Fast-Falling Battery Prices Boost Economic Benefits Expected from Heavy-Duty Vehicle Electrification

BY CHRIS BUSCH

FEBRUARY 2024

EXECUTIVE SUMMARY[i]

Diesel pollution is a deadly problem in the United States, especially for those who live near major roads and freeways. The Clean Air Task Force reported that roughly 8,800 deaths per year are caused by diesel emissions.[1] Some areas of Los Angeles are even designated "diesel death zones."[2] Most diesel pollution in the U.S is generated by heavy-duty vehicles (HDVs) such as large trucks using nearly every road in the country. But HDV's are now joining cars and other light-duty vehicles (LDV) in the movement towards electrification. The International Energy Agency identified the potential of electric commercial vehicles as one of the top five emissions reduction opportunities, globally.[3] In the U.S. alone, HDVs account for 27 percent of transportation sector carbon dioxide emissions, despite making up only 6 percent of vehicles on the road.[4]

In the U.S. and other countries, commercial trucks frequently rely on diesel combustion engines. While they're more effective for heavy loads than gas engines, diesel engines produce more hazardous pollution, and their local and regional air quality impacts are even more pronounced than their climate impacts. These innovations render battery electric vehicles (BEVs) cleaner than their conventional counterparts and pave the way for zero-emission transport. HDV purchase prices are especially sensitive to battery costs, because HDVs require larger batteries. For this reason, Bloomberg New Energy Finance's (BNEF) recent outlook for HDV battery packs marks a pivotal shift, indicating battery

ENERGY INNOVATION
POLICY & TECHNOLOGY LLC®

www.energyinnovation.org

98 Battery Street, Suite 202
San Francisco, CA 94111
policy@energyinnovation.org

electric HDV (BEHDVs) are expected to reach price parity with their diesel counterparts sooner than previously anticipated. The growing economic benefits associated with this shift underscore the urgency for policymakers to accelerate BEHDV adoption through enhanced vehicle emissions standards, leveraging the attendant economic, environmental, and public health benefits.

Understanding future battery price trends is vital given battery packs' central role in the cost of BEV production.[5] This study quantifies the implications of using BNEF's recent HDV battery pack price forecast to reevaluate future BEHDV purchase cost expectations. While BEHDVs are more expensive to purchase today, we conclude they are likely to become the more affordable option faster than previously expected.[6]

In our analysis, battery pack cost varies according to "updated" and "prior" forecasts. The updated forecast draws on BNEF's 2023 *Electric Vehicle Outlook*.[ii] [7] The prior forecast is based on International Council on Clean Transportation (ICCT) research, which the U.S. Environmental Protection Agency (EPA) used in its preliminary analysis of proposed HDV pollution standards.[8]

Table ES-1. HDV battery pack cost forecasts

	2030	2035	2040
Updated forecast (BNEF)	$85 per kWh	$65 per kWh	$59 per kWh
Prior forecast (ICCT)	$123 per kWh	NA[iii]	$97 per kWh

Sources: BNEF,[9] ICCT,[10] and EI calculations

Figures ES-1 and ES-2 show the price differences between BEVs and diesel vehicles for five types of HDVs. Results reveal that the updated forecast significantly advances the crossover threshold for when BEHDV prices are expected to fall below those of equivalent diesel trucks. A negative result, i.e., a difference in cost less than zero, means that a BEHDV is expected to cost less than the diesel equivalent.

2030 results for the updated battery forecast (labeled "@updated") shows that the expected BEVHD price is lower than the diesel equivalent in four of five cases. Class 6-7 rigid trucks offer the greatest up-front cost advantage in 2030, with the battery-electric saving $29,000 compared to an equivalent diesel vehicle. In the prior forecast (labeled "@prior"), BEHDV are projected to cost less than the diesel alternative in two of five vehicle price comparisons.[11]

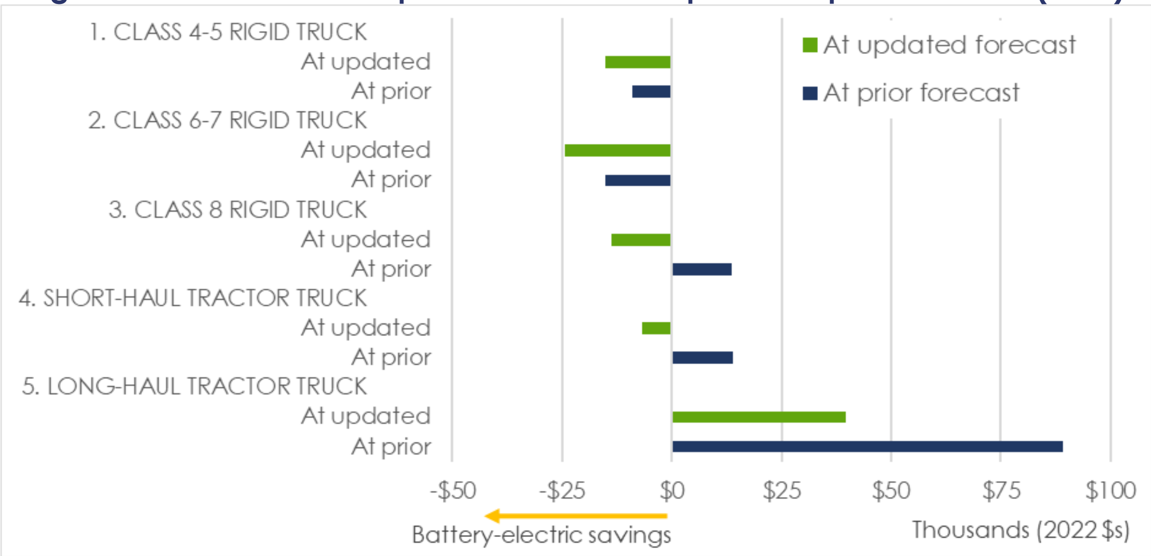
Long-haul tractor trucks are the most challenging type of HDV to electrify because they require the largest-capacity battery pack. However, these vehicles are also driven longer distances than any other vehicle type—100,000 miles per year on average, per the ICCT's estimate.[12] This intensive use means that fuel and maintenance savings for the electric version accumulate more quickly, so

[ii] All monetary values in this report are in 2022 dollars unless otherwise labeled.

[iii] NA means "not available." The report does not provide a 2035 value but does provide a value for 2036—$108 per kWh—per Table 3 of the ICCT's *Purchase costs of zero-emission trucks in the United States to meet future Phase 3 GHG standards* (2023).

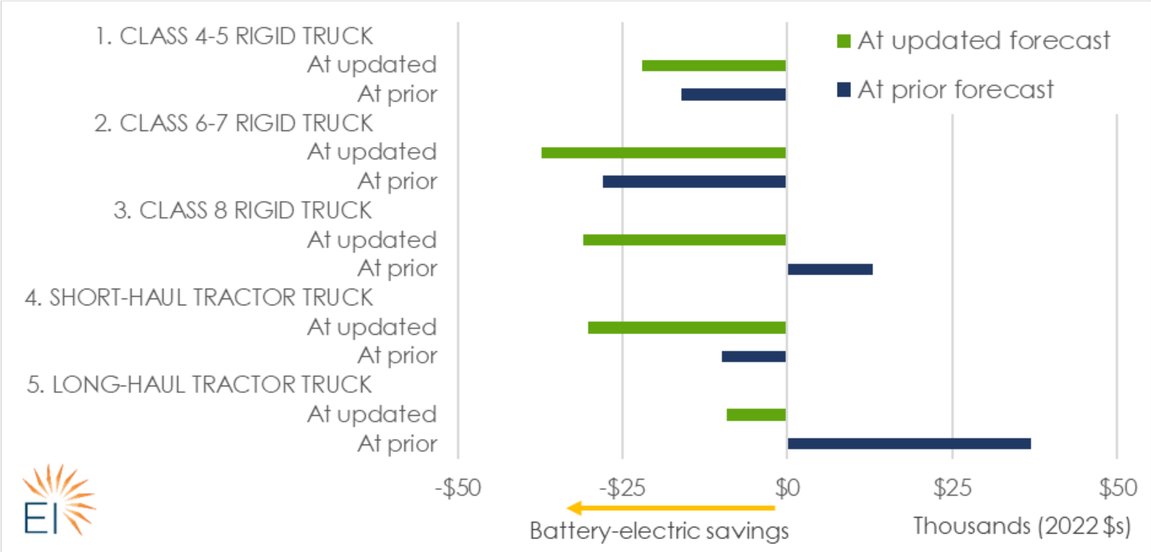
battery electric Class 8 long-haul tractor trucks will deliver total cost of ownership savings before 2030, even using the prior forecast for HDV battery packs and before accounting for available purchase incentives.[13]

Figure ES-1. BEV vs. diesel price difference at updated & prior forecasts (2030)



Sources: BNEF,[14] ICCT,[15] and EI calculations

Figure ES-2. BEV vs. diesel price difference at updated & prior forecasts (2040)



Sources: BNEF,[16] ICCT,[17] and EI calculations

Figure ES-2 illustrates the 2040 results for the expected price difference between BEHDVs and diesel equivalents. Under the updated forecast, battery electric versions cost less upfront for all five types of vehicles, including long-haul tractor trucks. Under both the updated and prior HDV battery pack forecasts, battery electric technology's economic advantages grow in 2040, reflecting the consensus view that learning-by-doing and economies of scale will continue to drive innovation and declining cost for decades to come.[18, 19]

Consider short-haul tractor trucks as an example of how the updated battery forecast affects vehicle costs. Businesses use short-haul tractor trucks—shown in Figure ES-3—for urban and regional freight delivery. These vehicles typically return to a home base at night, enabling the convenience of overnight re-charging and avoiding the much larger capacity battery pack requirements of long-haul tractor trucks.

Figure ES-3. Short-haul tractor truck with trailer

Source: PowerProgress.com[20]

Figure ES-4 offers a more detailed view of cost dynamics, showing the expected vehicle purchase cost along with the share attributable to battery cost, indirect expenses, and other costs. For battery-electric short-haul tractor trucks, substituting the updated forecast for the prior one lowers purchase cost by an estimated $21,000 in 2030 and $20,000 in 2040. Comparing the BEHDV purchase cost to an equivalent diesel vehicle, the battery electric short-haul tractor truck costs an estimated $7,000 less in 2030 according to the updated forecast, instead of costing $14,000 more according to the prior forecast. In 2040, a battery electric short-haul tractor truck is expected to cost $30,000 less than the diesel equivalent according to the updated forecast, compared to cost savings of $10,000 according to the prior forecast.

Figure ES-4. Comparing BEV and diesel vehicle costs for short-haul tractor trucks

Sources: BNEF,[21] ICCT,[22] and EI calculations

Table ES-2. Comparative costs for short-haul tractor trucks (2022$s)

	2030	2040
Battery & indirect cost difference (BEV @ updated vs. BEV @ prior)	-$21,000	-$20,000
Vehicle purchase cost difference (BEV @ updated vs. diesel)	-$7,000	-$30,000

Sources: BNEF,[23] ICCT,[24] and EI calculations

A total cost of ownership (TCO) analysis, which includes operational expenses, offers a more comprehensive view of the economic impacts of vehicles. BEVs provide considerable operational cost savings due to lower fuel and maintenance expenses, leading to more favorable outcomes compared to traditional vehicles.

The ICCT states, "By the end of this decade, battery electric trucks in long-haul operations are likely to achieve lower [TCO] than diesel trucks."[25] A study by Roush Industries for Environmental Defense Fund that considered a range of vehicle types finds that BEHDVs will be more cost effective in terms of ownership by 2027.[26]

Notably, these findings regarding lower ownership costs do not include government incentives; both the ICCT's and Roush's projections are based on unsubsidized costs. The outlook improves further for fleet purchases when accounting for fiscal incentives, such as rebates from significant U.S. policies like the Inflation Reduction Act (IRA) and the Infrastructure Investment and Jobs Act (IIJA).[27] And BEHDVs' total cost advantage is further boosted by updated, lower cost forecasts for HDV battery packs.

Presently, the US Environmental Protection Agency (EPA) is in the process of formulating the next generation of pollution standards for heavy-duty vehicles—a critical step forward in environmental stewardship.[28] We conclude the economic advantages of the EPA's April 2023 proposal are likely to surpass those estimated in its Draft Regulatory Impact Analysis.[29]

States wield a diverse array of tools to facilitate the transition to zero-emission vehicles, among which vehicle standards are paramount. Notably, for heavy-duty vehicles, states are presented with the choice to adopt California's pioneering Advanced Clean Trucks standards—a path already taken by 11 states.[30] Our study indicates benefits awaiting states that opt to embrace their own advanced clean trucks policy are likely to be greater than previously estimated. This evidence contributes to a compelling case for states still deliberating on the adoption of clean HDV standards, highlighting the potential for environmental and economic gains.

Table of Contents

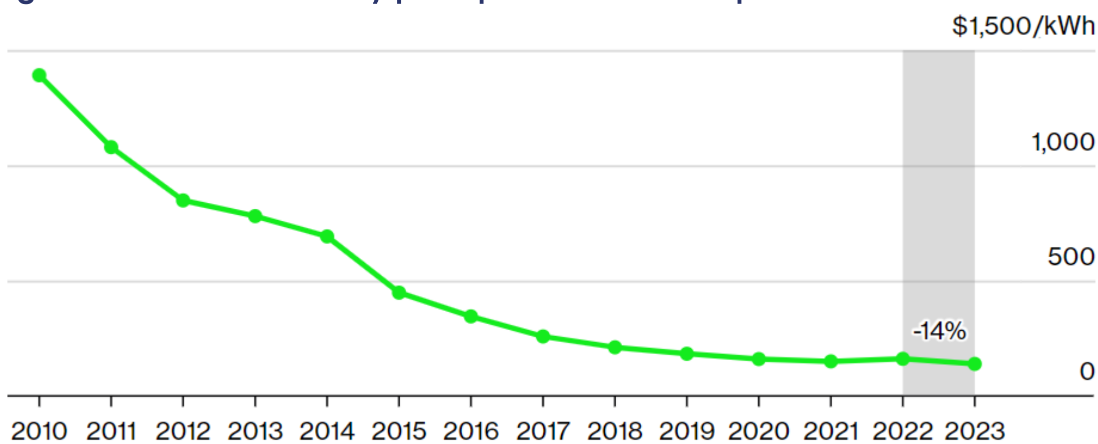
INTRODUCTION

BEHDVs present a significant opportunity for cost-effective pollution reduction, addressing both local and global environmental concerns. More greenhouse gas (GHG) emissions are released from the transportation sector in the U.S. than any other sector, and HDVs are responsible for 25 percent of those emissions—the second-largest contributor.[31] HDVs take an even higher toll on human health because they often use diesel combustion engines, causing an estimated 43 percent of premature deaths in the U.S. from transportation air pollution.[32]

The adoption of BEVs in the HDV sector is growing rapidly. In the U.S., the number of BEHDV sales jumped 53 percent in the first half of 2023 compared to all of 2022.[33] There are differences between light-duty and HDV battery packs, as covered below, but the underlying technology is more similar than different. BEVs are an increasingly mature technology with growing market success evident from more than 30 million battery electric cars and trucks on the road globally.[34] Even though BEHDV sales currently lag battery electric light-duty vehicle sales, the technology is ready.

Rapid innovation and falling battery prices, including a 14 percent reduction in lithium-ion battery packs in 2023 compared to 2022, have changed the economics of EVs because batteries are the main driver of purchase price differences between EVs and internal combustion engine vehicles. As production and market demand ramps up and BEVs becomes the market standard, there is strong confidence in the significant potential for continuing innovation and cost reductions in battery electric storage.[35]

Figure 1. Lithium-ion battery pack price declined 14 percent in 2023[iv]



Source: BNEF via Bloomberg[36]

[iv] This figure uses data on sale-volume-weighted-average price for all types of motor vehicle battery packs in 2023 dollars. Light-duty vehicles dominate BEV sales to date, and so will determine historical weighted-average prices.

The transition to battery electric cars and light trucks is more advanced than the transition to BEHDVs, which are at an earlier stage of market uptake. This is the main reason HDV battery packs are currently more expensive. In 2020, HDV battery packs cost an estimated $265 per kWh compared to $150 per kWh for light-duty vehicle battery packs.[37,38]

This study employs a 2023 BNEF forecast for heavy-duty commercial vehicles to reevaluate future vehicle prices and the expected impact of policies. The outlook for HDV battery pack costs is important because the vehicle component currently constitutes the most substantial portion of the manufacturing cost for BEHDVs.[39] Incorporating BNEF's recent forecast provides an updated view of electric HDV economics, helping to shape effective strategies for promoting pollution reduction through HDV electrification.

BACKGROUND

Vehicle Price vs. Total Cost of Ownership

To enable expeditious publication of these insights, the scope of this study is limited to vehicle prices. Specifically, we compare retail purchase prices before taxes or government incentives.

Up-front cost is most visible to buyers, but also offers a narrow perspective. The most important microeconomic metric to consider is ownership cost, which goes beyond vehicle purchase price alone to considers the full range of expenses associated with owning and operating a motor vehicle. Since BEVs offer substantial savings on fuel and maintenance, the comprehensive ownership cost perspective is more favorable for BEVs.[40]

Indeed, ownership costs for BEV trucks are expected to be lower than for diesel analogues across the board by 2030, even in the case of long-haul tractor trucks. For example, the ICCT concludes: "Battery electric trucks operating in long-haul are likely to achieve a lower TCO than diesel trucks before the end of this decade."[41] This research identifies battery electric technology, rather than hydrogen fuel cells, as the most cost-effective approach to decarbonizing HDVs: "When coupled with megawatt charging in the second half of this decade, battery-powered long-haul tractors are estimated to be the only zero-emission powertrain with the potential to achieve a lower cost per mile than long-haul diesel tractors."[42]

Roush Industries, a firm working primarily in the automotive industry, and Environmental Defense Fund collaborated on another recent TCO study of note. This research considered the vehicle types addressed here as well as buses, but not long-haul tractor trucks. Roush's technical analysis finds that in 2027, battery electric technology offers an ownership cost edge across the board.[43] (Note that 2027 is also the first year of the EPA's proposed Phase 3 extension of HDV emissions standards.[44]) An Environmental Defense Fund fact sheet adds that "when considering upfront purchase price alone, by 2027 electric freight trucks and buses will be less expensive than their combustion engine counterparts in all categories except shuttle buses (which are close to price parity)."[45]

As the EPA summarizes, "These studies were developed prior to passage of the IRA, and therefore we would expect the cost comparisons to be even more favorable after considering the IRA provisions. For example, the Rocky Mountain Institute found that because of the IRA, the TCO of electric trucks will be lower than the TCO of comparable diesel trucks about five years faster than without the IRA. They expect cost parity as soon as 2023 for urban and regional duty cycles that travel up to 250 miles and 2027 for long-hauls that travel over 250 miles."[46,47]

Climate, Air Quality, and Health Benefits

BEHDVs provide local and global air quality benefits by switching from fossil combustion engines to electric motors powered by batteries. battery-electric motors, which are increasingly powered by renewable electricity sources like wind turbines and solar photovoltaic (PV) panels. From a full lifecycle perspective, in the U.S., electric vehicles already emit 64 percent less climate pollution on average today. With solar PV and other renewable energy technologies having come to dominate new investment in power generation capacity year-after-year, grids around the globe are growing cleaner, further boosting EVs emission reduction payoff.

Globally, the International Energy Agency identifies the electric commercial vehicles as one of the top five climate pollution reduction opportunities.[48] In the U.S., HDVs account for 27 percent of transportation sector carbon dioxide emissions, despite making up only 6 percent of vehicles on the road.[49]

The health and air quality impacts of HDVs are largely due to their prevalent use of diesel combustion engines. While more effective for heavy loads than gasoline engines, diesel engines produce more hazardous pollution, creating local and regional air quality impacts that are even more pronounced than their climate impacts.[50] Diesel engine exhaust is estimated to cause 8,800 premature deaths annually in the U.S.[51]

One reason diesel exhaust is harmful is that it contains 40 cancer-causing substances.[52] HDVs are the largest source of on-road nitrogen oxides (NOx) pollution, contributing to over half of road vehicle NOx emissions in the U.S..[53] The global share of on-road vehicle NOx pollution that is attributable to HDVs is even larger, at 76 percent.[54] NOx pollution has been linked to respiratory issues, cardiovascular diseases, and other adverse health effects.

HDV emissions frequently are released in urban areas, near interstate highways, and on other trucking corridors. In the U.S., more than 45 million people, predominantly people of color, reside within 300 feet of major roadways.[55] This proximity leads to disproportionate HDV pollutant exposure, exacerbating the heavy air pollution burdens that people of color already face. [56]

How HDV Battery Packs Differ

HDV battery packs face different engineering requirements from battery packs for other vehicles, stemming from how HDVs must perform.[57] Compared to light-duty vehicles, HDVs:

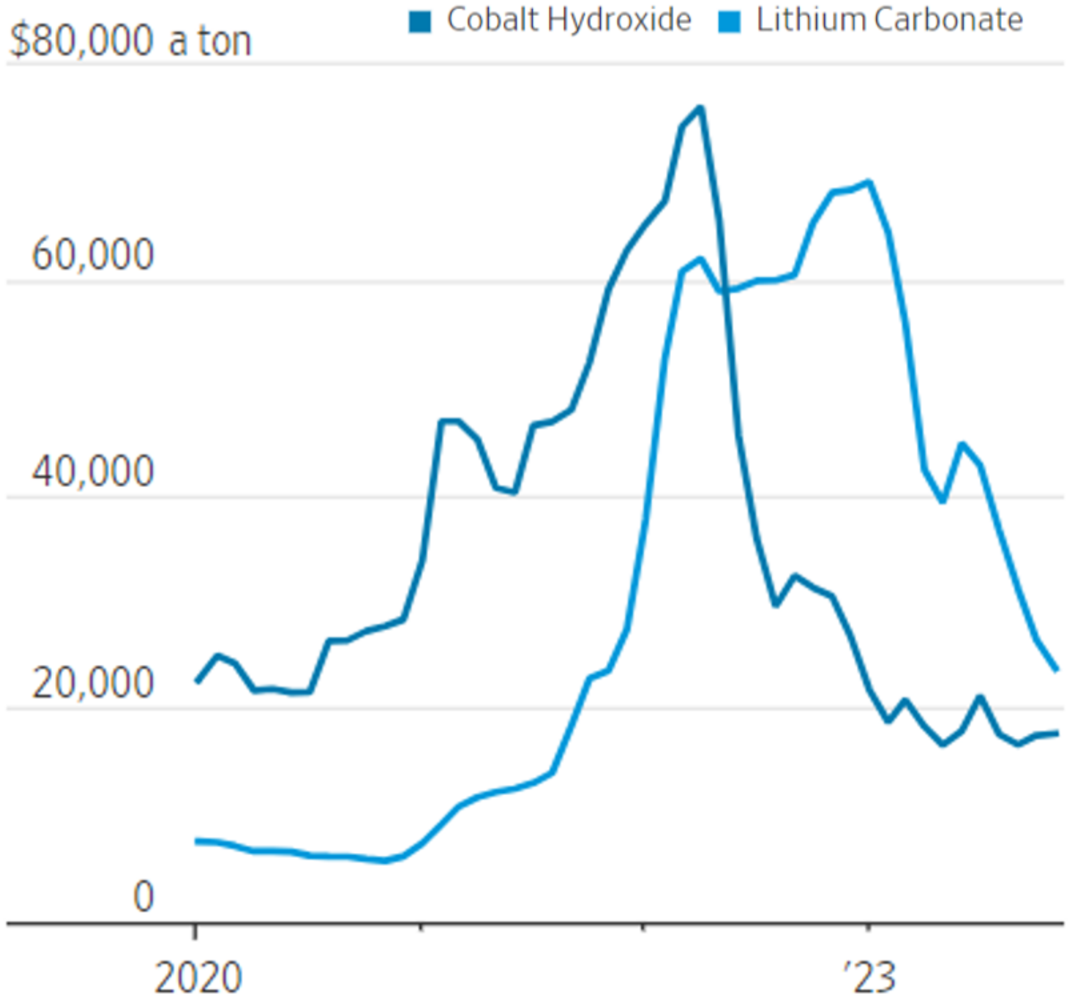
1. Require larger capacity and more powerful batteries to serve heavy loads. Larger batteries containing more battery cells can deliver more horsepower and are able to recharge more quickly.
2. Involve more challenging thermal management because of their larger-capacity battery packs.
3. Subject battery packs to more punishing conditions: one example is vehicle shaking, which increases the need for vibration dampening.[58]
4. Log greater daily and annual miles than typical small passenger vehicles, putting an increased premium on battery durability.[59]

HDV battery packs have some engineering advantages, too. A larger battery pack allows for more efficient design and packaging of the battery cells. In a larger pack, cells can be arranged more closely together, reducing the amount of wasted space and materials.

Battery Mineral Prices Dropped Sharply in 2023

In 2022, BEV battery packs increased in price, for the first time on record. From 2010 to 2021, the average inflation-adjusted cost of lithium-ion battery packs fell 89 percent according to BNEF's annual industry survey, which produces the most-often-cited average market price. for lithium-ion battery packs.[60] Mineral inputs important to battery production experienced pandemic-related supply chain disruption and inflation, peaking in 2022. Over the course of the next year, mineral prices fell sharply. By the end of 2023, lithium prices had fallen 70 percent, nickel prices had dropped by 45 percent, and cobalt prices had returned to their pre-pandemic level (see Figure 2). A *Wall Street Journal* headline captures the outlook: "Low Battery Metal Prices Set to Persist."[61]

Figure 2. Cobalt and lithium prices have fallen sharply from pandemic peaks



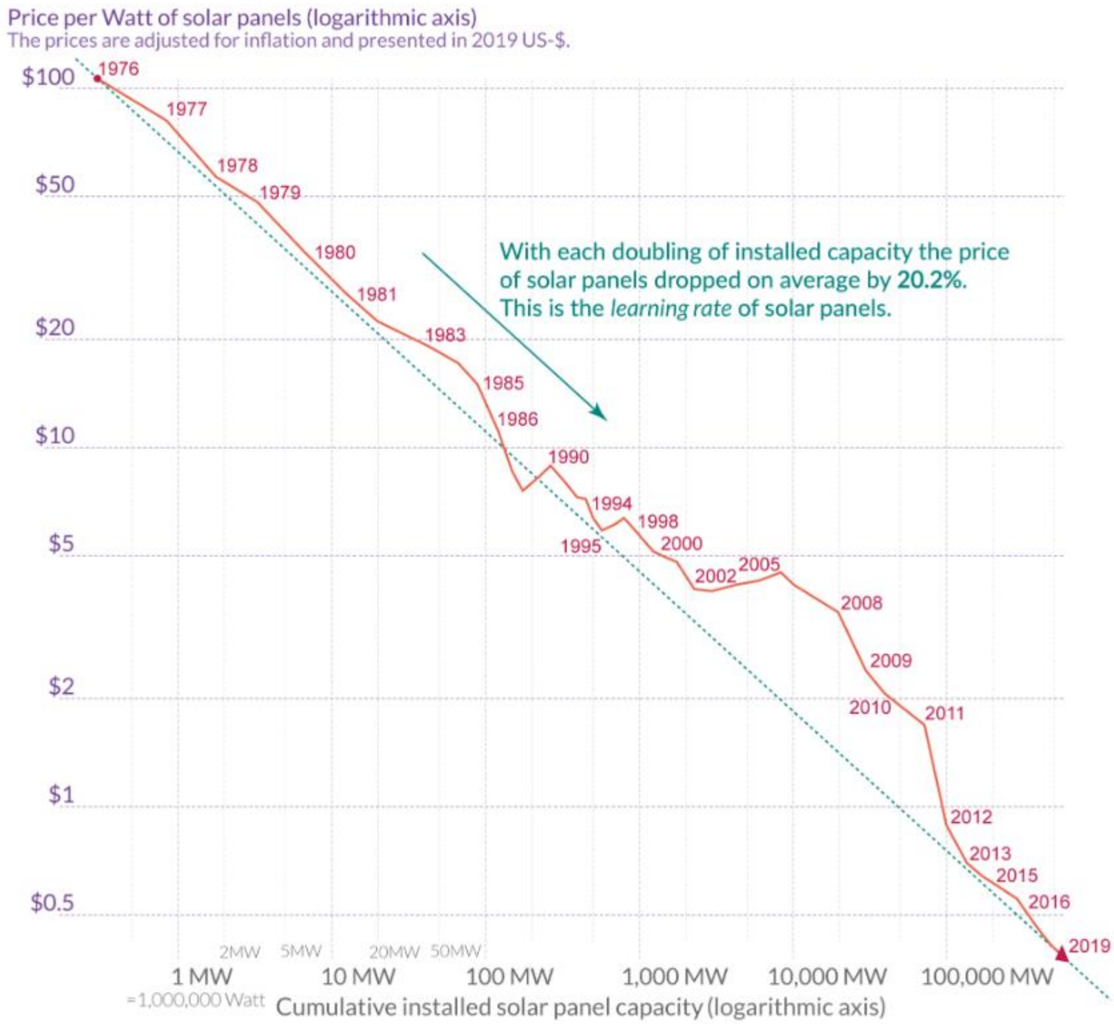
Source: Wall Street Journal[62]

Wright's Law

Confidence in continuing innovation and cost reductions for lithium-ion batteries stems from empirical work demonstrating Wright's Law.[63] Wright's Law captures the effects of economies of scale and learning by doing as technologies scale up and mature.[64] Wright's Law is not an inviolable principle like the laws of physics, but rather refers to a real-world phenomenon that has been robustly researched and empirically validated for dozens of technologies.

The upshot of Wright's Law is that deployment of a manufactured technology product leads to predictable cost effects, conditional on the level of deployment.[65] Wright's Law can be boiled down to a succinct mathematical relationship: For every cumulative doubling of a technology's deployment, its cost is expected to decline by a quantifiable percentage that remains relatively constant as adoption and time unfolds. Renewable electricity technology offers the most well-known case studies of Wright's Law. Over the past 40 years, the average learning rate—the reduction in cost observed with each doubling of installed capacity—has averaged 20 percent for solar PV and 13 percent for wind turbine technologies.[66]

Figure 3. Wright's Law effects for solar PV: a 20% learning rate since 1976



Source: Our World in Data[67]

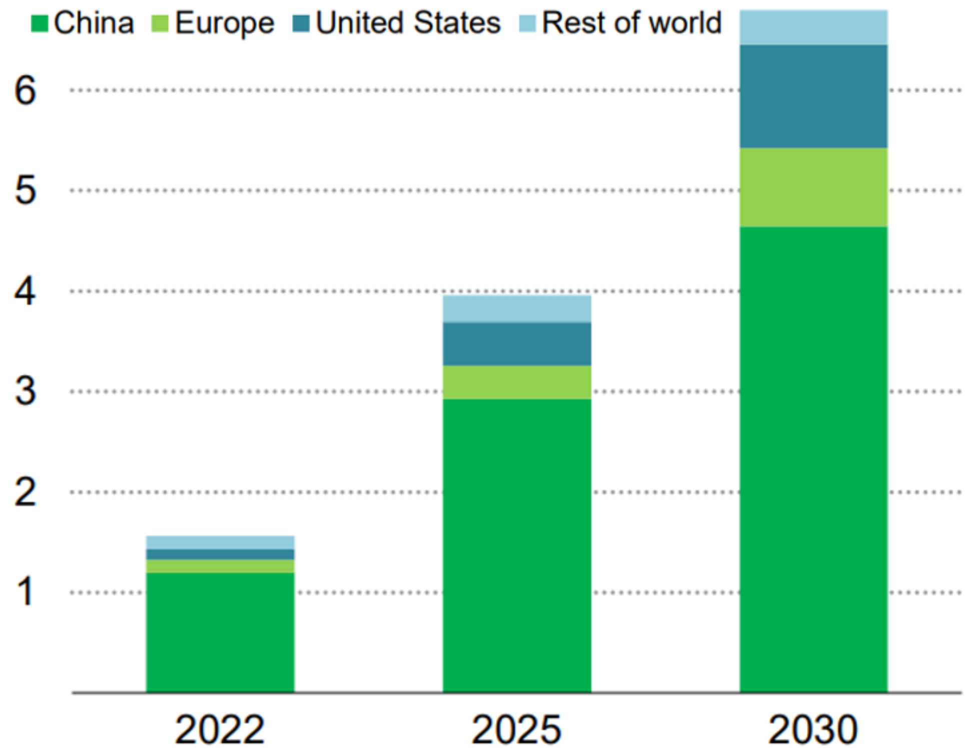
Wright's Law provides confidence that lithium-ion batteries and battery packs for EVs will continue to benefit from innovation and cost improvements in the years and decades ahead. Way et al.

observe: "From 1995 to 2018 the production of lithium-ion batteries increased at 30 percent per year, while costs dropped at 12 percent per year, giving an experience curve comparable to that of solar PV."[68]

Confidence in Continuing Effects of Wright's Law for HDV Battery Packs

Three factors bolster confidence that Wright's Law effects for HDV battery packs will continue. First, consider the historical pattern. Other than BNEF, energy modelers have repeatedly misjudged the future trend of battery prices. For an illustration of how even the most optimistic forecasts from other leading energy modelers have consistently underestimated future reductions in battery prices, see Figure 5c in Way et al., which is available in the open-access, peer-reviewed journal *Joule*.[69]

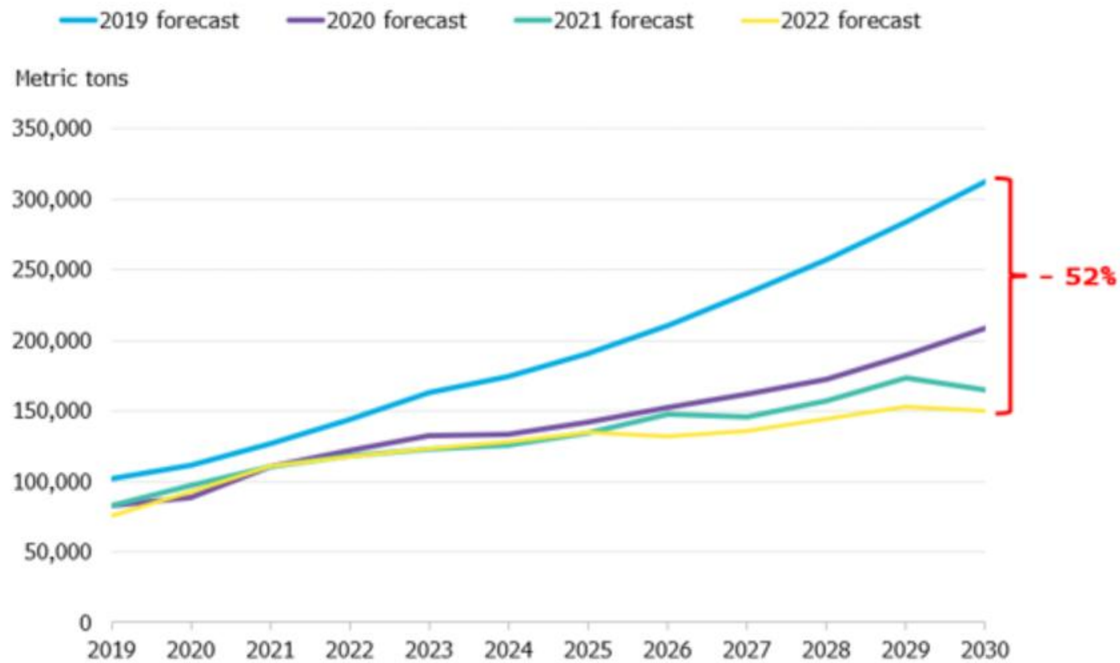
Figure 4. Lithium-ion battery manufacturing capacity (annual terawatt-hours)



Source: International Energy Agency[70]

Trends pointing to substantial scope for future economies of scale and innovation are the second and third reasons to expect continue Wright's Law effects. Both reasons are each grounded in the fact that HDV battery packs are at an earlier stage of deployment than light-duty vehicle battery packs and future Wright's Law effects are conditioned on the amount of experience to date. In this case, a smaller initial level of cumulative deployment means a given amount of future deployment is a larger multiple of the starting point. Expected future economies of scale, the second reason for confidence Wright's Law effects will continue, is evident in plans to scale up battery construction. Factories under construction and announced investments together would increase battery production capacity in 2030 by a factor of four compared to 2022 levels (see Figure 4).[71]

Figure 5. Rise of lithium iron phosphate batteries reduces cobalt demand



Source: BNEF[72]

Further working in favor of continuing innovation is progress on several novel battery chemistries nearing commercial availability. Each commercially viable combination opens new avenues for technological progress. Two emerging battery chemistries poised for commercial growth are sodium-ion batteries and lithium sulfur batteries.[73,74] BNEF estimates that sodium-ion deployment could lower lithium demand by 40 percent in 2035 in an "aggressive" scenario, representing faster than existing than but still feasible growth in its market share.

The emergence of lithium iron phosphate batteries provides a real-world case study of how new battery technologies can swiftly and significantly alter mineral demand.[75] Lithium iron phosphate batteries are cobalt free and claimed over 42 percent market share for battery packs globally in 2023, up from single digits in 2019.[76] The switch to lithium iron phosphate batteries, supplemented by the greater use of nickel to reduce cobalt demand for manufacturing batteries still using it, such as lithium nickel manganese batteries, have significantly lowered the long run demand forecast for

Cobalt. Due to these effects, as Figure 5 shows, expected 2030 demand for cobalt fell by 52 percent in BNEF's 2023 outlook compared to its 2019 outlook.[77]

A more diverse mix of battery technologies offers economic advantages, too. A greater array of commercial options will spread battery demand across a larger number of mineral inputs, tamping down demand-side price pressures and reducing the risk of supply bottlenecks. More commercially viable battery chemistries will also increase competition among battery technologies, discouraging excess profit taking.

The foregoing evidence of substantial opportunities for economies of scale and innovation and the historical tendency of forecasters other than BNEF to underestimated future battery cost reductions supports a strong outlook for the continuation of Wright's Law effects on HDV battery packs. More simply, these factors collectively underscore the potential for significant advances in battery technology and cost efficiency in coming years.

RESULTS

Results compare the impact of different HDV battery pack forecasts on expected electric HDV prices. According to BNEF's more recent forecast, HDV battery packs will fall to $85 per kWh in 2030 and $65 per kWh in 2040. BNEF's forecast shows HDV battery pack prices falling by 50 percent from 2023 to 2025. Extending BNEF's forecast from its last year, 2035, as discussed in the Methodology section, leads to a 2040 estimate of $59 per kWh. The prior forecast draws on an HDV battery pack price outlook by the ICCT.[78] The ICCT's forecast—which is a freely available reference, unlike BNEF's proprietary insights—served as the basis for expected future HDV battery pack prices in the EPA's Draft Regulatory Impact Analysis for the Phase 3 extension of HDV emissions standards. Table 1 provides details, showing the BNEF price is 31 percent lower in 2030 and 39 percent lower 2040.

Table 1. HDV battery pack price forecasts

	2030	2035	2040
Updated forecast (BNEF)	$85 per kWh	$65 per kWh	$59 per kWh[v]
Prior forecast (ICCT)	$123 per kWh	NA[vi]	$97 per kWh

Sources: BNEF,[79] ICCT,[80] and EI calculations

[v] The 2040 value is an extrapolation from BNEF's 2035 forecast for HDV battery pack costs, $65 per kWh, and the last year in BNEF's battery price outlook, as discussed further under Methodology.

[vi] NA means "not available." The report does not list a value for the year 2035, but the report does offer a value for 2036: $108 per kWh (Table 3 of the ICCT's *Purchase costs of zero-emission trucks in the United States to meet future Phase 3 GHG standards*).

Comparative results for electric versus diesel vehicle prices are illustrated in Figures ES-1 and ES-2 in the Executive Summary, and Table 2 provides numerical details underlying these figures. The right-most two columns spotlight whether the battery electric version of an HDV is expected to be less expensive (i.e., the vehicle price is lower than an equivalent diesel truck). "Yes" indicates the BEHDV price is forecasted to cost less than an equivalent diesel vehicle.

Table 2. Numerical results for BEV vs. diesel price differences (thousand 2022 $s)

	2030 difference	2040 difference	2030 BEVs save vs. diesel?	2040 BEVs save vs. diesel?
Class 4-5 rigid truck				
@ updated	-$15	-$22	**Yes**	**Yes**
@ prior	-$9	-$16	**Yes**	**Yes**
Class 6-7 rigid truck				
@ updated	-$24	-$37	**Yes**	**Yes**
@ prior	-$15	-$28	**Yes**	**Yes**
Class 8 rigid truck				
@ updated	-$14	-$31	**Yes**	**Yes**
@ prior	$14	$13	No	No
Short-haul tractor truck				
@ updated	-$7	-$30	**Yes**	**Yes**
@ prior	$14	-$10	No	**Yes**
Long-haul tractor truck				
@ updated	$40	-$9	No	**Yes**
@ prior	$89	$37	No	No

Sources: BNEF,[81] ICCT,[82] and EI calculations

Using the updated forecast, our analysis finds that electric HDVs will be less expensive than diesel equivalents for four of five vehicle types evaluated. In 2030, the only BEHDV price not lower than for the diesel version is that of long-haul tractor trucks, which require the largest capacity battery packs. By 2040, according to the updated forecast, the long-haul tractor truck price falls about $9,000 below that of a diesel version. For the other four vehicle types, cost savings expected from BEHDVs grows in 2040 compared to 2030.

Next, we take a closer look at Class 8 rigid truck cost dynamics, just as the Executive Summary examined short-haul tractor trucks. The aim of these vehicle type case studies is to provide a less abstract example, grounded through comparison of specific vehicle types, to illustrate and help develop intuition about the effects of using the BNEF forecast rather than the ICCT forecast. Class 8 rigid trucks include dump trucks, pictured in Figure 6, as well as cement mixers, sanitation trucks, and other "vocational" vehicles.

Figure 6. Dump truck example of a class 8 rigid truck

Source: Frank Deandro via Flickr[83]

For class 8 rigid trucks, substituting the updated forecast for the prior one lowers the BEHDV's purchase cost by an estimated $18,000 in 2030 and 2040, due to lower battery pack and indirect expenses. The reason 2030 and 2040 cost reductions are the same stems from two effects that cancel each other out.[vii] First, the difference between the updated and the prior forecasts is smaller in 2030 than 2040 (31 percent and 39 percent lower, respectively). The countervailing factor is that improving battery density means a smaller battery capacity is expected for a given type of BEHDV while maintaining the same performance level. Comparing the BEHDV purchase cost to an equivalent diesel vehicle, the battery electric class 8 rigid truck costs an estimated $14,000 less in 2030 according to the updated forecast, instead of costing $4,000 more according to the prior forecast. In 2040, we estimate a battery electric class 8 rigid truck will cost $31,000 less than the diesel equivalent according to the updated forecast, compared to cost savings of $13,000 according to the prior forecast.

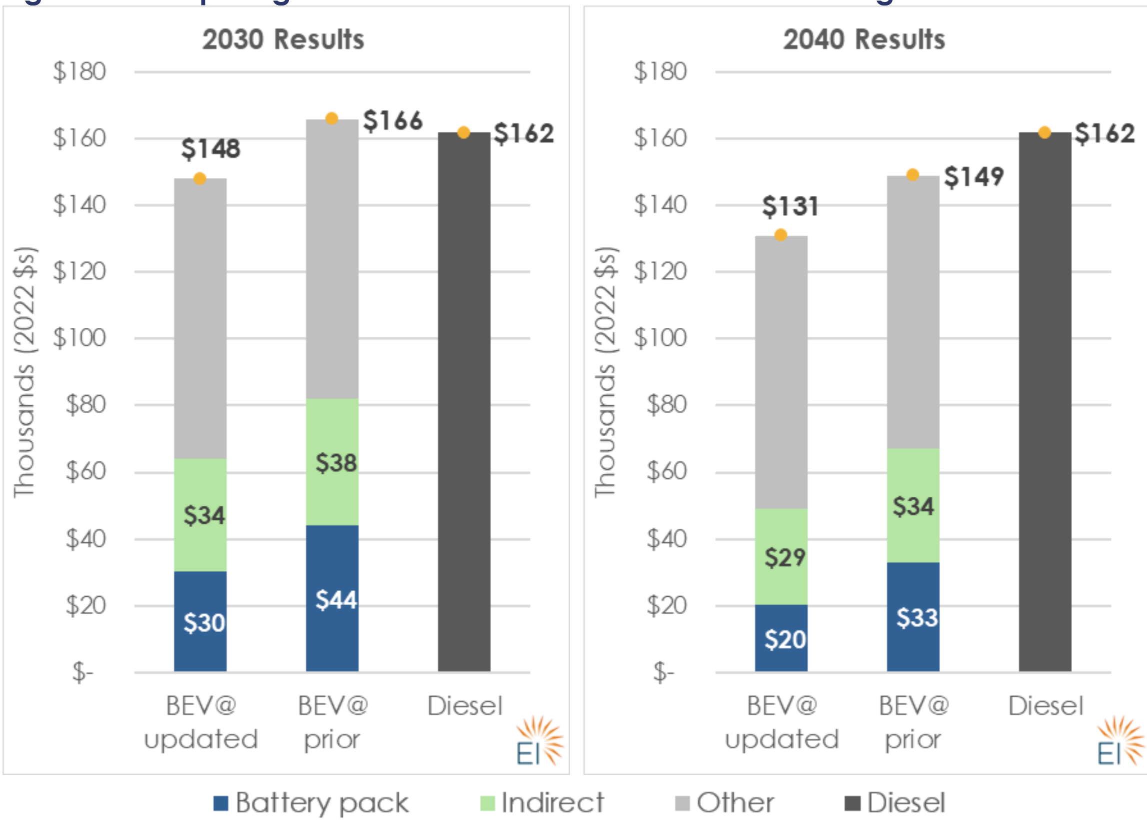
Table 3. Comparative costs for class 8 rigid trucks (2022$s)

	2030	2040
Battery & indirect cost difference (BEV @ updated vs. BEV @ prior)	-$18,000	-$18,000
Vehicle purchase cost difference (BEV @ updated vs. diesel)	-$14,000	-$31,000

Sources: BNEF,[84] ICCT,[85] and EI calculations

[vii] When we review results with additional significant figures, we see that the two effects do not exactly cancel each other out, though they do in the rounded results displayed.

Figure 7. Comparing BEV and diesel vehicle costs for class 8 rigid trucks



Sources: BNEF,[86] ICCT,[87] and EI calculations

Tables 4-8 provide details about the component costs of vehicle price for the five HDV types evaluated. The first four rows encompass the physical inputs necessary for vehicle manufacturing. The fifth row lists Indirect costs.[88]

Table 4. Class 4-5 rigid trucks: vehicle price and component costs

	2030			2040		
Results in Thousand 2022 $s	**BEV @ updated**	**BEV @ prior**	**Diesel vehicle**	**BEV @ updated**	**BEV @ prior**	**Diesel vehicle**
Baseglider	$19			$19		
Auxiliaries	$21			$21		
E-drive	$6			$5		
Battery	$10	$15		$7	$11	
Indirect	$17	$18		$15	$17	
Total (Vehicle Price)	$73	$79	$88	$67	$73	$89

Table 5. Class 6-7 rigid trucks: vehicle price and component costs

Results in Thousand 2022 $s	2030 BEV @ updated	2030 BEV @ prior	2030 Diesel vehicle	2040 BEV @ updated	2040 BEV @ prior	2040 Diesel vehicle
Baseglider	$23	"		$23	"	
Auxiliaries	$23	"		$23	"	
E-drive	$7	"		$5	"	
Battery	$16	$23		$10	$17	
Indirect	$21	$23		$18	$21	
Total (Vehicle Price)	$90	$99	$114	$80	$89	$117

Table 6. Class 8 rigid trucks: vehicle price and component costs

Results in Thousand 2022 $s	2030 BEV @ updated	2030 BEV @ prior	2030 Diesel vehicle	2040 BEV @ updated	2040 BEV @ prior	2040 Diesel vehicle
Baseglider	$44	"		$44	"	
Auxiliaries	$32	"		$32	"	
E-drive	$8	"		$6	"	
Battery	$30	$44		$20	$33	
Indirect	$34	$38		$29	$34	
Total (Vehicle Price)	$148	$166	$162	$131	$149	$162

Table 7. Short-haul tractor trucks: vehicle price and component costs

Results in Thousand 2022 $s	2030 BEV @ updated	2030 BEV @ prior	2030 Diesel vehicle	2040 BEV @ updated	2040 BEV @ prior	2040 Diesel vehicle
Baseglider	$36	"		$36	"	
Auxiliaries	$34	"		$34	"	
E-drive	$8	"		$6	"	
Battery	$35	$51		$23	$37	
Indirect	$33	$38		$28	$34	
Total (Vehicle Price)	$146	$167	$153	$127	$147	$157

Table 8. Long-haul tractor trucks: vehicle price and component costs

Results in Thousand 2022 $s	2030 BEV @ updated	2030 BEV @ prior	2030 Diesel vehicle	2040 BEV @ updated	2040 BEV @ prior	2040 Diesel vehicle
Baseglider	$42	"		$42	"	
Auxiliaries	$34	"		$34	"	
E-drive	$8	"		$6	"	
Battery	$84	$122		$52	$85	
Indirect	$46	$58		$35	$48	
Total (Vehicle Price)	$215	$264	$175	$169	$215	$178

Sources: BNEF,[89] ICCT,[90] and EI calculations

POLICY IMPLICATIONS

Scientific evaluation of public health and technological feasibility are deciding factors in design of all Clean Air Act policies, such as the proposed HDV vehicles standards. Still economics is a factor in technological feasibility. This comparative cost study finds the crossover point when the purchase price of BEHDVs falls below that of a comparable diesel alternative is likely to happen years earlier than previously expected. Advances in HDV economics mean a faster transition is possible and optimal, and that policy design should expedite a faster shift toward zero-emission HDVs.

More concretely, we also see implications for the EPA's ongoing Phase 3 process to design the next phase of HDV emissions standards, first launched in in April 2023.[91] Our analysis reveals that the economic benefits of adopting these standards are likely to exceed initial predictions.

Approval of the EPA's proposed emissions standards for HDVs as well as separate measures for light-duty vehicles would help bring U.S. transportation policy into alignment with its climate commitments. The IRA and IIJA were major steps toward the U.S. meeting its 2030 nationally determined contribution, but they are not enough on their own. Strong HDV emissions standards and other similar policies will signal the future direction of the market, building the confidence needed to optimally unleash private investment in vehicle manufacturing and charging infrastructure development.

While this study has a national focus, its implications extend to the state level. States have the option to adopt California's HDV standards, a choice that is especially relevant given the findings on the even more beneficial economics of BEHDVs. State policymakers should be aware the economic payoffs from the transition to BEHDVs are likely to be larger and arrive sooner than previously expected.

METHODOLOGY

Definitions

Definitions herein align with terminology used in the ICCT's *Purchase Costs of Zero-Emission Trucks in the United States to Meet Future Phase 3 GHG Standards*.[92] The term "heavy-duty vehicle" includes road vehicles with a fully loaded weight (or "Gross Vehicle Weight Rating") of at least 14,001 pounds, equivalent to U.S. class 4 vehicles and larger.[93] For this study, we limit our scope to comparison of battery electric and diesel combustion engine technologies to focus on the evolving landscape of HDV battery pack costs.

Battery cost and vehicle price represent retail price before taxes and before government fiscal incentives. The report typically refers to the cost to purchase a new vehicle as its "price" to emphasize that this is a retail price, including a profit margin and other "indirect costs." Like the ICCT study, this report estimates retail price as a function of manufacturing cost plus an indirect cost multiplier, which captures profit margin, research and development, marketing, and other costs not related to manufacturing. Battery packs and other BEHDV components are in the "High 1" complexity level, for which the indirect cost multiplier is 0.27. The ICCT's indirect cost adjustment factor is similar, conceptually and in magnitude, to the "retail price equivalent" calculation in the EPA's Draft Regulatory Impact Analysis.[94]

Data Inputs

To estimate future costs, our primary source is the ICCT report *Purchase Costs of Zero-Emission Trucks in the United States to Meet Future Phase 3 GHG Standards*.[95] This open-source study served as the foundation for the battery cost projections used in the EPA's Draft Regulatory Impact Analysis.[96] We draw extensively upon the study's comprehensive appendix, which provides detailed data, including base glider costs, auxiliary costs, battery pack costs, and others, as listed in Tables 3-7. The only exception is the updated forecast for battery pack prices.

In revising the updated forecast section, we integrate the primary HDV battery pack price forecast from the BNEF 2023 *Electric Vehicle Outlook* (EVO).[97] This forecast is based on assumptions from BNEF's Economic Transition Scenario, which projects future trends under the premise of existing public policies continuing without the introduction of new government initiatives to expedite decarbonization.[98]

Notably, BNEF's forecast concludes in 2035. Therefore, to extrapolate to 2040, we extend the forecast using a 17 percent learning rate, the same learning rate used in EVO 2023's central case.[99] To complete extrapolation of the HDV pack price to 2040, it also is necessary to estimate annual HDV battery pack deployment from 2036 to 2040. We draw upon annual HDV deployment as in BNEF's Economic Transition Scenario. These few inputs -- data on annual and cumulative HDV deployment as well as starting HDV battery pack price , provide the data needed to project the HDV battery pack prices forward to 2040, applying Wright's Law to guide our calculations.

Method of Calculation

The analysis centers on the calculation of how the updated HDV battery cost forecast affects battery cost. First, we calculate the percent reduction in HDV battery pack price per kWh of capacity according to the updated forecast. Then, we apply this percentage decrease to the per-vehicle battery cost in Table A5 of the ICCT's 2023 report.[100] The incremental cost of replacing a diesel HDV with a battery electric one is calculated as the price of the diesel vehicle subtracted from the BEV price. A negative result indicates that BEVs are likely to cost less than a commensurate diesel model, while a positive difference indicates that BEVs are expected to be more expensive.

CONCLUSION

Electrifying HDVs offers significant opportunities for both local and global climate pollution reductions. Greater than previously understood cost competitiveness advantages create the potential for an accelerated transition to electric vehicles, enabling greater clean air improvements faster. BEHDVs benefits from the same rapid innovation and falling prices that have led battery-electrics to capture 18 percent of the new car market globally.[101] In the U.S., sales of BEHDVs are growing rapidly, for example increasing by 53 percent in the first half of 2023 compared to 2022.[102]

Drawing on a recently released BNEF forecast for HDV battery pack prices, this study presents an updated perspective on future expected HDV purchase costs. By 2030, in almost every case, a BEHDV will cost less than the diesel alternative, even before factoring in government incentives. Better than previously understood purchase cost competitiveness enhances BEHDVs' total ownership cost advantage.

For federal and state policymakers, our results mean a faster transition to BEHDVs is possible and optimal. For the U.S. Environmental Protection Agency , working to finalize proposed Phase 3 HDV emission standards, we conclude economic benefits are likely to exceed initial estimates. Similarly, for state-level policymakers considering adopting California's more rigorous HDV emissions controls, the economic payoff will be greater than previously expected.

Looking ahead, it is imperative for policymakers to prioritize staying attuned to the rapid advances in battery technology and evolving battery markets. By doing so, they can have the confidence needed to craft the policies needed to support an expeditious transition to cleaner, more affordable freight transport. Establishing clear long-term policy signals is crucial in catalyzing the investments needed to fully realize the potential benefits of electrifying HDVs.

REFERENCES

[1] Clean Air Task Force, "Deaths by Dirty Diesel: Mapping the Health Impacts of Diesel Nationwide," n.d., https://www.catf.us/deathsbydiesel/.

[2] Tony Barboza, "As 'diesel Death Zones' Spread, Pollution Regulators Place New Rules on Warehouse Industry," Los Angeles Times, May 8, 2021, https://www.latimes.com/california/story/2021-05-07/diesel-death-zones-trigger-new-pollution-rule.

[3] International Energy Agency, "Net Zero by 2050" (Paris: IEA, 2021), https://www.iea.org/reports/net-zero-by-2050.

[4] Sara F. Camilleri et al., "Air Quality, Health and Equity Implications of Electrifying Heavy-Duty Vehicles," *Nature Sustainability* 6, no. 12 (December 2023): 1643–53, https://doi.org/10.1038/s41893-023-01219-0.

[5] BloombergNEF, "Electric Vehicle Outlook 2023," 2023, https://assets.bbhub.io/professional/sites/24/2431510_BNEFElectricVehicleOutlook2023_ExecSummary.pdf.

[6] Hussein Basma et al., "Total Cost of Ownership of Alternative Powertrain Technologies for Class 8 Long-Haul Trucks in the United States," (International Council on Clean Transportation, April 2023), https://theicct.org/wp-content/uploads/2023/04/tco-alt-powertrain-long-haul-trucks-us-apr23.pdf.

[7] BloombergNEF, "EV Outlook 2023."

[8] Yihao Xie, Hussein Basma, and Felipe Rodríguez, "Purchase Costs of Zero-Emission Trucks in the United States to Meet Future Phase 3 GHG Standards" (International Council on Clean Transportation, March 2023), https://theicct.org/wp-content/uploads/2023/03/cost-zero-emission-trucks-us-phase-3-mar23.pdf.

[9] BloombergNEF, "EV Outlook 2023."

[10] Xie, Basma, and Rodríguez, "Purchase Costs of Zero-Emission Trucks in the United States."

[11] Xie, Basma, and Rodríguez, "Purchase Costs of Zero-Emission Trucks in the United States."

[12] Pierre-Louis Ragon et al., "Near-Term Infrastructure Deployment to Support Zero-Emission Medium- and Heavy-Duty Vehicles in the United States" (International Council on Clean Transportation, May 2023), https://theicct.org/wp-content/uploads/2023/05/infrastructure-deployment-mhdv-may23.pdf.

[13] Basma et al., "Total Cost of Ownership of Alternative Powertrain Technologies for Long-Haul Trucks."

[14] BloombergNEF, "EV Outlook 2023."

[15] Xie, Basma, and Rodríguez, "Purchase Costs of Zero-Emission Trucks in the United States."

[16] BloombergNEF, "EV Outlook 2023."

[17] Xie, Basma, and Rodríguez, "Purchase Costs of Zero-Emission Trucks in the United States."

[18] Rupert Way et al., "Empirically Grounded Technology Forecasts and the Energy Transition," *Joule*, September 13, 2022, https://doi.org/10.1016/j.joule.2022.08.009.

[19] Max Roser, "Learning Curves: What Does It Mean for a Technology to Follow Wright's Law?," Our World in Data, April 18, 2023, https://ourworldindata.org/learning-curve.

[20] Mike Brezonick, "Kenworth Launches Its First Electric Class 8 Truck," Power Progress, October 14, 2020, https://www.powerprogress.com/news/kenworth-launches-its-first-electric-class-8-truck/5034896.article.

[21] BloombergNEF, "EV Outlook 2023."

[22] Xie, Basma, and Rodríguez, "Purchase Costs of Zero-Emission Trucks in the United States."

[23] BloombergNEF, "EV Outlook 2023."

[24] Xie, Basma, and Rodríguez, "Purchase Costs of Zero-Emission Trucks in the United States."

[25] Basma et al., "Total Cost of Ownership of Alternative Powertrain Technologies for Long-Haul Trucks."

[26] Environmental Defense Fund, "Key Findings from Roush Industries Medium- and Heavy-Duty Cost Evaluation," February 22, 2022, https://blogs.edf.org/climate411/wp-content/blogs.dir/7/files/2022/02/FINAL-Roush-Fact-Sheet-2.10.22.pdf.

[27] Ari Kahn, Gerard Westhoff, and Dave Mullaney, "The Inflation Reduction Act Will Help Electrify Heavy-Duty Trucking," *Rocky Mountain Institute* (blog), August 25, 2022, https://rmi.org/inflation-reduction-act-will-help-electrify-heavy-duty-trucking/.

[28] U.S. Environmental Protection Agency, "Proposed Rule: Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles – Phase 3" (Federal Register, April 27, 2023), https://www.govinfo.gov/content/pkg/FR-2023-04-27/pdf/2023-07955.pdf.
[29] US Environmental Protection Agency, "Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles: Phase 3," Draft Regulatory Impact Analysis, April 2023, https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P10178RN.pdf.
[30] Jacob Richard, Jessie Lund, and Baha M. Al-Alawi, "Zeroing in on Zero-Emission Trucks: The State of the U.S. Market," White Paper (CALSTART, January 2024), https://calstart.org/wp-content/uploads/2024/01/ZIO-ZET-2024_010924_Final.pdf.
[31] Offce of Transportation and Air Quality, "Proposed Standards to Reduce Greenhouse Gas Emissions from Heavy-Duty Vehicles for Model Year 2027 and Beyond - Fact Sheet" (U.S. Environmental Protection Agency, April 2023), https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P101762L.pdf.
[32] Susan Anenberg et al., "A Global Snapshot of the Air Pollution-Related Health Impacts of Transportation Sector Emissions in 2010 and 2015" (International Council on Clean Transportation, 2019), https://theicct.org/wp-content/uploads/2021/06/Global_health_impacts_transport_emissions_2010-2015_20190226.pdf.
[33] Richard, Lund, and Al-Alawi, "Zeroing in on Zero-Emission Trucks."
[34] International Energy Agency, "Global EV Data Explorer," May 23, 2022, https://www.iea.org/data-and-statistics/data-tools/global-ev-data-explorer.
[35] Way et al., "Empirically Grounded Technology Forecasts"; Laurens Speelman and Yuki Numata, "Harnessing the Power of S-Curves" (Rocky Mountain Institute, October 2022), https://rmi.org/insight/harnessing-the-power-of-s-curves/.
[36] Evelina Stoikou, "Battery Prices Are Falling Again as Raw Material Costs Drop," *Bloomberg.Com*, November 26, 2023, https://www.bloomberg.com/news/articles/2023-11-26/battery-prices-are-falling-again-as-raw-material-costs-drop.
[37] Xie, Basma, and Rodríguez, "Purchase Costs of Zero-Emission Trucks in the United States."
[38] BloombergNEF, "Battery Pack Prices Fall to an Average of $132/kWh, But Rising Commodity Prices Start to Bite," November 30, 2021, https://about.bnef.com/blog/battery-pack-prices-fall-to-an-average-of-132-kwh-but-rising-commodity-prices-start-to-bite/.
[39] Xie, Basma, and Rodríguez, "Purchase Costs of Zero-Emission Trucks in the United States."
[40] Vishnu Nair et al., "Technical Review of Medium and Heavy-Duty Electrification Costs for MY [Model Year] 2027-2030" (Roush Industries, Inc & Environmental Defense Fund, February 2, 2022), https://blogs.edf.org/climate411/wp-content/blogs.dir/7/files/2022/02/EDF-MDHD-Electrification-v1.6_20220209.pdf; Basma et al., "Total Cost of Ownership of Alternative Powertrain Technologies for Long-Haul Trucks"; California Air Resources Board, "Appendix H. Draft Advanced Clean Trucks Total Cost of Ownership Discussion Document"; Chris Harto, "Electric Vehicle Ownership Costs: Today's Electric Vehicles Offer Big Savings for Consumers" (Consumer Reports, October 2020), https://advocacy.consumerreports.org/wp-content/uploads/2020/10/EV-Ownership-Cost-Final-Report-1.pdf.
[41] Basma et al., "Total Cost of Ownership of Alternative Powertrain Technologies for Long-Haul Trucks."
[42] Yihao Xie and Ray Minjares, "Deploy Charging Infrastructure in 'No Regrets' Freight Zones and Corridors to Keep U.S. Commercial Truck Electrification Aligned with Climate Goals," *International Council on Clean Transportation* (blog), December 13, 2023, https://theicct.org/deploy-charging-infrastructure-in-no-regrets-freight-zones-and-corridors-to-keep-us-commercial-truck-electrification-aligned-with-climate-goals-dec23/.
[43] Nair et al., "Medium and Heavy-Duty Electrification Costs."
[44] U.S. Environmental Protection Agency, "Proposed Rule: Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles – Phase 3."
[45] Environmental Defense Fund, "Key Findings from Roush Industries Evaluation."
[46] U.S. Environmental Protection Agency, "Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles: Phase 3."
[47] Kahn, Westhoff, and Mullaney, "The Inflation Reduction Act Will Help Electrify Heavy-Duty Trucking."
[48] International Energy Agency, "Net Zero by 2050."
[49] Camilleri et al., "Air Quality, Health and Equity Implications of Electrifying Heavy-Duty Vehicles."
[50] Kenneth Davidson et al., "The Recent and Future Health Burden of the U.S. Mobile Sector Apportioned by Source," *Environmental Research Letters* 15, no. 7 (July 2020): 075009, https://doi.org/10.1088/1748-9326/ab83a8.

[51] Clean Air Task Force, "Deaths by Dirty Diesel," n.d., https://www.catf.us/deathsbydiesel/.
[52] Research Division, "Diesel Particulate Matter Health Impacts Summary," California Air Resource Board, n.d., https://ww2.arb.ca.gov/resources/summary-diesel-particulate-matter-health-impacts.
[53] Office of Transportation and Air Quality, "EPA Announces the 'Clean Trucks Plan'" (U.S. Environmental Protection Agency, August 2021), https://www.epa.gov/system/files/documents/2021-08/420f21057.pdf.
[54] Susan C. Anenberg et al., "Impacts and Mitigation of Excess Diesel-Related NOx Emissions in 11 Major Vehicle Markets," *Nature* 545, no. 7655 (May 2017): 467–71, https://doi.org/10.1038/nature22086.
[55] Office of Research and Development, U.S. Environmental Protection Agency, "Research on Near Roadway and Other Near Source Air Pollution," November 27, 2023, https://www.epa.gov/air-research/research-near-roadway-and-other-near-source-air-pollution.
[56] Sarah E. Chambliss et al., "Local- and Regional-Scale Racial and Ethnic Disparities in Air Pollution Determined by Long-Term Mobile Monitoring," *Proceedings of the National Academy of Sciences* 118, no. 37 (September 14, 2021): e2109249118, https://doi.org/10.1073/pnas.2109249118.
[57] Xie, Basma, and Rodríguez, "Purchase Costs of Zero-Emission Trucks in the United States."
[58] Xie, Basma, and Rodríguez, "Purchase Costs of Zero-Emission Trucks in the United States."
[59] Xie, Basma, and Rodríguez, "Purchase Costs of Zero-Emission Trucks in the United States."
[60] BloombergNEF, "Battery Pack Prices Fall."
[61] Yusuf Khan, "Low Battery Metal Prices Set to Persist in 2024, Adding Friction to Energy Transition," *Wall Street Journal*, December 28, 2023, https://www.wsj.com/articles/low-battery-metal-prices-set-to-persist-in-2024-adding-friction-to-energy-transition-3773ba00.
[62] Khan, "Low Battery Metal Prices Set to Persist in 2024."
[63] Way et al., "Empirically Grounded Technology Forecasts."
[64] Way et al., "Empirically Grounded Technology Forecasts."
[65] François Lafond et al., "How Well Do Experience Curves Predict Technological Progress? A Method for Making Distributional Forecasts," *Technological Forecasting and Social Change* 128 (March 1, 2018): 104–17, https://doi.org/10.1016/j.techfore.2017.11.001.
[66] Roser, "Learning Curves and Wright's Law."
[67] Roser, "Learning Curves and Wright's Law."
[68] Way et al., "Empirically Grounded Technology Forecasts."
[69] Way et al., "Empirically Grounded Technology Forecasts."
[70] International Energy Agency, "World Energy Investment 2023."
[71] International Energy Agency, "World Energy Investment 2023," May 2023, https://www.iea.org/reports/world-energy-investment-2023.
[72] BloombergNEF.
[73] Kate McAlpine, "1,000-Cycle Lithium-Sulfur Battery Could Quintuple Electric Vehicle Ranges," University of Michigan News, January 12, 2022, https://news.umich.edu/1000-cycle-lithium-sulfur-battery-could-quintuple-electric-vehicle-ranges/.
[74] Mingqiang Wang et al., "Multifactorial Engineering of Biomimetic Membranes for Batteries with Multiple High-Performance Parameters," *Nature Communications* 13, no. 1 (January 12, 2022): 278, https://doi.org/10.1038/s41467-021-27861-w.
[75] BloombergNEF, "EV Outlook 2023."
[76] BloombergNEF, "EV Outlook 2023."
[77] BloombergNEF, "Race to Net Zero: The Pressures of the Battery Boom in Five Charts," July 21, 2022, https://about.bnef.com/blog/race-to-net-zero-the-pressures-of-the-battery-boom-in-five-charts/.
[78] Xie, Basma, and Rodríguez, "Purchase Costs of Zero-Emission Trucks in the United States."
[79] BloombergNEF, "EV Outlook 2023."
[80] Xie, Basma, and Rodríguez, "Purchase Costs of Zero-Emission Trucks in the United States."
[81] BloombergNEF, "EV Outlook 2023."
[82] Xie, Basma, and Rodríguez, "Purchase Costs of Zero-Emission Trucks in the United States."

[83] Frank Deandro, “Https://Www.Flickr.Com/Photos/44576730@N06/8388886890/,” Creative Commons 2.0, January 17, 2013, https://www.flickr.com/photos/44576730@N06/8388886890/.
[84] BloombergNEF, “EV Outlook 2023.”
[85] Xie, Basma, and Rodríguez, “Purchase Costs of Zero-Emission Trucks in the United States.”
[86] BloombergNEF, “EV Outlook 2023.”
[87] Xie, Basma, and Rodríguez, “Purchase Costs of Zero-Emission Trucks in the United States.”
[88] Xie, Basma, and Rodríguez, “Purchase Costs of Zero-Emission Trucks in the United States.”
[89] BloombergNEF, “EV Outlook 2023.”
[90] Xie, Basma, and Rodríguez, “Purchase Costs of Zero-Emission Trucks in the United States.”
[91] U.S. Environmental Protection Agency, “Proposed Rule: Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles – Phase 3,” Federal Register, April 27, 2023, https://www.govinfo.gov/content/pkg/FR-2023-04-27/pdf/2023-07955.pdf.
[92] Xie, Basma, and Rodríguez, “Purchase Costs of Zero-Emission Trucks in the United States.”
[93] Xie, Basma, and Rodríguez, “Purchase Costs of Zero-Emission Trucks in the United States.”
[94] U.S. Environmental Protection Agency, “Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles: Phase 3,” Draft Regulatory Impact Analysis, April 2023, https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P10178RN.pdf.
[95] Xie, Basma, and Rodríguez, “Purchase Costs of Zero-Emission Trucks in the United States.”
[96] U.S. Environmental Protection Agency, “Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles: Phase 3.”
[97] BloombergNEF, “EV Outlook 2023.”
[98] BloombergNEF, “EV Outlook 2023.”
[99] BloombergNEF, “EV Outlook 2023.”
[100] Xie, Basma, and Rodríguez, “Purchase Costs of Zero-Emission Trucks in the United States.”
[101] Nathaniel Bullard, “Decarbonization: Stocks and Flows, Abundance and Scarcity, Net Zero,” https://www.nathanielbullard.com/presentations.
[102] Jacob Richard, Jessie Lund, and Baha M. Al-Alawi, “Zeroing in on Zero-Emission Trucks: The State of the U.S. Market,” White Paper (CALSTART, January 2024), https://calstart.org/wp-content/uploads/2024/01/ZIO-ZET-2024_010924_Final.pdf.