TECHNICAL BRIEF

JUNE 2024

Zero-emission locomotive technologies: Pathways for U.S. rail decarbonization

Tanzila Khan and Zhenying Shao

INTRODUCTION

The U.S. freight rail system is the largest in the world, and carries nearly 40% of the country's long-distance freight volume by tons per mile.[1] U.S. freight railroads rely predominantly on diesel fuel, and they accounted for about 12% of particulate matter ($PM_{2.5}$) emissions and 15% of nitrogen oxide (NO_X) emissions from on-road and off-road mobile sources in 2020.[2] These pollutants are widely recognized for associated impacts on climate, local air quality, and public health.

Emissions from U.S. freight rail are estimated to contribute to about 1,000 premature deaths and $6.5 billion in health damage costs each year.[3] Although the sector's contribution to total transportation-related greenhouse gas (GHG) emissions was about 2% in 2020, the share is expected to increase as the United States has committed to 100% zero-emission truck and bus sales by 2040.[4] This is primarily because locomotives typically have a long lifetime of about 50 years, during which they could be compliant with old standards for decades.[5]

---

[1] Association of American Railroads, *Freight Rail Facts & Figures*, October 2023, https://www.aar.org/facts-figures#2-fuel-efficiency.

[2] This excludes emissions from marine and aviation. U.S. Environmental Protection Agency, Online 2020 NEI Data Retrieval Tool, https://awsedap.epa.gov/public/single/?appid=20230c40-026d-494e-903f-3f112761a208&sheet=5d3fdda7-14bc-4284-a9bb-cfd856b9348d&opt=ctxmenu,currsel.

[3] Natalie D. Popovich, Deepak Rajagopal, Elif Tasar, and Amol Phadke, "Economic, Environmental and Grid-Resilience Benefits of Converting Diesel Trains to Battery-Electric," *Nature Energy, 6*(11): 1017–1025, https://www.nature.com/articles/s41560-021-00915-5.

[4] Jason Mathers and Peter Zalzal, "U.S. Signs Global Commitment to 100% Zero-Emission Trucks, Buses at COP 27," *Energy Exchange* (blog), November 18, 2022, https://blogs.edf.org/energyexchange/2022/11/18/u-s-signs-global-commitment-to-100-zero-emission-trucks-buses-at-cop27/.

[5] California Air Resources Board, *Technology Assessment: Freight Locomotives*, November 2016, https://ww2.arb.ca.gov/sites/default/files/classic/msprog/tech/techreport/final_rail_tech_assessment_11282016.pdf; Sarah Lazare, "The Filthy Emissions of Railroad Locomotives—and the Rail Unions Sounding the Alarm," *The American Prospect*, March 14, 2023, https://prospect.org/environment/2023-03-14-filthy-emissions-railroad-locomotives/; California Air Resources Board, *2022 Class I Switcher Rail Yard Emission Inventory*, July 2022, https://ww2.arb.ca.gov/sites/default/files/2022-07/2022%20Class%20I%20Switcher%20Emission%20Inventory%20technical%20document%2007112022.pdf; California Air Resources Board, *Public Hearing to Consider the Proposed In-Use Locomotive Regulation*, 2022, https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/locomotive22/isor.pdf.

www.theicct.org

communications@theicct.org

@theicct.org

THE INTERNATIONAL COUNCIL
ON CLEAN TRANSPORTATION

Acknowledgments: The authors thank all reviewers of this paper. For their guidance and constructive comments, we thank staff of the California Air Resources Board, Mike Swaney (BNSF), and Jayant Mukhopadhaya and Oscar Delgado (International Council on Clean Transportation).

Regional and industrial locomotives that operate short distances around railyards, seaports, and industrial facilities typically use the oldest engines, which often run close to less affluent communities and result in a higher environmental burden for the people who live in those communities.[6] Furthermore, because freight rail exclusively depends on diesel fuel, the total amounts of diesel consumption and CO_2 emissions from the rail sector are substantial. Freight rail emits 35 million tonnes of CO_2 each year and contributes to more than 90% of the U.S. rail energy use and GHG emissions.[7] However, there is still no clear roadmap to reduce emissions from the sector.

Many countries and regions outside of the United States have committed to zero-emission railways. For instance, Canada and the United Kingdom are aiming for rail sector decarbonization by 2050, and the United Kingdom aims to remove all diesel-only passenger and freight locomotives by 2040.[8] Scotland has committed to removing all diesel locomotives from its rail network by 2035.

The primary zero-emission technology used for locomotives outside of the United States has been electric propulsion with overhead catenary systems (OCS) using grid electricity. For example, Germany has electrified routes for 61% of its rail network and aims to electrify 68% by 2030.[9] As part of its rail decarbonization goal by 2030, India aimed to use catenary systems for its entire rail network and cease operation of diesel locomotives by the end of 2023, although progress toward that goal has continued into 2024.[10] As of April 2024, India has completed catenary system installation for 95% of their rail network.[11]

In contrast, less than 1% of the rail network in the United States has been electrified, primarily because U.S. freight railroads are privately owned—while nearly all rail networks around the globe are government funded—which creates a financial burden for the rail industry to bear the massive capital cost of electrifying rail network.[12]

For hard-to-electrify parts of the network, countries worldwide have started to adopt various low- and zero-emission technologies, such as battery-electric, hydrogen (H_2) fuel cell, and diesel-hybrid battery-electric locomotives.[13] The application of such

---

[6] California Air Resources Board, "CARB Fact Sheet: Class II, Class III, and Industrial Locomotive Operators" (2020), https://ww2.arb.ca.gov/resources/fact-sheets/carb-fact-sheet-class-ii-class-iii-and-industrial-locomotive-operators

[7] Popovich, et al., "Economic, Environmental and Grid-Resilience Benefits."

[8] Jim Lothrop, "Pathways to Decarbonizing the Rail Sector: A Canadian Perspective," (presentation, FRA Decarbonization Workshop, Spring 2023), https://railroads.dot.gov/sites/fra.dot.gov/files/2023-06/Pathways%20to%20Decarbonizing%20the%20Rail%20Sector%20A%20Canadian%20Perspective.pdf; Jennifer Elevique, "Rail Decarbonization – It's a Journey," (presentation, FRA Decarbonization Workshop, May 2023), https://railroads.dot.gov/sites/fra.dot.gov/files/2023-06/Rail%20Decarbonization%E2%80%AF-It%E2%80%99s%20a%20Journey%21.pdf.

[9] Tobias Fischer, "Deutsche Bahn's Global Decarbonization Strategies: Focus on Rail Transportation in Germany," (presentation, FRA Decarbonization Workshop, May 17, 2023), https://railroads.dot.gov/sites/fra.dot.gov/files/2023-06/Deutsche%20Bahn%E2%80%99s%20Global%20Decarbonization%20Strategies.pdf.

[10] Subhash Narayan, "Railways on Track to Meet Target of 100% Electrification by Dec," *Mint*, July 28, 2023, https://www.livemint.com/news/india/railways-on-track-to-meet-target-of-100-electrification-by-dec-11690543908598.html.

[11] Financial Express, "Indian Railways on Track to Achieve 100% Electrification with Rs 6500 cr Dedicated Budget in 2024-25, says officials," April 5, 2024, https://www.financialexpress.com/business/railways-indian-railways-on-track-to-achieve-100-electrification-with-rs-6500-cr-dedicated-budget-in-2024-25-says-officials-3447207/.

[12] Richard Nuno, "Electrification of U.S. Railways: Pie in the Sky, or Realistic Goal?" (Environmental and Energy Study Institute), https://www.eesi.org/articles/view/electrification-of-u.s.-railways-pie-in-the-sky-or-realistic-goal.

[13] Ian Hodkinson, "Global Trek Toward Decarbonization," (presentation, FRA Decarbonization Workshop, May 16, 2023), https://railroads.dot.gov/sites/fra.dot.gov/files/2023-06/Europe%E2%80%99s%20Rail%20Joint%20Undertaking%20Decarbonization%20Plan.pdf; Robert Moffat, "Decarb Down Under – An Australian Update," (presentation, FRA Decarbonization Workshop, March 16, 2023), https://railroads.dot.gov/sites/fra.dot.gov/files/2023-06/Decarb%20Down%20Under%20%E2%80%93%20An%20Australian%20Update.pdf; Hitoshi Hasegawa, "The Current Status of the Development of Carbon-Neutral and Energy-Conserving Rolling Stock for Railway Systems in Japan," (presentation, FRA Decarbonization Workshop, May 16, 2023), https://railroads.dot.gov/sites/fra.dot.gov/files/2023-06/The%20Current%20Status%20of%20the%20Development%20of%20Carbon-neutral%20%26%20Energy-conserving%20Rolling%20Stock%20for%20Railway%20Systems%20in%20Japan%20.pdf.

technologies has been mainly limited to short-distance and light-load locomotive segments, such as passenger rail and switchers, but is also being considered for freight locomotives in the long term.

It is urgent to remove and replace old diesel locomotives with a zero-emission fleet to avert the impacts of the rail sector on oil consumption, GHG emissions, and air pollution. This study supports U.S. rail decarbonization by identifying existing and emerging low- and zero-emission propulsion technology pathways for rail decarbonization and reviewing the global state of development. This study also reviews cost-benefit assessments of the technologies for various locomotive applications. It does not consider drop-in diesel alternatives such as renewable diesel (i.e., hydrotreated vegetable oil) or biodiesel blends for use in the interim, as these fuels can reduce CO_2 emissions only modestly and biodiesel produces higher NO_X emissions than conventional diesel. These fuels are also subject to upstream environmental and market impacts, feedstock supply constraints, low availability, and higher production costs.[14]

U.S. POLICY PROGRESS ON RAIL EMISSION REDUCTIONS

The U.S. Environmental Protection Agency (EPA) regulates tailpipe NO_X, hydrocarbon (HC), carbon monoxide (CO), and particulate matter emissions from locomotive engines, but does not regulate CO_2 emissions.[15] The oldest locomotives with the least-stringent emission limits are Tier 0, which were followed by the progressively more stringent emission standards of Tier 1, Tier 2, Tier 3, and the current Tier 4 standard. However, pre-1973 locomotives, which are not subject to any emission standards, still account for nearly half the engines used in short line railroads, resulting in an average fleet age of 45 years.[16] New locomotives are required to meet Tier 4 standards, which were adopted in 2008, starting from 2015. However, nearly half of all locomotives are certified to Tier 0 and Tier 1, and only 7% are subject to Tier 4 standards.[17] This is largely due to the end-of-useful life flexibility in which old locomotives could remain in the fleet without upgrading to next tier of emission limits, leading to slow turnover of old locomotives and a delayed phase-in of newer engines meeting more stringent standards. Even with the authority given by the Clean Air Act, EPA has not regulated GHG emission from locomotives.

In January 2023, the U.S. Department of Energy (DOE) released a national blueprint for decarbonization of all transport modes, including rail, by 2050.[18] The interagency high-level strategy document identifies battery electric technology and the use of hydrogen and sustainable liquid fuels as possible options for long-term rail decarbonization.[19]

---

[14] Jane O'Malley, *Assessing the Role of Biomass-Based Diesel in U.S. Rail Decarbonization Strategy* (International Council on Clean Transportation, 2024) https://theicct.org/publication/assessing-the-role-of-biomass-based-diesel-in-us-rail-decarbonization-strategy-april24/; Jane O'Malley, Nikita Pavlenko, Stephanie Searle, and Jeremy Martin, *Setting a Lipids Fuel Cap Under the California Low Carbon Fuel Standard* (International Council on Clean Transportation, 2022), https://theicct.org/publication/lipids-cap-ca-lcfs-aug22/; Jane O'Malley and Stephanie Searle, *Air Quality Impacts of Biodiesel in the United States* (International Council on Clean Transportation, 2021), https://theicct.org/publication/air-quality-impacts-of-biodiesel-in-the-united-states/; Yuanrong Zhou, Chelsea Baldino, and Stephanie Searle, *Potential Biomass-Based Diesel Production in the United States by 2032* (International Council on Clean Transportation, 2021), https://theicct.org/publication/potential-biomass-based-diesel-production-in-the-united-states-by-2032/#:~:text=The%20projected%20volume%20in%202032,gallons%20specified%20by%20the%20EPA.

[15] "Control of Emissions from Locomotives," *Code of Federal Regulations*, title 40, part 1033, https://www.ecfr.gov/current/title-40/chapter-I/subchapter-U/part-1033.

[16] Federal Railroad Administration, U.S. Department of Transportation, *Proceedings of FRA Workshop on Environmentally Sustainable Energy Technologies Powering Future of Rail*, (Office of Research, Development and Technology, 2022), https://railroads.dot.gov/sites/fra.dot.gov/files/2022-02/FRA%20Future%20of%20Rail%20Workshop.pdf.

[17] U.S. Environmental Protection Agency, *2020 National Emissions Inventory Locomotive Methodology*, prepared by Eastern Research Group, Inc., May 2022, https://www.epa.gov/system/files/documents/2023-01/2020_NEI_Rail_062722.pdf.

[18] U.S. Department of Energy, *The U.S. National Blueprint for Transportation Decarbonization: A Joint Strategy to Transform Transportation*, January 2023, https://www.energy.gov/eere/us-national-blueprint-transportation-decarbonization-joint-strategy-transform-transportation.

[19] The U.S. national blueprint defines sustainable liquid fuels as low-carbon fuels including certain types of biofuels, ammonia, hydrogen, and methanol.

The strategy for rail also suggests establishing specific emissions targets, developing technology pathways, setting targets for efficiency and zero-emission technology, and encouraging modal shift from road vehicles to passenger and freight rail. Modal shift to rail could potentially increase the total benefits from rail decarbonization by also reducing emissions from road transport in addition to eliminating the current 2% share of CO_2 emissions from the rail sector. Later in 2023, the U.S. Department of Transportation (DOT), DOE, and Canada's Ministry of Transportation announced the creation of a joint task force to reduce emissions from rail transport, with a goal of ensuring a net-zero rail sector by 2050.[20]

The U.S. Department of Energy is working closely with national laboratories, the rail industry, the Federal Railroad Administration, and other stakeholders and agencies to set preliminary strategies and conduct surveys, research, and laboratory tests on short- and long-term rail decarbonization pathways.[21] DOE's rail decarbonization work began in 2021 under the "Decarbonization of Rail, Marine, and Aviation" program. DOE's initial rail decarbonization focus is on the U.S. freight rail as the largest energy consuming locomotive segment. Freight rail includes line-haul, regional, and switchers or yard rail locomotives operated by U.S. Class I, Class II, and Class III railroad companies.[22]

The U.S. Department of Energy is targeting diverse technology solutions varying by locomotive application, technology readiness, and impact level.[23] For example, DOE is considering the use of battery-electric technology for switchers or yard locomotives which could be charged onsite, thereby not requiring extensive enroute charging infrastructure. Additionally, such application in or around rail yards would provide substantial air quality benefits for lower income communities. Moreover, DOE is evaluating low-carbon sustainable fuel options, such as renewable diesel, biodiesel blends, ethanol, methanol, and hydrogen, as a short-term strategy while transitioning to low- and zero-emission propulsion technology such as diesel hybrid battery-electric and hydrogen fuel cell technologies for line-haul freight locomotives. DOE emphasizes the use of green hydrogen produced with decarbonized grid electricity as an alternative fuel for internal combustion engine (ICE) technology over the short-term, as well as facilitating transition to hydrogen fuel cell technology in the long term.

Some progress in rail decarbonization is being made at the state level. California's In-Use Locomotive Regulation, adopted in April 2023, only allows the operation of diesel locomotives less than 23 years of age within the state and introduces zero-emission rail operation in California starting from 2030.[24] The regulation also requires that all new switcher and passenger locomotives must operate in zero-emission configuration

---

[20] U.S. Department of Transportation, *Joint Statement by Transport Canada, the United States Department of Transportation and the United States Department of Energy on Taking Action to Reduce Rail Sector Emission*, December 2023, https://www.transportation.gov/priorities/climate-and-sustainability/joint-statement-transport-canada-united-states-department.

[21] Siddiq Khan, "Rail Decarbonization – VTO Strategy and R&D," (presentation, FRA Decarbonization Workshop, May 16, 2023), https://railroads.dot.gov/sites/fra.dot.gov/files/2023-06/US%20DOE%20Vehicles%20Technology%20Office%20%E2%80%93%20Approach%20to%20Advancing%20Clean%20Energy%20Technologies%20for%20Rail.pdf.

[22] California Air Resources Board, *Technology Assessment*; Zhenying Shao, *California's In-Use Locomotive Regulation* (International Council on Clean Transportation, 2023), https://theicct.org/publication/californias-in-use-locomotive-regulation-jul23/. The 2022 operating revenues for the U.S. Class I, Class II, and Class III railroad companies are categorized, respectively, as having more than $943.9 million, between $42.4 million and $943.9 million, and less than $42.4 million. Class I national line-haul freight locomotives are typically of 4,000–5,000 rated horsepower (hp) and carry freight throughout the country. Class I switchers are smaller locomotives with maximum rated power of 2,300 hp or less, used to carry freight through railyards or for short distances outside railyards. Class II or regional railroad companies carry freight over short and medium distances, typically across a small number of states. Class III or short-line railroads carry freight over short distances such as between a port and a railyard or between a railyard and an industry.

[23] Khan, "Rail Decarbonization."

[24] California Air Resources Board, *CARB Passes a New In-Use Locomotive Regulation Estimated to Yield Over $32 Billion in Health Benefits*, April 27, 2023, https://ww2.arb.ca.gov/news/carb-passes-new-use-locomotive-regulation-estimated-yield-over-32-billion-health-benefits-0.

while in California starting from 2030, and the requirement extends to all new line-haul locomotives starting from 2035.[25] The California Air Resources Board estimates that from 2024 to 2050, the regulation will reduce cumulative statewide emissions by approximately 7,400 tons of $PM_{2.5}$, 386,000 tons of NO_X, and 21.6 million metric tonnes (MMT) of GHGs. The total statewide valuation of avoided adverse health outcomes as a result of the regulation from 2024 to 2050 is approximately $32 billion.[26]

Caltrans has developed a zero-emission strategy for California intercity passenger rail to achieve zero emissions by 2035.[27] The strategy is to adopt a feasible low-emission transition pathway by using renewable diesel for near-term emission reductions. In the long term, the strategy identifies hydrogen fuel cell technology as the zero-emission pathway most suited for intercity rail service.

The United States is still in the early phase of rail decarbonization and the adoption of zero-emission technologies for locomotives. Although an array of low- and zero-emission propulsion technologies could be used, their adoption could often present challenges due to technical, operational, infrastructure, permitting, supply chain, and economic constraints.

LOW- AND ZERO-EMISSION TECHNOLOGY PATHWAYS

The conventional propulsion system for locomotives is the diesel-electric ICE, in which a diesel engine powers an electric generator which powers the traction motors to drive the wheels.[28] Diesel engines have been the dominant locomotive technology because they offer the highest power output and range at the lowest cost compared with the various zero-emission propulsion technologies, such as batteries and hydrogen fuel cells.[29] Diesel also has a higher energy content on both an energy per volume and energy per mass basis, meaning it requires the least amount of storage space and adds the least weight. The alternative low- and zero-emission propulsion technology options are competing today with the conventional diesel powertrain to achieve a similar level of performance at comparable cost.

We consider zero-emission propulsion technologies as defined in California's In-Use Locomotive Regulation for zero-emission locomotives: "…a locomotive that never emits any criteria, toxic, or GHG pollutant from any onboard source of power at any power setting. Onboard source of power includes any propulsion power that is connected to and moves with the locomotive when it is in motion."[30] We define low-emission propulsion technologies as any diesel-hybrid or diesel-alternative powertrain which is not fully zero-emission but substantially reduces emissions of criteria pollutants and GHG compared with diesel-only operation, such as the diesel-hybrid battery-electric locomotive, or those that are defined in the regulation as zero-emission capable.

---

[25] The California Air Resources Board defines zero-emission configuration as a locomotive configuration that operates in zero-emission capacity, which can be either a zero-emission capable locomotive (e.g., a diesel hybrid battery-electric locomotive) or a zero-emission locomotive (e.g., a full battery-electric or H_2 fuel cell locomotive).

[26] California Air Resources Board, *Updated Informative Digest*, 2022, https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/locomotive22/uid.pdf.

[27] Momoko Tamaoki, "California, Net-Zero Rail by 2035: Caltran's Zero-Emission Strategy," (presentation, FRA Decarbonization Workshop, May 16, 2023), https://railroads.dot.gov/sites/fra.dot.gov/files/2023-06/California%20Net-zero%20Rail%20by%202035%20.pdf.

[28] Popovich, et al., "Economic, environmental and grid-resilience benefits."

[29] Andreas Hoffrichter, "Overview of Low- and Zero-Emission Technology Options for Railway Motive Power," (presentation, FRA Decarbonization Workshop, May 16, 2023), https://railroads.dot.gov/sites/fra.dot.gov/files/2023-06/Overview%20of%20Low-%20and%20Zero-emission%20Technology%20Options%20for%20Railway%20Motive%20Power.pdf.

[30] California Air Resources Board, *Public Hearing*.

In the following sections, we describe various low- and zero-emission propulsion technologies, provide examples of global applications, and identify the state of development for each technology for different locomotive segments.

ZERO-EMISSION PROPULSION TECHNOLOGIES

Electrification or overhead catenary systems

Electrification, also referred to as an overhead catenary system (OCS), overhead wiring system, or straight electric locomotive, transmits grid electricity to locomotives via catenary wire suspended above the tracks, which the electric locomotives convert to the proper voltage for use by the traction motors.[31] Electric locomotives have been reported to have the highest grid-to-rail energy conversion efficiency (90%), followed by battery-electric locomotives (77%) and hydrogen fuel cell locomotives (39%).[32]

The catenary system has been by far the most popular zero-emission pathway for rail outside of the United States. This technology is in widespread use in Europe and Asia, typically for passenger rail and in applications with high-power demand, such as high-speed rail. As shown in Table 1, Australia, India, South Africa, and Sweden use catenary systems for heavy-haul freight rail, as well.[33]

In addition to the upfront capital costs associated with installing an OCS, investments are typically needed to upgrade locomotives and modify existing road infrastructure to allow for the vertical clearance needed for overhead wiring. Catenary systems have been estimated to be about twice as expensive in the United States compared with Europe.[34] Lawrence Berkeley National Laboratory reported a range of cost estimates from $5.1–$31 million per km ($8.2–$50 million per mile) for overhead catenary construction in the United States for passenger rail, excluding the cost of double-stack locomotives.[35] The budget for catenary system construction for Caltrain's 51-miles long route was reported to be $848 million, and the total capital budget including new trains and other services was $1.9 billion.[36] The California Air Resources Board anticipates that catenary systems for freight railroads in California would cost 67% more per mile than the Caltrain passenger project, due to the higher power requirement for freight locomotives.[37]

Discontinuous or partial electrification is an alternative approach where only a portion of the network is electrified, and other forms of low- or zero-emission technology are used for the rest of the network. For example, in one approach being investigated by Tier 5 Locomotive LLC and CAD Railway Industries, high-voltage power is collected from overhead catenary lines, which is then conditioned and stored in a modified diesel locomotive to allow zero-emission operation in non-electrified parts of network.[38] Other similar solutions could be partial electrification combined with battery-electric locomotives or those powered by hydrogen fuel cells. As shown in Table 1, Europe,

---

[31] California Air Resources Board, *Transitioning to a Zero or Near-Zero Emission Line-Haul Freight Rail System in California: Operational and Economic Considerations*, prepared by RailTEC, University of Illinois at Urbana-Champaign, 2016. https://ww2.arb.ca.gov/sites/default/files/classic/railyard/docs/uoi_rpt_06222016.pdf; Popovich, et al., "Economic, Environmental and Grid-Resilience Benefits."

[32] Michael Iden, "Follow the Megawatt-Hours: Hydrogen Fuel Cells, Batteries and Electric Propulsion," *Railway Age*, March 12, 2023, https://www.railwayage.com/mechanical/locomotives/follow-the-megawatt-hours-hydrogen-fuel-cells-batteries-and-electric-propulsion/.

[33] Popovich, et al., "Economic, environmental and grid-resilience benefits."

[34] Popovich, et al., "Economic, environmental and grid-resilience benefits."

[35] Popovich, et al., "Economic, environmental and grid-resilience benefits."

[36] California Air Resources Board, *Appendix F Technology Feasibility Assessment for the Proposed In-Use Locomotive Regulation*, https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/locomotive22/appf.pdf.

[37] California Air Resources Board, *Appendix F*.

[38] Railway Age, *Follow the Megawatt-Hours: Hydrogen Fuel Cells, Batteries and Electric Propulsion*, https://www.railwayage.com/mechanical/locomotives/follow-the-megawatt-hours-hydrogen-fuel-cells-batteries-and-electric-propulsion/.

Japan, and the United Kingdom have already adopted such an approach for passenger locomotives where a battery-electric propulsion is used for the non-electrified part of the network, and batteries are charged on the electrified part of the network.[39]

Table 1
Examples of overhead catenary systems planned or in use

Technology adopted	Region of application	Developing or implementing entity (locomotive name)	Locomotive segment	Tractive power (battery capacity)	Phase of technology application
Catenary system	Norway and Sweden	Adtranz, Bombardier Transportation[40] (Iore)	Freight (mining, iron ore trains)	5.4 MW or 7,200 hp	In operation from 2000
Catenary system	Australia, China, Europe, India, South Africa	—	Heavy-haul freight	—	In operation
Catenary + battery-electric	Japan	Japan Railway or JR East (EV-E801)	Passenger	—	In operation
Catenary + battery-electric	Japan	JR, Kyushu Wakamatsu line (BEC819)	Passenger	—	In operation
Catenary + battery-electric[a]	Japan	JR Central (N700S Shinkansen)	Passenger	—	In operation
Catenary + battery-electric	Europe	Stadler, NAH.SH and DB (FLIRT Akku)	Passenger	—	In operation
Catenary + battery-electric	Europe	Alstom, Irish Rail (X'trapolis)	Passenger	—	In operation
Catenary + battery-electric	United Kingdom	Echion Technologies project UBER	Passenger	—	Under development

Note: Cells with dash indicate data is not available.
[a] Battery operation in case of power loss

Battery-electric locomotive

Battery-electric locomotives (BELs) are 100% battery-powered and require charging through sectional electrification, charging stations, or an electrified third rail.[41] Batteries can also be charged through regenerative braking, in which the onboard batteries capture and later reuse the energy used for dynamic braking during deceleration or maintaining speed while on descending grades.[42] However, the amount of energy stored through this mechanism is highly variable and depends on the operating speed and grade profile of the route. Railroads also often limit the amount of dynamic braking for handling safety.

As indicated in Table 2, BELs are best suited for relatively short-range locomotive segments, including passenger rail, yard rail or switchers, and regional freight. They are

---

[39] Hodkinson, "Global Trek;" Hasegawa, "The Current Status;" Elevique, "Rail Decarbonization;" *APTA Whitepaper on Battery-Electric and Hydrogen Passenger Rail Equipment*, presented by American Public Transportation Association, https://railroads.dot.gov/elibrary/apta-whitepaper-battery-electric-and-hydrogen-passenger-rail-equipment.

[40] Alstom acquired Bombardier Transportation in 2021; see Alstom, "A Transformational Step for Alstom: Completion of the Acquisition of Bombardier Transportation," press release, January 29, 2021, https://www.alstom.com/press-releases-news/2021/1/transformational-step-alstom-completion-acquisition-bombardier#_ftnref1.

[41] A third rail, also known as a live rail, electric rail, or conductor rail, provides electric power to a railway locomotive or train through a semi-continuous rigid conductor placed alongside or between the rails of a railway track.

[42] California Air Resources Board, *Transitioning to a Zero or Near-Zero*.

already in operation in Brazil, Europe, the United Kingdom, and the United States; a few other countries plan to begin trials and operations over the next few years.[43]

Battery-electric locomotives can be more than twice as fuel efficient as those using an ICE.[44] Furthermore, with lower annual maintenance costs, partially due to fewer moving components and the lower price of electricity compared with diesel, BELs could have a lower total cost of ownership than diesel powertrains.[45]

The major challenges to applying this technology to line-haul freight locomotives include the limited operating range of batteries, a heavy reliance on enroute charging infrastructure, slow charging rate and longer dwelling time, the high cost of batteries and infrastructure, and thermal challenges related to safety. The typical operating range of the batteries has been reported to be 20–60 miles, and more than 45 minutes is required for charging.[46] However, research suggests the range of BELs could be extended to at least a 241 km (150 miles).[47] With ongoing research and development, improvements are expected in battery energy density, charging speed, and battery costs, which could allow this technology to be used in line-haul locomotives.

Table 2
Examples of battery-electric locomotives planned or in use

Technology adopted	Region of application	Developing or implementing entity (locomotive name)	Locomotive segment	Tractive power (battery capacity)	Phase of technology application
Battery electric	Australia	Progress Rail (EMD® Joule SD70J-BB)	Regional freight (mining)	5.7 MW (14.5 MWh)	BHP Western Australia Iron Ore trial operation in 2024
Battery electric	Brazil, South America	Progress Rail (EMD® Joule GT38J)	Regional freight	1.5 – 2.4 MW (4 MWh)	In operation for Vale mining since 2019
Battery electric	Southern California, U.S.	Progress Rail, Pacific Harbor Line (EMD® Joule SD40JR)	Yard/heavy-haul switch	2.4 MW (4 MWh)	Testing; to be deployed
Battery electric	United States	Stadler, Utah State University (FLIRT)	Passenger	—	Target testing and proof of concept in 2025
Battery electric	Europe	Deutsche Bahn	Regional passenger	—	Starting operation in 2024
Battery electric	United Kingdom (first commercially viable battery train, retrofitted)	Vivarail	Passenger Class 230s (ex LU D-Stock)	—	In service from 2023
Battery electric	United Kingdom	Mersey rail metro service	Passenger	—	Deployed in 2023
Battery electric	Scotland	—	—	—	Field trials planned in 2026
Battery electric and third rail	Europe	Stadler (Merseytravel 777 class)	Passenger	—	In operation

Note: Cells with dash indicate data is not available.

---

[43] Hodkinson, "Global Trek;" Elevique, "Rail Decarbonization;" Fischer, "Deutsche Bahn's;" *APTA Whitepaper on Battery-Electric and Hydrogen Passenger Rail Equipment*; William C. Vantuono, "Next-Gen Motive Power," Railway Age, March 12 2023, https://www.railwayage.com/mechanical/next-gen-motive-power/; Wendy Schugar-Martin, "Progress Rail Decarbonization Solutions," (presentation, FRA Decarbonization Workshop, May 16, 2023), https://railroads.dot.gov/sites/fra.dot.gov/files/2023-06/Progress%20Rail%20Decarbonization%20Solutions.pdf; Martin Ritter, "How Stadler's Alternative Propulsion Products Make U.S. Transit More Sustainable," (presentation, FRA Decarbonization Workshop, May 16, 2023), https://railroads.dot.gov/sites/fra.dot.gov/files/2023-06/Hydrogen%20and%20Battery-%20How%20Stadler%E2%80%99s%20Alternative%20Propulsion%20Products%20Make%20US%20Rail%20More%20Sustainable.pdf.

[44] California Air Resources Board, *Appendix F*.

[45] California Air Resources Board, *Appendix F*.

[46] Hoffrichter, "Overview of Low- and Zero-Emission Technology Options."

[47] Popovich, et al., "Economic, Environmental and Grid-Resilience Benefits."

Hydrogen fuel cell

In hydrogen fuel cell locomotives, electricity is produced in the fuel cells by the electrochemical reaction of hydrogen from the fuel tank and oxygen from the air to power traction motors. The only byproduct from the reaction is water. Most fuel cell systems are augmented with battery packs.

Hydrogen fuel cell technology is being considered as a long-term solution for U.S. regional and line-haul freight locomotives, as they require few refueling stops and do not have the range limitations and charging infrastructure requirements of BELs.[48] Furthermore, the technology could be more cost-effective than catenary systems and battery-electric technologies for routes longer than 20 miles.[49] Hydrogen fuel cell locomotives can have 30% higher fuel efficiency for line-haul locomotives and 37% higher fuel efficiency for passenger locomotives than those using diesel engines.[50]

As shown in Table 3, hydrogen fuel cell technology is currently used for passenger locomotives in China and Europe.[51] There are also several ongoing or planned field trials and service operations scheduled for line-haul freight, switchers, and passenger locomotives in Canada, India, Japan, Scotland, the United Kingdom, and the United States.[52]

The major limitation of hydrogen fuel cell locomotives for a line-haul freight is low power output, which is typically overcome with augmented battery packs.[53] However, dependence on battery packs could cause charging limitations. The higher price of hydrogen compared with diesel is another challenge with this technology.

Because of hydrogen's lower energy density and volumetric energy, hydrogen fuel cell locomotives require more volume and space for fuel storage than those using diesel engines.54 To obtain the similar level of energy as 5,000 gallons of diesel for a typical line-haul freight locomotive, roughly 7,000 kg of hydrogen is required to be carried by tender cars.

---

[48] Hoffrichter, "Overview of Low- and Zero-Emission Technology Options."

[49] Hoffrichter, "Overview of Low- and Zero-Emission Technology Options."

[50] California Air Resources Board, *Appendix F*.

[51] *APTA Whitepaper on Battery-Electric and Hydrogen Passenger Rail Equipment*; Cristoph Grimm, "Running the World's First Commercial Hydrogen Train Fleet: Challenges & Lessons Learned," (presentation, FRA Decarbonization Workshop, May 16, 2023), https://railroads.dot.gov/sites/fra.dot.gov/files/2023-06/Lessons%20Learned%20and%20Best%20Practices%20from%204%2B%20Years%20of%20Safe%20Operation%20of%20iLint%20Hydrogen%20Fueled%20Train%20in%20Germany.pdf; Peter Nilson, *"CRRC Unveils 'World's Most Powerful' Hydrogen Train,"* Railway Technology, June 19, 2023, https://www.railway-technology.com/news/crrc-unveils-worlds-most-powerful-hydrogen-train/?cf-view; Erin Kilgore, "First Hydrogen Passenger Train Launched in China is Also a World First for Urban Transit," *Hydrogen Fuel News*, January 31, 2023, https://www.hydrogenfuelnews.com/hydrogen-passenger-train-china/.

[52] Ritter, "How Stadler's Alternative Propulsion;" Lothrop, "Pathways to Decarbonizing the Rail Sector;" *APTA Whitepaper on Battery-Electric and Hydrogen Passenger Rail Equipment*; Elevique, "Rail Decarbonization;" Vantuono, "Next-Gen Motive Power;" Matthew Findlay, "Hydrogen Locomotive Program," (presentation, FRA Decarbonization Workshop, May 17, 2023), https://railroads.dot.gov/sites/fra.dot.gov/files/2023-06/Hydrogen%20Hybrid%20Switcher%20Locomotive%20for%20Freight%20Movement%20in%20Canada.pdf; Takamasa Kadono, "Efforts Toward Decarbonization in Japan," (presentation, FRA Decarbonization Workshop, May 17, 2023), https://railroads.dot.gov/sites/fra.dot.gov/files/2023-06/Efforts%20Towards%20Decarbonization%20in%20Japan%20.pdf; Simon Walton, "Scotland's Hydrogen Train Project Looks Back to the Future," *Railtech.com*, November 21, 2022, https://www.railtech.com/all/2022/11/21/scotlands-hydrogen-train-project-looks-back-to-the-future/?gdpr=accept; "India's First Hydrogen Train Likely to Run from Haryana's Jind by 2024," *The Times of India*, June 26, 2023, https://timesofindia.indiatimes.com/travel/travel-news/indias-first-hydrogen-train-likely-to-run-from-haryanas-jind-by-2024/articleshow/101281042.cms.

[53] California Air Resources Board, *Appendix F*.

[54] Vantuono, "Next-Gen Motive Power."

Table 3

Examples of hydrogen fuel cell locomotives planned or in use

Technology adopted	Region of application	Developing or implementing entity (locomotive name)	Locomotive segment	Tractive power (battery capacity)	Phase of technology application
Hydrogen fuel cell	United States	Wabtec	Line-haul	—	Working with GM to utilize its Hydrotec fuel cell technology
Hydrogen fuel cell	Southern California, United States	Stadler, San Bernardino County Transportation Authority (FLIRT)	Commuter	—	Testing/field trials; to be in service from 2024
Hydrogen fuel cell (retrofitted)	Canada	Canadian Pacific Kansas City or CPKC	Line-haul and switcher	—	Testing/field trials; to be operational end of 2023
Hydrogen fuel cell (retrofitted)	Canada	Southern Railway of British Colombia, UBC, Transport Canada	Switcher	50 kW fuel cell	Field observations ongoing
Hydrogen fuel cell	Japan	JR East (HYBARI, FV-E991)	Passenger	95 kW or 127 hp	Running demo tests from March 2022
Hydrogen fuel cell	Europe	DB, Siemens (Mireo Plus H)	Regional passenger	—	In operation
Hydrogen fuel cell	Europe	DB, H2goesRail and Niederbarnimer Eisenbahn	Regional passenger	—	In operation
Hydrogen fuel cell	North America	Alstom (Chemin de fer Charlevoix iLint)	Passenger	—	Demonstration scheduled for 2023
Hydrogen fuel cell	United Kingdom	Alstom and Eversholt	Passenger	—	Under development
Hydrogen fuel cell (retrofitted)	Scotland	University of St Andrews, Transport Scotland (Class 614 (ex-Class 314))	Passenger	—	Testing
Hydrogen fuel cell (retrofitted)	United Kingdom	Vanguard and University of Birmingham	Switcher	—	Under development
Hydrogen fuel cell (retrofitted)	China (world's most powerful H_2 powered locomotive)	China Railway Rolling Stock Corporation or CRRC, Changchun Railway Company, Chengdu Rail Transit (Ningdong)	Passenger	—	Started operation from June 2023
Hydrogen fuel cell	China (fastest H_2 powered train to date)	CRRC, Changchun Railway Company, Chengdu Rail Transit	Passenger (urban transit)	—	Started operation from January 2023
Hydrogen fuel cell	India	Northern Railway	Passenger	—	To be in operation from 2024

Note: Cells with a dash indicate data is not available.

Linear synchronous motor systems

In a linear synchronous motor (LSM) system, electric motors are mounted on the track and used to power the locomotives, which are equipped with permanent magnets.[55] Although not widely considered for rail decarbonization, LSM was evaluated as one of the zero-emission locomotive technologies in a study conducted by the University of Illinois as a part of California's regulatory assessment for freight locomotives.[56] The study reported that LSM systems have been used for passenger rail but could be challenging to adopt for freight rail.

---

[55] California Air Resources Board, *Transitioning to a Zero or Near-Zero Emission Line-Haul Freight Rail System.*

[56] California Air Resources Board, *Transitioning to a Zero or Near-Zero Emission Line-Haul Freight Rail System.*

The major challenges with the use of LSM systems are the significant capital cost for infrastructure, such as the track-mounted electric motors and permanent magnets, and technical limitations with handling of the weight and length of a freight locomotive. The University of Illinois reported an estimated cost between $5 million to $20 million per track-mile for the LSM component materials.

LOW-EMISSION PROPULSION TECHNOLOGIES

Diesel hybrid battery-electric locomotive

Diesel hybrid battery-electric locomotives, also referred to as "BEL hybrid consist," use conventional diesel-electric propulsion coupled with either onboard batteries or battery tenders which can power a share of the trip, such as around the railyard or within a sensitive geographical area, to operate in zero-emission mode. This partial zero-emission operation has the potential to substantially reduce fuel consumption and local air pollution in high-exposure areas.

With onboard batteries, there is typically a separate locomotive for batteries, in addition to the diesel locomotive(s), that run for the entire trip. For example, Wabtec's FLXdrive 1.0 (see Table 4), which was piloted in California in 2021 on a line-haul locomotive, includes two diesel locomotives and one battery-electric locomotive.[57] In contrast, battery tenders can be attached to existing locomotives, so the purchase of new locomotives is not required.[58] In theory, battery tenders could be left at an exchange point after passing an area where zero-emission operation is required or recommended, beyond which only the diesel locomotive will continue. However, the operational and economic viability of tenders need to be tested regarding the placement of the locomotive with respect to the tender, maximum number of tender cars that could be added to meet battery capacity requirements while not risking safe operation of the train, loss of time spent while switching tenders in and out of the locomotive, and having service facilities and shops to support tenders.

The hybrid approach could be a relatively economical solution for near-term transition to zero-emission for Class I line-haul locomotives and switchers. Compared with a full battery electric approach, the diesel hybrid approach would require less extensive infrastructure to be built-out, have fewer technical constraints on battery capacity or range, and may not require the purchase of new locomotives. This approach also has the potential to offer large fuel cost savings and local air quality benefits compared with diesel-only operation.

For example, in the FLXdrive 1.0 pilot in California, the BEL hybrid consist, on average, reduced fuel consumption by 12% (6,200 gallons of diesel and 69 tons of CO_2 emissions), NO_x emissions by 8%, and CO, THC, and PM emissions by 3% each, compared with diesel-only operation. Wabtec's next generation FLXdrive 2.0, with a larger battery capacity (7.3 MWh) than the FLXdrive 1.0 (2.4 MWh), is expected to reduce fuel consumption by nearly 30%.[59]

As listed in Table 4, Australia and Canada are adopting FLXdrive 2.0 technology for long-haul freight locomotives.[60] Europe has also adopted this hybrid technology; such

---

[57] BNSF Railway, *BNSF Zero- and Near Zero-Emission Freight Facilities Project* (ZANZEFF) Data Acquisition Support, prepared by Garrett Anderson, May 2021, https://ww2.arb.ca.gov/sites/default/files/2022-11/zanzeff-bnsf-belreport.pdf.

[58] California Air Resources Board, *Transitioning to a Zero or Near-Zero Emission Line-Haul Freight Rail System*.

[59] William C. Vantuono, "FLXdrive 'electrifies' Pittsburgh," *Railway Age*, September 14, 2023, https://www.railwayage.com/freight/flxdrive-electrifies-pittsburgh/.

[60] Vantuono, "Next-Gen Motive Power;" Canadian National Railway Company, "CN Advances Sustainability Efforts With Wabtec's Battery-Electric Locomotive," press release, November 4, 2021, https://www.cn.ca/en/news/2021/11/cn-advances-sustainability-efforts-with-wabtecs-battery-electric/.

locomotives are either already in operation or orders have been placed for switchers and passenger locomotives.[61]

Table 4

Examples of diesel hybrid battery-electric locomotives planned or in use

Technology adopted	Region of application	Developing or implementing entity (locomotive name)	Locomotive segment	Tractive power (battery capacity)	Phase of technology application
Diesel hybrid battery-electric	Brazil	Progress rail (EMD® Joule GT38H)	Switcher	2.2 MW (0.55 MWh)	Concept under consideration
Diesel hybrid battery-electric	United States	BNSF, Wabtec (FLXdrive 1.0)	Line-haul	3.3 MW (2.4 MWh)	2021 pilot in California
Diesel hybrid battery-electric	Australia, Canada	BNSF, Wabtec; Canadian National Railway Company or CN (FLXdrive 2.0)	Line-haul	(7.3 MWh)	To be delivered to BHP Western Australia Iron Ore for trial; to be delivered to Canada in 2023
Diesel hybrid battery-electric	Europe	DB Cargo	Switcher	—	50 unit order placed
Diesel hybrid battery-electric + catenary	Europe	Stadler (South Wales Metro FLIRT Trimodal)	Passenger	—	In operation

Note: Cells with a dash indicate data is not available.

Solid oxide fuel cell with gas turbine

Unlike hydrogen fuel cells where onboard hydrogen is directly used to power batteries, solid oxide fuel cells with gas turbines (SOFC-GT) involve steam reforming of hydrocarbon fuel to produce hydrogen and CO_2. Hydrogen is then combined with oxygen to generate electricity in the fuel cell. Additional electricity is produced from combination of fuel cell residual gases (hydrogen and carbon monoxide) to form a synthesis gas combusted in a gas turbine. SOFC-GT has been reported to achieve 70% fuel efficiency in laboratory trials, which is much higher than the typical efficiency level of 30%–40% for an ICE. However, this technology is still under development; there is no working SOFC-GT prototype for line-haul locomotives. The University of Illinois preliminarily estimated the capital costs for this technology could be 2– 3 times higher and maintenance costs could be more than 3 times higher than conventional diesel-electric locomotives, which were estimated approximately $5 million per unit for capital cost and $3.75 per locomotive-mile for maintenance cost.[62]

Hydrogen internal combustion engine

Although hydrogen fuel combustion is an alternative fuel solution, as opposed to a new technology, it is considered a better decarbonization option than renewable diesel or biodiesel, because hydrogen is carbon-free and its combustion does not emit CO_2. The hydrogen ICE (H2-ICE) concept involves the combustion of hydrogen in an ICE, either fully replacing diesel or as a blend with diesel.[63] The hypothesis is that partial hydrogen use could substantially reduce GHG and PM emissions, while maintaining diesel-like efficiency and performance.

---

[61] *APTA Whitepaper on Battery-Electric and Hydrogen Passenger Rail Equipment*; Fischer, "Deutsche Bahn's;" Schugar-Martin, "Progress Rail Decarbonization Solutions;" Vantuono, "Next-Gen Motive Power."

[62] California Air Resources Board, Transitioning to a Zero or Near-Zero Emission Line-Haul Freight Rail System.

[63] Vantuono, "Next-Gen Motive Power;" Lothrop, "Pathways to Decarbonizing the Rail Sector."

As stated earlier, DOE is considering H2-ICE as a near-term rail decarbonization approach, and industry and other governments are also evaluating its feasibility and emissions reduction potential. Wabtec, in partnership with Argonne and Oak Ridge National Laboratories under a grant from DOE, are assessing how high a share of hydrogen can be blended with diesel to achieve an energy content of 90% or higher.

The Government of Canada and the National Research Council are investigating the emissions reduction potential of H2-ICE.[64] In their preliminary findings mainly based on laboratory testing, GHG emission reductions were highest, at 50%, when 50% hydrogen was used, but there was a substantial increase in NO_x emissions. They also reported challenges in managing the high temperature and pressure required for hydrogen combustion in a diesel engine at high load. which required extensive engine modifications.

COST AND BENEFITS ASSESSMENT

As low- and zero-emission propulsion technologies for locomotives are still evolving in terms of technology and real-world technical and economic feasibility, data and analysis on the cost-effectiveness or total cost of ownership of these technologies are not yet widely available. Some studies have either reported limited cost benefit items or evaluated limited types of technologies. To fill this data and information gap, in this review, we consolidate information on costs and benefits from multiple sources and identify further tools and models that could help support U.S. rail decarbonization efforts.

The Lawrence Berkeley National Laboratory estimated the net present value of the total cost of ownership over 20 years for converting diesel-electric line-haul locomotives to battery-electric locomotives (assuming batteries of 9.1 MWh capacity and 241 km range).[65] The study found that over 20 years, the capital and operating costs from the conversion would be $15 billion, while the benefits from battery-electric locomotive operation would be savings of $44 billion based on reductions of criteria air pollutants only and $94 billion accounting for emission reductions for both criteria air pollutants and CO_2. Based on a sensitivity analysis, charging station use rates and diesel price were identified as the largest sources of uncertainty in the estimates.

The ARPA-e project, sponsored by DOE, assessed and compared the annual operating costs of fuel/energy consumption for freight locomotives powered by conventional diesel, biodiesel, diesel-hybrid battery-electric, biodiesel-hybrid battery-electric, battery-electric, hydrogen fuel cell, and catenary system across the United States.[66] Compared with conventional diesel, catenary system and battery-electric locomotives had the largest annual fuel savings of nearly $9 billion, followed by hydrogen fuel cell at more than $2 billion, and diesel-hybrid battery-electric at $0.7 billion. Biodiesel options had higher fuel costs than the conventional diesel locomotive.

Transport Canada conducted a feasibility study on retrofitting an existing diesel switcher to run on a hydrogen fuel cell (Hydrail switcher locomotive project).[67] Initially, the operating costs of the technology were roughly twice those of diesel. However, the difference narrows over time. The hydrogen fuel cell is expected to provide net savings

---

[64] Lothrop, "Pathways to Decarbonizing the Rail Sector."

[65] Popovich, et al., "Economic, Environmental and Grid-Resilience Benefits."

[66] George List, Andreas Hoffrichter, and Lynn Harris, "Exploring Decarbonization Options using A-STEP," (presentation, FRA Decarbonization Workshop, May 17, 2023), https://railroads.dot.gov/sites/fra.dot.gov/files/2023-06/Multi-Decadal%20Decarbonization%20Pathways%20for%20U.S.%20Freight%20Rail.pdf.

[67] "Assessment of the Design, Deployment Characteristics and Requirements of a Hydrogen Fuel Cell Powered Switcher Locomotive," Transport Canada, last modified March, 28, 2023, https://tc.canada.ca/en/innovation-centre/priority-reports/assessment-design-deployment-characteristics-requirements-hydrogen-fuel-cell-powered-switcher-locomotive.

in a decade, depending on the future costs of diesel and power. The estimated cost of this conversion could range from roughly CA$5 million to CA$8 million, along with an added capital cost of nearly CA$300,000 per locomotive for hydrogen fuel delivery and storage. Transport Canada further estimated that adopting hydrogen fuel cell technology for Canada's rail industry could avert 78 Mt of GHG emissions from 2030 to 2050 at a capital cost of CA$32 billion.

As part of the regulatory assessment for the state's In-Use Locomotive Regulation, the California Air Resources Board estimated that transitioning to zero-emission locomotives would lead to statewide health benefits of $32 billion between 2024 and 2050, while the total net cost of the regulation would be $13.8 billion in the same timeframe.[68] The health benefits result from avoided early deaths, hospitalizations, and emergency room visits. The costs include capital costs for locomotives and supporting infrastructure, maintenance costs, electricity usage, administrative payments, operator administrative costs for registration and reporting, and opportunity costs. Cost savings include lower maintenance costs for zero-emission locomotives, diesel fuel savings, and locomotive salvage and sales revenue.

To help support the evaluation of the emerging technological pathways for locomotives, various cost estimation tools and models are becoming available with preliminary findings and validation results. For example, Northwestern University developed the Northwestern University Freight Rail Infrastructure & Energy Network Decarbonization (NUFRIEND) framework, which is a comprehensive industry-oriented tool for simulating the deployment of alternative propulsion technologies and alternative fuels for freight locomotives.[69] The tool can be used to perform lifecycle and techno-economic analyses to estimate carbon emission reductions, capital costs, cost of carbon reductions, and operational impacts. For U.S. Class I railroad networks, estimates showed that with a 50% deployment level of 800-mile range battery-electric locomotives, CO_2 emissions would be reduced by 46% with a cost of $0.06 per kg of CO_2 reduced. For 400-mile range battery electric locomotives, the emissions reduction benefits would drop to 16% with an increased cost of $0.11 per kg of CO_2 reduced.

National Renewable Energy Laboratory, in partnership with the rail industry, academia, and research organizations, has developed an open-source software tool, Advanced Locomotive Technology and Rail Infrastructure Optimization System (ALTRIOS), to evaluate the GHG emissions reduction potential and cost-effectiveness of various low- and zero-emission technologies and alternative fuel options.[70] This tool simulates and optimizes the rollout of cost-effective locomotive technologies for rail decarbonization. Outputs include CO_2-equivalent emissions per unit of energy consumption based on lifecycle analyses, and cost estimates including levelized cost of million tonne-km, net present value, and year-by-year itemized costs for user specified inputs. The model has been validated based on real-world data on real locomotive trips in California.

Table 5 shows the cost and benefit estimates reported by the University of Illinois for two low-emission propulsion technologies, diesel-hybrid battery-electric and SOFC-GT with LNG, for line-haul freight locomotives implemented for the entire network through North America (see Appendix for details).[71] The estimates include emission reductions, fuel use savings, and net benefits, relative to Tier 4 diesel-electric locomotives. The net benefit is the difference between total costs and total fuel savings, estimated over

---

[68] California Air Resources Board, *Public Hearing*.

[69] Adrian Hernandez, et al., "Evaluation of Rail Decarbonization Alternatives: Framework and Application," *Transportation Research Record: Journal of the Transportation Research Board*, 2678(1) (May 2023): 102–121, https://doi.org/10.1177/03611981231170182.

[70] National Renewable Energy Laboratory, ALTRIOS: *Advanced Locomotive Technology and Rail Infrastructure Optimization System*, https://www.nrel.gov/transportation/altrios.html.

[71] California Air Resources Board, T*ransitioning to a Zero or Near-Zero Emission Line-Haul Freight Rail System*.

15 years of initial mainline service of a long-haul locomotive, assuming a 10% discount rate.[72] The negative sign for net benefits estimates indicate that for both technologies, benefits are lower than the costs accounting for only fuel cost savings as benefits. However, benefits could be higher if emission reductions are included for GHG and criteria pollutants.

Table 5

Estimated emission reductions, fuel savings, and present value costs relative to a Tier 4 diesel locomotive, for selected low-emission technologies for line-haul locomotives in North America

Technology	CO_2 reduction	CO reduction	HC reduction	NO_x reduction	PM reduction	Diesel saved (millions of gallons)	Annual fuel cost saving $million (% reduction)	Net benefit ($million)[b]
Diesel hybrid battery-electric with onboard batteries + aftertreatment	15%	15%	15%	79%	79%	360	1,118 (15%)	-840
Solid oxide fuel cell – gas turbine with LNG	57%	47%	47%	47%	47%	980[a]	3,845 (52%)	-2,781

[a] Fuel consumption reported in diesel gallon equivalent (DGE) unit.

[b] Net benefits estimate here is the present value cost including capital and non-capital costs less the annual fuel saving for each technology relative to Tier 4, estimated over 15 years of initial mainline service of a long-haul locomotive, assuming a 10% discount rate.

SUMMARY

This study reviews global trends in efforts to reduce rail emissions, reviews state-of-the-art propulsion technologies to decarbonize locomotives, and summarizes cost and benefit assessments of the technologies.

Although the global trend outside of the U.S. for zero-emission locomotives has been mainly focused on the catenary system, battery-electric and hydrogen fuel cell technologies are being assessed for technological and economic feasibility. So far, there is no single technological solution applicable for line-haul freight, switcher, and passenger locomotives, and all types of rail networks or routes. Short- and long-term technological pathways could vary depending on factors such as the locomotive type, extent of technology development, and the economic and technical feasibility of the technologies.

As illustrated in Table 6, all the major zero-emission technologies have specific challenges and opportunities. For instance, batteries have higher energy efficiency, but shorter range than hydrogen fuel cells, and locomotives with battery tenders may have lower capital cost than catenary systems but have lower range and require extensive charging networks and charging time. Compared with the conventional diesel powertrain, zero-emission technologies could have much higher capital costs but could offer 100% emissions reduction on-board. Although the capital costs of catenary systems could be highly expensive, it is the most used technology globally, does not have power output and range limitations, and offers substantial fuel cost savings compared with diesel powertrains.

---

[72] Total costs include capital costs and the present value of non-capital costs. Capital costs include annual incremental costs of purchasing new locomotives and tenders (relative to Tier 4) and servicing facilities. Non-capital costs include the present value for annual incremental locomotive maintenance costs for each technology.

Table 6
Qualitative performance assessment of major zero-emission locomotive technologies

	Diesel ICE	Catenary system	Battery-electric	H_2 fuel cell
Energy efficiency	💪	💪💪💪	💪💪💪	💪💪
Range	🏃🏃🏃	🏃🏃🏃	🏃	🏃🏃
Cost of locomotives and infrastructure	$	$$$	$$$	$$$
Fuel cost	$$$	$	$	$$$
Emission reductions	★	★★★	★★★	★★★
Technological readiness	★★★	★★★	★	★

Catenary systems could be combined with other zero-emission pathways in the long-term, or with a hybrid of diesel powertrain as an interim solution. Partial electrification combined with batteries or fuel cells, or with diesel hybrid battery-electric technology, might prove viable and cost-effective for line-haul freight locomotives. Any planning or investment for low-emission technologies will need to be made with caution since those should only serve as temporary solution that will need to be gradually phased out by zero-emission pathways.

While partial electrification combined with batteries or fuel cells could be considered a long-term solution, particularly for line-haul freight locomotives, the transition to zero-emission technologies could vary over locomotive segments. Application of zero-emission technologies has been mostly limited to yard locomotives or switchers and passenger rail. Although line-haul freight locomotives are typically the most energy intensive locomotive segments and hence, a focus of rail decarbonization, switchers and passenger locomotives are typically easier to transition to zero-emission technologies considering available technologies and relative economics. Zero-emission operation for such locomotives also offer substantial local air quality improvement and health benefits, particularly with the switchers for less affluent communities in or around the rail yard. Short distance regional switchers and/or industrial locomotives are candidates for adopting battery-electric technology due to the shorter distances traveled and minimal need for charging infrastructure. Switchers and passenger locomotives could be prioritized for early decarbonization with specific technologies that prove viable based on field trials or pilots. Such strategic adoption could accelerate the transition and help create a market for technologies to further advance and mature.

The available estimates of technology costs and benefits from multiple studies indicate there are substantial benefits from adopting low- and zero-emission propulsion technologies in terms of fuel cost savings and health and climate benefits from reduced emissions. With technological advancement, commercial deployment, and market maturity of the technologies, the total cost of ownership is expected to be lower than the conventional diesel powertrain in the future.

APPENDIX

Table A1 and Table A2 show the cost and benefit estimates reported by the University of Illinois for specific low- and zero-emission technologies.[73] The estimates are for the respective technology's application in long-haul freight locomotives and include emission reductions, fuel use savings, and present value cost relative to Tier 4 diesel locomotives. Considering technical and feasibility constraints, some technologies were assessed only for the regional fleet inside California's South Coast Air Basin, while a few technologies were evaluated assuming full scale of deployment in North America. The present value cost estimates include capital and non-capital costs relative to a Tier 4 diesel locomotive baseline, estimated over 15 years of initial mainline service of a long-haul locomotive for a given technology and regional scale of operation. This assessment does not include hydrogen fuel cell and 100% battery-electric technologies. The application of these technologies on North American scale, in general, is more economical than the regional fleet.

Table A1

Estimated emissions reduction, fuel savings, and net benefits, relative to Tier 4, for selected low- and zero-emission pathways for long-haul locomotives

Technology[a]	CO_2 reduction	CO reduction	HC reduction	NO_x reduction	PM reduction	Diesel saved (millions of gallons) [b]	Annual fuel cost saving $million (% reduction)	Net benefit[d] ($million)
Catenary system (SCAB scale)	100%	100%	100%	100%	100%		116 (52%)[3]	-44,334
Diesel hybrid battery-electric with battery tenders (SCAB scale)	100%	100%	100%	100%	100%	29.7	41 (18%)[3]	-29,973
Linear synchronous motors (SCAB scale)	100%	100%	100%	100%	100%		116 (52%)[c]	—
Diesel hybrid battery-electric with onboard batteries + after treatment (North American scale)	15%	15%	15%	79%	79%	360	1,118 (15%)	-840
Solid oxide fuel cell – gas turbine (SCAB scale)	57%	47%	47%	47%	47%	29.7	117 (52%)	-13,727
Solid oxide fuel cell – gas turbine (North American scale)	57%	47%	47%	47%	47%	980	3,845 (52%)	-2,781

Note: Cells with a dash indicate data is not available. Blanks cells indicate the information is not applicable.

[a] Estimates are listed here for four technologies assessed for captive regional fleets in South Coast Air Basins (SCAB) and two technologies on a North American deployment scale for all SCAB and non-SCAB trains. Technologies for SCAB deployment include catenary system, LSM, Tier 4 diesel-hybrid battery-electric with battery tenders (which was assumed to operate on battery tenders or at zero-emission configuration as captive fleet within SCAB and that is exchanged with the diesel-electric locomotive at the exit or entrance to the area at a locomotive exchange point; tenders do not leave the SCAB area), and solid oxide fuel cell – gas turbine (SOFC-GT); two technologies assessed at North American scale of deployment include: Tier 4 diesel hybrid battery-electric with aftertreatment and onboard batteries, and the SOFC-GT, which is the only technology that was assessed in both scales of operation.

[b] Diesel saving estimates are only for the technologies that utilize diesel or LNG; for technologies using LNG, fuel consumption was reported in diesel gallon equivalent (DGE) unit.

[c] Battery tenders, catenary system, and LSM technologies (within SCAB area) consume electricity as fuel, hence, although there is no emission at the site (i.e., 100% reduction from Tier 4 level), there are fuel costs from electricity consumption, and some diesel consumption at exchange points for battery tender technology.

[d] Net benefits estimate is the present value cost including sum of capital and non-capital costs less the annual fuel saving for each technology relative to Tier 4, estimated over 15 years of initial mainline service of a long-haul locomotive, assuming a 10% discount rate.

---

[73] California Air Resources Board, *Transitioning to a Zero or Near-Zero Emission Line-Haul Freight Rail System*.

Table A2

Benefits and cost estimates breakdown by technology

Technology	Net benefits, $million (relative to Tier 4)[a]	Total capital cost ($million)[b]	Present value of annual non-capital costs (-ve) or benefits (+ve), $million (relative to Tier 4)[c]
Solid oxide fuel cell – gas turbine with LNG (SCAB scale)	-13,727	-4,460	-9,267
Catenary system (SCAB scale)	-44,334	-35,498	-8,836
Linear synchronous motors (SCAB scale)	Unknown	Unknown	Unknown
Diesel-electric with battery tenders (SCAB scale)	-29,973	-20,467	-9,505
Diesel hybrid battery–electric + after treatment (North American scale)	-840	-3,042	2,202
Solid oxide fuel cell – gas turbine with LNG (North American scale)	-2,781	-8,516	5,645

Source: California Air Resources Board, *Transitioning to a Zero or Near-Zero Emission Line-Haul Freight Rail System*.

[a] As shown in Table A1.

[b] Capital cost items vary by technology and regional scale of operation including purchase cost of new technology locomotive and tenders, capital cost of infrastructure such as for catenary and LSM, construction costs of new locomotive repair shop facilities and exchange facilities in south coast, cost of establishing servicing and fueling facilities, and annual incremental capital cost of purchasing new locomotives and tenders (relative to Tier 4) at North American scale of deployment.

[c] The annual non-capital costs were transformed to present value by assuming they are incurred over 15 years with a discount rate of 10 percent; non-capital cost items vary by technology and regional scale of operation including annual maintenance of catenary infrastructure, annual operating cost of personnel at locomotive exchange points, cost of train delay at exchange point, annual revenue loss due to freight shifting to truck resulting from delay at exchange point, annual fuel/energy cost savings relative to Tier 4 baseline, and annual incremental maintenance cost relative to Tier 4.

www.theicct.org

communications@theicct.org

@theicct.org

THE INTERNATIONAL COUNCIL
ON CLEAN TRANSPORTATION

BEIJING | BERLIN | NEW DELHI | SAN FRANCISCO | SÃO PAULO | WASHINGTON DC