



## BRIEFING PAPER

# Thematic Deep Dive Series 1: Technology Readiness and Economics of Technologies

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This Briefing Paper on the Technology and Economics of zero-emission medium- and heavy-duty vehicles (ZE-MHDVs) has been developed to support the Multi-Country Action Plan development process for countries who have signed the Global Memorandum of Understanding (MOU) on Zero-Emission Medium- and Heavy-duty Vehicles. It is intended to inform and provide guidance and resources to governments on strategies they can undertake to drive rapid deployment of ZE-MHDV to ensure the strategic and sequenced rollout of technologies and targeted deployments of capital and innovative financing mechanisms.

## **Key Takeaways**

- **ZE-MHDVs are operationally ready to tackle the majority of duty cycles today.** Present ranges meet or exceed the ranges required by most routes for trucks, buses, and vans on the road. These vehicles also have hauling capacity comparable to their ICE counterparts, and losses in freight efficiency due to extra weight of batteries can be mitigated through weight exemption policies—already introduced in the US and EU.
- **The economics and TCO of ZE-MHDVs are already favorable in select segments in certain regions today.** All electric vehicles segments are expected to break the TCO parity threshold by 2030 according to most current research studies. The economic advantages of ZE-MHDVs are already proving themselves in select regions with favorable conditions. Urban vehicles and those with lighter, regional duty cycles are well positioned to reduce costs for fleets who are looking to save on fuel and reduce emissions.
- **Coordinated stakeholder action will accelerate the technology commercialization pathway.** With governments stepping up ambition at COP 26, and manufacturers pledging to shift their products toward zero-emission solutions, there is an industry-wide recognition that ZEVs are the future. The beachhead strategy provides directional guidance through a phased approach to technology commercialization that requires the buy-in of stakeholders across the value chain. Without the support of more countries, the private sector, and

NGOs progress will not reach its maximum potential.

## **Urgency for Action on ZE-MHDV Technology**

### *Global Context*

Globally, MHDVs (medium- and heavy-duty vehicles—like trucks and buses) represent about 4% of the on-road fleet but are responsible for approximately 36% of on-road fuel consumption and respective GHG emissions. These vehicles emit 73% of on-road nitrogen oxide (NOx) emissions and 60% of particulate matter (PM2.5) emissions, which result in smog-forming air pollution and have detrimental impacts to human health (CALSTART, 2020).<sup>1</sup> Based on the data, MHDVs add a disproportionate share of pollution to the mix when compared to passenger cars and other light-duty vehicles. Considering these facts, it is a high priority to address key areas of concern regarding MHDV decarbonization and to clarify the outdated narratives surrounding technology readiness and economics of available technologies. This briefing will present the status of the zero-emission technologies available on the market and coming soon, as well as related economics that drive the uptake and deployment of such vehicles.

## **ZE-MHDV Technology Types, Timing, and Commercialization Pathways**

### *Types of ZE-MHDV Technologies*

This report focuses on the technology and economics of vehicles with no tailpipe emissions that are powered by electric batteries or hydrogen fuel cells. These vehicles represent the most promising and impactful technologies to combat the rising climate and criteria (air quality)

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<sup>1</sup> <https://globaldrivetozero.org/site/wp-content/uploads/2020/12/Moving-Zero-Emission-Freight-Toward-Commercialization.pdf>

emissions from the transportation sector.<sup>2</sup> Low emission and “fossil free” combustion options exist, such as methane combustion vehicles (commonly known as natural gas) making use of renewable sources of methane. But limits to renewable fuel feedstocks combined with production and distribution system leakage (methane is 20 times more potent as a greenhouse gas than CO<sub>2</sub>) and criteria pollutants from combustion make these fuels and strategies most useful during transition.<sup>3</sup> This report will illustrate that battery electric and fuel cell technology is available to match most ICE segments today. Given the extremely short timeframes remaining to reduce climate emissions and urban pollution, policy makers and industry must avoid distractions and focus on achieving full zero emission penetration by 2040 to meet climate outcomes. A scattershot approach will divert critical resources and dilute investments needed for a full transition.

**Battery-Electric Vehicles** – Or “BEVs” are vehicles whose propulsion system is powered by an electric battery. The electric motor(s) draw power from the battery to drive the vehicle. While the specific battery chemistry and type of motor may differ by region or brand, these vehicles emit no emissions and can even be safely operated indoors and in enclosed spaces. BEVs must be refueled through electrical charging equipment,

the most common of which is a plug-in system.<sup>5</sup>

- **Hydrogen Fuel Cell Electric Vehicles** – Or “FCEVs” are vehicles whose primary propulsion system is powered by an on-board fuel cell, often accompanied by a small battery. There are several different types of fuel cells, but the most common in transportation applications are known as polymer electrolyte (or proton exchange) membrane fuel cells (PEM). These fuel cells take advantage of a chemical reaction between hydrogen fuel, a catalyst, and oxygen to produce electricity, with the only biproduct being steam or water, making them a zero-emission solution. FCEVs must be refueled using compressed or liquefied hydrogen at a designated refueling station.<sup>6</sup>

#### *Road to Commercialization*

**ZE-MHDV segments have advanced toward commercialization at different rates.** Accurately assessing how close each ZE-MHDV segment is to commercialization is important for identifying policies and actions that will help develop supportive ecosystems for specific vehicle types. The advancement of each vehicle segment and technology will support the acceleration of the broader ZE-MHDV market due to the relative simplicity of ZE-MHDV vehicles that use fewer and more typically transferrable components

2 [https://ww2.arb.ca.gov/sites/default/files/2022-04/CARB%20-%20End%20of%20Useful%20Life%20Scenarios%20-%20STWD%20Summary\\_ADA.pdf](https://ww2.arb.ca.gov/sites/default/files/2022-04/CARB%20-%20End%20of%20Useful%20Life%20Scenarios%20-%20STWD%20Summary_ADA.pdf)

3 <https://www.epa.gov/gmi/importance-methane#:~:text=Methane%20is%20the%20second%20most,trapping%20heat%20in%20the%20atmosphere>

4 <https://www.mdpi.com/1660-4601/15/2/304>

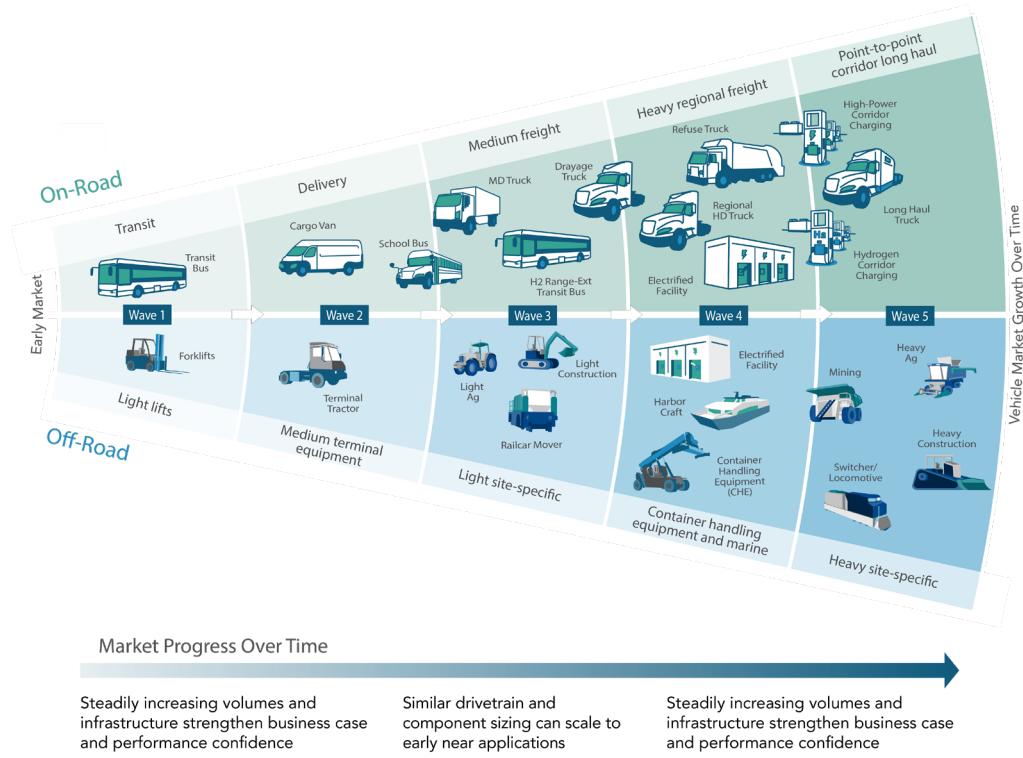
5 [https://afdc.energy.gov/vehicles/electric\\_basics\\_ev.html](https://afdc.energy.gov/vehicles/electric_basics_ev.html)

6 [https://afdc.energy.gov/vehicles/fuel\\_cell.html](https://afdc.energy.gov/vehicles/fuel_cell.html)

than their diesel-powered equivalents.<sup>7</sup> The Zero-Emission Beachhead (Figure 1) predicted that early success in the transit, urban delivery, and other early stage markets will develop initial supply chains and reduce costs, leading to the

deployment of additional and heavier duty applications. This has succeeded. The sequential and progressive nature of these pathways allows for effective planning for fleets, infrastructure, policies, incentives, funding, and use regulations.<sup>8</sup>

**Figure 1.** The Zero-Emission Beachhead



The Beachhead strategy suggests a logical, phased approach to the deployment of ZE-MHDVs across sectors with duty-cycle demand and operational capacity guiding successive market growth. While Figure 1 appears to be segmented into waves, the assumption that

these waves must be carried forward in mutual exclusivity is antithetical to this approach. The Beachhead strategy gives generalized and useful direction to decisionmakers who may not be familiar with the intricacies of new technology but must understand the advantages to sequencing

<sup>7</sup> <https://globaldrivetozero.org/site/wp-content/uploads/2020/12/Moving-Zero-Emission-Freight-Toward-Commercialization.pdf>

<sup>8</sup> [https://calstart.org/wp-content/uploads/2022/04/The-Beachhead-Strategy\\_Final.pdf](https://calstart.org/wp-content/uploads/2022/04/The-Beachhead-Strategy_Final.pdf)

the focus on certain segments as production volumes grow, vehicle efficiencies increase, and costs come down. In many instances the waves of the beachhead strategy have moved forward in parallel.

#### *Operational Capacity*

**ZE-MHDVs today are able to meet most operational range requirements in leading beachhead segments.** Numerous studies quantifying both the specific range requirement for ICE-MHDV segments and the reported operational range of comparable ZE-MHDVs have concluded that from an operational

perspective, ZE-MHDVs are ready to be deployed now. This reality is reflected in growing sales and deployments in first markets worldwide. Using data from the U.S. Department of Energy's National Renewable Energy Laboratory (NREL), researchers characterized operational ranges of several relevant MHDV vocational segments. Another study from the North American Council for Freight Efficiency's (NACFE) Run on Less – Electric program also characterizes the range and payload requirement.<sup>9</sup> This information is summarized below in *Table 1* that also includes examples of ZE-MHDV models available today and their respective specs.

**Table 1.** Characteristic operational requirements for MHDVs with examples for available ZE-MHDV models (2022)

SEGMENT	VEHICLE TYPES	DAILY DRIVING DISTANCE	PAYOUT REQUIREMENT	TECHNOLOGY READINESS LEVEL	AVAILABLE ZEVs + CAPACITY
<b>Long haul Trucking</b>	Tractor (U.S. Class 7/8)	1,606 km/1,000 mi	Up to 18,144 kg/40,000 lbs lbs18,144kg/40,000 lbs	TRL 7/8	Hyundai XCient (800km, 36,000kg GCWR) Daimler eActros (400km, 25,000kg GCWR) Futuricum FH (760km, 42,000 kg GCWR)
<b>Regional Haul Trucking</b>	Tractor (U.S. Class 7/8)	>480-km/300-mi	Up to 18,144-kg/40,000-lbs	TRL 8	PACCAR 579EV (321km, 36,000kg GCWR) Volvo VNRe (443km, 37,000kg GCWR) Nikola Tre BEV (560km, 37,000kg GCWR)

<sup>9</sup> <https://nacfe.org/run-on-less-electric-report>

<b>Urban Logistics Operations</b>	Logistics/cargo vans (U.S. Class 2b/3)	80 km/50 mi (Cargo Vans)	1,905 kg/4,200 lbs	TRL 9	Ford eTransit (200km, 4,300kg GVWR) Greenpower EV Star (240km, 6,500kg GVWR)
	Step vans (U.S. Class 3-6)	160-km/100-mi (Urban Delivery)	4,572 kg/10,080-lbs	TRL 9	Daimler MT50e (270km, 8,600kg GVWR)
	Straight trucks (U.S. Class 3-8)	>160-km/100-mi (Straight trucks)	6,804-kg/15,000-lbs	TRL 9	Navistar eMV (217km, 37,000kg GCWR) PACCAR EV220 (400km, 15,000kg GVWR)
<b>Urban Transit</b>	Transit buses (U.S. Class 3-8)	>300 km/185 mi	N/A	TRL 9	Proterra ZX5 (529km) BYD K8M (270km) MAN Lion City E (270km)
<b>Terminal Tractors</b>	Drayage tractors (U.S. Class 7/8)	80 to 160-km/50 to 100-mi	Up to 18,144-kg/40,000-lbs	TRL 7/8	BYD 8Y/8T (200km, 47,500 kg GCWR) Kalmar T2E+ (11hrs, 36,700kg GCWR) Orange EV T-Series (22 hrs, 36,700kg GCWR)

Source: *Zhang et al., NACFE Run on Less Electric, CALSTART 2013*

**Planned deployments must consider local operational and environmental features.** Applied research is vital in providing important industry benchmarks and indicators but will never be perfect in determining real-world details. Further specific analyses must always be carried out, taking regional environmental factors (such as extreme weather) and logistics pattern into account. In many instances, especially depending on the country, these vocational distances will be

shorter, but there are also cases where they will be longer. Beyond the examples offered in *Table 7*, the majority of ZE-MHDV models in the zero emission technology inventory database (ZETI) showed sufficient payload capacity and range to meet the requirements of their ICE counterparts across most segments.<sup>10</sup> A noteworthy element to highlight however, is that zero-emission vehicles tend to weigh more due to the added mass of the battery or fuel cell equipment on board, which

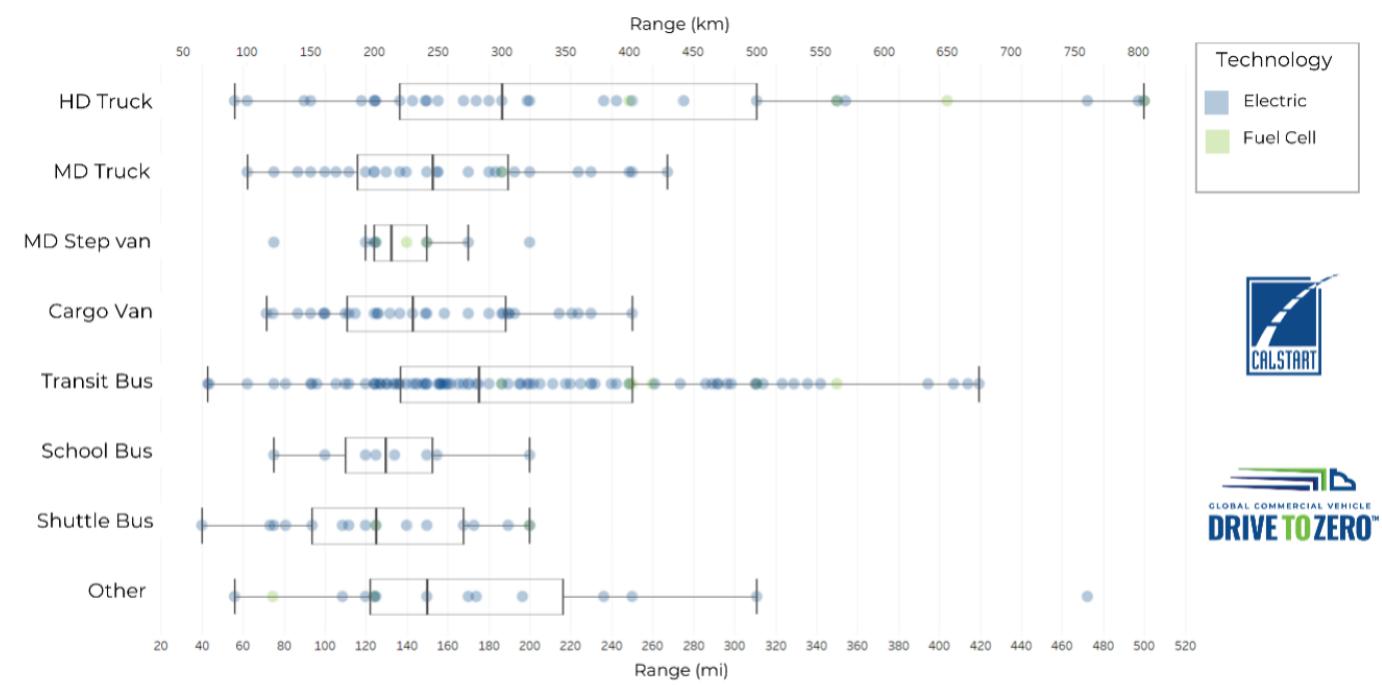
<sup>10</sup> <https://globaldrivetozero.org/tools/zero-emission-technology-inventory>

may impact total cargo capacity determined by weight limitations. In most operations, however, few trucks carry their maximum weight loads. In addition, regions such as the U.S. and E.U. have adopted compensating weight limit exemptions for ZE-MHDVs that will enable these vehicles to

carry cargo equal to a comparable diesel truck.<sup>11 12</sup>

The following figure represents current data from OEMs in leading markets and illustrates the broad selection of models and respective vehicle ranges available for acquisition today.

**Figure 3. ZE-MHDV Range by Segment**



**Long-haul technology race is still to be decided.** There is a common assumption amongst some decisionmakers that hydrogen fuel cell vehicles will ultimately perform the majority of long-haul duty cycles. However as the technology advances and battery electric ranges increase each year, the relative split between BEV and FCEV in these applications is still open. It is most likely that issues such as infrastructure investment and fuel cost will be as important in the decision. For policy makers, the key issue is not to wait but rather

to encourage a complementary transportation system. Both fuel sources rely on the same core powertrain design and architecture. While it is true in the near term that FCEVs can generally achieve longer ranges from a single refueling, compared to their BEV counterparts, rapid advancements in battery technology have continued to expand the operational radius of battery-electric vehicles. Moreover, promising developments in high-capacity mega-Watt charging to support corridors in Europe and the

11 [https://ops.fhwa.dot.gov/Freight/pol\\_plng\\_finance/policy/fastact/tswprovisions2019/index.htm](https://ops.fhwa.dot.gov/Freight/pol_plng_finance/policy/fastact/tswprovisions2019/index.htm)

12 <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32015L0719>

U.S. have the potential to make battery-electric long-haul trucking a reality without the need for thousand-mile ranges or enormous batteries.<sup>13</sup> <sup>14</sup> These innovations would allow a class 7/8 truck to recharge its battery in about 15 minutes, a timeframe comparable to a diesel refueling event. Coupling this with legal requirements for truck drivers to stop and take mandatory breaks every few hundred miles and there is compelling reason to see long haul trucking as not only feasible, but attainable in the near term.<sup>15</sup>

**ZE-MHDVs that are operationally ready for deployment should be prioritized.** Using the guidance and direction of the beachhead strategy to inform the approach to vehicle segmentation can lead to faster and more successful early deployments. These targeted deployments in conducive and proven vocational settings can result in more efficient operations, cleaner air, and cost savings for fleets. As a result, more infrastructure, knowledge, and awareness will be established as greater volumes of ZE-MHDVs penetrate the market, all elements that are critical to reaching market saturation. Be aware, however, that most of the beachhead applications have now “launched” and the corresponding vehicles are available to most regions worldwide. Economics will increasingly play the bigger role.

While it is important to understand the technology status, the equally important piece is understanding the economics behind the technology. There is industry-wide optimism

on total cost of ownership (TCO) and the rapidly declining costs of critical components that make certain segments more cost efficient today.

## **Economics of Zero-Emission Vehicle Technology**

### *Total Cost of Ownership*

**Total Cost of Ownership (TCO) helps fleets understand the lifetime costs of a vehicle.** Unique from the decarbonization of light-duty vehicles, from a fleet's perspective, commercial vehicles are viewed as working capital assets. Thus, beyond operational characteristics, ZE-MHDVs must also meet the economic criteria of the fleet's business operations. TCO is a framework for comparing the various costs of a zero-emission vehicle to a combustion engine vehicle. TCO is a more in-depth metric that goes beyond only the upfront cost of a vehicle to understand other costly elements that may affect a fleet's decision. To determine a fleet's TCO, detailed information about a vehicle's usage, maintenance and efficiency must be compiled together with fuel costs. There are many different TCO models that can be employed. Each will provide a slightly different result depending on the level of detail, but broadly TCO calculations will consider two main areas: Capital costs (or upfront cost) and operational costs.

### *Capital Costs*

The capital cost considered in a TCO model refers to the upfront price of acquiring a vehicle.

13 [https://traton.com/en/newsroom/press\\_releases/press-release-16122021.html](https://traton.com/en/newsroom/press_releases/press-release-16122021.html)

14 <https://www.prnewswire.com/news-releases/epri-calstart-receive-cec-funding-to-develop-megawatt-truck-charging-along-california-freight-corridors-301463759.html>

15 <https://eta-publications.lbl.gov/publications/why-regional-and-long-haul-trucks-are>

Capital cost can also refer to the residual value of a vehicle, or its remaining value after several years in operation. In the traditional truck market, there is a robust second or third hand market where fleets have more confidence in the resale value of their vehicle. In the case of ZE-MHDVs, upfront cost at present is almost always higher than the cost of a comparable combustion vehicle. However, leading regions have directed funding towards reducing the costs of acquisition to enable uptake ahead of schedule. California's Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) is a prime example of a program offering these kinds of cost reductions upfront to fleets. Beyond tangible costs like the price of a new vehicle and the residual value of an old vehicle, costs of capital are also important to consider and understand what financing mechanisms are available to smooth the transition.

#### *Operational Costs*

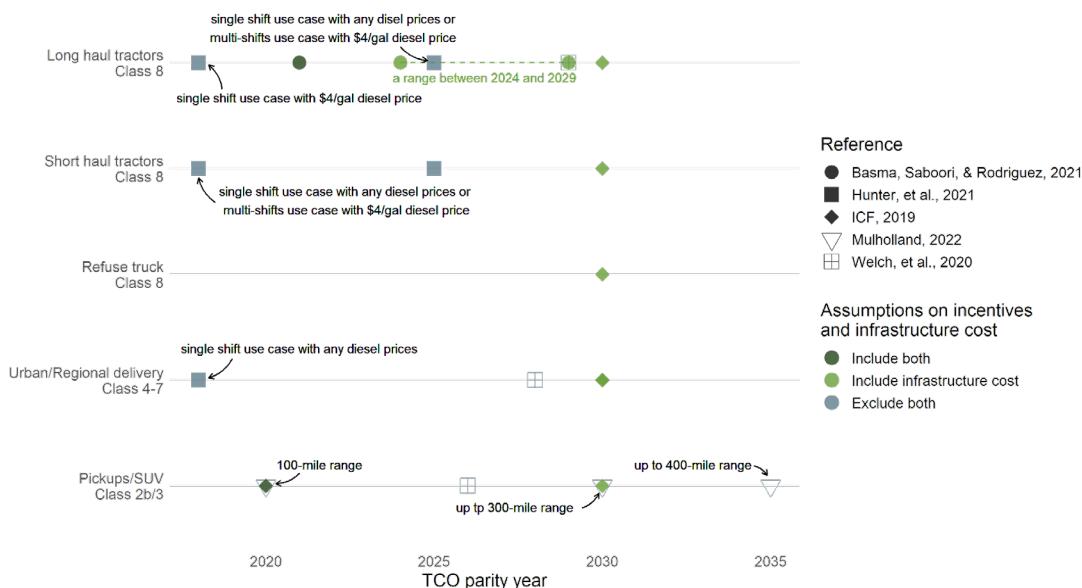
Operational costs refer to the expenses incurred through the use and maintenance of a vehicle. Key areas of focus include fuel costs and repair and maintenance costs. A major advantage of ZE-MHDVs is that they are far less mechanically

complex than diesel and other combustion engine vehicles, significantly reducing the number of components used and streamlining repair and maintenance procedures. The greater efficiency of ZE-MHDVs also bolster their advantageous operational costs and can benefit from technology like regenerative breaking to recapture energy that would have otherwise been lost. For example, savings from greatly reduced brake wear and extending brake life is a known benefit of ZE-MHDVs. When considering the operational costs incurred by a vehicle, understanding metrics like a vehicle's utilization, duty cycle, fuel efficiency, and route characteristics are critical for an accurate result.

#### *Total Cost of Ownership Roundup*

**A synthesis of recent TCO studies show most segments will achieve cost parity well before 2030.** The figure below summarizes several studies on TCO to give greater insight into the intricacies of this calculation. Each of these studies uses different assumptions which are simplified for convenience in the legend. It is important to keep in mind that the policy action of a country will impact this metric in a very significant way.

**Figure 4.** Review of studies on TCO parity year for battery electric trucks



**Regional factors like conducive policy and financial incentives will significantly accelerate the path to cost parity.** Despite the range of estimates on when ZE-MHDVs will achieve cost-parity with ICE vehicles, there is a consensus across research groups and industry that this key benchmark will be reached much sooner than previously projected. In countries with supportive policies and incentives, and conducive logistics patterns and driving environments, the timing to reach cost parity shifts forward significantly. According to one study, countries like the Netherlands, Germany, and France can reach cost parity by the end of 2022 for tractor trailers and other bus and truck segments with the UK, Italy, Spain, and Poland hitting this benchmark by mid-decade.<sup>16</sup> Another recent report highlighted that in areas of Europe electric vans are now cheaper to own and operate than diesel equivalents.<sup>17</sup> The U.S. DOE's National Renewable Energy Laboratory projects that ZECVs will achieve cost parity with diesel vehicles by 2035 for all medium- and heavy-duty vehicle classes without incentives. These projections include a mix of hydrogen FCEVs for longer ranges, and BEVs for ranges under 500 miles.<sup>18</sup> In a study from Lawrence Berkley National Lab, researchers determined that a Class 8 BEV truck with a 375-mile range running a route of 300 miles per day can achieve 13% lower cost of ownership compared to an equivalent diesel model. Additionally, this study showed that the extra costs of acquiring the BEV truck were paid back over 3 years, and over 15 years generated net present savings of \$200,000.

The scale and rate at which regions can achieve

cost parity for ZECVs is heavily dependent on the investments being made now by governments, OEMs, and fleets. Without the right policies, incentives, or targets in place, TCO will be stalled and will not move as quickly as it could. With further developments in global supply chains and manufacturing accelerating in parallel, costs will continue to decline, but it is in the hands of stakeholders to further influence how rapidly that decline will happen.

#### *Economies of Scale*

**Achieving coordination across global regions will allow production to be scaled and costs reduced.** The discussion on techno-economic feasibility would be incomplete without acknowledging the promising trends seen in the manufacturing of expensive vehicle components, namely battery packs. Batteries today are generally the most expensive component for ZEVs. Most analyses forecast a continuing, steady, and steep reduction in the price of battery cells and for full battery pack costs to continue this downward trend as well. Batteries can comprise up to 30% or more of a vehicle's current price depending on the type, weight, and vocation of the vehicle.<sup>19</sup> Battery costs today, on average, hover around \$135/kWh, down significantly from ~\$450/kWh in 2010. The price of batteries has already significantly decreased in the past decade with estimates predicting further price decreases in coming years. Several studies forecast the average prices of battery packs to reach \$94/kWh by 2024 and \$62/kWh by 2030, such as the Bloomberg New Energy Finance estimate shown in the figure below (Bloomberg, 2019).<sup>20</sup>

16 <https://theicct.org/publication/total-cost-of-ownership-for-tractor-trailers-in-europe-battery-electric-versus-diesel>

17 [https://www.transportenvironment.org/wp-content/uploads/2022/03/2022\\_03\\_van\\_TCO\\_report.pdf](https://www.transportenvironment.org/wp-content/uploads/2022/03/2022_03_van_TCO_report.pdf)

18 <https://www.greencarcongress.com/2022/03/20220308-nrel.html>

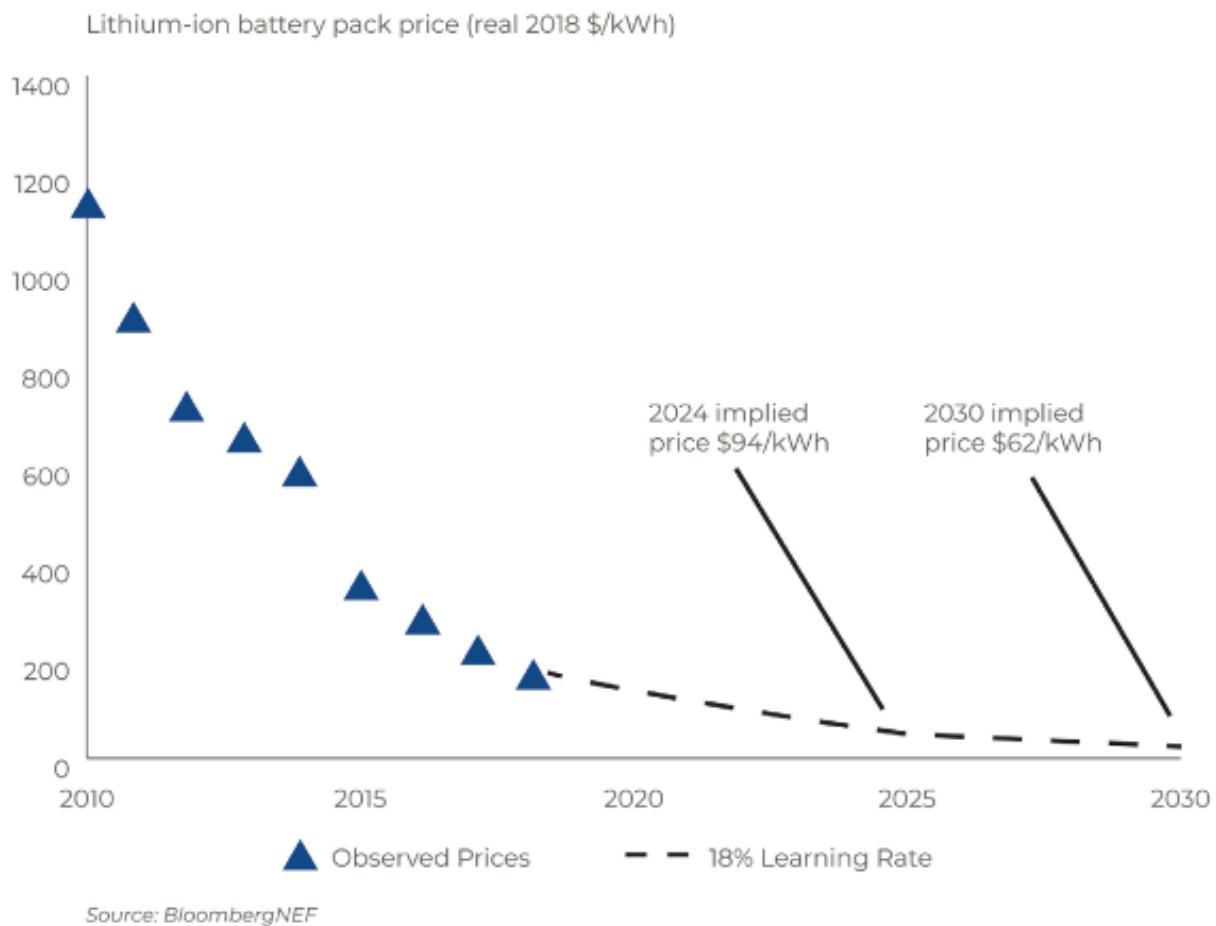
19 <https://www.statista.com/statistics/797638/battery-share-of-large-electric-vehicle-cost>

20 <https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices>

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**Figure 5.** Historic and projected battery price per kWh

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As more manufacturers recognize the value of ZEV technology, their success is tied directly to how quickly advancements can be made and costs can be reduced. This reality is reflected by the commitments made by several high-profile international auto groups. For example, the European Automobile Manufacturers Association, the umbrella organization which includes vehicle manufacturers such as Scania, Daimler, Ford, MAN, DAF, Iveco, and others, announced that by 2040 all new commercial vehicles sold must be fossil-free to ensure

carbon neutrality by 2050.<sup>21</sup> Never before has the industry had this level of alignment, and the momentum catalyzed by these agreements must be turned into swift, strategic action to drive MHDV emissions to zero. The major automotive markets, in particular China/Asia and Europe, have made significant investments in major scale battery production.

#### **Conclusions on technology and Economics**

**ZE-MHDVs are operationally ready to tackle most**

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<sup>21</sup> <https://globaldrivetozero.org/publication/analysis-of-public-sales-commitments-of-medium-and-heavy-duty-vehicle-manufacturers-and-expected-volumes>

**duty cycles today.** Present ranges meet or exceed the ranges required by most routes for trucks, buses, and vans on the road. These vehicles also have comparable hauling capacity to their ICE counterparts, and losses in freight efficiency due to extra weight of batteries can be mitigated through weight exemption policies—already introduced in the US and EU. Using the guidance and direction of the beachhead strategy to inform the approach to vehicle segmentation, targeted deployments in conducive vocational settings will result in more efficient operations, cleaner air, and cost savings for fleets.

**The economics and TCO of ZE-MHDVs are already favorable in select segments in certain regions today.** All electric vehicles segments are expected to break the TCO parity threshold by 2030 according to most current research studies. The economic advantages of ZEVs are already proving themselves in select regions with favorable conditions. Urban vehicles and those with lighter, regional duty cycles are well positioned to reduce costs for fleets who are looking to save on fuel and reduce emissions. Financial incentives found in countries like the U.S., China, Canada, Austria, and Norway among others can result in more favorable TCO sooner and help build out the market ahead of schedule.

**Coordinated stakeholder action will accelerate the technology commercialization pathway.** With governments stepping up ambition at COP 26, and manufacturers pledging to shift their products toward zero-emission solutions, there is an industry-wide recognition that ZEVs are the future. The beachhead strategy provides directional guidance through a phased approach to technology commercialization that requires the buy-in of stakeholders across the value chain. Without the support of more countries, the private sector, and NGOs progress will not reach its maximum potential. No one actor has the

ability to influence the whole market, but when stakeholders are aligned on common goals and understand the steps to achieving those goals, even the heaviest MHDVs can be decarbonized.