Segments, strategies and uncertainties: recent evidence on low-carbon technologies for commercial vehicles

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Key messages

- **Context and strategic interests shape low-carbon technology pathways.** National priorities, legacy industries, existing infrastructure and geopolitical relationships are critical in determining which technologies scale. These factors directly affect infrastructure roll-out, access to cost-competitive energy and the availability of advanced technologies.

- **Cost competitiveness of long-range low-carbon trucks remains uncertain.** Battery electric trucks (BETs) have a clear technological lead, but studies show mixed results on total cost of ownership (TCO) for long-range trucks. Differences in assumptions about purchase costs, technology maturity, and the costs of energy and infrastructure make the relative cost competitiveness of technological alternatives highly variable.

- **Diversification vs scale in the decarbonization race.** Original equipment manufacturers (OEMs) are justified in pursuing multiple pathways to avoid technological lock-in and policy misalignment. However, diversification must be balanced against the economies of scale required for economic viability and the urgency of deep decarbonization, where battery electric vehicles (BEVs) currently lead in technology maturity and market deployment.

Glossary

BET	Battery electric truck
BEV	Battery electric vehicle
EV	Electric vehicle
FCET	Fuel cell electric truck
FCEV	Fuel cell electric vehicle
H2ICET	Hydrogen internal combustion engine truck
OEM	Original equipment manufacturer
TCO	Total cost of ownership
ZEV	Zero-emission vehicle

Cover image credit:

Fuel cell electric hydrogen truck / Volvo

1. Potential solutions for decarbonizing commercial transport

Commercial road transport accounts for a small share (5%) of the global vehicle stock but a disproportionately large portion (37%) of road-transport CO2 emissions (Sen et al., 2025). Accordingly, global ambitions to curb these emissions are increasing, with 38 nations – representing 27% of medium- and heavy-duty vehicle sales – signing the Global Memorandum of Understanding on Zero-Emission Medium- and Heavy-Duty Vehicles (Sen et al., 2025). This landmark agreement aims to accelerate the adoption of zero-emission vehicles (ZEVs), targeting 30% of all new truck and bus sales by 2030 and 100% of new sales by 2040 (MacDonnell & Kodish, 2024).

Initial progress in sales of low-carbon commercial vehicles has, for the most part, been driven by battery electric vehicles (BEVs) (BloombergNEF, 2024). Battery electrification is widely regarded as the most mature and cost-effective ZEV technology for commercial vehicles (IEA, 2025a). However, it remains uncertain whether BEVs can be competitive across all use cases, particularly in long-range applications. This uncertainty is further influenced by regional market conditions, which vary globally with differences in fuel and electricity prices (Horesh et al., 2024). With adequate charging infrastructure, BEVs can also compete in the heaviest commercial-vehicle segments (Nykvist & Olsson, 2021). Nevertheless, their limited range makes them a less flexible option for transport operators and leaves them reliant on highly utilized charging networks and well-developed electricity grids.

Hydrogen fuel cell electric vehicles (FCEVs) have long been discussed as a ZEV option (Azar et al., 2003). While FCEVs offer longer ranges and fast refuelling, costs are still high, and so far, they account for only a small share of the ZEV market (IEA, 2025a). Although costs for both BEVs and hydrogen FCEVs have rapidly declined, analyses indicate that hydrogen FCEVs remain significantly more expensive than BEVs and that FCEVs were only able to enter the market much later, after reductions in fuel cell and hydrogen fuel costs (IEA, 2025a; Link et al., 2024). Other commercially available solutions include biofuels; however, resource constraints and sustainability concerns may limit their role to niche applications, such as markets where biomass can be produced sustainably and at low cost, or where strong public incentives encourage adoption (Muratori et al., 2023).

Moreover, another low-carbon option attracting growing attention is the use of hydrogen as a fuel in hydrogen internal combustion engine vehicles, particularly in heavy-duty and long-range applications. This technology has been identified as a strategic priority in China's long-term hydrogen development plan (Xue et al., 2025). Globally, several original equipment manufacturers (OEMs) are exploring this technology. These include Ashok Leyland (Ahluwalia, 2023), Tata Motors (Tata Motors, 2025), Volvo Trucks (Volvo Trucks, 2024), MAN Truck & Bus (Amann & Carey, 2024), Cummins (Cummins, 2025), Daimler Truck (Daimler Truck, 2024), PACCAR and DAF Trucks (Lockridge, 2023), as well as Scania and Westport (Heavy Duty Trucking, 2023). Around 40 such vehicles were projected to enter the commercial market in 2024, primarily in India (Parkes, 2024). However, evidence of actual registrations remains limited. These developments suggest that OEMs are pursuing multiple technological pathways towards low-carbon heavy-duty transport.

This raises important questions: why is another low-carbon heavy-duty technology attracting growing attention, and why do OEMs continue to invest resources across multiple alternatives when BEVs are advancing more quickly in both technological development and market adoption? Indeed, while hydrogen internal combustion engine vehicles may offer a viable alternative to hydrogen FCEVs in market segments where decarbonization is harder to achieve with BEVs, pursuing diverse technological pathways could risk slowing overall pace of decarbonizing commercial transport.

This report aims to explain why OEMs are pursuing multiple technological pathways towards low-carbon heavy-duty transport by examining some of the factors influencing the viability of different technologies. We review recent research, reports and policy developments to compare insights from total-cost-of-ownership (TCO) analyses and to consider how geopolitical, industrial and geographic contexts shape preferences for certain technologies.

2. Key assumptions driving cost competitiveness

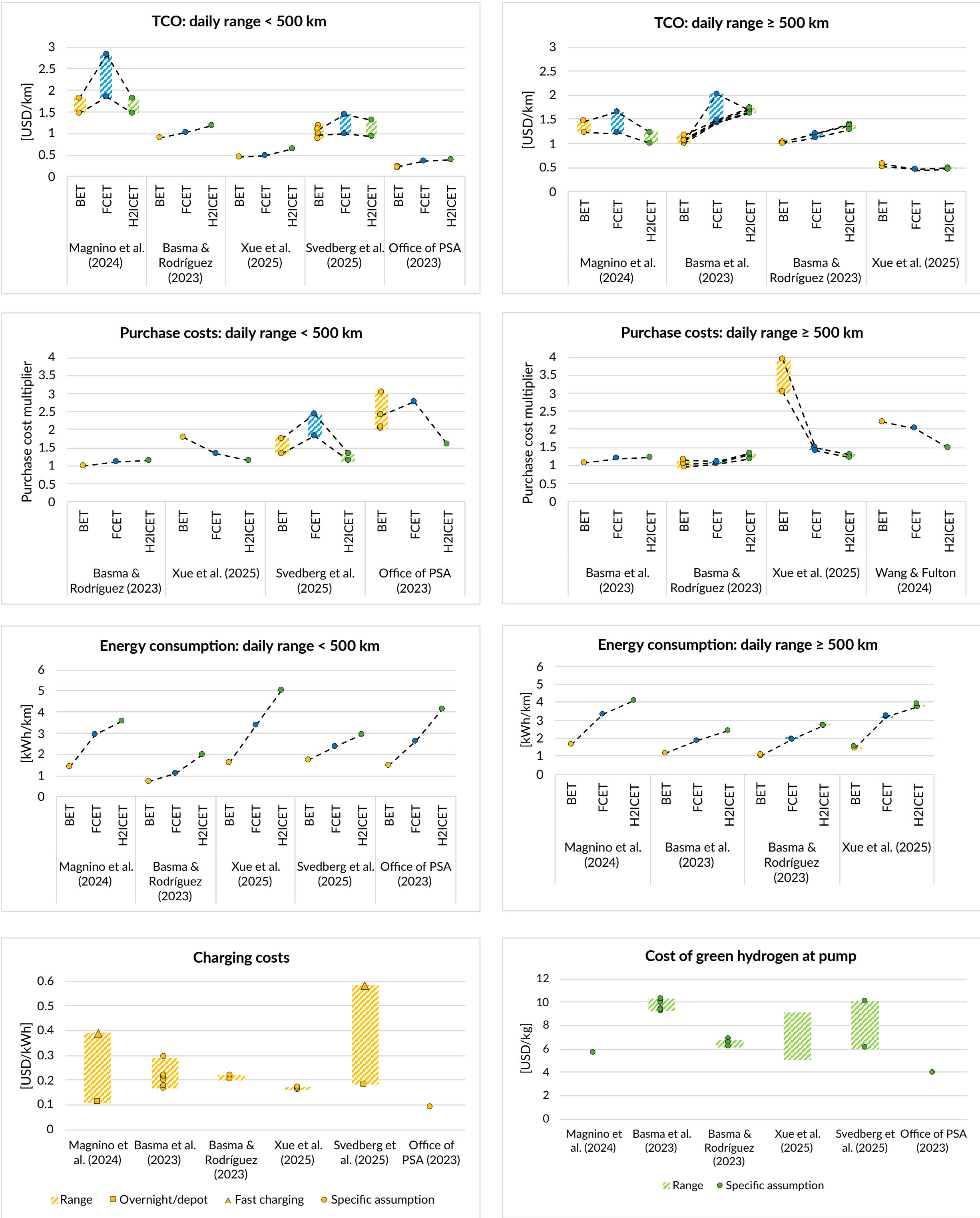
As TCO analyses are sensitive to assumptions, we chose to focus on studies comparing all three alternatives, examining battery electric trucks (BETs), hydrogen fuel cell electric trucks (FCETs) and hydrogen internal combustion engine trucks (H2ICETs). Figure 1 demonstrates that BETs have the lowest TCO for daily ranges under 500 kilometres. For daily ranges above 500 km – representative of longer-range applications – the results are more balanced across technologies. The TCO ranges are as follows: USD 0.5–1.5/km for BETs, USD 0.5–1.75/km for H2ICETs and USD 0.5–2 /km for hydrogen FCETs. The relatively narrow, overlapping ranges indicate that H2ICETs can be cheaper than, or at least on par with, hydrogen FCETs. In some cases, they are in fact less costly than BETs. Depending on the assumptions made in each study, this leaves room for H2ICETs to emerge as a cost-competitive alternative. For example, Magnino et al. (2024) report favourable TCOs for H2ICETs, as do Xue et al. (2025) in the context of long-range use cases. It is important to note, that these studies assume optimistic hydrogen pump prices, ranging from USD 6 to 7/kg. When a higher price of USD 10/kg is assumed, H2ICETs become uncompetitive (e.g. Basma et al., 2023).

Furthermore, assumptions about vehicle purchase costs are also crucial in determining which technology is the most cost-competitive. However, studies vary in their assumptions about which technology has the lowest purchase costs (e.g. Basma & Rodríguez, 2023; Wang & Fulton, 2024). In analyses conducted by Magnino et al. (2024) and Xue et al. (2025), H2ICETs emerge as the cheapest alternative, largely due to assumptions regarding mid-life battery and fuel cell stack replacement. By contrast, other studies suggest that such replacements are not required for commercial BETs to be cost-competitive (Nykvist & Olsson, 2021). The study by Basma et al. (2023) identifies BETs as the most competitive alternative, primarily because it assumes subsidized purchase prices for BETs, making them cheaper than H2ICETs – an assumption relatively uncommon in other studies. Adopting a similar study approach, Basma & Rodríguez (2023) find that even when lower hydrogen pump prices are assumed, BETs remain more competitive due to their lower, subsidized purchase costs; in other words, purchase-cost assumptions outweigh the effect of cheaper hydrogen. Likewise, studies such as Svedberg et al. (2025) show that high purchase-cost assumptions make hydrogen FCETs appear the most expensive alternative. At the same time, projections of declining fuel cell costs suggest that hydrogen FCETs could emerge as the most cost-competitive option in the future (Xue et al., 2025).

Broadly speaking, the less advantageous fuel economy of H2ICETs generally results in a higher TCO. This occurs, for instance, when pump prices for green hydrogen are assumed to be relatively high, around USD 10/kg (e.g. Svedberg et al., 2025). However, this outcome is also evident under other assumptions: when studies assume both low electricity costs and relatively low pump prices for green hydrogen (e.g. Office of PSA, 2023), the impact of H2ICETs' higher fuel consumption – around 2.5 times that of BETs and 1.4 times that of hydrogen FCETs (see Figure 1, energy consumption) – still outweighs the higher purchase costs of BETs.

Additionally, techno-economic assumptions in both the academic and grey literature vary considerably, with significant implications for TCO analyses. On average, BETs appear more competitive, including in applications with daily ranges exceeding 500 km, though only by a small margin. It therefore remains unclear which alternative is most suitable. In the next section, we look more closely at the factors that may influence this variation in assumptions.

Figure 1. Comparison of key assumptions across TCO studies.



Purchase cost multiplier indicates a truck's purchase costs relative to those of a comparable diesel internal combustion engine truck.

3. Globally varying market conditions

The literature confirms that BETs are cost-competitive for trucks covering shorter distances, but hydrogen-fuelled trucks may be suitable where driving conditions are challenging, operating schedules and charging infrastructure are constrained (with limited downtime) or payload capacity is crucial (Magnino et al., 2024; Office of PSA, 2023; Svedberg et al., 2025; Xue et al., 2025). The forestry sector exemplifies such a niche: increasingly heavier trucks, transient driving cycles, demanding terrain and dynamic routing create complex challenges for vehicle energy consumption and charging access (Iyer et al., 2025). Notably, in Sweden – a country with substantial forestry activity – such use cases account for over 20% of greenhouse gas emissions from heavy-duty transport (Iyer et al., 2025). In these conditions, both BET and hydrogen-fuelled vehicles are a potential solution, as explored by Lundblad et al. (2022).

The techno-economic analyses studied in this report show that there is potential for all alternative technologies to be cost-competitive in such niche segments. However, uncertainties remain regarding energy and infrastructure costs and access, the market access to competitive battery technology and the level of support for alternatives. Accordingly, national strategies, industrial policy decisions and the geopolitical landscape also help shape the conditions that favour one alternative over another, particularly when it comes to scaling charging networks and green hydrogen refuelling infrastructure, as well as ensuring technology access.

3.1 Refuelling infrastructure and industrial synergies

Hydrogen use in heavy-duty and long-distance road transport can play a strategic role in energy transitions. The results above highlight the importance of securing cost-effective hydrogen supply, while the nascent state of hydrogen refuelling infrastructure, with slowing growth in deployment (IEA, 2024), remains a significant challenge to the wider adoption and scaling of hydrogen-fuelled trucks. In their study, Xue et al. (2025) note the increasing prominence of hydrogen in China's energy transition, with several policies and incentives supporting its use in transportation. Indeed, of the 12 900 hydrogen FCEVs sold globally in 2024, more than 7000 were in China (Collins, 2025).

The use of hydrogen in transport is also likely to rely on synergies across industrial sectors to accelerate the development of green hydrogen supply, infrastructure and value chains. Large scale and integrated supply and demand in sectors such as the steel and chemical industries can help scale up investment in infrastructure for hydrogen production and storage (Kountouris et al., 2024). This, in turn, can lower costs and improve availability, benefiting multiple end users, including the transport sector. Beyond China, regions with abundant renewable energy resources are emerging as possible front-runners in the green hydrogen economy. Chile, for instance, aims to become one of the world's leading green hydrogen exporters by 2040 (IEA, 2025b). The country's National Green Hydrogen Strategy has prioritized heavy-duty road transport – along with ammonia production, oil refineries and the electricity grid – as key application areas in its first wave, with the aim of building up domestic supply chains (Ministry of Energy, Government of Chile, 2020). Similarly, the first phase of India's National Green Hydrogen Mission proposes to focus on developing domestic green hydrogen production and uptake, including undertaking pilot projects concerning long-haul heavy-duty transport and steel production (Ministry of New and Renewable Energy, Government of India, 2023). As part of this mission, five pilot projects using hydrogen fuel cell and hydrogen internal combustion engine vehicles have already been sanctioned by the Ministry of New and Renewable Energy (Sreejith, 2025).

3.2 Access to alternative technologies

The TCO analysis points to uncertainties regarding the purchase price of technology alternatives, stemming from both upfront costs and recurring expenses associated with component replacements during overhauls. While subsidy assumptions for different vehicle technologies vary across studies and have clear economic impacts, assumptions about battery and fuel cell lifetimes are particularly significant for cost estimates, especially in long-range applications (Magnino et al., 2024; Xue et al., 2025).

More broadly, uncertainties surrounding technological advancements and market access to these are key factors influencing cost competitiveness. In the European Union, concerns about strategic dependencies and unfair competition have prompted the introduction of measures to regulate foreign electric-vehicle (EV) entry, with a view to protecting EU BEV producers (European Commission, 2024). However, this may not only increase the cost of EVs but also delay innovation and access to the most advanced BEV technologies, potentially slowing the EU's green transition (Dadush & McCaffrey, 2025).

By contrast, Thailand and Indonesia have pursued strategies that encourage foreign investment in local production, aiming to improve access to advanced technologies in order to accelerate their ambitions of becoming EV manufacturing hubs. In both countries, foreign automotive manufacturers must commit to starting local BEV production to remain eligible for tax exemptions and subsidies on personal EV imports (IEA, 2025a). In Thailand, this approach is embedded in the "30@30" policy, which has set a target for 30% of domestic vehicle production – including battery manufacturing – to be electric by 2030 (The Nation, 2021). This strategy relies largely on foreign direct investment (Intarakumnerd & Charoenporn, 2024), with recently approved measures including tax reductions to promote the adoption of electric trucks and cash grants to support battery cell manufacturing (Thailand Board of Investment, 2024). The lack of turnkey-ready hydrogen-fuelled trucks is another hurdle to consider, as retrofitting or converting vehicles can be both costly and time-consuming (Svedberg et al., 2025).

3.3 Location, location, location

While strategic motivations play a decisive role in promoting hydrogen-fuelled or electric vehicles, commercial BEV adoption remains contingent on a stable electricity system and robust charging infrastructure. The challenges involved in achieving these conditions, however, vary around the globe. For example, in Europe and the United States, the main challenges involve permitting and siting charging infrastructure, upgrading the electricity grid to ensure access (Herlt et al., 2024; US Department of Transportation, 2025), and managing system impacts that arise from integrating the transport and electricity sectors (Muratori et al., 2023). In the broader context of low- and middle-income economies, other key hurdles include a lack of detailed strategies and policy frameworks for charging infrastructure, a lack of infrastructure standards, as well as challenges in establishing reliable electricity supply – areas that are often prerequisites for clear investment signals (Tankou et al., 2023). Thus, the difficulty of establishing robust charging networks differs across geographical contexts and, when combined with strategic interests in specific technologies, may influence why certain markets evolve along particular technological pathways.

Additionally, both geography – including the physical landscape, which determines transport distances – and the nature of a country's existing industrial base can shape strategies for accessing various technologies. For example, Thailand's lack of domestic expertise in upstream battery production creates opportunities for exporters and foreign direct investment (US International Trade Administration, 2024). As a member of the Association of Southeast Asian Nations, with geographical proximity to China and economic partnerships with both American and Chinese markets, Thailand is also well positioned to benefit from rerouted production. Such shifts are evident in the "China Plus One" strategy, which encourages manufacturers in China to diversify supply chains (Maciejewska & Alifandi, 2023), and in efforts by Chinese producers to bypass US tariffs – though recent tariff announcements may constrain this (Loh, 2025).

4. Technology timelines

The literature on low-carbon commercial trucks now anticipates that H2ICETs will have a cost advantage over hydrogen FCETs in the near term, owing to their lower capital costs and their ability to draw on legacy industries' engineering expertise, supply chains and production capacities (Xue et al., 2025). At the same time, technological advancements in fuel cell systems are expected to help mitigate their durability limitations and offset the high upfront costs of hydrogen FCETs (Magnino et al., 2024). Adopting hydrogen FCETs and H2ICETs as complementary solutions could therefore serve to accelerate the scaling and market penetration of these technologies. Indeed, both rely on the same refuelling infrastructure and hydrogen tank technology, and adopting them in parallel may help de-risk investments and facilitate the growth and availability of hydrogen refuelling stations and lower hydrogen pump prices, as well as foster technological advancements and cost reductions across the two powertrain systems.

While hydrogen-fuelled vehicles address many of the current limitations associated with battery technology – such as range, refuelling time and load capacity – they remain at a much earlier stage of development and deployment compared with BEVs. Drawing on decades of technological learning from passenger cars, BETs have benefited from key advancements in technology and associated cost reductions (Muratori et al., 2023), and BEV technology continues to develop. In its 2030 projections for long-range commercial vehicles, the (IEA, 2025a) estimates that batteries will account for about 35% of BETs' upfront costs. Yet in hydrogen FCETs, fuel cell systems and hydrogen storage tanks together are expected to make up around half of all upfront costs (IEA, 2025a).

Moreover, all of the technologies studied here require significant expansion of supporting infrastructure. For hydrogen, refuelling infrastructure could benefit from synergies between hydrogen FCETs and H2ICETs, as well as with other industrial sectors – evidently, this may be an area of strategic interest in countries pursuing hydrogen strategies. Realizing this potential, however, is not an easy task, as it involves building a hydrogen economy from scratch. Expanding and advancing charging infrastructure also presents significant challenges, though such developments can benefit from existing electricity grids. All in all, BET charging infrastructure is less costly than hydrogen refuelling infrastructure in the three current leading markets for BETs and hydrogen FCETs – China, the EU and the US – where refuelling infrastructure accounts for around 3–10% of the TCO for BETs and around 10–15% of that for hydrogen FCETs (IEA, 2025a).

Lastly, from an emissions perspective, it should be noted that while hydrogen internal combustion engine vehicles are low-carbon, they do not eliminate tailpipe emissions entirely, unlike BEVs and hydrogen FCEVs (Muratori et al., 2023). High combustion temperatures generate nitrogen oxides, and CO2 trail emissions from lubricating oil persist. Achieving near-zero tailpipe emissions thus requires aftertreatment, optimized engine design and specific combustion modes (Bibiloni-Ipata et al., 2025; Turner, 2025). In addition, emissions associated with the local electricity grid and hydrogen supply should also be considered when assessing each technology's role in decarbonizing commercial vehicles.

5. Conclusions

Commercial transport is complex, with a broad range of use cases. Given this diversity in demand, it is important to recognize that no single low-carbon technology is universally optimal or able to capture the entire market. Indeed, the choice between technologies such as BEVs, hydrogen FCEVs, and hydrogen internal combustion engine vehicles depends on how the technologies will develop and matching the right technology to its use case, as well on infrastructure considerations. Emerging literature comparing the TCOs of BETs, hydrogen FCETs and H2ICETs suggests that H2ICETs and BETs may be the most cost-competitive options for long-range applications. Nevertheless, significant uncertainties remain due to varying assumptions about vehicle purchase costs, technology maturity, energy prices and supporting infrastructure.

These factors are likely to be shaped by local market conditions and the broader geopolitical context. This report examined strategic national interests in specific infrastructures and technologies, the prevalence of legacy industries, existing infrastructure and economic partnerships as examples of contextual factors that play a critical role in how markets evolve towards particular technologies. Such factors may also influence the scaling of supporting infrastructure and access to cost-competitive energy, as well as the access to and affordability of advanced technologies required to decarbonize commercial transport in a feasible manner.

For these reasons, OEMs' hesitancy to commit to a specific technological pathway, choosing instead to pursue multiple alternatives, remains justified. Diversification helps them avoid "putting all their eggs in one basket" and missing out on future viable solutions, thereby reducing the risk of technological lock-in. Yet decisions on where to invest are clearly guided by infrastructure build-out, national strategies, and adherence to local policy priorities. Moreover, maintaining a broad portfolio of technological solutions is important for addressing a diverse range of use cases and geopolitical contexts.

However, the rationale for such diversification is challenged by the economies of scale required to make these pathways economically viable. Among ZEV technologies, BEVs currently lead in maturity and technological deployment, while continuing to experience rapid development and cost reductions. Further, it is important not to lose momentum when pursuing a deep-decarbonization trajectory. Hydrogen-fuelled vehicles may still find niches in markets with strong decarbonization ambitions and clear roadmaps for developing a hydrogen economy, particularly where electricity infrastructure is limited. But a key question for hydrogen is if refuelling infrastructure can scale cost effectively and rapidly enough. Finally, it is important to remember that maintaining multiple technological pathways risks slowing progress towards meeting decarbonization timelines set by the 2015 Paris Agreement.

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