MAKING ZERO-EMISSIONS TRUCKING POSSIBLE

An industry-backed, 1.5°C-aligned transition strategy

TRUCKING TRANSITION STRATEGY / JULY 2022

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At current emissions levels, staying within a global carbon budget aligned to 1.5°C might slip out of reach in this decade. Yet efforts to slow climate change by reducing greenhouse gas (GHG) emissions run into a central challenge: the biggest emitters of carbon dioxide equivalent (CO_2e) into the atmosphere — transportation sectors including aviation; shipping; and trucking; and heavy industries including steel, aluminium, cement, and chemicals manufacturing — are the hardest areas in which to lower emissions. Moreover, transitioning these industries to carbon-neutral energy sources is complex, requiring a comprehensive approach across entire value chains, with collaboration among companies, suppliers, customers, banks, institutional investors, and governments.

Catalysing these changes is the goal of the Mission Possible Partnership (MPP), an alliance of climate leaders focused on supercharging efforts to decarbonise these industries. Led by the Energy Transitions Commission, RMI, the We Mean Business Coalition, and the World Economic Forum, MPP has as its objective to propel a committed community of CEOs from carbon-intensive industries — together with their financiers, customers, and suppliers — to agree on the essential decisions required for decarbonising industry and transport. More importantly, the coalition must act on those decisions. MPP will orchestrate high-ambition disruption through net-zero industry platforms for seven of the world's most carbon-intensive sectors: aviation, shipping, trucking, concrete, steel, aluminium, and chemicals.

Transitioning these seven hard-to-abate sectors to net-zero emissions by 2050 will require significant changes in how they operate. MPP facilitates this process by developing sector transition strategies for all seven hard-to-abate sectors.[1]

A Sector Transition Strategy informs decision makers from the public and private sectors about the nature, timing, cost, and scale of actions necessary to achieve net zero within the sector by 2050.

1 Zero-emissions truck technology is or will be viable for almost all use cases. The sector remains a challenge to decarbonise because of the scale of change, the costs for some users, and new infrastructure required.

All sector transition strategies are based on similar assumptions about the costs and availability of technologies and resources such as renewable electricity, green hydrogen (H_2), and sustainable biomass. By providing a harmonised, cross-sectoral perspective, we hope to inform decision makers with a fair assessment of transition strategies for all seven sectors and to expedite innovation, investments, and policies to support the transition.

Within MPP, the Road Freight Zero (RFZ) initiative is working towards the goal of zero-emissions truck (ZET) deployment. A broad set of global stakeholders are engaged in this initiative, including major buyers of transportation, leading transporters and logistics companies, significant players in energy and infrastructure, financial institutions, and public-sector organisations. They all have the same ambition: to accelerate decarbonisation of heavy-duty urban, regional, and long-haul trucking.

This report sets out a zero-emissions transition strategy for the heavy-duty trucking (HDT) sectors in the United States, Europe, China, and India. It identifies what needs to happen to enable this future between now and 2050. The Trucking Transition Strategy model ("the model") underpins this transition strategy, which has three main aims:

- Provide a detailed reference point for the changes needed over the next 30 years to underpin corporate target setting, science-based targets, and financial sector alignment methodologies.
- Inform the 2020s' priority actions, trade-offs, and decisions of stakeholders that will shape the road freight markets, including transport buyers, logistics players, fleet owners, truck manufacturers, energy and infrastructure providers, policymakers, and financial institutions.
- Catalyse actions from stakeholders across the value chain that together will unlock investments in zero-carbon solutions.

The model used and the analytics behind it will be made open access to promote transparency and collaboration, such that the inputs and assumptions are available for inquiry, and future iterations may build on this effort. This open-access approach lends itself to regular refinement as data and insights evolve. Critically, it also ensures that the industry can align behind a strategy it considers technically and economically feasible, subject to appropriate value-chain collaboration, finance, and policy support.

Through this work, we hope to inspire and inform an accelerated transition to net zero for the HDT sector, including actions – innovations, investments, policies, and procurement decisions – taken by the broader industry value chain essential to support the transition.

Industry support for MPP's Trucking Transition Strategy

This effort benefitted from the input of the MPP RFZ community, consisting of over 50 companies and 20 organisations representing the entire trucking value chain. Members of the initiative have validated the model and architecture and endorse the general thrust of the arguments made in this report, but should not be assumed to agree with every finding, input, or recommendation. These companies agree on the importance of reaching zero emissions from the HDT sector by mid-century and share a broad vision of how to achieve the transition.

This agreement among industry leaders should give decision makers around the world confidence that it is possible to meet global HDT demand and simultaneously reduce emissions from the sector to net zero by 2050. It should also inspire belief that the critical actions required in the 2020s to set the sector on the right path not only are clear but can be pursued without delay and that the industry is ready to collaborate with its value chain to achieve those goals.

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This effort was prepared in collaboration with Mission Possible Partnership partners World Economic Forum, Energy Transitions Commission, RMI, and McKinsey.

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PREPARED BY

Mission Possible Partnership (MPP)

Led by the ETC, RMI, the We Mean Business Coalition, and the World Economic Forum, the Mission Possible Partnership (MPP) is an alliance of climate leaders focused on supercharging the decarbonisation of seven global industries representing 30% of emissions: aviation, shipping, trucking, steel, aluminium, cement/concrete, and chemicals. Without immediate action, these sectors alone are projected to exceed the world's remaining 1.5°C carbon budget by 2030 in a Business-As-Usual scenario. MPP brings together the world's most influential leaders across finance, policy, industry, and business. MPP is focused on activating the entire ecosystem of stakeholders across the entire value chain required to move global industries to net-zero. **www.missionpossiblepartnership.org**

Energy Transitions Commission (ETC)

ETC is a global coalition of leaders from across the energy landscape committed to achieving net-zero emissions by mid-century, in line with the Paris climate objective of limiting global warming to well below 2°C and ideally to 1.5°C. Our commissioners come from a range of organizations – energy producers, energy-intensive industries, technology providers, finance players, and environmental NGOs – which operate across developed and developing countries and play different roles in the energy transition. This diversity of viewpoints informs our work: our analyses are developed with a systems perspective through extensive exchanges with experts and practitioners. **www.energy-transitions.org**

RMI

RMI is an independent nonprofit founded in 1982 that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and NGOs to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; and Beijing. **rmi.org**

World Economic Forum

The World Economic Forum is an International Organization for Public-Private Cooperation. The Forum engages the foremost political, business, cultural, and other leaders of society to shape global, regional, and industry agendas. The Forum brings together stakeholders to help address the greatest ecological crises of our time, focusing on topics like climate, mobility, energy, and the circular economy. The World Economic Forum's platforms aim to facilitate action-oriented communities of stakeholders from all parts of the international system, and the organisation is one of the core partners for the Mission Possible Partnership. **https://www.weforum.org**

McKinsey & Company

McKinsey & Company is a global management consulting firm committed to helping organizations create change that matters. In more than 130 cities and 65 countries, their teams help clients across the private, public, and social sectors shape bold strategies and transform the way we work, embed technology where it unlocks value, and build capabilities to sustain the change. Not just any change, but change that matters – for their organizations, their people, and in turn society at large. McKinsey & Company is a knowledge partner for the Mission Possible Partnership and provided fact-based analysis for this report. Learn more at **www.mckinsey.com**.

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Road Freight Zero

Road Freight Zero is a multi-stakeholder, cross-value chain coalition of first-mover champions, working together to fast-track zero-emission, heavy-duty trucking toward a 1.5° trajectory by 2030. It focuses on accelerating the viability and deployment of HD ZE fleets and infrastructure by aligning stakeholders on a common vision and roadmap; performing scalable corridor pilots that create learnings and replicable blueprints for ZET fleet and infrastructure; scaling up innovative financing to overcome first-mover disadvantages; and connecting companies with leading-edge solutions to start reducing emissions today. Road Freight Zero is led by the World Economic Forum, with support from knowledge partners including McKinsey, ETC, and RMI on specific projects such as this Transition Strategy. **https://www.weforum.org/projects/decarbonizing-road-freight-initiative**

North American Council on Freight Efficiency (NACFE)

NACFE works to drive the development and adoption of efficiency-enhancing, environmentally beneficial, and cost-effective technologies, services, and operational practices in the movement of goods across North America. NACFE provides independent, unbiased research, including confidence reports on available technologies and guidance reports on emerging ones, which highlight the benefits and consequences of each, and deliver decision-making tools for fleets, manufacturers, and others. NACFE partners with RMI on a variety of projects, including the Run on Less demonstration series, electric trucks, emissions reductions, and low-carbon supply chains. Visit **NACFE.org** or follow NACFE on Twitter @NACFE_Freight.

CONTENTS

TEN CRITICAL INSIGHTS ON THE PATH TO A ZERO-EMISSIONS HEAVY-DUTY TRUCKING SECTOR

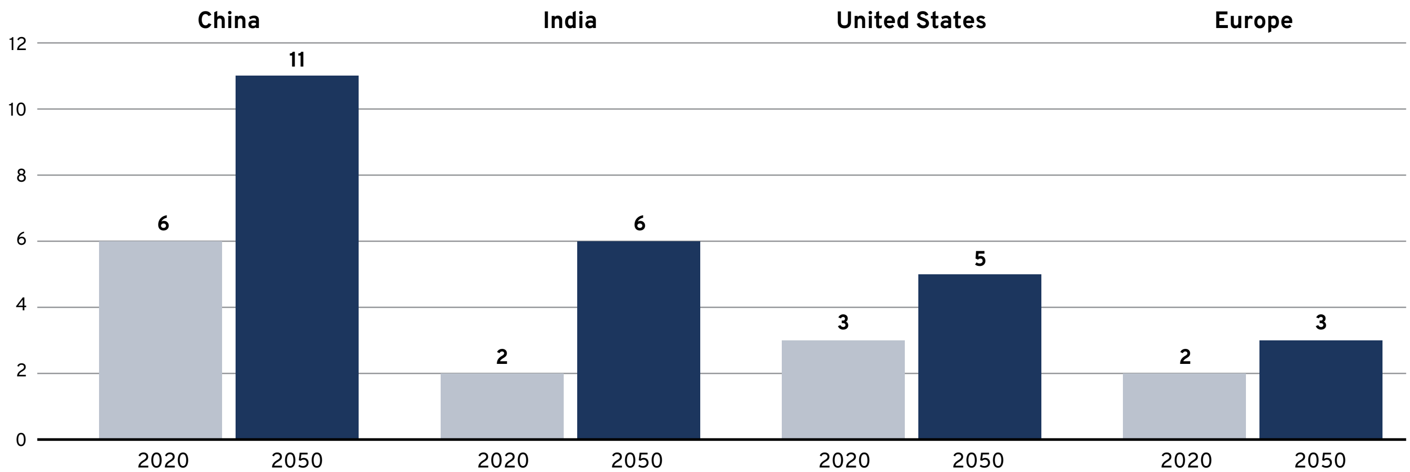
1. Trucking demand is surging globally, making it an important sector to decarbonise. A swift, decisive move to zero-emissions trucks and a rapid rollout of infrastructure are needed to achieve net zero by 2050.

Heavy-duty trucking in China, Europe, India, and the United States emits approximately 1.5 gigatonnes (Gt) of CO_2 equivalent (CO_2e) today. Trucking demand is projected to more than double and increase from 12 trillion tonne-kilometres (tkm) to 26 trillion tkm. India's approximate 5% demand growth will be the fastest, and China will continue to have the highest demand (Exhibit A).[2] Today, 95% of heavy-duty trucks use diesel. If most trucks continue to use diesel, by 2050 heavy-duty trucking in the modelled regions will emit nearly 3 Gt of CO_2e, double current levels.

EXHIBIT A

Heavy-duty trucking demand expected to grow through 2050

Annual trillion tonne-kilometres



Source: MPP analysis

Surging trucking demand and expected technology availability have largely dictated this report's recommended decarbonisation strategies.[3] Renewable diesel, renewable natural gas (RNG), and other transitionary fuels can play a role in the near term with legacy vehicles but have drawbacks, and other new fuels are likely to be prioritised for use in other sectors such as aviation and marine.

The main pathway to decarbonising trucking will be developing and using new vehicles and drivetrains: battery electric trucks (BETs) and hydrogen electric trucks (HETs), powered with fuel cells. This analysis concludes that achieving net zero by 2050 requires all trucks sold by 2040 to be either BETs or HETs.

Zero-emissions trucks (ZETs) are in early-stage production by manufacturers, are just starting to have an equivalent total cost of ownership (TCO) with diesel vehicles for many uses, and are already experiencing an encouraging level of adoption. Further actions can help ensure that trucking achieves two goals: reaching zero emissions by 2050 and reducing the cumulative amount of GHG emissions between now and then. Those actions include stakeholders putting in place the market incentives, policy frameworks, continued vehicle development, and timely charging infrastructure necessary for this major transition. It also depends on the rapid deployment of renewable generation for both electric vehicle charging and hydrogen production.[4]

2 Autonomous vehicles, though not modelled in this report, would likely further increase total freight miles travelled and increase each vehicle's miles per year.

3 Efficiency improvements, such as shortening supply chains, ensuring that truck trailers are carrying fuller loads, and shifting to trains and ships, do play a role and can reduce trucking's emissions intensity by 20%.

4 In the MPP model, 100% of the H_2 is assumed to come from renewable sources. Electricity for BETs in the four regions is expected to be sourced from a grid that is 90% renewables and storage, with the remainder using carbon capture and sequestration. Reports from the International Energy Association and the Energy Transitions Commission consider a 90% renewable grid feasible. See the *Appendix* for more information on grid assumptions.

2. Most ZETs are expected to reach TCO superiority with diesel trucks between 2025 and 2034.

A zero-emissions industry is fundamentally possible because battery and hydrogen trucks are increasingly cost competitive. ZETs typically have higher upfront costs but lower operating costs than internal combustion engine (ICE) trucks. As technological development and economies of scale in production lower the upfront costs of ZETs, the ability of those lower operating costs to recoup increased upfront investment is growing. Zero-emissions vehicles may achieve TCO superiority in most use cases between 2025 and 2034, depending on usage and region.[5]

This report divides the trucking market into three usage categories: urban, regional, and long haul. For urban deliveries, BETs reach TCO superiority most quickly. They will have capital expenditure costs competitive with those of diesel, and greater operating cost advantages because of efficiencies during idling and stop-and-go traffic. Long-haul trucking requires larger batteries and more costly high-powered charging or extensive hydrogen infrastructure; these trucks should achieve TCO parity between 2032 and 2037 in every region except India, which will take longer.

A few key trends in ZET adoption will determine the pathway to zero emissions:

- Sales uptake for BETs will accelerate fastest in urban and regional segments compared with long-haul segments, due not just to TCO but also to operational feasibility such as shorter trips and greater charging availability. BETs, rather than HETs, will dominate this market.

- Long-haul HDT should see a higher uptake of HETs than urban and regional duty cycles, mainly due to hydrogen's higher energy density and shorter refuelling times. Up to 50% of long-haul truck sales will be HETs; BETs will likely be adopted for predictable routes that have on-the-go charging.

- Of the regions we studied, Europe will adopt zero-emissions vehicles fastest due to ambitious net-zero policies.[6] Europe will be followed by the United States, which has ambitious state policy frameworks and some supportive federal policies. China, which lacks significant policy for ZETs but has ambitious policies for other transportation segments, will follow later. Because of vehicle costs and lower policy support, India will be last among our studied regions to adopt ZETs.

- ZET policy works with existing fleet costs and behaviour to influence market outcomes. Because existing diesel vehicles are more expensive in the United States and Europe, ZETs have a greater cost advantage than ICE vehicles – positioning them for faster adoption. In Europe, this advantage is compounded by high diesel fuel prices. India and China have cheaper ICE trucks and relatively low fuel prices, leading to a later transition.

- Transitionary fuels and drivetrains are expected to coexist during the next 5–10 years before BETs and HETs reach TCO parity at scale. These technologies will likely include liquefied/compressed renewable natural gas (renewable LNG/CNG) and biodiesel trucks (Exhibit B).

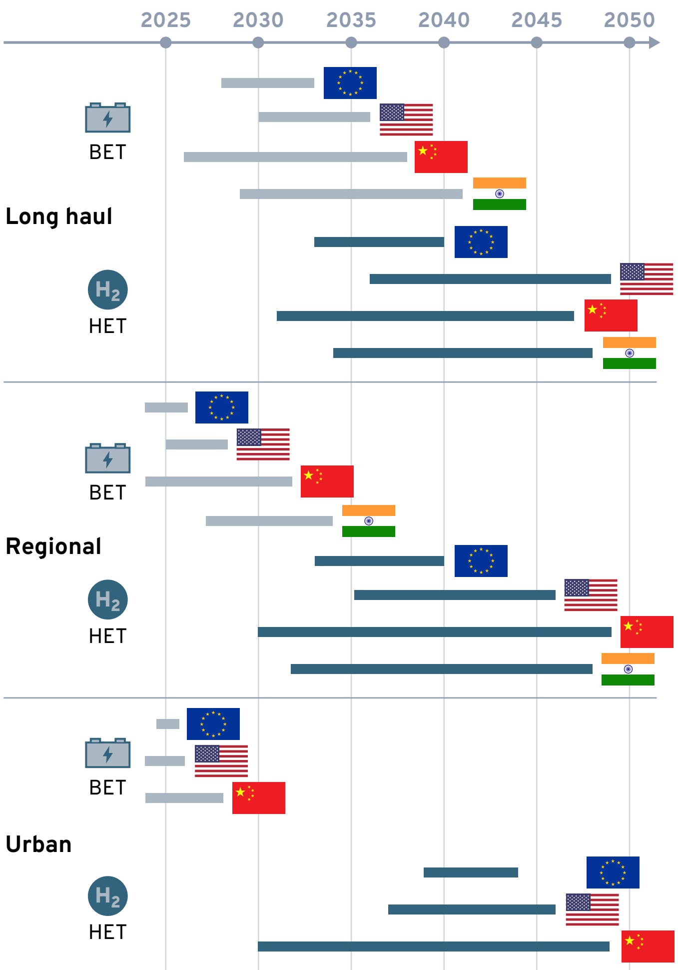
5 Total cost of ownership is the cost of the truck, the fuelling infrastructure (diesel, electric, or hydrogen), and the ongoing fuel and maintenance operating costs over the vehicle's lifetime. The *Appendix* further describes the analysis.

6 The EU has introduced targets for heavy-duty vehicles to reduce emissions by 15% as of 2025 and by 30% as of 2030.

3. Adoption of ZETs based on cost optimisation can substantially advance progress towards net zero.

EXHIBIT B

ZET TCO parity varies depending on usage, technology development, and policy choices



Note: Flags reflect TCO dates of Expected Adoption scenario. Bars reflect range of TCO breakeven dates for the other modelled scenarios. HDT is legally restricted from urban deliveries in India; the country is therefore excluded from the segment analysis.

Source: MPP analysis

This report models four scenarios for increasing ZET adoption, and the "Do Nothing" Baseline of fossil fuel usage at current levels.

First is the *Expected Adoption scenario* as the TCO of BETs and HETs improves. This is a market-based scenario. Many fleets will buy ZETs because they make financial and operational sense, and by 2050, 80% of trucks on the road will produce zero emissions. Yet without additional action to support ZETs, trucking will not achieve zero emissions by 2050. Trucking will also create 41 Gt CO_2e between now and then, consuming nearly 6% of the world's remaining "carbon budget". TCO improvements, infrastructure development, and new policy are needed to enable a zero-emissions industry by 2050.

The second scenario, the *Rapid Technology Improvement scenario*, is also solely market based. However, the significant economic superiority of ZETs leads to a nearly zero-emissions trucking sector by 2050, even without policy intervention.[7] This scenario is modelled in two different ways: accelerated BET deployment and accelerated HET deployment. They include achievable improvements in vehicle supply, fuel costs, and fuelling station usage. In these scenario models, we also relax non-cost constraints on BET adoption (e.g., battery weight makes hauling heavy loads impossible), reflecting non-cost technology gains, such as greatly increased battery energy density.

It is possible that technological improvements will happen more quickly than is currently anticipated. (Consider that zero-emissions vehicle prices have decreased far more than was projected a decade ago.) This scenario assumes rapid development of renewable electricity generation and transmission, as well as hydrogen production and transportation.[8] Complementary clean energy investments in adjacent sectors can also help, including:

- Charging infrastructure for medium-duty vehicles
- Hydrogen production infrastructure for heavy industry
- Lessons and economies of scale from light-duty electric powertrains and battery production that reduce BET costs
- Guaranteed demand through investor and institutional climate commitments

There are many plausible developments that can further reduce the projected costs of zero-emissions technologies.

7 Modelling assumptions leave a minimal amount of continued ICE usage.

8 The EU has introduced targets for heavy-duty vehicles to reduce emissions by 15% as of 2025 and by 30% as of 2030.

4. Policy is another means of helping trucking achieve zero emissions by mid-century. Strategies that prioritise ZET uptake before 2050 prevent 6–13 Gt of cumulative CO_2e emissions.

Unlike the Expected Adoption scenario and the Rapid Technology Improvement scenario described earlier, the remaining two scenarios below rely on both vehicle policy and market forces for completely decarbonising HDT by 2050. The *Zero-Emissions – ZET Mandate scenario* (*"Zero-Emissions scenario"*) represents the implementation of a diesel ban by 2040, the latest date to ensure that trucks on the road in 2050 will produce zero emissions. Between now and 2050, it would avoid 6 Gt CO_2e compared with the Expected Adoption scenario (Exhibit C).

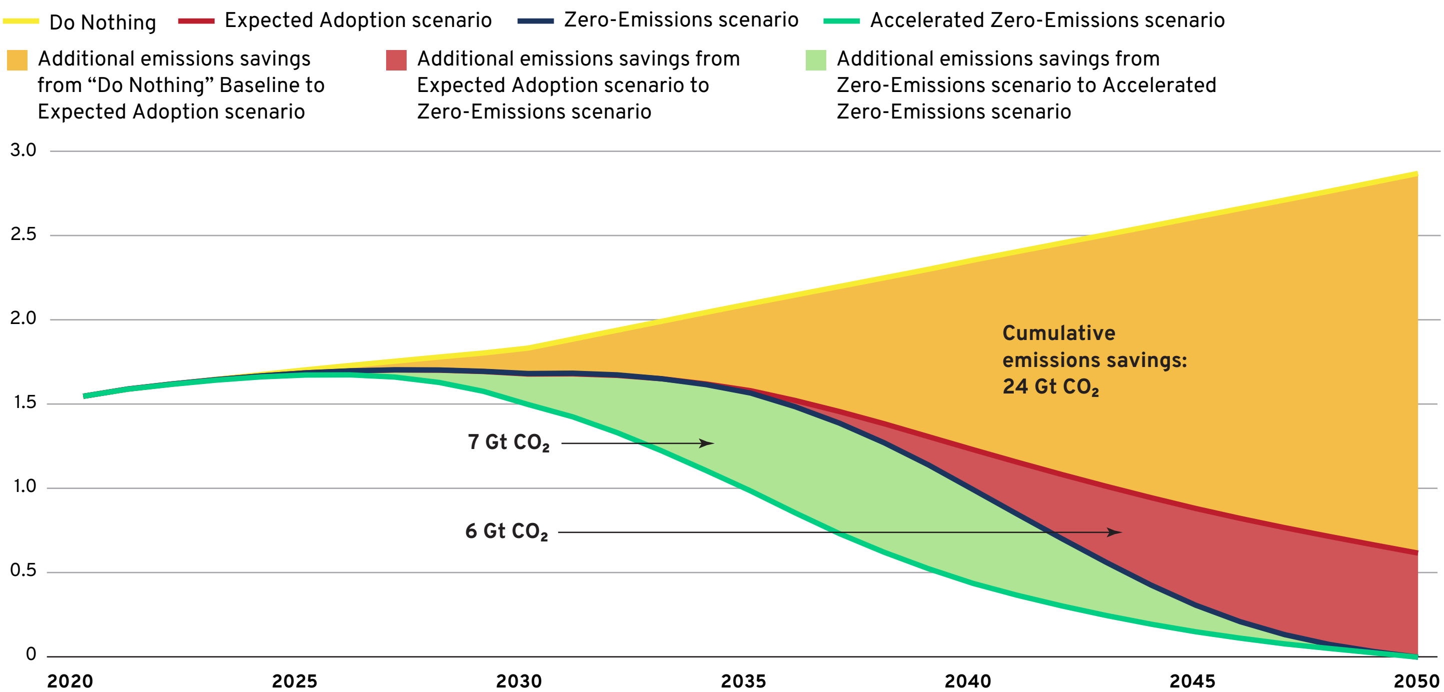
The *Accelerated Zero-Emissions – Carbon Cost scenario* (*"Accelerated Zero-Emissions scenario"*) represents policy measures in which the cost of carbon affects the TCO of trucks powered by fossil fuel and other CO_2e-emitting technologies.[9] This scenario achieves net zero by 2050 and avoids 13 Gt CO_2e compared with the Expected Adoption scenario.

MPP's Rapid Technology Improvement scenario nearly achieves zero emissions, while the Zero-Emissions scenario and Accelerated Zero-Emissions scenario reach the no-GHG goal. Each MPP scenario assumes different, discrete policies and technology developments to reach zero emissions. However, a real-life path to net zero is likely to include elements of all three.[10]

EXHIBIT C

Fully decarbonising trucking requires market forces and other action

Annual GHG emissions by scenario, Gt CO_2e



Source: MPP analysis

9 Well-to-wheel emissions, including tailpipe emissions, are included in this report's greenhouse gas analysis.

10 See *Appendix* for a detailed review of TCO and main TCO assumptions.

5. Achieving zero-emissions trucking is cheaper than continuing to burn fossil fuels. Higher vehicle costs will be more than recouped through lower operating costs.

A trucking sector that is zero emissions is not only more sustainable than the status quo but also more economical. When compared with the cumulative investment that would have been required in a "Do Nothing" diesel-dominated future, investments in ZETs are cheaper in all markets. Though BETs and HETs will usually have higher upfront costs, they more than recover the difference from reduced fuel and operating expenses (Exhibit D).

As the market continues to scale, ZETs will represent a growing share of vehicle sales. A zero-emissions industry by 2050 is cheaper than a diesel-dominated one and is only slightly more expensive than a cost-only optimised mix of ICE trucks and ZETs. However, there are important regional differences: Europe and the United States have lower transition costs than do China and India.

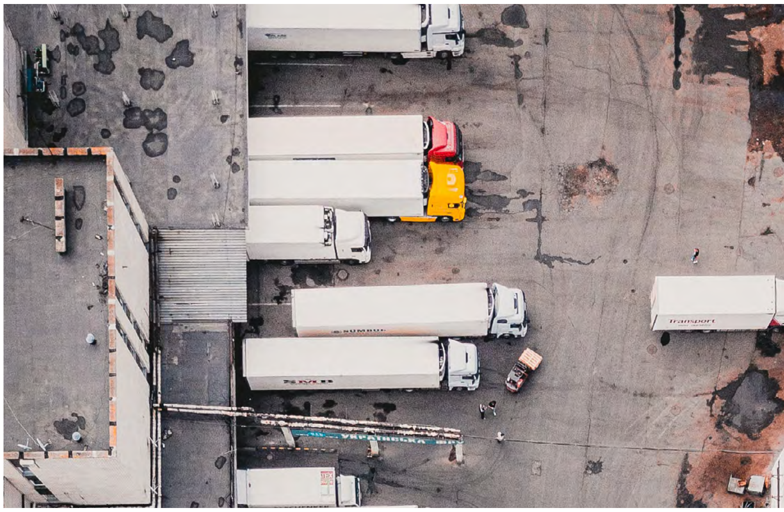
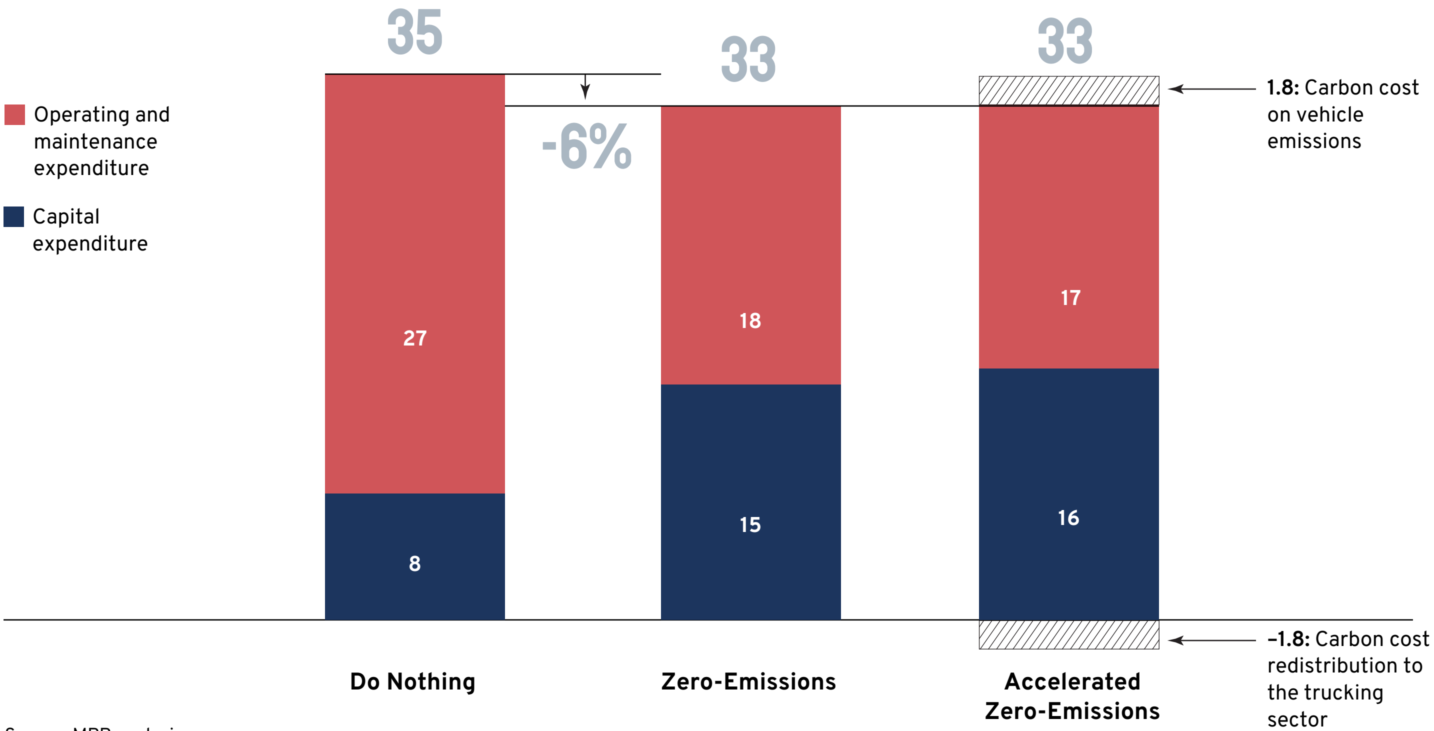


EXHIBIT D

ZETs are expected to reduce overall trucking costs

Cumulative capital investments and operating expenditures by scenario, Trillion US$, 2020–50



Source: MPP analysis

6. Financing the transition in developing economies will require more capital, creating an opportunity for global climate finance to enable a worldwide transition to zero emissions.

In the United States and Europe, where ICE trucks are substantially more expensive than in India and China, the upfront net capital investment required to achieve net zero is 25% to 30% more than continuing to use mostly diesel. However, in India and China, where ICE trucks are cheaper, the incremental costs of ZETs and their infrastructure are more significant (Exhibit E).

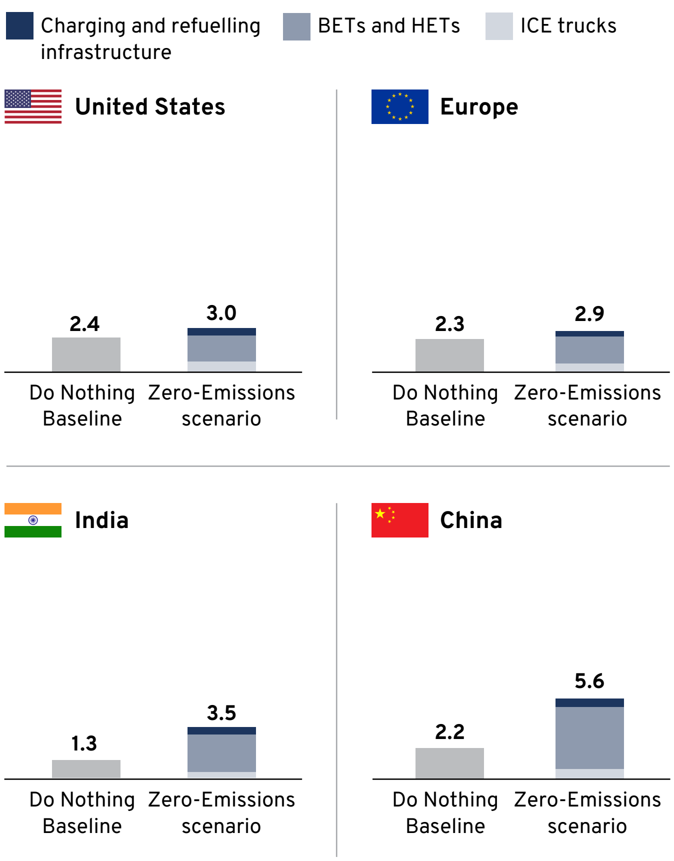
However, even in India and China, where the overall capital burden from the transition is highest, making the transition is better than continuing on the current pathway. The value of operational savings from ZETs justifies the transition (Exhibit F).

Mobilising the financing to secure this transition in developing countries will be an important enabler for a zero-emissions trucking industry. Global multilateral financing bodies should align their financing portfolios with the needs of the trucking industry.

EXHIBIT E

Diesel truck costs vary by region, impacting ZET's upfront cost competitiveness

Net present value of 2020–50 capital costs by scenario, Trillion $

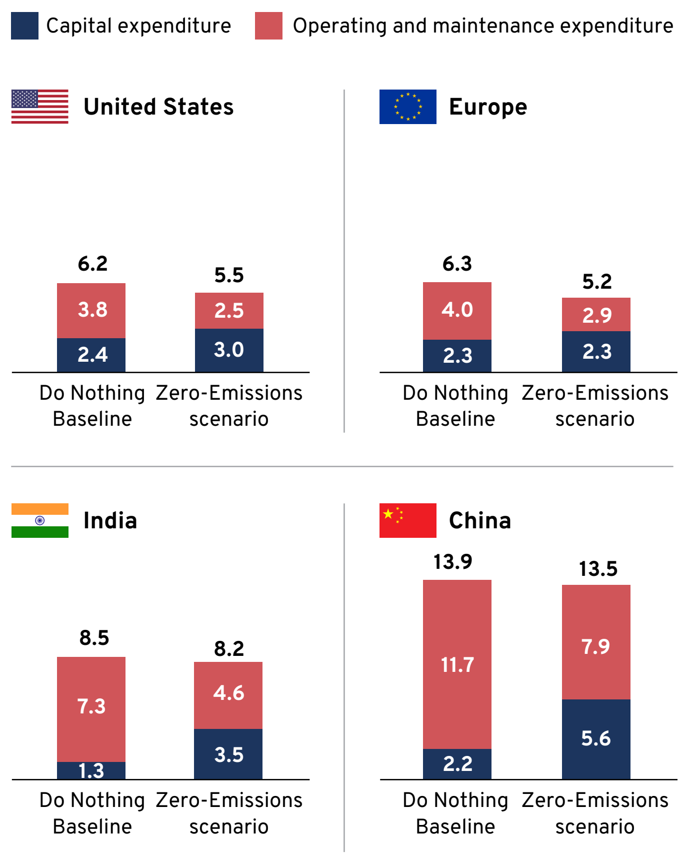


Source: MPP analysis

EXHIBIT F

ZET operating savings are projected to create positive TCO in all regions

Net present value of all 2020–50 costs by scenario, Trillion $



Source: MPP analysis

7. Innovative business models and financing instruments can leverage ZETs' lower operating costs in order to mobilise capital to pay for their purchase.

A fleet's access to financing depends on national financial infrastructure and the fleet's size. Typically, larger fleets have better access to capital than small ones, meaning they will be in a better position to finance the purchase of expensive ZETs and ultimately recoup those extra costs through operational savings. However, globally, most fleets are owned by small businesses, which sometimes have just a single vehicle.

These small businesses typically have much less access to capital than their larger competitors and often have less ability to maintain and repair new technologies such as ZETs. The market needs models that reduce this burden on small businesses and enable them to gain access to ZETs without having to make large upfront payments or develop specialised maintenance capabilities. Business models such as truck-as-a-service (TaaS) and battery-as-a-service (BaaS) are short-term leasing arrangements that can help small fleets gain access to these new and expensive technologies. The transition should include innovative financing and business models that can minimise economic harm to individual firms.

Furthermore, many truck operators understand the promise of ZETs but see substantial near-term risk in the transition. ZETs are a new technology with a relatively short track record. If they fail prematurely, they will be very expensive to replace or repair. Offering extended warranties for critical components such as batteries and including original equipment manufacturer (OEM) service agreements can bolster fleets' confidence in ZET ownership and accelerate the transition. Another way to increase fleets' confidence is to strengthen the residual value of their end of life trucks. Though this analysis does not measure second hand market value for either diesel trucks or ZETs, cultivating the downstream battery recycling industry helps the environment and improves the ZET business case.

8. Enabling policy and coordination in the timing of supply and demand for both vehicles and refuelling infrastructure can reduce fleets' risk during this transition.

Although trucking decarbonisation is ultimately enabled and accomplished by ZETs that are technically and economically superior to ICE vehicles, local policy designed to promote ZETs can help secure the transition – especially in the early stages. Those enacting policy should focus on simultaneously bringing to market the supply of ZETs, creating demand for them, and ensuring the upstream infrastructure that enables them. If any of those three elements is lacking, the transition will be slowed and net zero may not be achieved by 2050.

Of the three, demand has historically been where most policy action has been focused. A very common policy approach increases demand for ZET technologies with vehicle purchase incentives that support early market development. A similar approach is to alter the economics of operating trucks in favour of ZETs by increasing the prices of fossil fuels and subsidising the purchase of green electricity and hydrogen. Finally, more forceful demand-side tools such as diesel bans and diesel truck purchase requirements have been announced in several jurisdictions.

Although demand is crucial, if policymakers stimulate demand for ZETs that is then unmet by supply, they will only have created increased costs to fleets. Especially in the early stages of market development, increased demand alone is not sufficient to draw supply into the market in a way that is compatible with ambitions for zero emissions. Policies designed specifically to induce supply must also exist. Such policies could include tax incentives or other subsidies to produce ZETs, such as in the Netherlands, as well as specific regulatory regimes that require the ZETs to make up an increasing share of vehicles sold, as in California.

Finally, both supply and demand for ZETs are contingent on upstream value chains that enable the production and use of those vehicles. Policymakers should look upstream at issues such as the ability of OEMs to ethically source raw materials for critical ZET components and should invest in the infrastructure to distribute electricity and hydrogen to places where trucks will need it.

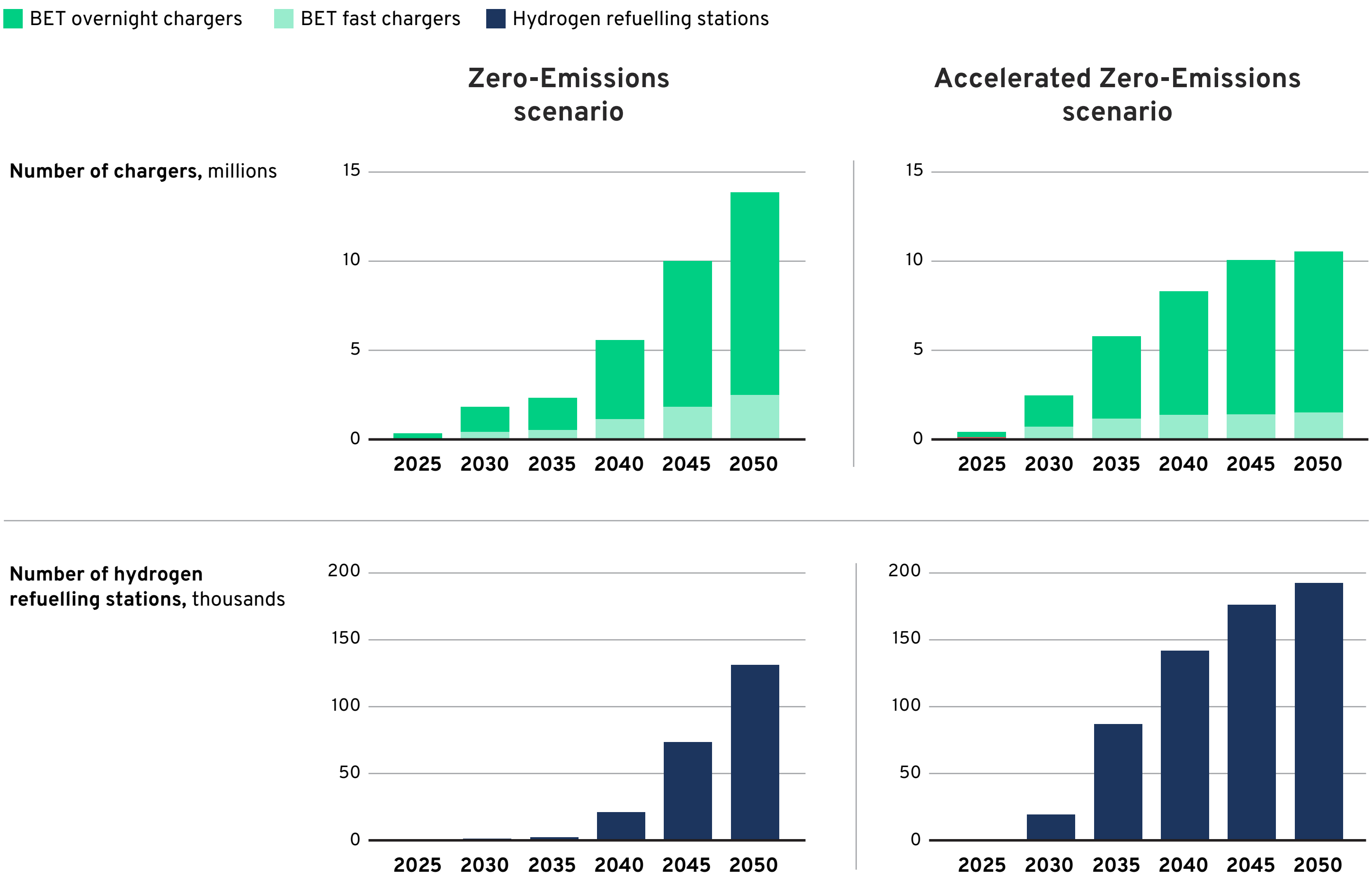
As they formulate these portfolios, policymakers should ensure both that they are catalysing the action needed from all parties (supply, demand, and infrastructure) and that any costs created by their policy portfolios to a particular party do not exceed the ability of that party to pay.

9. Operators need more public charging and hydrogen stations, a more mature ZET production value chain, and enough grid power for both charging and hydrogen production.

Depending on the scenario, there will be between 6 million and 9 million ZETs by 2030. These trucks will require dense charging and refuelling networks (Exhibit G).

EXHIBIT G

ZET adoption requires a major infrastructure ramp-up



Note: Overnight chargers are assumed to have a capacity of 100 kW and fast chargers are assumed to have one of 500 kW.

Source: MPP analysis

By 2030 about 1.4 million to 1.8 million overnight depot chargers and 400,000 to 700,000 public high-speed chargers will be needed for BETs, and 1,000 to 19,000 hydrogen refuelling stations across key markets will be needed for HETs. Putting such an infrastructure in place requires cooperation with governments and utilities, which must enable and support it.

A gradual build-out of public charging is already happening in urban areas. Continued infrastructure development of major transportation routes and the electrification of HDT hubs (e.g., large harbours, large industrial areas) would trigger the transition to ZETs for longer and more heavy-duty cycles. For infrastructure build-out, it will be necessary to balance the needs of various stakeholders. For example, fleet operators need enough conveniently located charging stations to serve their routes, whereas charging station developers need to have sufficient station utilisation to justify their investments. While this report models 500 kW public fast charging, charging of a MW or more can improve BET economics. With higher powered chargers, each station can serve more vehicles and potentially access lower cost electricity generation. Improved economies of scale and lower energy costs would improve TCO, particularly for long-haul trucking. Parties have to coordinate charging and vehicle investments to be successful.

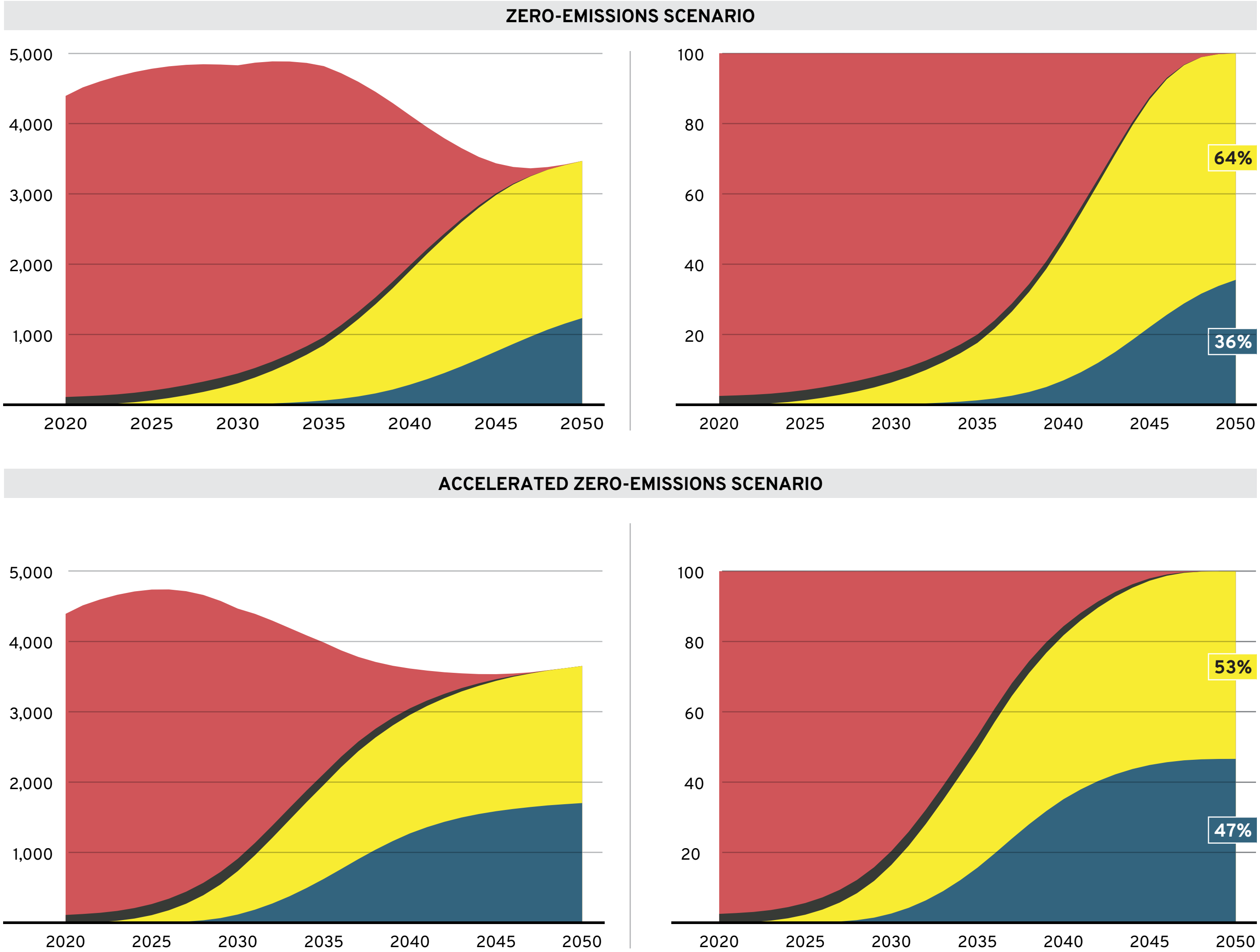
Needs go beyond charging infrastructure availability. Increased electricity generation, grid upgrades, and the development of green H_2 production and distribution are also required to meet significant demand increases over the next decades. Electricity demand for HDT will likely increase more than 100-fold between 2020 and 2030, and in our Zero-Emissions scenario, green hydrogen demand takes off from zero in 2020 to as much as 1,000 terawatt-hours (TWh) in 2040 (Exhibit H).

EXHIBIT H

Energy consumption by scenario, 2020–50

Diesel Biodiesel Electricity Hydrogen

Total energy demand by fuel, TWh **Total energy demand by fuel,** %



Source: MPP analysis

10. Fleets today are already successful with ZETs. Their experiences help identify the bottlenecks that must be addressed in the larger market in order to kick-start the transition to ZETs.

Some of the world's largest fleet owners have committed to taking action to reduce their carbon emissions in this decade. These forward-looking fleet owners are transitioning to ZETs. Fleets that are successful with ZETs share some characteristics: they match vehicles to predictable routes, have enough electrical and physical space for depot charging, receive incentives based on purchase price or distance travelled to improve vehicle TCO, have OEM support, and utilise "green corridors" that provide charging for many vehicles.

These fleet owners' success helps identify the steps necessary to enable wider adoption of BETs. They include:

- **Removing electric distribution cost and technical constraints.** Depots often have limited capacity for charging, and electrifying the full fleet can require upgrading the power grid connections at depots. EV charging loads are a new challenge for grid operators, requiring more power for more customers in less time than traditional building or industrial loads. These electric service updates require alignment between utilities, regulators, and the industry, which can, in a worst-case scenario, take years.
- **Creating truck-centric infrastructure.** Public charging is also currently focused on passenger vehicles, with pricing, locations, and layouts that may not suit trucks. For example, some trucks will require ultra-fast charging at power levels of up to 1 MW, nearly three times the level of the fastest public charging stations.
- **Achieving expected TCO.** Although BETs are at or near cost parity in the urban segment, the current TCO of a BET is higher in regional and long-haul use than a comparable diesel truck (including infrastructure). ZETs achieve TCO superiority as vehicle, electricity, and hydrogen price declines add to existing maintenance savings. HETs require greater price declines than BETs to reach TCO parity. In addition, hydrogen vehicle and fuelling technology is less available and less market proven.
- **Increasing product variety and availability.** Limitations in the quantity and variety of vehicles available inhibit fleet adoption. Vehicle manufacturers currently offer only a limited number of models to accommodate the variety of use cases among fleet operator services. Also, fleet owners experience uncertainty about product availability when placing orders.

CONCLUSION

Trucking is correlated with a country's economic health, and thankfully ZETs enable the trucking industry to grow and result in zero emissions. Trucking demand is growing just as ZETs are becoming increasingly viable. This makes reaching zero emissions very possible under several scenarios that involve government policy, technological improvements, or likely a mix of the two.

The economics vary, both by region and usage (urban, regional, and long haul). For those reasons, private financing, transport buyers, and government policy must be attuned to fleets that are less able to make the technology shift. New needs include building fuelling infrastructure and managing high initial costs. In general, sooner action is better action. An early signal allows stakeholders to plan, and encouraging fleets that have positive TCO today to adopt ZETs creates a virtuous circle of increased product development, experience, and core fuelling infrastructure. Though building the needed infrastructure is comparable to past efforts to electrify or create fuelling networks, it is still a massive and challenging endeavour. We can learn from fleets that are already successful and follow in their footsteps.

To summarise, there is no single policy or measure that alone can decarbonise the trucking industry. Decarbonising trucking is a shared responsibility that will require action from all market participants — including manufacturers, vehicle owners, government, utilities, and energy suppliers. Collaboration between industry players across the value chain is needed, as is a portfolio of policies that address the cost of ZETs, the ability of small fleets to procure ZETs, supply bottlenecks involving ZETs, and the availability of ZET refuelling infrastructure. Resolving the sector's barriers is a shared responsibility that can be overcome with ambitious and smart policy, financing, and corporate leadership. The rest of this report seeks to elaborate on actions to take and opens the door to increased dialogue and deeper alignment on the path forward to zero-emissions trucking.

MAIN REPORT

ZERO-EMISSIONS TRUCKING: A HEAVY-DUTY TRANSITION STRATEGY

PART I

DECARBONISING TRUCKING: IMPORTANCE, CHALLENGES, AND SOLUTIONS

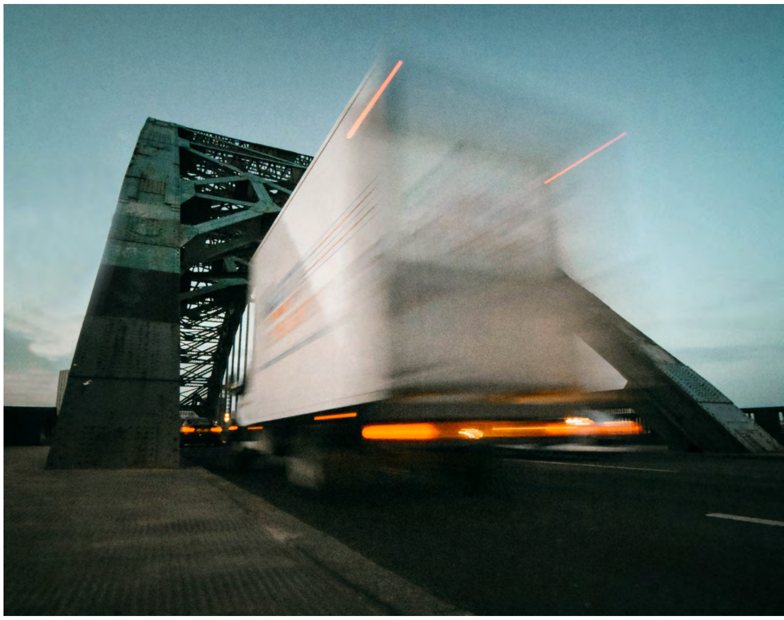
1.1 Decarbonising trucking is critical for achieving climate goals and creating other vital benefits

Heavy-duty trucks are vital for global supply chains. They move the goods an economy creates and enable economic growth. Today, the heavy-duty trucking (HDT) sector produces significant carbon dioxide equivalent (CO_2e) emissions because of ongoing reliance on diesel-fuelled trucks. Transportation accounts for about 16% of total global greenhouse gas (GHG) emissions. About a third of that total comes from road freight — more than aviation and shipping combined. HDT is the source of more than 40% of freight emissions and around 2.1% of global CO_2e emissions.

In this report, we focus on four regions (China, Europe, India, and the United States) that represent 50% of global HDT emissions. In these regions, 95% of the trucks now travel on diesel, creating 1.5 gigatonnes (Gt) CO_2e of annual emissions. Moreover, HDT demand in these regions is expected to more than double by 2050. If trucks continue to use diesel without any additional ZET adoption, annual emissions will grow to 3 Gt CO_2e by 2050. Moving to zero-emissions trucks (ZETs) in these key regions now would avoid putting an additional 31 Gt cumulative CO_2e into the atmosphere by 2050.

ZETs also create societal benefits, by eliminating the refining, fuel transportation, and tailpipe pollution caused by diesel trucking. Refining diesel releases toxic metals, gasses, and other materials into the air. Transporting diesel creates the risks of pipeline leaks or spills during shipping. When diesel is combusted in an engine, it creates airborne pollutants such as carbon monoxide (CO), sulphur and nitrogen oxides (SO_x, NO_x), and fine particulate matter (PM2.5). These harm human health by contributing to heart disease, asthma, and other illnesses.[11] What is more, internal combustion is noisy and jarring for pedestrians and drivers.

Moving to ZETs now would provide societal benefits, reduce climate impacts, and reduce the number of diesel trucks that risk becoming stranded assets. Early action creates a positive feedback loop between ZET demand, efficiency gains, and infrastructure development, driving overall costs lower by 2050.



1.2 The transition to zero-carbon trucking is complex

1.2.1 Decarbonisation will require an array of technologies

Trucking decarbonisation is a difficult proposition. The technologies to tackle it are currently expensive and limited in capabilities, yet they must be deployed in complex real-world situations. Broadly, there are three options for decarbonising trucking: (1) battery electric trucks (BETs), (2) hydrogen electric trucks (HETs), and (3) internal combustion engine (ICE) trucks powered by zero-carbon fuels such as biofuels or synfuels.

Currently, only one fuel — diesel — satisfies the needs of almost every trucking use case. Diesel has high energy density, is cost-effective and reliable, and is easy to transport along well-established infrastructure. But although diesel has many positives, it also has serious drawbacks. Its combustion releases harmful air pollutants that are difficult and expensive to remove from exhaust streams. It exhibits substantial price volatility in response to economic or geopolitical events. Critically, its continued use past mid-century is not compatible with a stable climate.

Diesel is akin to a Swiss army knife — capable of performing in a wide variety of applications — whereas the zero-emissions technologies that will replace it are more specialised tools, with more pronounced costs and benefits.

BETs have some very attractive operational features. They are quiet and have no tailpipe emissions, enhancing driver comfort and reducing their negative effects on nearby people and businesses. They also have very high torque and can recover energy lost in braking, making them perform very well in start-and-stop urban and metropolitan driving conditions.

However, batteries have less energy density than diesel fuel. That means that heavy battery packs must be carried on all BETs, limiting both the range of the vehicle and the weight of the cargo it can carry. Furthermore, charging those batteries requires both time and infrastructure. Charging at higher powers can reduce the time needed to refuel, but also requires more expensive infrastructure — especially on the part of electric utilities that often lack the capability to supply electricity to the locations where trucks need to charge at the power levels that trucks need for very fast charging.

In general, this makes BETs most suitable for use in urban and metropolitan areas, in return-to-base applications where overnight charging is available and limited range is required. This implies that urban and regional segments will adopt BETs most rapidly and thoroughly, but not to the exclusion of the long-haul segment. As we will explore later, the model shows that BET growth will occur in the long-haul segment. Under most scenarios, BETs will make up the majority of long-haul segment vehicles. This growth will be faster and greater if the technology experiences major improvements, which are uncertain but possible. If they come to pass, these vehicle or fuel cost savings will improve BET adoption in all the segments, most notably in long-haul trucking.

HETs operate differently. Hydrogen can be quickly added to tanks in time frames that are competitive with those of diesel. However, although hydrogen is very light, it uses a lot of space. To be moved, it must be transported either as a liquid or as a

11 https://www.epa.gov/dera/learn-about-impacts-diesel-exhaust-and-diesel-emissions-reduction-act-dera.

gas at very high pressures. Both pose difficulties: liquefying hydrogen requires both low temperatures and high pressures, meaning a lot of equipment and energy is needed if it is in liquid form; transporting it as a gas requires equipment and energy to compress it and a lot of space for high-pressure tanks.

Currently, all HETs in production use gaseous hydrogen, and most hydrogen transportation is done via high-pressure tanks on trucks. As a result, HETs must be longer to accommodate on-board hydrogen storage — or cargo storage volume must be reduced to make room for the hydrogen tanks. Additionally, hydrogen requires at-scale distribution for HETs to reach costs competitive with BETs.

Carbon-free and low-emissions combustible fuels (e.g., biodiesel, RNG, synfuels) are more or less chemically identical to their fossil-based cousins and offer very similar performance. This would seem to make them an ideal fuel for trucks. However, each of those fuels is made by converting feedstocks into fuels via industrial processes. Those feedstocks are limited, and those processes can be expensive. For both sustainable biofuels and RNG, the highest-value use cases for the biomass feedstocks is in other industries, especially aviation and petrochemicals. Power-to-Liquids (PtL), in which CO_2 is converted into combustible fuels by a chemical reaction known as the Fischer–Tropsch process, relies on high-purity CO_2 and H_2 as feedstock and renewable electricity to produce the intermediate synfuels. Although these gasses are abundant, obtaining them in high-purity form is difficult and expensive. Similarly, converting them into usable fuels takes a lot of energy and requires substantial investment. For those reasons (i.e., cost and feedstock availability), combustible fuels are expected to play a very limited role in truck decarbonisation.

1.2.2 Technologies must be matched to the operational needs of trucks

The truck market is not monolithic. Although most trucks look similar, they are used in very different ways.

Some trucks travel across countries (or even continents), drive up to 1,000 km per day, and will go weeks or months without returning to a large depot, picking up and dropping off freight as the market demands. This flexible-route, **long-haul** market, which necessitates long ranges and has no "home base" to return to with guaranteed charging available, is most capably served by HETs. BETs may become more competitive in this market with ubiquitous fast charging or battery advances that enable greater range or lower vehicle weight.

Other trucks drive long distances daily, but in more metropolitan areas, and return to base at night. This type of activity, known as **regional**-haul trucking, often occurs in and around major industrial clusters. This intermediate market may see both HETs and BETs competing depending on the specific needs of a truck. These trucks typically have shorter daily travel distances and have a base at which they can charge overnight, in favour of BETs. However, they also sometimes carry heavy loads, operate multiple shifts per day without the opportunity to charge in between, or are based out of depots without access to the high-power electricity infrastructure needed to charge a fleet of BETs. Those use cases may be more suitable for HETs.

Finally, there is short-haul or **urban** trucking. In this application, trucks operate in dense urban areas, typically at low speeds and with many stops. An example of this market segment would be delivery of fresh foods or beverages to stores and restaurants. We expect BETs to dominate in this space. The relatively low daily range requirements of these vehicles allow for smaller, lighter battery packs and, considering their tendency to return to base at night, allow for overnight charging with lower-powered chargers. Furthermore, the handling characteristics of a BET with high torque and regenerative braking are ideal for stop-and-go urban driving. However, some cities, especially in India and China, ban heavy trucks in city centres. In India, this duty cycle is nearly nonexistent, so we do not analyse it there.

Will low-emissions HDT powertrain technologies coexist with ZETs?

Before ZET HDT technologies such as BETs and HETs become economically and operationally viable, alternative lower-emissions powertrain technologies such as renewable LNG/CNG and biofuels may play roles as transitional technologies to ensure emissions reduction in the next 5–10 years. These technologies use ICE technologies for propulsion, which lowers the entry barrier. However, all these alternative fuels still generate tailpipe emissions (GHG, particulates, and others), making them less attractive as options for achieving net zero emissions in 2050, especially in cities. Moreover, bio- and synthetic fuels face limited supplies and carry price premiums compared with diesel. This report covers only ZET technologies.

1.2.3 The economics of trucking are more complex in a zero-emissions world

Historically, trucking drivetrains were "one size fits all". Trucks mostly used diesel fuel, and range had little impact on vehicle costs. Diesel prices are volatile, but unlike with electricity, diesel's costs do not vary on an hourly basis or by the speed at which the fuel is dispensed. The world of zero emissions trucking requires new purchasing and fuelling planning and practices.

BETs' large battery packs make their upfront cost significantly higher, but ongoing operational costs such as maintenance and fuelling (i.e., charging) are substantially lower. Electricity prices not only contribute to a lower cost per mile, but also are historically more stable. However, electricity does not have a single price. The price of electricity varies widely according to the time at which it is used, the place it is used, and the power at which it is drawn from the grid. Furthermore, the cost of an electric vehicle such as a BET is largely dependent on the battery size of the vehicle, making truck range a newly important element of the vehicle purchase decision. Collectively, BETs promise to be cheaper to own and operate than diesel trucks. Realising those cost advantages, however, will require operators to optimise their purchases of both trucks and fuel in a whole new way.

HETs have less complex economics. Hydrogen pricing will likely remain relatively stable, and the range of an HET does not substantially affect its purchase cost. However, HETs are expensive. Both the vehicles and their fuel are currently substantially more expensive than diesel. However, we expect those cost disadvantages to abate. Green hydrogen production benefits from economies of scale, and large electrolysers are expected to reduce hydrogen costs by 50%–70% in the next several years. Similar cost reduction potential exists in the production of the vehicles themselves — with fuel cells expected to fall considerably in cost as the technology gains traction. Cost reductions in both fuel and the vehicle can make HETs commercially viable.[12]

Finally, the evolution of costs of both high-carbon and zero-carbon technologies in the future is uncertain. BETs and HETs are both significantly more expensive than diesel trucks. However, they are also relatively new technologies, whereas diesel trucks have been around for a century. Furthermore, diesel trucks are produced in much larger volumes than either HETs or BETs, giving them economies of scale in production that the other technologies do not yet enjoy. As tech develops and economies of scale in production are achieved, ZET costs will likely fall, as they have for other low- and zero-emissions technologies such as solar photovoltaic panels, wind turbines, battery energy storage, heat pumps, and LED lighting.

Diesel trucks, on the other hand, will likely get more expensive. As regulators increasingly focus on the public health impacts of air pollution, they are limiting diesel tailpipe emissions. To meet these standards, trucks are required to be equipped with ever more expensive exhaust aftertreatment systems, greatly increasing the cost of the vehicles. BETs and HETs, which have no pollutant emissions, are not subject to these costs.

The 2022 diesel prices are some of the highest ever.[13] If diesel remained persistently expensive, ZETs would enjoy an earlier and larger cost advantage, and market-based ZET adoption would be faster. In a high-cost diesel world, policy would play a smaller role because ZET fleet economics are simpler, and the original equipment manufacturer (OEM) scaling that leads to further ZET cost declines would be more certain.

This model does not assume that today's historic diesel prices become permanent. It models that technology maturation and economies of scale will make ZETs cost competitive with ICE trucks in the same way that past zero-emissions technologies supplanted incumbent ones. Accelerating those ZET cost declines will be a critical enabler of zero-emissions trucking by 2050.

What role will alternative charging technologies play?

Innovative charging technologies (e.g., catenaries, induction chargers, battery swaps) are likely to have a place in the future HDT landscape. Their rapid deployment could accelerate BET uptake, but their development and implementation still have many uncertainties. However, we believe that although these solutions are likely to be used in discrete contexts, they will not represent the backbone of the system by 2050.

1.2.4 Infrastructure availability will be a key enabler of the transition

The supply chain for diesel — the infrastructure to produce and transport it — is very mature. There is a global system of oil wells, refineries, pipelines, ships, and filling stations for delivering diesel. In comparison, the infrastructure for competing zero-carbon technologies is not well developed.

Although the countries we are focusing on in this report all have functional electricity systems, those electricity systems were not built with trucks in mind. BET charging is likely to happen at high power and in concentrated locations. Upgrading the electricity grid to provide that electricity is a major investment in grid infrastructure and will require significant capital. Some grids are also more developed than others. Managing truck charging electricity loads can reduce, but not eliminate, the substantial investments in grid capacity that will be required.

Furthermore, BETs qualify as zero emissions only if the electricity used to charge them also qualifies as zero emissions. Many countries have plans to decarbonise their power sectors with renewables. Doing so is likely to require substantial investments

12 Combustion engines for hydrogen have lower manufacturing costs than fuel cells in the short term but have fundamental efficiency and pollution disadvantages.

13 United States Energy Information Administration, No. 2 Retail Diesel Prices, June 24, 2022, https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=EMD_EPD2D_PTE_NUS_DPG&f=M.

not only in renewable generation and transmission, but also in various types of storage to balance supply with demand.

Finally, hydrogen infrastructure is the least mature of the technologies in both its production and its transportation. Like electricity, hydrogen is not necessarily zero carbon. Today, most hydrogen is produced from fossil fuels (e.g., steam methane reformation and coal gasification). Zero-carbon green hydrogen can be produced through electrolysis, which uses renewable electricity to split water into its constituent hydrogen and oxygen molecules. Today this process is expensive, resulting in fuel costs for HETs that are well above those of diesel. For HETs to be viable, the supply of green hydrogen will need to grow exponentially, and its cost will need to fall substantially.

Similar benefits of scale exist in conditioning, transport, and dispensing of hydrogen. Broadly, three options exist for hydrogen distribution:

- Transporting it as a compressed gas in trucks, which is expensive and not easily scaled
- Transporting it as a liquid, which requires specialised equipment and supply chains
- Transporting it in new or upgraded pipelines (the most likely long-term solution)

Today, none of those transportation systems exist at scale. Whatever hydrogen transportation solution is adopted, significant infrastructure investment will be required to provide it as a fuel reliably.

1.2.5 Matching demand and supply cycles is challenging for buyers and truck manufacturers

Fleet owners typically order new trucks yearly to both minimise costs of operation and ensure that fleets can meet customer and regulatory requirements. As the costs of ZETs fall rapidly and both shippers and regulators increasingly require the fleets to decarbonise operations, the market demand for ZETs has the potential to expand rapidly.

The supply of ZETs, however, is less flexible in the near term. Building out the productive capacity for ZETs requires substantial investment not only in the production of ZETs themselves but also in the supply chains for ZET components. Furthermore, demand for ZETs is highly dependent on ZET pricing. Production at small scale leads to high prices, which leads to lowered demand for ZETs, slowing purchases and inhibiting the development of economies of scale. Similar chicken-and-egg dynamics exist with the deployment of grid infrastructure to enable ZET charging.

Collectively, these two factors slow the adoption of ZETs and make achieving net zero by 2050 difficult. As countries chart their course to zero-emissions trucking, keeping in mind the importance of supply of both vehicles and infrastructure can help to ensure that the transition stays on track. Regulatory tools that incentivise ZET supply can avoid a situation in which the supply of ZETs chronically lags behind demand.

For example, in California and China, zero-emissions vehicle (ZEV) credit trading schemes require that electric vehicles (EVs) account for a certain percentage of sales of light-duty vehicles for all companies producing vehicles. Companies that produce more EVs than they are required to can sell the resulting credits to underproducing companies. This both incentivises expansion in vehicle supply in the market and enables EVs to be sold at lower prices, as the sale of credits by EV producers can lower the cost at which those EVs can be offered to the market. Europe has a similar system for light-duty vehicles, with suppliers required to meet ever-increasing standards of average CO_2/km emissions limits on the cars they sell – with EVs receiving special treatment to increase their impact on calculated average CO_2/km. Again, those that exceed the limits must buy credits from those that have outperformed them.

These types of credit trading schemes, which both incentivise the entry of EV suppliers to markets and enable EVs to be sold at a price the market will bear, can be applied to trucks as well. For example, California has applied ZEV credit principles to its Advanced Clean Trucks (ACT) rule, and the EU is planning to expand the light-duty average CO_2 requirements to heavy-duty markets.

It is likely that regulators and ZET manufacturers in different geographies will craft unique paths to spur the ZET transition. But in all markets, ensuring vehicle supply that meets demand at a price that markets can bear will be a key enabler of net zero by 2050.

1.2.6 Truck decarbonisation will not be uniform across geographies

A final element of the complexity of truck decarbonisation is the differing geographies in which it will have to be implemented. Some geographies are well positioned to move quickly; others are more likely to move later. The main drivers will be local policies, differing economics, infrastructure availability, and truck travel patterns that will influence drivetrain selection.

Given the still immature economics of trucking decarbonisation, policy has been its main driver. Currently, Europe is doing the most to incentivise truck decarbonisation; it has an array of policies already in place, creating an early lead for truck decarbonisation in that region. These measures include planned phasing out of diesel and petrol, and incentives to buy ZETs. In the United States, there is little policy support for ZETs at the national level, but strong policy from California and some other states. This is likely to lead to a rapid but uneven transition, some states leading and others lagging.

China, on the other hand, has strong national policy for electrification of lighter vehicles, but little policy focus to date on heavy-duty trucks. As a result, China is trailing in heavy truck decarbonisation. However, China has shown itself to be capable of rapidly driving transitions to electric vehicles through policy and infrastructure packages. If China does make a policy move to decarbonise trucking, it is likely to be effective.
Finally, India is a relative newcomer to the electric vehicle world, and its policy portfolio has largely been focused on very light vehicles (scooters and rickshaws) and buses. As a result, it is most likely to be a late mover in aggressively pursuing truck decarbonisation policies.

Additionally, economics, operational patterns, and infrastructure may influence the timing, cost, and shape of the transition in different countries. In China and India, a new diesel truck is much cheaper to purchase than it is in the United States or Europe, largely because of differing regulatory regimes. That hurts the economics of ZET adoption in those geographies, leading to a later transition (especially in the expensive long-haul segment).

Operational patterns also differ by country. For example, the United States – a large land mass with low population density, and economic centres on its East and West coasts – generates very long trips for trucks. This length of haul makes truck decarbonisation more challenging. Europe, on the other hand, tends to have shorter lengths of haul due to greater population densities and more even distribution of economic activity. China is similar to Europe in this regard. Although it is a very large land mass, both its population and its economic activity are highly concentrated on its east coast and in certain economic mega regions such as the Pearl River Delta or the greater Beijing area (known as Jing-Jin-Ji).

Given the still immature economics of trucking decarbonisation, policy has been its main driver.

In India, trucks travel shorter daily distances at slower speeds. Furthermore, much of the truck traffic in India is concentrated in several corridors that are collectively known as the golden quadrilateral. However, the easiest-to-electrify use case, urban transportation, is nonexistent in India. This argues for a relatively late starting transition in the country, but one that is potentially fast moving once it gains momentum.

Finally, infrastructure availability may affect technology selection. For example, India has a relatively underdeveloped power grid compared with those of the United States, Europe, and China. Delivering the power to provide high-powered charging for millions of trucks may conflict with other goals such as increasing power reliability to existing users. This, combined with suitable geography for hydrogen production, may lead to an increased use of HETs. Similar situations may play out in other countries where power delivery to certain sites is prohibitively expensive, leading to hydrogen use in applications where BETs would otherwise make sense.

1.3 The transition has already started

Many leading stakeholders (e.g., transport buyers, logistics players and fleets, OEMs, energy and infrastructure providers, policymakers, and financial institutions) are pursuing decarbonisation. Governments around the globe are inducing demand for and supply of ZETs by implementing stricter emissions targets, fuel standards, or both. Major logistics companies and large truck buyers are committing to decarbonisation and emissions reductions, thereby creating increased ZET demand along the way. Incumbent OEMs and new entrants are investing heavily in the development of ZET models, while fleet owners are investing in vehicles and on-site infrastructure. Some examples of innovative ZET deployments:

Many leading stakeholders (e.g., transport buyers, logistics players and fleets, OEMs, energy and infrastructure providers, policymakers, and financial institutions) are pursuing decarbonisation.

1.3.1 China

- In **Shihezi industrial park**, a fleet of 100 battery electric trucks serve business based in the park. The trucks, with a gross weight rating of 38 tonnes, are manufactured by Sany and SAIC Hongyan and feature swappable batteries ranging from 275 kWh to 425 kWh. The trucks typically make trips of about 100 km and swap batteries at a facility in the industrial park.
- In July 2021, **HeSteel Group** deployed 30 fuel cell trucks transporting iron ore on a 150 km round-trip route.
- In 2021, the **Baoding government** deployed 100 fuel cell trucks for short-distance transportation of construction materials to building sites in Xiong'an. By 2024 it plans to deploy a total of 1,000 such trucks along with 6–10 hydrogen fill stations en route.

1.3.2 Europe

- **DHL** has announced plans to accelerate the transition by deploying 44 new Volvo trucks (Volvo FE and Volvo FL) for routes in Europe. These trucks will be used for package delivery in urban areas.
- **Amazon** has launched five electric 37-tonne trucks in the UK. They are operating from the fulfilment centres in Milton Keynes and Tilbury. Four more electric trucks are expected by the end of 2022.
- **Dachser**, a family-owned logistics company from Germany, will introduce at least 50 additional battery electric trucks on European routes by the end of 2023.

1.3.3 India

- **Tata Steel** contracted for 27 electric trucks in 2021 to transport finished steel. The trucks have a 35-tonne carrying capacity and are equipped with a 2.2-tonne, 230.4 kWh lithium-ion battery pack.
- **Dalmia Cement Bharat** is set to purchase 22 electric trucks as part of its e-truck initiative. Dalmia will deploy the RHINO 5536 manufactured by IPL TECH trucks, which has a gross vehicle weight of 55 tonnes and a 258 kWh battery pack. The company also commissioned two charging stations at its Rajgangpur unit in the Sundergargh district of Odisha.

1.3.4 United States

- **NFI.** The North American supply chain solutions provider is testing a pre-production Volvo VNR electric with over 280 km of range and a class 8 terminal tractor out of its Los Angeles–area depots. It has plans to operate over 100 battery electric tractor-trailers by early 2023.
- **Frito-Lay North America.** In Modesto, California, the packaged-foods giant is using electric vehicles in its warehouse and delivery operations. That includes electric forklifts, yard trucks, and six 220EV Peterbilt electric box trucks for local distribution. The company has also placed an order for 15 Tesla semi-trucks.
- **Anheuser-Busch.** The world's largest beer producer is adding 20 electric trucks to its California fleet, including a Class 8 BYD electric tractor-trailer.[14]
- **A.P. Moller-Maersk.** A global leader in shipping services that employs approximately 95,000 people, it recently ordered 110 Volvo VNR and 300 Einride electric tractors. It expects to deploy 450 electric trucks in North America from various manufacturers in 2022–23.

14 More information on fleet and vehicle performance can be found at NACFE's Run on Less website: **https://runonless.com/participant-profiles/**.

PART 2

A MODEL TO UNDERSTAND THE TRANSITION TO ZERO-EMISSIONS TRUCKING

BOX 1

An array of approaches are complementary to zero-emissions truck adoption

In this report, we model how the transition to ZETs could play out. ZETs are not the only solution relevant to freight transport decarbonisation, but they are the most impactful. However, other strategies that reduce the total amount of truck driving required are also valuable; these include demand reduction, increased logistical efficiency, use of sustainable fuels, and application of hybrid powertrain technology.[15]

Three main strategies could be applied to reduce freight kilometres travelled:

1. **Encourage a mode shift from long-haul trucking to rail.** A diesel freight train in the United States is three to four times as fuel efficient as a truck, reducing emissions by up to 75%. Outside the United States, existing and planned electrification of rail allows for transport with little to no emissions.[16] Furthermore, rail typically is the most effective method for very-long-haul shipments, the segment of the market most difficult to decarbonise, making trains a valuable complement to ZETs.

2. **Increase supply chain efficiency.** Shorter, less transport-intensive supply chains could potentially reduce the total travelled distances by about 3.5%.[17]

3. **Improve logistical efficiency.** Improvements in net load factor (e.g., due to reducing return trips with empty or below-capacity trucks) and higher fleet utilisation from operator consolidation can move more goods using less space.

Collectively, these strategies could reduce HDT sector demand, thus reducing emissions by roughly 20%.[18]

15 High-cost CO_2 removal solutions are expected to play a limited role in heavy-duty trucking, because technologies are already available for the industry to transition to ZETs.

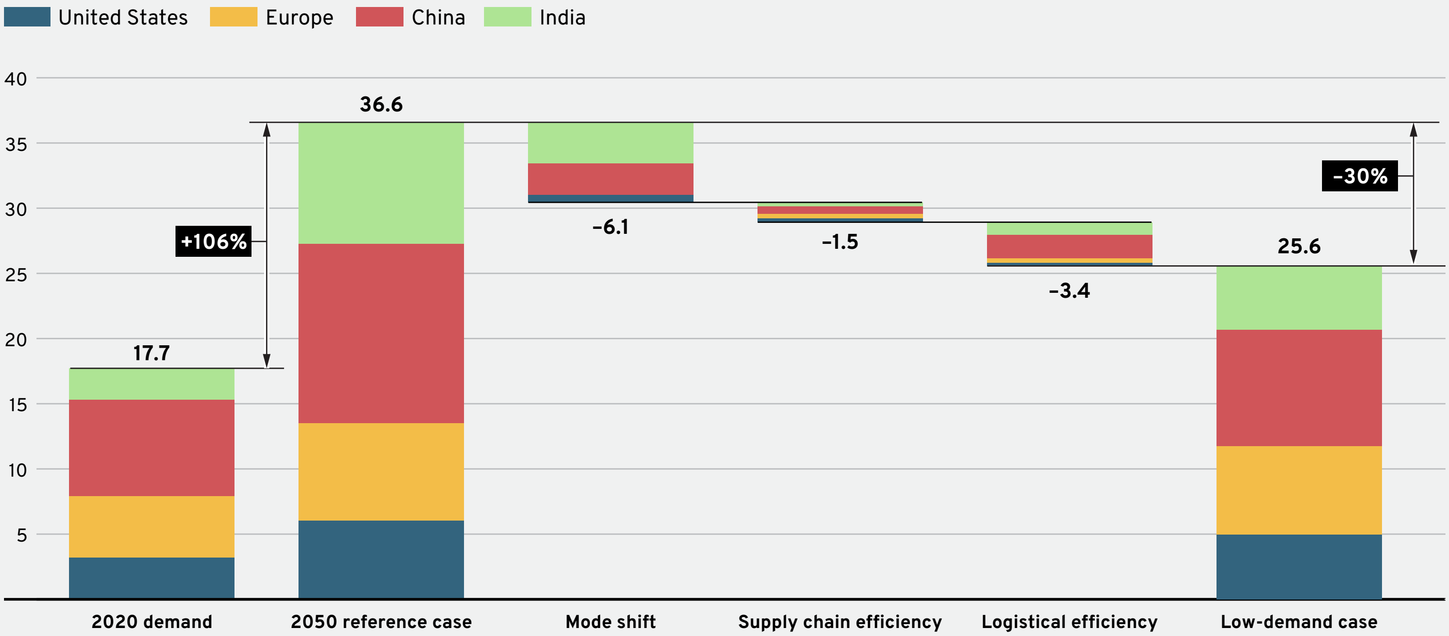
16 Association of American Railroads, "Sustainability Fact Sheet", 2020, AAR.org; and Rapid Transition Alliance staff, "**On Track to Full Electrification: Low Carbon Railways**", *Resilience*, July 21, 2021.

17 MPP Road Freight Zero initiative research.

18 Expert estimate and team analysis.

Change in HDT demand due to efficiency improvements

In millions of trucks



Note: Baseline case is used for subsequent modelling in this report.

Source: MPP analysis

Although mode shift, efficiency, and reduced fuel usage cannot create a zero-emissions industry, they reduce the remaining need for full decarbonisation. Demand reduction lessens the number of zero-emissions trucks required, and efficiency reduces the industry's electricity, batteries, and hydrogen requirements.

2.1 MPP models a cost-effective transition to zero-emissions trucks

Although MPP recognises the importance of demand reduction as a decarbonisation tool, actually meeting demand with ZETs will deliver the bulk of the sector's decarbonisation. To understand how this transition is likely to play out, we have developed a model that estimates how quickly ZETs can be deployed and what the rough costs of doing so will be.

The model approaches the decision to deploy ZETs much as a truck purchaser would, by seeking to minimise the cost of the truck over its lifetime — known as its total cost of ownership (TCO) — while complying with applicable regulations. TCO covers the full cost associated with putting a truck on the road (purchase cost, registration fee, charger/filling station cost, and other costs) and the net present value of operating expenses (i.e., fuel, maintenance, CO_2e costs, insurance, charger/filling station costs) discounted over the truck's lifetime using a 5% real discount rate.[19]

19 The model includes some ZET adoption ahead of TCO-positivity and some ICE use afterwards for users that choose ICE vehicles even after ZETs make greater economic sense.

Furthermore, as discussed above, the trucking market is not monolithic. The most cost-effective technology is dependent on the use case of the vehicle. To capture this dynamic, the model employs three distinct duty cycles for HDT that are modelled separately: long-haul, regional, and urban.

TCO is usually important for vehicle purchasers, but it isn't always the determining factor. Many fleets today would like to purchase BETs and HETs, but there is not enough supply of those vehicles, and it takes time to build out the capacity to supply them. To capture this reality, we model constraints on vehicle supply in the near future, which can slow down adoption even when greater adoption would be cost-effective.[20]

Detailed definitions of duty cycles, constraints, and costs, as well as a detailed walkthrough on the modelling methodology, can be found in the *Appendix*.

2.1.1 We model four scenarios to explore pathways to zero-emissions trucking

Expected Adoption scenario

We recognise that although the market is nascent, some degree of ZET adoption is likely through 2050 and beyond. To understand how far the transition to ZETs is likely to go without aggressive policy action and more rapid technological development, we model an Expected Adoption scenario. In this scenario, there is no additional policy action by government, and we use consensus estimates of the evolution of fuel and truck prices through 2050.

Rapid Technology Improvement scenario

Over the past decade, many analysts have drastically underestimated the rate at which zero-emissions technologies (e.g., wind, solar, batteries) would decline in cost and gain market share. Similarly, the adoption rate of passenger electric vehicles has frequently outpaced market forecasts, requiring analysts to revise new forecasts upwards. To capture a similar potential for ZETs, we model a separate policy-agnostic scenario, the Rapid Technology Improvement scenario, which sees faster development of low-cost BETs and HETs.

Both the Expected Adoption scenario and the Rapid Technology Improvement scenario see significant levels of ZET adoption, and they are both market based. However, it is also likely that some policy action will be required to achieve zero-emissions trucking by 2050. For that reason, we model two policy-focused scenarios, below.

Zero-Emissions — ZET Mandate scenario

Sales mandates or sales bans are a common tool used by policymakers around the world to achieve ZET adoption targets. The Zero-Emissions — ZET Mandate Scenario models a policy of phasing out new fossil fuel truck sales by 2040 to ensure a zero-emissions fleet by 2050. This captures the logic at play in policies such as California's ACT and Advanced Clean Fleet rules and the diesel bans enacted by several European countries.

Accelerated Zero-Emissions — Carbon Cost scenario

In the Zero-Emissions — ZET Mandate scenario, operators still minimise TCO, but the cost of carbon increases the TCO of non-zero-emissions technologies. This second policy-focused scenario captures the dynamics at play in policies such as the EU Emissions Trading System (EU ETS) or California's Low Carbon Fuel Standard (LCFS).

The purpose of the scenarios described above is not to advocate for any path that they describe, but rather to have a framework to evaluate the costs and benefits of different approaches (Exhibit 2.1). We anticipate that individual countries will ultimately formulate their own policy packages that implement features from each scenario and also add other elements that we have not modelled (e.g., subsidies, particular tax treatments).

20 In the short term, battery supplies are constrained because of growing demand for long-range passenger electric vehicles. Battery production capacity is growing rapidly. Trucking is highly cost-sensitive, and if battery supply remained constrained, the passenger car market and others might be willing to pay more per kWh for batteries than truck purchasers are.

EXHIBIT 2.1

An overview of the scenarios modelled

BASELINE

Do Nothing

TCO minimisation with no ZETs

- Only ICE powertrains
- Possible emissions trajectory in absence of coordinated policy, finance, and value-chain support

MARKET SCENARIOS

Rapid Technology Improvement scenario

Accelerated BET

- ~30% lower power price at the chargers
- 10% higher max charging infrastructure utilisation (20%–45% versus 10%–35%)
- Assumes no operational constraints for BETs

Accelerated HET

- ~30% lower hydrogen prices at the pump
- 10% higher max HET infrastructure utilisation (20%–45% versus 10%–35%)

Expected Adoption scenario

TCO minimisation

- No policy changes
- Vehicle mix based on individual fleet economics and adoption behaviour

POLICY SCENARIOS

Zero-Emissions scenario

TCO minimisation with diesel phase-out and operational constraint

- **ZET mandate is announced in 2030 and implemented in 2035 for shorter routes, and announced in 2035 and implemented in 2040 for long-haul** as a last measure to reach net zero by 2050 — ICE sales are distributed to HET and BET

Accelerated Zero-Emissions scenario

TCO minimisation with carbon cost and operational constraint

- **Carbon cost of $0–$250/t CO_2** (increasing linearly from 2023 to 2050) applied on GHG well-to-wheel emissions for diesel and biodiesel ICE trucks
- **Carbon cost as a proxy for coordinated policy actions**

Note: Carbon cost is based on BP Energy Outlook 2050, and diesel phase-out timeline is based on maximum vehicle lifetimes.

Source: MPP analysis

PART 3

ACHIEVING ZERO EMISSIONS BY 2050: POSSIBLE TRAJECTORIES

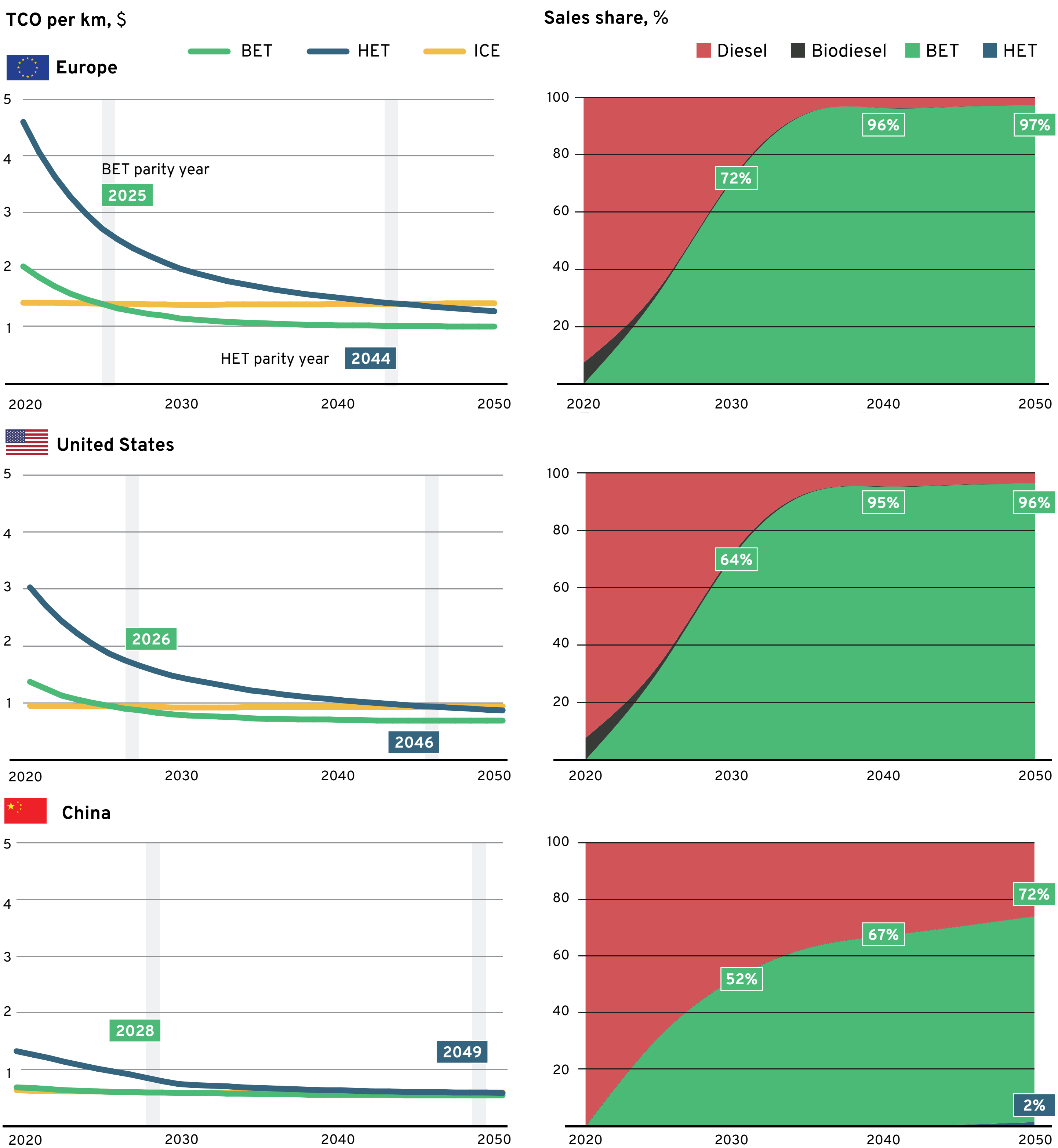
3.1 Expected declines in cost of zero-emissions technologies will deliver substantial decarbonisation, but sales of diesel vehicles will persist to 2050 and beyond

The cost of ZETs is falling quickly, and those vehicles are rapidly gaining market acceptance. We anticipate that early-mover market segments — urban and regional — will reach cost parity in this decade and see substantial growth in sales share. In developed markets, that early cost parity will drive these lower-mileage segments close to net zero by 2050.

However, in developing markets, such as India and China, competing diesel vehicles are substantially cheaper than in the United States or Europe. In those markets zero-emissions technologies will have a less pronounced cost advantage (Exhibits 3.1 and 3.2). As a result, achieving net zero in those geographies will require more effort.

EXHIBIT 3.1

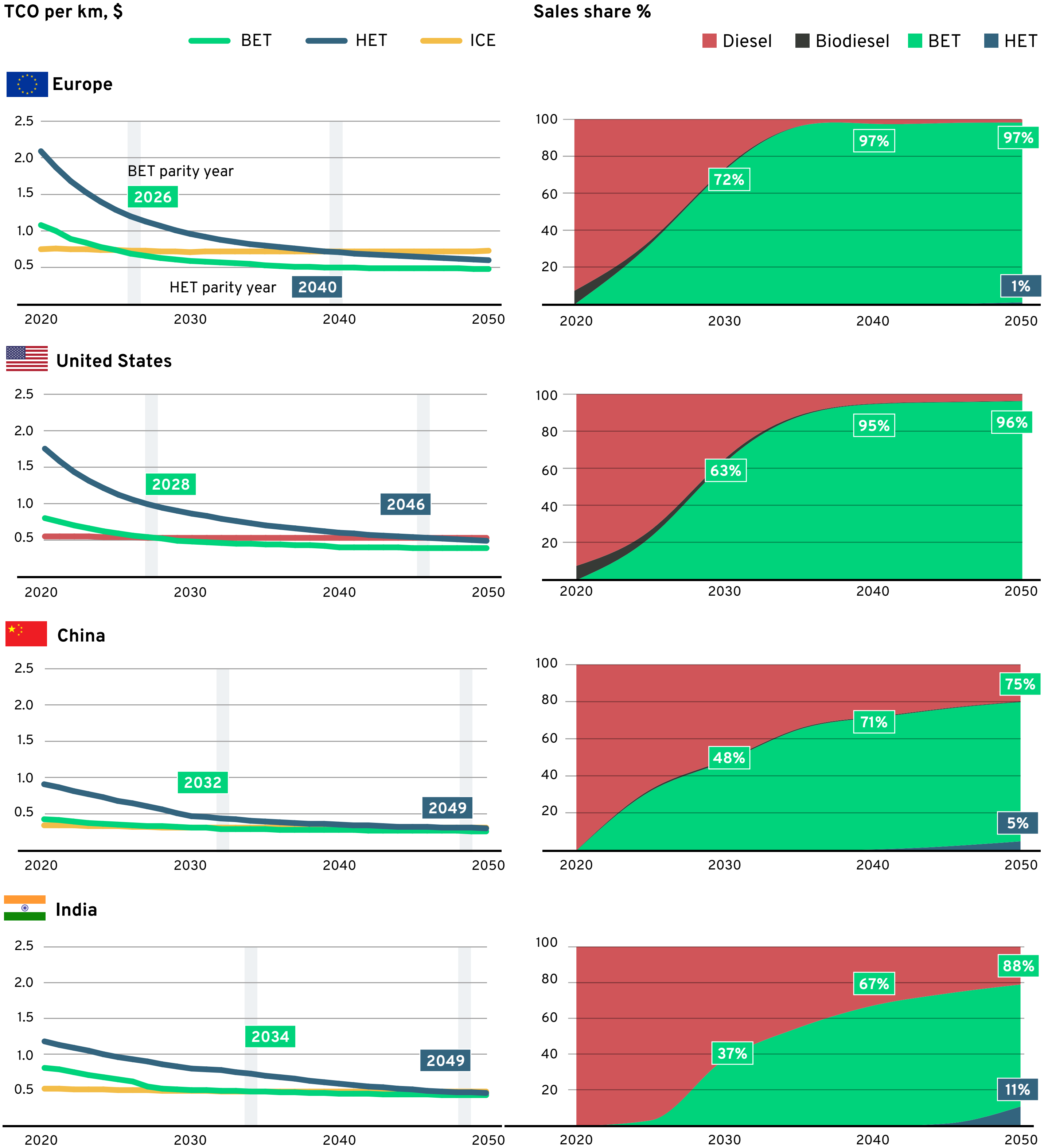
TCO and sales shares for the Expected Adoption scenario, urban segment



Note: HDT is legally restricted from urban deliveries in India; the country is therefore excluded from the segment analysis.
Source: MPP analysis

EXHIBIT 3.2

TCO and sales shares for the Expected Adoption scenario, regional segment



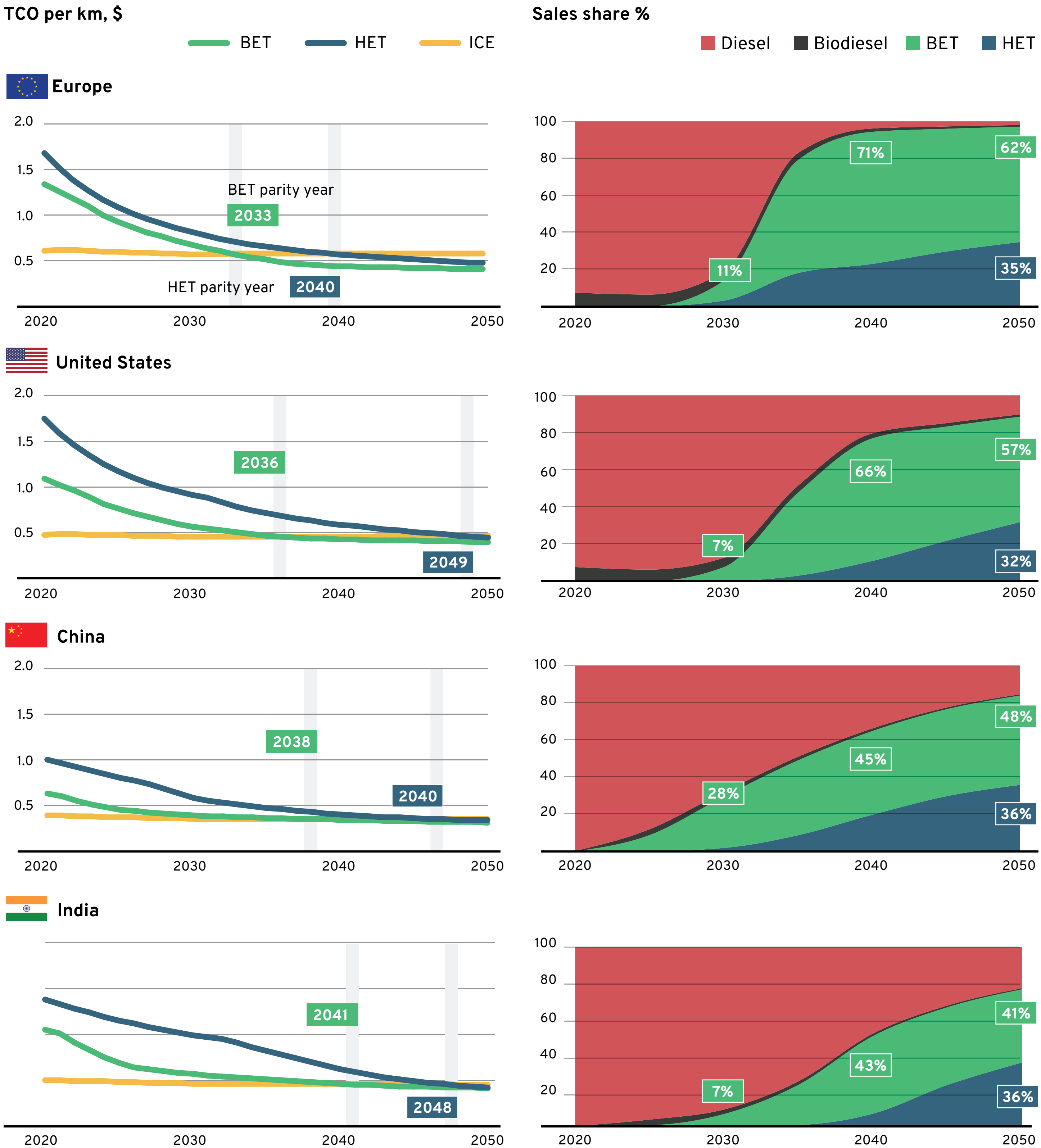
Soruce: MPP analysis

The projection of India and China as relatively late movers in urban and regional market segments is based on today's vehicle regulations. Currently, regulatory regimes in developed markets are substantially stricter than those in developing markets, imposing higher costs on truck manufacturers. Over the past decade, however, India and China have more stringently regulated trucks. If that trend continues, China and India's urban and regional ZET trajectories would become more like those of the United States and Europe.

Long-haul duty cycles will be more difficult to decarbonise (Exhibit 3.3). To decarbonise long-haul, two pathways exist: (1) BETs with very large battery packs and ubiquitous high-powered public charging and (2) HETs with a national hydrogen distribution network. Either solution will create substantial extra upfront vehicle costs and require substantial infrastructure development. We project that these segments will not see cost parity until the next decade and see significant sales share only by the second half of the 2030s, too late for a 2050 zero-emissions transition without faster technology improvement or policy intervention.

EXHIBIT 3.3

TCO and sales shares for the Expected Adoption scenario, long-haul segment



Soruce: MPP analysis

3.2 Getting to zero emissions will require rapid decarbonisation, particularly of long-haul trucking, with contributions from both the public and private sectors

Broadly speaking, there are two ways to achieve a full zero-emissions transition in trucking. One is by altering the cost-optimal decisions that truck purchasers make, such as through accelerated tech development, subsidisation, or some form of carbon pricing. The second is by allocating those costs back to truck manufacturers via a sales requirement or to truck fleets via a purchase requirement. We have modelled these scenarios separately, but all approaches are likely to be used — indeed, that is already how things are playing out.

For example, in California, a sales requirement (the ACT rule) mandates an ever-growing share of vehicles sold to be ZETs and a purchase requirement (the Advanced Clean Fleet rule) requires fleet owners to purchase those newly made vehicles. At the same time, truck purchases are subsidised via California's HVIP programme, and low-carbon fuels are subsidised via California's LCFS programme. This combination of stick and carrot, which simultaneously requires the use of ZETs and substantially improves the economics of their use, has made California the centre of ZET adoption in the United States. Meanwhile, the Global Drive to Zero MOU, the First Movers Coalition, and the Climate Champions Breakthrough Agenda are tremendous examples of how public- and private-sector voluntary action can accelerate the normalisation of the transition.

As mentioned above, projected cost declines are expected to be enough to motivate ZET adoption in urban and regional trucking, both of which are already largely on a zero-emissions pathway. For that reason, in the following sections, we focus on the impact of these policies and tech development in long-haul markets, which are not expected to naturally achieve net zero. Further discussion of how those easier-to-electrify markets react to the zero-emissions policy and market developments can be found in the *Appendix.*

3.2.1 Getting close to net zero via accelerated cost declines

In recent years, clean technologies such as wind, solar, and batteries have fallen in cost far faster than even the most optimistic projections. In the light-duty market, declining battery prices have led to rapid consumer acceptance and widespread adoption of EVs. We attempt to capture those dynamics in our Rapid Technology Improvement scenario, in which the costs of ZETs and their fuel fall more rapidly, vehicle production is not limited by production constraints, and charging infrastructure is used by more vehicles.

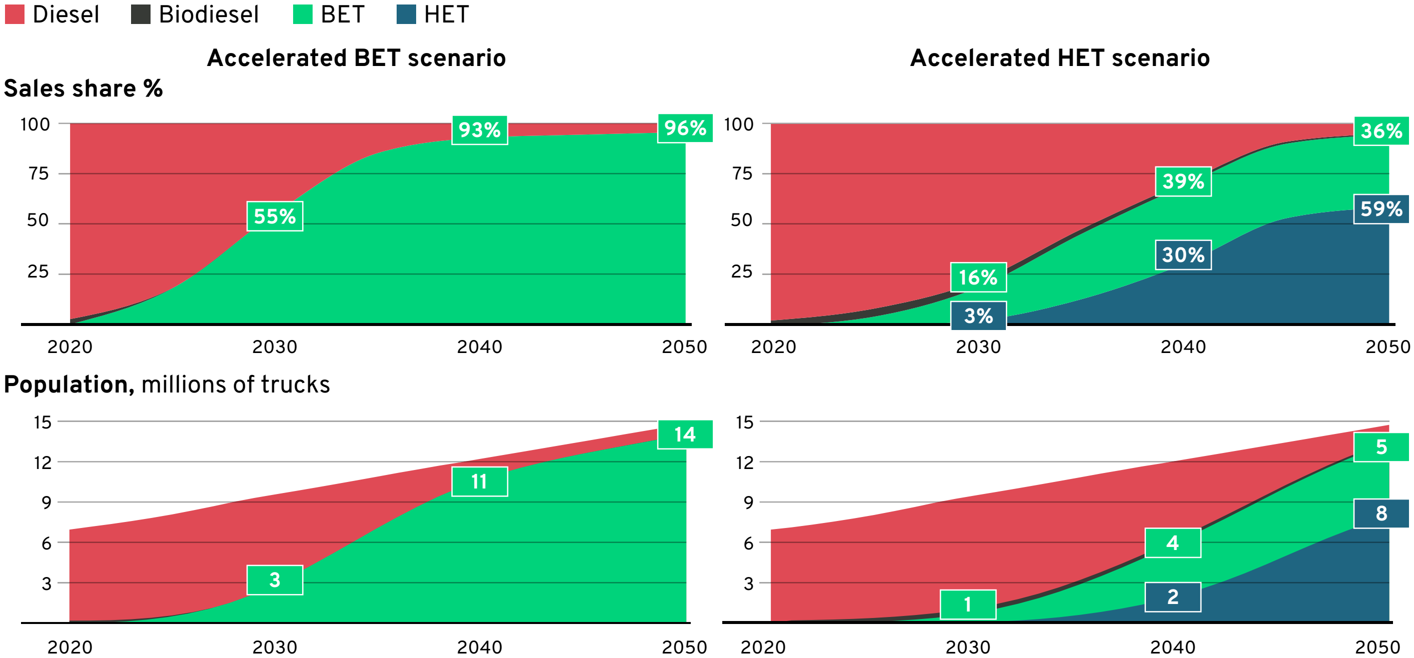
MPP models two potential pathways for accelerated technological development — one in the BET ecosystem and one in the hydrogen ecosystem. The BET breakthrough represents some combination of battery improvements and industry advances including prevalent megawatt fast charging. Solutions such as these can eliminate the problem of reduced cargo carrying capacity and truck downtime. These improvements can come from new technology or an industry that achieves efficiencies faster than assumed in the model's Expected Adoption scenario. This breakthrough enables near full electrification of trucks by 2040 even in the long-haul segment – an outcome that is near compliant with net zero by 2050. In this world, hydrogen sees almost no role because BETs both are cost superior and provide the operational capabilities needed in long-haul operations.

A breakthrough in the hydrogen ecosystem would see the costs of both the vehicle and the hydrogen fuel go down. Absent a parallel breakthrough in BETs, it does not alone deliver a zero emissions by 2050 trajectory (Exhibit 3.4). This is because as hydrogen gets cheaper, it increasingly captures market share from BETs, but it does not gain cost superiority and sales share over diesel trucks before 2040 sufficient to enable a full retirement of diesel vehicles by 2050. However, if a hydrogen breakthrough occurs in the 2020s and the capability to make hydrogen ubiquitously available to trucks emerges soon after, this scenario could prove to be conservative.

For the sake of brevity, we do not show the individual breakdowns of sales by country for these scenarios. Here we show only the globally aggregated view of the transition. Country-specific details are available in the *Appendix.*

Sales share, total trucking fleet population by year in the Rapid Technology Improvement scenario, long-haul segment

EXHIBIT 3.4



Source: MPP analysis

To create cost breakthroughs that enable a more market-driven trajectory to zero emissions, both governments and private financial institutions must direct capital to high-priority research and development, such as breakthrough battery chemistries or low-cost hydrogen electrolysis. Countries must also continue unbottling renewables through new electricity generation and transmission, and hydrogen distribution capabilities.

3.2.2 Altering costs through policy levers to achieve zero emissions

Even with strong investment and innovation, technology development is an inherently uncertain process. If technology development is unable to maintain the strong pace of the previous decade, governments can intervene to ensure truck decarbonisation.

3.2.3 ZET sales and purchase requirements

One policy is a sales mandate requiring that supply to enter the market. In this Zero-Emissions — ZET Mandate scenario, we model a required sales trajectory starting in 2035, which leads to a full exit of fossil fuel–powered trucks from the fleet by 2050.

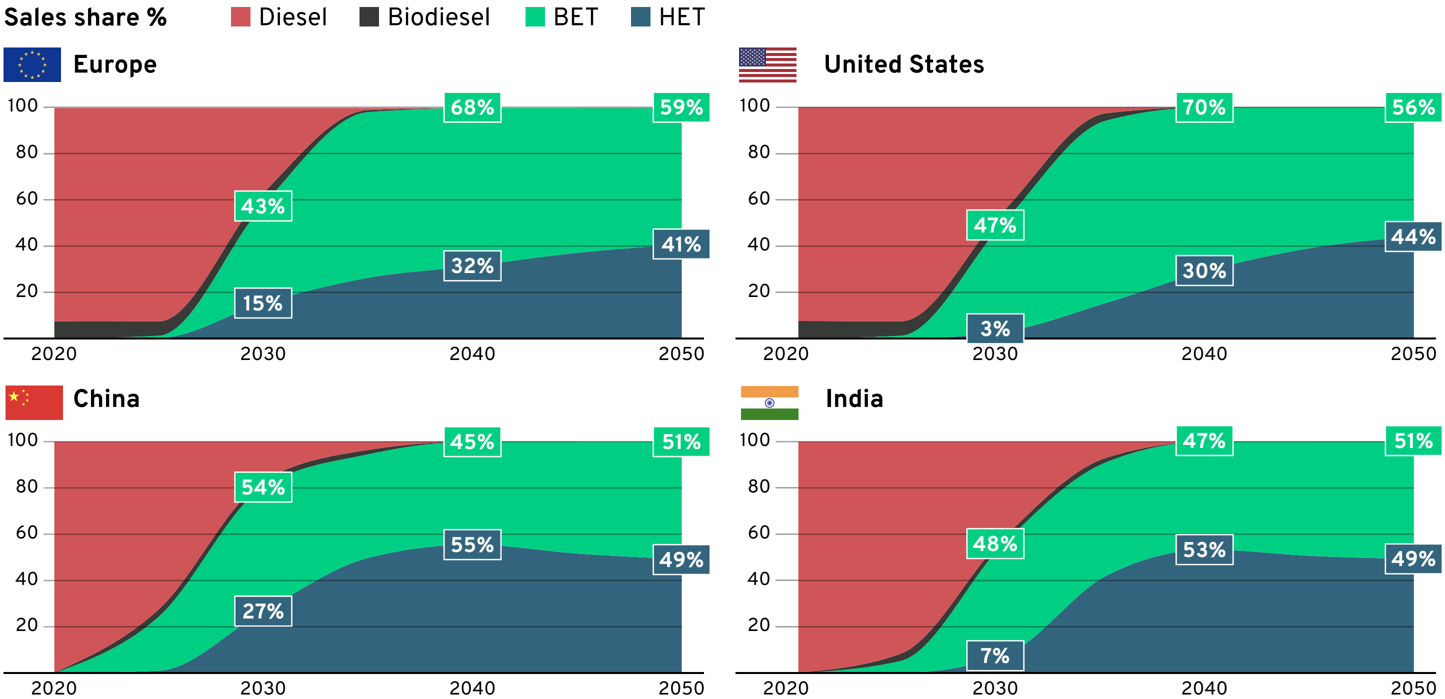
Many European nations have effectively committed themselves to this path through announcements or bans on internal combustion engines at specific dates in the future. Furthermore, the EU has mandated two binding reduction targets for each manufacturer's sales, setting a target of 15% in 2025 and 30% in 2030 from the 2019 baseline. Some countries in the European region have gone further. The UK government has announced its intention to phase out the sale of new diesel and petrol heavy-duty trucks by 2040. The Netherlands has announced that cities will allow only ZET deliveries after 2025. In the United States, California is already following this path through its ACT and Advanced Clean Fleet rules. The Global MOU is further encouraging ambition around the globe.[21]

Under this scenario, sales until 2035 follow the same trajectory as they would under the Expected Adoption scenario. However, beginning in 2035, sales of ZETs ramp up rapidly as the requirement begins to be enforced. For geographies that already have seen extensive market development led by favourable TCOs, such as Europe, this ramp-up in sales is not particularly steep. However, for markets with less favourable TCOs in the early years, the ramp-up in sales after 2035 is more abrupt (Exhibit 3.5).

21 Sixteen leading nations signed a Global Memorandum of Understanding (MOU) for ZE-MHDVs. The MOU establishes the goal of at least 30% vehicle sales being zero emissions by 2030 and 100% by 2040 at the latest. Supported by over 50 subnational government and industry endorsements, the MOU aligns with Paris Agreement goals and establishes a pathway for the commercial on-road transportation sector to reach net zero carbon by 2050.

EXHIBIT 3.5

Sales share by region in the Accelerated Zero-Emissions scenario, long-haul segment



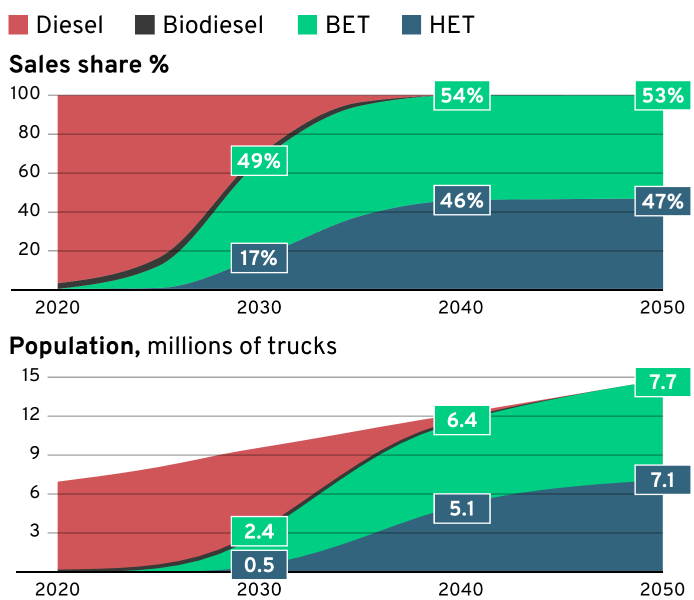
Source: MPP analysis

Under this policy scenario, global action in the mid- to late 2030s becomes critical. Sales of ZETs increase from less than 40% in 2035 to 100% by 2040, leading to a fully zero-emissions fleet by 2050 (Exhibit 3.6).

Although we have modelled this scenario as having the most deferred ZET adoption, that need not be the case. Depending on the timing of sales requirements, the ramp-up in production and sale of ZETs can be achieved earlier. As discussed later, in California, an effective carbon price via the LCFS and a supply mandate via ACT have been implemented in tandem — simultaneously addressing both supply and demand constraints for ZETs. Programs that incentivise fleets to retire old trucks also accelerate GHG reductions. Rather than viewing policy tools as mutually exclusive or viewing a sales requirement as a last resort, policymakers should explore these coordinated policy approaches and provide a predictable target that stakeholders can use to plan. The more gradual a transition to ZETs is and the more widely the costs of that transition are distributed, the more smoothly it is likely to play out.

EXHIBIT 3.6

Sales share and total trucking fleet population by year in the Accelerated Zero-Emissions scenario, long-haul segment



Source: MPP analysis

3.2.4 Fuel carbon pricing

Carbon pricing is an approach that is already used globally, both through carbon credit trading systems, which exist in Europe and China, and through policies such as California's LCFS, which effectively increases the price of fuels depending on their carbon intensity.

This approach represents a more active role from government but continues to rely on cost optimisation as the mechanism for the transition. This approach is promising but also has some difficulties. Because carbon pricing is essentially a tax on fuels, the burden of the transition will sit with fleets – which are often the worst-equipped to deal with rising costs due to highly competitive markets and slim margins. However, to the extent that carbon costs are captured in the cost of fuel at the pump, fleets can rely on existing practices such as fuel surcharges to pass costs up to shippers in a transparent way. This can help minimise market dislocations from policy intervention.

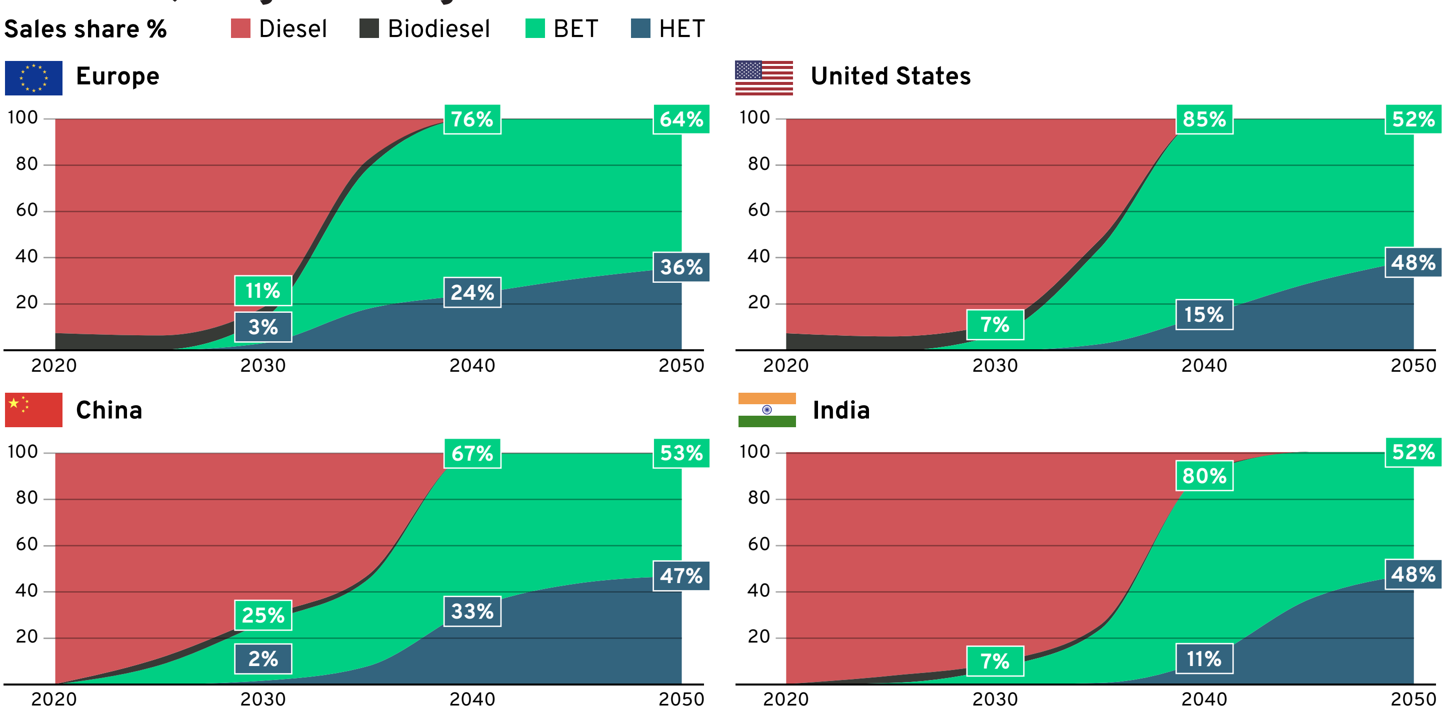
Furthermore, as discussed above, the supply of electric trucks is unlikely to be able to adjust as quickly as demand to policy instruments such as carbon taxes. For that reason, it is best that policy approaches that materially affect demand, such as carbon pricing, be implemented in tandem with policies ensuring that supply is available in the market to meet that increased demand.

Finally, it should be noted that the carbon prices needed to achieve the transition shown below are substantial. Details of the costs used in this Accelerated Zero Emissions – Carbon Cost scenario can be found in the Appendix, but they start out relatively low and grow steadily, leading to a rapid transition in the late 2020s and early 2030s, and continue growing to 2050.

In this scenario, TCO parity is accelerated in all countries, leading to rapid acceleration in ZET deployment in the late 2020s. As carbon prices increase into the mid-2030s, the TCO superiority of ZETs grows, leading to full adoption in all markets in the late 2030s (Exhibit 3.7). The expansion of demand is quite rapid, especially in countries such as India and China, which arrive to TCO parity somewhat later, leading to very rapid growth in ZET sales that may challenge the ability of suppliers to meet market demand.

EXHIBIT 3.7

Sales share by region in the Zero-Emissions – ZET Mandate scenario, long-haul segment



Source: MPP analysis

Globally, this policy scenario leads to very strong sales growth of both BETs and HETs in the late 2020s and early 2030s. With the majority of sales ZETs by 2030 and nearly 100% of sales ZETs by 2035, 95% of all trucks on the road by 2040 would be zero emissions (Exhibit 3.8).

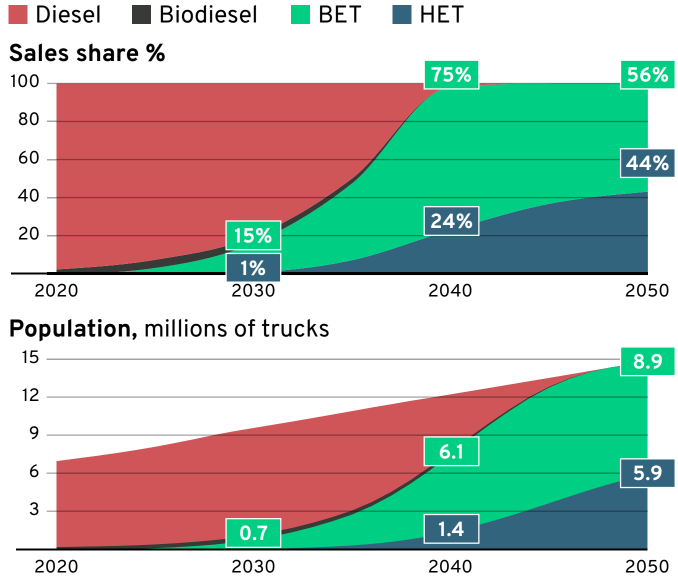
As policymakers implement policies such as carbon pricing, they should consider the market's ability to provide supply in response to these very rapid expansions in demand. If carbon pricing is not paired with vehicle availability, it will not effectively accelerate the transition to ZETs; it will just impose costs on the industry that will ultimately be passed on to consumers.

3.2.5 Different approaches to net zero have differing cumulative carbon emissions

Together, the modelled policy and market scenarios form an emissions envelope and provide insights into how the HDT industry can transition to net zero (Exhibit 3.9).

EXHIBIT 3.8

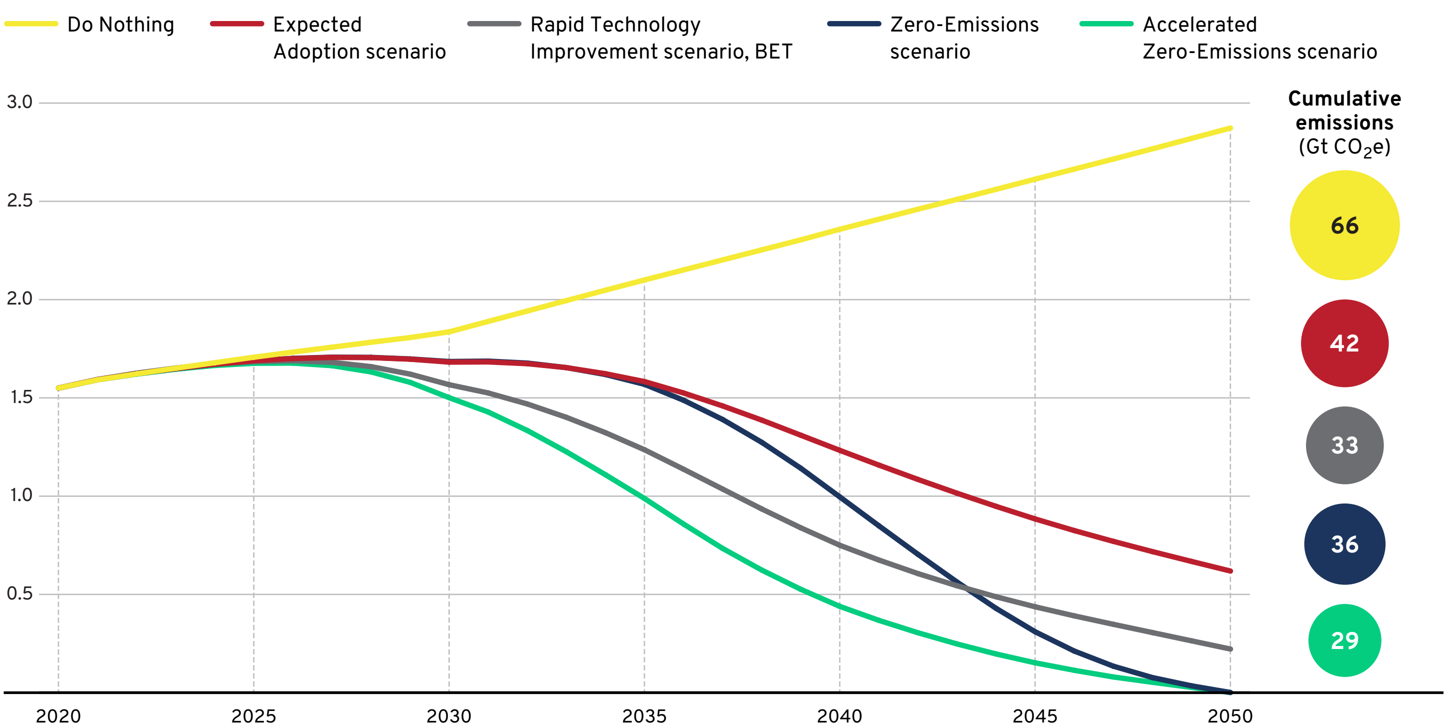
Sales share and population in the Zero-Emissions – ZET Mandate scenario for the long-haul segment



Source: MPP analysis

EXHIBIT 3.9

Annual GHG emissions by scenario, Gt CO_2e



Source: MPP analysis

Under the Expected Adoption scenario, ZETs gain market share as fleet owners optimise costs, reducing emissions by 24 Gt CO_2 compared with continuing diesel usage at current levels. The scenarios that go beyond the Expected Adoption scenario reduce as much as an additional 13 Gt CO_2. The emissions-reduction potential is the highest in the Accelerated Zero-Emissions — Carbon Cost scenario, given its earlier transition to ZETs. The earlier implementation of a carbon cost drives the earlier adoption of ZETs, resulting in fewer cumulative emissions. In the Zero-Emissions — ZET Mandate scenario, the acceleration in emissions reductions starts after the announcement of the diesel phase-out in 2035 (five years before the enactment of the ban). Before then, the sector follows roughly the same emissions-reduction pathway as the Expected Adoption scenario. This highlights the positive effect on emissions reduction of early coordinated action. It allows cumulative emissions — the main drivers of climate change — to decrease.

3.3 Different regions will follow different paths to zero emissions

Broadly speaking, we project a similar transition in Europe, the United States, China, and India. Each region has a viable path to zero-emissions trucking by 2050, but some regions are positioned to move more quickly and at lower incremental cost, whereas others may see a later, but more jarring, transition. In the following sections, we explore these regional differences. Although we focus on aggregated outcomes within regions, details of the transition for each market segment, in each scenario, for each region can be found in the accompanying *Appendix*.

3.3.1 Europe

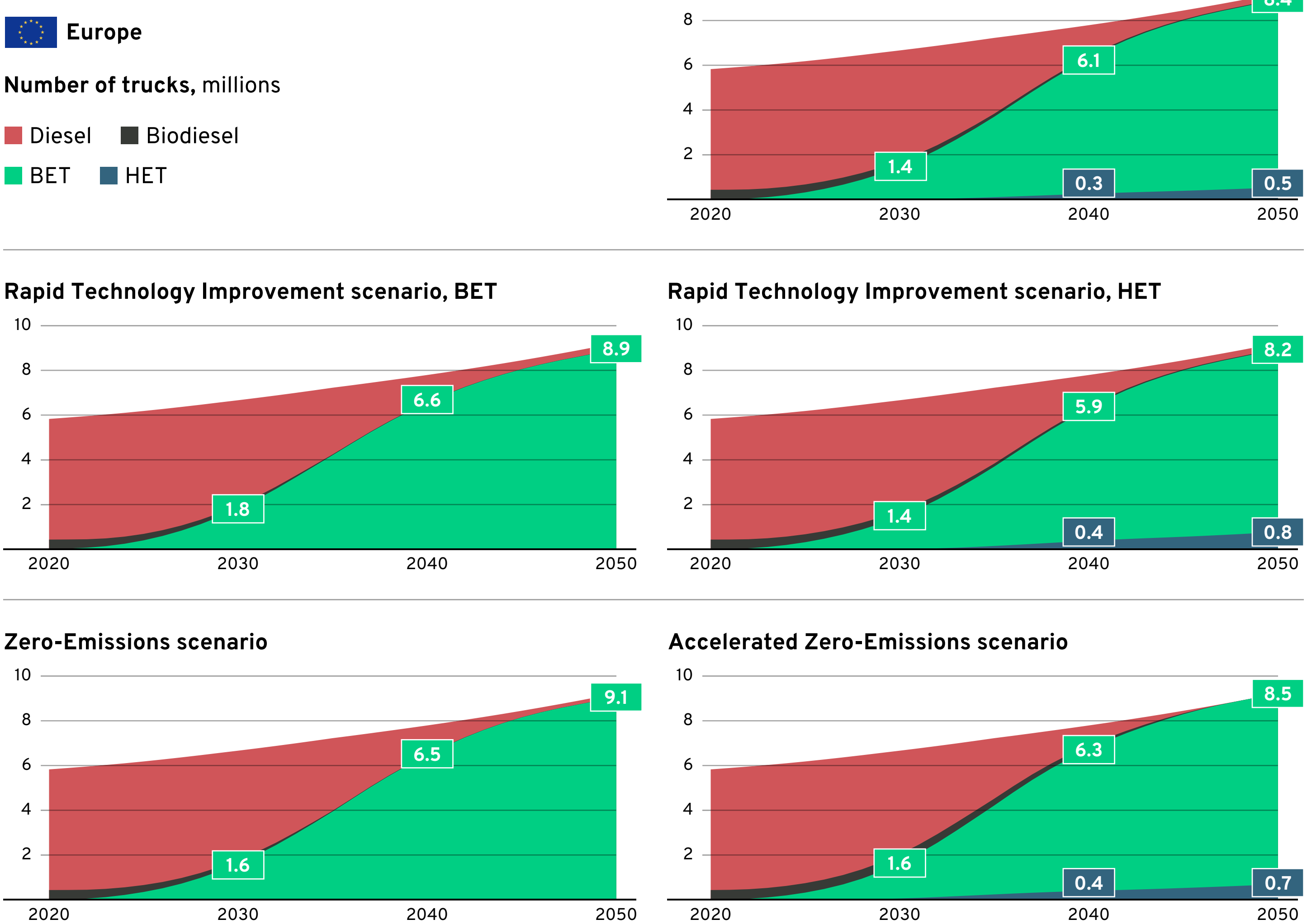
Europe is likely to be the fastest to transition to ZETs because of a mix of market and policy drivers.

One factor propelling momentum is that new diesel trucks in Europe are relatively expensive to buy as well as operate. High diesel prices combined with high upfront costs for a diesel truck improve the relative TCO of ZETs. Furthermore, lengths of haul in Europe are shorter on average than in the United States, so BETs can generally use smaller, cheaper battery packs. As a result, Europe is already on a strong glide path to zero emissions by 2050 (Exhibit 3.10), and the burden on industry of extra policy action to achieve zero emissions will be limited.

This dynamic is apparent in our modelling outcomes, with Europe coming close to reaching zero emissions by 2050 even in the Expected Adoption scenario. This does not suggest that the EU should ease its existing policy and technological efforts to decarbonise trucking, but rather that the probability of those efforts succeeding is high. Broadly, the goal for Europe can be ensuring that demand for ZETs, brought on by cost competitiveness, is met by both vehicle supply and infrastructure. Europe has the opportunity to ensure that forthcoming regulation ensures this is the case with its ambitious Alternative Fuels Infrastructure Regulation (AFIR) framework and revision of the CO_2 standards. Furthermore, if ZETs do not exhibit the cost declines – especially of batteries – projected in our modelling, industry and policymakers may need to take more active steps to stimulate demand.

EXHIBIT 3.10

Trucking fleet population by scenario



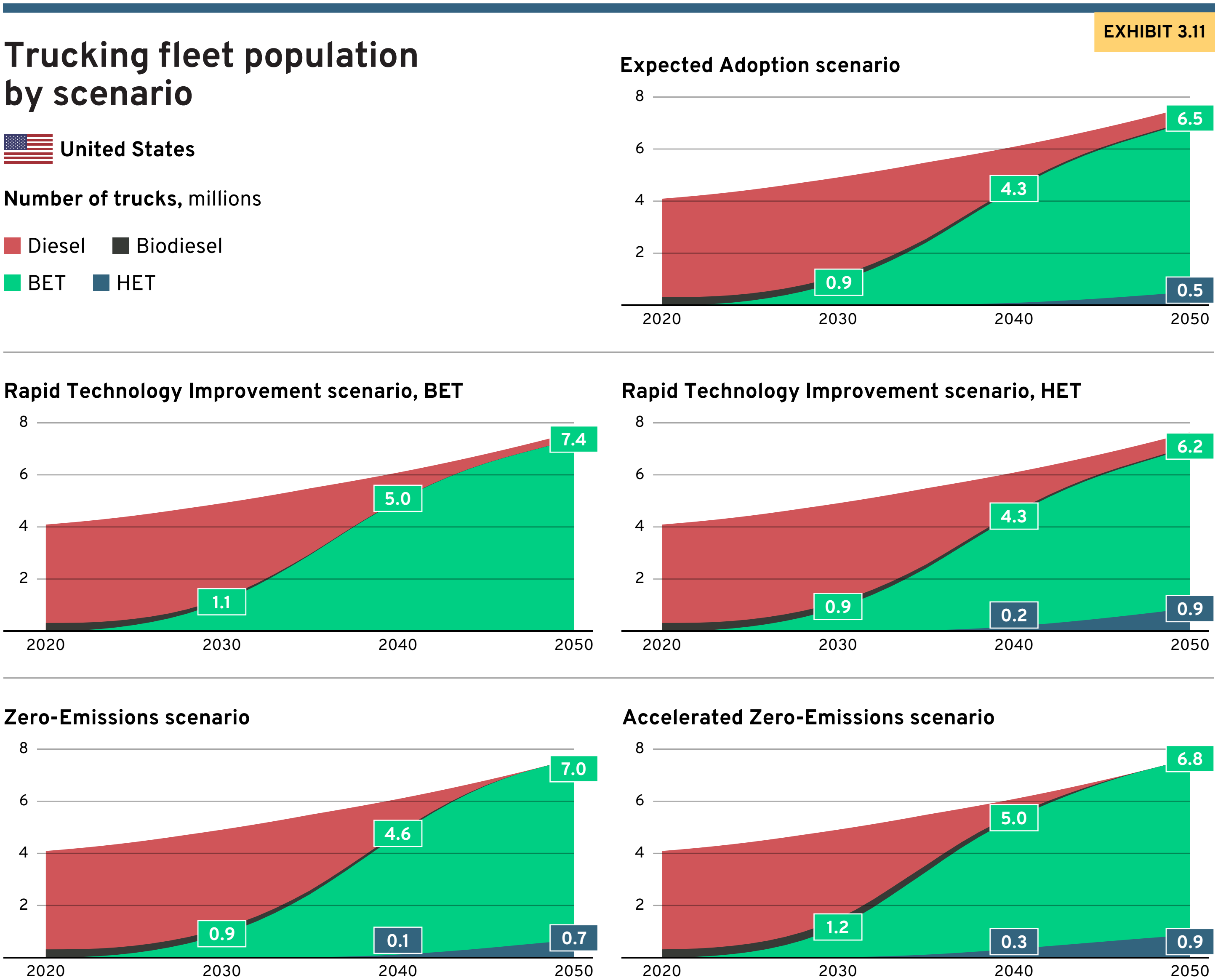
Source: MPP analysis

3.3.2 United States

Quickly following Europe, the United States is likely to be a second mover to decarbonisation of trucking. Fuel prices in the United States are not as high as in Europe, but diesel truck prices are moderately higher. However, haul lengths are relatively long, necessitating larger, more expensive battery packs. Together, the higher incremental capital costs of a transition along with the lower operational savings lead to a slightly slower transition in the United States than Europe as cost parity arrives a few years later.

On the policy side, the United States has a fragmented policy framework that will create a varied pace of transition in different areas of the country. Some locations, predominantly the Northeast and the West Coast, will adopt California's ACT policy framework and accelerate the transition in early years. The rest of the country (with a few exceptions) will follow a less stringent federal policy framework. Still, even these slow-moving states will benefit from the economies of scale achieved by faster-moving states, ultimately helping facilitate a nationwide transition over time.

Like Europe, the United States will need to only modestly increase its deployment of ZETs from the Expected Adoption scenario if it is to achieve zero emissions by 2050 (Exhibit 3.11). However, although the United States is strongly positioned for a market transition, it is less strongly positioned than Europe in the policy work because its regulatory framework is much more patchwork. If the cost-competitiveness of ZETs evolves more slowly than we have projected, the transition in the United States is more at risk than in Europe.



Source: MPP analysis

3.3.3 China

Though China has the most ZETs on the road of any market over the medium term, it is likely to be the third mover of the regions we studied purely thanks to economics. The primary reason for China having a slower transition is that it has substantially cheaper diesel trucks than either the United States or Europe. These low-priced diesel trucks create an increased price premium for ZETs, which is not easily recovered by reduced operating expenses. Over the years, declines in battery and hydrogen prices will create the economic incentives for a transition, but this process will play out more slowly in China than other geographies.

However, China has shown itself to be highly capable of catalysing a rapid transition to EVs in the light-duty vehicle (LDV) segment. Although we predict a relatively slow transition in China based on economics, that process could speed up rapidly if China decides to deploy a policy and infrastructure investment approach to trucks similar to what it has for cars (Exhibit 3.12). Furthermore, in its quest for LDV electrification, China has built mature battery supply chains and gained expertise in developing large fast-charging infrastructure projects. These major assets (not captured in our modelling) could substantially accelerate the transition should China make a significant push into the ZET market.

Primarily because of relatively cheap models of diesel trucks in China and the large cost gap between those low-cost trucks and expensive ZETs, we project that cost optimisation will leave China relatively far away from zero emissions by 2050. However, China may well surprise the world with an unexpectedly rapid transition, because its capability and demonstrated willingness to deploy policy and rapidly develop technologies to support decarbonisation are very strong. By either bringing the policy tools it used to develop the electric LDV or increasing the costs of diesel trucks via stronger regulatory regimes, especially with respect to air pollution emissions, China could rapidly shift towards faster adoption.

EXHIBIT 3.12

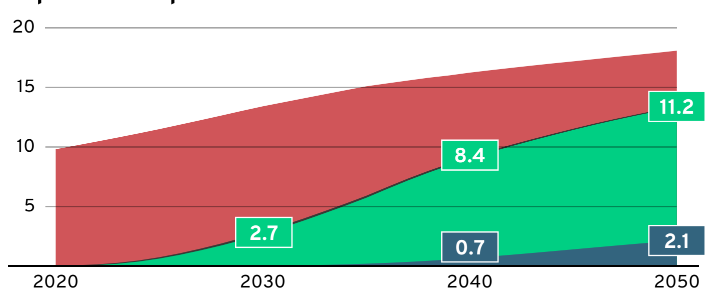
Trucking fleet population by scenario

China

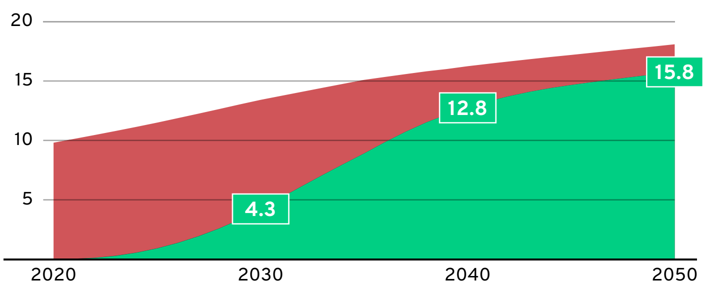
Number of trucks, millions

Diesel | Biodiesel | BET | HET

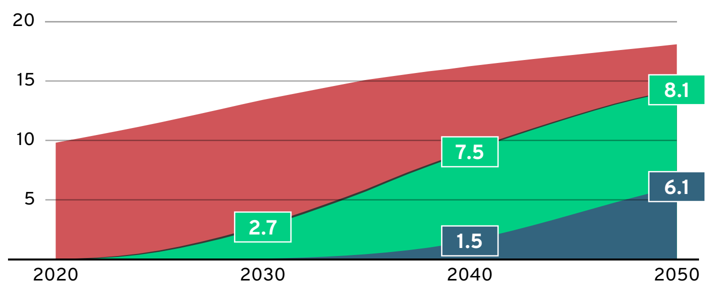
Expected Adoption scenario



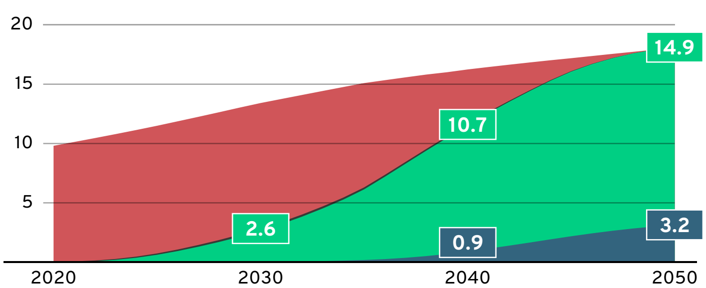
Rapid Technology Improvement scenario, BET



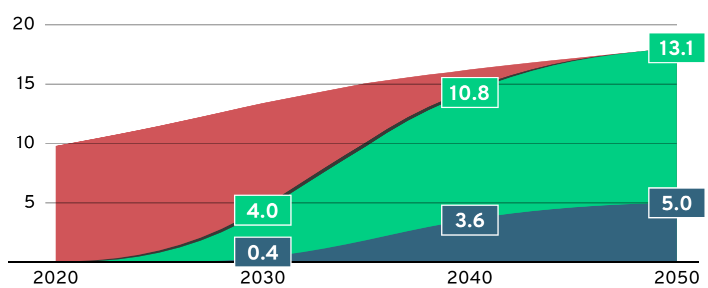
Rapid Technology Improvement scenario, HET



Zero-Emissions scenario



Accelerated Zero-Emissions scenario



Source: MPP analysis

3.3.4 India

We project India to be the last mover of the four regions studied. This is largely because India has very cheap diesel trucks, lower in cost even than those used in China. These low-cost vehicles coupled with moderately priced fuel – comparable to the United States and China – will lead India to have the latest transition (Exhibit 3.13).

Furthermore, on the policy side, India has yet to take a position on truck electrification and decarbonisation. India does, however, have a robust and rapidly growing market for electric light-duty vehicles and buses, which was catalysed by supportive national policies such as FAME and FAME II,[22] as well as myriad state and city policies. By bringing similar types of policies to the trucking market, India could make the transition more rapidly than we project, and could more fully realise its potential as a policy leader in transportation decarbonisation for developing economies. Additionally, of all the countries we analysed, India has the least developed electricity grid. The complexity of integrating very high-powered charging into a still developing grid could delay the transition to BETs and create interest in increased use of HETs.

Finally, mostly due to low costs for diesel trucks (even lower than in China), India is the last region studied to achieve zero emissions. Cost optimisation alone is insufficient, and India currently has no policy framework to support zero-emissions trucks. For the transition to occur in India, substantial additional effort will be required not only from Indian policymakers and industry, but also from global climate finance and development organisations.

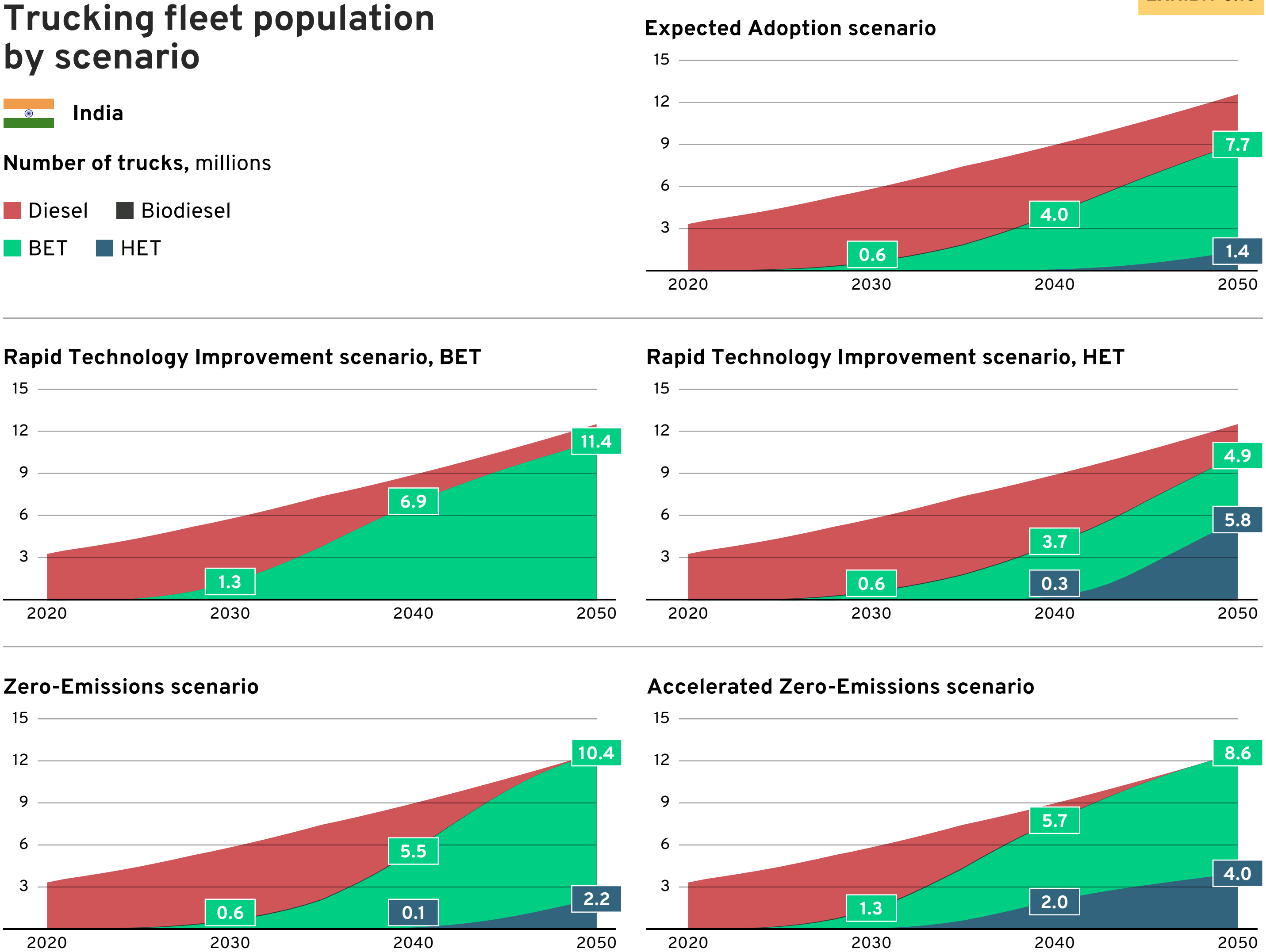
EXHIBIT 3.13

Trucking fleet population by scenario

India

Number of trucks, millions

Diesel, Biodiesel, BET, HET



Source: MPP analysis

22 Faster Adoption and Manufacture of (Hybrid and) Electric Vehicles.

PART 4

INFRASTRUCTURE, GRID UPGRADES, AND FINANCE ENABLE THE TRANSITION TO NET ZERO

Our models focused primarily on sales trajectories required to ensure that a 2050 fleet is 100% ZETs — and the policies and cost declines needed to make those trajectories a reality. But vehicles alone cannot deliver zero emissions. Other adjacent sectors, especially finance and infrastructure, must play a role if the transition is to be successful.

4.1 Infrastructure fuels tomorrow's zero-emissions fleet

4.1.1 Electric truck charging

Partly because the technology is more mature, BETs reach TCO parity earlier than HETs, fostering higher adoption rates earlier across regions and duty cycles. Though they have a head start, heavy-duty BETs are still new and are sensitive to power prices and electricity availability. Delivering electricity to trucks will require substantial investments in new charging infrastructure of various types. Trucks in urban and regional applications will likely be able to use depot charging with powers ranging from approximately 20 kW level 2 chargers up to 50 kW DC fast chargers — depending on the energy needs of the truck. Trucks operating in long-haul segments will require much more powerful charging equipment, relying on a network of ubiquitous, high-powered DC fast chargers ranging from 350 to 1,000 kW.

Building the number of chargers needed will be a substantial challenge. However, ZET market development in urban, then regional, and finally long-haul segments lends itself to a staggered, more economically efficient rollout of public infrastructure. Urban trucking will rely almost exclusively on depot charging, with fast charging added as a failsafe for completing atypically energy-intensive routes.[23] Regional trucking will benefit from the market scaling created by urban demand, and although it will require more en route charging, some of that infrastructure will have been built to serve urban trucking. Long-haul trucking follows the same pattern, with vehicles and infrastructure development cost savings enabled by prior demand.

Charger costs are not the only roadblock in infrastructure development. Delivering the power to those chargers is also a major task. Current electricity grids are not built for truck charging. Large collections of high-powered truck chargers, as are likely to be found on major trucking corridors, will require very high levels of power, which in turn will require direct connections to high-voltage transmission lines. In many cases, this infrastructure is not where it needs to be, and bringing it to those locations is both costly and time consuming.

Depot charging for urban and regional trucking will face related problems. Lower-powered chargers aggregated at a single depot can still require more power than a location has, and electricity distribution grids typically do not have the capacity to serve a large collection of new industrial loads coming online in urban areas at the same time — as must happen for trucking decarbonisation to be viable by 2050. For urban locations, increasing local grid capacity often requires laborious and slow construction. These infrastructure build-out requirements will strain electric utilities.

23 The model also reflects the benefits of urban density for fast-charging infrastructure. Europe's urban fast chargers achieve higher utilisation because they have more potential users nearby.

Furthermore, extensive utility-side infrastructure investment could cause utility costs to rise and trigger an increase in the costs of electricity. If that happens, assumptions about BETs' TCO would no longer hold. Creating this grid-side infrastructure without increasing costs to truck operators will be a key challenge in the transition.

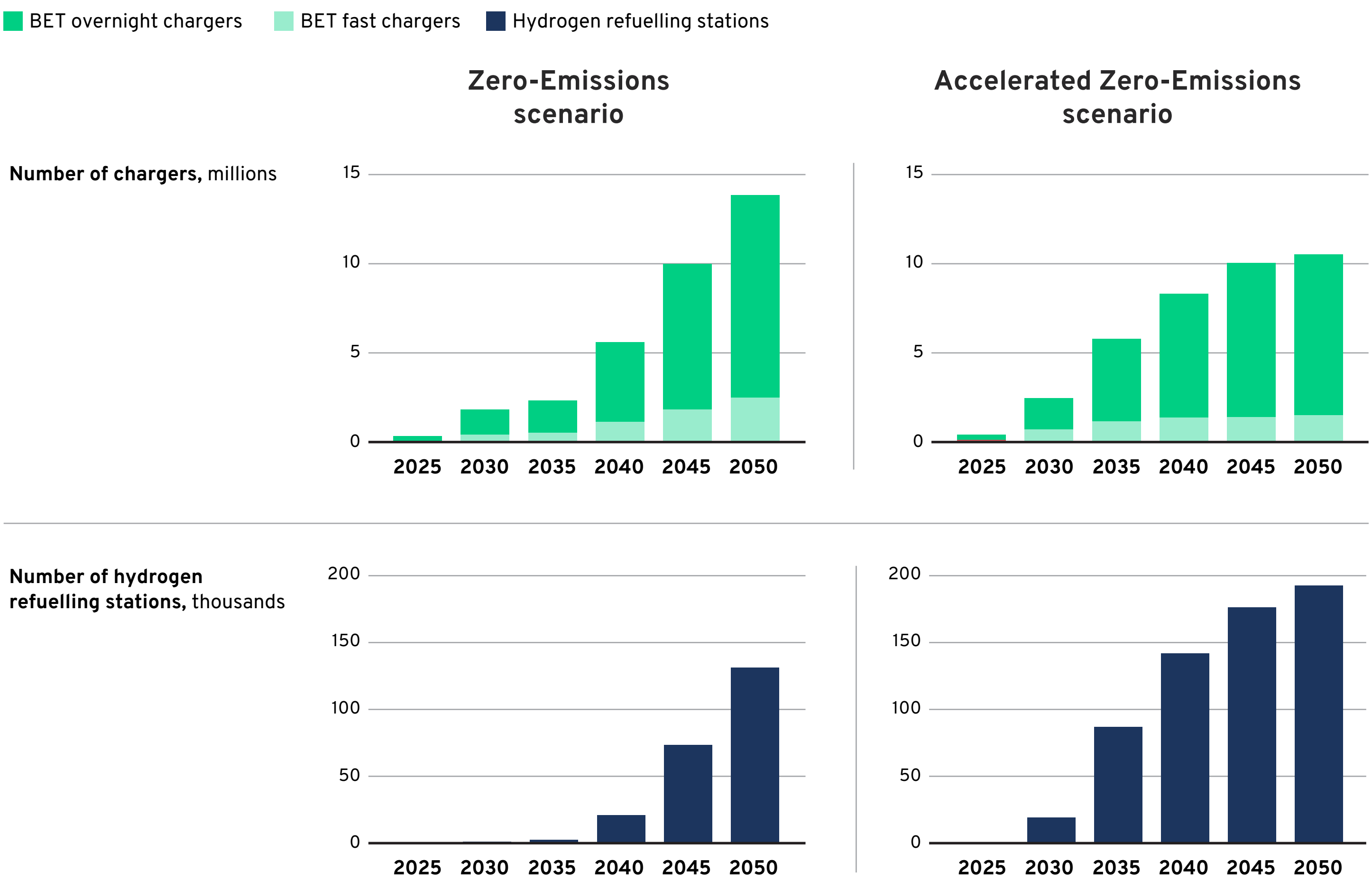
4.1.2 Hydrogen truck refuelling

HETs must also have substantial infrastructure needs fulfilled if they are to be viable. Hydrogen is more like diesel in that trucks will be able to quickly fill up at public stations, such that far fewer hydrogen filling points will be needed than charger plugs. Depending on the scenario, we believe that 130,000–190,000 H_2 filling points will be needed by 2050 in the regions under study in this report. However, the similarities to diesel end there.

Compared with hydrogen, diesel is much easier to transport and has an existing mature distribution network. To be practical, hydrogen will also need a widespread network, entailing substantial investment in the distribution system to make that hydrogen available. It may be possible to repurpose natural gas pipelines as natural gas loses market share in a net-zero world. However, repurposing existing pipelines requires significant modifications to ensure that hydrogen does not escape from pipelines and does not corrode them.

EXHIBIT 4.1

ZET adoption requires a major infrastructure ramp-up



Note: Overnight chargers are assumed to have a capacity of 100 kW and fast chargers are assumed to have one of 500 kW.

Source: MPP analysis

4.1.3 Energy and fuel production

In all scenarios, the HDT sector would see a shift in consumption away from diesel in favour of electricity and H_2 consumption. The consumption of electricity will increase before the consumption of green H_2, given the earlier sales uptake of BETs. These earlier BET sales in the Accelerated Zero-Emissions scenario also translate to increased electricity consumption in the first decade (Exhibit 4.2).

Between 2025 and 2035, the demand for electricity for HDT will multiply by almost 10 in both the Zero-Emissions scenario and the Accelerated Zero-Emissions scenario. By 2035, total electricity consumption of 900–1,300 TWh is expected to power BETs, equivalent to 20%–35% of total final energy used in the HDT sector. China is likely to see the most dramatic change in consumption due to the size of its BEV fleet, followed by the United States and Europe, whereas India's electricity grid will require more investment to enable the supply and distribution of zero-emissions electricity and hydrogen. Electricity demand will continue to increase through 2050.

Green hydrogen demand should accelerate after 2035 as HET uptake increases. Demand for hydrogen will multiply by 10 to 20 times from 2030 to 2040, when it will reach 250–1,100 TWh of H_2 final energy use, or 6%–32% of energy use, depending on the scenario.

Increased green hydrogen supply will translate into higher electricity demand, as renewable energy is required to power the production process. However, this electricity for hydrogen production is not included in the electricity demand in Exhibit 4.2, which refers to end-use electricity only. For reference, the H_2 multiplier (defined as the kWh of energy required to provide 1 kWh of energy to the HET wheels) is estimated to be between 4 and 10 in 2030 and between 3 and 8 in 2050.

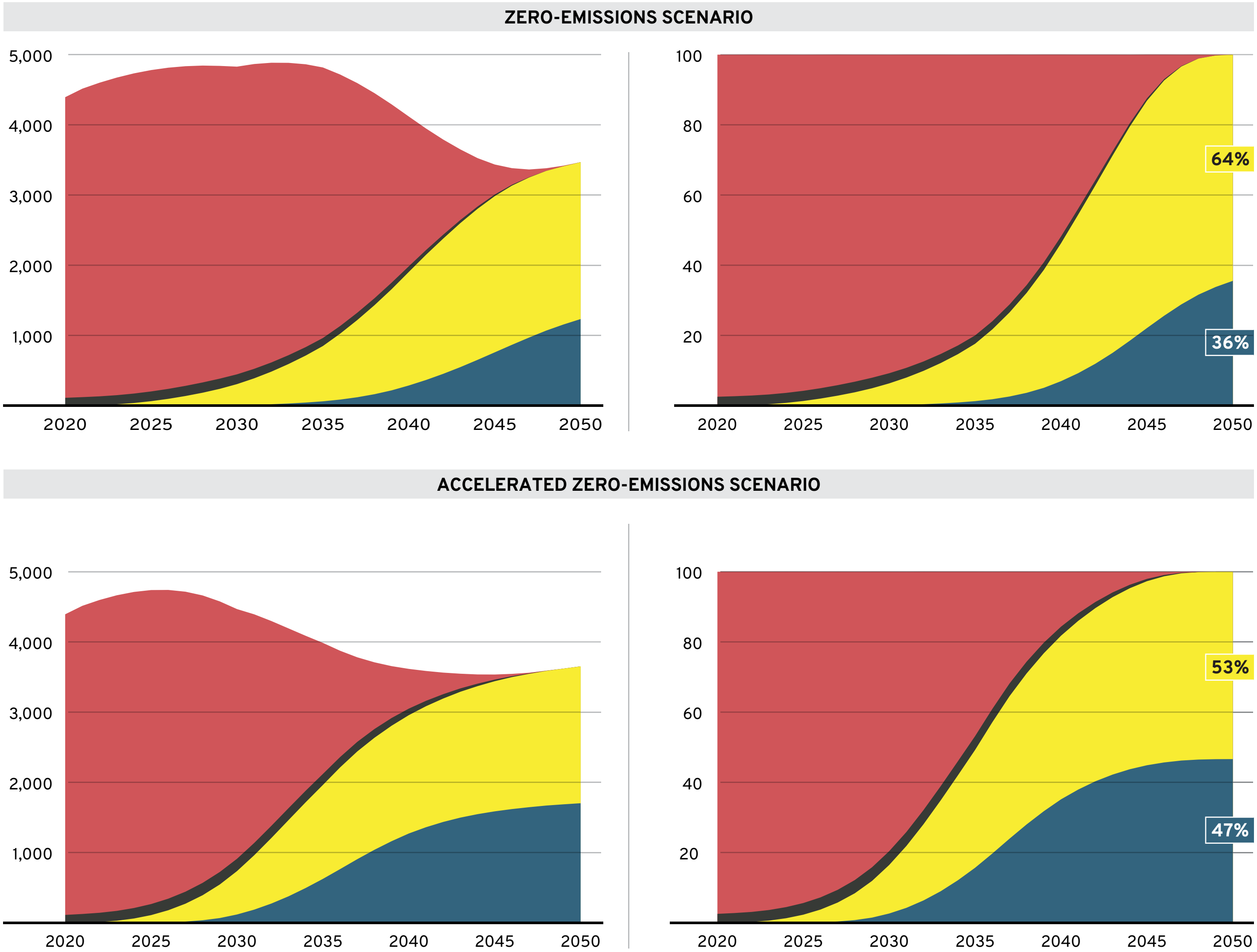
EXHIBIT 4.2

Energy consumption by scenario, 2020–50

Diesel · Biodiesel · Electricity · Hydrogen

Total energy demand by fuel, TWh

Total energy demand by fuel, %



Source: MPP analysis

4.2 TCO alone cannot catalyse a transition; finance must mobilise the capital needed to deploy solutions

4.2.1 Financing needs by region

Reaching zero emissions in 2050 will require additional investments in zero-emissions trucks and charging infrastructure. Although these investments will be substantial, they both avoid the need for substantial investments in diesel trucks that would otherwise occur and enable substantial savings in operating expenditures.

When one looks at these dynamics between now and 2050, a few key points emerge. The first is that increased capital expenditures in developed markets between the "Do Nothing" Baseline and the Zero-Emissions scenario is manageable for developed countries (Exhibit 4.3). In Europe, the incremental capital expenditure, in net present value terms, is about $565 billion, and in the United States it is about $680 billion (a 25%–30% increase over continued use of diesel). This is largely because in Europe and the United States, diesel trucks are already expensive, and as battery prices fall and economies of scale accrue to ZET manufacturing, the cost gap between diesel vehicles and ZET alternatives rapidly shrinks. Because most adoption in a Zero-Emissions scenario occurs in the late 2020s through the 2030s, when ZETs are purchased, the incremental investment is rapidly recouped with fuel savings.

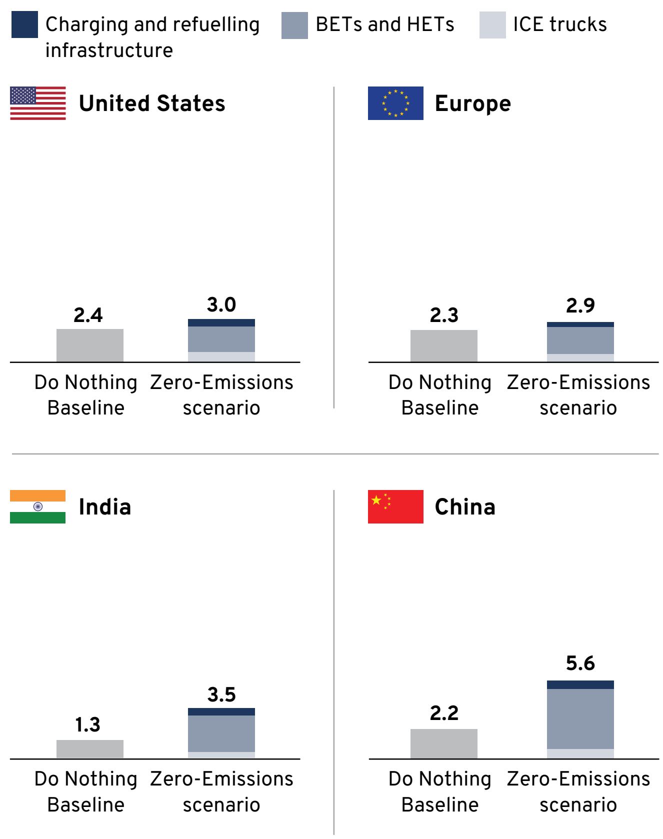
However, because developing markets have much lower prices for diesel trucks, the dynamic there is very different. In India and China, the incremental capital expenditure between the Zero-Emissions scenario and full continued use of diesel has a net present value of $2.3 trillion in India and $3.4 trillion in China (a 160%–180% increase over the continued use of diesel). Financing these substantial incremental capital costs in developing economies will be a key enabler of the global transition to zero-emissions trucking.

However, incremental capital expenditure alone does not capture the investment dynamics of the transition. ZETs are substantially cheaper to operate than diesel vehicles. When one considers both operating costs and capital costs, going net zero is cheaper in all regions. In the United States and Europe, following a zero-emissions path reduces total cost by a net present value of $0.64 trillion and $1.1 trillion (10% and 17%, respectively). In India and China, where capital expenditure dynamics are less favourable, cost reductions have a net present value of $.35 trillion and $.36 trillion (4% and 3%, respectively) (Exhibit 4.4).

EXHIBIT 4.3

Diesel truck costs vary by region, impacting ZET's upfront cost competitiveness

Net present value of 2020–50 capital costs by scenario, Trillion $



Source: MPP analysis

This is a critical point for developing markets. The transition to net zero is cheaper than the continued use of diesel vehicles but imposes significant upfront costs. Mobilising the financing that enables operating expenditure savings to pay for those increased capital costs must become a major focus of the global climate finance industry if the transition is to be successful in developing economies.

4.2.2 Innovative financing approaches and business models

The ability to convert operational savings into the upfront capital to purchase expensive ZETs does not only inhibit the ability of less wealthy countries to decarbonise their economies. It also inhibits the ability of smaller, less sophisticated, and less well capitalised trucking fleet owners, or fleets, to transition their own operations to a zero-emissions approach that is ultimately more cost-effective than the continued use of diesel.

Large, sophisticated fleets have several advantages in adoption of ZETs. First, large fleets serve a variety of use cases and can best deploy ZETs in their fleets to meet specific needs. For a small fleet that may consist of only one vehicle, that vehicle must be able to do any job required of it on any given day. This makes diesel's flexibility a very valuable asset to small fleets.

Second, ZETs promise lower maintenance costs, but when maintenance is required, new and specialised expertise is needed. Large fleets can develop this expertise in-house and use it to serve their own vehicles. Small fleets cannot; they must outsource that maintenance to a market that does not yet exist for ZETs.

Third, for many small fleets, the investment in charging equipment and expertise to cost-optimally charge EVs is both considerable and overly complex. Large fleets can optimise EV charging to minimise costs, a proposition that is much more difficult for small fleets.

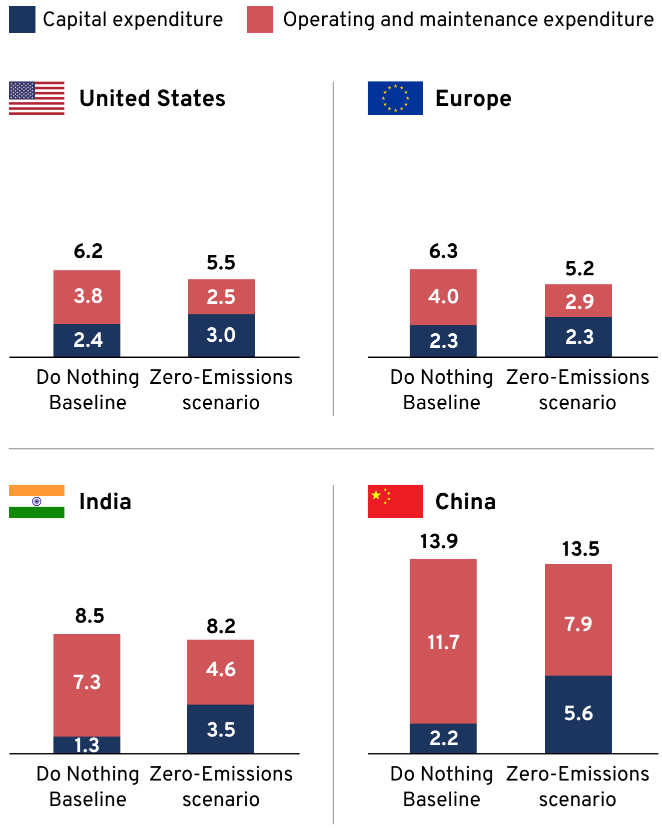
Finally, large fleets typically have much better access to credit than do small fleets – which are often just family businesses. This enables large fleets to gain access to credit at rates that preserve the TCO advantages of ZETs. Small fleets would make higher monthly payments on a loan for the same truck – eroding the ZET's TCO advantage.

New business models have emerged to fill this gap. Companies now offer electric trucks for rent or via leasing packages that include maintenance and access to shared charging for a fixed monthly payment. This "truck-as-a-service" approach allows small fleets to have access to ZETs when they need them, without needing internal maintenance or infrastructure expertise, and without having to make a large upfront payment.

EXHIBIT 4.4

ZET operating savings are projected to create positive TCO in all regions

Net present value of all 2020–50 costs by scenario, Trillion $



Source: MPP analysis

These leasing models come in many flavours; another is "battery-as-a-service". Under this model, the fleet takes direct ownership of the truck itself and takes on risk associated with maintenance and charging of the vehicles. However, it does not actually own the battery or any associated maintenance. This can substantially reduce the upfront costs of those vehicles and bring their purchase price below that of ICE trucks.

However, battery-as-a-service models are most often used when the battery is easily separable from the vehicle, as with vehicles capable of battery swapping. When the battery is not separable, OEMs can offer extended battery warranties. Those warranties do not reduce the cost of buying a vehicle, but they do reduce the risk of owning it. Reduced risk to the owner can in turn reduce the risk to the financier, which would become the vehicle owner in the event of default. This lowered risk can enable the owner to access capital at lower rates.

PART 5

RECOMMENDATIONS FOR POLICIES AND COORDINATED ACTION TO ENABLE A ZET TRANSITION

In the Glasgow Climate Pact, agreed upon in 2021, the parties to the United Nations Framework Convention on Climate Change (UNFCCC) recognise "that limiting global warming to 1.5°C requires rapid, deep and sustained reductions in global greenhouse gas emissions, including reducing global carbon dioxide emissions by 45 percent by 2030 relative to the 2010 level". They add that this will require accelerated action this decade, on the basis of the best available scientific knowledge.

Although the HDT sector may not reach this 2030 goal, rapid decarbonisation is technically and financially possible. Industry, policymakers, and other stakeholders need to ensure market adoption in two critical ways. First, stakeholders must continue reducing costs in batteries, electricity, and public charging that drive zero-emissions TCO. Cost decline trends must maintain or exceed their current trajectories. Second, fleet operators need support so that soft costs related to considering or deploying ZETs or an inability to purchase ZETs or their fuels does not derail positive developments in TCO.

HDT stakeholders should target key areas for interventions in the 2020s in order to unlock decarbonisation's potential. Identified actions include:

1. Use milestones that collectively indicate whether the transition is on course.
2. Create and deploy policy frameworks.
3. Stimulate innovative business models, financing models, and industry partnerships.
4. Coordinate with other sectors to achieve economies of scale.

5.1 Develop and adhere to key milestones in vehicle production and technology as well as infrastructure deployment

5.1.1 Vehicle TCO, performance, and supply

TCO, operational performance, and product availability will affect a fleet owner's decision when investing in a new truck. All stakeholders must have a shared view of how the transition to ZETs will play out and collectively agree on real economy "milestones" to calibrate whether that transition is on track. Such milestones include:

Product availability

- Expand ZET sales to reach HDT populations of at least 2.6 million units in China, 1.5 million units in Europe, 0.9 million units in the United States, and 0.6 million units in India by 2030.
- Have 400 GWh capacity of annual battery manufacturing for heavy-duty trucks in the modelled regions by 2030, rising to over 1,200 GWh by 2050. Current total electric vehicle battery production is approximately 631 GWh per year.[24]
- Have production capacity for over 15,000 fuel cells globally per year by 2030, rising to 1 million by 2050.

Cost

- Reduce HET costs by 60% to 75% through reduced fuel cell stack costs of up to 85%.
- Achieve hydrogen costs of near $3/kg by 2050.
- Reduce BET costs by approximately 50%, enabled by battery price declines of up to 55%.

Operational performance

- Reduce weight penalty of long-haul BETs compared with diesel trucks by increasing battery energy density by up to 50%.

Charging and refuelling infrastructure

The lack of charging infrastructure will constrain the ZET transition. Gaining scale in infrastructure development will result in cost optimisation and lead to a positive impact on TCO. Investments designed to improve the availability of charging and refuelling stations are also critical to eliminating operational concerns.

A ZET scale-up will require two dimensions of infrastructure development: first, improved charging and refuelling station coverage (including at depots for charging), and second, an enhanced overall supply of green electricity and hydrogen. Green hydrogen can unlock decarbonisation potential for multiple hard-to-abate sectors and will face steep increases in demand. Improving charging and refuelling availability will require significant capital investments ($700 billion to $800 billion) and will require utilities to provide the hydrogen and electricity to users in a timely and affordable way.

Example targets in line with the results obtained in the Zero-Emissions scenario:

- Boosting the installed capacity of BET chargers to reach about 160 GW in China, 55 GW in Europe, 45 GW in the United States, and 40 GW in India by 2030. At 300 GW total, this is five times the electric demand of the Tokyo metropolitan area.[25]
- Grid electricity production for BETs to reach 184 TWh in China, 42 TWh in India, 40 TWh in Europe, and 26 TWh in the United States by 2030.
- Dedicated zero-carbon electricity production to produce green hydrogen for HETs to reach 265 TWh in China, 50 TWh in Europe, 40 TWh in India, and 35 TWh in the United States by 2040.[26] Currently just 0.3% of hydrogen is produced using renewable electricity.[27]
- Increasing the number of H_2 refuelling stations to reach 36,100 in China, 6,600 in Europe, 5,600 in the United States, and 2,200 in India by 2040.[28] These are significant investments and also just a fraction of existing infrastructure. For example, there are approximately 116,000 gasoline fuelling stations in the United States.[29]

24 Jakob Fleischmann et al., "Unlocking growth in battery cell manufacturing for electric vehicles", *McKinsey Insights*, October 2021, https://www.mckinsey.com/business-functions/operations/our-insights/unlocking-growth-in-battery-cell-manufacturing-for-electric-vehicles.

25 Presentation, Tokyo Electric Power Company, March 19, 2015, http://az545403.vo.msecnd.net/uploads/2015/03/5-tepco.pdf.

26 Figures refer to actual energy utilised by vehicles. To supply that amount of power, a greater amount needs to be produced to account for losses during, e.g., hydrogen production and grid transmission.

27 IEA, "Hydrogen Tracking Report", November 2021, https://www.iea.org/reports/hydrogen.

28 Figures refer to actual energy utilised by vehicles. To supply that amount of power, a greater amount needs to be produced to account for losses during, e.g., hydrogen production and grid transmission.

29 Statista, June 27, 2022, https://www.statista.com/statistics/525107/number-of-gasoline-stations-in-the-united-states/.

Large amounts of hydrogen and electricity are needed to achieve an accelerated ZET transition. Stakeholders must manage the soft costs and split incentives to enable the building of this infrastructure.

5.2 Create and deploy policy frameworks that enable the transition and address key bottlenecks in vehicle supply, demand, and fuelling

In the near term, the transition to ZETs will be difficult because of high costs resulting from poor economies of scale and technological immaturity. Policy action can help to both catalyse the industry to take on those costs and enable the costs to be allocated to different segments of society so that they remain bearable.

5.2.1 Supply

Investing in the new supply chains needed for a ZET transition will challenge manufacturers. New factories or factory retoolings are very expensive and require years of planning and permitting to be built. Policymakers can extend financial incentives through tax credits, preferential land use, or other policy levers that subsidise the development of ZET production facilities. Furthermore, to ensure that such factories can be completed in a time frame that is compatible with a zero-emissions trucking future, they can minimise regulatory red tape.

Building ZET factories alone is not enough; a whole supply chain of ZET components must exist if that factory is to produce vehicles. These upstream activities also have their own financing and permitting needs. Policymakers should coordinate closely with ZET manufacturers to understand and address operational constraints on ZET production due to upstream issues.

Although incentives and soft cost reductions for both vehicle production and upstream supply chains may help spur supply, the effects of financial support on production levels are unpredictable. To achieve certainty of supply at a price which the market will bear, policymakers can introduce sales requirements, as currently exist in California and the EU. These can take the form of ZEV credits, as is common in California and China, or the form of CO_2 credits, as is common in Europe. In either case, these credit-based systems both guarantee sufficient supply and create a market framework in which the incremental cost of bringing ZET supply to the market is ultimately borne by the producers of ICE vehicles – not the purchaser of the ZET.

5.2.2 Demand

As with vehicle supply, levels of demand for ZETs are highly dependent on their cost feasibility. In the early stages of market adoption, when costs are high and TCO is poor, governments can work to spur demand by offering incentives for vehicle purchase in the form of upfront subsidies, tax incentives, or financing instruments such as loan guarantees. They can also offer incentives for vehicle use such as forms of carbon tax like LCFS credits that transfer cost from renewable fuels used by ZETs to fossil fuels used by ICE vehicles.

However, similar to the supply situation, the effects of subsidisation on adoption are unpredictable, and the cost of ongoing subsidisation of more mature markets can be prohibitively high. At later stages of market development, policymakers can use levers that more forcefully affect demand in non-financial ways. For example, they can put direct purchase requirements on fleets, as California did with the Advanced Clean Fleet rule, or they can create zero-emissions zones in cities, which essentially ban the use of an emitting vehicle in areas where the impacts of air pollution are high. As they use these more forceful tools, policymakers must keep in mind the feasibility of compliance by operators. Just as a factory cannot produce ZETs without upstream supply chains, fleets cannot use ZETs if they cannot buy or charge them. As a result, it is critical that policymaking be holistic and simultaneously take on issues in supply, demand, and infrastructure.

5.2.3 Fuelling infrastructure

The supply chain by which a stream of raw materials eventually turns into ZETs on the road is not the only one that policymakers must concern themselves with. How renewable electricity eventually becomes energy in a truck's battery or hydrogen in a truck's fuel tank is equally important.

Policymakers must be aware of how these fuel supply chains work and what matters require policy resolution to be functional at scale. Although many issues exist, two have outsized importance. First is ensuring that fuels can be transported from the point of production to the point of use while maintaining strong cost superiority over diesel. That requires separate action from policymakers for hydrogen and electricity.

In many jurisdictions, electrical transmission and distribution is a regulated monopoly. That means that private utilities must apply to government-appointed regulators for permission to build the capacity to serve ZET charging needs. This process is often inefficient and slow, and its outcomes are uncertain. Furthermore, the operators of ZETs are frequently required to bear the cost of building this infrastructure even though utilities will make money by selling more electricity through that infrastructure. Policymakers must design regulatory regimes that both facilitate rapid investment decisions and ensure that costs are not allocated in such a way that the growth of the ZET industry is stifled.

Similar dynamics exist in hydrogen markets. In the long term, the only way in which hydrogen can be delivered to refuelling points at a reasonable cost is via pipeline – perhaps supplemented by delivery trucks in the final mile. This will require considerable investment in new hydrogen pipelines. In several of the regions under study, these types of public works projects are often slow and costly. Policymakers must proactively identify legal barriers to hydrogen pipeline investment and ensure that they do not derail the ZET transition.

The second issue of outsized importance is ensuring that sufficient points of sale can exist. Many times, the deployment of charging infrastructure, especially public infrastructure, can come into conflict with local land use regulations and permitting processes – slowing down infrastructure deployment and creating extra soft costs that are ultimately passed on to infrastructure users as real financial costs. Policymakers, particularly those at sub-national levels, must proactively address issues that slow or prevent the emergence of a robust ZET refuelling network.

5.3 Stimulate innovative business models, financing models, and industry partnerships

5.3.1 Establish innovative partnerships up and down the truck value chain to share risk and enable scale

Zero-emissions trucks come with a new and different set of challenges for operators. They often create risks that fleets are unable to shoulder, and opportunities that demand new types of expertise to capture. Innovative partnerships can help to diffuse these risks and take advantage of those opportunities.

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Financing and risk management

ZETs are expensive up front, but cheap to operate. Although these vehicles may ultimately be profitable to operators, many fleets, especially smaller ones, do not have the access to capital to buy ZETs. Fleets may also lack the ability to readily provide ZETs with the required charging infrastructure or maintenance. To address these barriers, partnerships could include the following:

- **Leasing models:** Providing ZETs for relatively short periods without the need for a large upfront payment can make them more accessible for smaller fleets. These leases can be structured for smaller windows of time to reduce the need for long-term commitments that small fleets may be unable to make.

- **Truck-as-a-service:** These models provide the entire suite of services needed to operate a ZET on a short-term basis. The service provider owns, maintains, and charges the vehicle – the operator needs only to drive it.

- **Battery warranties:** The battery is the most expensive component of the ZET, but vehicle batteries have been known to fail early, making fleets wary of purchasing expensive assets with unknown lifetimes. Robust battery warranties would reduce risk and provide peace of mind.

Infrastructure

Like ZETs themselves, the infrastructure to power ZETs typically has a long lifetime and is expensive up front. Partnerships formed to mobilise capital can accelerate their deployment.

- **Committed offtake:** ZET refuelling stations (chargers or hydrogen) rely on revenue streams from truck operators to be financeable. By agreeing to long-term offtake of either hydrogen or electricity from a specific station, truck operators can create revenue certainty for station operators and enable the financing of those stations.

- **Long-term supply contracts:** The facilities needed to produce green hydrogen or green electricity also become more easily financed with committed purchasers. Similar to how power purchase agreements enable renewables deployment, or certificates enable the financing of plants that produce Sustainable Aviation Fuels (SAF), long-term supply contracts can enable production of expensive assets such as the electrolysis plants that produce green hydrogen.

- **Utility collaboration:** Electric vehicle charging can be good for the grid. Charging increases the use of the grid, often during off-peak hours. This increased utilisation can put downwards pressure on all customers' electric rates. Many utilities promote electric vehicle adoption by reducing the costs of utility and customer-sided infrastructure. These "make-ready programmes" make BETs more attractive through reduced total TCO.

Demand certainty

Vehicle producers often cite lack of firm demand for ZETs as a barrier to investing in the plants needed to produce them. However, collaboration can demonstrate strong demand for ZETs that potential manufacturers need to see. By pooling demand, for example, would-be ZET buyers can work together to quantify total market demand for vehicles and stimulate investment in production capacity by OEMs.

Similarly, purchasers of transportation services – oftentimes large manufacturing or industrial companies – can provide demand certainty to ZET operators and pay a "green premium" for zero-emissions transportation services. In this way, especially in the short term, shippers of goods can support the development of the ZET industry by enabling operators to pass on their higher TCO to the final consumer of the goods that are being shipped.

Scaller LLC photo

5.4 Coordinate with other sectors to achieve economies of scale on the shared path to net zero

Trucking decarbonisation will require a wholesale shift to new fuel sources to become a reality. However, ZET actors are not on this path alone. Other industries will be undertaking similar changes on a similar timeline – creating opportunities for shared costs and economies of scale in both the production and distribution of those fuels. Those opportunities include the below.

5.4.1 Sharing the cost of electricity grid upgrades with buildings, industry, and light-duty vehicles

The “electrification of everything” is a key pillar of the decarbonisation of the global economy. To achieve this outcome, sectors as varied as heating and cooking in buildings, passenger transportation, and many industrial heat processes are also moving towards electrification. These actions will also require new capacity to generate and move electricity. Sizing the required upgrades to the needs of all electrifying sectors from the start will reduce the total cost of infrastructure borne by any single sector. Furthermore, by avoiding individual upgrades for individual sectors, electric utilities can save time and soft costs related to permitting and regulatory approvals for investment.

5.4.2 Coordinating with industry and shipping on creating scaled production of green hydrogen

Like electricity, green hydrogen will be a key enabler in decarbonising hard-to-abate sectors. Ocean shipping will need hydrogen to make ammonia, for example, and many industrial processes that currently use natural gas for heat, such as steel production, will switch to hydrogen as a heat source. Like many other fuel production processes, hydrogen electrolysis shows strong economies of scale. A hydrogen electrolysis plant that is directly connected to utility-scale wind and solar can produce green hydrogen at far lower costs than can a smaller installation or one that is grid-connected. By co-developing regional hydrogen production hubs that supply multiple users of green H_2 in each area, the trucking industry can both benefit from economies of scale in production and help reduce the need for hydrogen transportation.

5.4.3 Coordinating with aviation on biodiesel production

Although we see a minimal role for biodiesel in a fully decarbonised world due to limited cost-effective sustainable feedstock, the trucking industry should use what zero-carbon liquid fuels are available to it. The primary user of biofuels is expected to be the aviation industry. In many SAF production pathways, both SAF and biodiesel are co-produced. This can be valuable in the trucking market. By coordinating with SAF plants to use those by-products, trucking can have a supply of liquid fuels to enable the decarbonisation of use cases that are not appropriate for either hydrogen or battery electric trucks.

THE WAY FORWARD

The HDT industry finds itself at a significant intersection. The trucking sector can and must rapidly decarbonise. The foundations of such efforts are emerging and growing steadily, with intensive product development projects, risk-sharing partnerships, and infrastructure projects already under way. These concerted efforts are receiving support from new trucking regulations and numerous collaborative initiatives aimed at creating the conditions for investment in zero-emissions solutions.

At the core of heavy-duty trucking decarbonisation, stakeholders need to solve the “first-mover disadvantage”. Finding multilateral solutions to existing and emerging regulatory challenges will be critical to unlocking the first wave of near-zero-emissions trucking. Government must clearly signal its zero-emissions intent and commitment to create an early mandate, and OEMs, fleet owners, and infrastructure players must align their strategies.

The MPP Trucking Initiative and its members will contribute actively to mobilising the industry’s value chain to enhance the environment for investment. It will also support financial institutions in designing interventions that will help put the global trucking sector and its stakeholders on the path to reaching zero emissions. This is the best way to help this committed community of stakeholders act on the essential decisions required to deliver a sustainable future for this industry and the planet.

The Mission Possible Partnership is an alliance of climate leaders focused on supercharging efforts to decarbonise some of the world's highest-emitting industries in the next 10 years.