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TOTAL COST OF OWNERSHIP FOR HEAVY TRUCKS IN CHINA: BATTERY-ELECTRIC, FUEL CELL ELECTRIC, AND DIESEL TRUCKS

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EXECUTIVE SUMMARY

The decarbonization of on-road freight rests on three pillars: the supply of zero-emission technologies, the roll-out of the required infrastructure, and strong economic incentives to shift demand away from diesel vehicles. This paper focuses on the latter by examining the total cost of ownership (TCO) of heavy-duty new energy vehicles (HD-NEV). We find that—with the right policies—HD-NEVs provide substantial TCO benefits compared to diesel trucks. To reap these economic benefits, it is important to implement policies that ensure a robust supply of HD-NEVs. Thus, we recommend that the upcoming revision to new energy vehicle (NEV) sales targets include heavy trucks as one of the regulated categories.

The 2025 NEV targets in China aim to increase the share of NEV sales to about 20% of all vehicles sold in 2025. It is still unclear which vehicle segments will be targeted in the upcoming policies. The heavy-duty vehicle (HDV) sector is a heavy polluter in China, responsible for more than 74% of total NO_x emissions from road transport and 52% of total PM emissions from road transport.

In this study we analyze the TCO of zero-emission truck technologies in China, namely battery-electric trucks (BETs) and fuel cell electric trucks (FCETs), for three HDV segments including tractor-trailers, dump trucks, and straight trucks. The study aims to identify the TCO-parity point between zero-emission trucks and diesel trucks for the analyzed HDV segments in Beijing, Shanghai, and Shenzhen, thereby providing an analytical basis to support the development of NEV targets for those HDV segments. The analysis is based on a thorough modeling of TCO and simulations of energy consumption.

Our analysis finds that all BET segments can achieve TCO parity with diesel trucks as of the second half of this decade. Battery-electric dump trucks are cost-effective compared to their diesel counterparts as early as 2025. Battery-electric tractor-trailers and straight trucks will reach TCO parity with diesel toward the end of the decade.

Fuel cell electric trucks will almost reach TCO parity with diesel trucks toward the end of the decade for straight and dump trucks. This delay compared to BETs is driven by the more gradual learning rates in the manufacturing of fuel cell stacks and by higher energy costs. However, the gap between the TCO of diesel trucks and FCETs is narrowed in the second half of the decade.

Targeted policy measures can bring forward by several years the TCO parity of BETs and FCETs compared to diesel trucks. An earlier point of TCO parity has the potential of creating robust demand for HD-NEVs in the first half of the current decade. This, in turn, translates into market incentives for vehicle manufacturers to increase the model availability and ramp up production. The reduction of NEV manufacturing costs is largely dependent on the volume of production—due to learning curves and economies of scale. Thus, demand side policies targeting lower TCO for HD-NEVs can have long-lasting positive impacts on the supply side of the equation, enabling the setting of ambitious sales targets for HD-NEVs. We assessed the following demand-side policies:

» A partial exemption of road tolls for HD-NEVs
» Reform in the demand charges for direct electricity use in HD-NEVs
» Subsidies for green hydrogen production
» Purchase incentives for HD-NEVs
» Introduction of carbon pricing of fossil fuels

Figure ES 1 and **Figure ES 2** summarize the TCO parity year for the different truck segments across the three Chinese cities analyzed in this study. Solid truck icons correspond to a no-policy intervention scenario, whereas transparent truck icons represent a package of interventions combining all previously mentioned policies. As shown in **Figure ES 2**, the combined impact of applying these policy measures is substantial. The TCO parity of HD-NEVs can be brought to the first half of the decade in most cases, with BET achieving TCO parity immediately in 2021.

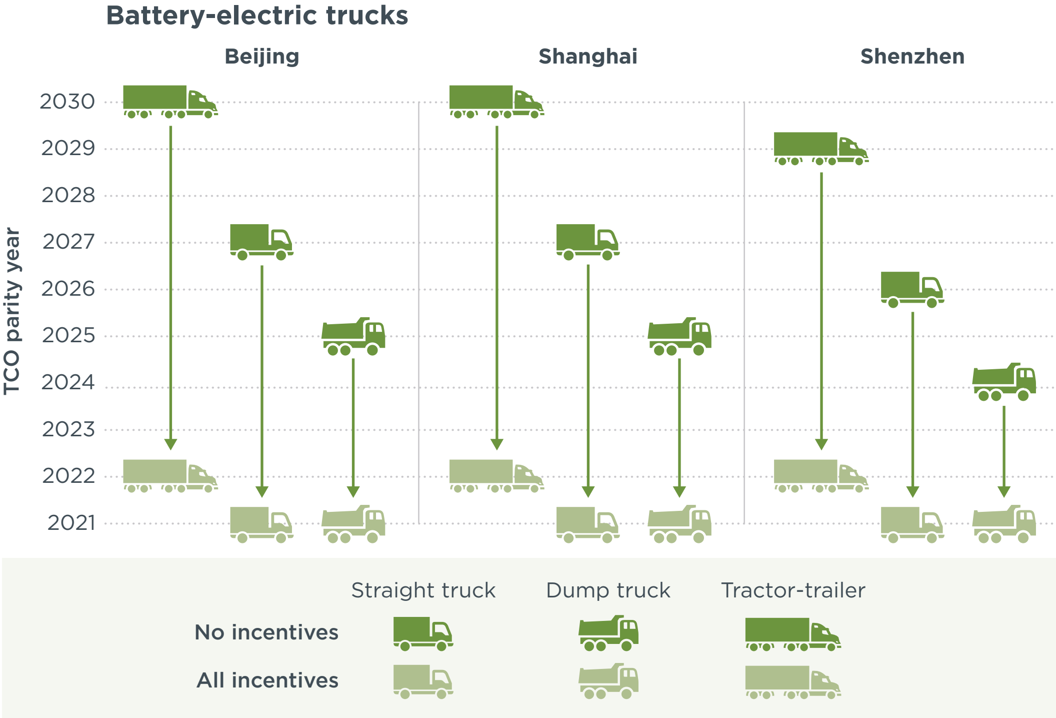

Figure ES 1. Summary of TCO parity years for BET with and without policy incentives

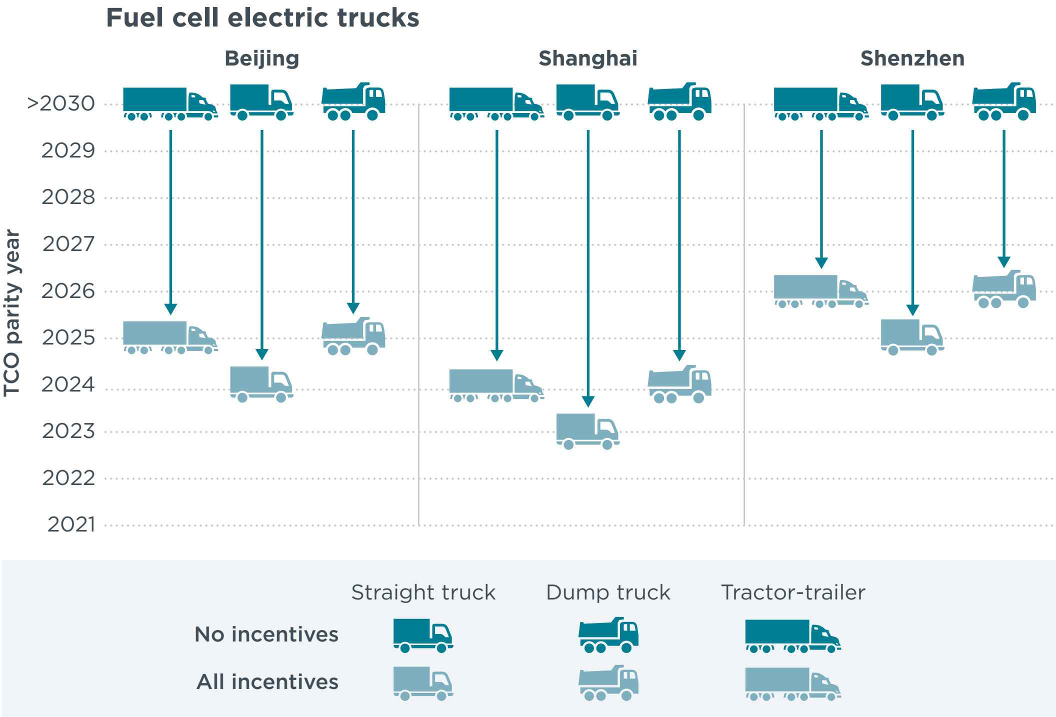

Figure ES 2. Summary of TCO parity years for FCETs with and without policy incentives

Based on our findings, we recommend the following for the development of policies designed to drive the adoption of HD-NEVs in China:

Set ambitious sales requirements for HD-NEVs in the near term. Truck operators will only reap the economic benefits of HD-NEVs if there is a robust supply of them. California provides a best practice example for the setting of targets, requiring 11% of new heavy rigid trucks to be zero emission by 2025 and 50% by 2030. For tractor-trailers the zero-emission sales requirements are 5% and 30% by 2025 and 2030, respectively. China's ambition to become carbon neutral by 2060 requires that the central government introduce targets at least as ambitious as those adopted in California.

Set long-term zero-emission sales targets to provide manufacturers a clear picture for future product planning and investment. The combination of near-term binding sales requirements with long-term nonbinding targets set by the government is desirable. The former ensures the immediate kick-start of the needed supply chains; the latter provides the certainty that the investments made will have a long life. The combination of the two is important to create a large and long-lasting market, whose economies of scale will drive down manufacturing costs and, consequently, the TCO of HD-NEVs.

Provide incentives to bring the TCO parity of HD-NEVs with diesel trucks to the first half of this decade. Policy can create adequate incentives to close the TCO gap between diesel HDVs and HD-NEVs in the next 5 years. Subsidies—which are not fiscally sustainable—should be limited in scope and duration to stimulate demand in early phases. Policies following the polluter pays principle can generate the revenue needed to fund incentive programs in the long term.

Design policies that are application-specific but technology-neutral. Policies must target the deployment of zero-emission vehicles in the segments with the highest CO_2 emissions, such as tractor-trailers. At the same time, they should aim for a level playing field between battery-electric and fuel cell trucks to favor the most cost-effective technological pathway in the long term. Our analysis shows that battery-electric trucks have a cost advantage in the absence of incentives.

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INTRODUCTION AND SCOPE

OVERVIEW OF HEAVY-DUTY VEHICLES MARKET

China's commercial vehicle market has been surging in recent years, as the total sales of commercial vehicles increased from 1.8 million in 2005 to 4.3 million in 2019 (OICA, 2020) as shown in **Figure 1**. Heavy-duty vehicles, or HDV, are commercial vehicles designed specifically for heavy-duty workload and transportation with a gross vehicle weight (GVW) of more than 3.5 tonnes in China. HDV commonly includes several segments, such as straight trucks, dump trucks, tractor-trailers, and coaches or buses. China's heavy-duty vehicle market has become the largest in the world (Muncrief & Sharpe, 2015) with more than 1 million vehicles produced every year since 2010 (J. Li, 2016). Nevertheless, the HDV segment is now imposing an environmental burden in China that should be addressed. HDVs contribute a great proportion of total emissions in terms of CO_2, NO_X, $PM_{2.5}$, and other pollutants. In China, HDVs emit 74% of total road transport NO_X and 52.4% of total road PM emissions (MEE, 2020) while representing only 7.8% of total road transport sales and ownership (Xinhua News, 2018). HDVs also contributed 6.1% of all GHG emissions in China in 2015, according to a study by Tsinghua University (Song et al., 2017).

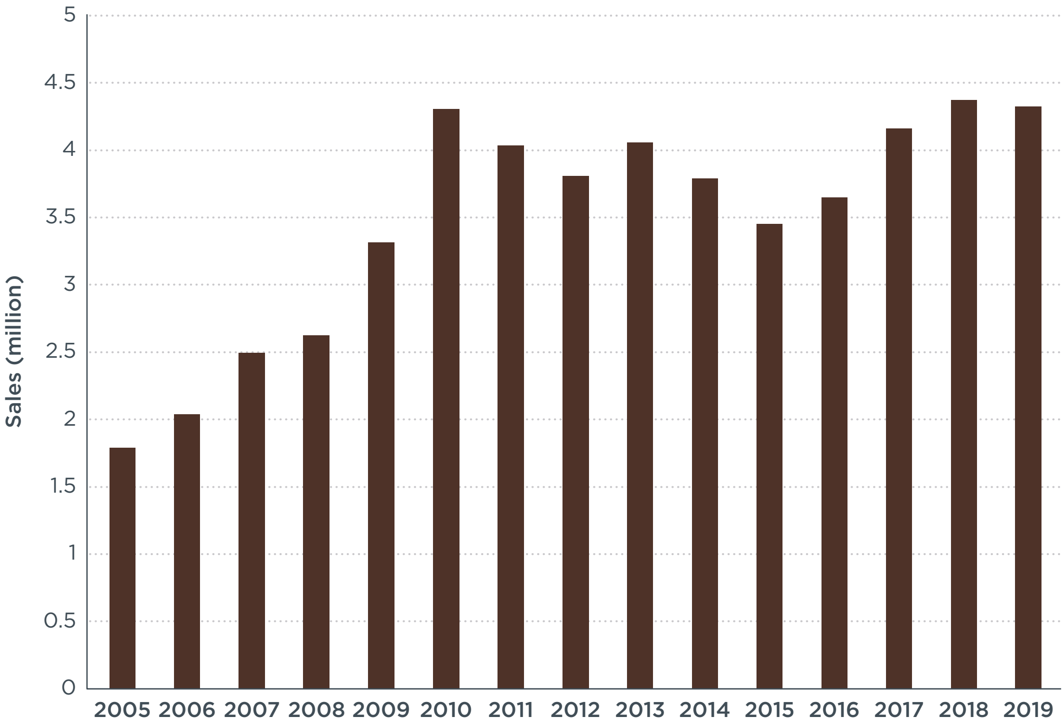

Figure 1. China's commercial vehicle sales from 2005 to 2019 (OICA, 2020)

China is aiming to promote zero-emission commercial vehicles, including trucks and buses, to reduce road transport emissions resulting from HDVs. China's central government and local authorities are encouraging manufacturers and operators to deploy more zero-emission HDV technologies—including battery-electric and fuel cell electric HDV—by providing subsidies and incentives. In the last decade, the zero-emission HDV market witnessed exponential growth in China. Total sales of heavy-duty new energy vehicles (HD-NEVs) peaked in 2016 when more than 200,000 trucks were sold, after a boom in the production capacity of HDV fleets for consecutive years. However, the abundance of zero-emission HDV production was to some degree driven by fraudulent activities aimed at taking advantage of subsidy schemes in China. After five zero-emission HDV manufacturers were sanctioned in 2016 (People.cn, 2016), subsidies for production of zero-emission HDVs were reduced in subsequent years, and the technical requirements for HD-NEVs to qualify for the subsidies were made more stringent. Since then, the sales volume of zero-emission HDVs in China decreased significantly, as shown in **Figure 2**.

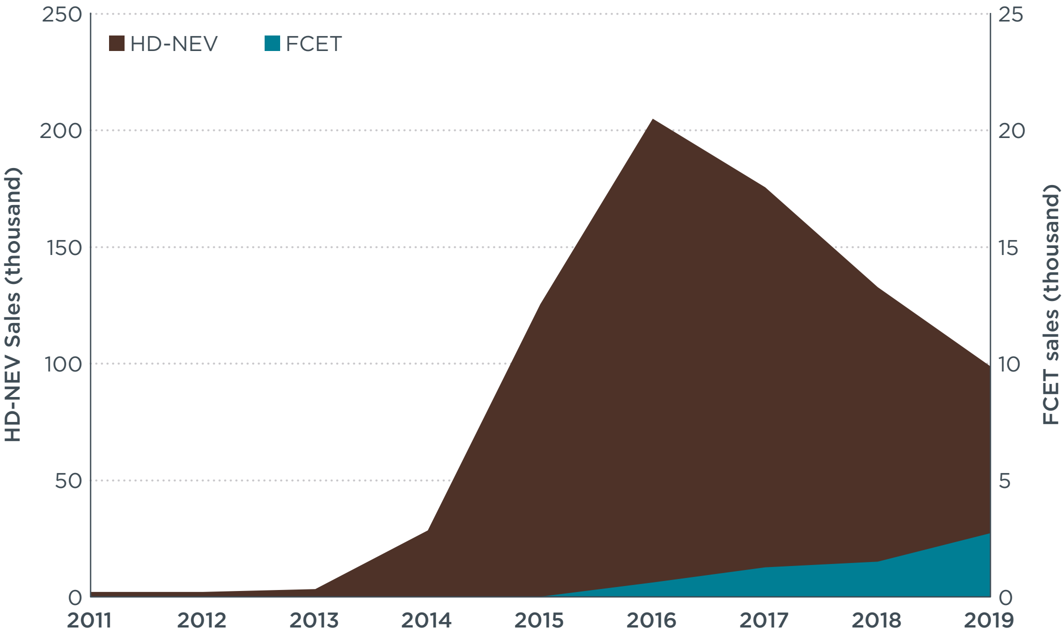

Figure 2. Sales of HD-NEVs and FCETs from 2011 to 2019 (Monika, 2020)

SCOPE OF THE STUDY

This study evaluates the total cost of ownership of HD-NEVs in China—namely, battery-electric and fuel cell electric trucks—focusing on three specific truck segments:

1. Straight trucks
2. Dump trucks
3. Tractor-trailers

These truck segments are chosen because they are the mainstream choices for most commercial truck use in China. Straight and dump trucks are mostly used on construction sites, mines, and so on for short distance delivery, and tractor-trailers are commonly used for both medium-range drayage and long-haul transportation. Further, evaluation of the potential of tractor-trailers for electrification is critical because this segment contributes the most GHG emissions of any vehicle segments in China (Delgado & Rodríguez, 2018).

The economic performance of those trucks will be compared to their diesel counterparts to identify when the HD-NEV version of each truck segment could reach cost parity with diesel trucks from a first-user perspective, defined as the first 5 years of ownership. The study considers three Chinese cities, namely Beijing, Shanghai, and Shenzhen.

POLICY BACKGROUND

In the past decade, China has rapidly become the world's largest electric vehicle market, a result of targeted policy efforts at the national and local level that used pilot programs, incentives, and sales targets and other concrete initiatives to drive sales. China's pilot programs, in combination with central subsidies and incentives, managed to catalyze the electric vehicle market to reach a mature point where it was capable of sustaining further regulatory pull. After 2018, China began to shift from subsidizing the industry to providing a combination of incentives and sales requirement regulations to ensure the continuation of innovation, investment, and model availability.

The new energy vehicle (NEV) mandate policy, requiring increased electric vehicle production and sales, has been the single most important driver of electric vehicle model availability and increased sales volume for light-duty vehicles. Now that the electric heavy-duty market is entering a stable growth phase, thanks to the pilot and subsidy programs of the past years, China is evaluating the introduction of an equivalent policy for trucks and buses (Caixin, 2021). The recently released Energy-saving and New Energy Vehicle Technology Roadmap 2.0, prepared by the Society of Automotive Engineering (SAE) China, proposes targets of 12% of annual sales by 2025, 17% by 2030, and 20% by 2035 for new commercial heavy-duty NEVs (SAE-China, 2021).

The Chinese government is also accelerating the transition to HD-NEVs, including battery-electric and hydrogen fuel cell vehicles, through purchase incentives. To this end, the central government has implemented a series of financial incentives since 2009, as summarized in **Table 1** and **Figure 3**.

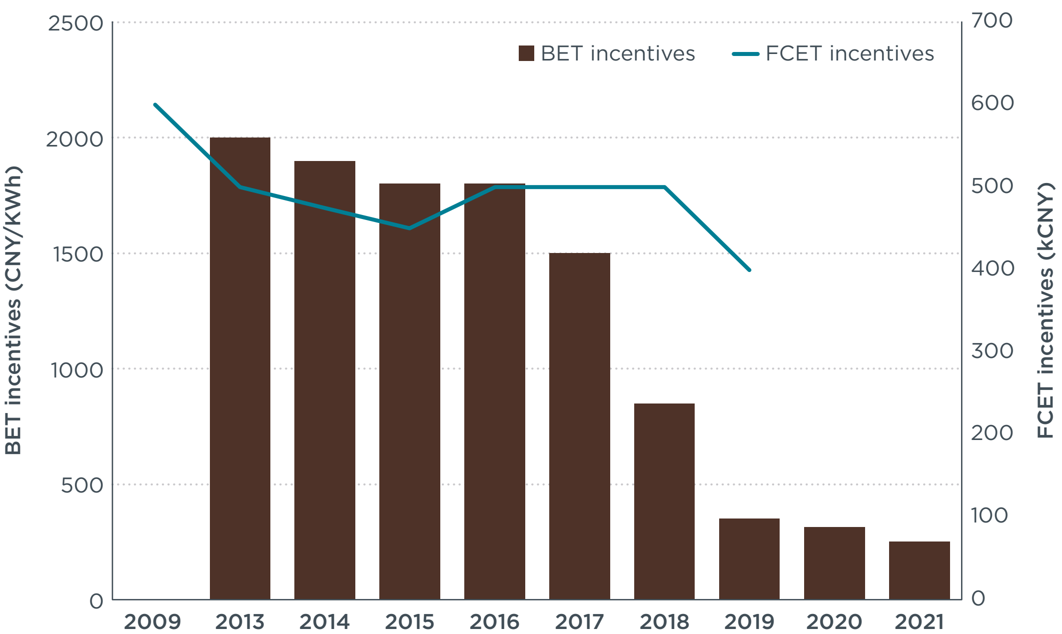

Figure 3. Visualized financial incentives for HD-NEVs since 2009

Table 1. Summary of incentives for HD-NEVs in China

Year	Segment	Energy capacity	Incentives	Other requirements
2009	BET	ANY	—	—
	FCET	ANY	600,000 CNY	—
2013	BET	ANY	2,000 CNY/kWh	Capped at 150,000 CNY
	FCET	ANY	500,000 CNY	—
2014	BET	ANY	1,900 CNY/kWh	Capped at 142,500 CNY
	FCET	ANY	475,000 CNY	—
2015	BET	ANY	1,800 CNY/kWh	Capped at 135,000 CNY
	FCET	ANY	450,000 CNY	—
2016	BET	ANY	1,800 CNY/kWh	Range ≥ 80km
	FCET	ANY	500,000 CNY	Range ≥ 200km with a hard cap at 130,000 CNY
2017	BET	≤ 30 kWh	1,500 CNY/kWh	1. System energy density ≥ 90 Wh/kg 2. Ekg[a] ≤ 0.5 Wh/km*kg 3. Capped at 150,000 CNY
		30–50 kWh	1,200 CNY/kWh	
		> 50 kWh	1,000 CNY/kWh	
	FCET	ANY	500,000 CNY	Range ≥ 300 km
2018	BET	≤ 30 kWh	850 CNY/kWh	1. System energy density ≥ 115 Wh/kg 2. Ekg ≥ 0.4 Wh/km*kg 3. Capped at 100,000 CNY
		3,050 kWh	750 CNY/kWh	
		> 50 kWh	650 CNY/kWh	
	FCET	ANY	500,000 CNY	1. Rated power > 30 kw 2. Range ≥ 300 km
2019	BET	ANY	350 CNY/kWh	1. System energy density ≥ 125 Wh/kg 2. Range ≥ 80 km 3. Ekg ≤ 0.35Wh/km*kg 4. Capped at 55,000 CNY
	FCET	ANY	400,000 CNY	
2020	BET	ANY	315 CNY/kWh	1. System energy density ≥ 125 Wh/kg 2. Range ≥ 80 km 3. Ekg ≥ 0.29 Wh/km*kg 4. Capped at 50,000 CNY
	FCET	Not announced until update of fuel cell vehicle pilot city initiative		
2021	BET	ANY	252 CNY/kWh	Capped at 40,000 CNY (for nonpublic use)
			315 CNY/kWh	Capped at 49,500 CNY (for public use)
	FCET	Not announced until update of fuel cell vehicle pilot city initiative		

[a] Ekg is the specific energy consumption on load capacity, Ekg = E/M, where E implies energy consumption, Wh/km; M implies the affiliated mass. M = load capacity if load capacity ≤ 180 kg, or M = 180 kg if load capacity between 180 kg and 360 kg, or M = 0.5*load capacity if load capacity ≥ 360 kg.

In general, financial incentives for both fuel cell electric trucks (FCETs) and battery-electric trucks (BETs) are being reduced steadily, from 500,000 Chinese yuan (CNY) in 2016 to 400,000 CNY (2019) for FCETs and from 1,800 CNY/kWh in 2016 to 252 CNY/kWh in 2021 (estimated) for BETs. For FCETs specifically, China paused subsidies for them in 2020 and is developing a new type of incentive measure for fuel cell powered trucks, which is expected to be announced alongside China's fuel cell vehicle pilot city initiative in 2021. Instead of granting financial incentives directly to qualified manufacturers and users, China is trying to promote FCET models in a more sustainable way, including direct and indirect investment in hydrogen infrastructure and coordinated participation of different industries and companies in various regions.

INTERNATIONAL CONTEXT

California is the only region that has adopted legally binding legislation requiring the sale of zero-emission heavy-duty vehicles. Its Advanced Clean Trucks (ACT) Regulation, adopted in 2020 (CARB, 2020), is the first of its kind in the world to require manufacturers to sell increasing percentages of zero-emission trucks. The regulation defines zero-emission truck sales requirements for three heavy-duty vehicle groups, defined based on their weighting, starting from model year (MY) 2024. By 2025, 11% of new rigid trucks heavier than 6.3 tonnes must be zero-emission. The targets for this vehicle segment increase to 50% by 2030 and 75% by 2035. The targets for new zero-emission tractor-trailers are 7%, 30%, and 40% by 2025, 2030, and 2035, respectively.

Several regions have communicated nonbinding targets setting a long-term vision that gives manufacturers a clear expectation of where policy and the economy are heading. In contrast to binding targets, such as California's ACT, nonbinding targets are political in nature and shape the development of implementing regulations. California has set a nonbinding target of requiring that all HDVs on the road—that is, not only new sales but the complete HDV stock—be zero emission by 2045 (State of California, 2020). Although the current U.S. administration has not yet set a federal target for zero-emission HDVs, so far 15 states have signed a memorandum of understanding (MOU) stating their intent to reach a penetration of ZE-HDVs of 30% by 2030 and 100% by 2050 (NESCAUM, 2020). Internationally, the Netherlands is spearheading a global MOU to accelerate the zero-emission HDVs market by setting zero-emission targets of 30% by 2030 and 100% between 2040 and 2050, while encouraging nations to be more ambitious. Austria, Canada, Chile, Germany, Greece, the Netherlands, Norway, and Sweden have signed this global MOU (TDA, 2021).

Fiscal and nonfiscal policies aimed at incentivizing zero-emission HDVs vary in scope and design across regions. They are not detailed in this paper; another recent ICCT report provides an extensive overview of these policies around the world, along with recommendations for China (Xie & Rodríguez, 2021).

LITERATURE REVIEW

The total cost of ownership, often abbreviated as TCO, is an analysis focusing on the cumulative total of costs contributed by each stage of a product's life cycle. It is widely acknowledged (Qian, 2019; Yang et al., 2018) that the TCO of zero-emission trucks should consist of several critical elements, for example, purchase price (C_p), cost in use (C_u), maintenance (C_m), and salvage value (or residual value) (C_s). Some extra costs such as opportunity cost (C_o) and recycling cost during scrappage (C_r) are also used in some studies about trucks, which are summarized in **Table 2**. Therefore, the equation of total cost of ownership can be generally expressed as follows:

$$C_{total} = C_p + C_u + C_m + C_o + C_r - C_s$$

OVERVIEW OF TCO STUDIES FOR HD-NEV IN CHINA

Generally speaking, studies on TCO for popular truck categories are few in number because of the limited availability of HD-NEV models in the Chinese market. Existing studies on HD-NEVs may not be directly comparable because of the great variations in assumptions and case studies.

According to Qian (2019), the TCO of a light zero-emission logistics vehicle in 2019, at 70,600 CNY, was lower than the TCO of conventional vehicles (77,700 CNY). Zhang et al. analyzed several fuel cell vehicles (FCV) in 2018 and found that logistics FCV were less expensive than diesel vehicles in terms of TCO, given that China heavily subsidized the zero-emission transition in the logistics industry as 6,000 CNY/kW (Zhang & Peng, 2018).

A study conducted in 2020 demonstrated that electric sanitation vehicles, used for daily sweeping and sanitation projects on streets, showed better economic performance than their fossil-fuel-driven counterparts. The electric sanitation vehicles were 820,000 CNY more expensive than conventional vehicles but were able to save 930,000 CNY more than conventional vehicles over an 8-year operating period. Hence, even if subsidies were phased out, electric sanitation vehicles would still be 60,000 CNY cheaper than diesel vehicles. (Wang et al., 2020).

Yang et al. also analyzed electric trucks with battery-swap technology and compared the total costs with diesel trucks, plug-in electric trucks, and battery-swap electric trucks, respectively. The light plug-in electric trucks were very competitive with diesel trucks of similar size, but light battery-swap electric trucks could not compete with diesel trucks; that was almost the same case for medium-size trucks in terms of TCO, according to this study (Yang et al., 2018).

EV100, a prominent think-tank in China for NEV policy studies and analysis, estimated the TCO of a typical city bus (10.5m), a logistics vehicle (9 tonnes) and a heavy-duty truck (42 tonnes) with fuel cell technology. Using simulations, they found that the bus, logistics vehicle, and heavy-duty truck would cost about 4,481,000 CNY, 2,000,000 CNY, and 5,350,000 CNY, respectively, assuming a hydrogen cost of 60 CNY/kg in 2020, which turned out to be a conservative estimate. The total cost for each segment is projected to decline even more in 2025 and 2030 (**Figure 1**).

China Automotive Technology and Research Center (CATARC), a prestigious institute in China for the study of automobile technology, concluded that the TCO of a typical fuel cell truck will still be more expensive than electric vehicles. However, it is estimated that the key components of fuel cell technology will decline more rapidly than electric counterparts. For example, the fuel cell stacks will cost about 316 and 148 CNY/kWh by 2030 and 2050, 50% and 62% cheaper than battery power train, respectively (CATARC, 2021).

Table 2. TCO estimates for HD-NEV in China

Vehicle type	Technology	Year	TCO gap (Diesel—Alt.)	Source
Logistics vehicle (light)	Battery	2019	CNY 7,100	(Qian, 2019)
Logistics vehicle (medium)	Fuel cell	2020	—	(EV100, 2020)
Logistics vehicle (heavy)	Fuel cell	2018	CNY 800	(Zhang & Peng, 2018)
Sanitation vehicle	Battery	2020	CNY 60,028	(Wang et al., 2020)
Truck (light)	Plug-in	2018	CNY 149,352	(Yang et al., 2018)
Truck (light)	Battery	2018	CNY -79,389	
Truck (medium)	Plug-in	2018	CNY 37,334	
Truck (medium)	Battery	2018	CNY -106,040	
Truck (heavy)	Fuel cell	2020	—	(EV100, 2020)
Bus	Fuel cell	2020	—	
Truck	Fuel cell	2021	—	(CATARC, 2021)
Truck	Battery	2021	—	
Bus	Fuel cell	2021	—	
Bus	Battery	2021	—	

METHODOLOGY AND DATA SOURCES

VEHICLE ENERGY CONSUMPTION MODELING

Due to energy costs' large share of a truck's TCO, it is important to determine accurately the energy consumption of each power train type, whether it is fuel consumption for diesel trucks, electric energy consumption for battery-electric trucks, or hydrogen consumption for fuel cell electric trucks. To fairly compare different power train technologies for each truck segment studied (tractor-trailer, dump truck, and straight truck) and to enable the realization of future technology potential, models were developed for each case using a one-dimensional multiphysics vehicle simulation software. Nine vehicle models were therefore obtained to cover the full combination of power train types and truck segments. The benefits of using vehicle simulation rather than certified energy consumption values from the market are twofold. First, the technical specifications for the few zero-emission truck models currently on the market differ significantly from their diesel counterpart, meaning that any difference in energy consumption is partly due to different vehicle characteristics and might not translate each technology's potential adequately. By obtaining an easily scalable model of a diesel truck that matches its certified fuel consumption, the model can be adapted to its zero-emission counterparts by changing the power train only, keeping the main vehicle specifications unchanged.

The second reason to use model-based simulations is that there is a proven gap between the certified and real-world energy consumption of diesel trucks arising from the certification procedures used in China, and a similar issue may become evident for zero-emission trucks as evidence accumulates. In particular, the China World Transient Vehicle Cycle (C-WTVC) used across all truck segments to determine fuel consumption during type approval is not the most representative of real-world operation (Hanzhengnan et al., 2019). Certifying the trucks at their maximum payload capacity also contributes to this gap (Mao et al., 2021). Instead, we simulated the vehicle's performance under conditions that are more representative of their real-world operation to increase the accuracy of the energy cost estimates. Additionally, it allows easy estimates of the future performance of all vehicle and power train technologies across a range of characteristics, including road load reduction, increased internal combustion engine (ICE) efficiency, battery energy density, fuel cell efficiency, and power density.

VALIDATION OF THE DIESEL TRUCK MODELS

To validate the use of the simulation software, models were first obtained for the three diesel trucks based on vehicle and engine specifications of best-selling versions of each segment: a 6x2 tractor-trailer from FAW,[1] an 8x4 dump truck from Sinotruk,[2] and a 4x2 straight truck from JAC.[3] The technical specifications for these trucks are summarized in **Table 3**. When not stated otherwise, these specifications were obtained from the reference trucks.

The diesel truck models were validated by simulating their fuel consumption with the parameters used in the certification methodology and comparing the results against the reported certified values, which are announced by the Ministry of Industry and Information Technology (MIIT) on type-approval lists. The C-WTVC driving cycle was used here, as it is used for the certification of all truck segments in China. However, CATARC recently developed a series of new driving cycle tests—the China heavy-duty

1 "FAW Jiefang VA4250P66K24T1A1E5 Diesel cabover tractor unit (#274)," Auto-Che, accessed September 30, 2021, http://auto-che.com/v/ca/ca4250p66k24t1a1e5-274-faw-jiefang.html.

2 "Sinotruk Hohan ZZ3315N3563E1 Dump truck (#282)," Auto-Che, accessed September 30, 2021, http://auto-che.com/v/zz/zz3315n3563e1-282-sinotruk-hohan.html.

3 "JAC Junling V9L 170 horsepower 6.8m hurdles onboard truck (HFC1181P3k1A53S6V)," accessed September 30, 2021, https://product.360che.com/m202/50741_index.html.

commerical vehicle test cycle (CHTC)—that are more representative of each segment's real-world operation. The latter were used when determining the trucks' energy consumption based on real-world parameters (discussed later). For validation purposes, the truck models were run at their maximum payload capacity as specified in **Table 3**.

Regarding road load parameters (air drag coefficient and rolling resistance coefficient), manufacturers have the freedom to certify their trucks either by measuring them or by using standard values, which is a much more cost-effective option. Because the stringency of the fuel efficiency standards in China allows original equipment manufacturers to comply using these relatively high default values, the latter option is often preferred, as discussed in a previous ICCT study (Mao et al., 2021). For the model validation, we assumed that the certified fuel consumption values for all truck segments were obtained using the default parameters. Calibration of the model was performed to ensure that the simulated fuel consumption matched the certified values. This entailed adapting the driver's acceleration, breaking, and gear-shifting behaviors. As shown in **Figure 4**, the resulting simulated fuel consumption matches the certified values with high accuracy—within ±0.05%.

Table 3. Main technical specifications for diesel models of the three truck segments analyzed (tractor-trailer, dump truck, and straight truck).

	Tractor-trailer	Dump truck	Straight truck
Driving cycles			
Certification driving cycle	C-WTVC	C-WTVC	C-WTVC
New representative driving cycle	CHTC-TT	CHTC-D	CHTC-HT
Vehicle specifications			
GCWR (kg)	49,000	31,000	18,000
Axle configuration	6x4	8x4	4x2
Vehicle curb mass (kg)	8,805 (trailer: 7,000[a])	15,040	7,850
Maximum payload capacity (kg)	33,195	15,960	10,150
Representative payload (kg) (% maximum)	29,731 (75%)	11,970 (75%)	7,613 (75%)
Drag area (C_dA) (m^2) [a]	6.0	6.0	6.0
Tire rolling resistance coefficient [a]	0.006	0.006	0.006
Tires dimensions	12R22.5 (Tractor, x10) 12R22.5 (Trailer, x12)	11R20 (x12)	11R22.5 (Front, x2) 10R20 (Rear, x4)
Diesel power train specifications			
Engine rated power (kW)	312	225	125
Engine displacement (L)	11.05	6.87	3.92
Number of cylinders	6 (in-line)	6 (in-line)	4 (in-line)
Air induction system	Single-stage, fixed geometry turbocharger	Supercharger (modeled as a turbocharger)	Single-stage, fixed geometry turbocharger
Engine peak brake thermal efficiency [a]	0.45	0.40	0.40
Transmission	12 speed MT	12 speed MT	12 speed MT

[a] (Meszler et al., 2019)

REAL-WORLD FUEL CONSUMPTION MODELING

To obtain more representative fuel consumption values, the simulation parameters, including road load and payload, were adjusted to values more representative of the trucks' real-world performance.

Given their certified fuel consumption, the reference tractor-trailer and straight trucks conform to Stage 2 of the Chinese fuel efficiency standards. Implemented in 2015, Stage 2 introduced targets of 47 L/100km and 31 L/100km for the tractor-trailer and straight truck, respectively. However, the standards are now in their third stage.

Therefore, adjustments were made to conform to the Stage 3 standards to ensure the fuel consumption values we used to compute fuel operating costs were representative. The respective improvements in road load were implemented, according to the results obtained in a previous ICCT study (Meszler et al., 2019).

The payloads were also adjusted to values more representative of the real-world operation of each truck. Due to the lack of China-specific data, we assumed a representative payload of 75% of the maximum payload capacity for all segments, corresponding to what is used in Europe. Tractor-trailers in China are mainly used for the transport of bulk materials and tend to be overloaded, sometimes above their gross combined vehicle weight rating or GCWR (Delgado et al., 2016). However, this is compensated for by empty runs and cases where trucks reach their maximum volume before reaching their combined weight limit, referred to as "cubing out." Straight trucks are typically used for delivery from a central warehouse to individual stores. The truck starts the day fully loaded and ends empty, with potential reloading events along the way. A similar rationale is applied to dump trucks, which are usually either empty or fully loaded. The resulting fuel consumption was assessed on each segment's specific cycle of the CHTC series, summarized in **Table 3**, for improved representativeness.

As shown in **Figure 4**, simulating the Stage 3–compliant trucks' performance with the assumed real-world parameters yields much lower fuel consumption than the previous certification values for the three truck segments. For the tractor-trailer and straight truck, the newly introduced CHTC cycles are less energy intensive than the C-WTVC cycle used for certification, on top of the reductions already achieved by using lower, more representative values of the road load parameters. For the dump truck, the fuel consumption obtained with the CHTC-D cycle is higher than that obtained with the certification cycle, although the implementation of the improved road load performance together with the lower representative payload also result in a reduction in the simulated fuel consumption.

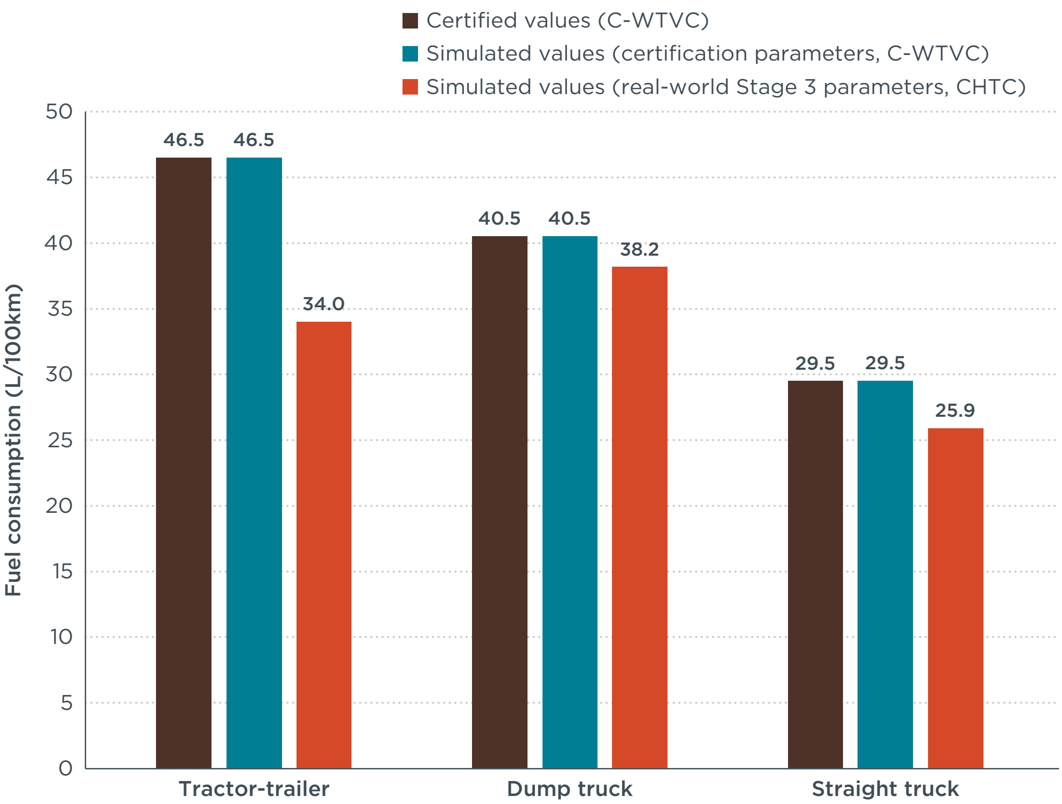

Figure 4. Validation of the simulated fuel consumption values obtained with the baseline diesel truck models. For the tractor-trailer and straight truck, the brown and blue bars correspond to Stage 2 vehicles.

Future diesel technology potential

This latter set of results was used to evaluate the fuel operating costs of these trucks, together with energy prices discussed later in this paper. The corresponding models were used as the base for the modeling of the zero-emission trucks, discussed in the following section, as well as for the implementation of future technology potential. Improvements common to all power train technologies include reduction in road load and light-weighting—assuming no improvement in trailer weight or the aerodynamics of the tractor-trailer. Additionally, power-train-specific improvements are expected. For the diesel trucks, this mainly consists of engine brake efficiency. The values assumed for the diesel trucks in 2030 are based on a previous ICCT study (Meszler et al., 2019) and summarized in **Table 4**. In particular, the reduced curb weight of the trucks will allow for additional payload capacity, which is beneficial for operators. However, we still modeled the 2030 energy consumption values with the same payloads as the original values from **Table 3** to model the effects of improved vehicle technology only.

Table 4. Diesel truck technology potential for 2030 (and improvements relative to 2020).

	Tractor-trailer	Dump truck	Straight truck
Vehicle specific improvements			
Drag area (C_dA) (m^2)	3.5 (-42%)	4.4 (-27%)	4.4 (-27%)
Tractor curb mass	7,397 (-16%)	12,634 (-16%)	6,594 (-16%)
Power-train-specific improvements			
Engine peak brake thermal efficiency	0.52 (+16%)	0.50 (+25%)	0.48 (+20%)

Zero-emission trucks modeling

When adapting the diesel truck models to their zero-emission equivalents, the main vehicle specifications in **Table 3** were retained. These included, among others, the axle configuration, chassis weight, wheel size, and trailer weight. Most importantly, the road load parameters and typical payloads were unchanged. In addition, the power-train-specific assumptions made for the zero-emission vehicles are summarized in **Table 5** and discussed below. The electrical machines were sized to yield the same output power as the original ICEs, and the transmissions of the zero-emission trucks were designed to yield the same torque at the wheel as the original trucks. With both zero-emission technologies, we assumed an average power of 3kW was taken from the machine and fed to electrical fittings.

Table 5. Main assumptions and specifications for the zero-emission trucks, including weight adjustments relative to the baseline diesel trucks.

	Tractor-trailer	Dump truck	Straight truck
EV range (km)	500	300	400
E-motor type	Interior permanent magnet synchronous machine		
E-motor power rating (kW)	312	225	125
Weight adjustments			
Weight of diesel power train removed (kg)	2,154	1,690	943
Battery energy density (Wh/kg)	160	160	160
Fuel cell power density (W/kg)	280	280	280
H_2 storage weight (kg/kgH_2)	20	20	20
Mass of motor, inverter and gearbox (kg)	628	628	628
Additional specifications— BET			
Battery chemistry	LFP (cell-to-pack)		
Battery capacity (kWh)	845	365	375
BET curb mass (kg)	12,561	16,259	9,879
BET payload capacity (kg) (loss vs. diesel truck)	29,439 (-11%)	14,741 (-8%)	8,121 (-20%)
Additional specifications— FCET			
H_2 storage type	700-bar compressed hydrogen		
H_2 storage size (kg)	42.5	18	18
Fuel cell peak power (kW)	190	150	120
Fuel cell average efficiency	0.52	0.52	0.52
Battery capacity (kWh)	70	50	40
FCET curb mass (kg)	9,288	15,204	8,592
FCET payload capacity (kg) (loss vs. diesel truck)	32,712 (-1%)	15,796 (-1%)	9,408 (-7%)

BET assumptions

For the BET, the diesel power train in the original model was replaced with a large traction battery pack, a permanent magnet electric motor, and an inverter. The motor was sized to deliver the same power as the original ICE and the transmission designed to ensure the same torque at the wheels. The truck featured a lithium-ion-phosphate (LFP) battery, which is the main chemistry used for automotive applications in China. In contrast to the nickel-cobalt battery chemistries typically used in Europe and the United States (NCA and NMC), the cell energy density of LFP batteries has nearly reached its maximum potential already, at around 250–280 Wh/kg for batteries produced in China (InsideEVs, 2020b). Most of the remaining potential in this technology therefore lies in the integration of the cell power to the vehicle power train, with innovative arrangements such as cell-to-pack (CTP) and cell-to-chassis (CTC). The former technique skips the module step and integrates the cells directly into a battery pack, leading to up to 50% increase in volumetric energy density (InsideEVs, 2020a). CTP is already used in China by manufacturers like CATL and BYD, leading to a current best-in-class LFP battery energy density of about 160 Wh/kg. The latter value is used for the current BET performance. Moreover, the automotive battery manufacturer Guoxuan has announced its ambition to produce battery cells with 260 Wh/kg energy density by 2022, corresponding to 234 Wh/kg at the pack level (InsideEVs, 2021). Although this announcement seems quite ambitious, we assume the latter value for 2030, which makes the improvement more conservative. The use of battery and cabin thermal control technologies may result in a considerable impact on the BET driving range. In a previous ICCT study (Basma et al., 2021), we estimated that using heat pumps for battery and cabin thermal management systems can reduce the driving range of a tractor-trailer by 5%–9% for temperatures ranging between -7°C during winter and reaching 35°C during summer.

FCET assumptions

The FCET was fitted with a proton exchange membrane (PEM) fuel cell stack, with power ratings for each truck segment presented in **Table 5**. It includes a compressed hydrogen storage system and a small buffer battery to provide for extreme power demands and to enable regenerative breaking energy capture, as well as an electric motor similar to that of the BET. A 700-bar compressed hydrogen storage was assumed, as it is currently being considered as one of the most promising options for long-haul freight transportation. The weight of the hydrogen storage, which was scaled with the amount of hydrogen being carried, is assumed to be 20 kilograms (kg) per kg of hydrogen (FCHJU & Roland Berger, 2020). For the fuel cell stack, a power density of 280 W/kg is assumed, including power electronics and a water management system, corresponding to the current industry state-of-the-art (Ballard, 2020). Because intensive research is ongoing in hydrogen power trains, a 5% yearly improvement in fuel cell power density is assumed out to 2030, bringing the value to 460 W/kg. The latter is in agreement with the Roadmap 2.0 projections from (SAE-China, 2021). As a reference, the U.S. Department of Energy's ultimate target is 650 W/kg (DOE, 2015). The fuel cell efficiency was set to 52% according to current best-in-class performance (Ballard, 2020), and we assume a 1.3% yearly improvement out to 2030 to meet the U.S. DOE's target of 60%. Finally, the LFP battery pack was set at 70 kWh for the tractor-trailer, based on a review of existing models and prototypes (Hyundai Hydrogen Mobility, 2020; Daimler AG, 2020) and scaled down proportionally to energy consumption for the other two segments, as shown in **Table 5**. The same energy density values are assumed as with the battery of the BET. To ensure minimal energy consumption in the FCET, the model includes an energy management system, which calculates the optimal energy balance between the fuel cell stack and the battery pack, based on an equivalence factor.

Weight and range assumptions

The curb weight of the different trucks was adapted to each power train technology. The first step was to remove the weight of the diesel power train, including engine and transmission, which was evaluated at around 2.2 tonnes for the tractor-trailer (Mareev et al., 2018). For the other two truck segments, this was scaled down to account for the smaller engines. The weight of the energy storage from the zero-emission trucks was then added, based on the energy and power density assumptions listed above. Finally, a weight of 630 kg is assumed for the electric motor, inverter, and transmission across all segments for both the BET and FCET (Sharpe, 2019), yielding the updated curb weights in **Table 5**.

The size of the batteries and the hydrogen storage in the case of the FCET were set so that the zero-emission trucks are able to meet their desired range on a single charge, which was determined from the typical daily mileage of each truck segment. Overnight charging of the battery at the depot is favored as it represents the cheapest option for operators. The size and weight of the energy storage were dynamically adjusted until the desired range was obtained, yielding the final energy consumption values in **Figure 6**. The range of the BET was determined from the simulated depth-of-discharge (DoD) over the fixed cycle distance, extrapolating over the total usable state-of-charge (SoC) of 80%. The battery SoC window of operation is considered to be between 15 and 95% to avoid battery deep discharge and battery overcharge, which accelerate battery aging, and to provide a buffer for potential battery capacity degradation that may impact the truck driving range.

The battery is assumed to reach its end life[4] after 5 years of operation. It is assumed that it can always provide sufficient energy to meet the truck driving range requirements, given the buffer provided by the SoC window, as well as the decreasing annual vehicle kilometers traveled (VKT) throughout its lifetime, as highlighted in the "Annual vehicle kilometers " section later in this study. In addition, as the battery capacity degrades during its operation, its internal resistance increases, reducing the battery charge and discharge efficiency. This issue is not captured in our models as we assume a constant battery internal resistance as a function of time.

A sensitivity analysis was conducted to assess the required battery size to yield different EV ranges with a constant payload. As shown in **Figure 5**, the required size of the battery increases in a quasi-linear fashion with the desired range of the truck. However, at high EV ranges, the weight of the battery pack becomes significant, requiring a larger portion of the energy to move the weight of the energy storage, hence the required battery size increases faster. This is particularly significant with today's relatively low battery energy density. With the projected improvements in energy density in 2030, the required battery size is expected to increase less with increased range, also reducing the quasi-linear gap at high EV ranges.

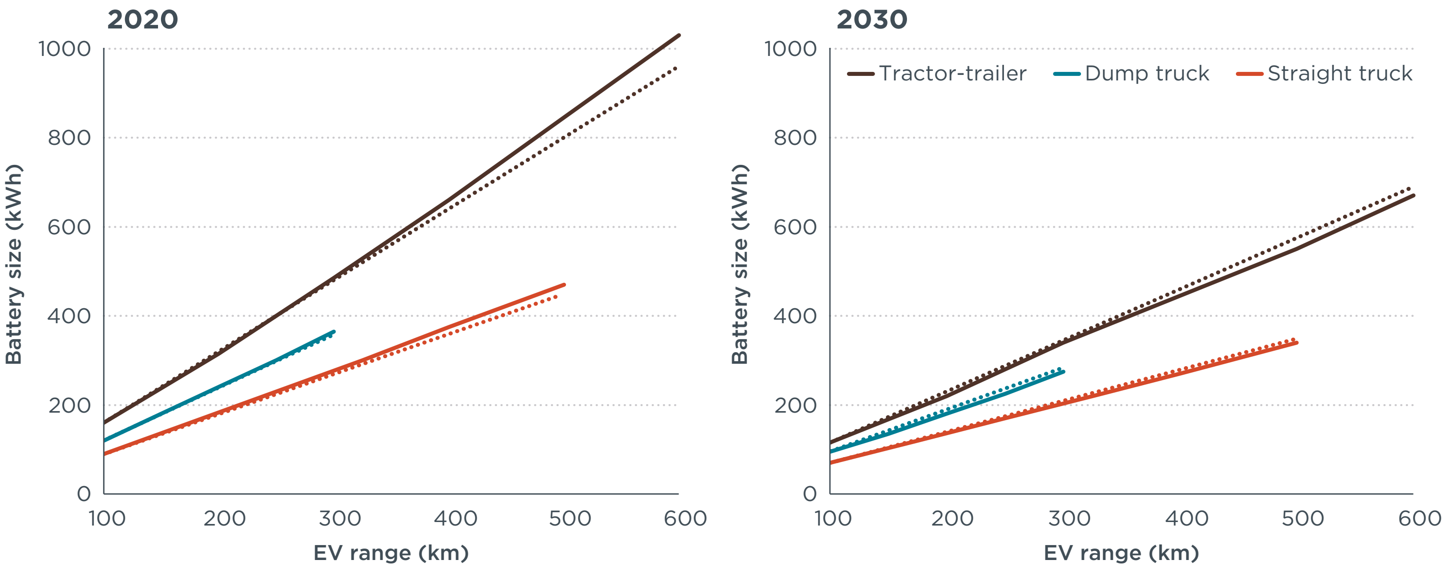

Figure 5. Influence of the desired EV range of the BET on the required battery size for the three truck segments for 2020 (left) and 2030 (right) at constant payload. The dotted lines represent what a proportional increase in battery size with range would look like.

The daily driving ranges for each truck segment were obtained from our estimate of annual VKT (see section "Annual vehicle kilometers ") aiming for the zero-emission trucks to rely mainly on overnight depot charging. That is, these trucks should be able to reach most of their daily driving ranges under a single charge, without having access to recharging or refueling infrastructure during the day. Still, given the battery size gap identified in **Figure 5** and the important cost of batteries, it was assumed that the tractor-trailer and straight trucks could charge the equivalent of 100 km of range on the road while the driver rests, with fast charging for the BET and by refilling the hydrogen tank for the FCET.

We assumed that the average tractor-trailer, dump truck, and straight truck would drive 600 km, 300 km and 400 km per day, respectively, covering the vast majority of applications. Factoring in opportunity charging, this gives EV ranges of 500 km

4 Battery end life is mainly defined as a 20% loss in the original battery charge capacity.

and 400 km for the tractor-trailer and straight truck, respectively. Reducing the range allowed us to downsize the assumed battery size of the BET and the hydrogen storage in the FCET for these two segments, which had a considerable impact on energy consumption and cost. In the case of the dump truck, it was assumed that access to a fast charger is not guaranteed due to its use profile outside urban areas and main highways. Therefore, the EV range was set as the daily mileage of 300 km. This yields the battery sizes specified in **Table 5**.

FUTURE ZERO-EMISSION TECHNOLOGY POTENTIAL

For future considerations, the power-train-specific technology potential relies mainly in battery energy density for the BET and in fuel cell efficiency for the FCET, respectively, as discussed above. Our assumptions for the 2030 technology potential are summarized in **Table 6**. The size of the small buffer battery in the FCET was kept the same as in 2020.

Table 6. Zero-emission trucks technology potential for 2030 (and improvements relative to 2020).

	Tractor-trailer	Dump truck	Straight truck
BET technology potential			
Battery energy density (Wh/kg)	234 (+46%)	234 (+46%)	234 (+46%)
Battery capacity (kWh)	550 (-35%)	275 (-25%)	270 (-28%)
BET curb mass (kg)	8,466 (-33%)	12,917 (-21%)	7,484 (-24%)
BET payload capacity (kg)	33,534 (+14%)	18,083 (+23%)	10,516 (+29%)
FCET technology potential			
H_2 storage size (kg)	25 (-41%)	11.5 (-36%)	11.5 (-36%)
Fuel cell power density (W/kg)	460 (+63%)	460 (+63%)	460 (+63%)
Fuel cell average efficiency	0.60 (+14%)	0.60 (+14%)	0.60 (+14%)
FCET curb mass (kg)	7,269 (-22%)	12,457 (-18%)	6,950 (-19%)
FCET payload capacity (kg)	34,731 (+6%)	18,543 (+17%)	11,050 (+17%)

In general, the zero-emission trucks were heavier than their diesel counterparts, which resulted in important reductions in the maximum payload capacity—as much as 20% for the 2020 BET. This will incur a significant penalty for operators, as either more trucks will be needed, or the same number of trucks will need to travel more kilometers to ensure the same freight activity. Both scenarios represent an increase in costs at the fleet level. The payload capacity is expected to increase in 2030 for all power trains with the reductions in vehicle curb mass discussed above. The payload gap between diesel and zero-emission trucks is expected to reduce through 2030. In some cases, the zero-emission trucks are even expected to have better payload capacity in 2030 than their diesel counterparts. Despite these observations, as the aim was to compare each power train's energy consumption based on a single vehicle's performance, we set the representative payload to be the same across all power trains and constant through 2030.

Final energy consumption values

Figure 6 summarizes the simulated energy consumption values for the full combination of trucks segments analyzed (tractor-trailer, dump truck, and straight truck) and the power train technologies (DT, BET, and FCET) for both 2020 and 2030, using the real-world parameters.

Interestingly, despite having the highest energy consumption with the diesel power train, the dump truck's energy consumption is much lower relative to other truck segments with zero-emission power trains. This is mainly due to the driving cycles used to determine these values. As the CHTC-D truck is very transient—that is, it has many acceleration and braking events—the dump truck makes greater use of regenerative energy capture during braking events, therefore driving its energy consumption down.

Further, improvements in 2030 are more significant with the tractor-trailer than with the other two truck segments, in particular with the battery-electric power train. This results from two combined phenomena. First, the improvements in aerodynamics are expected to be greater for these long-haul trucks. Second, because their range requirement is higher, they have larger batteries. Therefore, as improvements in battery energy density are achieved up to 2030, these trucks benefit from a greater weight reduction, which also drives energy consumption down more significantly.

The results in **Figure 6** are used to evaluate current and future energy costs associated with operating each truck, assuming a linear yearly improvement between the 2020 and 2030 energy consumption values.

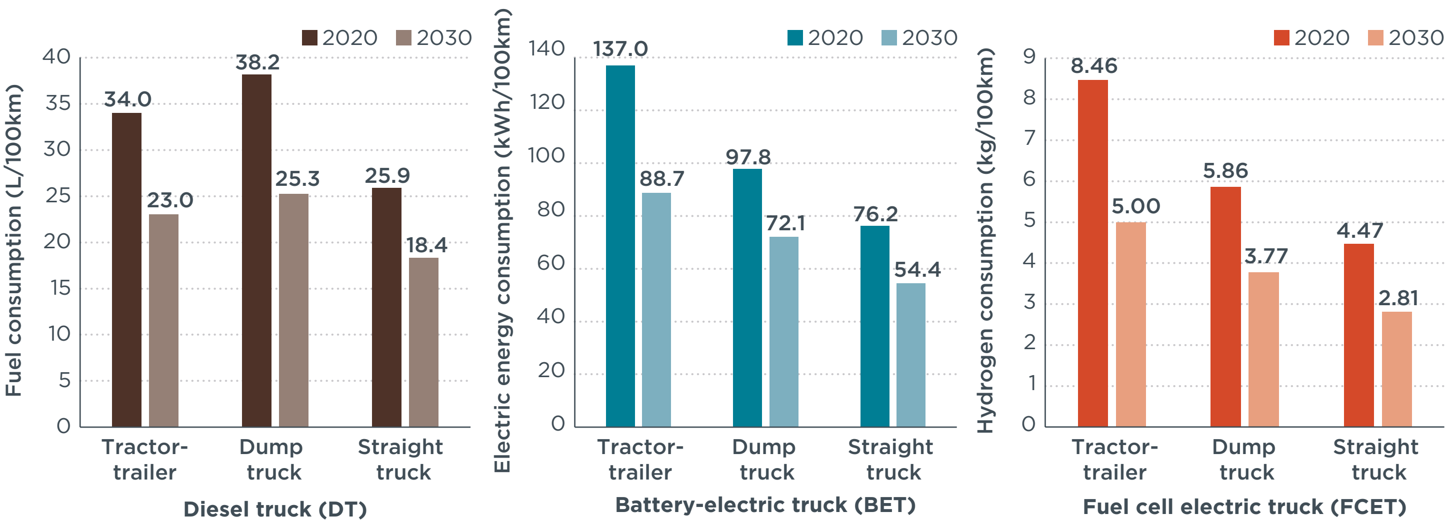

Figure 6. Final energy consumption values used to compute energy operating costs for the full combination of power train technologies and truck segments, in 2020 and 2030.

FIXED COSTS

Vehicle price

Based on publicly available market data (Chinacar.com, 2021), we estimate the price for a new diesel vehicle—that is, model year 2021—in each truck segment (see **Table 7**). The price in subsequent model years is adjusted upward to account for the technology deployment required to improve fuel consumption. This assumes that future Stage 4 fuel consumption standards are introduced in 2025, mandating a fuel consumption improvement of approximately 30% compared to Stage 3 (see previous section). Cost curves previously developed by ICCT (Meszler et al., 2019) were used to estimate the price increase from fuel efficiency technologies. The price increase from the additional technology deployment already includes a markup to account for expenditures in research and development, overhead, marketing and distribution, and profit margins. The estimated prices for model-year 2030 trucks are shown in **Table 7**.

Table 7. Actual 2021 and estimated 2030 diesel truck prices for the segments studied

Truck segment	2021 price	2030 price
Tractor-trailer	Tractor unit: 360,000 CNY Trailer unit: 60,000 CNY	Tractor unit: 502,730 CNY Trailer unit: 83,788 CNY
Dump truck	330,000 CNY	446,263 CNY
Straight truck	139,000 CNY	209,298 CNY

To assess the price of the BET and FCET, the price of the diesel component was subtracted from the diesel truck price, resulting in an estimate for the price of a glider truck—that is, without a power train. The diesel power train (e.g., engine, exhaust, fuel tank, transmission) is estimated to be 51.7% of the total diesel truck price[5] (Fries et al., 2017). For the tractor-trailer segment, the trailer unit price remains constant between diesel and electric trucks for a given year.

The electric power train is a major piece of the retail price of the battery-electric truck. To estimate this cost, we make use of publicly available data in the literature. Available cost data are often based on differing assumptions about indirect costs such as research and development, overhead, marketing and distribution, warranty expenditures, and profit markups. To account for these differences, the cost data is first adjusted to reflect the direct manufacturing cost (DMC).[6] Then, all indirect costs are estimated through the use of indirect cost multipliers (ICMs). We apply estimates developed by consultants commissioned by the ICCT[7] to estimate the direct manufacturing cost of the electric drive. These include the electric motor, transmission and inverter, power electronics, on-board charger, and battery thermal management system, as summarized in **Table 8**. The cost estimates of the hydrogen storage tank are based on the SAE-China Roadmap 2.0 (SAE-China, 2021).

Table 8. Electric power train components direct manufacturing costs[8]

	2020	2030
Electric drive (CNY/kW)	553.5	121.5
Power electronics (CNY/kW)	182.25	182.25
On-board charger (CNY/kW)[9]	486	486
Thermal management system (CNY/kW)	60.75 (FCET), 141.75(BET)	60.75 (FCET), 141.75(BET)
Hydrogen storage tank (CNY/kg)	5,600	2,000

Indirect costs vary with the complexity of associated technology and are roughly estimated to range from 15% to 75% of direct manufacturing costs. The combination of direct and indirect costs is the expected retail price contribution associated with a particular technology, excluding VAT. The ICMs used in this study, which are shown in **Table 9**, correspond to the *high technology complexity level*, as defined by the U.S. Environmental Protection Agency (EPA & NHTSA, 2016), and have been subjected to rigorous development and review.

Table 9. Indirect cost multipliers for technologies with a high technology complexity level

Complexity level	ICM	2020 (near-term)	2030 (long-term)
High 1	Warranty costs	0.073	0.037
	Nonwarranty costs	0.352	0.233
	Total	0.425	0.27
High 2	Warranty costs	0.084	0.056
	Nonwarranty costs	0.486	0.312
	Total	0.570	0.368

5 For tractor-trailer trucks, the diesel power train componentry cost is estimated at 51.7% of the tractor unit cost only, excluding the trailer cost.

6 DMCs reflect the costs of materials and labor required to produce and assemble technology componentry and essentially represent the cost of a component to the vehicle or engine manufacturer.

7 Ricardo Strategic Consulting, "E-Truck Virtual Teardown Study," 2021.

8 Considered currency exchange rates: USD 1 = CNY 6.75, EUR 1 = CNY 7.7625.

9 It is assumed that the BETs are equipped with 44 kW on-board chargers, and the FCETs are equipped with 6.6 kW on-board chargers.

The respective cost estimates for the different battery and fuel cell electric trucks base glider and power train componentry costs in 2020 and 2030 are presented in **Figure 7**. The substantial reduction in the cost of the hydrogen storage tank is due to the reduction in its mass-specific cost (5,600–2,000 CNY/kg as stated in **Table 8**) and also due to energy efficiency improvement in the fuel cell power train reducing the tank *size* significantly (see the previous section "Final energy consumption values").

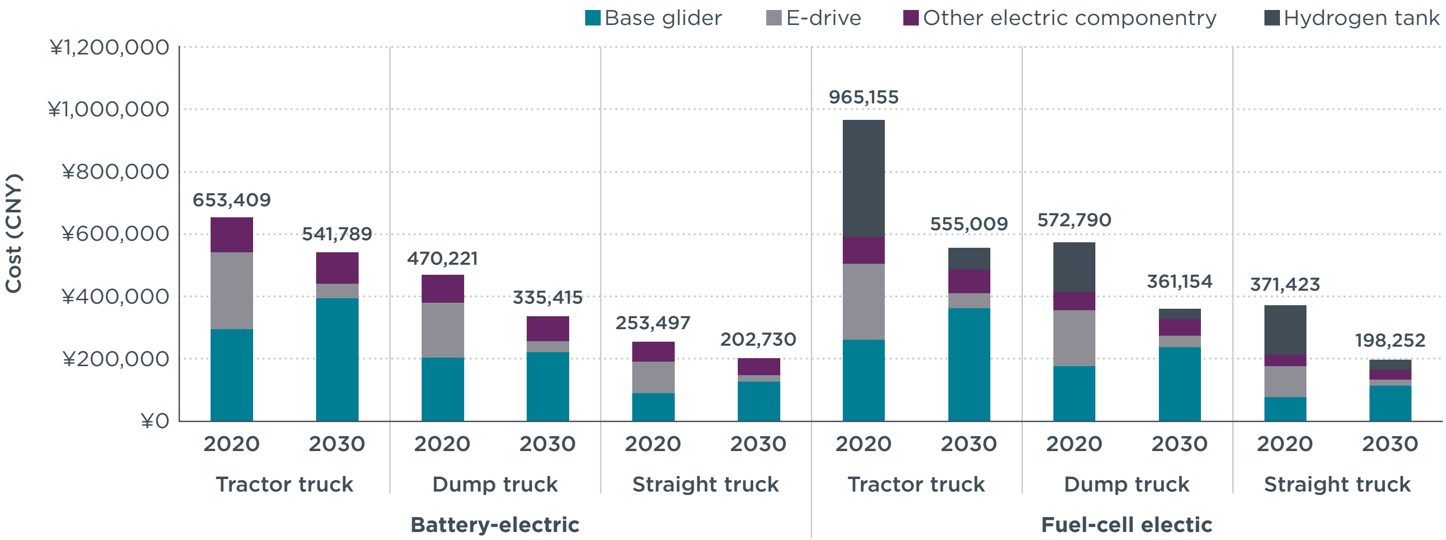

Figure 7. Cost of the battery and fuel cell electric trucks excluding their power units

The retail price of the ZE trucks is validated against publicly available data announced by truck manufacturers, online platforms that provide commercial vehicles services, and other studies in the literature. The details can be found in Annex A: ZE truck retail price validation.

Three scenarios were analyzed for the battery price that were taken from publicly available sources for 2019 (Frith, 2020) and forecasted based on a previous ICCT analysis (Lutsey & Nicholas, 2019). While the cost of battery cells has dropped significantly in the past years, there are important differences at the battery pack level between heavy- and light-duty vehicles, such as durability, voltage level, power output, thermal management, and modularization. As a result, the current pack-to-cell cost ratio in heavy-duty vehicles is above 2, whereas in light-duty vehicle applications it is only 1.3 (Frith, 2020). The battery pack costs used in this study are referred to SAE-China Roadmap 2.0, which is shown in **Figure 8**. As for the fuel cell pack costs, numbers were also adopted from SAE-China Roadmap 2.0 (SAE-China, 2021) where the fuel cell pack cost is estimated to be around 5,000 CNY/kW in 2020. This number decreases to 2,000 CNY/kW in 2025 and 600 CNY/kW by 2030.

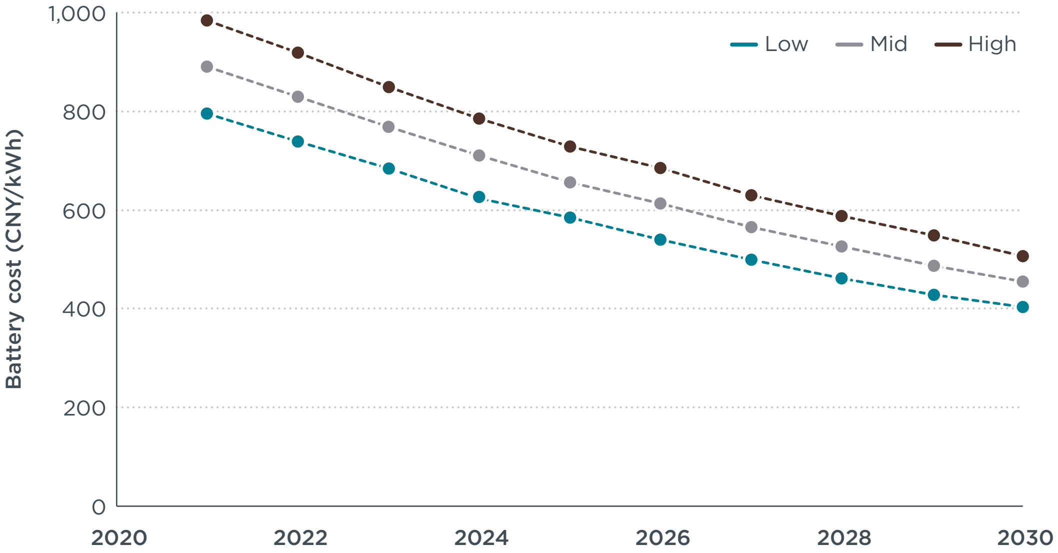

Figure 8. Three scenarios analyzed for the cost of heavy-duty battery packs

The total truck retail price evolution (including the power units) of the diesel, battery, and fuel cell electric trucks in the period 2020 to 2030 is shown in **Figure 9**. Unless otherwise stated, the medium price scenario for the battery is used in the remainder of this paper. The diesel truck retail price increases between 2020 and 2030 due to the technology deployment required to improve the fuel consumption.

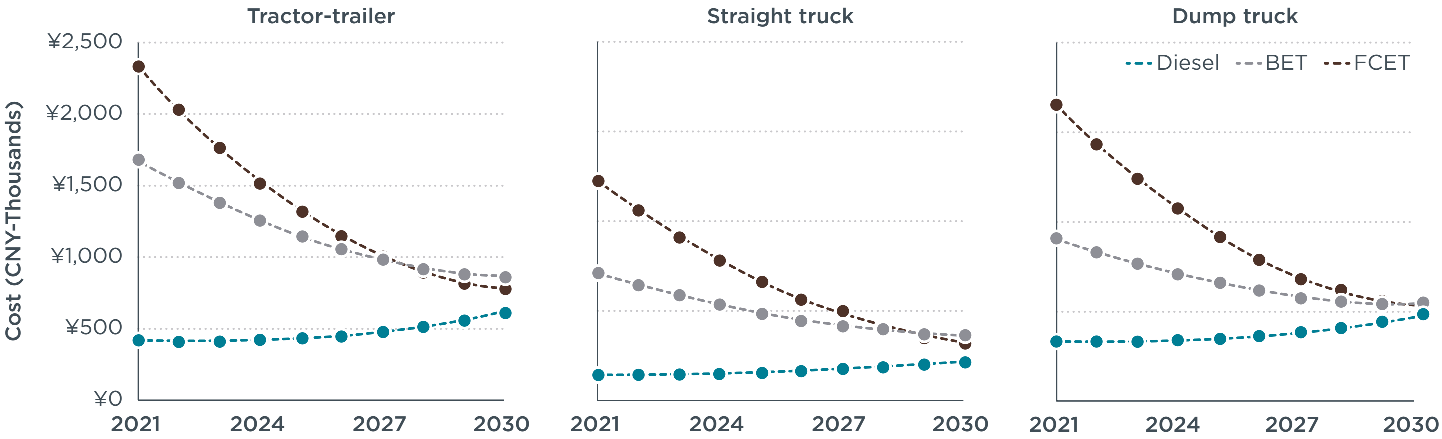

Figure 9. Estimated total truck retail price of battery-electric, fuel cell electric, and diesel technologies in the 2020–2030 period

Truck financing

The People's Bank of China (China's central bank) and China Banking and Insurance Regulatory Commission (CBIRC) state that truck loans shall be no more than 70% of the diesel truck price and no more than 75% of battery-electric and fuel cell electric trucks prices since 2018 (PBC & CBIRC, 2017). The common practice for truck financing is to apply a loan period of 3 years with 10% annual interest. **Table 10** summarizes the truck financing approach we analyzed in this study. It might be common for some truck operators to consider leasing options for their truck fleets. While not analyzed in this paper, we estimate that the financial costs of leasing are similar to those of purchasing with loans.

Table 10. Summary of truck financing information

Maximum share by loans			Duration	Interest rate
DT	BET	FCET		
70%	75%	75%	3 yr	10%/yr

Residual value

The truck residual value due to depreciation is dependent on its power train technology and type of application. In China, trucks are allowed to operate for 15 years at most (MOF et al., 2013), resulting in a zero residual value after 15 years of operation. However, vehicles with battery-electric and fuel cell electric truck technologies may depreciate faster than normally expected. It is reported that the residual value for secondhand trading is falling lower than 60% for most electric models (China Economic Daily, 2019). For this study, the depreciation should also consider the battery and fuel cell pack replacement due to aging and durability concerns. In this study, we consider both the truck depreciation and its corresponding power unit depreciation as well (battery and fuel cells).

Regarding the truck depreciation without its power unit, we adopt a twofold depreciation model similar to Feng & Figiliozi (2012): (1) fixed depreciation rate due to time passage, typically ranging between 5 and 10% per year (Machado et al., 2021), and (2) a variable depreciation rate as a function of the number of kilometers driven per year. Thus, there exists a different depreciation curve for each truck application as shown in **Figure 10**. The fixed depreciation term is considered to be 7.5% per year, an average value in the typical 5%–10% range while the variable depreciation rate per km is tuned in such a way that the residual value of the truck reaches zero after 15 years. The shape of each curve is highly influenced by the annual vehicle kilometers traveled, which varies among the different types of truck and also changes from year to year as will be explained later in this study (see section "Annual vehicle kilometers"). Because this study tackles the first use of trucks over 5 years only, we are interested in the residual value of each truck after 5 years of operation, which is highlighted on the figure.

Regarding the depreciation of the battery and fuel cell packs, it is assumed that no replacement is needed for both power units as the battery pack can achieve more than 2,000 cycles (Wang et al., 2011), roughly equivalent to 5 years of operation, and the fuel cell pack durability permits up to 5 years of operation as reported by Burke & Sinha (2020). As for the residual value of the battery pack, it will be dependent on the repurposed battery selling price for its second-life use case. The National Renewable Energy Laboratory (NREL) predicts that these batteries will be 30%–70% less expensive when compared to new batteries (Neubauer et al., 2015), and considering the projected price of the battery pack, the residual value of the battery pack could be around 15% of its purchase cost. Improvement in battery cycle life is also expected to ramp up in the years ahead, reaching one to two times the current battery cycle life according to the Battery 2030+ Initiative (Battery 2030+, 2020).Three scenarios for battery pack residual values are presented in **Figure 11** with low, medium, and high battery life-cycle improvements. Note that these residual values correspond to the DMC of the battery, and they do not include the ICMs.

As for the fuel cell packs, end of life is yet to be reached for several trucks currently in operation, and second-life studies and applications are still immature (Deloitte China & Ballard, 2020). In this study, the fuel cell pack residual values are adopted from SAE China Roadmap 2.0 (SAE-China, 2021), and they are presented in **Figure 11**. This residual value corresponds to the fuel cell pack excluding the raw material and precious metals used in the fuel cell unit and also excluding the ICMs. We assume that these precious metals can be recovered at 100% residual value.

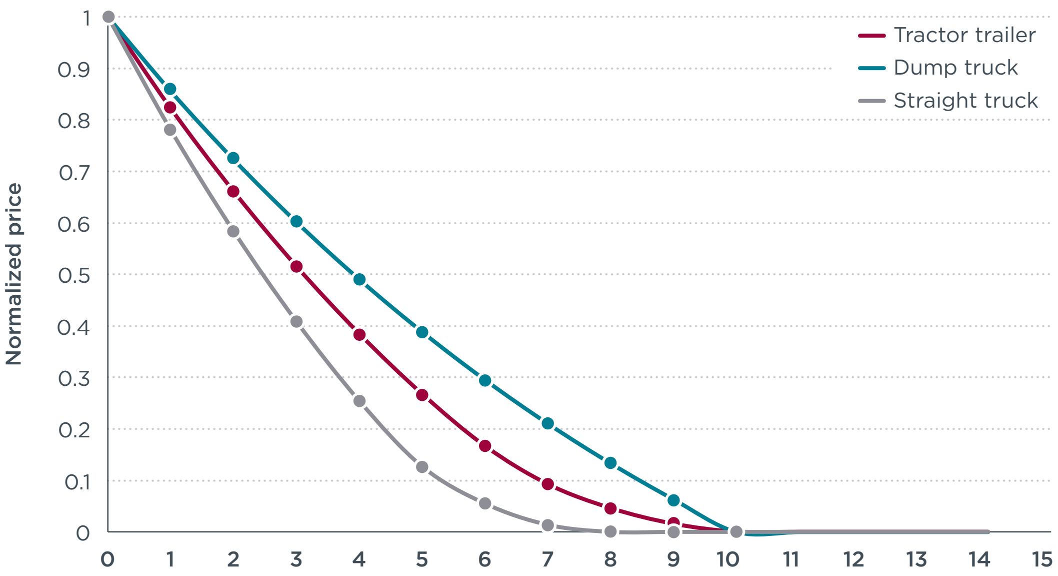

Figure 10. Depreciation curve of HDV by truck application

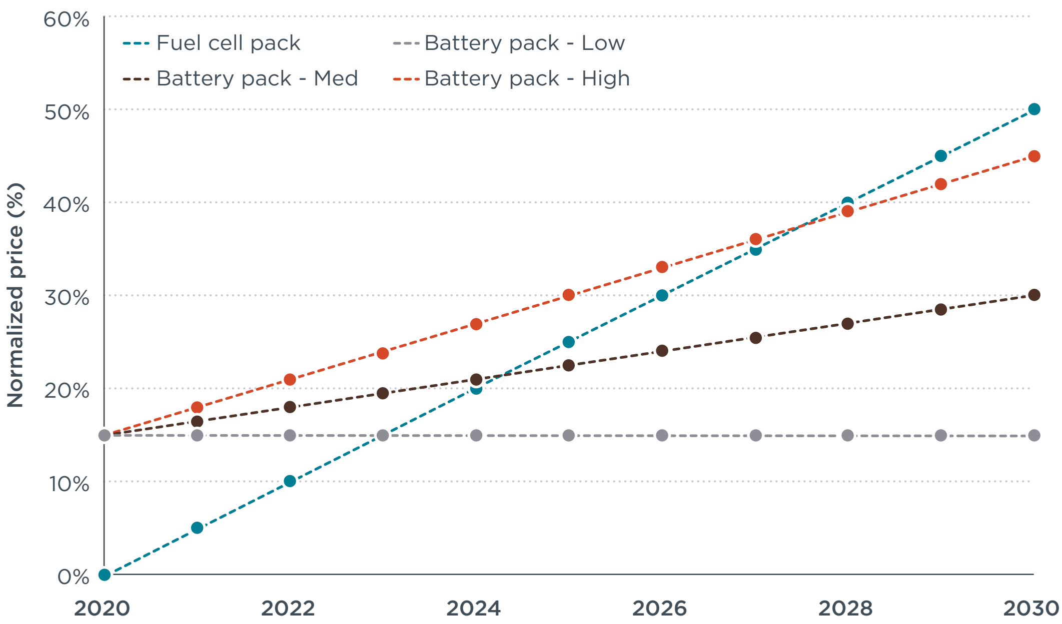

Figure 11. Battery and fuel cell packs' 5-year residual values as function of model year

Registration and ownership taxes

The tax system of trucks in China consists of a registration and purchase tax and an ownership tax. While diesel trucks are required to pay a registration tax and ownership tax, battery-electric trucks and fuel cell trucks are, so far, waived from all taxes (MOF et al., 2018); however, it should be expected that registration and ownership taxes will be applied to alternative fuel trucks in the next couple of years. Here, we assume that all taxes will still be waived for alternative fuel trucks from 2026 onward (Beijing Investment Promotion Service Center, 2018; People's Government of Shanghai, 2011; People's Government of Shenzhen, 2013).

Table 11. Summary of tax information on trucks per technology

City	Diesel		Battery-electric		Fuel cell	
	Registration tax	Ownership tax (CNY/curb weight in tonnes*yr)	Registration tax	Ownership tax (CNY/curb weight in tonnes*yr)	Registration tax	Ownership tax (CNY/curb weight in tonnes*yr)
Beijing	10%	96	0%	0	0%	0
Shanghai	10%	90	0%	0	0%	0
Shenzhen	10%	96	0%	0	0%	0

Discount rate

Table 12 summarizes the discount rates analyzed for similar TCO studies in China. In this study, we are considering a 10% discount rate in the TCO analysis.

Table 12. Summary of discount rate assumptions for TCO analysis

Discount rate assumption in other studies	Source
4%, 7%, 10%	(Meszler et al., 2019)
5%	(Hsieh & Green, 2020)
10%	(Agenbroad et al., 2016)
10%	(Zhu et al., 2016)

OPERATIONAL COSTS

Annual vehicle kilometers traveled

Operational costs are proportional to the distance covered by the trucks in a given year. Therefore, the TCO calculations are highly sensitive to the choice of value for annual VKT. However, there are no official statistics available that document the annual VKT of the different truck segments analyzed in this study. Therefore, we performed an extensive literature review to estimate the annual VKT per truck segment in China as summarized in **Table 13**.

Table 13. Literature summary of VKT estimates for HDVs in China

VKT range	Notes	Source
~106,500 km	Development for the first national census on pollution sources	(China.org.cn, 2010)
~114,418 km	Survey of 698 truck drivers in the Guangdong Province, HDVs over 20 tonnes	(CAI-Asia Center & World Bank, 2010)
29,200–82,000 km	Authors acknowledge there is very little information on the VKT variation	(Huo et al., 2012)
50,000–80,000 km	Beijing and Tianjin, increasing steadily from the lower bound from 2001 until 2010	(Lang et al., 2012)
48,000–182,500 km	Range for all road freight, including rigid trucks, and short-/long-haul tractor-trailers	(China Federation of Logistics Purchasing, 2016)
150,000–200,000 km	Long-haul tractor-trailer	(CATARC, 2016 as reported by Xing et al., 2016)
> 200,000 km	Heavy logistics truck, high frequency	
80,000–100,000	Dump truck	
100,000–150,000 km	Long-haul freight truck	(CATARC, 2018)
250,000–300,000 km	Delivery vehicles owned by express enterprises	
~50,000	Urban logistics distribution vehicle	

The VKT estimates found in the literature range widely and in many cases lack details to assess the vehicle type, the specific application of the vehicles (i.e., the use case), evaluation year, and location. However, recent reports by CATARC[10] do provide solid estimates for the vehicle segments and use cases for this study. In particular, we based our estimates on the lower range of the VKT reported by Xing et al. (2016).

It is necessary to account for the survival rate of the average truck because as the number of trucks in service declines with age, so does the average VKT. The age distribution of road tractors in service in China is subject to significant uncertainty. Details on the survival rate or the VKT dependence on age found in the literature are summarized in **Table 14**.

Table 14. Literature review of survival rates for trucks in China

Survival rate information	Notes	Source
50% after 13 years for heavy- and medium-duty trucks	Survival patterns modeled by a Weibull distribution	(Hao et al., 2011)
50%–65% reduction in VKT after 8 years	Estimates for cities of Yichang and Foshan. No specifics on the vehicle type or use case	(Huo et al., 2012)
~60% survival rate after 10 years for rigid trucks and after 12 years for tractor-trailers	Survival patterns modeled by a Weibull distribution	(W. Li et al., 2015)
Average retirement age of 8 years for tractor-trailers, 10 years for heavy logistics truck, and 3 years for dump trucks	Data obtained from four large truck manufacturers in China	(CATARC, 2016 as reported by Xing et al., 2016)
~90% survival rate after 5 years, ~50% after 10 years, 0% after 15 years	Modeled based on available literature and mandated scrappage after 15 years	(Meszler et al., 2019)

As was the case for the VKT estimates, survival rate estimates range widely in the literature, mainly regarding the age associated with a 50% survival rate. However, survival rates found in the literature in the first 5 years tend to be similar, with only a small reduction in the rate of survival. For this study, we base the survival rate curve on previous work done by the ICCT (Meszler et al., 2019) and use the selected curve to adjust the VKT. The 100% scrappage age, that is, the year for a survival rate of 0%, is adjusted for each vehicle segment to total a lifetime of approximately 1 million kilometers.

The resulting VKT as a function of age for each vehicle segment studied is shown in **Figure 12**. These VKT profiles are considered to be representative of the typical usage of the vehicle segments analyzed. Still, given that the annual VKT varies significantly across regions and applications, we performed a sensitivity analysis on this input variable (see section "Sensitivity analysis").

10 CATARC is a centralized, state-owned technical organization that provides services to the auto industry and the national government and acts as the primary vehicle testing authority in China.

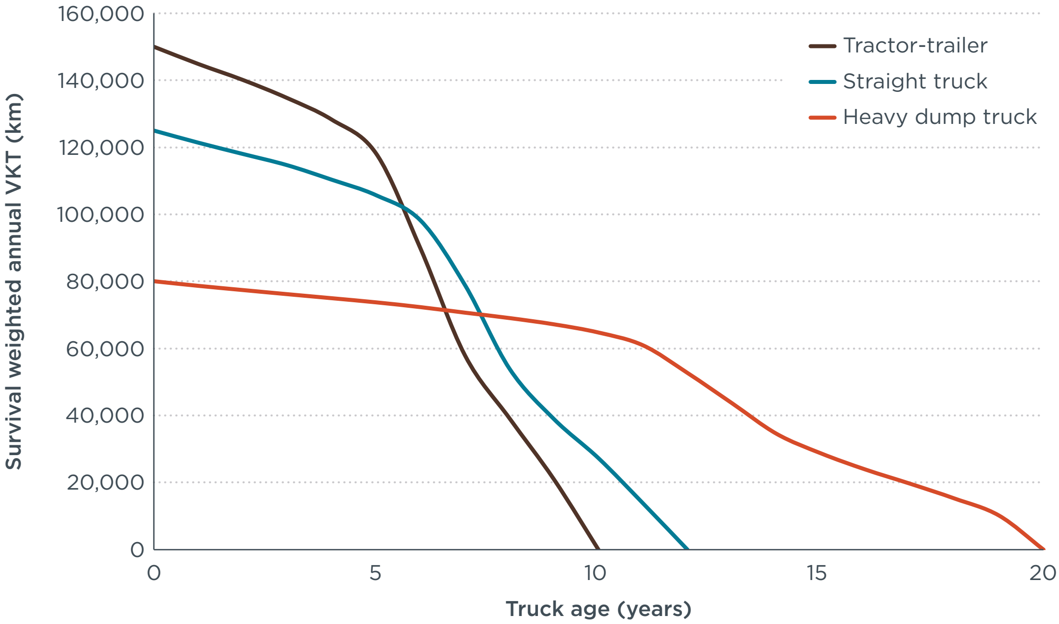

Figure 12. Annual VKT for the three truck segments adjusted by the estimated survival rate

Maintenance costs

Maintenance costs vary greatly depending on the truck application and power train technology. Several studies and reports in the literature highlight the maintenance costs of diesel trucks, but very few present a detailed description of HD-NEV maintenance costs. First, maintenance costs for diesel trucks in China are estimated at 0.325[11] CNY/km as reported in Yang et al. (2018). Regarding the maintenance costs of the battery and fuel cell electric trucks, the German Aerospace Center reports a 33% reduction in battery-electric truck maintenance costs in comparison to diesel trucks and a 30% reduction for the fuel cell trucks (Kleiner & Friedrich, 2017), resulting in maintenance cost of 0.218 CNY/km and 0.228 CNY/km for the battery and fuel cell trucks respectively. Note that these numbers do not consider the replacement costs of battery and fuel cell packs.

Another variable, tire wear and changes, affects maintenance costs implicitly. Electric trucks put forth maximum torque when accelerating from the very start, subjecting tires to greater torque and friction. Tires on electric trucks can therefore be subject to greater levels of stress during running, which in turn affects tires' endurance and values (Manges, 2021). In this study, however, we do not particularly examine the difference of tire duration between electric and diesel trucks as no applicable data on this topic are available.

Table 15. Truck maintenance costs rate by power train technology

Technology	Maintenance cost (CNY/km)
Diesel	0.325
Battery-electric	0.218
Fuel cell electric	0.228

Diesel prices

As a country more than 70% dependent on oil imports, China's domestic diesel price is highly affected by crude oil prices and political risks. To maintain stable diesel prices,

11 The reported value is 0.0484 USD/km, and it is converted to CNY/km using the following exchange rate: I USD = 6.7 CNY.

China’s diesel price is guided and adjusted by the National Development and Reform Commission (NDRC) every 10 working days.

The price of crude oil fluctuated greatly in 2020 due to the COVID-19 pandemic. The price of China’s domestic diesel oil averaged 6.5 CNY/L in 2020, which will be used as the starting point for total cost analysis of diesel trucks and for simulation of diesel prices in the next decade.

China’s domestic diesel price is composed of several costs, for example, crude oil price, consumption tax, value added tax, other fees and expenses, and so on. Each component will be evaluated for future change according to the forecast price in the next 10 years.

Table 16. Oil price breakdown (Hyqfocus.com, 2019)

Component	Share
Crude oil	36.50%
Consumption tax	20.97%
Value added tax (VAT)	13.79%
Revenue for gas station	13.24%
Revenue for refinery	2.38%
Transportation and operation costs	6.90%
Other fees and expenses	6.22%
Total	**100%**

Electricity prices

Like diesel fuel prices, the electricity price system is a government-guided market in China. In this study, we analyze Beijing, Shanghai, and Shenzhen because of the high penetration rate of alternative fuel trucks in these cities. In general, electricity prices are diverse for different cities with different use cases and regions. Beijing, in particular, may charge a wide range of electricity prices depending on end use (residential, commercial, or industrial); area (district, urban area, or suburb); and time of day (peak hours, high hours, normal hours, and night hours). Beijing, Shanghai, and Shenzhen also charge prices by different voltage capacities for use of electric energy. In addition, there are extra fees on maximum potential demands of electricity and facilities in practical use (**Table 18**).

Other than electricity from normal sources, China also regulated renewable energy prices by region in 2020 (**Table 17**). Beijing is in Region II, and Shanghai and Shenzhen are in Region III: In 2020, 0.4 CNY/kWh and 0.49 CNY/kWh were charged for each region, respectively.

Table 17. Renewable electricity prices in 2020 by region

Regions	Price (CNY/kWh)
Region I (Other regions)	0.35
Region II (Beijing is included)	0.4
Region III (Shanghai and Shenzhen are included)	0.49

Table 18. Electricity prices for commercial uses in Beijing, Shanghai, and Shenzhen in 2020

City	Region	Scenario		Electricity price						
				Price by use (CNY/kWh)					Surcharge (CNY/KW*mo)	
				Voltage capacity	Peak hours	High hours	Normal hours	Night hours	Capacity	Use
Beijing (InsideEVs, 2020c)	Economic Development District	Commercial		1–10 KV	0.7787	0.7030	0.4386	0.2085	32	48
	Suburb	Commercial		1–10 KV	1.3551	1.2268	0.7081	0.2407		
Shenzhen (Shenzhen Development and Reform Commission, 2019)	All regions	Commercial	> 250kWh/mo	10 KV	1.0049		0.6524	0.2084	22	54
Shanghai (Shanghai Development and Reform Commission, 2020)	All regions	Commercial	Summer	10 KV	0.9160		0.5670	0.2130	22.68	34.02
			Others	10 KV	0.8880		0.5380	0.2660	22.68	34.02

In addition to the standard regulated prices of electricity, charging station operators will charge an additional fee, mainly referred to as overhead (OH) charges per unit of electric energy supplied to the consumer (kWh), to accommodate the initial investment in the hardware and installation costs of the charging station and also to include the different operating costs to run the station, including the demand charge tariffs imposed in each region. These additional OH charges are then composed of a capital expenses component (CAPEX) representing the infrastructure costs and an operating expenses component (OPEX) representing the running costs, such as rent, insurance, customer service, maintenance, and also the demand charge costs of the charging station. It is important to mention that these costs don't include the connection costs to the high-voltage electricity grid, which may represent a major cost component of the total charging infrastructure costs. In addition, we assume that the charging station is accommodated in an already established commercial building to be rented by the charging station operator, and thus no construction costs are considered in this analysis, only rental costs. The CAPEX estimation is based on the current and future projection of hardware and installation costs of DC chargers in China adapted from Sandalow & Hove (2020), where the 2020 hardware cost is estimated at 600 CNY/kW and the corresponding installation cost around 450 CNY/kW. This very low hardware cost in China in comparison to the global average, and the United States in particular, is mainly driven by substantial governmental subsidies for deploying new charging stations (L. Zhang et al., 2018). CAPEX reduction is expected to exceed 35% in 2030, assuming that the current subsidies are still in place then.

The OPEX are mainly composed of the electric utility bill and the costs incurred during operating the charging station, such as licensing, maintenance, customer service, and so forth. In this study we assume that the electric utility bill corresponds to 50% of the fast charging station total OPEX, and 75% of the total OPEX for the overnight charging station (Levy et al., 2020). **Table 19** summarizes the needed inputs and different assumptions used to estimate the OH charges. The charging power for each truck type is estimated based on its energy needs during the day and night (presented in the weight and range assumptions section and rounded to the nearest integer 10) while considering the available charging time.

Table 19. Inputs and assumptions used to estimate overhead charges

Truck type	Fast charging station			Overnight charging station		
	Dump truck	Straight truck	Tractor-trailer	Dump truck	Straight truck	Tractor trailer
Number of chargers	10			10		
Charger power	0	280 kW	360 kW	70 kW	70 kW	120 kW
Hardware cost	650 CNY/kW—2020 Prices					
Installation cost	450 CNY/kW—2020 Prices					
Utilization rate	33%			33%		
Charging time	0.5 hours			8 hours		
Energy rate	*f*(Region)					
Demand charge rate						
Utility bill share of OPEX	50%			75%		

The OH charges are then estimated by considering the NPV of the total incurred CAPEX and OPEX amortized to the total energy throughput during the station service life, which is considered to be 15 years in this study, while considering a 9.5% internal rate of return (IRR). **Figure 13** shows the average weighted[12] overhead charges for each truck application across the different regions for 2020 and 2030. Finally, these overhead charges will be added to the electric energy rates, resulting in the total electricity prices to be paid at the charging station.

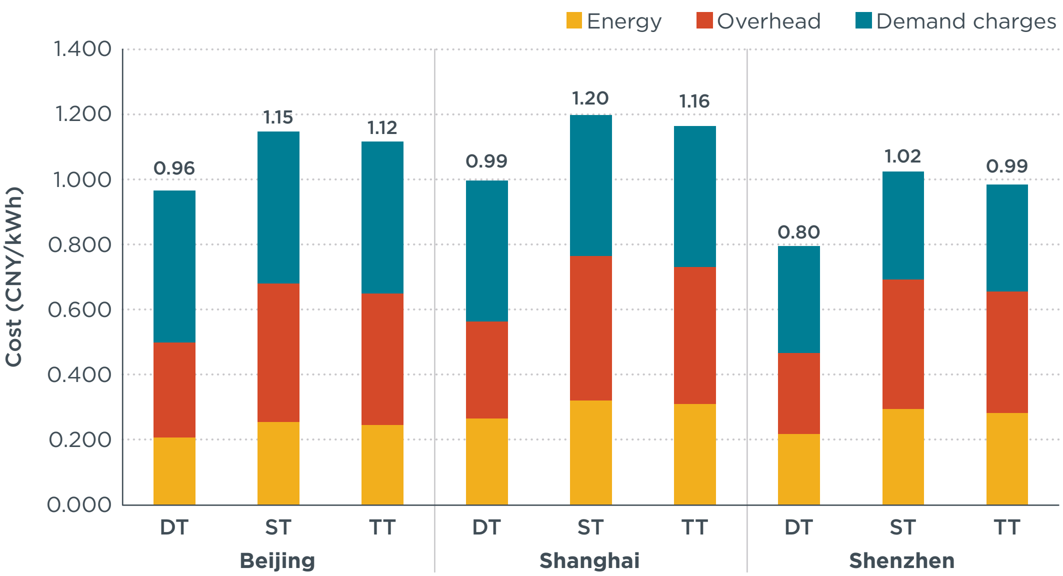

Figure 13. Average weighted total electricity prices per truck application per region in 2020 (DT: dump truck, ST: straight truck, TT: tractor-trailer)

Hydrogen prices

The price of hydrogen at the pump is affected by several factors and parameters, the major components being the cost of production, delivery of hydrogen from the production site to the fueling station, and operation of the fueling station. In this study, we provide some preliminary estimates of the 2020 and 2030 price per kg of hydrogen in three cities—Beijing, Shanghai, and Shenzhen—using two models previously developed within the ICCT (Baldino et al., 2020; Christensen,

12 The average weighted overhead charges are composed of the fast and overnight charging stations overhead charges where 80% of the energy needs are supplied overnight and only 20% are supplied through fast charging during the day.

2020). Because those models focused on the United States and the European Union, we adjusted them to include China-specific information such as data on fuel prices. However, some of the underlying assumptions from the experience of Western markets, such as electrolyzer costs, were not changed. In addition, we did not account for potential taxes collected along the hydrogen supply chain, nor the marginal profits at each stage that is likely to be passed on to consumers and reflected in the price at the pump. In other words, the final hydrogen cost in this study is merely a sum of production, delivery, and fueling costs.

Green hydrogen production: Green hydrogen is produced from renewable electricity using electrolysis. We followed the methodology in Christensen (2020) by developing two sets of discounted cash flow models: one for levelized cost of renewable electricity and the other for levelized cost of green hydrogen production in the three cities in China. To model renewable electricity price, we collected capital and operational costs of solar and wind power plants in China (CPIA, 2020; IRENA, 2019; NEA, 2020). We also collected solar and wind capacity factor in Beijing, Shanghai, and Shenzhen specifically (Burandt et al., 2019; Liu et al., 2018). For future renewable electricity price projections, we followed the cost reduction rate and technology improvement rate from NREL (2020). We assumed that green hydrogen production is directly connected to the renewable generator. This means that the modeled levelized cost of renewable electricity price is used directly as an input to the hydrogen cost model without adding grid transmission fees; in addition, the capacity factor of hydrogen production is limited by the capacity factor of renewable electricity. To model the green hydrogen production cost, we used the same electrolyzer capital and fixed operational cost in Christensen (2020) but updated the variable operational cost using modeled renewable electricity price and water price in the three Chinese cities. We also follow the same assumptions for cost reduction and efficiency improvements as (Christensen, 2020) for future hydrogen cost projection.

Blue hydrogen production: Blue hydrogen is produced from natural gas using carbon capture and storage (CCS). The estimation of blue and gray hydrogen production costs is based on the model developed by Baldino et al. (2020). That model uses separate cost components covering nonfuel hydrogen production, fuel (i.e., natural gas), carbon capture and storage (CCS), and other costs for blue hydrogen. We collected retail natural gas prices for industrial users in the three Chinese cities and plugged them into the model. We updated other (nonfuel) costs and CCS costs in Baldino et al. (2020) using China specific inputs from other studies (China Hydrogen Alliance, 2019; Jiang et al., 2019; Liu et al., 2018; S. Zhang & Peng, 2018). For the projection of blue hydrogen costs, we assumed other costs and CCS costs remain constant, at current levels, because the steam methane reforming (SMR) technology of producing hydrogen from natural gas is already relatively mature and is unlikely to experience significant cost reductions. Regarding CCS, however, there is still great uncertainty regarding future prices. Therefore, in this study, we only considered changes in fuel costs for blue hydrogen production and assumed that natural gas prices in China follow the growth trend of the global market (EIA, 2020).

Hydrogen delivery—pipeline transport: We assumed that China builds pipeline networks for hydrogen delivery due to its economic advantage in large-scale and long-distance transport compared to other forms of hydrogen delivery (China Hydrogen Alliance, 2019). We updated the per meter cost of building new transmission pipelines in the model, which was developed by Baldino et al. (2020), using Chinese information (EV100, 2020). We estimated the potential pipeline distance for the three cities with respect to the size of each city and number of fueling stations, which are detailed in the next section. We amortized the calculated total pipeline cost over the pipeline lifetime of 20 years. We then used annual hydrogen delivery volume (next section) to estimate the per kg hydrogen transport cost.

Hydrogen fueling station: **Table 20** shows the assumptions of a number of fueling stations as well as annual hydrogen demand in 2020 and 2030 for each city. We estimated the number of fueling stations based on existing and planned projects in the city, such as Beijing (Beijing Municipal Bureau of Economy and Information Technology, 2020) and Shanghai (SHEITC, 2020). We assumed all fueling stations in 2020 have a capacity of 500 kg hydrogen per day, which is typical today (Si & Yu, 2019). For 2030, we assumed about one-third of the fueling stations are of the same capacity as in 2020, while the rest have a greater capacity of 1,000 kg hydrogen per day to meet higher demand. Based on these assumptions, we calculated the annual hydrogen demand, shown in **Table 20**. In terms of cost in 2020, we took the average fueling station cost in China from three studies, which have fueling station capacity around 500 kg (China Hydrogen Alliance, 2019; EV100, 2020, p. 100; Si & Yu, 2019). For future cost projections, we assumed cost reductions of 1% annually from 2020 to 2030 for 500-kg fueling stations, following a previous study (CARB, 2019). From there, we followed the commonly used exponential relationship between equipment capacity and cost, which is a scaling factor of 0.7, to estimate the cost of 1,000-kg fueling stations.

Table 20. Assumptions of the number of fueling stations and annual hydrogen demand in 2020 and 2030 in Beijing, Shanghai, and Shenzhen

Year	Beijing		Shanghai		Shenzhen	
	2020	2030	2020	2030	2020	2030
Number of fueling stations	25	150	10	150	5	50
Annual hydrogen demand (tonne)	4,562.5	45,625	1,825	45,625	912.5	15,512.5

Table 21 and **Table 22** show the modeled at-the-pump cost of blue and green hydrogen in the three Chinese cities in 2020 and 2030. We also considered the impact of policy support on hydrogen cost. There are typically two forms of financial support provided to hydrogen fueling stations: (1) a grant for fueling station construction, and (2) a subsidy, capped at 20 CNY/kg of hydrogen fueled. Currently, Beijing and Shenzhen do not provide any form of financial support, while Shanghai provides 2 million CNY per fueling station as the construction grant. The current financial support scenario factors in the existing policy impact on the final cost. We also provide a hypothetical scenario that all three cities provide a 20 CNY/kg subsidy on top of current policy design. Blue hydrogen prices with no financial support are considered in this analysis unless stated otherwise.

Table 21. Modeled at-the-pump cost of blue hydrogen in three cities in 2020 and 2030

Blue hydrogen cost	Beijing		Shanghai		Shenzhen	
	2020	2030	2020	2030	2020	2030
No financial support (CNY/kg)	43.7	38.87	46.73	36.07	54.37	46.03
With current financial support in place (CNY/kg)	43.7	38.87	42.05	32.46	54.37	46.03
Hypothetically, with the strongest possible financial support (CNY/kg)	23.7	18.87	22.05	12.46	34.37	26.03

Table 22. Modeled at-the-pump cost of green hydrogen in three cities in 2020 and 2030

Green hydrogen cost	Beijing		Shanghai		Shenzhen	
	2020	2030	2020	2030	2020	2030
No financial support (CNY/kg)	94	66.2	76.8	49.6	113.5	75.7
With current financial support in place (CNY/kg)	94	66.2	69.2	44.7	113.5	75.7
Hypothetically, with the strongest possible financial support (CNY/kg)	74	46.2	49	24.7	93.5	55.7

RESULTS

KEY FINDINGS

Figure 14 shows the additional incurred TCO for the BETs and FCETs compared to DTs for the three truck segments across the three Chinese cities. For the BET models, TCO parity relative to DT is mainly achieved during this decade. Battery-electric tractor-trailers will reach TCO parity relative to their diesel counterparts by 2029–2030, while straight trucks achieve cost parity by 2026–2027 and generate a cost advantage exceeding 100,000 CNY by 2030 relative to diesel straight trucks. Battery-electric dump trucks will become more cost-effective than diesel dump trucks as early as the middle of this decade (2024–2025), representing the most promising truck segment to be electrified at the moment. In addition, their cost advantage will reach ~200,000 CNY by the end of the decade.

Regarding FCETs, cost parity will not be achieved before 2030 for all truck segments, and the TCO of this technology is many times higher than the diesel and battery-electric trucks. FC straight and dump trucks can achieve TCO parity in the early years after 2030 with no policy interventions in place, whereas the TCO parity of tractor-trailers will be reached long after 2030. However, FC tractor-trailers witness a significant reduction in their TCO gap relative to their diesel counterparts, reaching 500,000–700,000 CNY by 2030 depending on the projected hydrogen fuel prices in each city, which is much lower than the current TCO gap of 2,800,000–3,200,000 CNY. **Table 23** summarizes the cost-parity year for each truck segment in each city.

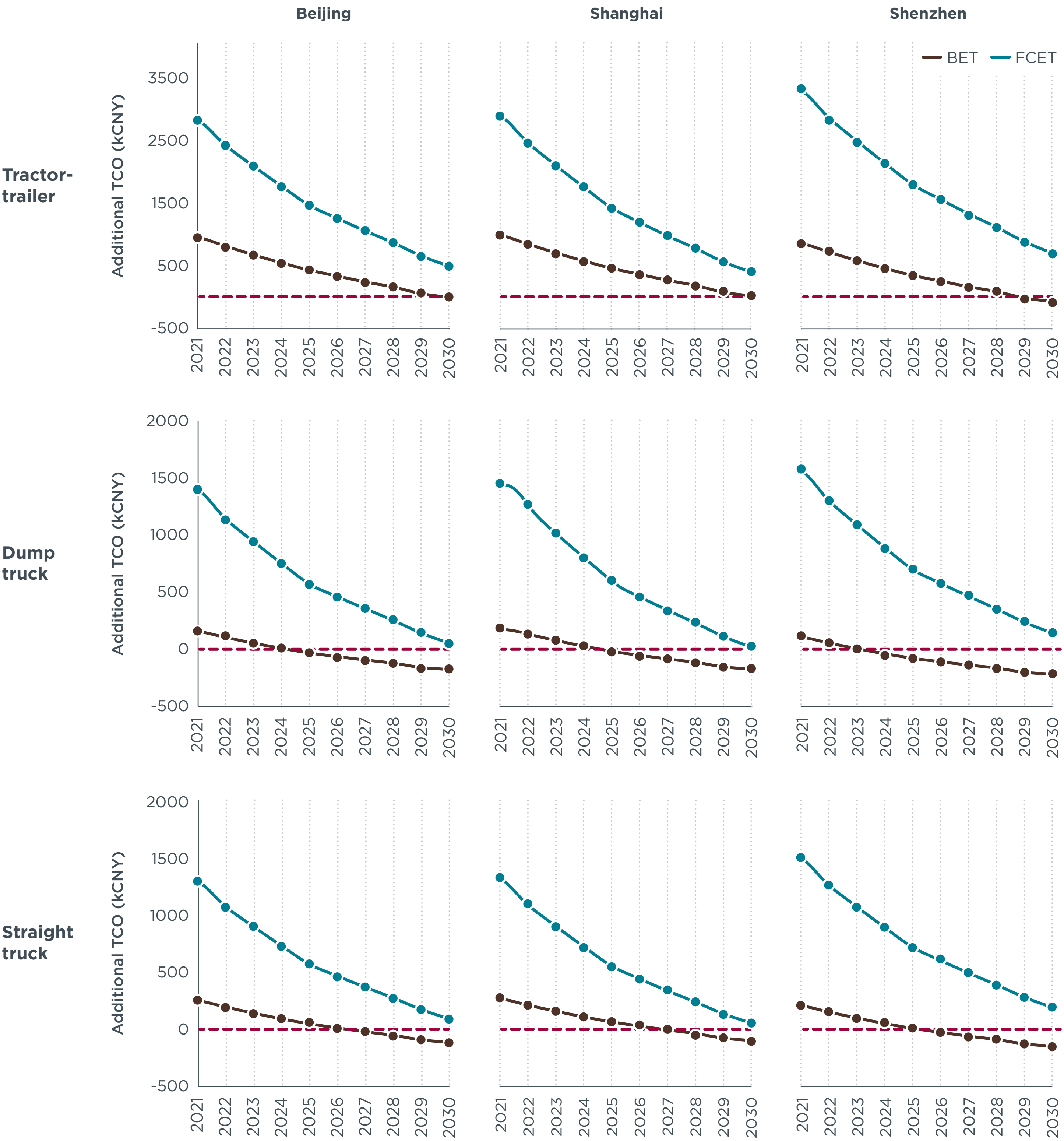

Figure 14. TCO gap variation for different truck model years relative to diesel trucks

Table 23. TCO parity year for the different analyzed truck segments

		Beijing	Shanghai	Shenzhen
Dump truck	BET	2025	2025	2024
	FCET	> 2030	> 2030	> 2030
Straight truck	BET	2027	2027	2026
	FCET	> 2030	> 2030	> 2030
Tractor-trailer	BET	2030	2030	2029
	FCET	> 2030	> 2030	> 2030

To better understand the TCO-parity behavior across the different truck segments and technologies, **Figure 15** shows the TCO breakdown for the model years 2020 and 2030 for the battery and fuel cell electric trucks relative to diesel trucks. We present only the case of Beijing, as trucks operating in other cities show a similar behavior.

Battery-electric dump trucks achieve the earliest TCO parity thanks to their substantially lower fuel costs compared to diesel dump trucks. This behavior is driven largely by two factors:

1. *Differential energy consumption*. Diesel dump trucks' fuel consumption is the highest among all truck segments, while battery-electric dump trucks benefit from energy recovery during braking, which lowers BETs' overall energy consumption. (See **Figure 6**).
2. *Differential electricity tariffs.* Battery-electric dump trucks are subject to the lowest total electricity tariffs (including energy costs, demand charges, and overhead charges) because they use a single charging station at night, which reduces overhead charges and energy tariffs (see **Figure 13**).

Other truck segments achieve TCO parity roughly by the end of the decade as their fuel costs decrease due to both efficiency improvements that offset their higher truck purchase costs and a reduction in the truck and energy storage systems and power unit costs.

Regarding fuel cell electric technologies, no truck segment is capable of achieving TCO parity with diesel technology this decade due to the substantially higher costs of fuel cell trucks and hydrogen fuels. However, by 2030, the TCO gap will narrow significantly due to improvement in the trucks' energy efficiency and reduction in hydrogen fuel costs; those two factors combined decrease fuel costs, while truck costs also continue to decrease. This dynamic is promising because it suggests that with proper policies in place, fuel cell electric technology can reach TCO parity this decade, as will be analyzed in the next section. The tractor-trailer suffers the highest TCO gap by 2030, and most of this cost difference is related to its higher fuel cost. Even by 2030, with a substantial reduction in truck fuel consumption and hydrogen prices, the fuel cell electric tractor-trailers still witness a very high fuel cost mainly driven by high hydrogen prices. This stresses the importance of subsidizing hydrogen fuel prices.

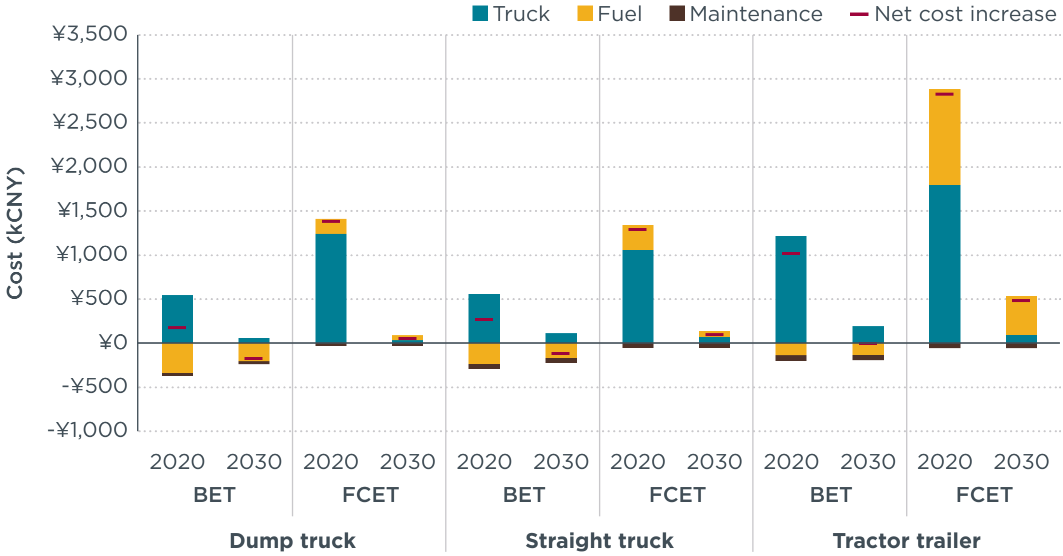

Figure 15. TCO breakdown for all truck segments and technologies relative to diesel technology: the case of Beijing

ANALYSIS OF POLICY MEASURES

This section presents a set of policies that can be implemented to accelerate the deployment of zero-emission HDVs across the cities analyzed in this study. Several types of policy interventions could be applied such as purchase premiums and in-use incentives (incentives that target the operational costs of trucks). The impact of six policy measures on TCO parity is studied:

1. Purchase premiums
2. Exempting zero-emission HDV from VKT road charges
3. Providing energy incentives for electricity and hydrogen fuel
4. Applying road GHG charges to diesel trucks
5. Imposing carbon taxes on tailpipe emissions
6. A combination of these policies

The scope of analysis is limited to assessing the impact of the aforementioned policies on the TCO of NEV and on their cost parity year. The analysis does not quantify the policy cost to the government as this is beyond the scope of this paper. In addition, the paper does not introduce policy phase-out scenarios between 2020 and 2030.

Purchase premiums

Purchase premiums are mainly paid by local authorities to help truck operators reduce their trucks' purchase costs, incentivizing adoption of zero-emission HDVs. In this study, we consider that FCETs can benefit from 400,000 CNY (Xiao, 2019) purchase premiums, while BET purchase incentives are at 252 CNY/kWh of battery capacity for a maximum of 40,000 CNY (MOF et al., 2020) for nonpublic applications. Based on the required battery size per truck as presented in the section "Weight and range assumptions," all BETs can benefit from a maximum purchase incentive of 40,000 CNY. We assume that all analyzed Chinese cities provide the same purchase premiums.

Table 24 compares the TCO parity with (w) and without (w/o) purchase incentives. Mainly, FCETs benefit the most from purchase premiums due to the high incentives at 400,000 CNY per truck, reducing the time to reach TCO parity by 2–3 years (2027–2028) for the dump and straight trucks. Tractor-trailers are still incapable of achieving TCO parity before 2030 even with purchase incentives. On the other hand, BETs do not benefit from this policy measure due to the low provided incentives at 40,000 CNY per truck, where only a 1-year reduction in its time to reach TCO parity is realized for the straight and dump trucks. However, BET purchase incentives are not high enough to move the TCO-parity point any earlier.

Table 24. TCO parity year for analyzed truck segments, with purchase premiums

		Beijing		Shanghai		Shenzhen	
		w	w/o	w	w/o	w	w/o
Dump truck	**BET**	**2024**	2025	**2024**	2025	**2023**	2024
	FCET	**2028**	> 2030	**2028**	> 2030	**2029**	> 2030
Straight truck	**BET**	**2026**	2027	**2026**	2027	**2025**	2026
	FCET	**2027**	> 2030	**2027**	> 2030	**2029**	> 2030
Tractor-trailer	**BET**	2030	2030	2030	2030	2029	2029
	FCET	> 2030	> 2030	> 2030	> 2030	> 2030	> 2030

Bold numbers indicate a change in the TCO parity year for each truck segment and technology across the different cities.

Exempting zero-emission HDV from VKT road charges

Local authorities in China apply distance-based road tolls, and those charges vary across the different truck segments. Dump trucks and tractor-trailers are subject to a 1.5 CNY/km road tolls, whereas straight trucks realize higher road tolls at 2 CNY/km. In addition, the total road tolls per truck are driven by the VKT on roads that impose road charges. **Table 25** summarizes the road tolls applied in China. This policy intervention aims at waiving 75% of the total road tolls for zero-emission vehicles.

Table 25. Summary of road charges applied in China

	Dump truck	Straight truck	Tractor-trailer
Road charges (CNY/km)	1.5	2	1.5
% of VKT with road tolls	10%	10%	50%

Table 26 shows the TCO-parity point with and without VKT road charges exemption for zero-emission trucks. The battery-electric tractor-trailer benefits the most from the policy intervention as its time to TCO parity is reduced by 3–4 years across all three cities, achieving TCO parity with its diesel counterpart no later than 2026–2027. Similarly, this policy helps the battery-electric straight truck to achieve TCO parity by 2024–2025. This significant reduction in cost-parity point for the tractor-trailer is mainly pushed by the fact that 50% of its total VKT is driven on roads that impose road tolls in China, which makes it the truck segment to benefit the most from this tax exemption.

The FCETs do experience a reduction in their TCO due to this policy intervention, amounting to around 350,000 CNY for the tractor-trailer and 30,000–90,000 CNY for the straight and dump trucks; however, the reduction is not significant enough to close the gap with their diesel counterparts before 2030, especially for the tractor-trailer (see **Figure 14**). The dump and straight trucks realize a minor benefit from this policy intervention because only 10% of their total VKT is driven on roads with imposed tolls, which explains why their TCO-parity point is not achieved before 2030, despite the very low TCO gap with their diesel counterparts by 2030 as presented in **Figure 14**.

Table 26. TCO parity year for the different analyzed truck segments with road charges exemption

		Beijing		Shanghai		Shenzhen	
		w	w/o	w	w/o	w	w/o
Dump truck	BET	**2024**	2025	**2024**	2025	**2023**	2024
	FCET	> 2030	> 2030	**2030**	> 2030	> 2030	> 2030
Straight truck	BET	**2025**	2027	**2025**	2027	**2024**	2026
	FCET	> 2030	> 2030	**2030**	> 2030	> 2030	> 2030
Tractor-trailer	BET	**2027**	2030	**2027**	2030	**2026**	2029
	FCET	> 2030	> 2030	> 2030	> 2030	> 2030	> 2030

Bold numbers indicate a change in the TCO parity year for each truck segment and technology across the different cities.

Electricity and hydrogen fuel incentives

Truck fuel cost is a major component of its TCO, and proper incentives on the fuel price can significantly shift the cost-parity point. We consider the following energy incentives for the hydrogen fuel prices and electricity prices:

- 20 CNY/kg of hydrogen incentives for the three Chinese cities analyzed in this study.
- Waiving the demand charge tariffs reducing the total electricity prices by 0.45 CNY/kWh for the straight truck and tractor-trailer and by 0.33 CNY/kWh for the dump truck.

Table 27 presents the TCO parity year with the previously mentioned energy incentives. Regarding BETs, dump trucks achieve cost parity almost immediately under this policy scenario by 2022. Compared to the case without incentives, straight trucks reach cost parity 3 years earlier by 2023–2024 across the three cities. Tractor-trailers' cost-parity point is reduced by 2–3 years, reaching TCO parity in the second half of the decade.

FCETs, on the other hand, also benefit from the proposed hydrogen fuel incentive; however, those benefits vary greatly across truck segments and also across the three cities. Dump and straight trucks reach TCO parity by 2027–2028 in Beijing and Shanghai, while in Shenzhen they do not achieve cost parity before 2029. This is due to the already higher hydrogen prices in Shenzhen (see section "Hydrogen prices"), almost 20% higher in comparison to hydrogen prices in Beijing and Shanghai. Tractor-trailers realize limited benefits in their TCO-parity point due to the already high TCO gap with their diesel counterparts (400,000–700,000 CNY in 2030), except in Shanghai where cost parity could be reached by 2028 thanks to the lower imposed hydrogen prices.

Table 27. TCO parity year for the different analyzed truck segments with energy incentives

		Beijing		Shanghai		Shenzhen	
		w	w/o	w	w/o	w	w/o
Dump truck	BET	**2022**	2025	**2022**	2025	**2022**	2024
	FCET	**2028**	> 2030	**2027**	> 2030	**2029**	> 2030
Straight truck	BET	**2023**	2027	**2024**	2027	**2023**	2026
	FCET	**2028**	> 2030	**2027**	> 2030	**2029**	> 2030
Tractor-trailer	BET	**2027**	2030	**2028**	2030	**2027**	2029
	FCET	**2030**	> 2030	**2028**	> 2030	**2030**	> 2030

Bold numbers indicate a change in the TCO parity year for each truck segment and technology across the different cities.

Apply GHG road charges on diesel trucks

Applying road GHG charges helps local authorities to address problems related to road infrastructure financing, traffic congestion, and GHG emissions. In this study, we propose GHG road charges of 0.5 CNY/km applied only on diesel trucks, in an approach similar to the EU proposal for HDVs (Council of the European Union, 2020) where a GHG road charge of EUR 8 cents/km is applied. The trucks are subject to those charges only on the roads that impose tolls. Those charges are applied on 10% of the total VKT for the straight and dump trucks and 50% of the total VKT of the tractor-trailers.

Table 28 presents the TCO parity in applying GHG road charges to diesel trucks. The battery-electric tractor-trailer segment benefits most from this policy intervention due to its high VKT on roads that impose GHG road charges (50% of its total VKT), in contrast to the other truck segments. Battery-electric tractor-trailers' TCO parity could be reached by 2028–2029, a year earlier than under a no-policy intervention scenario. FCETs do not record any improvement in their TCO parity under this policy intervention. Although tractor-trailers do benefit from significant cost reduction under this policy intervention (~150,000 CNY), their high TCO gap with their diesel counterparts limits any improvement. Straight and dump trucks benefit from ~20,000 CNY cost advantage under this policy intervention due to their low VKT on roads that impose GHG charges (only 10% of their total VKT).

Such a policy intervention, unlike other policies, is fiscally sustainable in the long term because it captures the external costs of diesel trucks incurred by society due to air and climate pollution by imposing taxes on their GHG emissions. However, if this policy is to have a significant impact on the deployment of NEV, higher GHG road charges should be applied.

Table 28. TCO parity year for the different analyzed truck segment with road GHG charges on diesel trucks

		Beijing		Shanghai		Shenzhen	
		w	w/o	w	w/o	w	w/o
Dump truck	BET	**2024**	2025	**2025**	2025	**2023**	2024
	FCET	> 2030	> 2030	> 2030	> 2030	> 2030	> 2030
Straight truck	BET	**2026**	2027	2027	2027	**2025**	2026
	FCET	> 2030	> 2030	> 2030	> 2030	> 2030	> 2030
Tractor-trailer	BET	**2029**	2030	**2029**	2030	**2028**	2029
	FCET	> 2030	> 2030	> 2030	> 2030	> 2030	> 2030

Bold numbers indicate a change in the TCO parity year for each truck segment and technology across the different cities.

Imposing tax for tailpipe GHG emissions

China launched its Emissions Trading Scheme (ETS) in February 2021 for several specific industries, creating the world's largest carbon market for the power sector (Zhou, 2021). This ETS may include carbon taxes on transport sector tailpipe GHG emissions, which would increase the TCO of diesel trucks. In this study, we assume that a carbon tax per tonne of CO_2e will be applied on diesel trucks at the rates presented in **Table 29**. The numbers presented below are based on a surveying report conducted by the China Carbon Forum in 2019, thus they are expected prices (China Carbon Forum, 2019).

Table 29. Expected carbon price in the China ETS (China Carbon Forum, 2019).

Year	2020	2025	2030
Tax (CNY/tonne CO_2e)	43	75	116

Table 30 introduces the TCO-parity point by applying the previously mentioned tailpipe GHG emissions tax. The improvement in cost parity is not significant for all truck segments and not significant for the BET and FCET technologies, driven by the very low imposed carbon tax, which is many times lower than the carbon price imposed in the European Emissions Trading Systems at 26.87 EUR/tonne CO_2e in 2020 (roughly equivalent to 210 CNY considering an exchange rate of EUR 1 = CNY 7.83), in comparison to the 43 CNY/tonne CO_2e imposed in China. The diesel fuel carbon intensity at the tailpipe (tank-to-wheel) is assumed to be 2627 gCO_2e/liter of diesel fuel.

Therefore, if this policy is to make an impact on advancing the TCO-parity point of BETs, the imposed GHG tailpipe emissions tax should be 3–5 times higher for straight trucks to reach cost parity in the next 2–3 years, and 10 times higher if tractor-trailers are to reach cost parity by the middle of the decade. FCETs require substantially higher carbon taxes, which cannot be justified under this policy.

Table 30. TCO parity year for different truck segments, with the tailpipe GHG emissions tax applied

		Beijing		Shanghai		Shenzhen	
		w	w/o	w	w/o	w	w/o
Dump truck	BET	**2024**	2025	**2024**	2025	**2023**	2024
	FCET	> 2030	> 2030	**2030**	> 2030	**2030**	> 2030
Straight truck	BET	**2026**	2027	2027	2027	**2025**	2026
	FCET	> 2030	> 2030	> 2030	> 2030	> 2030	> 2030
Tractor-trailer	BET	2030	2030	2030	2030	2029	2029
	FCET	> 2030	> 2030	> 2030	> 2030	> 2030	> 2030

Bold numbers indicate a change in the TCO parity year for each truck segment and technology across the different cities

Policy package

In this section, we consider a policy package that includes the five aforementioned policy interventions together. **Figure 16** shows the TCO parity for all BET segments with all policy incentives applied where the data labels highlight their cost advantage relative to diesel trucks. All BET segments reach immediate cost parity with their diesel counterparts by 2021–2022.

On the other hand, FCETs cannot reach TCO parity with diesel trucks during this decade without policy interventions as shown in **Figure 17**, where most FCET segments still realize a considerable TCO gap relative to diesel trucks as shown in the data labels for the year 2030. The benefits of FCETs become more significant when the five policies are combined, which allows FCETs to reach TCO parity in the next 3–4 years, except for the city of Shenzhen, which witnesses a delayed cost-parity point by 2 additional years due to higher imposed hydrogen fuel prices.

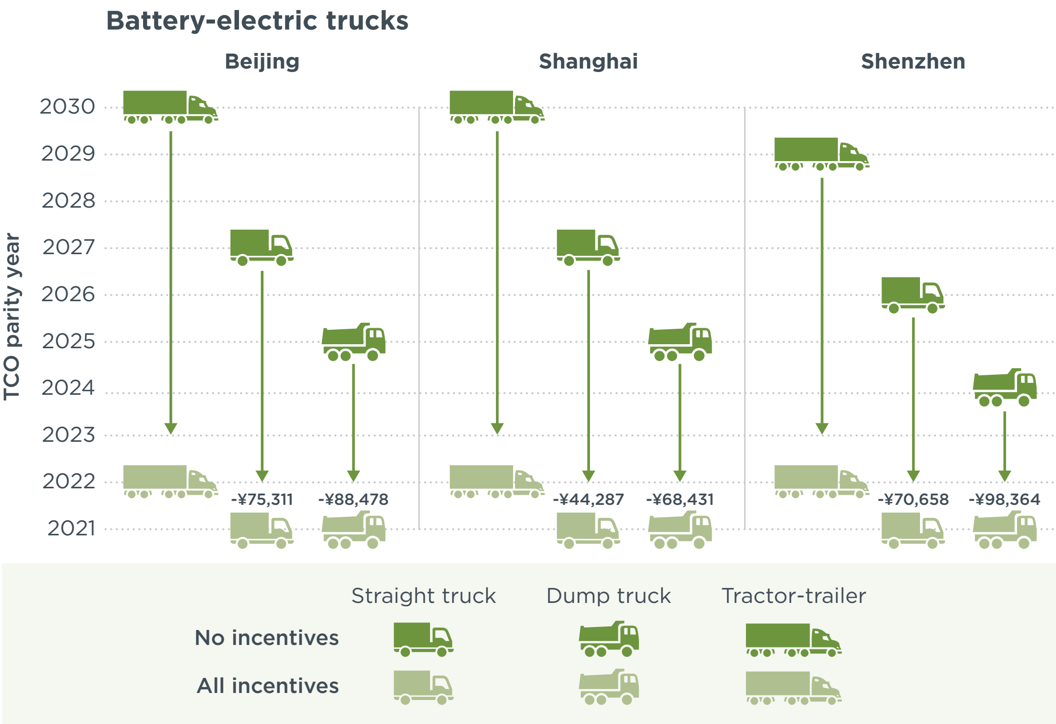

Figure 16. TCO parity year for BETs with all incentives applied (data labels correspond to TCO gap relative to diesel trucks)

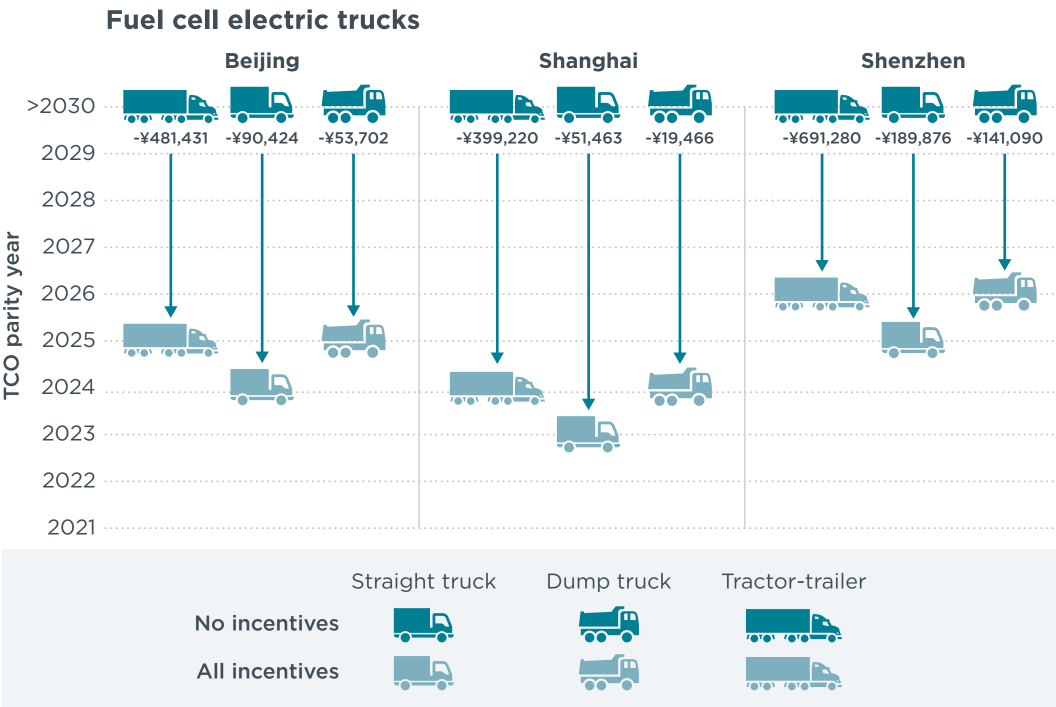

Figure 17. TCO parity year for FCETs with all incentives applied (data labels correspond to TCO gap relative to diesel trucks)

Other policies not analyzed

At the local level, some cities are setting up zero-emission zones to regulate vehicle access. Only vehicles that meet environmental performance standards set for the zones are granted unrestricted access. Chengdu, the capital of Sichuan province, is seeking a holistic implementation of its zone to improve local air quality. Hence, Chengdu allows only zero-emission logistics vehicles within urban areas, while conventional trucks are banned during most daytime hours (EVHUI, 2019).

Given the uncertainty regarding the level of such access charges and the frequency of trips into the zero-emission zones, we did not attempt to quantify the impact on TCO.

SENSITIVITY ANALYSIS

Annual VKT and driving range

The truck's annual vehicle kilometers traveled (VKT) and daily driving range have a significant impact on its TCO, which may shift its time to reach cost parity. The annual vehicle kilometers traveled (AVKT) and daily driving range may vary geographically across the Chinese cities studied. For this reason, a sensitivity analysis is performed in this section considering several scenarios of AVKT and daily driving ranges. The trucks in this study are designed to operate for a certain range each day and are assumed to provide 1 million kilometers of service over their lifetimes. This section explores several scenarios for the annual VKT and daily driving range for each truck segment as presented in **Table 31** with the reference scenario referred to as the "high scenario," meaning a high level of daily driving range. Two other scenarios are introduced representing a 20% (medium scenario) and 40% (low scenario) reduction in the daily driving range and annual VKT relative to the high scenario. The required battery size is estimated based on the driving range sensitivity analysis presented in **Figure 5**, whereas the hydrogen storage tank size is assumed to change linearly with the variation in the daily driving range as the hydrogen tank weight has a negligible impact on the FCET energy consumption.

Table 31. Annual VKT and daily driving range sensitivity scenarios

	Dump truck				Straight truck				Tractor-trailer			
	Battery size (kWh)		Hydrogen tank[13] (kg)		Battery size (kWh)		Hydrogen tank (kg)		Battery size (kWh)		Hydrogen tank (kg)	
Scenario	2020	2030	2020	2030	2020	2030	2020	2030	2020	2030	2020	2030
Low (-40%)	216	162	10.8	6.9	221	163	10.8	6.9	485	340	25.5	15
Med (-20%)	288	216	14.4	9.2	295	225	14.4	9.2	660	445	34	20
High (ref)	365	275	18	11.5	375	270	18	11.5	845	550	42.5	25

For brevity, we present in this section the results of just two truck segments and two cities. **Figure 18** presents the case of the Beijing tractor-trailer BET under the three scenarios. On the left panel, the evolution of the truck TCO difference relative to the diesel truck is plotted as a function of the model year. The general behavior is that for the low VKT scenario, the TCO difference decreases, allowing the tractor-trailer to reach TCO parity sooner (2029 for low VKT in comparison to 2030 for high VKT). There are two opposing factors driving this behavior, and this can be explained by analyzing the truck and fuel costs variation across the three scenarios as presented in the right panel of **Figure 18**. With lower VKT, the truck cost decreases due to a reduction in the required battery size as previously explained. On the other hand, the BET fuel cost advantage when compared to diesel becomes less for lower truck VKT, increasing the time to reach cost parity in this case. However, the former factor is dominant in this case as the overall time to reach cost parity decreases with lower VKT. In other words, truck applications with shorter routes and low daily driving ranges can achieve cost parity more easily due to their smaller batteries. Other truck segments witness a less sensitive behavior with negligible variation in time to parity mainly due to their lower battery sizes and lower cumulative VKT over the 5-year analysis period of this study.

13 This is the usable hydrogen fuel weight inside the tank. The hydrogen storage tank weight is estimated to be at 20kg/kgH2 fuel.

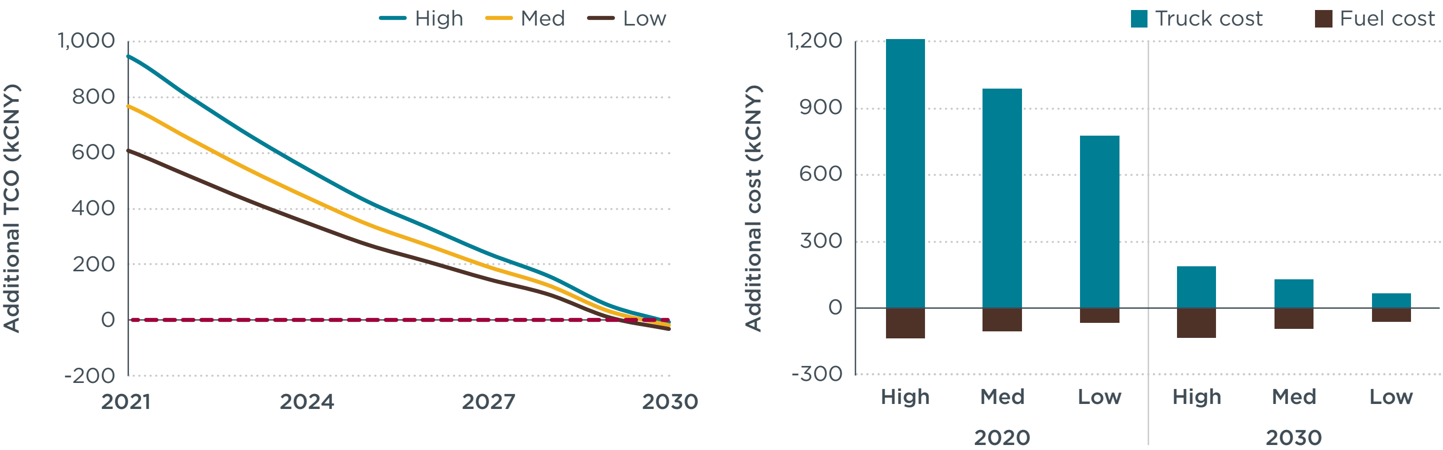

Figure 18. Annual VKT and daily driving range sensitivity: the case of the Beijing tractor-trailer BET

Figure 19 presents the case of the Shenzhen dump truck BET under the three scenarios. Although the battery-electric dump truck achieves cost parity with the diesel truck under all VKT scenarios in 2024, it is interesting to analyze the TCO gains. By 2030, the low VKT scenario is resulting in a higher TCO difference when compared to diesel trucks (lower TCO benefits in comparison to diesel dump trucks), an opposite behavior to what is observed in the previous case of Beijing tractor-trailers. In this case, the reduction in the truck cost at lower VKT is more than compensated by the reduction in fuel cost benefits as shown in the right panel of **Figure 19**. This is mainly driven by the low electricity costs in Shenzhen, the lowest among all other cities at 20% less in the case of the dump truck.

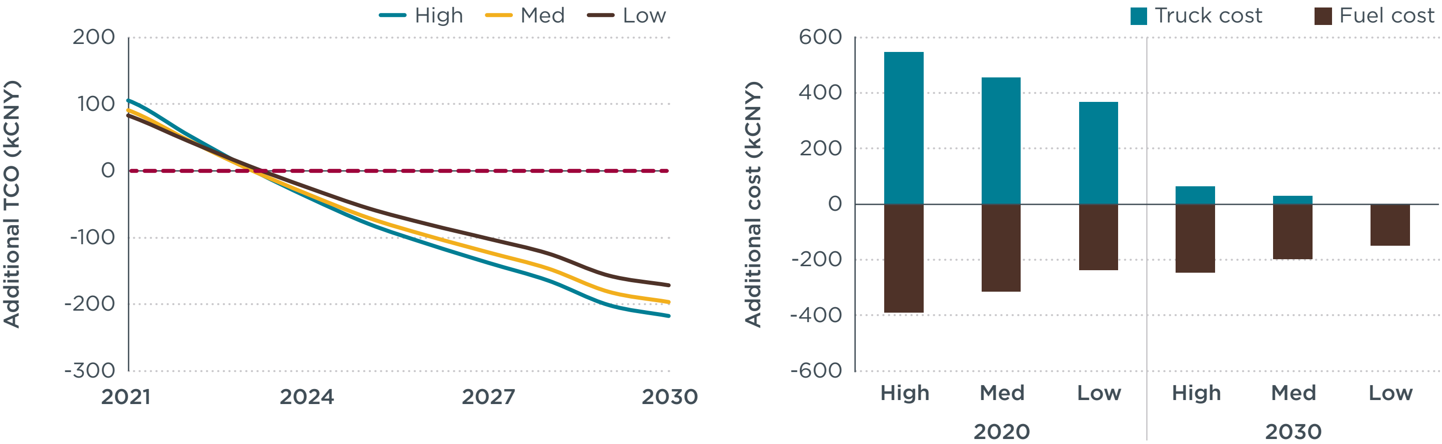

Figure 19. Annual VKT and daily driving range sensitivity: the case of the Shenzhen dump truck BET

For the FCET, one case is presented here for brevity. **Figure 20** presents the case of Beijing tractor-trailers FCET under the three scenarios. Lower VKT results in a lower TCO difference relative to the diesel truck thanks to the reduction in the cost of both the truck and the fuel. At lower VKT, the hydrogen storage tank becomes lighter, reducing the total truck cost. However, the main driver behind this behavior is the reduction in cost of hydrogen fuel. By considering fuel prices and truck fuel economy, the distance-specific fuel cost for the FC tractor-trailer in Beijing is 3.7 CNY/km in 2020, whereas diesel trucks benefit from a reduced cost, at 1.76 CNY/km in 2020; those numbers decrease to 1.94 CNY/km for the FCET and 1.20 CNY/km for the diesel truck. This explains the reduction in the fuel cost gap at lower VKT between the fuel cell and diesel trucks. Other truck segments show a similar behavior but with less sensitivity to the variations in the VKT due to their lower cumulative VKT and hydrogen fuel consumption relative to the tractor-trailer.

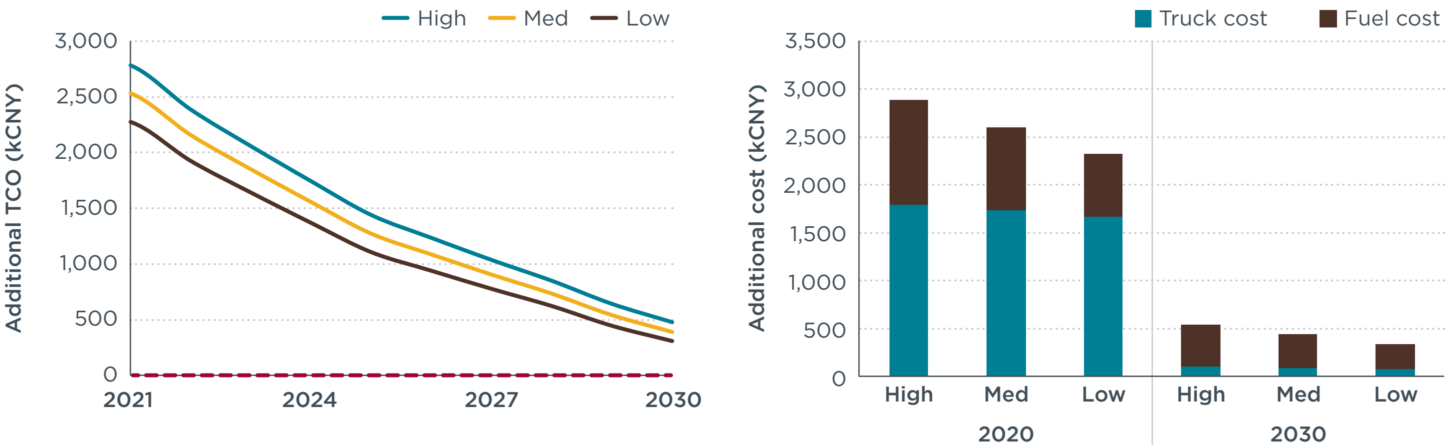

Figure 20. Annual VKT and daily driving range sensitivity: the case of Beijing tractor-trailers FCET

Renewable electricity and green hydrogen

China's current electric grid is still predominantly supplied by thermal power plants. To date, coal-based power supply accounts for more than 60% of China's total grid capacity (Baležentis & Štreimikienė, 2019). Even though China's State Grid Corporation, which runs most electric utilities and grids across the country, is committed to increasing the proportion of nonfossil fuels in primary energy consumption to 25% by 2030 (Zheng, 2021), supply from coal-based plants will still account for almost half of total generation mix capacity—leaving a grid that is still too dirty. To fully exploit the environmental benefits of NEV in China and significantly reduce the well-to-wheel (WTW) CO_2 emissions of HDV, we examine the impact of using 100% renewable electricity and green hydrogen fuel on TCO parity. For brevity, we present only the tractor-trailer and dump truck scenarios for Shenzhen and Shanghai, as presented in **Figure 21**. The choice of those two cities is based on our estimation that the price of green hydrogen will be lowest in Shanghai and highest in Shenzhen (see section "Hydrogen prices").

For the battery-electric tractor-trailer, the use of renewable electricity delays the cost parity with diesel trucks beyond the end of the decade, due to the higher price of renewable electricity. However, the TCO gap relative to diesel trucks drops below 750,000 CNY by 2025; that is, with proper electricity incentives, battery-electric tractor-trailers can still achieve cost parity by the middle of this decade even with renewable electricity. Dump trucks are already at cost parity with diesel trucks under the current electricity market prices in China by 2025, and their parity point is delayed until 2028 when using renewable electricity. This delay in cost parity is not significant, as the TCO gap in 2025 between battery-electric and diesel dump trucks is just around 100,000 CNY when using renewable electricity, a figure that can be narrowed by doubling the current truck purchase premiums (around 40,000 CNY per BET). Renewable electricity does not have a major impact on the BET cost parity point with diesel trucks, and setting proper policy interventions can easily narrow the TCO gap resulting from the use of expensive renewable electricity.

The use of green hydrogen for FCETs further delays their cost parity with diesel trucks. In Shanghai, where the green hydrogen fuel prices are expected to be the lowest, the TCO gap between the fuel cell tractor-trailer and its diesel counterpart is around 1 million CNY by 2030 when using green hydrogen fuel, significantly higher than the gap while using blue hydrogen fuel, at 400,000 CNY in 2030. In the case of Shenzhen, this gap will even be higher, reaching 2 million CNY by 2030 for the tractor-trailer because we estimate the green hydrogen fuel prices to be the highest in Shenzhen among all the cities in this study. The dump truck also witnesses a similar behavior across both cities, but its TCO gap by 2030 is lower than that of the tractor-trailer due to its lower

VKT and fuel consumption. This gap is around 250,000 CNY by 2030 in Shanghai and 650,000 CNY in Shenzhen. It will be challenging for FCETs operating on green hydrogen fuel to become cost-effective during this decade unless significant policy interventions are put in place.

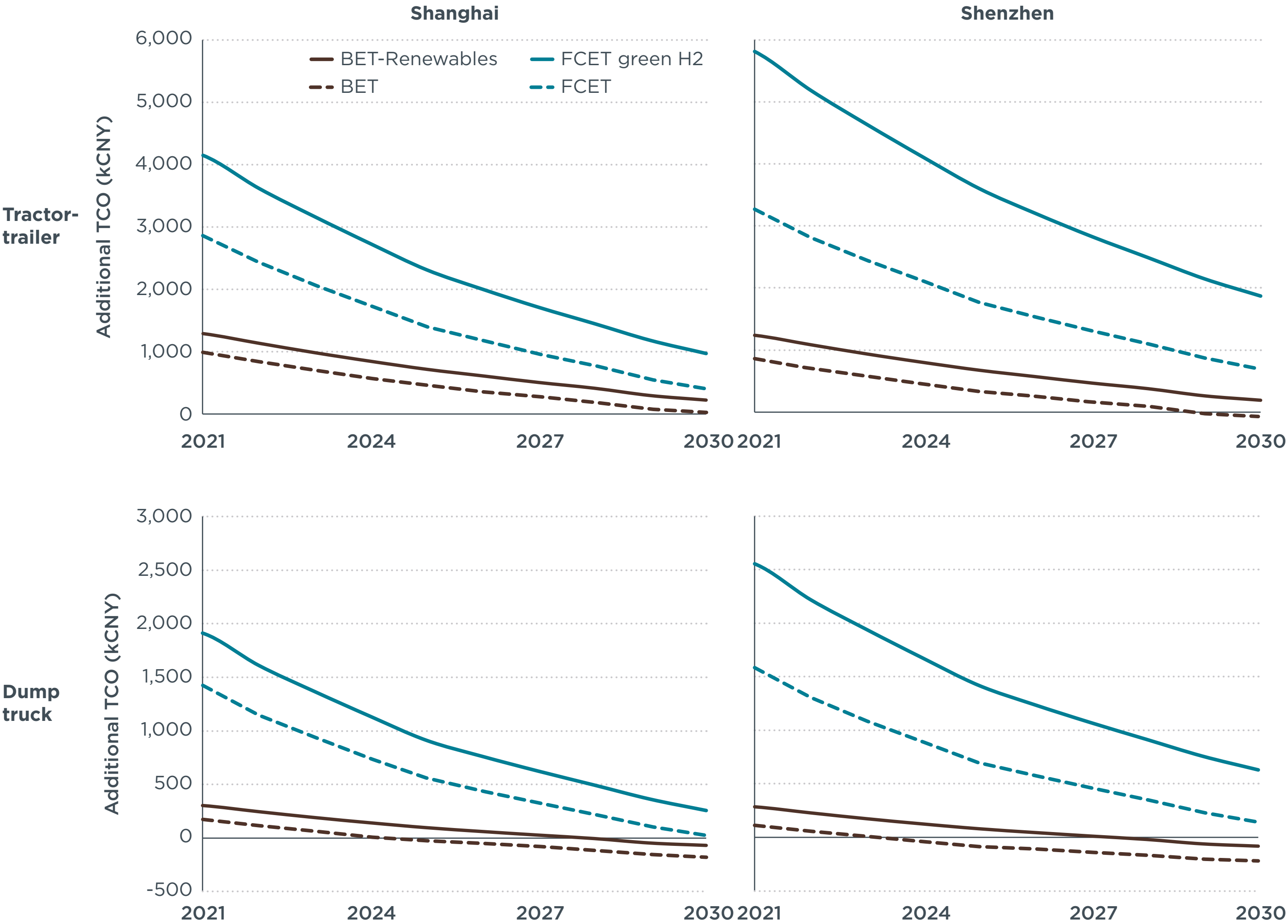

Figure 21. Impact of renewable electricity and green hydrogen on TCO

CONCLUSIONS AND POLICY RECOMMENDATIONS

As part of the Chinese government ambition to push for heavy-duty new energy vehicles (HD-NEV), this paper examines the techno-economic performance of HD-NEVs in China for three truck segments, namely dump trucks, straight trucks, and tractor-trailers. The study considers battery-electric trucks (BETs) and fuel cell electric trucks (FCETs) operating in the cities of Beijing, Shanghai, and Shenzhen. The total cost of ownership (TCO) of each truck segment and technology is assessed across the three Chinese cities between the years 2020 and 2030. We arrive at the following key findings:

» **All BET segments achieve TCO parity during this decade:** BETs witness lower energy consumption and lower fuel costs per unit of energy in comparison to diesel trucks, giving them a significant fuel cost advantage that more than compensates for the higher truck purchase costs. By the end of the decade, BET tractor-trailers are projected to be 50,000 CNY cheaper than their diesel counterparts while straight trucks will be 100,000–150,000 CNY cheaper.

» **The battery-electric dump truck will have a cost-advantage relative to its diesel counterpart as early as 2024–2025:** BET dump trucks realize a very low energy consumption thanks to the brake energy recovery feature in electric power trains, while diesel dump trucks have the highest fuel consumption across all segments due to the highly transient driving behavior. This provides the BET dump truck with a substantial fuel cost advantage making it cost-effective by 2024–2025. In addition, dump truck charging solely takes place at night, resulting in reduced electricity costs and overhead charges.

» **FCET cost parity is reached beyond 2030 for all truck segments:** Dump and straight tucks can achieve cost parity just after 2030, mainly driven by the fuel cell unit cost reduction due to economies of scale and a slight reduction in hydrogen fuel cost. Tractor-trailers will reach cost parity far beyond 2030, but the cost gap relative to their diesel counterparts can go below 500,000 CNY by 2030, so that proper incentives can make them cost-effective by 2030.

» **The use of renewable electricity to power BETs shifts the time to TCO parity by 3 years:** Despite the higher costs of renewable electricity compared to the current electricity generation mix in China, the impact on the TCO parity is quite limited as BET dump trucks powered by renewable electricity are already at cost parity by 2027 and only 170,000–200,000 CNY more expensive in 2021. Tractor-trailers could still achieve TCO parity beyond 2030 with the use of renewable electricity, and they are almost 750,000 CNY more expensive by 2025. Proper policy interventions can make BETs cost-effective immediately even if they are powered with renewable electricity.

» **The use of green hydrogen fuel in FCETs requires extensive policy measures to compete with BETs and diesel trucks:** The different truck segments have a substantial TCO gap when compared to diesel trucks due to the high costs of green hydrogen fuel. The largest cost gap is observed with tractor-trailers and reaches 1 million CNY in Shanghai and 2 million CNY in Shenzhen. The difference in hydrogen prices across the different Chinese cities is mainly driven by the local cost of renewable electricity. Other truck segments have a slightly lower TCO gap. Extensive policies are needed if FCETs powered by green hydrogen fuel are to become cost-competitive with BETs and diesel trucks.

The study also investigates several policy interventions that could help reach TCO parity earlier this decade. We find that:

» **Exempting HD-NEVs from road tolls could help BETs reach TCO parity by 2024–2027 for all segments:** Road tolls constitute a significant cost component of the TCO of trucks, especially for tractor-trailers. Partial exemption (75%) from road tolls can help tractor-trailers achieve TCO parity by 2027. Straight trucks can achieve cost parity by 2025. FCETs also benefit from those exemptions, but the impact on their cost-parity point is not significant.

» **Waiving electricity demand charges helps BETs reach their TCO parity 3 years earlier (2022–2027):** Demand charges are a significant component of the electricity bill, representing 33%–40% of the total electricity costs. Waiving those charges helps tractor-trailers achieve cost parity by 2027. In addition, straight trucks become cost-effective by 2023–2024, while the TCO-parity point for dump trucks is achieved as early as 2022.

» **Green hydrogen incentives up to 20 CNY/kg could help some truck segments to achieve cost parity by the second half of the decade:** FCET straight and dump trucks could reach cost parity by 2027 under this policy, especially in Shanghai where hydrogen prices are expected to be the lowest. Tractor-trailers benefit from marginal changes in their parity point due to the very high TCO gap with their diesel counterparts, which exceeds 750,000 CNY in 2030.

» **Carbon pricing—that is, taxes on the CO_2 tailpipe emissions of diesel trucks—can help BETs reach TCO parity in the next 3–4 years:** The current Emissions Trading Scheme in China can accommodate such a tax where the tailpipe CO_2 emissions of diesel trucks are subject to emissions tax. With the current CO_2 taxes, the resulting benefits are marginal for HD-NEV; however, increasing this tax three- to fivefold can make straight trucks cost-effective immediately. BET tractor-trailers require a substantially higher CO_2 tax to be imposed on their diesel counterparts to become cost-effective in the meantime, whereas it is difficult for this policy to have an impact in time to reach cost parity of all FCET segments.

» **Purchase incentives can bring TCO parity 1–3 years earlier, an effect similar to what can be achieved by a combination of in-use incentives:** While it is still unclear what the FCET purchase incentives will be in 2021, the 400,000 CNY incentive applicable in 2019 is needed for FCETs to achieve TCO parity this decade. BETs, with purchase incentives capped at 40,000 CNY, benefit only marginally from this subsidy. The effect of purchase incentives is similar to other measures targeting operational costs.

Based on the findings above, we offer the following policy recommendations for the development of policies targeting the deployment of HD-NEVs in China:

» **Set ambitious sales requirements for HD-NEVs in the near term:** Zero-emission straight and dump trucks will have better TCO than diesel trucks before 2025 and zero-emission tractor-trailers by 2028. However, truck operators will only reap these economic benefits if there is a robust supply of HD-NEVs. California—the only region that has adopted legally binding legislation requiring the sale of zero-emissions heavy-duty vehicles—provides a best practice example for the setting of targets. California will require 11% of new heavy rigid trucks to be zero emission by 2025 and 50% by 2030. For tractor-trailers the zero-emission sales requirements are 5% and 30% by 2025 and 2030, respectively. China's ambition on carbon neutrality by 2060 requires that the central government introduces ambitious targets at least at the level of those adopted in California.

- **Set long-term zero-emission sales targets to provide manufacturers the clarity they need for product planning and investment:** The combination of near-term binding sales requirements and long-term nonbinding targets set by the government is desirable. The former ensures the immediate kick-start of the needed supply chain, and the latter provides the certainty that the investments made will have a long life. The combination of the two is important to create a large and long-lasting market whose economies of scale will drive down manufacturing costs and, consequently, the TCO of HD-NEVs, especially for tractor-trailers—the most important and challenging segment to decarbonize, given its delayed TCO-parity point with diesel trucks toward the end of the second half of this decade.
- **Provide incentives to bring the TCO parity of HD-NEVs with diesel trucks to the first half of this decade:** Policy can create adequate incentives to close the TCO gap between diesel HDVs and HD-NEVs. These include purchase incentives, reforms or subsidies in energy cost, and reduction of other operational costs dictated by government, such as road tolls. Given that subsidies are not fiscally sustainable in the long term, they can be limited in duration to generate sufficient demand during market ramp-up and can be phased out as manufacturing costs drop through economies of scale. For the long term, fiscally sustainable alternatives—such as the polluter pays principle—can be adopted. This includes taxing the purchase and operation of diesel trucks at a higher rate, capturing the external costs of diesel trucks—for example air and climate pollution—and providing the funds to finance programs to incentivize zero-emission technologies.
- **Apply policies for the promotion of HD-NEVs that go beyond the fiscal incentives examined in this study:** Privileges for HD-NEV accessibility to zero- and low-emission zones, for example, can increase the demand for HD-NEV over diesel trucks. This study does not quantify the TCO impact of those policy incentives. Chengdu, the capital city in Sichuan province, adopted such a policy with positive outcomes. After applying this policy for 2 years, Chengdu became the leading city in China for NEV truck sales in March 2021.
- **Design policies that are application specific but technology neutral:** Cognizant of the different emission footprints for vehicles in different segments and applications, policies must be targeted to drive the development and adoption of zero-emission vehicles in the segments responsible for the greatest share of emissions. For example, tractor-trailers are the segment responsible for the highest share of emissions and, at the same time, face greater challenges achieving cost parity with diesel in the first half of the decade. Therefore, policy measures that target this vehicle segment would result in the highest mitigation of CO_2 emissions. Given the stark differences in TCO between different zero-emission technology pathways, policies should aim to avoid favoring battery-electric or hydrogen fuel cell trucks in the long-term. In the early phases of market development, differentiated incentives for battery-electric and fuel cell trucks might be warranted to spur innovation and reduce manufacturing costs in both technology pathways. However, once the market has been ramped up and incentives are phased out, a level playing field will favor the most cost-effective technology for a given application. Our analysis shows that battery-electric trucks have a cost advantage in the absence of incentives.

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ANNEX A: ZERO-EMISSION TRUCK RETAIL PRICE VALIDATION

The retail price of the zero-emisison trucks is validated against publicly available data announced by truck manufacturers, online platforms that provide commercial vehicles services, and other studies in the literature. Due to incomplete data availability, the retail price of three trucks is validated: battery-electric dump truck, battery-electric tractor-trailer, and fuel cell electric tractor-trailer. The validation is done by comparing the base glider truck costs, excluding the power unit and/or energy storage systems, as the reported price estimates of these components vary greatly. In addition, the price estimates for these components are reported by SAE China (SAE-China, 2021), providing credible China-specific cost estimates. **Table 32** summarizes the truck models used to validate the zero-emission trucks retail price.

Table 32. Truck models used to validate the retail price of ZE trucks

Truck segment	Model	Total cost (CNY)	Battery size (kWh)	Fuel cell power (kW)	H2 Tank (kg)	E-drive power (kW)
Dump truck—BET	Shaanxi Delong M300—8x4	850,000	234	—	—	210
Tractor-trailer—BET	Shaanxi Delong M300—6x4	825,000	234	—	—	210
Tractor-trailer—FCET	Not specified	1,500,000	100	80	40[14]	215

Figure 22 compares the reference and modeled retail price for zero-emission trucks base glider and e-drive system. The results show that the modeled prices fall within the same order of magnitude of the publicly available retail price, recording a cost difference below 10%. This cost difference is insignificant as the majority of vehicle retail price is composed by the battery and fuel cell unit costs.

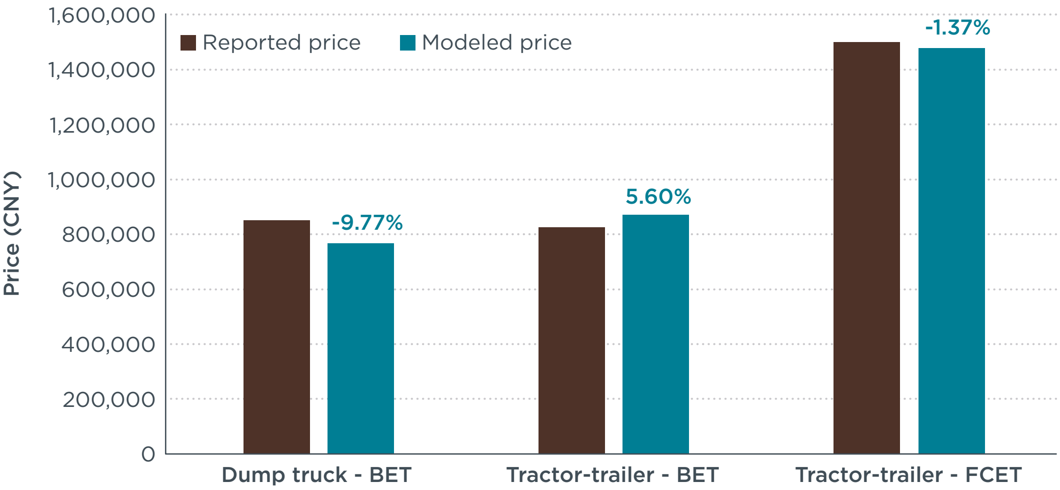

Figure 22. Zero-emission truck price validation for model year 2020

14 The hydrogen storage tank size is not explicitly stated in kg of usable hydrogen, however; technical specifications such as the tank volume and pressure allow a rough estimation of 40 kg of usable hydrogen.