McKinsey Center for Future Mobility

Preparing the world for zero-emission trucks

The mainstays of commercial road transport will soon benefit from cost-effective, zero-emission horsepower

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Preparing the world for zero-emission trucks

In less than a decade, electric powertrains have expanded from a tiny niche to become the almost inevitable powertrain for tomorrow's passenger vehicles. Continuing this trend toward sustainable transport, medium- and heavy-duty trucks will soon embark on a similar journey.

Given a highly supporting environment, we expect that zero-emission powertrains will gain momentum over the next two to three years. Within the next decade, they will become the dominant powertrains in new vehicle sales in the United States, Europe and China, and will reach 85 percent market share in vehicle sales by 2040. However, trucks are built to last. Even such a fast ramp-up in sales will take a decade to appear in the vehicle fleet. Hence, time is of the essence, especially given that road freight vehicles account for approximately 5 percent of all global CO_2 emission.[1]

The pathway to decarbonization of road freight will be shaped three main factors: regulation; technology and cost; and truck market dynamics and infrastructure.

Regulation

Governments at various levels have introduced regulations and incentives to promote zero-emission trucks. Actions at the national level include subsidy programs or tax breaks for zero-emission trucks, components, and infrastructures, discounts on road tolls, tightened fleet emission standards, or sales bans on combustion-engine vehicles. Some regional and city governments complement these actions with zero-emission vehicle procurement targets for their fleets or entry bans for internal combustion engine (ICE) vehicles.

While taking different forms in different geographies, regulation favoring zero-emission vehicles (ZEVs) has helped energize the transition and will likely accelerate the deployment of battery-electric vehicles (BEV) and fuel cell electric vehicles (FCEV) in this decade. In fact, regulatory activity has intensified across various markets, with comprehensive regulatory frameworks announced in both the European Union (Fit-for-55 program already includes CO_2 regulation for light vehicles, changes in emissions regulation for heavy trucks are expected to be announced later this year) and the United States (as part of the Inflation Reduction Act).

Technology and cost

To ensure the at-scale deployment of zero-emission trucks, total cost of ownership (TCO[2]) is a key factor. While some regulatory interventions seek to reduce TCO for zero-emission trucks, industry players are also accelerating innovations around key zero-emission powertrain components. While commercial vehicles can borrow some approaches from passenger vehicles, in most cases specifications and scale considerations require different solutions. The main objective is to reduce costs further for key elements such as batteries, fuel cell systems, and hydrogen and make zero-emission trucks economically competitive with their diesel equivalents. In the next decade, we expect a steep learning curve for relevant FCEV components such as fuel cell systems (and electrolyzers for hydrogen production) and continued progress on batteries, which have already seen a steep decline in costs from USD 1,000 per kilowatt-hour (kWh) to USD 100 per kWh for some applications over the past decade. Also on charging hardware, we have already seen up to 50% cost reductions over the last 5 years alone for high-power DC fast chargers, and expect further cost reductions as the industry reaches scale.

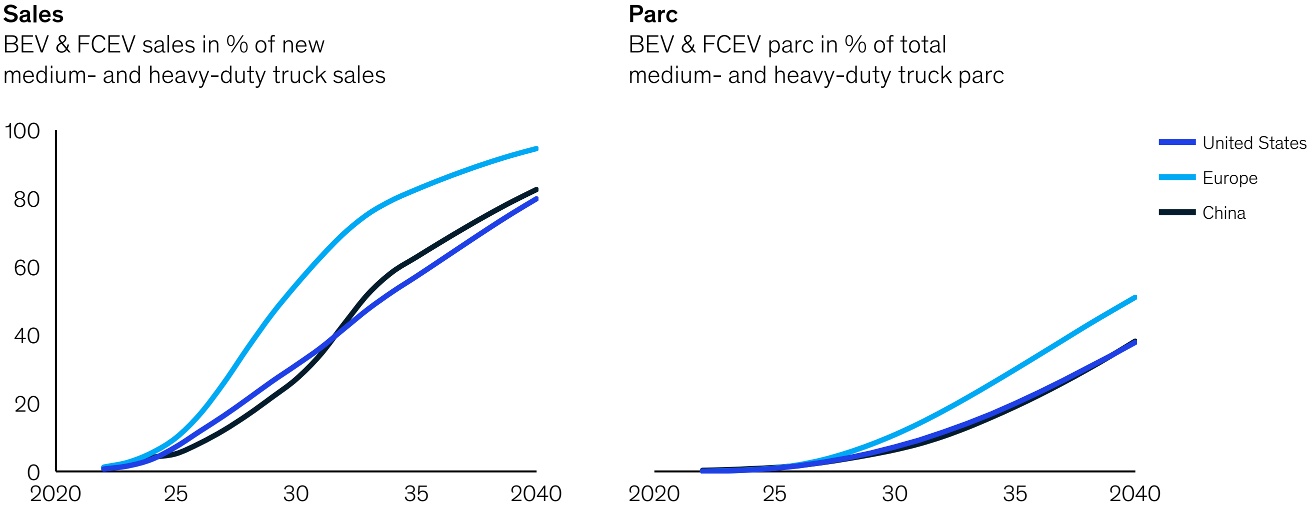
[1] Hannah Ritchie, Max Roser and Pablo Rosado (2020) – "CO_2 and Greenhouse Gas Emission." Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/co2-and-other-greenhouse-gas-emission' [Online Resource]

[2] Total Cost of Ownership (TCO) includes the upfront cost, depreciated over time and distance traveled, as well as costs for maintenance, fuel, charging/refueling infrastructure, and tolls. It does not include insurance and driver costs

Exhibit 1

By 2035, majority of new trucks will be electric in US, EU & China

Current Trajectory Scenario



Source: McKinsey Center for Future Mobility

Additional benefits will result from increased scale in truck production, further reducing unit costs. Once the technology is ready and production reaches scale, it should support a substantially lower total cost of ownership (TCO) compared with current diesel trucks. In return, fleet operators will adopt zero-emission trucks quickly to seize these cost benefits.

Truck market dynamics and infrastructure

Fleet operators and freight buyers are becoming increasingly aware of their carbon footprints. More than 3600 companies globally are committing to science-based targets[3], many aim to source zero-emission trucks or logistics soon, with some even willing to pay a premium. The increase in demand faces tight supply volumes, with both start-up and incumbent OEMs likely only achieving larger production volumes in Western markets in the next few years. In this environment, both fleet operators and OEMs have an incentive to further accelerate their deployment of zero-emission trucks.

However, trucks are only one side of the equation. To allow the deployment of zero-emission trucks at scale, the corresponding networks for charging and hydrogen refueling infrastructure need to be in place. The necessary roll-out will require substantial investments in electricity grids, the hydrogen supply chain, and corresponding refueling infrastructure. While first investments are already underway, only a comprehensive network will allow for the at-scale use of zero-emission trucks. Addressing such challenges will be even more important in markets like Europe, with a large share of smaller, outsourced fleets, serving ad-hoc requests with limited predictability on times and routes.

[3] https://sciencebasedtargets.org/companies-taking-action

Batteries and fuel cells will be go-to technologies for ZE trucks

By 2030, battery and fuel cell electric powertrains will be the winning technologies from an emission and TCO perspective. They thus represent the two most relevant options for fleet operators. Operational cost savings (mainly energy and potentially maintenance) will offset the higher capital expenditures (capex) for batteries and fuel cell systems within two to four years. Until then, technological advancements concerning batteries and charging speeds will allow sufficient range and acceptable charging speeds for BEV trucks. Likewise, a broad build-up of hydrogen refueling infrastructure and improvements in thermal management of the powertrain will allow the deployment of FCEV trucks at scale.

Compared with diesel trucks, both BEV and FCEV trucks have payload restrictions due to the weight of the battery or the size of the hydrogen tank. However, at this point, the practical consequences remain limited given that many regulators allow for exceptions in vehicle dimensions or weight to balance out these disadvantages. Yet, physical limits of the built infrastructures (i.e. roads and bridges) may not allow maintain such exceptions when they would be required by a large share of the fleet. Over time, improved battery energy density and higher-pressure or liquid hydrogen tanks will likely further close the gap.

Other zero-emission options include hydrogen combustion and renewable fuels. Given today's high battery costs, nascent infrastructure build-up, and limited BEV/FCEV production volumes, both options can help to accelerate truck fleet decarbonization.

Hydrogen combustion powertrains feature modified versions of natural gas combustion engines. Companies can thus adapt them and put them on the market faster than FCEV powertrains. However, hydrogen combustion trucks would still need access to hydrogen refueling infrastructure, which remains scarce. In addition, hydrogen combustion engines will likely have lower fuel efficiency than FCEV powertrains at low and medium loads, rendering them uncompetitive for typical truck operations. More likely long-term applications of hydrogen combustion include off-highway segments with their higher peak-power requirements.

Renewable diesel (RD), renewable natural gas (RNG), and other renewable and synthetic fuels can support the faster decarbonization of existing diesel fleet and compressed or liquified natural gas (CNG/LNG) fleets. They have the advantage of being compatible with current infrastructure and powertrains and they are commercially and technically available – ready to deploy. Their availability has remained limited so far and despite a faster scale-up at the moment, their total theoretical contribution is constrained to low tens of % of total fuel need given feedstock constraints. Production scale-up is expected to continue, with a focus on demand from aviation, marine, chemicals and industrial sectors. Yet, without regulatory support, RNG and RD will remain costlier than fossil fuels and will not be cost-competitive with BEV or FCEV powertrains in most road transport applications in the long term. Thus, renewable fuels will likely serve as transition fuels over the next few decades, with potential long tail demand towards and beyond 2050, for example in remote or sparsely populated regions.

Exhibit 2

- Favoring powertrain adoption
- Neutral to powertrain adoption
- Limiting factor for powertrain adoption
- Zero-emission powertrain/ fuel options
- Fossil fuels

				Key TCO determinants 2030			Operational considerations 2030		
	Tailpipe emissions	Availability today	Projected TCO by 2030	Powertrain capex	Efficiency Well-to-wheel	Infrastruc-ture costs	Range	Refueling time[1]	Payload
Battery electric	**Zero**	**Low** Limited production volume and high vehicle costs	**Low** Lower TCO than for current Diesel powertrain	High	High	High	Medium	Medium	Medium
H_2 Fuel cell electric	**Zero**	**Low** Limited production volume and high vehicle costs	**Low** Lower TCO than for current Diesel powertrain	High	Medium	High	High	Fast	Medium
Hydrogen ICE	**Low** NOx emissions (requires SCR after-treatment)	**Low** No truck models on the market today	**Medium** Lower TCO than for current Diesel powertrain, but higher than BEV/FCEV	Medium	Medium	High	High	Fast	Medium
Bio-/ Synfuel	**Medium** CO_2 (depending on CO_2 source), NOx and PM emissions	**Medium** Limited availability of fuels	**High** Expected to remain more expensive than fossil Diesel/ natural gas	Low	Low	Low	High	Fast	High
CNG/ LNG	**High** CO_2 and PM emissions	**Medium** Limited availability of refueling infrastructure	**Medium** Lower TCO than Diesel powertrain	Low	Low	Medium	High	Fast	High
Diesel	**High** CO_2, NOx and PM emissions	**High** Standard fuel today	**Medium**	Low	Low	Low	High	Fast	High

1. Refueling times for Diesel, gas and hydrogen are approx. 15-20 min. Recharging times for BEV trucks will depend on the charger technology used and can range from 30-45 min to multiple hours

Source: McKinsey Center for Future Mobility, McKinsey Hydrogen Insights

A new world without one-size-fits-all solutions

No universal solution exists for zero-emission powertrain technologies for future trucks. Instead, the answer will depend on a truck's weight class, its use case, and the environment in which it operates. And the answer is not clear yet – as there are multiple unknows, which can shift the future market into either direction:

1. **Development in technology costs:** Battery costs have already dropped by an order of magnitude over the past 10 years, and are expected to decline further until 2030. Fuel cell and electrolyzer systems are only at the beginning of their learning curve, with steep cost declines and technological improvements expected over the next decade, also driven by other applications. For both technologies, substantial cost reductions are still needed to become economically viable.
2. **Operational characteristics:** Today, both BEV and FCEV trucks often carry operational constraints. For BEV, these include payload restrictions (due to battery weight), recharging times, or limited ranges. For FCEV, payload restrictions can result from the larger space required for their hydrogen tanks. Overcoming these constraints will be required to unlock demand.
3. **Infrastructure availability:** BEV trucks will require a dense network of (fast) charging infrastructure to allow deployment at scale. The corresponding upgrades of the electricity grid are not always trivial. FCEV trucks need a comprehensive coverage of hydrogen refueling stations, many more than the approximately 700 stations in operations globally today[4]. Substantial investments will be required, before long-haul fleets can be addressed at scale.

In addition, fleet-specific drivers may lead operators to prefer one technology over another. One example for such drivers are the type of truck use cases: Battery costs scale with vehicle range, which leads to an advantage for BEV for short- and mid-range use cases as well as for predictable, regular routes. For long-haul use cases with less predictable routes, FCEV can be advantageous given their shorter refueling times and lower upfront cost compared to high-range BEV trucks. As a result, most MDT trucks are expected to transition to BEV powertrains, while for HDT trucks, also FCEV powertrains are expected to play a relevant role, especially in long-haul use cases.

A second key driver will be local energy prices and availability: FCEV trucks have a 50% lower well-to-wheel energy efficiency than BEVs,[5] but hydrogen is transportable over long distances more cheaply than electricity. Hence, depending on the local availability and nature of renewable energy, electricity versus hydrogen fuel costs could skew heavily to favor one or the other powertrain.

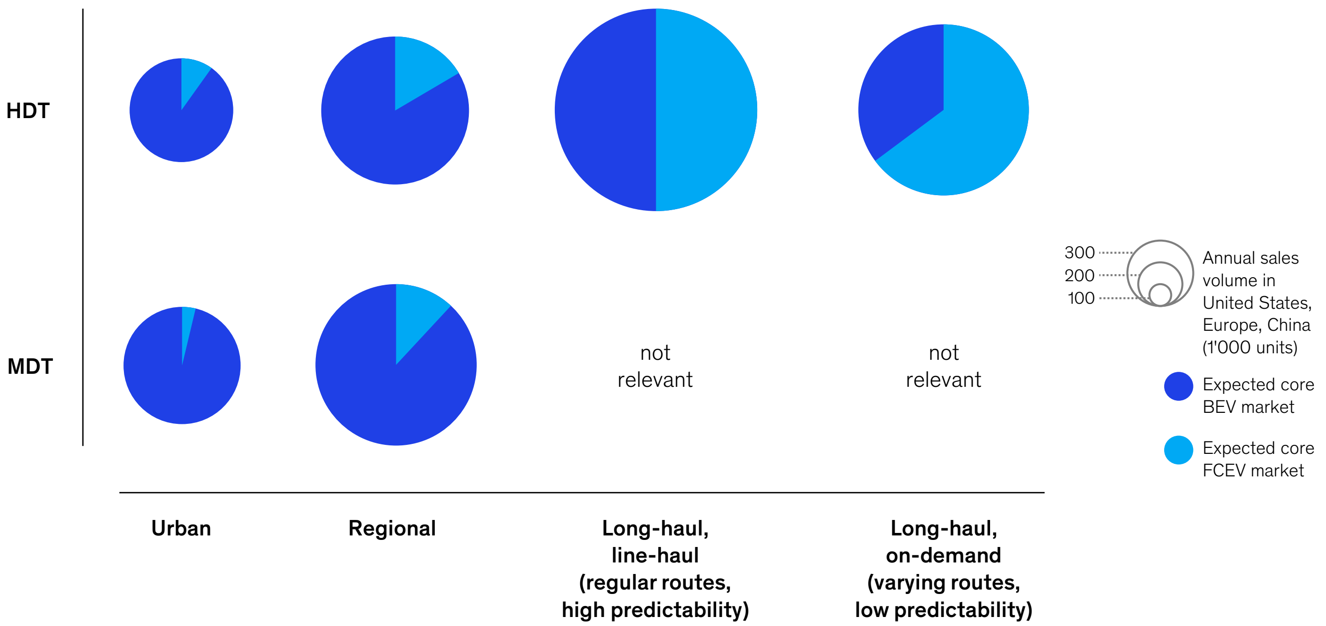
In this race to the market, BEV trucks will have a head-start as they will be available at scale earlier than FCEV trucks. They will also benefit from synergies with technological advances in electric passenger cars. This way, fleet operators will already phase in a zero-emission truck type and adjust their operations accordingly, potentially limiting the appetite for a second powertrain and fuel type. In turn, FCEV will benefit from both developments in batteries and electric powertrains for BEV trucks as well as fuel cell and electrolyzer developments for industrial, and other transport applications, such as aviation and marine. Also, given the slow fleet renewal cycles, approximately 90% of all trucks in operation by

4 Ludwig Bölkow Systemtechnik (2022) 14th Annual assessment of H2stations.org
5 ICCT (2022) *Fuel-cell electric tractor trailers: Technology overview and fuel economy*

Exhibit 3

Potential long term powertrain shares by segment and use case[1] (2040+)

Illustrative



1. Urban: Distribution use cases with daily mileages of 150 km or less; Regional: Distribution use cases with daily mileages of 250 km or less, returning to base at the end of the day; Line-haul: daily mileages of 500 km along predictable, regular routes; On-demand: daily mileages of 500-800 km, in ad-hoc settings with limited predictability

Source: McKinsey Center for Future Mobility

2030 will still run on internal combustion engines, most of the fleet will still be up for the transition when FCEV trucks reach scale.

The above drivers will likely play out differently in different geographies. For example, operational constraints are less of a challenge in North America, where there are less tight vehicle dimension requirements. Also electricity and hydrogen prices as well as the speed of their infrastructure roll-out can vary significantly between geographies. Finally, the head-start of BEV powertrain technology will likely be strongest in Europe, driven by an early regulatory push to accelerate the transition to zero-emission powertrains.

The trucking industry is at the starting blocks

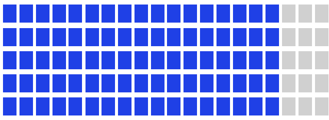
By 2040, 85% of the new trucks sold in the United States, Europe and China will run on zero-emission powertrains, joining the 40 percent of the vehicle fleet already equipped with BEV or FCEV powertrains. OEMs are already embarking on this and start to bring zero-emission truck models to the market. Eventually, zero-emission trucks will allow fleet operators to reach their decarbonization targets but at the same time can help reduce fleet operating costs.

Making this transition work will require substantial investments in production capacity and infrastructure. For example, the currently announced 2024 production volumes of BEV and FCEV trucks correspond to only 2 percent of annual truck sales. To get to a sizeable scale, the whole value chain needs to act in concert. For instance, the industry will need additional battery production capacity equal to 12 giga-factories by 2030, along with the corresponding amounts of raw material supplies. What's more, electric trucks will add about 6 percent to today's electricity demand and require USD 450 billion in investments into charging and hydrogen refueling infrastructure through 2040.

Exhibit 4

Medium- and heavy-duty trucks[1], United States, Europe, China, 2040

Current Trajectory Scenario

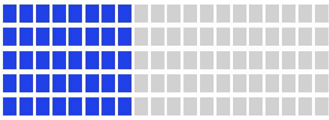


85%
of new truck sales with ZE powertrain[2], 2040

70+
zero-emission truck models to be available by 2024 in Europe and US

10%+
TCO savings in reach within the next 5-10 years

60%
of fleet operators have announced decarbonization targets



40%
of trucks on the road with ZE powertrain[2], 2040

12
Battery giga-factories by 2030[3]

6%
additional electricity demand by 2040

$450 bn
Infrastructure investments required by 2040

1. Weight class definitions: US: HDT: Class 8 (>15t), MDT: Class 4-7 (6-15t); EU: HDT >16t, MDT: 7.5-16t; CN: HDT >14t, MDT: 6-14t
2. ZEVs include BEVs & FCEVs
3. Assumes an average Gigafactory with annual capacity of 25 GWh

Source: McKinsey Center for Future Mobility

OEMs are already at the drawing boards, with over 70 truck models available by 2024

A variety of BEV and FCEV truck models are already on the market. By 2024, fleet operators in Europe and North America will be able to choose from more than 70 different models, compared with almost 130 models available with diesel powertrains.[6] However, most trucks available today have been designed for urban and regional use cases, lacking the ranges required to be deployed for long-haul use cases. Also, production volumes will remain low, at fewer than 30,000 units annually through 2024 in Europe and North America. Most of these will be BEV trucks, with FCEV production volumes remaining in the low thousands. The limited supply leads to long wait times for potential truck buyers. As a result, procuring even a small fleet of zero-emission trucks can be difficult for fleet operators in the short-term. Production volumes in China are already double this volume output, reflecting the earlier start of the local industry.

BEV trucks will become available in larger volumes before FCEVs, given that both the powertrain technology and refueling infrastructure are more mature at this point. Driven by technology readiness, urban and regional use cases will transition first, with model offerings and volumes of BEV trucks already growing now. The key drivers for a faster uptake are the lower battery sizes required for these use cases, which limit the price differences with diesel trucks. Furthermore, urban and regional use cases can rely on depot charging and thus do not depend on still incomplete highway charging infrastructure networks. Long-haul BEV trucks will follow at larger scales beginning in two to four years, after a further decline in battery pack prices and as the availability of fast-charging infrastructure grows, while FCEVs will likely reach scale another few years later.

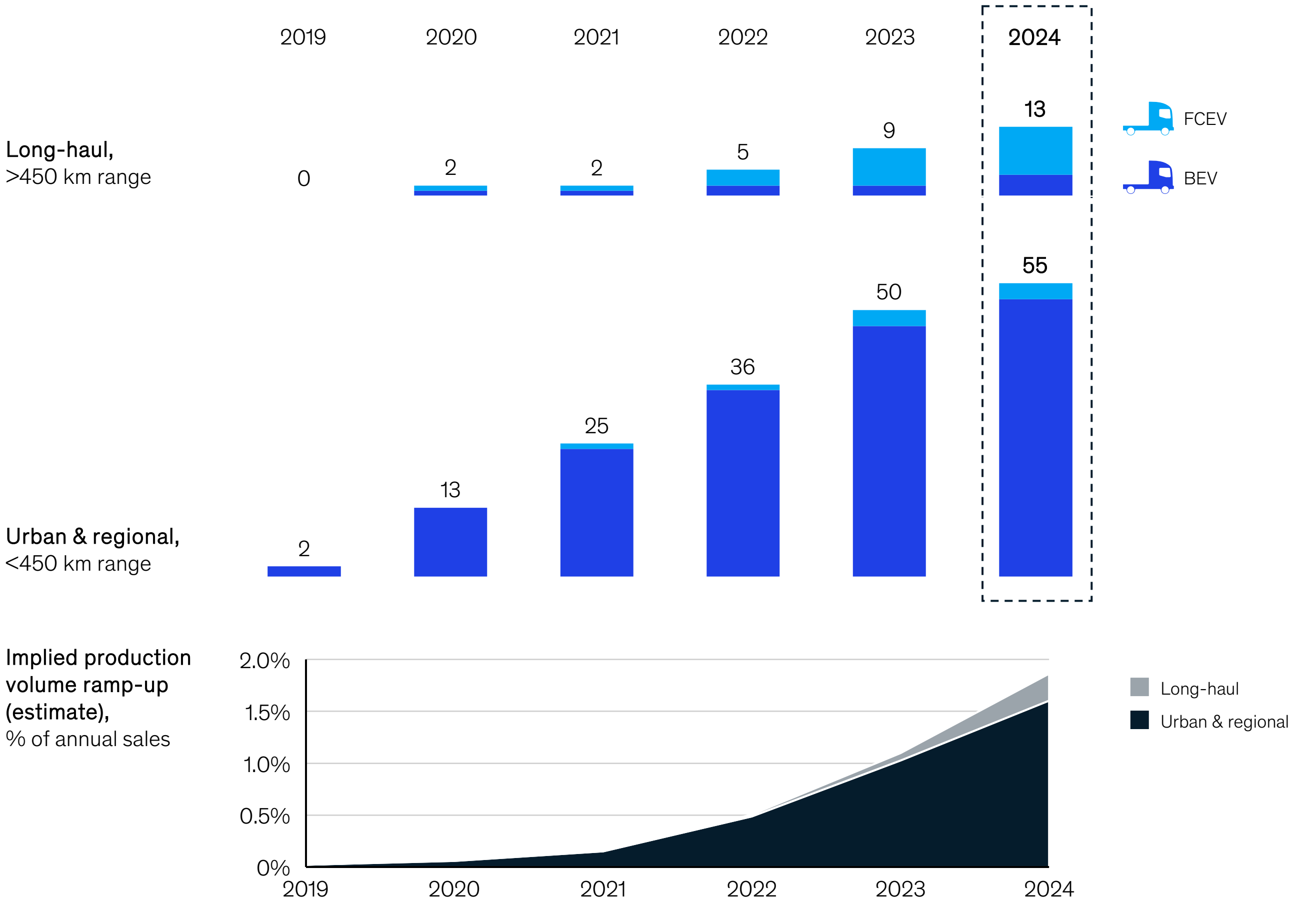
Along with the growing scale of zero-emission truck production, the OEM and model landscape will also change. Today, attackers such as start-up OEMs and retrofitters account for a large share of the ZE truck models on the market, having invested in the electrification trend early on. Consequently, many of these start-up OEMs are not bound to legacy vehicles but use tailored EV-only platforms for their models, exploiting the full benefits of the new powertrain designs. In contrast, the first-generation electric trucks launched by incumbent OEMs mainly use ICE platforms and will likely migrate to EV-only platforms in future model generations.

[6] Models with production volumes of more than 100 units a year

Exhibit 5

ZEV medium and heavy-duty truck models on the market

Cumulative, # of models available in Europe and North America



1. Models with production volume >100 units p.a.

Source: Press; OEM web sites

ZE trucks will trump diesel in 5 to 10 years, with +10% savings in TCO likely within that period

TCO is a deciding factor when it comes to enabling the roll-out of zero-emission trucks because fleet operators are much more sensitive to operating costs than private car buyers. We expect BEVs or FCEVs to reach TCO parity with diesel engines by 2030 across most use cases and geographies. In the long term, TCO savings compared with diesel can be as high as 30 percent, depending on the use case.

To accelerate adoption, several regulators across the globe have launched incentive programs, including subsidies or toll discounts. Although typically only available for limited periods of time, or for a limited number of vehicles, such programs can pull forward TCO parity by up to five years, which could make ZE trucks highly competitive within the next three years, depending on the incentives available.

TCO for zero-emission trucks will decrease by up to 65 percent by 2040, driven by three factors. The first involves advancements in technology and associated cost reductions of batteries, fuel cell systems and refueling infrastructure. The second includes increased scale in vehicle production that will lower the per-unit costs of both components and assembly. The third is increased on-road deployments that will reduce the per-truck costs of charging and refueling infrastructures, thus bringing down operating costs.

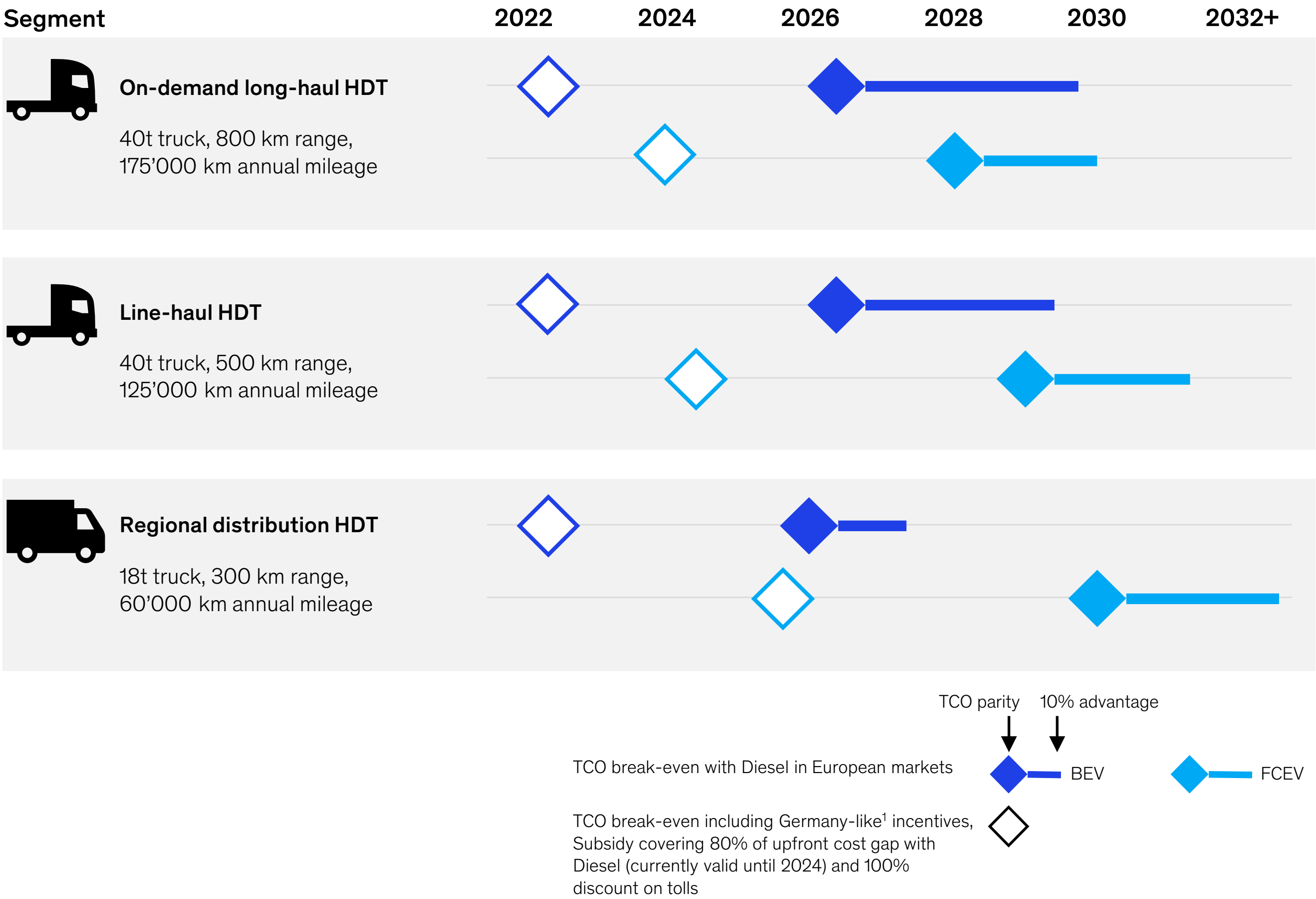
We expect BEVs and FCEVs to take complementary roles in the mid-term since their cost structures position them as solutions for different use cases. For BEVs, charging costs are low at fleet hubs and upfront costs typically scale with the required range, making it a competitive choice for distribution use cases or long-haul use cases with predictable, regular routes. In turn, economics are less favorable for BEV in use cases with high variance in daily distances, which lead to a lower utilization of the battery. For FCEVs, upfront costs are higher but do not scale much further with the required range. Also, hydrogen refueling will likely remain substantially faster than charging, making it competitive for long-haul operations that require higher levels of flexibility. As a result, OEMs will tailor future trucks to their specific use cases far more than they do with current diesel trucks, sizing the battery and/or hydrogen tank according to the needs of their customers' specific use cases.

In the long term, we expect the TCO performance of BEVs and FCEVs to reach virtual parity with each other so that the respective market adoption decisions will depend primarily on their operational characteristics and local energy prices. In this regard, fleets will likely make specific trade-offs to maximize vehicle uptime depending on numerous factors such as local grid capacity, the availability of hydrogen refueling stations along their core networks and required charging patterns.

Exhibit 6

TCO parity years by use case

Current Trajectory Scenario, Europe



Note: TCO model assumes the following cost levels for HDT long-haul line-haul truck in Europe in 2030: Upfront vehicle costs: 110k USD (ICE)/170k USD (BEV)/180k USD (FCEV); diesel price: 1.20 USD/l, electricity price: 0.13 USD/kWh, hydrogen price: 4.4 USD/kWh. Due to intense truck use, TCO is highly sensitive to energy prices

Source: McKinsey Center for Future Mobility

60% of fleet operators have announced decarbonization targets, but big challenges remain

Driven by the positive TCO outlook and the expectation that road transport will be easier to decarbonize than other parts of a company's operations, many fleet operators and freight buyers have already announced decarbonization targets. According to a recent McKinsey survey, more than 60 percent of fleet operators across the US, Europe, and China plan to transition to zero-emission fleets within this decade. Most have not developed concrete implementation plans yet, but some have already started to deploy ZEVs on the road.

Fleets seeking to transition to zero-emission trucks quickly face a limited supply of available vehicles. To secure supply, some large fleets have even taken stakes in e-truck or e-van startups, while other fleets have partnered with OEMs to run joint pilot programs.

The transition to zero-emission trucks is more complex than just phasing in another new truck. Both BEVs and FCEVs have larger financing needs as they are two to four times more expensive compared with diesel trucks today. There is also substantial technology risk, given the high cost of fuel cell systems or batteries, and fleets lack experience concerning their durability in real-life operations at scale. The risk is not inconsequential: vehicle uptime and reliability are extremely important to fleet operators. The lack of trust in these new powertrains is a strong counterargument against even the most favorable TCO comparison. To counteract those risks, partnerships between fleet operators and OEMs (incumbents and disruptors) doubled between 2017 and 2021, according to a recent McKinsey survey.

BEV trucks also require investments in charging infrastructure. Potential upgrades of the local grid in a timely manner can be costly and possibly unfeasible. Furthermore, companies may need to adjust the layout of fleet depots to accommodate charging processes. Due to scale effects, FCEV trucks will rely more on public refueling infrastructure in the future. With few hydrogen refueling stations available today, FCEV trucks face an uphill battle in the short term.

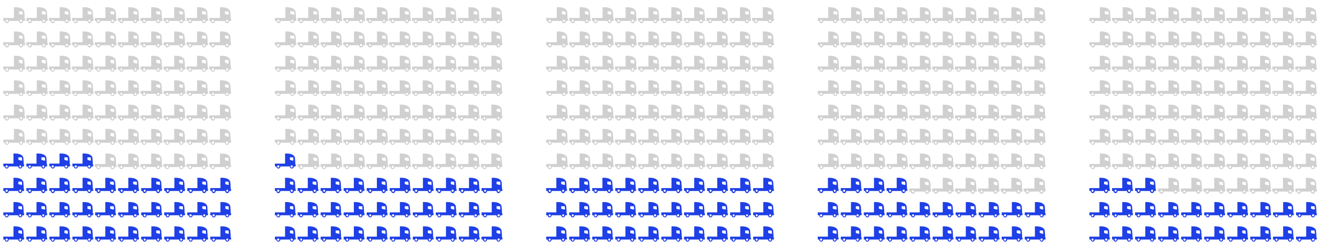
The transition challenges become even more complex in markets where freight buyers typically do not maintain their fleets but rely on third-party logistics (3PL) providers. In such setups, most trucks belong to independently operated small fleets that depend even more on uptime and seamless access to infrastructure to deploy their vehicles as flexibly as possible. These fleets are even less able to shoulder the investments needed to deploy zero-emission trucks. According to a recent survey, only approximately one-third of fleet operators across major markets are willing to accept 10 percent or more additional upfront costs for zero-emission trucks, despite their substantially lower operating costs. Consequently, the industry will require new financing and ownership models to further scale deployment.

Exhibit 7

Future of Commercial Mobility Survey among fleet operators, US & Europe

What are the pain points for introducing zero-emission trucks?[1]

BEV



34% Limited battery lifetime

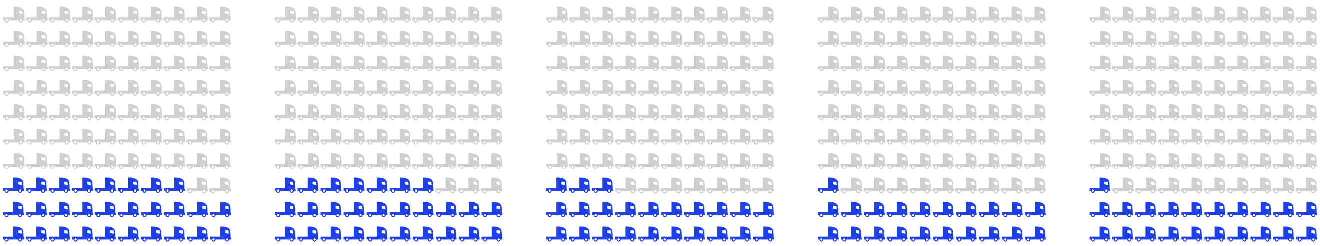
31% Long charging time

30% Limited driving range

24% Reliability/quality issues

23% Concerns about the sustainability of batteries

FCEV



28% High maintenance costs

27% High total cost of ownership

23% Reliability/quality issues

21% High uncertainty about general hydrogen availability

21% High upfront investments

1. % of fleet operators perceiving the given items as pain points

Source: McKinsey Center for Future Mobility

12 more giga-factories of batteries are needed to support ZE truck demand by 2030

Total battery demand will grow about 22 times between 2020 and 2030. Trucks will take a minor share of this growth, representing up to 6 percent of total battery demand by 2030. Still, battery demand from trucks in 2030 will roughly equal today's total battery demand across all applications. Although battery sizes can be 5 to 10 times larger than those for passenger cars, the expected total BEV truck production volume of approximately 700'000 units globally in 2030 is negligible compared to an expected production volume of 36 million BEV passenger cars by that time. Although production volumes of electric trucks will continue to grow beyond 2030, they will remain a relatively small end-use segment for batteries.

Battery supply constraints are likely in 2030, so setting up the right battery sourcing strategy will be the key for truck manufacturers over the next few years. While large, global truck OEMs can benefit from joint sourcing and low cell pricing, smaller truck OEMs, integrators or retrofitters will likely face higher prices due to their smaller demand volumes. Truck players with less than 3-4 GWh of battery demand a year (the average annual battery production line output) will face even higher prices. This low negotiation power will also result in limited room for customized specifications in cell design, making it more difficult to trade off energy versus power.

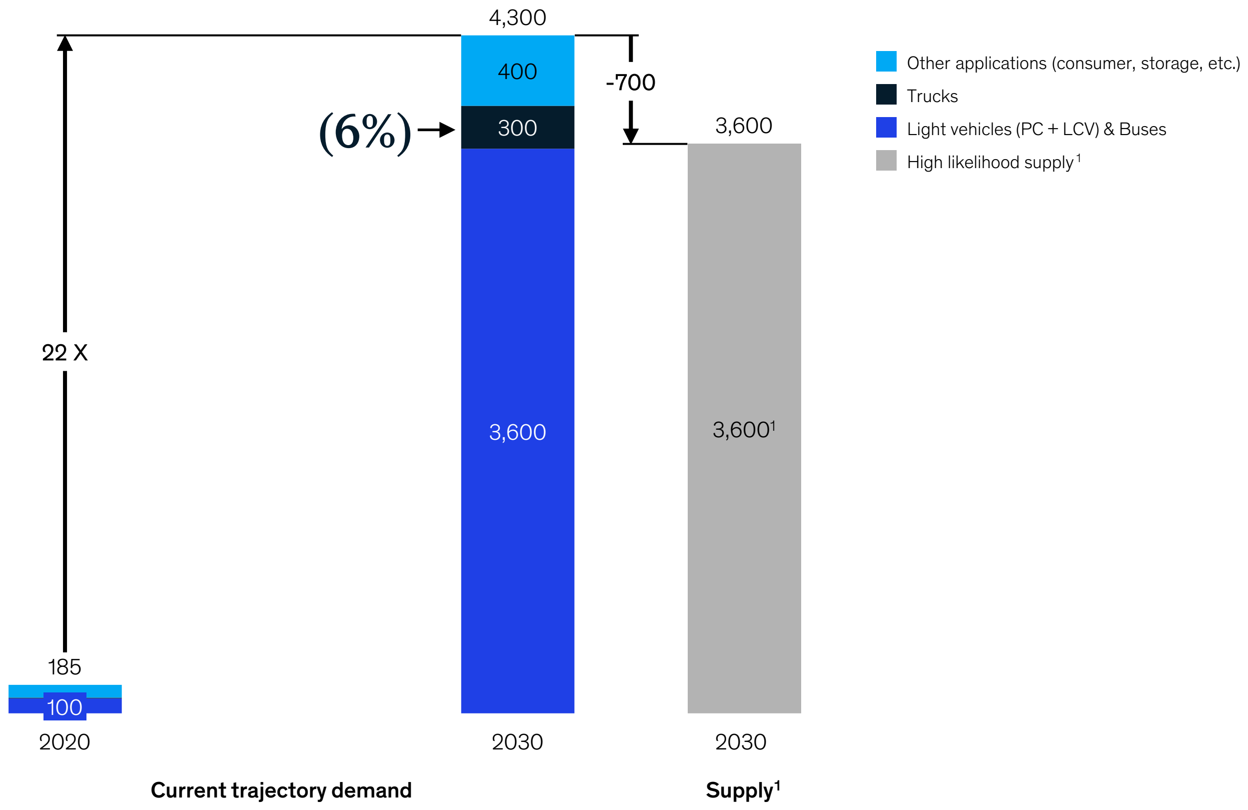
To achieve lower battery cell prices, truck players could form partnerships to increase volumes and negotiation power. They could also go through battery pack integrators, which could pool battery demand across participants to limit the price premiums, or they could try to leverage synergies with battery cell production for passenger cars. In supply-constrained times, battery makers ramping up new lines might prefer high-paying small volumes over low-cost large orders. Furthermore, battery packaging will be the key for trucks with modular battery designs. For example, an urban truck needs about half the battery size of a regional one, which is an ideal modular battery application.

Exhibit 8

Global demand, United States, Europe & China supply

Current Trajectory Scenario

Global battery cell demand and supply
GWh



1. Based on US, EU, and CN battery plant announcements which do not account for ramp-up issues; accounts for ramp-up issues and slow yield for share of announced capacity (15% of incumbents, 25% of JV, 35% of integrators, 50% of startups)

Source: McKinsey Center for Future Mobility (July 2022); McKinsey battery supply tracker (June 2022)

Trucks to consume just 4 percent of electricity demand in 2040

Despite expected strong fleet electrification, commercial vehicles (CVs) will account for only about 4 percent of global electricity demand by 2040, including electricity needed to produce H2 for FCEV trucks and buses. Consequently, ZE trucks will require only limited additional electricity generation. However, the high power requirements for fast chargers could pose challenges to local grids that will require significant upgrades.

For BEVs to be truly emission-free, owners must recharge them using renewable sources of electricity. In 2019, about 40 percent of electricity production in the United States, Europe and China was from zero-emission sources such as renewables and nuclear, which we expect to increase to 77 percent by 2040; a pool that a variety of transport applications will compete for. Today, in regions such as Europe and the US, BEVs are already cleaner than ICEs, a phenomenon that will spread globally before 2030, including to India and China, thanks to the ongoing shifts from coal to cleaner energy sources.

Trucks will only contribute a limited share to the expansion of hydrogen demand, accounting for only 15% of its growth and constituting only 8 percent of global hydrogen demand in 2040. Hydrogen demand should pick up strongly after 2030, as heavy-duty FCEVs enter the market at scale and stakeholders deploy the corresponding infrastructure. The smaller role in the overall hydrogen ecosystem means that FCEV trucks may also benefit from new technologies and scale in hydrogen production from other end-use sectors like industrials or power.

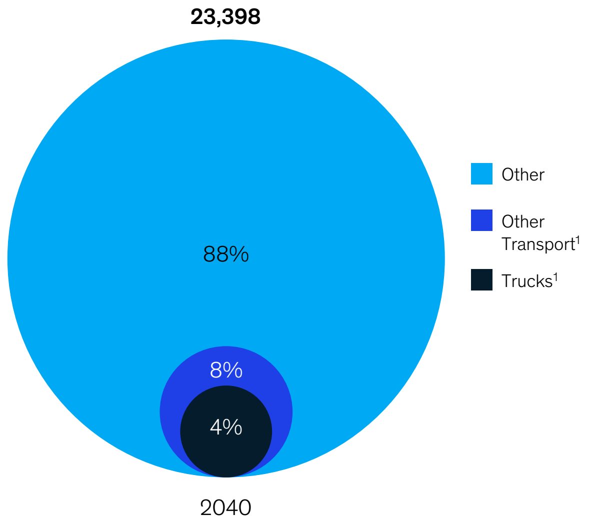
Although hydrogen production today relies heavily on fossil fuels, future hydrogen supply for trucks will likely come from “clean” sources, either in the form of blue (fossil fuel with carbon capture) or green (from renewable sources) hydrogen. FCEVs will also benefit from the substantial increase in hydrogen demand in non-transport sectors, which will account for 80 percent of total hydrogen demand by 2030. Moving to at-scale production facilities and distribution networks, at-the-pump prices for hydrogen could drop by as much as 70 percent by 2040 (compared with today’s level). A faster scale-up of hydrogen supply before 2030 could be difficult due to the long lead times of required infrastructure investments, given the need to simultaneously deploy capital-intensive technologies such as renewables, electrolyzers, and refueling infrastructure.

Exhibit 9

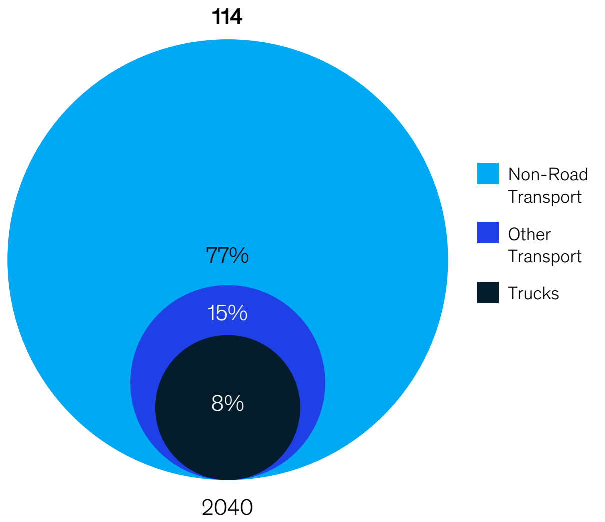
Energy demand by sector

Current Trajectory Scenario

Electricity demand, United States, Europe & China
TWh



Hydrogen demand, United States, Europe & China
Mtpa



1. Includes electricity generated hydrogen used for FCEV vehicles

Source: McKinsey Global Energy Perspective

Refueling infrastructure to cost $450 billion by 2040

The roll-out of the refueling infrastructure required for BEVs and FCEVs will likely require investments of approximately USD 450 billion by 2040, most of which will probably focus on China, given its large truck fleet. Because both FCEV trucks and renewable hydrogen supply will reach scale later than BEVs, their infrastructure roll-out will lag that of BEVs. Consequently, the BEV charging infrastructure roll-out will begin to saturate after 2040, whereas FCEV infrastructure deployment will likely more than double in the decade after 2040.

The types of refueling technology will likely evolve. Early years will see slower chargers and smaller hydrogen refueling stations (HRS),[7] gradually moving toward a higher share of fast chargers with 500 megawatts (MW) or more and HRS sizes of 4,000 kg daily capacity. Apart from operational benefits, higher-power chargers and larger HRS should lead to lower per-unit costs if utilized well. The shift toward higher-power chargers will also help reduce the charging times required and thus decrease the downtime penalty of BEV trucks compared with FCEV trucks.

Because only two to three trucks will likely ensure the efficient utilization of a depot charger, EV charging infrastructure (EVCI) can scale faster at smaller fleets than HRS, which require at least seven trucks per day to be cost-efficient.[8] For these reasons, many expect BEV infrastructure to operate at fleet hubs (80 percent, compared with 20 percent along highways). In contrast, most FCEV infrastructure will probably be situated along highways or on key arterials (70 percent, versus 30 percent at fleet hubs). In both cases, investment into infrastructures will have to precede demand – to enable trucks to even operate on zero-emission powertrains.

On a per-truck basis, costs for refueling infrastructure will be substantially higher for BEV trucks (0.11 USD/kWh) than for FCEV trucks (0.03 USD/kWh).[9] This reflects the expectation the network of charging infrastructure will be more widespread (with 1 public charger per 9 trucks[10]), whereas hydrogen refueling stations can be more concentrated to locations with high demand (with 1 HRS per 200+ trucks). The overall energy costs will be similar for BEV and FCEV, driven by the higher production costs of hydrogen.

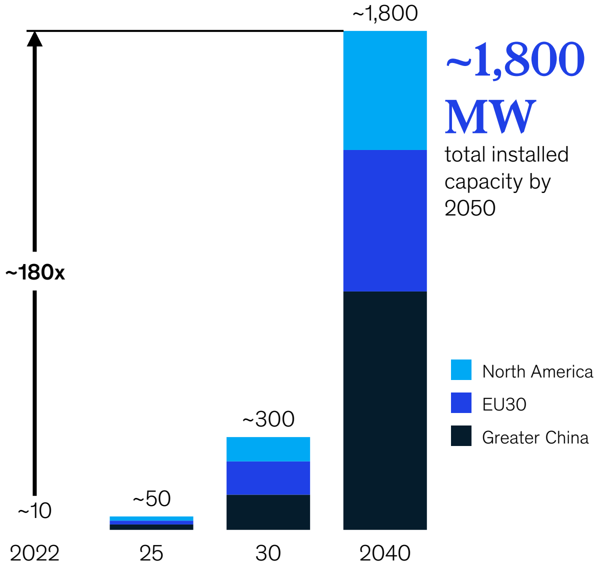
7 Medium-sized HRS with daily hydrogen capacity of 480 kg and large stations with 1,000 kg
8 Also compare: https://www.mckinsey.com/business-functions/operations/our-insights/global-infrastructure-initiative/voices/unlocking-hydrogens-power-for-long-haul-freight-transport
9 For heavy-duty long-haul truck in Europe, 2030
10 When also taking into account fleet-depot chargers, the ratio decreases to 1.5 trucks per charger

Exhibit 10

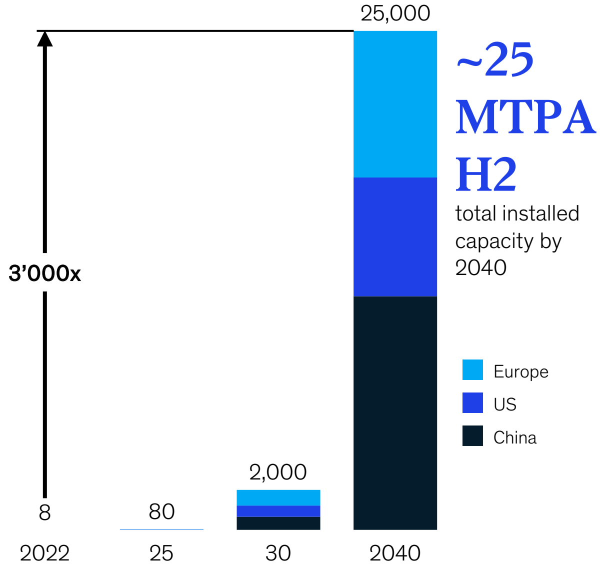
MDT & HDT charging infrastructure, North America, EU30 & Greater China

Current Trajectory Scenario

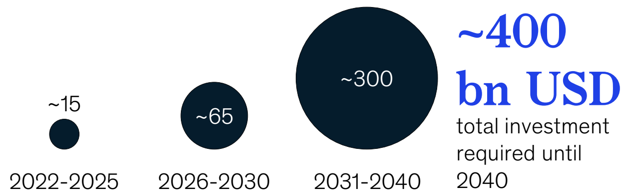
Installed charging capacity,
cumulative in MW



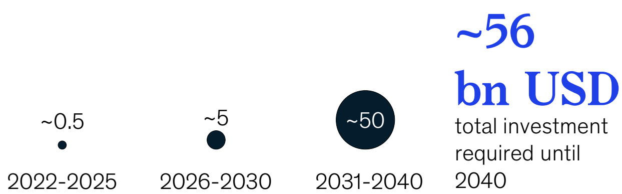
Installed Hydrogen Refueling station Capacity,
cumulative in ktons H2



Investment charging infrastructure[1],
cumulative in bn USD



Investment Hydrogen Refueling Station infrastructure,
cumulative in bn USD



1. Excluding potentially required upgrades of electricity grids

Source: McKinsey Center for Future Mobility, McKinsey Hydrogen Insights

The trucking value chain will be re-shuffled

The ZE truck transition in commercial vehicles will disrupt the entire truck value chain and its players. New players, partnerships, and products are expected. For example, the new battery value chain is a battleground among three players: large OEMs going directly into cell and pack manufacturing; incumbent tier-1 suppliers trying to enter the field; and pure battery integrator players that often specialize in packaging. Since 30-50% of the BEV truck price can depend on the battery, this will remain a critical element in the value chain.

Incumbent tier-1 suppliers will likely prepare for the ZEV transition by extending their portfolios into e-motors, plus potentially hydrogen tanks and fuel cells, but will likely face declining value pools for BEV trucks given the lower value per vehicle and OEMs that will vertically integrate on fuel cell powertrains.

Incumbent OEMs in Western markets face new competition from established Asian EV truck and bus manufacturers, mainly from China and Korea, that already offer cost-competitive and proven BEV and FCEV trucks today. In addition, several start-ups have formed in the trucking space, designing purpose-built EV truck platforms that promise superior performance and efficiency versus legacy-based incumbent platforms.

Charging infrastructure remains one of the largest bottlenecks, especially for heavy-duty long-haul trucks. However, the emergence of the megawatt charging standard (MCS) that allows charging speeds of 700-800kW can solve the technical challenge of truck charging. Likewise, OEMs are partnering to jointly solve the challenge of building out highway ultra-fast charging infrastructure in Europe. This way, OEMs are moving down the value chain to give fleets confidence and likely are also hoping to access new value pools. In addition, the longer re-charging times for BEV trucks may trigger new business models around route optimization and advance reservations of overnight parking for trucks.

Overall, the energy and fuel spaces will remain competitive, with traditional oil and gas players seeing new players in the electricity and hydrogen energy provision system. For BEVs, about 60 percent of energy provision will shift to onsite charging in fleet depots, away from traditional refueling stations.

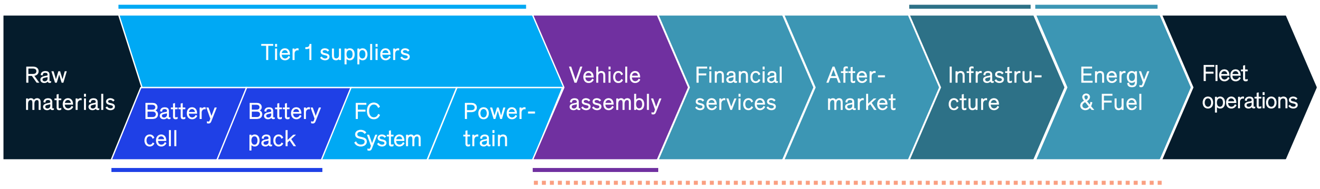
The biggest value chain change will involve the shift toward trucks-as-a-service for ZE trucks. This change will affect vehicle provision, financing (i.e., leasing), aftermarket parts and services, infrastructure, and energy provision. Given the high upfront capex of zero-emission trucks (two to four times that of diesel trucks) combined with high technology and residual value risk (less clarity regarding a used vehicle's "second life"), fleet providers will prefer leasing options that also take care of charging infrastructure provisions and maintenance.

Regulation will likely also shape the structure of the future commercial vehicle value chains. For example, the recently adopted Inflation Reduction Act (IRA) in the United States provides substantial subsidies in form of tax breaks but requires further localization of production and supply chains for truck models and components to qualify.

Overall, the CV value chain will feel a greater impact from the zero-emission powertrain transition than passenger cars. Commercial vehicles will have higher complexity in powertrains and infrastructures with two complementary but different technologies, infrastructures, and fuels. But given their smaller scale, truck players are not large enough to occupy each step along the value chain by themselves (e.g., batteries), requiring them to form partnerships to offer fleet operators the competitive products they demand.

Exhibit 11

High-level value-chain moves



Insourcing ZE powertrains

E-powertrains mainly out-sourced so far, dominated by legacy powertrain players, but lower value per vehicle than for Diesel powertrains

OEM JV

Truck OEMs starting to co-invest in large-scale charging infrastructure roll-out to debottleneck consumer ZEV adoption

New battery integrators

Smaller OEMs likely to rely on integrators for cell sourcing and packaging, with larger OEMs already starting to in-source today

Competition from new sectors

Strong competition in ZE truck re-fueling with traditional fuel retailers, utility companies and hydrogen ecosystem players competing for market share

Startup OEMs/Asian OEMs

New strong competition for incumbent players from Asian EV leaders and new EV startups with dedicated EV platform without ICE legacy

Trucks as a service

Higher upfront costs and larger technology risk to trigger shift towards new ownership and operating models, including integrated “as-a-service” concepts billed on a per-km basis

Conclusion

Medium- and heavy-duty trucks are due for a major paradigm overhaul. By 2040, we believe some of the largest automotive markets in the world – the EU, US and China – will have transitioned most of their new commercial vehicles to zero-emission powertrains. At first, the transition will still require regulatory tailwinds through subsidies and other incentives, but soon, the expected superior TCO performance will fuel much of the uptake of BEV and FCEV powertrains.

The path to zero-emission trucking is plastered with uncertainties. Chief among them will be the question of the role BEV and FCEV powertrains will play in future truck fleets. With a continued steep learning curve, both powertrains will be cheaper to operate than diesel. However, they will have different profiles along technology costs, operational constraints and infrastructure availability, leading to a market in which trucks and their powertrains will be much more tailored to a fleet's specific use cases and environment. BEV and FCEV will play complementary roles in this more complex new world, but the exact balance between them is not clear yet and will likely also vary by region.

Players along the trucking value chain need to get ready for the disruption soon. With value pools shifting towards powertrain technologies such as batteries and fuel cell systems, some diesel-specific incumbents will decide to focus on a sunset game, while others try to explore opportunities in zero-emissions trucks or innovative go-to-market strategies. They will meet new partners, but also new competition from start-up OEMs to utility companies, who all claim a share of the zero-emission trucks market. Fleet operators in turn will benefit from lower operating costs, which will likely result in positive impacts for freight buyers, too.

Over the next 1-2 decades, the new ecosystem will have huge challenges to solve. A first priority will be to reach technological maturity for BEV and FCEV powertrains, so that fleet operators trust them as much as diesel trucks today. But this alone will not be enough: More than USD 450 bn investments will be required to develop new recharging and refueling infrastructures alone. These investments need to be made before zero-emission trucks can be deployed at scale, but they will only pay off once fleet sizes are large. In addition, a dozen giga-factories worth of battery supply will need to be developed, and renewable power generation expanded to support the decarbonization needs of not only transport, but wider society. Any additional acceleration in uptake of zero-emission trucks means a further scale-up across the whole value chain.

Don't under-estimate the silent hum of a zero-emission truck. It is going to re-shape a whole industry.

Our capabilities

The McKinsey Center for Future Mobility (MCFM) aims to help all stakeholders in the mobility ecosystem navigate the future by providing independent and integrated evidence about possible future mobility scenarios. Our view of the trends reflects advanced multi-level driver-based models already validated across industries and players. Each model is based on proprietary data and contributes to an integrated perspective on future mobility trends and scenarios including modal mix, miles traveled, vehicle sales, autonomy, powertrain electrification, battery demand, charging infrastructure, components, consumer behavior, and value/profit pools.

This article leveraged insights from multiple MCFM models as well as contributions from Hydrogen Insights' Refueling Infrastructure and Hydrogen Cost Perspective as well as from Energy Insights' Global Energy Perspective. Please get in touch if you would like to learn more.

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