National Center for Sustainable Transportation
A USDOT University Transportation Center

Research Report

April 2025

Review and Analysis of Current and Future Battery Technologies for Heavy Duty Electric Vehicles

Bingtao Hu, University of Southern California

Petros Ioannou, University of Southern California

METRANS Transportation Consortium
USC | CSULB

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NCST-USC-RR-25-10	N/A	N/A

4. Title and Subtitle Review and Analysis of Current and Future Battery Technologies for Heavy Duty Electric Vehicles	**5. Report Date** April 2025 **6. Performing Organization Code** N/A
7. Author(s) Bingtao Hu, https://orcid.org/0009-0007-5215-4967 Petros Ioannou, Ph.D., https://orcid.org/0000-0001-6981-0704	**8. Performing Organization Report No.** N/A
9. Performing Organization Name and Address University of Southern California METRANS Transportation Consortium University Park Campus, VKC 367 MC:0626 Los Angeles, California 90089-0626	**10. Work Unit No.** N/A **11. Contract or Grant No.** Caltrans 65A0686 Task Order 088 USDOT Grant 69A3552348319 and 69A3552344814
12. Sponsoring Agency Name and Address U.S. Department of Transportation Office of the Assistant Secretary for Research and Technology 1200 New Jersey Avenue, SE, Washington, DC 20590 California Department of Transportation Division of Research, Innovation and System Information, MS-83 1727 30th Street, Sacramento, CA 95816	**13. Type of Report and Period Covered** Final Research Report (June 2024 – December 2024) **14. Sponsoring Agency Code** USDOT OST-R Caltrans DRISI

15. Supplementary Notes
DOI: https://doi.org/10.7922/G2736P76

16. Abstract
The transportation sector contributes significantly to emissions, with heavy-duty (HD) vehicles responsible for a disproportionately large share. Zero-emission trucks, particularly battery electric trucks (BETs), have emerged as potential solutions to reduce these emissions. BETs offer benefits such as high energy efficiency with low operating noise while facing the challenges such as range anxiety and inadequate infrastructure. This report presents a survey of the latest advancements in battery technologies and primarily focusing on Class 7 and Class 8 heavy-duty vehicles due to their critical role in freight transport. This report further provides information of the status and future expectations of BETs. Finally, a feasibility analysis is presented to assess the battery requirement and operating cost for a 410-mile route from Long Beach, CA to San Francisco, CA. The results highlight the importance of charging scheduling and strategic planning for infrastructure to lower the operating cost and accelerate the widespread adoption of zero-emission trucks. These findings aim to offer insights for policymakers and researchers working toward sustainable freight transport.

17. Key Words		18. Distribution Statement	
Battery electric truck, state of charge, operating cost		No restrictions.	
19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified	Unclassified	44	N/A

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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Acknowledgments

This study was funded, partially or entirely, by a grant from the National Center for Sustainable Transportation (NCST), supported by the U.S. Department of Transportation (USDOT) and the California Department of Transportation (Caltrans) through the University Transportation Centers program. The authors would like to thank the NCST, the USDOT, and Caltrans for their support of university-based research in transportation, and especially for the funding provided in support of this project.

Review and Analysis of Current and Future Battery Technologies for Heavy Duty Electric Vehicles

A National Center for Sustainable Transportation Research Report

Bingtao Hu, Ming Hsieh Department of Electrical Engineering, University of Southern California

Petros Ioannou, Ming Hsieh Department of Electrical Engineering, University of Southern California

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Executive Summary

The transportation sector contributes significantly to emissions, with heavy-duty (HD) vehicles responsible for a disproportionately large share. Zero-emission trucks, particularly battery electric trucks (BETs), have emerged as potential solutions to reduce these emissions. BETs offer benefits such as high energy efficiency with low operating noise while facing the challenges such as range anxiety and inadequate infrastructure.

This report provides a comprehensive survey of the latest technologies related to Class 7 and Class 8 battery electric heavy-duty vehicles. It introduces the requirements of batteries used in BETs and examines the current battery technologies available considering their key performance indicators. The findings indicate that lithium-ion technology is approaching its inherent limitations and will reach its performance bottleneck. Its specific energy and energy density are unlikely to meet the increasing performance demands for electric trucking industry. The study then evaluates the emerging batteries, such as solid-state and lithium-sulfur batteries, and explores their potential applications in BETs. Additionally, it discusses charging standards and the current and future charging infrastructure, including megawatt charging systems (MCS) and battery swapping technologies. Infrastructure support is as crucial as the electric vehicle itself. For passenger vehicles, charging stations at parking areas along with apps to locate them and notify users when charging is completed, helps minimize the inconvenience associated with refueling. Similarly, for trucks, diverse charging methods, such as overnight charging at depots and innovative solutions like battery swapping, can also help mitigate the inconvenience of long charging times.

Several manufacturers have already developed and published battery-operated trucks. These include Tesla, Volvo, Daimler Benz, etc. This report presents the specifications of current BETs that are on the market. The findings show that current ranges for class 8 BETs vary from 150 to 300 miles on a full charge. Some advanced models like Tesla Semi aim for ranges up to 500 miles. The initial purchase cost of the current BET is still high compared to the diesel operated vehicles of similar size. However, we are interested in exploring the operating cost given the current BET technologies and current infrastructures. Using an energy consumption model and specific assumptions, a case study is conducted on the 410-mile route from Long Beach to San Francisco to assess the feasibility of BET operations. The result indicates that the operating cost of BETs is sensitive to the charging price.

The findings of this report indicate that current BETs can achieve operating cost parity with diesel trucks for short-haul and regional routes. However, they face challenges for long-

haul trips due to insufficient infrastructures and battery limitations. The result highlights the importance of charging scheduling and strategic planning for infrastructure and provides insight for the effective deployment of current BETs.

1. Introduction

The transportation sector is responsible for a significant portion of emissions globally as well as energy consumption [1]. In the U.S., transportation contributed 29% of U.S. emissions in 2021 [2]. In Europe, transportation contributed 782 million tons of emissions in 2021, accounting for 22.7% of total emissions for the year [3]. Decarbonizing heavy duty vehicles are crucial to alleviate emissions from the transportation sectors, as they have a highly disproportionate contribution to emissions. Globally, heavy-duty vehicles make up about 11% of motor vehicles but account for nearly half (46%) of vehicle carbon dioxide (CO_2) emissions and over two-thirds (71%) of vehicle particulate emissions [4]. Moreover, motorized traffic is major source of air pollutants such as nitrogen oxides (NO_X) and suspended particulate matter emissions. Medium- and heavy-duty vehicles contribute about 32% of mobile source NO_X emissions in the U.S. in 2017. These harmful emissions from heavy duty trucks in city traffic threatens public health and lead to an increased risk of mortality and respiratory morbidity, particularly in communities that are overburdened and underserved [5, 6].

To address or at least alleviate emissions and air pollution generated by heavy duty vehicles, zero emission trucks are needed. Two feasible options are battery electric trucks (BETs) and fuel cell electric trucks (FCETs). The first electric-powered carriage came out in the early 19th century when horses and buggies were the primary means of transportation. However, the first prototype was powered by non-rechargeable battery, and significant advancements in electric vehicles (EV) didn't occur until the 1880s and 1890s, several decades after Anderson's initial creation of an EV and after Faure's improvement on the lead-acid battery [7, 8]. Electric trucks emerged almost in the same age as the first electric cars. EVs, including trucks, were popular in the early 20th century due to their quiet, smooth operation and absence of tailpipe emissions. Nevertheless, electric trucks began to lose ground to the internal combustion engine (ICE) counterparts in the late 1920s owing to their longer range, quicker refueling, and widespread availability [9]. It wasn’t until the 21st century that significant attention returned to electric trucks, and companies started investing in electric trucks, driven by stricter emissions regulations and a shift towards sustainability. Certain benefits owing to the electric powertrain include the absence of tank-to-wheel emissions, high energy efficiency, and significantly reduced operating noise [10]. In addition, EVs cost less to operate as they do not need regular oil changes, and regenerative braking allows for less brake wear [11, 12]. However, due to concerns such as range anxiety, availability of charging infrastructure, and high upfront cost, BETs are still in their infancy. At the same time, FCETs serve as a critical supplement to BETs offering distinct advantages for users. The convenience of FCETs stems from their ability to cover long distances and their long range on a single refueling cycle, making them particularly suitable for long haul transportation [13]. The overall development strategy for trucks in chronological order and the classification of zero-emission trucks are illustrated in Figure 1. The popularity of ICE dominated the market until communities and states became more sensitive to pollution. The lack of reliable technologies to replace the ICE and yet maintain a similar performance with respect to range and refueling time led to hybrid engines which provided intermediate solutions as fully electric propulsion systems began to emerge.

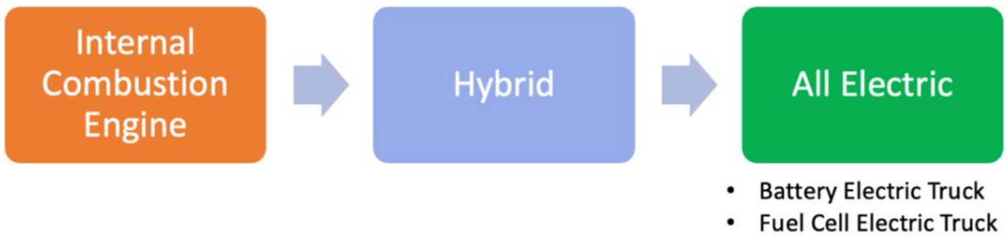

Figure 1. Development strategy for zero-emission trucks.

This report reflects the state-of-the-art technologies of BETs and their future expectations. This involves examining battery and charging technologies, analyzing charging infrastructures, and examining the feasibility and operating cost. Analysis of the status of BETs and related technologies is a vital step to promote the widespread adoption of zero-emission vehicles and encourage more research in advancing control and optimization strategies of zero emission heavy-duty trucks and related fields. The report mainly focuses on heavy-duty trucks, specifically Class 7 and Class 8 vehicles, due to their significant contribution to emissions within the freight transport sector.

2. Review of Current and Future Projections of Advanced Battery Technologies

The battery is a crucial component in electric trucks. Its weight, size, cost, and energy density are some of the important measures that determines EV's safety, performance, and usability. This section explores the various battery technologies currently being employed in EVs, examining their characteristics, advantages, and challenges. In general, a rechargeable battery works as an energy storage system in EVs and converts chemical energy into electrical energy which drives the motors that generate motion. During discharge phase, the anode of a rechargeable battery loses electrons which travel through an external circuit to the cathode, while simultaneously ions move through the electrolyte. This flow of electrons through an external circuit provides the electrical energy to power motor that moves the vehicle. During recharge phase, an external electrical energy source is coupled to the battery, which forces the electrons to flow in the opposite direction compared to when the battery discharges. This reverse flow of electrons effectively reverses the chemical reactions that occur at each electrode and increases the chemical potential energy, thus recharging the battery [14]. The first rechargeable battery used in vehicles was a lead-acid battery invented by French physicist Gaston Plante in 1859 [15]. In the following century, nickel-based and lithium-based batteries emerged and became widely adopted in automobiles [16, 17]. In the late 20^{th} century, the booming of energy storage technologies such as lithium-ion batteries (LIBs) has led to advances in EVs. In recent years, LIBs have still been widely used in commercial EVs as a result of their high energy density, long battery life, and high safety [18]. This section conducts a literature review on some battery storage systems (BSS) used in BETs and discusses their key performance indicators such as lifetime, power (density and specific), energy, etc. Literature reviews are presented in the sequence, which includes battery technologies in use today and future developments [19-25].

2.1 General Requirements for Batteries in BEVs and Medium/Heavy-duty BETs

Battery attributes, including safety, performance, energy density, cost, and fast charging availability are the major factors for consideration for BEV application [20, 26]. Above all, safety is the most critical factor in EV battery design due to the severe risks associated with battery failure which may lead to explosion and/or fire. International regulations mandate rigorous testing for EV batteries, such as impact, thermal, and vibration tests, before they enter the market [26]. Failures can result from external factors (such as crashes or overcharging) or internal issues (like lithium dendrite growth), leading to heat generation, exothermic reactions, and potentially thermal runaway. These issues require new battery materials that have a good balance between safety and performance. In addition to materials, safety features for EV batteries such as fuses, vents, current interrupt devices, and battery management systems also help reduce safety risks.

Besides safety, the driving range is another concern, as the limited energy density of batteries compared to fossil fuels plus the confined space and weight of a truck can limit the driving range of BETs. According to a report by IEEE Spectrum [27], the best energy density currently available for LIBs is around 750 Wh/L (Watt hour per Liter). However, Panasonic has promised to reach about 850 Wh/L by 2025 and eventually aims to reach a 1,000-Wh/L product. Next-generation batteries are expected to exceed the energy densities of LIBs, with a predicted energy density of >750 Wh/L and >350 Wh/kg (Watt hour per kilogram). Table 1 demonstrates a more specific goal for battery energy density reproduced from [28].

Table 1. Battery density targets for EVs.

Speciation	Unit	Targets in 2020	Targets in 2025	Targets in 2030
Cell level specific energy	Wh/kg	350	400	500
Pack level specific energy	Wh/kg	250	280	350
Cell level energy density	Wh/L	650	800	1000
Pack level energy density	Wh/L	320	500	700

In terms of cost, the battery pack is usually the most expensive component in an EV, constituting around 40% of the total manufacturing cost [24, 29]. The cost of the battery pack consists of component manufacturing, cell production, module production, and pack assembly [30]. Although battery prices have dropped dramatically in the past few years, the cost of the battery is still an important consideration in developing future battery technology as well as promoting BETs. The price of the battery pack was reported to be $139/kWh in November 2023, and it's still going down [31, 32]. The expected battery pack and cell cost should be below $125/kWh and $100/kWh, respectively, to have a comparable cost to ICE vehicles based on today's oil prices [20]. Lowering the pack costs to under $40-50 per kWh would significantly speed up the transition to EVs. However, this target is becoming more challenging to achieve. The improvements in the energy density of the highest performance LIB has slowed down to 1-2% annually as the technology has matured [33]. Several strategies can be employed to minimize expenses. One approach is to use high-energy density materials, which can decrease the material volume and thus reduce the energy-normalized cell cost. An alternative approach is to substitute current materials with cheaper options. For example, replacing lithium with sodium could lower the EV cell material costs from 1.5-3% without changing the cell manufacturing process, depending on the price of lithium and copper. However, these substitutions currently can result in a 15-40% decrease in cell energy density, which subsequently raises the energy-normalized cell cost and the cost of the battery management system which is considered uneconomical at present as well as in the near future [33].

Charging time is a critical aspect of the EV customer experience, alongside driving range. While current BETs often require hours to fully charge, which is suitable for overnight or workplace charging, this becomes inconvenient for long-haul trucking that requires mid-shift recharging. Recent advancements such as MCS (megawatt charging system) have enhanced EVs' charging capabilities, significantly reducing charging times. However, to achieve the goal of charging EVs to 80% SOC within 10 to 15 minutes, further efforts on fast charging are needed. The main challenge for fast charging is related to cell chemistry and material properties. In LIBs, lithium ions move between the cathode and anode during charging, but the speed is limited by intercalation rate and ion diffusivity. High charging rates cause lithium plating on the anode and a rapid temperature rise, impacting capacity, lifespan, and safety. Solutions include pre-warming cells to enhance electrode kinetics and using higher voltage systems to lower current levels. Optimizing charging algorithms to enable fast charging without compromising battery life and safety is essential for future EVs.

2.2 Current Generation of Batteries

The most popular battery types we use today are the LIB and lead-acid battery. In EV industry, the current generation of batteries is primarily focused on lithium-based technologies. They can be classified into Li-ion, lithium-ion polymer (LIPO), and lithium-metal (Li-metal) or solid-state variants based on the electrolyte. Rechargeable LIB is the most common type of battery proposed for battery power packs in BETs. It has been extensively used in EV applications owing to its high energy density (250–693 Wh/L and 100–265 Wh/kg [20]), high energy efficiency, long lifecycle and not having memory effect [34]. At the cell level, LIB cells comprise a carbon or silicon-carbon anode, a layered metal oxide cathode, and the electrolyte, typically a Li-salt mixed in an organic solvent. Due to the liquid properties, Li-ion batteries have a narrow range of operating temperatures. Typical operating temperatures ranges from 0 to 45℃ for charging and -20 to 60 ℃ for discharging [35]. The cathode is a critical component among the major component of a LIB cell, as it directly influences the operating voltage and capacity, thereby influencing the energy density of cells and batteries. It is also the most expensive component of the battery cost followed by manufacturing cost and then the anode. Consequently, selecting an appropriate cathode material is essential for building reliable batteries for EVs [36]. The choice for cathode varies among EV manufactures, such as LCO ($LiCoO_2$), LFP ($LiFePO_4$), LMO ($LiMn_2O_4$), NMC ($LiNiMnCoO_2$), and NCA ($LiNiCoAlO_2$). The LIPO battery, similar to the LIB but with polymer-based electrolytes, delivers higher specific energy and power but it exhibits functional instability both during overload conditions and when the battery discharges below a certain value [37]. It should be noted that while an increased specific energy is desirable, achieving this comes at the expense of a higher overall manufacturing cost [24]. The LIPO battery is considered an intermediate step between current and future battery technologies, whereas Li-metal batteries are viewed as the batteries of the future. However, since Li-metal batteries are mainly primary (non-rechargeable) batteries, we do not consider it as a candidate for EV applications.

Based on the cell designs, LIBs can be also categorized into three types: cylindrical, prismatic, and pouch cells [38, 39]. The cylindrical cell, commonly used in EVs, consists of a steel cylindrical casing which provides strength and protection. The well-established manufacturing processes make it well suited for high-speed automatic mass production, which keeps the cost low compared to the other two types. On the other hand, the cylindrical cells leave gaps when packed, which reduces the pack level energy density. The prismatic cell is characterized by its rectangular or square shape. Owing to the shape and the stackable design, the prismatic cell offers high energy density compared to the other two battery types. It also offers advantages in battery thermal management due to its cubic shape which help heat dissipation [40]. Unlike the other two types, pouch cells have a flexible (soft casing) and pouch-shaped design. This type of battery is often used in consumer electronics which require light weight but might not be suitable for EVs due to concerns about the safety of cells' swelling and bulging. They have been gradually marginalized over the past few years [41].

2.3 Future Generation of Batteries

The current generation Li-ion battery comprises some essential minerals that are becoming increasingly challenging to extract and process. As demand for these batteries continues to grow, the scarcity and environmental impact pose significant challenges in achieving an economic transition to electrified transportation. Moreover, Li-ion technology is approaching its inherent limitations and will inevitably reach its bottleneck. Its specific energy and energy density will no longer be sufficient for the increasing performance demands for electric trucking industry. To address these challenges, the development of the "future generation of batteries" is critical. These future batteries must match and exceed the performance metrics of the current Li-ion technology [22]. Current research works are focused on creating and refining these advanced batteries, which have significant potential for commercialization and application in the EV industry. This new generation includes using novel materials such as using silicon-based anodes and sulfur-based cathodes, as well as new battery designs such as solid-state batteries and metal-air batteries. The following subsections provide an overview that discusses the motivations and challenges of selected "future generation of batteries."

A. Silicon Anodes [42]

Silicon anode batteries are the type of LIBs that replace graphite anode with silicon as the primary material. The maximum energy density of a Li-ion cell is primarily determined by two key factors: the cell voltage and the specific capacities of the anode and cathode. Among known Li-ion anode materials, silicon stands out with the highest specific capacity of 4200 mAh/g. Compared to the specific capacity of carbon, which is around 300 mAh/g, silicon provides a higher energy density. It also offers reduced propensity for lithium plating during fast charging owing to its high lithiation potential. It also offers enhanced safety as silicon is less flammable than carbon. However, silicon undergoes a massive volume change during cycling which leads to anode pulverization (a physical degradation of the anode material in batteries), which in turn leads to a loss of electric connectivity.

B. Lithium-sulfur (Li-S)

The Li-S battery uses lithium as the anode and sulfur as the cathode. Sulfur's high gravimetric capacity and low cost make it attractive for achieving high energy density in Lithium-sulfur batteries. Theoretically, Li-S batteries can achieve energy density exceeding 2000 Wh/kg which is over 400% increase in pack-level energy density. There have been notable advancements in this area since the 1960s [43]. However, Li-S batteries have several challenges that limit their commercial application, including low electronic conductivity, the complexity of multi-electron reactions, and the issue of soluble lithium polysulfide intermediates [44]. Despite these challenges, some researchers are optimistic about the future application of lithium-sulfur batteries for high-energy electric and hybrid propulsion.

C. Sodium-ion (Na-ion)

The Na-ion battery is a type of rechargeable battery that utilizes sodium ions as charge carriers. Its operational concept and design are similar to that of the Li-ion battery, with the primary distinction being the substitution of lithium with sodium [45]. Na-ion batteries emerge as one of the most promising next-generation energy storage technology owing to their low cost and the global abundance of sodium [46]. The cost can be further reduced by employing cobalt/nickel-free cathode materials and using aluminum for the anode current collector [47]. The configuration of Na-ion batteries also provides a potentially safe alternative for battery storage and transportation because the aluminum current collector does not dissolve into the electrolyte at 0 V, allowing Na-ion batteries to be shipped and stored safely in a fully discharged state [48]. However, Na-ion are larger and heavier than lithium ions, which reduces the energy density.

D. Solid-State Batteries (SSBs)

SSBs use a solid electrolyte instead of the liquid or gel polymer electrolytes in conventional LIBs. The key advantages of solid-state batteries include higher energy densities and improved safety since they do not have a liquid electrolyte which can lead to leaking and thermal runaway. Several solid-state electrolytes have been developed for SSBs. First are the solid oxide electrolytes containing natrium superionic conductor (NASICON) type, perovskite-type, garnet-type, amorphous/glass-type, etc. The second is solid sulfide electrolytes such as $\mathrm{Li_2}S\text{–}\mathrm{P_2}S_5, \mathrm{Li_2}S\text{–}SiS_2$, and thio-Li super ionic conductor (thio-LISICON) based electrolytes. The third is solid polymer electrolytes (SPEs) consisting of poly (ethylene oxide) (PEO) and PEO-like based SPEs, non-polyether, and single Li-ion conducting based SPEs [49]. Among solid-state batteries, lithium-sulfur (Li-S) and lithium-air (Li- O_2) batteries are the most promising products from the perspective of automakers due to their remarkably increased energy density and driving range for EVs [22]. SSBs can theoretically achieve energy density exceeding 500 Wh/kg. That is, around 50% pack-level energy density increase, approaching the need for electrified heavy trucks. On the other hand, SSBs have several problems, such as the significant external pressures required, interfacial charge-transfer process issues, and poor cycling performance.

E. Metal-Air

A metal-air battery generates electricity through the reaction of a pure metal anode with oxygen from the air and has high energy density potential. The metal-air family includes zinc-air, aluminum-air, iron-air, magnesium-air, calcium-air and lithium-air. Zinc-air battery is the most promising one and have been commercially available for decades for both consumer and industrial applications, such as hearing aids uses, but is still under extensive research [50, 51]. Lithium-Air (Li-O_2) batteries have the highest energy density potential and can be divided into four categories based on their electrolytes: nonaqueous, aqueous, hybrid aqueous/nonaqueous, and solid-state [23]. The Li-O_2 battery with nonaqueous electrolytes has the potential to achieve an extremely high specific energy of approximately 11,700 Wh/kg, which is comparable to gasoline [23]. The high specific energy of the Li-O_2 battery with nonaqueous electrolytes makes it a promising candidate for use in EVs and other applications that require high energy density. However, there are still several technical challenges that need to be addressed before the Li-O_2 battery can be commercialized, such as the development of stable cathodes, electrolytes, and anodes. The Li-O_2 batteries with aqueous electrolytes have a high risk of battery burning but have a relatively low decomposition voltage. The hybrid aqueous/nonaqueous Li-O_2 battery combines the advantages of both electrolytes. Researchers have made significant efforts to identify the causes and search for probable approaches to improve the operational efficiency and cycle life of Li-O_2 batteries, particularly for electrode protection. However, challenges still persist, and fundamental research is necessary for several years to commercialize Li-O_2 batteries.

To conclude, Table 2 provides a comparison of theoretical performance for some selected future generation of batteries. Future generations of battery technology have the potential to improve energy density and reduce costs, addressing market demands and technical requirements for heavy trucks. Emerging concepts such as the abovementioned SSBs and Li-S batteries would be highly impactful on the industry.

Table 2. Theoretical performance metrics of emerging batteries.

Battery Type	Energy Density (Wh/L)	Specific Energy (Wh/kg)	Cycle life (cycles)
Si/ SiO_x anode [52, 53]	1000	500	500
Na-ion [54]	250-500	150	100-500
Li-S [55]	400-600	2600	1500
Li-O_2 [56]	1200	900	200-1000

3. Review of the Status of HD Battery-Electric Trucks

This section reviews the status of electric trucks with respect to performance, costs, and infrastructure support. Table 3 tabulates the key aspects of selected heavy-duty BEVs currently in the market. These vehicles highlight the current advancement in BET technologies. In particular, the nominal ranges for class 8 BETs claimed by the manufacturers vary from 150 to 300 miles on a full charge and can satisfy most local and regional operations. Some advanced models like Tesla Semi aim for ranges up to 500 miles. However, the actual driving range could be significantly lower due to the environmental conditions, the use of peripherals such as air conditioning, and driving behaviors. For example, the North American Council for Freight Efficiency organized a "Run on Less – Electric DEPOT" event to explore the deployment of electric trucks which features 15+ class 3 to class 8 heavy duty BEVs [57]. Data collected during the event revealed the gap between the actual range of BETs and the figure claimed by manufacturers. This discrepancy is related to payload weight, driving speed, and environmental conditions, all of which can impact energy consumption and the vehicle's range. For instance, the Tesla semi tuck 1 at PepsiCo (Sacramento) depot exhibited an actual range of approximately 400 miles on day 11 under various conditions, as opposed to the expected 500-mile range.

Comparatively, conventional trucks still have a significant advantage over BETs, as they travel up to 2000 miles without refueling. On the other hand, considering the maximum driving time of 11 hours within 24 hours and the 30-minute mandatory break after eight consecutive hours of driving, a driver who travels 65 miles per hour in average during an 11-hour shift covers 715 miles daily. According to the California Trucking Association, most long-haul drivers run about 500 miles daily. Charging during mandatory breaks and loading intervals would enable electric semi-trucks to uphold efficient schedules. However, today's BETs use the same charging standard as passenger EVs. Most have a maximum charging power between 200 kW and 400 kW, though the Tesla Semi stands out with the capability of reaching 1 MW (megawatt) charging level. For most class 8 BETs shown in Table 3, the charging levels require about 90 minutes to recharge from 0% to 80% SOC. This charging time increases the cost of operation when comparing to the 10-15 minutes refueling time for a class 8 diesel truck with 300-gallon tank [58]. Therefore, as of today, BETs have primarily been used in drayage applications [59].

Table 3. Current BETs.

Class		GCW (lbs)	Battery Capacity (kWh)	Typical Range (miles)	Max Charging Power (kW)	Recharge Time (80%)	Max Power (HP)	Estimated Cost ($) [60]
Class 8 (33001 – 80000 lbs)								
Freightliner eCascadia [61]	Single drive	65000	438	230	270	90 min (CCS1 @ 600 A)	395	210,000
	Tandem drive	82000	438	220	270	90 min (CCS1 @ 600 A)	470	
Volvo VNR Electric [62]	6X4 Tractor	82000	565	275	250	90 min (@250 kW)	455	200,000
	6x2 Tractor	82000	565	275	250	90 min (@250 kW)	455	
	4x2 Tractor	66000	375	175	250	60 min (@250 kW)	455	
LION8 [63]	Chassis	54600	252	142	-	90 min	470	230,000-307,000 [64]
	Tractor	82000	630	250	-	90 min	536	
NIKOLA TRE BEV [65]		82000	738	330	350	90 min (@350 kW)	645	-
BYD 8TT [66, 67]		105000	563	200	185	210 min	483	-
Tesla Semi [68, 69]		82000	850-1000	500	1000	30 min (70%)	1500	150,000-180,000
Mercedes eActros 600 [70]		97000	621	310	400	60 min (CCS2 @ 500 A)	600	-

Class		**GCW (lbs)**	**Battery Capacity (kWh)**	**Typical Range (miles)**	**Max Charging Power (kW)**	**Recharge Time (80%)**	**Max Power (HP)**	**Estimated Cost ($) [60]**
Class 6-7 (19501 – 80000 lbs)								
Freightliner eM2 [71]	Cl6 (Single Motor)	26000	194	180	180	60 min (CCS1 @ 400 A)	190	~139,000
	Cl7 (Dual Motor)	33000	291	250	180	90 min (CCS1 @ 400 A)	255	
LION6 [63]	Chassis	26000	252	218	-	120 min	335	-

The popularization of today's heavy duty BEVs also face the challenge such as the high upfront costs for both vehicles and charging infrastructure make BETs adoptions economically challenging [72]. The total cost of ownership of a BET consists of capital cost (truck price), maintenance costs, and the life time fuel costs (charging costs) [73]. Among these, the capital cost is heavily influenced by the battery price, often the most significant factor. Current BET technologies are equipped with LIBs, classified by their cathode materials, such as LFP, NCA, and NMC. For example, the Tesla Semi is equipped with the Tesla 4680 cell, which uses an NMC-811 cathode [74, 75]. However, the battery details are unpublished by most BET manufactures. For reference, Table 4 provides a summary of some popular battery types and their estimated key performance indicators [76].

Table 4. LIB types and key performance indicators.

Li-ion battery type	Specific energy (Wh/kg)	Energy density (Wh/L)	Cost ($/kWh)
NMC-111	180	400	145
NMC-532	220	500	130
NMC-622	260	650	100
NMC-811	280	700	90
NCA	280	750	90
LFP	185	430	80

Furthermore, current infrastructure support, including depot charging and charging networks, also challenges the transition to BETs. Existing charging infrastructure is mainly designed for passenger EVs and light-duty EVs. Charging options for heavy duty BEVs are very limited. However, electric truck charging infrastructure developers are expanding their public charging networks for fleets in California as well as nationwide. WattEV, for example, received $75.6 million to expand Westcoast electric truck charging corridor [77], while Greenlane announced a plan to build an 280-mile EV charging corridor along interstate 15, connecting Los Angeles and Las Vegas for freight transportation [78]. Similarly, Terawatt is constructing a network of charging stations for BETs along interstate 10, spanning from the Port of Long Beach, CA to El Paso, TX [79]. Currently, most existing and planned charging stations for heavy-duty BEVs support speeds of up to 360 kW, with plans for future upgrades to 1MW. Federal and state-level incentives also play an important role in accelerating the electrification of the trucking industry. The Inflation Reduction Act of 2022 invests $1 billion for the clean heavy-duty vehicle program and offers a commercial clean vehicle credit to encourage businesses to purchase medium- and heavy-duty electric trucks [80]. The act also includes funding and incentives to build the charging infrastructure necessary for supporting long-haul trucking. Other incentives include the Clean Heavy-Duty Vehicle Program which invests $1 billion to replace existing traditional heavy-duty vehicles with zero-emission vehicles and the National Electric Vehicle Infrastructure Formula Program which is part of the Bipartisan Infrastructure Law that invests $5 billion to establish a nationwide network of EV charging stations.

Furthermore, with a higher level of electrification in the future, the transition to BETs also face the challenge of power shortages and an uncertain future for electricity [81]. Other issues, such as energy prices volatility, the transition from fossil fuels to renewable sources, and the pace of technological advancements emphasize the importance of strategic planning and investment in the energy sector to meet the growing demands of electrification in the transportation sector. However, advancements in truck technologies are expected to address some of the above-mentioned issues, including developing more cost-effective batteries with higher energy density, expanding renewable energy sources to stabilize electricity costs, and increasing investments in charging infrastructure. Future BET technologies have some key advancement to expect. These include the use of higher energy density batteries, which aim to power up to 500 miles of range to ensure drivers on interregional and long-distance routes to complete their full working day without having to recharge. New models of BETs with longer ranges are being developed and released by manufacturers every year. For example, Volvo announced in September 2024 that their new version of its FH Electric will be able to reach up to 600 km (375 miles) on one charge. The company develops new driveline technology which creates more space for a larger battery pack onboard and improves the overall efficiency [82]. Moreover, future BETs aim to achieve faster charging capabilities. In the near term, the use of 800-volt DC fast charging can support charging speeds of up to 350 kW [83]. In the long term, the application and popularization of MCS will achieve a charging rate of maximum 3.75 megawatts, further reducing the charging time. Other future advancements include a more efficient drivetrain and autonomous drive or drive assistance technologies. All these innovations aim to enhance the efficiency and accessibility, addressing the current limitations of range, and make them a more viable option for the future. As the transportation industry moves towards zero-emissions goals, BETs will play a critical role in reducing the carbon footprints while satisfying the commercial demands.

4. Charging Capabilities and Facilities for Current Advanced Batteries for Routing HD Vehicles

Charging Methods

EV charging technologies can be evaluated based on the method of charging, whether through onboard or offboard chargers, and the power supply technique, which varies depending on the location and specific requirements. In this report, charging is categorized into three main charging techniques [86,87], i.e., conductive charging, wireless charging, and battery swapping, as depicted in Figure 2. While conductive charging is the major way for replenishing energy for both passenger EVs and heavy-duty vehicles, battery swapping, and wireless charging represent emerging technologies that can complement traditional charging methods. For heavy-duty vehicles, charging can be further divided into two types —mid-shift (fast) and off-shift (slow). Off-shift charging is opportunistic, taking place when a truck is not being driven and dwelled at a home base or depot. Mid-shift charging occurs during a shift when a BET's SOC drops to 10%, and fast charging is needed for off-shift charging to minimize shipment delays. The fast-charging sessions end when the battery reaches 80% SOC to reduce the impact of charge power tapering at high C-rates (slowing down of charging rate when reaching maximum capacity). The following subsections expand these topics and discuss the charging technologies and their application for BETs.

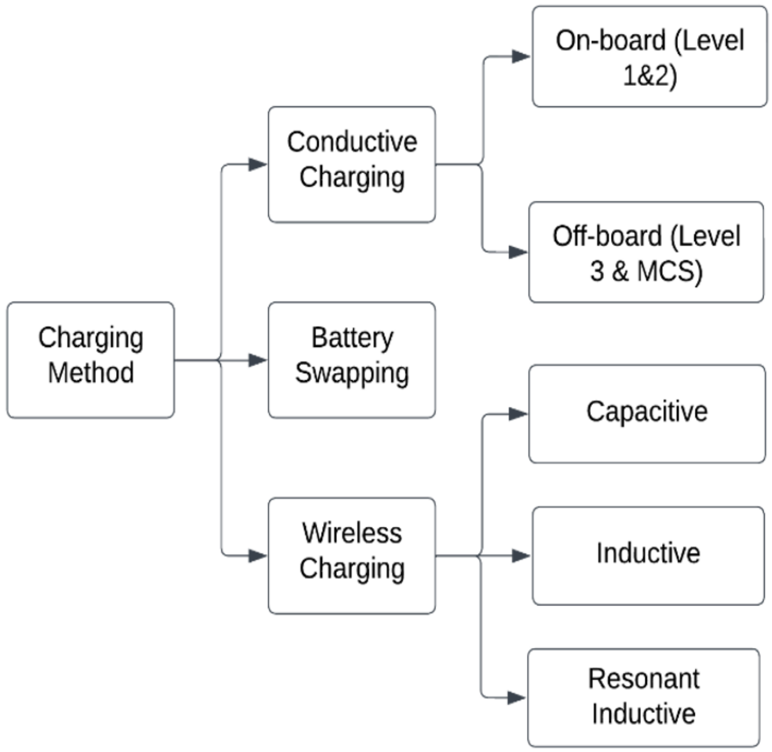

Figure 2. EV charging methods [86].

Conductive Charging

Conductive charging involves an electrical connection between the charging inlet and the vehicle. Conductive chargers are categorized as either on-board or off-board. On-board chargers have rectifiers and battery current regulators within the vehicle, whereas off-board chargers have these components located outside the vehicle [84]. Conductive charging can also be classified into three level: Level 1, Level 2, and Level 3, each defined by its power level. Level 1 charging uses a 120V single-phase AC power supply, has the slowest charging speed, and is typically used domestically with low power levels (up to 1.92 kW) without needing additional infrastructure. Level 2 charging can deliver up to 19.2 kW of power for both single-phase and split-phase systems with voltages of 208 V AC or 240 V AC, making it 3 to 5 times faster than Level 1 chargers due to its higher power output. Both Level 1 and Level 2 charging follow the same set of standards and are used with AC power in onboard chargers, whereas

Level 3 chargers are connected to the vehicle via off-board chargers linked to the three-phase power grid. Level 3 charging offers a higher power range between 20 kW and 350 kW, supplying DC voltage of around 300 Vdc to 800 Vdc through off-board chargers. Level 3 fast charging connectors includes CHAdeMO, Tesla superchargers and Combined Charging System (CCS) combo 1. Table 5 tabulates the specifications of the three conductive charging levels [85].

In the U.S., most heavy-duty BETs, including battery electric transit vehicles, utilize the CCS for charging, which allows for DC fast charging up to 350 kW. This equates to approximately 3 miles (4.8 km) of range per minute added to the vehicle, based on an average energy consumption rate (ECR) of 2 kWh per mile (1.2 kWh per km). Although CCS is well suited for passenger EVs and light-duty BEVs, offering up to 20 miles (32 km) of range per minute, it's not sufficient to provide a satisfying charging speed for heavy-duty truck. As a result, development is underway for a new MCS standard, which will be rated for charging at a maximum rate of 3.75 megawatts (3,000 amps at 1,250 volts DC), providing charging speeds about 10 times faster than CCS [86].

Table 5. Comparisons of current EV charging levels [85, 87, 88].

	Level 1	**Level 2**	**Level 3**
Power Output	1.44 kW-1.9 kW	3.1 kW-19.2 kW	20 kW-350 kW
Estimated Range per Hour of Charging	2-5 miles	10-20 miles	180-240 miles
Charger Type	Onboard – off shift	Onboard – off shift	Offboard – mid shift
Charging Location	Private	Private and commercial	Commercial
Power Supply	120/230 Vac, 12A-16A, Single phase	208/240 Vac, 12A-80A, Single phase/Split phase	208/240 Vac & 300-800Vdc, 250-500A Three phase
Connector Types	J1772 connector	J1772 connector J3400 connector	CCS connector CHAdeMO connector J3400
Standards	SAE J1772, IEC 62196-2, IEC 61851-22/23, GB/T 20234-2		IEC 61851-23//24 IEC 62196-3

Research on MCS in truck applications includes its influence on reducing the onboard battery size to improve BET performance. Nykvist et al. [89] show that heavy BETs are highly sensitive to battery technology. If electric trucks can be fast-charged in a megawatt scale, smaller batteries and a usage pattern similar to diesel trucks would be possible, and thus, electrification would become much more realistic. Schneider et al. [90] investigate the downsizing of batteries that are associated with the operating strategy and available charging power up to 3.75 MW enabled by MCS. They have concluded that battery size of 798 kWh at 761 kW can be achieved if charging is only intended during the single mandatory rest period of 45 min. They also found that a charging power of 2802 kW, which is significantly lower than the proposed MCS standard, is the most beneficial charging power in their scenarios. This suggests that the maximum MCS standard output power is unnecessarily high for the truck application.

Regardless, the primary obstacles to fast charging are the cell chemistry and material properties of LIBs. During charging, lithium ions move from the cathode to the anode, with their speed determined by the intercalation rate and ion diffusivity. High charging rates can lead to lithium plating on the anode surface and a rapid increase in cell temperature, negatively impacting battery capacity, lifespan, and safety. Strategies to increase charging rates include pre-warming cells to enhance electrode kinetics and using higher voltage systems to lower current levels. Optimizing charging algorithms that facilitate fast charging without compromising battery life and safety is a crucial focus for future EV development [20].

Wireless Charging [84, 91]

The wireless charging system for vehicles can be divided into the following three categories based on the state of motion of the EV:

A. Stationary Wireless Power Transfer (SWPT)

SWPT works by transferring electrical energy from a charging station to an EV without the need for a physical, wired connection. Compared to plug-in wired chargers, SWPT differs only with the wireless energy transfer. The SWPT system typically involves two pads: one for receiving, installed on the vehicle, and the other for transmitting, installed in the charging station. The transmitting pad generates a magnetic field, which induces an electric current in the receiving pad on the vehicle. This current is then used to charge the vehicle's battery. The efficiency and effectiveness of WPT systems depend on factors such as the distance between the pads, the alignment of the pads, and the power levels involved. However, compared to the other two types of WPT, SWPT has a better efficiency because of an ideal alignment.

B. Quasi Dynamic Wireless Power Transfer (QDWPT)

The QDWPT charges the vehicle using fast wireless charging system for short term charging. This type of wireless charging is especially suitable for public transportation, for which QDWPT can charge the battery at the stationary position at bus stops, utilizing the few minutes of stopping time to charge the battery on a bus. Additionally, QDWPT at traffic signals could also be beneficial. In this setup, each stopping lane would be equipped with primary power pads. These power pads could be controlled individually by separate converters or collectively by a single converter. Activation and deactivation of the pads could be managed using a controller linked to the traffic light controllers.

C. Dynamic Wireless Charging (DWC)

DWC is an emerging technology in which electrical energy is transmitted to an EV using a wireless medium while in motion so that vehicles do not need to stop and wait for charging. It is based on the magnetic coupling between the transmitter coils embedded under the road surface and the receiver coils installed in an EV. It can potentially address the limited range to problems for EVs, solving range anxiety, and reducing needed battery size. However, due to the significant power loss caused by wireless power transfer, improving the charging efficiency remains a major challenge [92].

In general, SWPT systems have the advantage of convenient charging, eliminating shock hazards from wires, and the ability to be installed in convenient locations such as parking lots or home base. QDWPT systems offer charging to EVs during short stops, such as at traffic lights, extending the vehicle's range while reducing its energy storage needs. DWC systems charge the EV continuously while driving through designated charging lanes on the road, further increasing the driving range and reducing the EV's required battery size. Recent studies have highlighted that deploying wireless charging at transit stops, despite the high upfront costs and environmental impacts from manufacturing the equipment, can significantly reduce battery size and vehicle weight, reducing operational costs and energy consumption [93].

Battery Swapping [94]

Battery swapping was introduced as an early solution in 1896 to enhance the driving range of EVs, and still presents a viable solution for rapid charging. Hartford Electric implemented this practice in the early 20th century, allowing customers to purchase battery-less electric trucks from the General Vehicle Company and then buy electricity through Hartford Electric's swappable battery system. Over the years, the technology behind battery swapping has been progressively evolving, driven by the goal of accelerating the electrification of transportation. Today, battery swapping has become an efficient and fast process. The battery swapping process involves robotic arms, which are often used in BSS to efficiently remove and replace the depleted batteries in EVs. This process can be finalized in less than 5 minutes, significantly faster than the time required to refuel a heavy-duty ICE vehicle. The bottom-swapping technique, mainly used for light-duty EVs with batteries positioned under the vehicle body, can usually be completed within 3 minutes. This process allows an EV to enter the BSS, wait for robotic arms to exchange its battery pack, and exit. In today’s semi-BETs, battery packs are often installed in or under the tractor and on the truck’s chassis. This design is not ideal for battery swapping technology due to the size of heavy-duty vehicles and the limited space available at a BSS. To address this, we introduce a new BET design for easier battery swapping process. As illustrated in Figure 3, the battery pack (highlighted in green) is mounted on the chassis and connected to the tractor. It can be easily removed when trucks are parked at the designated battery swapping area.

Figure 3. Proposed BET design for easy battery swapping.

Battery swapping for BETs provides a cost-effective transition to electrification by reducing upfront costs and operating costs because fleets do not need to own battery packs and drivers do not need to spend hours for mid-shift charging. Additionally, battery swapping significantly increases vehicle uptime, as it allows trucks to receive a full charge within minutes, minimizing downtime. The process can also occur simultaneously with loading or unloading with the proposed BET design, further improves operational efficiency. Furthermore, a retired battery can be safely removed from the battery circulation and sent for recycling, promoting sustainability. Future battery swapping may utilize cost-effective primary (non-rechargeable) batteries such as aluminum-air batteries and lithium-air batteries. However, challenges remain. Standardizing battery packs across manufacturers is difficult, and this could limit innovation and restrict the adoption of new battery designs like cell-to-pack or cell-to-chassis structures. Moreover, manufacturers may be reluctant to give up on their proprietary designs. High infrastructure costs, including siting, permits, and maintenance, also remains uncertain, making large-scale adoption more difficult.

5. HD Electric Vehicle Operations with Current and Advanced Batteries

Different from passenger EVs, BETs require bulkier energy storage systems due to their greater range, weight, and aerodynamic load demands. This adds extra mass to the battery packs and reduces the cargo capacity since the total weight of the truck needs to remain constant during electrification [95]. It can be challenging for Heavy BETs to achieve a comparable range to their diesel counterpart due to the higher energy requirement and the low energy density of batteries. Thus, it is essential to evaluate quantitatively whether the battery can meet the energy needs for trucks, which experience significant change of load and have longer range requirements. Existing efforts on estimating the battery size for BETs includes building equations based on standard performance requirements, developing simulations for different transportation scenarios, and investigating the relationship between battery sizing and cargo capacity. Sripad et al. use the vehicle dynamic model to estimate the required battery pack energy (E_p, in joules) based on the standard performance requirements of a Class 8 diesel truck [96].

$$E_p = \left[\frac{\left(P_{drag} + P_{rr} + P_g\right)}{\eta_{dr}} + \left(\frac{1}{2} W_T * v * a \left(\frac{1}{\eta_{dr}} - \eta_{dr} * \eta_{brk} \right) \right) \right] * \frac{D}{v} \qquad (1)$$

where:

$P_{drag} = \frac{1}{2} \rho * C_d * A * v_{rms}^3$ represents the power required to overcome aerodynamic drag, where:

ρ : air density

C_d : coefficient of drag

A : frontal area of truck

v_{rms} : root-mean-square of the velocity

$P_{rr} = C_{rr} * W_T * g * v$ represents the power needed to overcome rolling resistance, where:

C_{rr} : coefficient of rolling resistance

W_T : gross on-road vehicle weight (GVW)

g : acceleration due to gravity

v : average velocity

$P_g = t_f * W_T * g * v * Z$ represents the power needed to overcome the elevation changes, where:

Z : average road gradient (r/100), where r is the percentage road grade

t_f : fraction of time vehicle spent on road with road grade of r%

a : mean acceleration or deceleration

η_{dr} : drivetrain efficiency

η_{brk} : braking efficiency

D : daily driving distance

To demonstrate the feasibility of electrifying a fully loaded class 8 truck for long-haul routes and to estimate the required battery size, we consider the trip from the Port of Long Beach to the Port of San Francisco. This route spans approximately 400 miles, mainly along Interstate 5. In this analysis, we make the following assumptions regarding the parameters:

Table 6. Vehicle specifications [96-98].

W_T	A	C_d	C_{rr}	η_{dr}	η_{brk}	a	v	v_{rms}
80,000 lb (36287 kg)	10 m^2	0.6	0.006	0.85	0.7	0.112 m/s^2	49 mph (22 m/s)	43 mph (19 m/s)

Table 7. Other specifications [95].

ρ	g	Z	t_f	D
1.2 kg/m^3	9.8 m/s	0.01	0.15	650,000 m

Feasibility analysis

Assume the truck starts the journey with a fully charged battery and does not charge along the route, the required energy E_p can be calculated as 3.666×10^9 joules using equation 1 and above assumptions. The battery capacity needs to be at least 1018 kWh. (Energy efficiency is 1.56 kWh/km (2.5 kWh/mile).) Given the current energy density and battery costs, installing such a large battery is economically impractical and would significantly reduce space and payload capacity. A more practical approach involves truck drivers making one stop en route, recharging when the state of charge (SOC) drops below 10% and resuming the trip once the SOC reaches 80%. Under this scenario, the minimum battery capacity required is approximately 600 kWh. In less time-sensitive situations, where drivers can make multiple stops for charging, the required battery capacity can be further reduced. Here, we assume that 6 equally spaced DC fast charging stations exist along this route. i.e. 82 miles (131 km) between each charging station. BETs only need to cover the longest distance between charging stations. Using Equation 1, the required battery capacity for this scenario is only 205 kWh.

Other studies have also estimated the battery size needed to meet the demands of long-haul trucking. For example, Mareev et al. simulate long-haul BETs in different transportation scenarios in Germany incorporating charging during driver breaks [99]. They assume a truck driving at 80 km/h (50 mph) with a GVW of up to 40 t, which results in a 360 km (225 miles) driving distance within one 4.5 h driving period (EU legislative regulation requires a rest period of at least 45 min after 4.5 h driving). They show that considering the aging of batteries, traffic, tire wear, and weather conditions, the average traction battery capacity to cover a 4.5 driving period on a highway result in approximately 600 kWh for the truck configuration “low losses” and approximately 825 kWh for the truck configuration “average losses”, given 1.33 kWh/km (2.13 kWh/mile) in “low losses” scenario and 1.83 kWh/km (2.93 kWh/mile) in “average losses” scenario. For the high consumption driving route scenario with 2.0 kWh/km (3.2 kWh/mile), the required energy amount for one driving period is 720 kWh. Considering the 20% reserved capacity to account for battery aging, the resulting traction battery capacity is 900 kWh. In this study, they also show that an 825 kWh battery could weigh 6.6 t which leaves 20 t maximum payload for the truck with up to 40 t GVW, considering the weight of vehicle body and electric drivetrain components. Similarly, the 900-kWh battery weighs around 7.2 t which leaves about 19.4 t payload. Compared to a conventional diesel truck, BETs with 825 kWh battery sacrifice about 20% of the maximum payload and BETs with 900 kWh battery sacrifice about 23% of the maximum payload. Despite the heavy weight of the batteries, smaller battery packs can be placed on HDTs with a more extensive fast charging network. With shorter ranges and more frequent charging, the savings from electrification increase more quickly than the costs and the negative impact on load capacity [89]. Leonard et al. investigate the effect of battery pack sizing and cargo capacity of a class 8, 41-ton truck on its overall energy performance and technical parameters [95]. They show that the electrification of the class 8 truck resulted in a decrease in its cargo capacity from 13.5 tons to 11.77 tons, 11.36 tons, and 10.96 tons by increasing the battery pack size to 399 kWh (35 rows), 456 kWh (40 rows), and 513 kWh respectively. Assume an efficiency of 1.7 kWh per mile, these numbers convert to 235 miles, 268 miles, and 302 miles respectively.

Cost Analysis

As of November 2024, existing public DC fast charging stations along the route from Long Beach, CA to San Francisco, CA, include WattEV charging depots in the Port of Long Beach, Gardena, and Bakersfield, offering charging speeds of up to 360 kW. Planned DC fast charging locations include Kettleman City [100] and along the proposed freight EV corridors outlined in the California's Deployment Plan for the National Electric Vehicle Infrastructure (NEVI) Program [101]. Given the current infrastructure, most class 8 BETs either do not satisfy the requirements for the trip or need excessive amount of time during mid-shift charging. Thus, in this analysis, we assume that the total distance is 410 miles, and 6 equally spaced DC fast charging stations exist along this route, i.e., 82 miles between each charging station. We also establish the following assumptions regarding BETs and their diesel counterparts to make a comparison of operating costs.

BET assumptions:

- Charging stations are always available
- Charging speed is 350 kW (current) and 1 MW (future)
- SOC is 95% at origin
- The compensation for driver is $49 /hour
- Example Truck: maximum range of 310 miles
- Speed: 50 mph
- SOC is 95% when departing from the origin
- Efficiency is 2 kWh/mile
- Electricity price ranges from $0.2 to $0.6 per kWh

Charging:

- Charge only when the vehicle's SOC is insufficient to reach the next stop plus an additional 10% buffer; Stop charging once SOC = min{80%, sufficient to reach the destination + 10% buffer}

Diesel truck assumptions:

- Diesel cost $5 per gallon
- Fuel efficiency: 7 miles per gallon
- No refueling

Other Assumptions:

We assume the available SOC increases linearly with time during charging (0 to 80%). In practice, the charging speed does not consistently remain at its peak due to factors such as the battery chemistry and the battery management system. This would result in an underestimated labor cost associated with during charging-related waiting times.

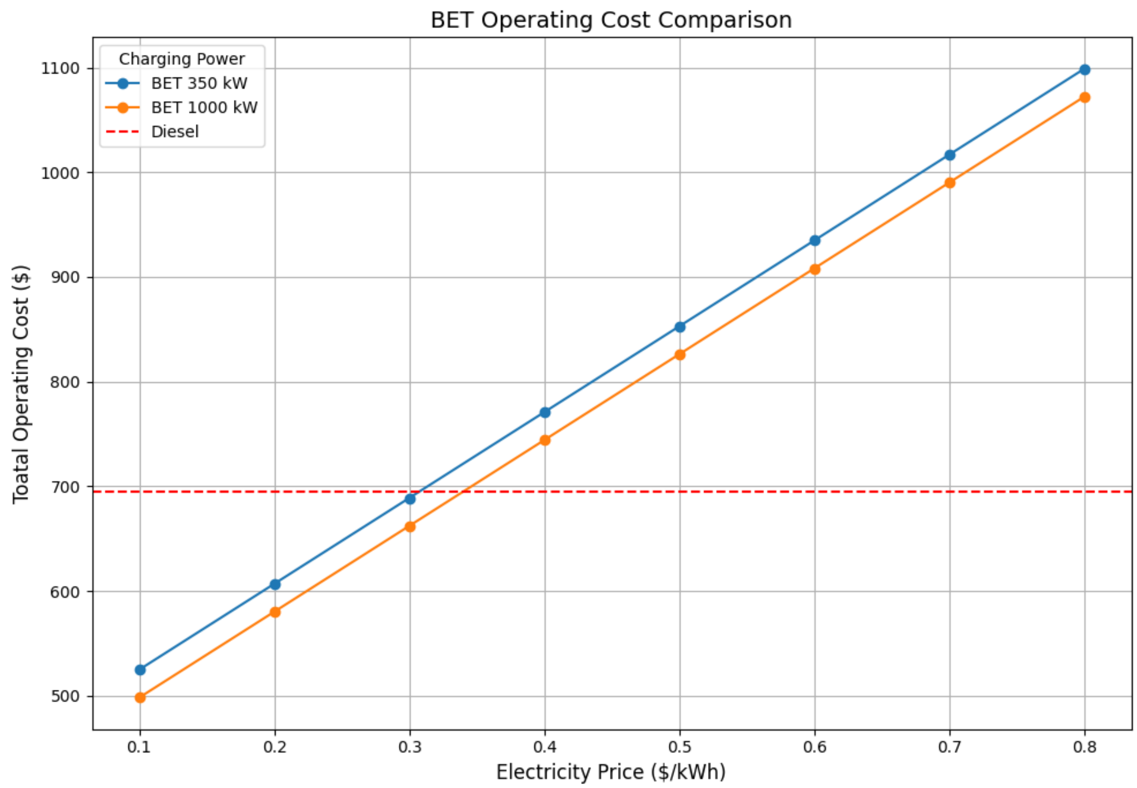

Figure 4. Operating cost comparison.

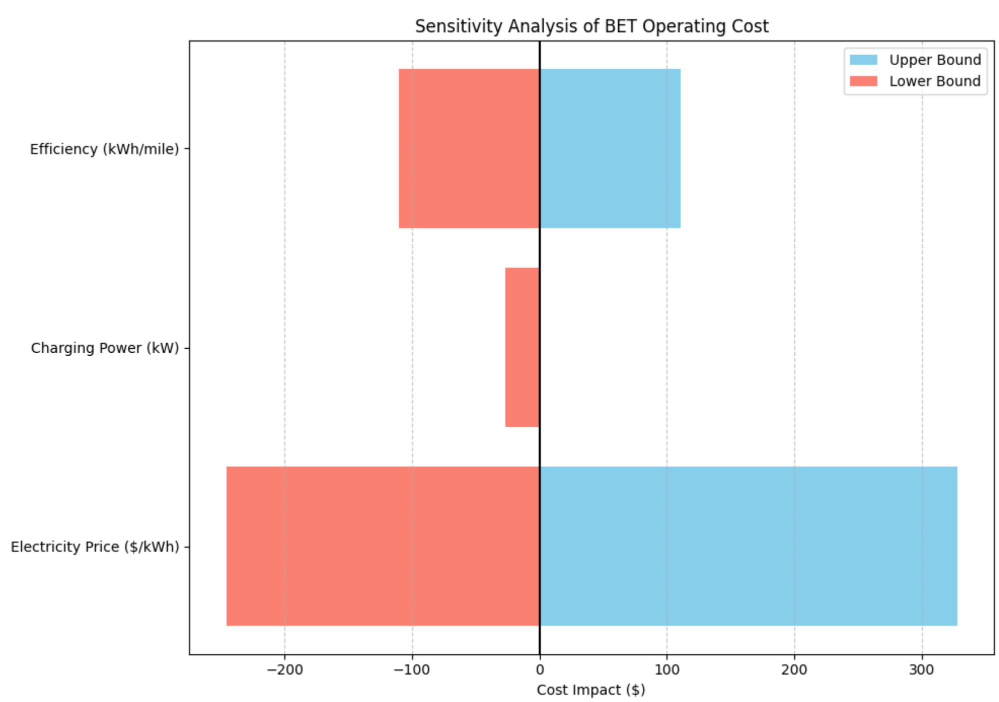

Figure 5. Sensitivity analysis of BET operating cost.

Results:

The example vehicle needs to make one stop at the 4th charging station to charge from 16% SOC to 63% SOC. The minimum total trip time for BET is 9.04 hours (0.84 hours for charging) if the maximum charging power is 350 kW and 8.49 hours (0.29 hours for charging) if the charging power is 1 MW. Figure **4** demonstrate the operating cost comparisons between diesel trucks and BETs depending on the electricity price for both cases. Apparently, current BETs do not have a clear operating cost advantage over diesel trucks. However, Figure 5 also shows that for a relatively short trip (410 miles), electricity price has the greatest influence on BET operating costs. Considering future improvements in the powertrain efficiency, achieving cost parity with diesel trucks is feasible.

Limitations of the study:

This analysis simplifies several aspects of BET operation and cost estimation. It assumes a linear charging function under certain SOC range, a linear energy consumption rate, and presumes equally spaced charging stations. In reality, the vehicle dynamic, payload and the use of ancillary systems all influence the maximum remaining range of BETs [102]. Future research incorporating detailed geographic and the impact of utility rate on energy demand [103], along with realistic vehicle routing and nonlinear energy models, would provide more accurate assessments of BET feasibility and economic competitiveness.

6. Conclusion

Electrifying heavy-duty vehicles, particularly Class 7 and Class 8 trucks, can lead not only to large environmental benefits but is also associated with several advantages for the truck managers or owners, including improved performance, lower operating costs, and government incentives. This study identifies these aspects of zero-emission trucks. Given the current battery technologies, current heavy duty BEVs have a range of around 200-300 miles per full charge with future projections toward 500 miles. We can conclude that current BET technology is optimally utilized for light vehicles and short-range travel due to the range limitations and the lack of fast charging facilities. The advantage of BETs increases with more volume constraint of the cargo, as the additional weight of the battery pack does not limit cargo capacity. Based on the current technologies and assumptions made in the previous section, we conclude that the operating cost of a heavy-duty BET is heavily influenced by energy and fuel cost. We see that BETs do not have clear cost advantages over diesel trucks for long-haul operations due to high cost of DC fast charging. Future research could explore BET scheduling strategies to minimize operating cost. Due to significant efforts in battery technologies, charging technologies and infrastructure adequate support the future of electric HD vehicles looks promising for at least short and medium haul operations. Additionally, it would be beneficial to explore fuel cell electric vehicle technology as a complementary approach, considering its advantage for long haul transit and the decision by transit agencies to adopt fuel cells for inter-city routes.

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Data Summary

Products of Research

Data used in this report was collected from publicly available sources (e.g., vehicle manufacturers, websites, and publications), and is cited herein.

Data Format and Content

Data used in this report such as BET specifications and vehicle specifications in section 5 is stored as tabular text files in CSV format.

Data Access and Sharing

CSV files of the vehicle specifications can be provided upon request. All other data and outputs from this study are presented in the body of the report and can be directly accessed.

Reuse and Redistribution

There are no restrictions on how the data can be reused and redistributed by the general public.