White Paper

Component Costs for Zero-Emission Medium- and Heavy-Duty Commercial Vehicles

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CALSTART

CALIFORNIA AIR RESOURCES BOARD

Acknowledgments

This report will be updated on a periodic basis in support of the publication of the California Air Resources Board's Appendix D: Long-Term Heavy-Duty Investment Strategy (HDIS). A previous version of this information was published in the Fiscal Year 2021-22 HDIS.

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List of Acronyms

Acronym	Definition
AC	Alternating Current
DC	Direct Current
GM	General Motors
HD	Heavy-Duty
HDIS	Long-Term Heavy-Duty Investment Strategy
kWh	Kilowatt-Hour
OEM	Original Equipment Manufacturer
PTC	Production Tax Credit
ZE	Zero-Emission
ZEV	Zero-Emission Vehicle

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I. Understanding Zero-Emission Component Costs

Introduction

Incentive programs such as California's Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) and the Clean Off-Road Equipment Voucher Incentive Project (CORE) were created to overcome the most significant barrier to zero-emission (ZE) vehicle and equipment adoption: higher incremental purchase or lease costs relative to gasoline- or diesel-powered equivalent vehicles. ZE vehicles and equipment across weight classes and duty cycles currently cost more upfront. As clean vehicle segments mature and expand, higher acquisition costs for ZE transportation may be expected to decline, but prices depend upon many factors.

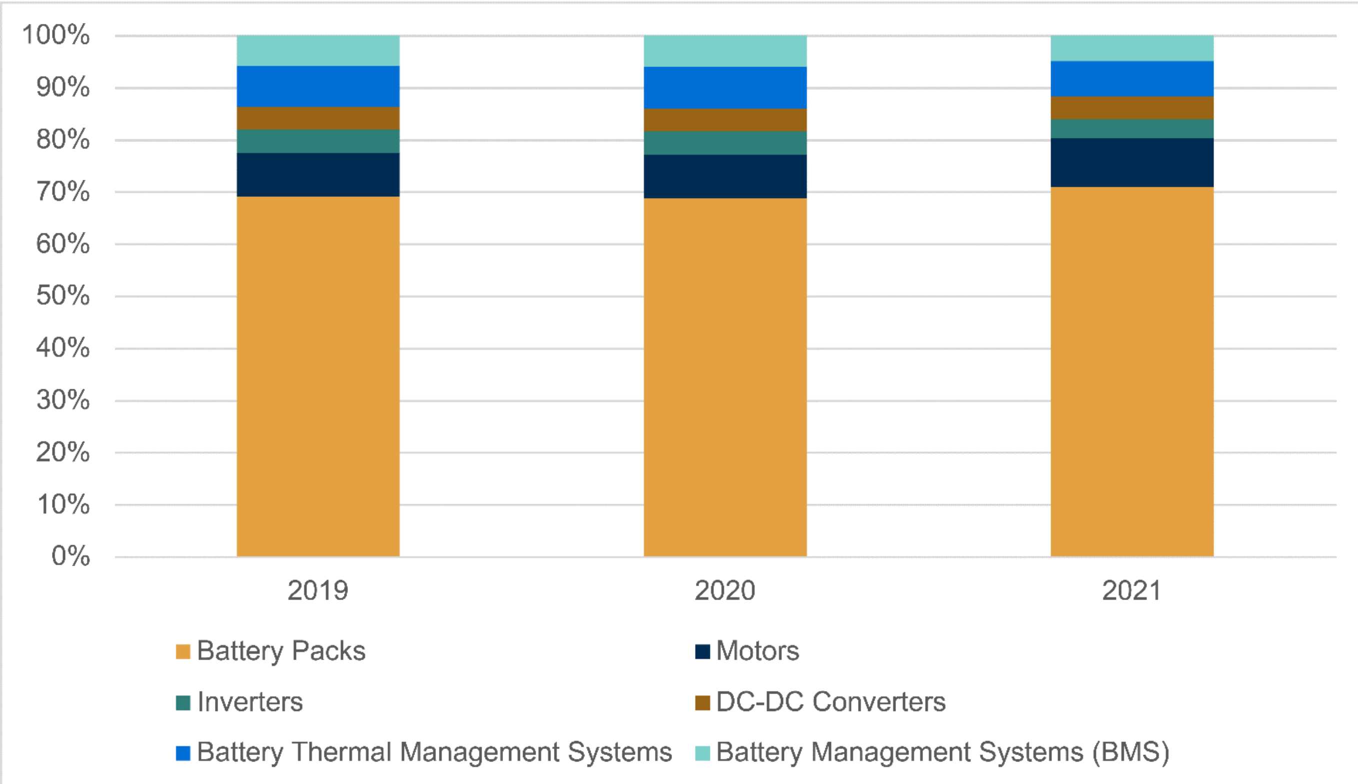
The following discussion focuses exclusively on ZE vehicle (ZEV) component costs—particularly those for heavy-duty (HD) ZEVs—and the key contributors to these higher incremental costs, such as batteries and the components that make up drivetrains. Each of these components is specific to ZEVs and represents an added cost relative to diesel vehicles. Following the beachhead model of successful component and supply chain integration, the cost to develop, manufacture, and integrate these shared components could apply to many vehicle and equipment segments and applications.

This report was developed through literature review and in combination with market research provided by Interact Analysis. Unless otherwise cited, all data used to create the figures in this report were derived from Interact Analysis' proprietary data set on electric bus and truck powertrain pricing. This report, which is published in support of the California Air Resources Board's Appendix D: Long-Term Heavy-Duty Investment Strategy (HDIS), will be updated periodically. Detailed research on and inclusion of ZE equipment component costs, among other updates, will be considered for future iterations of this analysis.

Battery Costs

The cost of batteries is a clear driver in incremental cost and therefore a crucial factor related to ZE vehicle and equipment uptake. As Figure 1 shows, batteries consistently account for the majority of average incremental HD ZEV costs, equaling nearly 70% in each of the past three years (Interact Analysis, 2021).

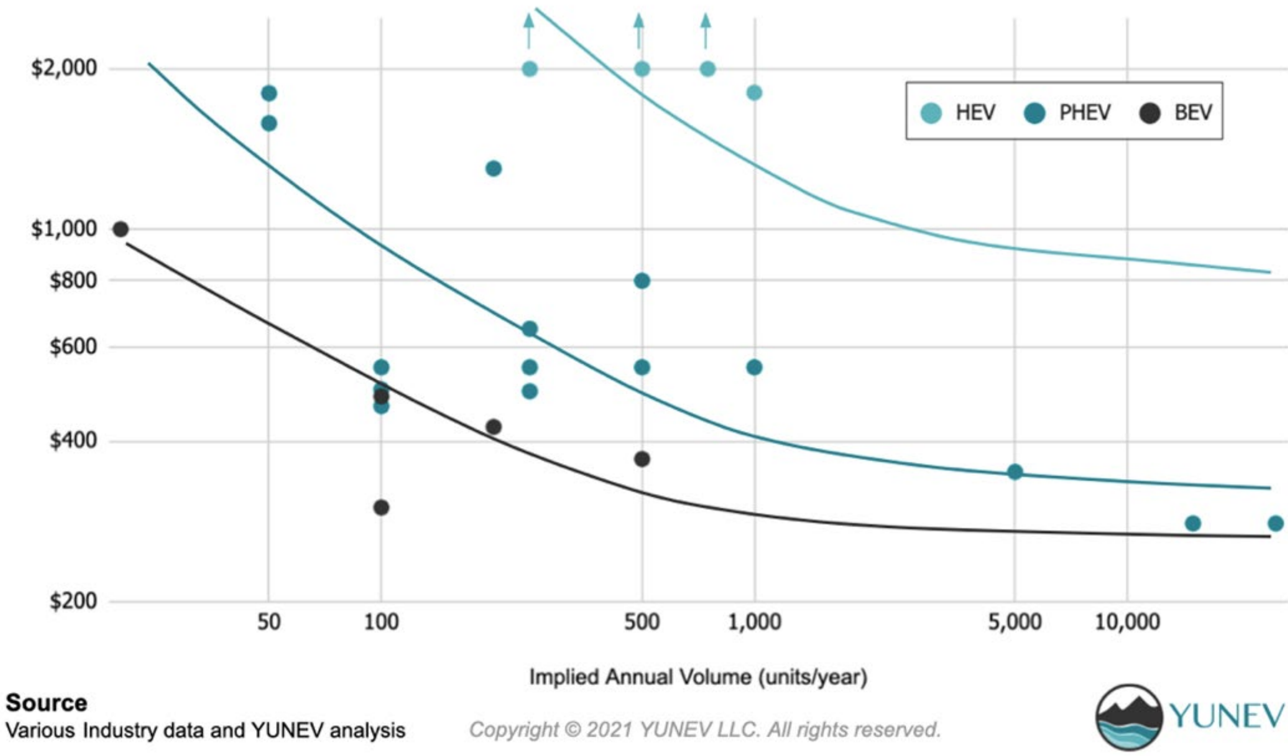
Figure 1. Incremental Battery-Electric Vehicle Costs Over Time



HD ZEVs are particularly susceptible to high battery costs for two reasons: larger vehicles need larger battery packs to meet the on-board energy storage needs for such vehicles and cargo loads, and the costs of building battery cells and modules into purpose-built and low-production volume packs is more expensive relative to light-duty applications.

Global electric vehicle battery production has ramped up steeply over the past decade, and improvements in design and production have accordingly reduced the cost for battery cells. Since 2010, global industry average costs for battery packs (light-duty) have fallen by nearly 90%, from $1,200 per kilowatt-hour (kWh) down to $132 per kWh in 2021 (BloombergNEF, 2021). Such a decline in battery costs presents tremendous potential for the broader electric vehicle industry to increase market share as purchase prices become cost-competitive with gasoline- and diesel-powered vehicles. Global costs are not representative of all markets, however—research by BloombergNEF and YUNEV indicates the U.S. industry average for light-duty battery cells is higher than the estimated average global battery cell prices. Research by YUNEV also indicates that battery pack prices for HD battery-electric vehicles in the United States remain higher than global average prices, coming in above $300 per kWh (Figure 2).

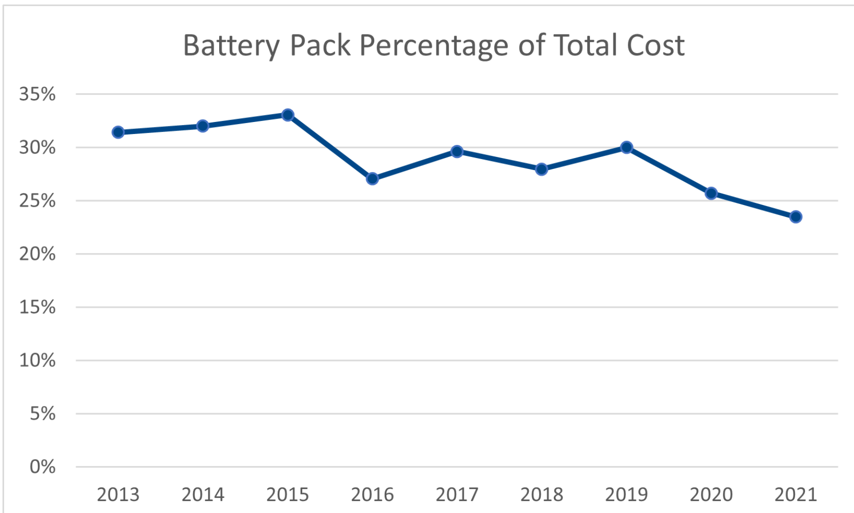
Figure 2. Commercial Vehicle Battery Pack Costs ($/kWh) (YUNEV, 2021)



Additionally, and in most cases in the United States, the full value of lower battery cell costs is diminished when converting cells into battery packs, which can account for a large percent of the delivered cost of ZEV battery packs. Supplemental costs to transform cells into battery packs is typically higher in the HD applications than for mass-market passenger vehicles. The added costs of battery packs in the HD segment may stem from complex configurations to meet new models and relatively low volumes that do not benefit from mass-market production efficiencies. These complexities, combined with supply chain and production disruptions arising from the 2019 coronavirus outbreak, have restricted HD battery pack cost improvements to zero annually across all battery chemistries in the past three years. Some variability between battery chemistry costs has emerged. For instance, the LFP (Lithium Iron Phosphate) battery chemistry has experienced a cost reduction of 16% annually over the past two years. The trend in the overall cost of batteries, however, has been stalled by increasing prices for other prominent chemistries.

Greater production volumes and the proliferation of standardized production models will likely reduce HD battery pack costs. In the light-duty sector, battery pack construction represents a smaller percentage of total battery costs, and the percentage continues to shrink as companies improve their processes and increase production volumes, thereby reducing overall vehicle costs and encouraging consumers to purchase electric vehicles (Figure 3).

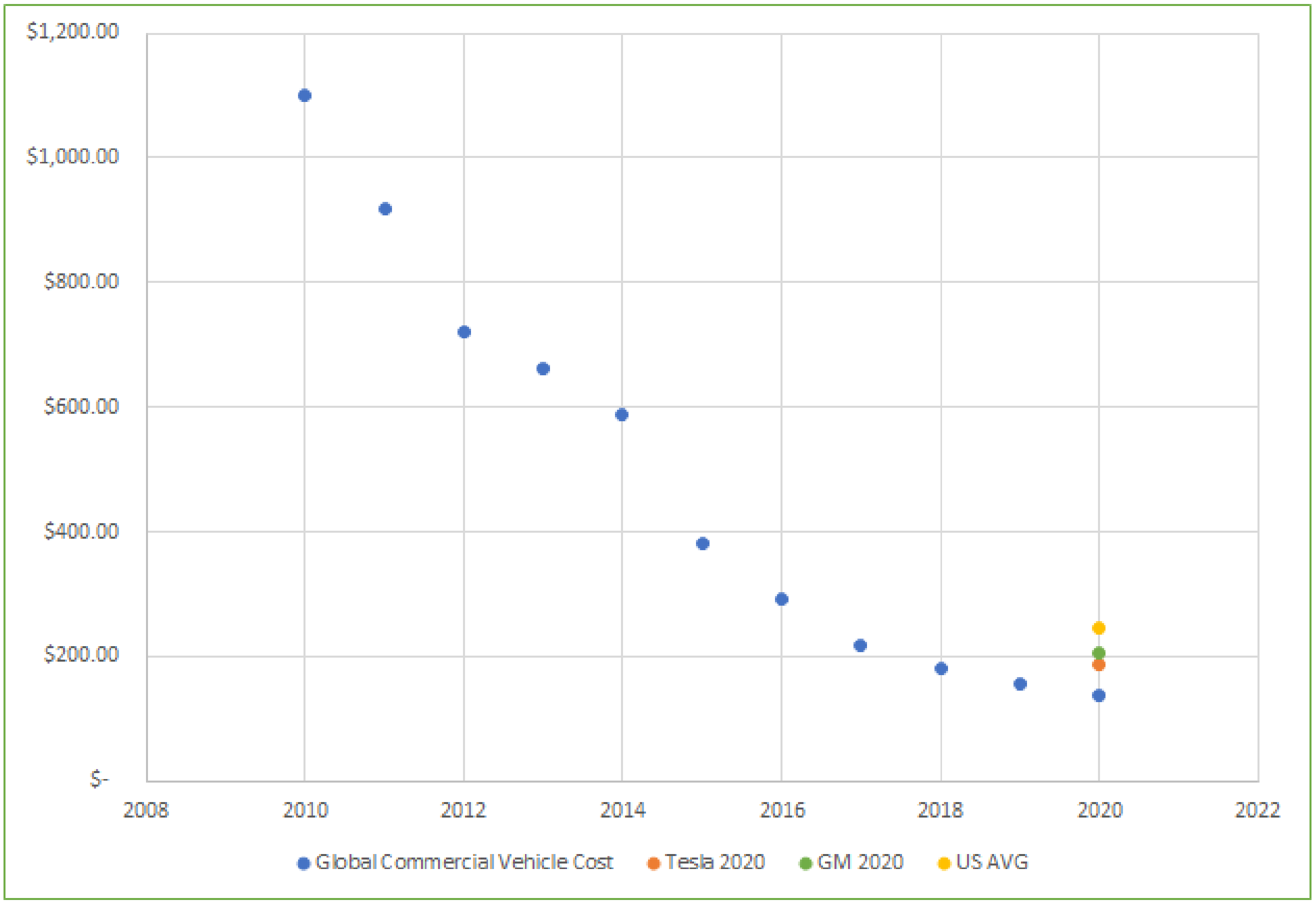
Figure 3. Battery Pack Construction Costs as a Percentage of Total Battery Costs Over Time (Light-Duty) (BloombergNEF, 2021)



Some manufacturers have developed a competitive advantage for access to lower-cost battery cells. In the light-duty market, Tesla's estimated average battery packs cost $187 per kWh, and General Motors' (GM) estimated average battery packs cost $207 per kWh. These companies have achieved their cost reductions through large company-owned battery production facilities or through large-scale purchasing contracts, respectively. Their lower battery costs also reflect the supply chains and investments made in light-duty applications that will benefit HD products. As the higher $246 per kWh average industry U.S. battery pack cost indicates, most light-duty firms are not yet able to achieve such cost reductions and may often exceed the industry average.

Access to established manufacturing capabilities also creates a challenge for most HD manufacturers as they continue to grow their battery supply chains. Figure 4 below illustrates the relatively high 2020 battery pack costs for Tesla, GM, and the United States on average as compared to the global light-duty commercial vehicle cost.

Figure 4. Battery Cell Costs Over Time by Geography and Select Manufacturers ($/kWh)



Inexpensive batteries from China primarily lower the average global battery cost, which is lower than the cheapest U.S. batteries. However, it should be noted that the Inflation Reduction Act, passed by Congress in August 2022, includes a new production tax credit (PTC) for U.S. battery manufacturing, including $35 per kWh ($/kWh) of capacity and $10/kWh for battery modules. This PTC is expected to help accelerate manufacturing and reduce costs for U.S.-made batteries, including those for commercial vehicles.[1]

1 For additional and more detailed information on commercial vehicle battery costs, see CALSTART's Commercial Vehicle Battery Costs Assessment report, authored by YUNEV LLC (YUNEV, 2021).

Drivetrain Costs

ZE drivetrain components, though not as significant as batteries, add to the incremental costs of HD ZEVs. Descriptions of ZEVs' major incremental cost sources and the components that make up ZEV drivetrains can be found in Table 1.

Table 1. Sources and Descriptions of Zero-Emission Vehicle Component Costs

Source	Description
Battery pack	A device or container consisting of one or more electrochemical cells, in which chemical energy is converted into electricity and stored and later used as a source of power. This excludes supercapacitors.
Electric motor	A machine that converts electrical energy into mechanical energy/motion.
Inverter	A machine that converts direct current (DC) into alternating current (AC). In practice, inverters often also include control/intelligent functionality and rectification (AC-DC) for returning energy to the battery during braking.
DC-DC converter	A device that converts a source of DC from one voltage level to another.
Battery thermal management system	A system that regulates temperature level and distribution, typically using systems of cooling, heating, insulation, or ventilation, to keep the battery within parameters that are optimal for safety and lifetime.
Battery management system (BMS)	An electronic system that manages the state of the battery to keep it within safe operating parameters, controlling factors such as voltage and charge of each cell.

These drivetrain components have largely been established for several years, and therefore costs have not reduced significantly. Based on Interact Analysis' proprietary data set, costs for commercial electric vehicle drivetrains have reduced 4% annually since 2019. These costs, like battery packs, are attributable to unique HD designs and low production volumes. These costs may also be impacted by supply chain and production disruptions from the 2019 coronavirus outbreak and the 2022 Russian invasion of Ukraine and subsequent war, so it is possible that further and deeper cost reductions will be achieved in the next few years as supply chains recover. Since many of these components could be transferable between platforms, growing HD ZEV demand should support scaled-up production of each component, and with greater production volumes, these component costs are likely to decline (CALSTART, 2022).

Near-Term and Long-Term Costs

While commercial HD battery pack and ZEV drivetrain prices have not reduced as quickly as in the light-duty segment, market indicators suggest that in the coming years prices will fall more dramatically. Revenue from both batteries and ZEV drivetrains have more than doubled since 2019, according to market research from Interact Analysis. This expanding revenue stream is indicative of a rapidly growing market and a rapidly increasing demand for these products. This expansion of the market will lead to a higher and more stable demand for batteries, leading HD manufacturers to lower costs in the long run by devoting more resources to improving both battery and electric drivetrain supply chains. Many leading truck original equipment manufacturers (OEMs) and parts suppliers are currently developing key supply chains for these crucial components and will ultimately lead the industry into an increasingly competitive and profitable market.

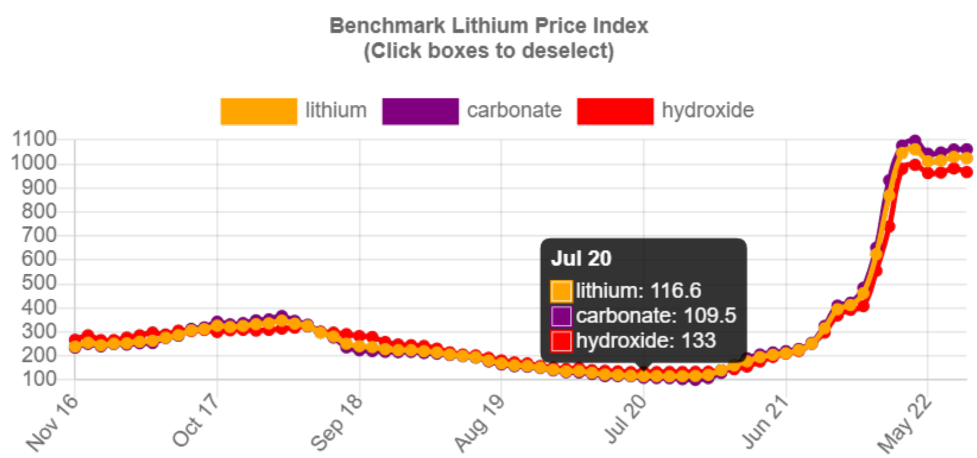
While price reductions are expected on the horizon, the relatively low rate of battery pack and drivetrain cost declines suggest that higher incremental costs will persist for the immediate near term. In this context, incentives for HD ZEVs seek to bridge the gap to commercialization by targeting incremental cost of ZEVs as compared to conventional vehicles and will remain integral to supporting the growth of and investments in the commercial ZEV sector.

II. Supply Chains

Securing predictable and reliable supply chains for the raw materials that make up batteries—the single largest driver of high HD ZEV incremental costs—is critical to reducing costs and volatility. The price of batteries is strongly tied to the costs of these raw materials. Figure 5 below illustrates the cost of lithium, carbonate, and hydroxide over the course of November 2016 to May 2022.

The cost of lithium, which is the main component of industry-leading lithium-ion battery configurations, provides a good example of volatility in the marketplace. Lithium is relatively inexpensive and abundant, but mining operations are still securing rights to deposits and scaling up operations to meet rapidly expanding global demand. Though the cost of lithium has fallen in recent years, prices have suddenly spiked in the past several months (Figure 5). Battery manufacturers and OEMs without sufficient reserves of lithium and associated raw materials may be exposed to market fluctuations that add costs to the prices of battery cells, which are already high relative to internal combustion engine vehicle designs.

Figure 5. Cost of Essential Battery Materials (Benchmark Mineral Intelligence, 2022)



Though ZEV battery manufacturers compete in a global marketplace, domestic raw material production may result in less expensive battery packs due to lack of tariffs and shipping costs while also creating new economic opportunities. As of July 2021, the United States has only one large-scale lithium mine that supplies approximately 2% of the world's lithium. The outlook for lithium production is more promising in coming years and may yield a tenfold increase in domestic output by the end of the decade. Mining operations in

Nevada are poised to produce $3.9 billion of lithium, and new opportunities in brine ponds such as California's Salton Sea can potentially be used for large-scale lithium extraction in a more environmentally sustainable manner than a conventional mine (New York Times, 2021). Other potentially viable brine ponds can be found in Arkansas, Nevada, and North Dakota. Recent announcements by OEMs to secure domestic lithium supplies indicate that OEMs are working quickly to secure lithium supply for their increasing ZEV needs.

Lithium and other raw materials used in batteries and drivetrain components are not only vulnerable to price spikes but also to variations in how they are used in ZEV components. Lithium-ion batteries are currently the dominant industry battery chemistry, and cobalt has been a critical and expensive material that the U.S. Department of Energy describes as the highest material supply chain risk for ZEVs in the short and long term (Vehicle Technologies Office, 2021). Even if battery manufacturers and OEMs are able to secure these raw materials, battery designs may shift away from using these and other materials. Battery improvements touting solid-state designs that shift away from lithium-ion or cathodes that reduce or eliminate cobalt use could improve performance and reduce costs but would also require large-scale investors in those raw materials to quickly alter their commodity investments and production plans.

Similarly, rare earth metals are used in electric motors and impact drivetrain costs. Deposits of these metals are few and typically found in foreign nations, making the market for them competitive and oligarchic, with prices potentially manipulated by a few controlling interests. Investments in rare earth metals may be expensive and necessary, but new designs that reduce or eliminate their use may emerge that render these investments costly and unnecessary. This uncertainty over the sources and incorporation of rare earth metals is emerging in the marketplace, as trade friction with Chinese-controlled rare earth metal suppliers has encouraged automakers to develop new designs that eliminate or reduce the need for rare earth metals (Onstad, 2021).

The uncertainty inherent in the evolution of ZEV batteries may have the greatest impact on OEMs that have incorporated vertical integration into their supply chains. Vertical integration is an impactful way to reduce battery costs per kWh by streamlining supply chains and processes, but it also exposes vertically integrated companies to risk if battery designs shift significantly. Along with the large capital investment and increased risk associated with building the infrastructure, scientific breakthroughs in battery technology may render the current battery technology obsolete. If a new generation of battery is developed that eradicates the lithium-ion design, companies that have invested in vertically integrating their battery component supply chain will have a much harder time pivoting than companies that buy battery cells and assemble them into battery packs.

Recent semiconductor chip shortages have also slowed vehicle production across the automotive market. Shortages have mostly impacted high-volume light-duty vehicle manufacturers, though continued supply constraints may create more significant delays in medium- and heavy-duty segments that have already begun to impact truck manufacturers, particularly as demand has increased over the past year (Smith, 2021). Some automakers have begun to prioritize electric vehicle manufacturing with available chips to meet their production commitments (Shead, 2021).

III. Findings

Based on this analysis, important findings regarding commercial ZEV component costs include:

- Higher incremental costs will persist for the immediate near term. In this context, incentives will remain integral to bridge the gap to commercialization for HD ZEVs and to support the continued investment in and development of the commercial ZEV sector.
- The 2019 coronavirus outbreak and the Russian invasion of Ukraine and subsequent war have resulted in supply chain challenges that have increased prices of raw materials and batteries. Much complexity remains around both events, though industry experts hope to resolve these supply chain challenges as quickly as possible.
- The Inflation Reduction Act's PTC for U.S.-manufactured batteries is expected to reduce battery costs while supporting additional U.S. manufacturing capacity, thereby insulating U.S.-based manufacturers somewhat from global price volatility in the long term.
- As demand increases for medium- and heavy-duty ZEVs, production volumes will increase, thereby maturing component supply chains and further driving down costs.
- Significant uncertainty remains around the next generation of battery chemistries (and the extent to which they include rare earth minerals). New chemistries may improve performance and reduce costs, though they would also require investors to quickly alter their commodity investments and production plans. Vertically integrated companies are exposed to the most risk if battery designs shift significantly.

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