2-t weight allowance, the TCO of 18-t BET500 straight trucks will be reduced by about 330,000 CNY, compared with other incentives' 40,000 to 110,000 CNY effects on TCO reduction.

For FCETs, the proposed policies exert similar impacts on FCETs' TCO parity years across all use cases, reducing the FCETs' time to reach TCO parity by only zero to one year in most use cases. However, these policies' impacts on TCO reduction vary by use case, specifically:

- Although BETs are cost competitive without purchase subsidies, the proposed FCET purchase subsidy is found to be one of the most influential policy interventions in reducing TCO in all use cases. The measure is particularly effective in UD, where it leads to the largest TCO reduction. However, due to large TCO gaps between FCETs and ICEVs, this policy's effect on advancing TCO parity years is limited: FCETs' time to TCO parity is only reduced by only zero to two years, achieving TCO parity with the diesel counterparts by MY2026–2030 for all use cases.

- The proposed tax exemption and financing cost reductions are particularly effective to bridge the TCO gaps between FCETs and ICEVs in UD, with their effect on TCO reduction only following the purchase subsidy. However, as daily VKTs increase, both policies become less effective.

- The proposed road access privilege and road toll reduction measures rise to become the most effective policy in long-distance use cases like RD and DDC in reducing TCO, whereas the ZET weight allowance is useful for heavy goods transportation, particularly in RD.

- Although in many use cases, the proposed hydrogen fuel incentive fails to move the TCO parity years earlier, it is the most influential policy in TCO reduction in the early years of FCET adoption. Because this study assumes that the hydrogen incentive will keep at-pump green hydrogen prices no greater than 30 CNY/kg, the benefit of the incentive decreases drastically over time. For example, the incentive for an 18-t FCET500 straight truck in RD will drop from about 100,000 CNY in MY2026 to 0 CNY in MY2030, insufficient to bridge the TCO gaps during the time period. On the other hand, in the early years of FCET adoption (during MY2022–2025), the benefit of the hydrogen fuel incentive is the highest among the eight policies in most use cases (except for 4.5-t LDTs), making the policy most effective in bridging the TCO gaps between FCETs and ICEVs.

- Like BETs, due to the low carbon price adopted in this study, carbon pricing makes a limited contribution to FCETs' TCO reduction.

Figure 23 | **ZET TCO parity relative to ICEVs with policy incentives**

a. 4.5-t LDT

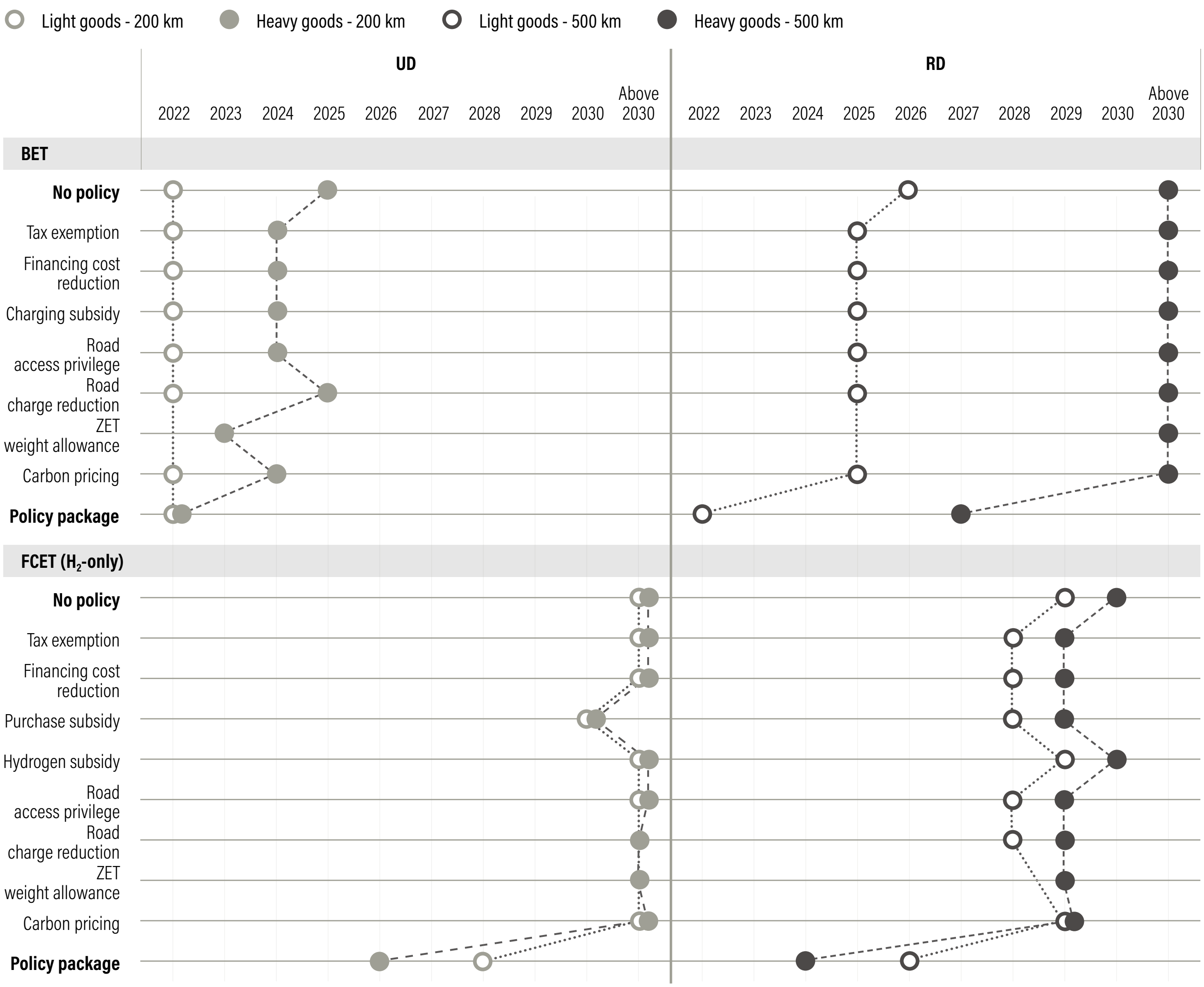


Figure 23 | **ZET TCO parity relative to ICEVs with policy incentives (cont.)**

b. 18-t straight truck

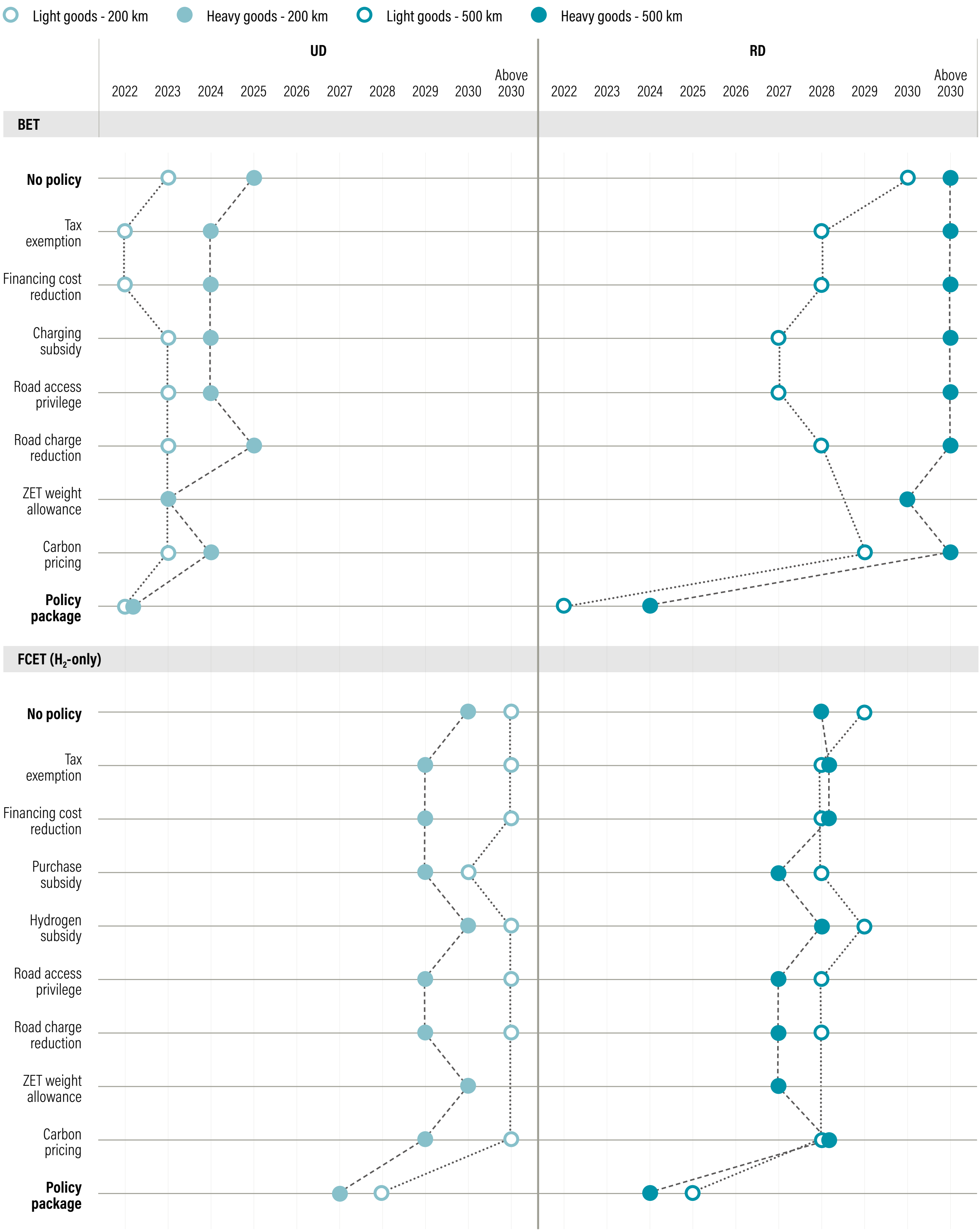


Figure 23 | **ZET TCO parity relative to ICEVs with policy incentives (cont.)**

c. 31-t dump truck

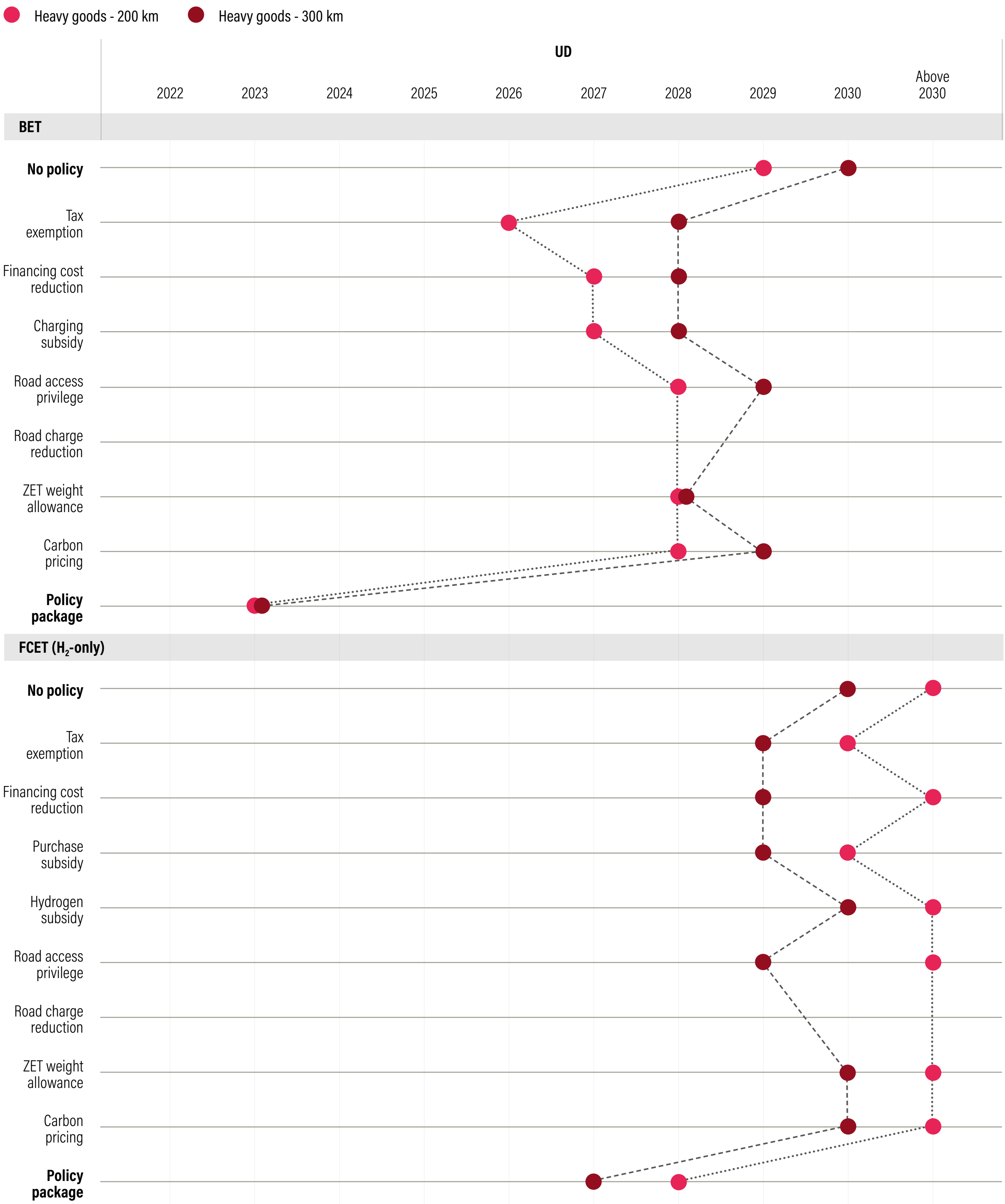
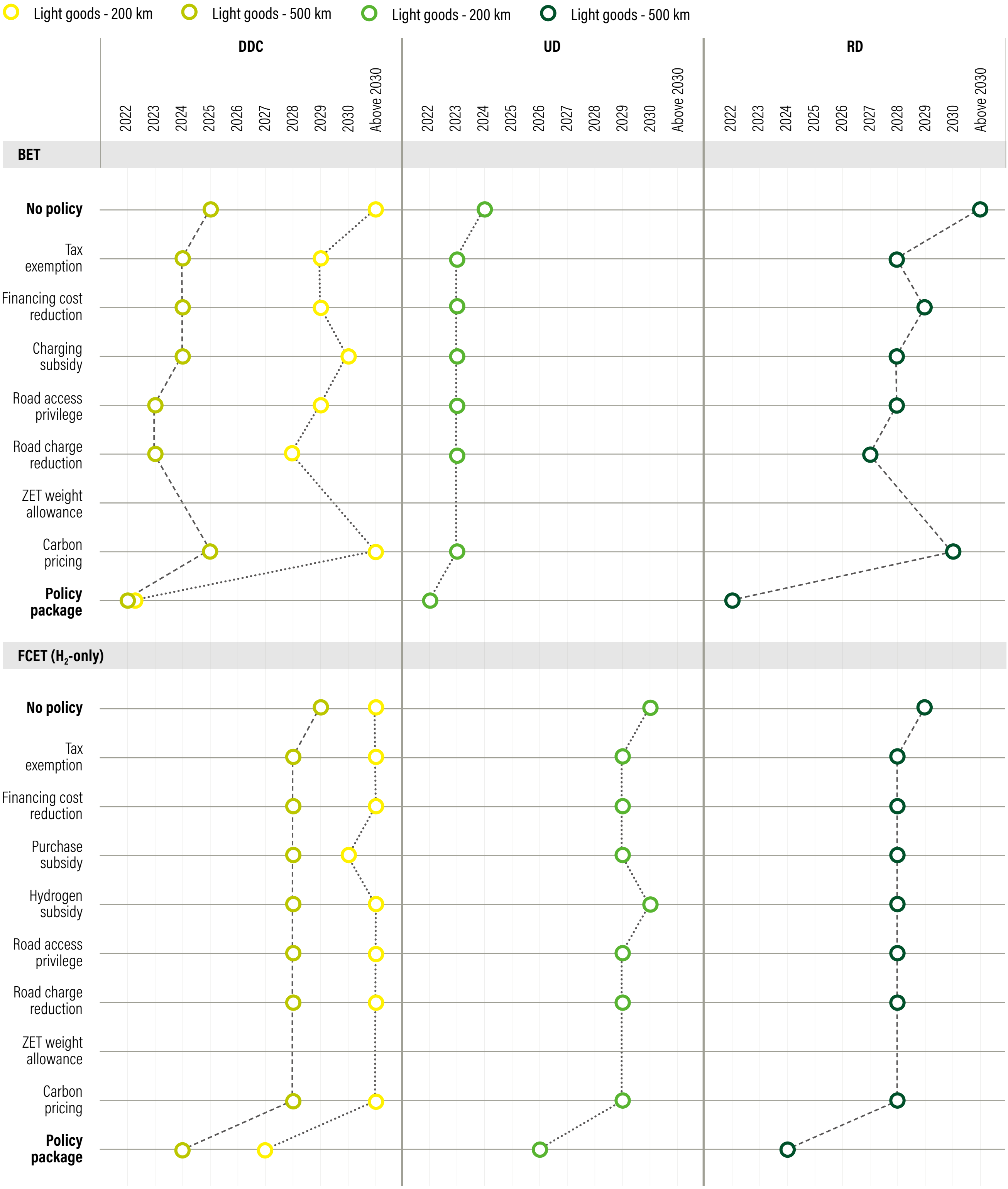


Figure 23 | **ZET TCO parity relative to ICEVs with policy incentives (cont.)**

d. 42-t tractor trailer



Notes: For the 42-t tractor trailer, DDC denotes the DDC_TRIP use cases for BETs and the DDC_DVKT use cases for FCETs.

Source: WRI authors' calculation.

3.3 Applicability to other Chinese cities should be treated with caution

It is noteworthy that even in the same use case, the vehicle model deployed, the types of goods transported, and driving cycles differ by cities. Therefore, readers should be cautious when applying this study's conclusions to other Chinese cities.

Here, we use DDC as an example to illustrate possible regional disparities in ZET configurations and TCO parity years. The reason for choosing DDC is because the previous analysis shows that BETs are likely to reach TCO parity with their diesel counterparts before MY2025 in Shenzhen.

The case is different in Tangshan, Hebei Province. Tangshan is another important port city in China, home of the world's second largest bulk commodity port (Hebei Government 2023). Although Shenzhen Port often employs 42-t tractors trailers for container transportation, Tangshan Port uses 49-t tractor trailers for iron ore and steel products (that are, heavy goods) shipments (Mao et al. 2023). Further, because some trucks in Tangshan serve local factories with trip distances within 100km (Mao et al. 2023), BET100 would be sufficient to meet daily operational needs, contrary to a BET200 adopted in this study for Shenzhen. Further, because the 49-t tractor trailers in Tangshan have a large proportion of the daily VKTs performed near dock or in the urban environment (Mao et al. 2023), their EER (2.8) is higher than it is in Shenzhen in 2022 (EER=2.3). This means ZETs are relatively more energy-efficient than their diesel counterparts in Tangshan. Therefore, a 49-t BET100 tractor trailer can reach immediate TCO parity with its diesel counterpart in MY2022 in Tangshan, earlier than in Shenzhen.

Even so, the conclusions from the study would be applicable to cities with similar use-case characteristics, including truck segments deployed, types of goods transported, driving cycles, and ambient temperature.

Figure 24 | **ZETs' TCO parity years relative to diesel trucks for the DDC use case in Shenzhen and Tangshan**

BET FCET (hybrid) FCET (H_2-only)

VEHICLE	DUTY CYCLE	CARGO TYPE	DAILY VKT (KM)	2022	2023	2024	2025	2026	2027	2028	2029	2030	Above 2030
49-t tractor trailer (Tangshan)	DDC_TRIP	Heavy goods	200				BET						
			300	BET									
			400	BET									
			500	BET									
	DDC_DVKT		200				BET					FCET (hybrid), FCET (H_2-only)	
			300					BET				FCET (hybrid), FCET (H_2-only)	
			400						BET			FCET (hybrid), FCET (H_2-only)	
			500							BET		FCET (hybrid), FCET (H_2-only)	
42-t tractor trailer (Shenzhen)	DDC_TRIP	Light goods	200										BET
			300				BET						
			400	BET									
			500				BET						
	DDC_DVKT		200										BET, FCET (hybrid), FCET (H_2-only)
			300									FCET (hybrid), FCET (H_2-only)	BET
			400								FCET (hybrid), FCET (H_2-only)		BET
			500							FCET (hybrid)	FCET (H_2-only)		BET

Notes: This study assumes that the trip distance for Tangshan's DDC use case is 100 km, while that for Shenzhen is 200 km. Further, the energy consumption of a MY2022 49-t diesel tractor trailer is 64L/100 km, BET is 230kWh/100 km, and FCET is 18kg/100 km.

Abbreviations: BET=battery electric truck; FCET=fuel cell electric truck; ICEV=internal combustion engine vehicle; DDC_TRIP=drayage duty cycle (using the "trip distance" method).

Source: WRI authors' calculation.

Although the methodology of this study is universally applicable, this study remains a simplified version of reality with caveats in the research scope and methodology and possible uncertainties in the research conclusions:

First, from the demand side, intangible factors—such as non-cost elements, revenue gains from ZET transition, and the supply-side limitations of ZET manufacturing—would also affect ZET TCO. For example, except for operation feasibility and costs, fleet operators in reality would also take the following factors into consideration: safety and security of ZETs, shippers' requirements, market demands and profitability, and customers' awareness of the recent development in ZETs when deciding if ZET transition is feasible (QTLC and MOV3MENT 2022). Further, the resilience of the global supply chain for ZET manufacturing and the prices of critical materials would also affect ZETs' costs (BNEF 2022).

Second, improvements on the TCO analytical framework are needed to capture perceived TCO by small fleet operators and draw more comprehensive recommendations. For example, estimating the costs associated with the downtime incurred by prolonged charging time or maintenance time is useful to inform charging network expansion and after-sale service improvements for ZETs. Evaluating the TCO impacts from a low-temperature or hilly-terrain operation would also be instrumental in expanding the analysis's geographic applicability. Further, taking into consideration the differences in residual values between ZETs and ICEVs will be helpful in improving TCO estimation and develop measures to guarantee ZETs' residual values.

Third, data are important to improve the TCO estimation and to inform policymaking. Energy efficiency and EER would greatly affect ZETs' parity years and use case to prioritize ZET promotion; therefore, it is important to gather ZETs' real-world energy efficiency by use case. Further, the mileage profiles of current truck fleets are also critical to the design of broadly applicable ZETs.

These areas could serve as future avenues to improve the robustness and applicability of our conclusions.


中國農業銀行

SECTION 4

CONCLUSIONS AND RECOMMENDATIONS

The results indicate that policy incentives, operational optimization, technology improvements, and financing mechanisms are critical for the future uptake of ZETs in Chinese cities. To accelerate ZET adoption, both private and public entities play important roles.

This study assessed the techno-economic feasibility of ZETs over the time frame of 2022–2030 across 14 use cases for Shenzhen and Foshan.

The results indicate that policy incentives, operational optimization, technology improvements, and financing mechanisms are critical for the future uptake of ZETs in Chinese cities. To accelerate ZET adoption, both private and public entities play important roles:

First, without policy incentives, BET promotion in PO, DDC, and UD could be prioritized, given that the TCO parity with diesel trucks in these use cases will be reached as early as MY2022–2025. To achieve TCO parity, both operational optimization and technology improvements are important:

- For fleet operators, OEMs, and local governments, choosing BETs with smaller batteries, ensuring that charging facilities are sufficiently available, and adjusting operation schedules (for example, timing charging with loading or unloading of trucks or break times of drivers) are important to reduce BETs' TCO. In the near term (up to 2030 in this study), DDC would be an ideal use case for operational optimization because of predictable destinations and operation schedules, return-to-base operation, as well as relatively small geographic coverage relative to RD. Over the long term, with ample charging facilities along the highway network, ZETs in RD would also benefit from operational optimization to reduce TCO.

- For OEMs and key component manufacturers, accelerating technology developments is essential. Battery cost reduction, vehicle energy efficiency improvement, and battery energy density increases are critical for reducing BETs' TCO, while the cost reduction of the fuel cell systems and green hydrogen prices are essential to bring down FCETs' TCO. Further, given the day-to-day operation variability of small fleet operators, OEMs should design broadly applicable BETs capable of meeting the majority operation in terms of range.

- For financial institutions and other private stakeholders, providing new business models (such as leasing and battery swapping) is useful to ease ZETs' up-front purchase costs.

Second, comprehensive policy incentives are important to close TCO gaps between ZETs and ICEVs. Further, policies are also essential to unlock the potentials of business models and operational optimization.

- With the comprehensive policies analyzed in this study, the TCO parity years of BETs in most use cases are earlier than FCETs, making BETs the most cost competitive ZET option.

- ZETs benefit from most measures analyzed in this study, except for carbon pricing. Because the impacts of policies on ZETs' TCO parity years and TCO reduction are use-case-specific, comprehensive policy incentives are more effective to bringing forward ZETs' TCO parity years to an earlier date than single measures.

- Subsidies analyzed in this study—including purchase subsidies and hydrogen fuel incentives—are one of the most influential policy interventions to bridge FCETs and ICEVs' TCO gaps; however, governments should refrain from using large purchase subsidies to boost ZET adoption to avoid flooding the freight market with excessive truck capacity.

- Because changes in energy prices will greatly affect ZETs' parity years with diesel trucks, removal of diesel subsidies (Black et al. 2023), carbon taxes on diesel prices (OECD 2022), or alternative energy incentives should be considered to maintain the cost competitiveness of ZETs.

- Although charging facilities can be delivered by the private sector or through public-private partnerships, public support is essential to enable BETs' operational optimization. This public support takes the form of land-use planning, land acquisition, grid capacity expansion, and capital grants or energy incentives to install or operate ultra-fast charging facilities. To guide government investments, fleet operators should provide information on charging hotspots, such as depots and warehouses.

- To foster the proliferation of business models, governments and financial institutions could consider reducing the minimum down payment requirements on ZET loans, unlocking green finance (through reduced interested rates and extended repayment terms) for ZET financing, and providing tax benefits or flexible depreciation for ZET leasing.
- Data on ZETs' energy efficiency and existing diesel truck fleet mileages are important to inform both policymaking and ZETs' design. Therefore, it is useful for governments to gather ZETs' real-world energy efficiency and ICEVs' mileage data by use case and share this information with key stakeholders like OEMs to facilitate ZETs' real-world application and technology advances.
- It is also necessary to go beyond the policies examined in this study to consider other policy options, such as enhancing ZETs' fire safety, enforcing air pollution prevention policies, improving ZETs' residual values, and organizing public education campaigns, particularly for small fleet operators.

Last, the conclusions from the study would be applicable to cities with similar use-case characteristics, including truck segments deployed, types of goods transported, driving cycles, and ambient temperature. City with different characteristics should be cautious when applying this study's conclusions.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APPENDICES

APPENDIX A. ACCESS PRIVILEGES FOR NEW ENERGY TRUCKS IN SELECTED CITIES IN GUANGDONG

Table A-1 | **Access privileges for new energy trucks in selected cities in Guangdong Province**

■ All-day restriction in all regions ■ All-day restriction in some regions ■ Daytime restriction in some regions ■ Peak-hour restriction in some regions

■ No restriction ✔ Permits to enter restricted areas are available

FOSHAN

	ICE truck		New energy truck	
	LDT, certain MDT[a]	MDT & HDT	LDT, certain MDT[a]	MDT & HDT
Zero-emission freight zones[c]	All-day restriction in all regions	All-day restriction in all regions	No restriction	No restriction
City center	Daytime restriction in some regions ✔	Daytime restriction in some regions ✔	No restriction	Daytime restriction in some regions ✔
City peripheral	No restriction	Daytime restriction in some regions ✔	No restriction	Daytime restriction in some regions ✔

SHENZHEN

	ICE truck		New energy truck		
	LDT	MDT & HDT	LDT	Certain MDT & HDT[b]	MDT & HDT[b]
Zero-emission freight zones[c]	All-day restriction in all regions	All-day restriction in some regions	No restriction	Peak-hour restriction in some regions	All-day restriction in some regions
City center	Peak-hour restriction in some regions	All-day restriction in some regions	No restriction	Peak-hour restriction in some regions	All-day restriction in some regions
City peripheral	No restriction	All-day restriction in some regions	No restriction	No restriction	All-day restriction in some regions

GUANGZHOU

	ICE truck		New energy truck	
	LDT & MDT	HDT	LDT & MDT	HDT
Zero-emission freight zones[c]	X	X	X	X
City center	Peak-hour restriction in some regions	Daytime restriction in some regions	Peak-hour restriction in some regions	Daytime restriction in some regions
City peripheral	No restriction	Daytime restriction in some regions	No restriction	Daytime restriction in some regions

DONGGUAN

	ICE truck		New energy truck	
	LDT	MDT & HDT	LDT	MDT & HDT
Zero-emission freight zones[c]	All-day restriction in all regions ✔	All-day restriction in all regions ✔	No restriction	No restriction
City center	Peak-hour restriction in some regions ✔	Daytime restriction in some regions ✔	No restriction	No restriction
City peripheral	No restriction	No restriction	No restriction	No restriction

Note: [a] In Foshan, for ICE trucks, medium-duty box trucks with a vehicle length within 6 meters and a GVW within 8 tons have the same access restrictions as light-duty trucks. For new energy trucks registered in Guangdong Province, those with a payload capacity within 5 tons (including light-duty trucks) and medium-duty box trucks with a vehicle length within 6 meters and a GVW within 8 tons are not subject to access restrictions. (Foshan MEEB and Foshan PSB 2022).

[b] In Shenzhen, battery electric medium- and heavy-duty trucks with a vehicle length within 6 meters have the same access restrictions as light-duty ICE trucks. Battery electric medium and heavy-duty trucks with a vehicle length exceeding 6 meters have the same access restrictions as medium- and heavy-duty ICE trucks (Shenzhen PSB 2023a).

[c] In Foshan, among the four zero-emission freight zones, two have restricted the access of medium- and heavy-duty diesel trucks. In Shenzhen, the zero-emission freight zones only restrict the access of light-duty diesel trucks (Shenzhen PSB 2023b).

[d] Access restrictions on non-local trucks are not included in the table.

Abbreviations: ICE=internal combustion engine; LDTs=light-duty trucks; MDT=medium-duty trucks; HDTs=heavy-duty trucks; X=no policy.

Source: WRI authors' summary.

APPENDIX B. INTERVIEWS CONDUCTED FOR THIS STUDY

We conducted semi-structured online and offline interviews to the following stakeholders. The detailed interview methods are explained in Table B-1.

Table B-1 | **Interviews conducted for this study**

RESPONDENTS	SAMPLING METHOD	NUMBER OF RESPONDENTS	INTERVIEW QUESTIONS
Fleet operators of different sizes	Convenient sampling by use case	• 10 operators specialized in 4.5-t LDTs' UD and RD operations in Shenzhen and Foshan. • 7 operators on 42-t tractor trailers' DDC in Shenzhen. • 2 operators for PO in Shenzhen. • 7 operators specialized in 42-t tractor trailers' RD and long-haul operation in Shenzhen and Foshan. • 5 operators specialized in 18-t straight trucks' UD and RD operation in Shenzhen.	Typical use cases, status quo on ZET adoption and challenges, energy consumption, purchase costs, TCO (such as maintenance costs)
Truck dealers	Convenient sampling	• 3 truck dealers in Shenzhen and Foshan.	Energy consumption, purchase costs, TCO (such as loan and insurance costs)
OEMs and key component manufacturers	Convenient sampling	• 2 OEMs and key ZET component manufacturers	Weights and cost of key components, mainstreamed design of ZETs, TCO (such as replacement costs of key components)

Note: The Authors also managed to include four small fleet operators in the interviews to obtain information about the unique challenges faced by small fleet operators.

Source: Authors' summary.

ABBREVIATIONS

BET	battery electric truck
BEV	battery electric vehicle
CNY	Chinese yuan
DDC	drayage duty cycle
DMC	direct manufacturing cost
EER	energy efficiency ratio
FC	fuel cell
FCET	fuel cell electric truck
FCEV	fuel cell electric vehicle
HDT	heavy-duty truck
ICEV	internal combustion engine vehicle
ICM	indirect cost multiplier
GVW	gross vehicle weight
GCW	gross combined weight
LDT	light-duty truck
MY	model year
NEV	new energy vehicle
PO	port operation
RD	regional delivery
TCO	total cost of ownership
UD	urban delivery
VKT	vehicle kilometer traveled
ZET	zero-emission truck

ENDNOTES

1. NEVs include battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell electric vehicles (FCEVs).
2. Clean-energy vehicles include NEVs and natural gas vehicles.
3. Freight density is calculated by dividing the volume by the weight of the cargo.
4. This is estimated by assuming that the FCEV uses the hydrogen-only mode.
5. C-rate is the rate at which a battery is discharged relative to its maximum capacity.
6. How to predict the future capacities of battery packs is explained in the previous section.
7. The costs are assumed to be 486 CNY/kW for the OBC and 389 CNY/kW for the DC/DC converter. Further, these costs are assumed to be constant over time.
8. Vehicle purchase costs are assumed to be the same in Shenzhen and Foshan.
9. BETs often need to be charged over two charges per day, when using the "trip distance" method to size the battery capacities.
10. This means the future cost reduction in battery packs are not considered.
11. This means that for the case without policy incentives, demand charges are also waived for ZETs.
12. The low (green) hydrogen prices can be made possible with low-cost renewable energies (0.13-0.22 CNY/kWh) (Yu et al. 2024) and pipeline transportation in 2030.
13. Non-native electric vehicles are BETs or FCEVs that use existing platforms from ICEVs; whereas native electric vehicles are BETs or FCEVs that are designed from the ground up.
14. The cost is the tractor's cost, excluding trailer's price.
15. Currency exchange rate: 1 US dollar = 7.0 CNY.
16. This study doesn't differentiate FCEVs' energy efficiency in UD and RD due to the lack of empirical evidence.
17. Guangdong Province is one of seven regional ETS pilots in China; it is characterized by the largest trading volume among all the pilots.

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ABOUT THE AUTHORS

Ke Chen, China Mobility Research Analyst, WRI China.
Email: ke.chen@wri.org

Lulu Xue, China Mobility Manager, WRI China.
E-mail: lulu. xue@wri.org

PHOTO CREDITS

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WORLD RESOURCES INSTITUTE

WRI CHINA
RM K-M, 7/F, TOWER A, THE EAST GATE PLAZA,
#9 DONGZHONG STREET, BEIJING, CHINA, 100027
PHONE: 86 10 6416 5697
FAX:86 10 6416 7567
WWW.WRI.ORG.CN