Battery Swapping for Truck Electrification in the United States

FEBRUARY 2025

The purpose of this topic brief is to scope out the advantages and challenges associated with battery swapping as a potential solution to electrify medium- and long-haul heavy-duty vehicles (HDVs) in the United States. Medium- and long-haul trucks' daily travel distances as well as operational and logistical considerations around payload capacity, range, and charging times make them particularly hard to electrify. Electric heavy-duty trucks on the market today constitute only 4% of all zero-emissions trucks in the United States (Al-Alawi and Richard 2024). Scaling up electrification efforts to reduce HDV emissions will thus require the consideration of zero-emissions solutions that can complement battery electric trucks (BETs) with fixed batteries to provide a zero-emissions solution that will meet the needs of zero-emissions long-haul freight. One promising technology is battery swapping.

Many current BETs can travel more than 200 miles on a full charge (CALSTART 2024).[1] Battery swapping for trucks involves swap-capable trucks switching out their batteries at a swapping station, either automatically or manually, when they run low on charge. The technology can be implemented as an add-on battery attachment for traditional diesel trucks or through specialized BETs designed for battery swapping. Although HDVs still need to stop for battery swapping, the process allows for the vehicle range to be extended and recharged within a short amount of time. Battery swapping is used extensively in China and is being explored in a few other countries. Research on battery swapping in the United States is limited.

This topic brief, informed by literature review and interviews with battery swapping experts in the United States, summarizes the technology's potential; it is intended as a resource for transportation researchers and policymakers as they consider options to deploy battery swapping domestically.

Market Status

Internationally, China is currently the largest market for deploying battery swapping trucks. In 2023, 14% of all zero-emissions heavy-duty vehicles sold (12-month average) in China were swap-capable (Jin and Mao 2024). Tractor-trailers and dump trucks were the main applications for battery swap-capable HDVs in China, with 50% of zero-emissions tractor-trailers and 53% of zero-emissions dump trucks sold in 2023 being swap-capable (Jin and Mao 2024).

Battery swapping is also emerging in other international markets beyond China. Janus Electric, an Australian manufacturer, advertises ranges of around 250–370 miles (400–600 km) for its HDV technology that allows for battery swapping. In Japan, Ample, Inc., an American-based battery swapping company focused on light- and medium-duty electric vehicles (EVs) serving shorter ranges, and Mitsubishi Fuso is piloting its technology with Mitsubishi's light-duty eCanter electric truck using Ample's battery swapping technology (Ample 2024). The pilot will test battery swapping for shorter driving ranges (around 62–200 miles) in an urban environment (Ample 2023a).

[1] For U.S. data; Version 1.5 of the CALSTART Drive to Zero's Zero-Emission Technology Inventory Data Explorer.

Both light- and heavy-duty battery swapping applications remain limited in the United States. In addition to Ample (mentioned above), which is currently used for last-mile delivery, rideshares, and light-duty fleets, Revoy developed a battery-powered swappable component that can be attached between any long-haul semi-tractor and trailer, converting a traditional diesel truck to an electric hybrid with a range of up to 250 miles (Revoy 2024). Revoy is currently piloting their electric dolly system technology with Ryder, a trucking logistics company, for a portion of their highway route between Texas and Arkansas (Moseman 2024).

Low consumer demand and high swapping station capital costs in previous commercial trials dampened interest in battery swapping technology for the past few years (Bernard et al. 2022).[2] However, with the resurgence of the technology in China, a desire to explore other charging solutions for EVs, and challenges with other zero-emissions approaches such as hydrogen, there has been recently renewed interest in battery swapping in the United States, as demonstrated by Ample and Revoy (London Business School 2024; Wilson 2023). As a result, the advantages and challenges of scaling up battery swapping for HDVs require further consideration.

Advantages of Battery Swapping

Cost reductions: Swap-capable trucks can also make up for some of the shortcomings of BETs. Decoupling of battery and vehicle costs through a battery-as-a-service model can reduce the up-front cost of a heavy-duty EV by as much as 50% (depending on the type of HDV), resulting in a much lower investment for the truck purchaser and also reduce total cost of ownership (Bernard et al. 2022; Liu 2024).[3] Battery swapping solutions designed to work with traditional diesel tractor-trailer trucks instead of electric trucks, such as Revoy's electric dolly system, have an upfront cost of $0 for truck operators, since no vehicle purchase is needed (Revoy 2024).

Shorter charging/refueling time: Battery swapping also eliminates charging time and/or refueling downtime concerns that often affect longer distance battery electric trucks, with the added benefit of minimizing disruptions to daily operations.[4] Companies providing HDV battery swapping solutions list their battery swap times at four minutes (Janus Electric) to under five minutes (Revoy 2024).

Grid benefits and reduced need for larger batteries: Charging batteries for a swap station in bulk can allow for easier grid management and improved charging management, benefiting both the station operator and the power system (Levi Tillemann, vice president for policy and international, Ample, Inc., pers. comm., May 2024; Vallera, Nunes, and Brito 2021). Battery swapping for BETs can also eliminate the need for larger batteries, reducing total vehicle weight, which can allow for longer distance applications with shorter recharge times (Bernard et al. 2022).

A complementary solution to cable charging: With the growth and build out of EVs and related infrastructure across a range of applications in the country, battery swapping can also serve as a

---

[2] A battery swapping station, much like a gas station or an EV charging station, is a central location for swap-capable vehicles to replace their batteries. Swapping stations often store multiple batteries that vehicles can access as needed.

[3] In a battery-as-a-service business model for electric trucks, battery swapping station operators provide and pay for the battery component of an electric truck, whereas the truck/fleet operators only pay for cost of the truck without the batteries (Bernard et al. 2022).

[4] Charging heavy-duty long-haul trucks (500-mile range) can take at least one hour even with megawatt-level charging (Burnham et al. 2021).

complementary solution to cable charging for electric trucks. In China, battery swapping emerged as a solution after HDV industry stakeholders realized that cable-charging alone was insufficient to meet all their needs and began exploring alternatives (Danilovic and Liu 2021). Battery swapping experts in the United States think the technology could serve as a similar complementary solution, filling charging gaps where needed (Levi Tillemann, vice president for policy and international, Ample, Inc., pers. comm., May 2024). Furthermore, with the United States already heavily investing in an EV infrastructure buildout, battery swapping could further alleviate challenges of building out a whole new zero-emissions fueling system, such as for fuel cell trucks, which can already be more expensive than electric vehicle stations (Wilson 2023), thereby saving on resources and time spent.

Challenges

Lack of battery standardization: A lack of standardization in electric vehicles is the most cited obstacle associated with battery swapping. This can result in lack of interoperability between swap-capable vehicles made by different manufacturers due to differences in battery designs. It can also impede the technology from being scaled up since achieving larger battery swapping scale generally requires standardization of different vehicle components (Danilovic and Liu 2021). Unless managed in the initial stages of vehicle development (either by manufacturers or through regulations by the government), swap-capable vehicles might need to be redesigned at a later stage, which could also be costly (Danilovic and Liu 2021). Lack of standardization remains an issue even in China, the largest battery swapping market, where truck drivers can only use stations that meet the needs of their vehicle (Cui, Xie, and Niu 2023). However, companies such as Ample and Revoy have overcome this problem by developing swapping solutions that allow for interoperability between vehicles. Ample has substantially increased its coordination with vehicle manufacturers in the past 18 months, to coordinate the use of Ample's technology with the vehicles, highlighting the need for at least some level of harmonization with manufacturers (Levi Tillemann, vice president for policy and international, Ample, Inc., pers. comm., May 2024).

Infrastructure costs: While studies on battery swapping in the United States are limited, one study modeling long-haul battery swapping in the United States cautions that capital costs associated with batteries at a swapping station might deter wide-scale build out of the technology (Sader et al. 2023). Even in China, the capital costs for setting up a battery swapping station can be between ~$1–1.1 million USD to over $1.5 million USD, as a result of battery costs being a substantial portion of that total (i.e., between 30% and 50%) (Bernard et al. 2022; Cui, Xie, and Niu 2023). In China, the capital cost of battery swapping stations for trucks are more expensive than charging stations that have a similar service capacity (Bernard et al. 2022). There remains a lack of understanding for what the same costs might look like in the United States for trucks, along with a lack of consumer knowledge and trust.

Battery swapping remains largely untested for medium- and long-haul applications: The lack of real-world experience with battery swapping for medium- and long-distance trucking can lead to unforeseen issues and steeper learning curves to fully grasp the technology's potential. Even in China, the largest market for battery swappable zero-emissions vehicles, applications for swap-capable heavy-duty vehicles have been limited to shorter distance applications with multiple daily trips.[5] Swap-capable

[5] For example, in-port drayage trucks with a roundtrip of up to 1 km, making 100–150 daily trips, and local concrete delivery trucks with a roundtrip distance of 20–60 km making up to 20 trips a day (Niu et al. 2024).

battery electric vehicles for all relevant HDV applications in China have a nominal vehicle range of ~140–200 miles (225–325 km) (Jin and Mao 2024). China's first (and so far, longest) battery swapping trucking route, the Ningde-Xiamen Trunk Line for heavy-duty trucks, only opened in 2023 (CATL 2023). This 260-mile (420-km) line with four battery stations is expected to serve thousands of heavy-duty trucks in the Fujian province, eliminating refueling anxiety (CATL 2023). Pilot efforts for long-haul trips recently started in the United States in 2024: Revoy is currently testing its electric dolly swapping system for a ~200-mile stretch of a much longer trucking route between Dallas, Texas, and Prescott, Arkansas (P. Reinhardt, chairman, Revoy, pers. comm., September 2024).

Policies Enabling Battery Swapping

Regulations and national strategy plans by federal agencies further necessitate scaling up long-haul truck electrification. The Environmental Protection Agency's (EPA's) latest HDV emissions rule, finalized in March 2024, anticipates emissions reductions for long-haul trucks through an increase in zero-emissions vehicles (ZEVs), estimating that 25% of long-haul trucks sold in 2032 will be ZEVs. In March 2024, several federal agencies also jointly released a National Zero-Emission Freight Corridor Strategy, charting a path to gradually establish clean freight corridors across the country. Disadvantaged communities stand to benefit immensely from cleaner trucks because the impacts of long-haul freight transportation in the country disproportionately affect communities living along highways and near truck depots.

The lack of policies and support for battery swapping in the United States is another challenge, with only limited support for battery swapping technology at the federal level, such as through technology neutral incentives such as the 30C tax credit (IRS 2024).[6] To realize the full extent of freight electrification (beyond tax credits), federal agencies have the opportunity to establish additional policies. For example, in China, a combination of battery-swap station subsidies, tax reductions and exemptions for new energy vehicles, and government-led pilots have helped scale up the adoption of HDV battery swapping (Bernard et al. 2022; Lin et al. 2024; Nåbo et al. 2024). Research and funding support for piloting the technology can provide real-world data needed to understand implementation issues in a U.S. context. Federal funding for utilities to explore battery swapping for grid resiliency and for utility-led charging infrastructure is also an option. Grant funding from California's Energy Commission for Ample to scale up modular battery production is one example of state-level support (Ample 2023b). Encouraging major trucking corridors to be zero emissions in the coming decades is a priority under the National Zero Emissions Freight Corridor Strategy (Chu et al. 2024).

Research Gaps to Prioritize

There remains a need for additional research and data to inform future feasibility and development of battery swapping in the United States, especially for long-haul trucking corridors. Our research revealed the following as leading research gaps (Danilovic and Liu 2021; McGrath et al. 2022; Nåbo et al. 2024; Speth and Funke 2021):

[6] According to the IRS website, charging infrastructure must be "used to (1) recharge electric motor vehicles (including certain electrical energy storage technology) or (2) store or dispense clean-burning fuel (such as hydrogen fuel for fuel cell vehicles)" to qualify for the 30C tax credit, among other requirements (IRS 2024).

- Analyzing the optimal mix of stationary charging solutions (traditional BETs) and emerging complementary solutions;
- Exploring the feasibility of different battery swapping business models under different application scenarios;
- Addressing information gaps around how vehicle standardization processes might work;
- Evaluating different charging strategies at a swapping station;
- Understanding the technical specifications around interoperability and uptime; and
- Implementing more pilot projects to collect real-world data.

Conclusion

As the United States expands its EV ecosystem for an increasing number of use cases, additional research into how the range of available charging technologies can be efficiently and optimally implemented for specific HDV use cases can alleviate future electrification concerns. Battery swapping is one of the options available on the market that could potentially serve as a complementary solution for some HDV applications such as long-haul trucking. However, its nascency in the United States necessitates additional research around challenges to inform future policy pathways. Transportation researchers and policymakers can work to address the research gaps identified above.

Acknowledgments

The author gratefully acknowledges the external reviewers who supported this report. External expert reviewers included Peter Reinhardt from Revoy and Levi Tillemann from Ample, Inc. External review and support do not imply affiliation or endorsement.

References

Al-Alawi, Baha M. and Jacob Richard. 2024. "Zeroing in on Zero-Emission Trucks." CALSTART. calstart.org/wp-content/uploads/2024/05/ZIO-ZET-May-2024-Market-Update_Final.pdf.

Ample. 2023a. "Next: Trucks. Announcing Our Partnership with Mitsubishi Fuso Truck and Bus Corporation." ample.com/2023/07/25/next-trucks-announcing-our-partnership-with-mitsubishi-fuso-truck-and-bus-corporation.

_____. 2023b. "Ample Receives $15M Grant from the California Energy Commission." ample.com/2023/02/28/ample-receives-15m-grant-from-the-california-energy-commission/.

_____. 2024. "Yamato, Let's Electrify Last-Mile Delivery." ample.com/2024/08/15/yamato-lets-electrify-last-mile-delivery/.

Bernard, Marie Rajon, Alexander Tankou, Hongyang Cui, and Pierre-Louis Ragon. 2022. "Charging Solutions for Battery-Electric Trucks." Washington, DC: ICCT. theicct.org/wp-content/uploads/2022/12/charging-infrastructure-trucks-zeva-dec22.pdf.

Burnham, Andrew, David Gohlke, Luke Rush, Thomas Stephens, Yan Zhou, Mark A. Delucchi, Alicia Birky, Chad Hunter, Zhenhong Lin, Shiqi Ou, Fei Xie, Camron Proctor, Steven Wiryadinata, Nawei Liu, and Madhur Boloo. 2021. "Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains." Argonne National Laboratory. publications.anl.gov/anlpubs/2021/05/167399.pdf.

CALSTART. 2024. "Drive to Zero's Zero-Emission Technology Inventory Data Explorer. Version 1.5." globaldrivetozero.org/zeti-data-explorer/.

CATL. 2023. "China's First Battery Swapping Trunk Line for Heavy-Duty Trucks Put into Operation." www.catl.com/en/news/6107.html.

Chu, Kang-Ching (Jean), Kevin George Miller, Alex Schroeder, Alycia Gilde, and Michael Laughlin. 2024. "National Zero-Emission Freight Corridor Strategy." Joint Office of Energy and Transportation. driveelectric.gov/files/zef-corridor-strategy.pdf.

Cui, Hongyang, Yihao Xie, and Tianlin Niu. 2023. "China Is Propelling Its Electric Truck Market by Embracing Battery Swapping." ICCT. theicct.org/china-is-propelling-its-electric-truck-market-aug23/.

Danilovic, Mike, and Jasmine Lihua Liu. 2021. "Exploring Battery-Swapping for Electric Vehicles in China 1.0." www.diva-portal.org/smash/get/diva2:1628149/FULLTEXT01.pdf.

IRS (Internal Revenue Service). 2024. "Businesses and the Alternative Fuel Vehicle Refueling Property Credit." www.irs.gov/pub/irs-pdf/p6028.pdf.

Jin, Lingzhi, and Shiyue Mao. 2024. "Zero-Emission Bus and Truck Market in China in 2023." ICCT. theicct.org/wp-content/uploads/2024/08/ID-191-%E2%80%93-EU-R2Z-Q1_final-1.pdf.

Lin, Jane, Yi-Ling Cheng, Xi Cheng, Hui Shen, Ajay Pawar, and Karol Koziel. 2024. "Development of Commercial Vehicle Emission Inventory and Analysis." Illinois Center for Transportation. doi.org/10.36501/0197-9191/24-002.

Liu, Xinran. 2024. "In China, a Growing Body of Real-World Data on Electric Trucks." ICCT. theicct.org/china-growing-rw-electric-trucks-mar24/.

London Business School. 2024. “The Rebirth of EV Battery-Swapping Services and Why Their Time Is Now.” Forbes, April 15. www.forbes.com/sites/lbsbusinessstrategyreview/2024/04/15/the-rebirth-of-ev-battery-swapping-services-and-why-their-time-is-now/.

Moseman, Andrew. 2024. “The Dream of Swappable EV Batteries Is Alive in Trucking.” Heatmap, October 4. heatmap.news/electric-vehicles/revoy-electric-trucking#.

McGrath, Teresa, Luke Blades, Juliana Early, and Andrew Harris. 2022. “UK Battery Electric Bus Operation: Examining Battery Degradation, Carbon Emissions and Cost.” doi.org/10.1016/j.trd.2022.103373.

Nåbo, Arne, Mats Abrahamsson, Harrison John Bhatti, Maria Björklund, David Daniels, Mike Danilovic, Per Haugland, Petter Huddén, Jens Portinson Hylander, Svetla Käck, Per Lindahl, Jasmine Lihua Liu, and Uni Sallnäs. 2024. “Battery-Swapping for Heavy Duty Vehicles: A Feasibility Study on Up-Scaling in Sweden.” Swedish National Road and Transport Research Institute (VTI). vti.diva-portal.org/smash/get/diva2:1826965/FULLTEXT02.pdf.

Niu, Tianlin, Hongyang Cui, Yihao Xie, Guozhu Guo Song Wu and Hongqing Li. 2024. “Electrifying On-Road Freight: Port Tractor-Trailers and Concrete Mixer Trucks in Hainan Province, China.” ICCT. theicct.org/wp-content/uploads/2024/04/ID-95-%E2%80%93-Hainan-ZETs_final2.pdf.

Revoy. 2024. www.revoy.com/why-revoy.

Sader, Kariana Moreno, Sayandeep Biswas, Rob Jones, Marian Mennig, Reza Rezaei, and William H. Green. 2023. “Battery Electric Long-Haul Trucking in the United States: A Comprehensive Costing and Emissions Analysis.” chemrxiv.org/engage/chemrxiv/article-details/656e4691cf8b3c3cd7c96810.

Speth, Daniel, and Simon Árpád Funke. 2021. “Comparing Options to Electrify Heavy-Duty Vehicles: Findings of German Pilot Projects.” www.mdpi.com/2032-6653/12/2/67.

Vallera, A. M., P. M. Nunes, and M. C. Brito. 2021. “Why We Need Battery Swapping Technology.” www.sciencedirect.com/science/article/pii/S0301421521003517.

Wilson, Sam. 2023. “Hydrogen-Powered Heavy-Duty Trucks A Review of the Environmental and Economic Implications of Hydrogen Fuel for On-Road Freight.” Union of Concerned Scientists. www.ucsusa.org/sites/default/files/2024-04/hydrogen-powered-heavy-duty-trucks.pdf.