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Economic, environmental and grid-resilience benefits of converting diesel trains to battery-electric

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Nearly all US locomotives are propelled by diesel-electric drives, which emit 35 million tonnes of CO₂ and produce air pollution causing about 1,000 premature deaths annually, accounting for approximately US\$6.5 billion in annual health damage costs. Improved battery technology plus access to cheap renewable electricity open the possibility of battery-electric rail. Here we show that a 241-km range can be achieved using a single standard boxcar equipped with a 14-MWh battery and inverter, while consuming half the energy consumed by diesel trains. At near-future battery prices, battery-electric trains can achieve parity with diesel-electric trains if environmental costs are included or if rail companies can access wholesale electricity prices and achieve 40% use of fast-charging infrastructure. Accounting for reduced criteria air pollutants and CO₂ emissions, switching to battery-electric propulsion would save the US freight rail sector US\$94 billion over 20 years.

Scientific consensus asserts that global greenhouse gas (GHG) emissions must be reduced by 45% from 2010 levels by 2030 to limit global warming to 1.5 °C and minimize climate catastrophe¹. The US freight rail sector provides a unique opportunity for aggressive near-term climate action. It transports more goods than any other rail system in the world² and depends on diesel fuel, which accounts for over 90% of the rail sector's total energy consumption³. Currently transporting 40% of national intercity freight⁴, its capacity is projected to double by 2050⁵. Without substantial changes to its propulsion system, the US freight rail system will be responsible for half the global diesel used in the freight rail sector by the same year². These diesel locomotives emit 35 million tonnes of CO₂ each year and produce air pollution that causes about 1,000 premature deaths annually, accounting for approximately US\$6.5 billion in health damage costs per year^{6,7}. Despite being more fuel efficient than trucks, these locomotives produce close to twice the air pollution damages compared with heavy-duty trucks per unit of fuel consumed owing to less stringent pollution controls on locomotives^{6,8}. Since 2015, new and remanufactured locomotives have been required to install a catalytic converter, reducing nitrogen oxides (NO_x) and fine particulate matter (PM_{2.5}) emissions by 80–90% by 2040⁹. Notably, these measures do not impact GHG emissions.

Efforts to identify zero-emissions pathways for freight rail are underway, with national sector-wide emissions-reductions targets and more stringent Environmental Protection Agency (EPA) emissions-reductions requirements for the US freight rail sector¹⁰. A few viable pathways have emerged for achieving zero emissions: rail network electrification via catenary, hydrogen fuel cells and battery-powered locomotives. The catenary approach involves electrifying part or all of the rail network via overhead lines coupled with grid-scale storage of renewable energy and it has been more thoroughly investigated^{11,12}. Hydrogen fuel cells have also received increased attention^{13–15}, although their zero-emissions potential depends on the source of hydrogen and the process used to extract it¹⁶. Nearly all hydrogen is currently produced with fossil fuels¹⁷.

We consider the battery-electric pathway on the basis of leveraging recent technological advances to add battery cars to existing diesel-electric locomotives. This approach allows rail operators to exploit existing surplus renewable energy sources at low prices.

Three recent developments support a US transition to battery-electric rail: plummeting battery prices, increasing battery energy densities and access to cheap renewable electricity. Between 2010 and 2020, battery energy densities tripled and battery pack prices declined 87% (ref. ¹⁸). Average industry prices are expected to reach US\$100 kWh⁻¹ by 2023 and US\$58 kWh⁻¹ by 2030, with some automakers already achieving lithium-ion battery pack prices of US\$100 kWh⁻¹ (ref. ¹⁹). At the same time, electricity from renewable sources costs about half as much as electricity from fossil fuels²⁰. A few studies have considered battery-electric rail propulsion, but their price estimates are outdated owing to the rapid innovation in battery technology and none consider the effects of charging-infrastructure capacity use on infrastructure costs^{2,21}. Prior studies have also relied on average service-level electricity tariffs, which overestimate charging costs because they do not account for potential to charge batteries when surplus renewable electricity is available or consider economies of scale of transmission- or distribution-level services on routes with high travel volumes.

We examine the case for zero-emission, battery-electric propulsion in the US freight rail sector on the basis of current and forecasted energy storage technologies combined with access to renewable energy at industrial rates. We consider only Class I railroads here, defined as railroads that earn over US\$505 million in revenue per year, which together accounted for 94% of freight rail revenue in 2019²². We show that a 241-km range (the average daily distance travelled by US Class I freight trains) can be achieved using a single boxcar equipped with a 14-MWh battery and inverter, while consuming half the energy consumed by diesel trains. At near-future battery prices (US\$100 kWh⁻¹), battery-electric trains can achieve parity with diesel-electric trains if environmental costs are included or if rail companies can access wholesale

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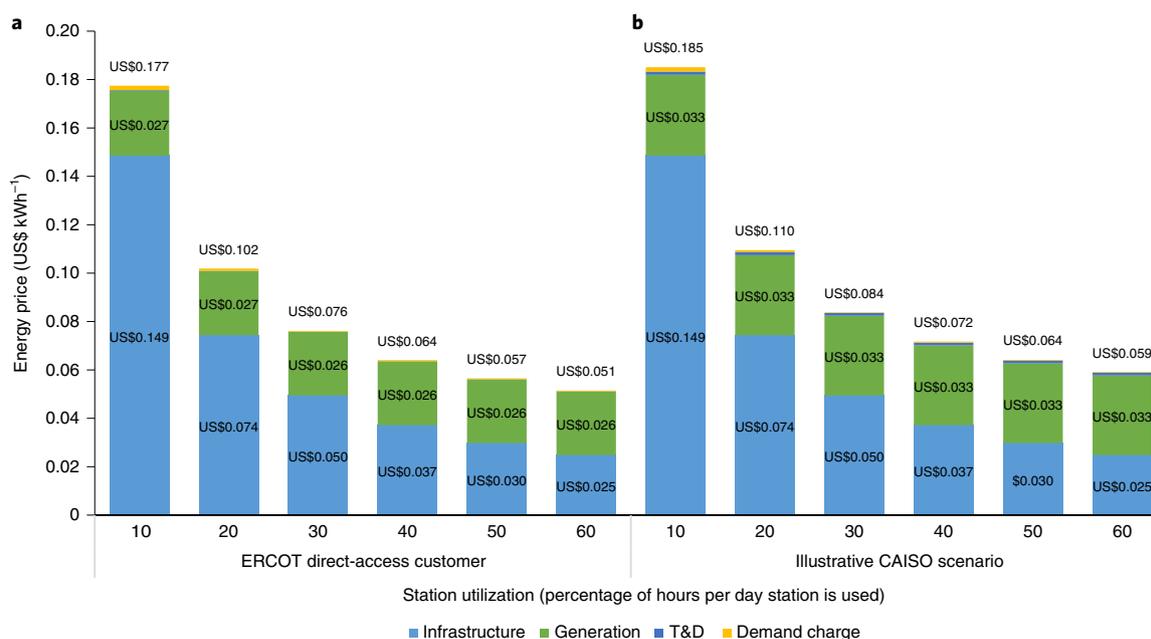


Fig. 1 | Energy prices inclusive of fast-charging infrastructure at various station use rates for a 72-MW charging station. a, Depiction of the ERCOT market, which assumes rail customers have access to wholesale prices. **b,** Depiction of an illustrative CAISO market which assumes ERCOT's CPP rate structure and no resource adequacy surcharges. Baseline assumptions include an 80% depth of recharge, eight tender cars per station, 1-h charge time, 7% capital expenditure revenue return⁵³ and 10% efficiency losses in power conversion. Station lifetimes are estimated at 20 years. Generation prices are average hourly prices observed for each market for all hours 2017–2019.

electricity prices and achieve 40% use of fast-charging infrastructure. Accounting for reduced criteria air pollutants and CO₂ emissions, switching to battery-electric propulsion could save the US freight rail sector US\$94 billion over 20 years. We consider the sensitivity of our results to battery pack assumptions, electricity rates and diesel prices.

Technical feasibility of battery-electric propulsion

US Class I locomotives are diesel-electric: a diesel engine drives an electric generator that powers traction motors to drive the axles. Such a locomotive can be converted to battery-electric by adding one or more battery tender cars, referred to as tender cars, with wiring that delivers electricity to the drivetrain. A tender car could transmit electricity via cable to the locomotive's central electrical bus and then transmit that electricity to the traction motors. Alternating current (a.c.) and direct current (d.c.) traction motors have different retrofit requirements; both types are used in US locomotives, although a.c. motors are increasingly common. The d.c. locomotive requires only cables and a charge controller from the battery tender car, incurring negligible cost. Each locomotive with an a.c. traction motor would require a transformer (we account for this cost under charging infrastructure in the electricity tariffs) and an onboard inverter for the 3.3-MW traction motor. Alternatively, traction motors could be added under battery tender cars as a cable-less locomotive (rail representative, personal communication).

The freight rail sector is three to four times more fuel efficient (revenue-tonne⁻¹ of diesel) than road-based freight, on average⁴. This advantage provides trains with a margin for adding the battery-related weight, volume and energy consumption needed to achieve a sufficient daily range while maintaining very high efficiency. In addition, the nature of battery technology and rail operations provides plentiful opportunities for recharging during long hauls. Here, we show that adding a single boxcar of battery equipment could enable battery-powered trains to achieve requisite

operational ranges while surpassing the energy efficiency of diesel-electric trains.

Our analysis is based on a representative Class I train operating in California, with four 3.3-MW locomotives pulling 100 boxcars and 6,806 revenue-tonnes (or tonnes of payload). A standard 14.6-m boxcar has a rated payload capacity of 114 t (ref. ²³), although some heavy-duty cars can carry up to 337 t (ref. ²⁴). We use lithium ferrous phosphate (LFP) batteries because they have a longer cycle life and lower temperatures²⁵ than do lithium nickel manganese cobalt oxide (NMC) batteries and are more economical given the distances travelled by freight trains (2.4 million km over 20 years)²⁶. Furthermore, LFP batteries require negligible service maintenance, have a recharge rate up to 4C (ref. ²⁷), are cheaper than lithium titanate oxide (LTO), are not sensitive to unpredictable price fluctuations in cobalt or nickel²⁸ and can operate over a wide range of temperatures²⁹. While LTO presents some advantages relative to LFP, such as extreme fast charging, we select LFP due to the lower price, higher energy density, higher voltage³⁰ and relative stability³¹. Assuming the current best energy density achieved by LFP batteries, a single boxcar could accommodate a 14-MWh battery with a 241-km range on a single charge, the average distance travelled between stops for US Class I freight trains. Our estimate is much larger than existing estimates based on outdated battery energy densities that suggest a single tender car could carry only 5.1–6.2 MWh (refs. ^{13,32}).

Using cell-specific energy figures for LFP batteries and a typical packing fraction (cell weight per pack weight) of 0.76 (ref. ³³), we estimate the total weight of a 14-MWh battery plus inverter to be 114 t, well within the 121-t constraint of certain sections of the US rail network, such as bridges³⁴. Assuming the ratio of pack energy density (kWh⁻¹) to pack specific energy (kWh kg⁻¹) is the same as at the cell level, we estimate a total battery volume of 39 m³. The combined volume of the battery plus inverter (13.7 m³) is about 40% of the estimated volume of a standard boxcar (129 m³) (ref. ²³). Hence,

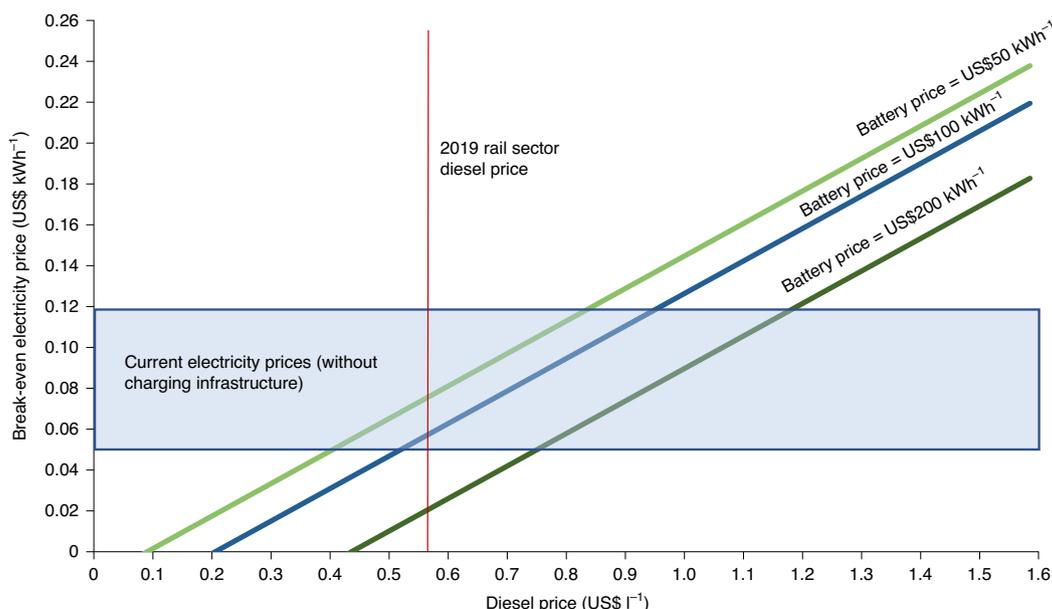


Fig. 2 | All-inclusive electricity prices needed to reach diesel parity based on total cost of ownership. These prices include electricity costs plus charging infrastructure costs, assuming LFP technology over a 20-year horizon. The battery prices considered are US\$200 kWh⁻¹ (dark green), US\$100 kWh⁻¹ (blue) and US\$50 kWh⁻¹ (light green). Current electricity prices are depicted by the shaded blue box. The vertical red line demarcates the 2019 average diesel price paid by the rail industry. At current wholesale diesel prices of US\$0.56 l⁻¹ and ignoring environmental damages, all-inclusive electricity prices would need to approach US\$0.056 kWh⁻¹ with battery prices at US\$100 kWh⁻¹ and US\$0.074 kWh⁻¹ with battery prices at US\$50 kWh⁻¹ to compete with diesel. These estimates are based on a locomotive with a 241-km range with a 9.1-MWh battery tender car pulling 1,090 revenue-tonnes. TCO is annualized over a 20-year horizon with a 3% discount rate.

it is feasible on a weight and volume basis to achieve a 241-km range using a single boxcar equipped with a 14-MWh battery and inverter.

The energy consumed by battery freight trains increases by 5% (241-km range) because of the additional battery weight but it is still about half the energy consumed by diesel trains owing to the high efficiency of all-electric drives. After accounting for the average energy intensity of the sector³⁵, diesel locomotive engine efficiency²¹ and cooling requirements for the battery, we estimate that trains with a 241-km range (14-MWh battery) require approximately 0.0345 kWh revenue-tonne-km⁻¹ with LFP technology. For comparison, an existing estimate of the energy requirements for battery-electric locomotives with regenerative braking is 0.014 kWh tonne-km⁻¹ (ref. ²¹). Existing passenger rail battery-electric locomotives in Japan have larger batteries for the operating ranges (for example, 3.6 MWh for a 27-km route) but the maximum ranges are not reported¹⁵. Preliminary findings from a battery-electric locomotive demonstration project in California suggest that our estimates are reasonable (rail representative, personal communication).

Battery-powered trains with at least a 241-km range should have ample opportunity to charge during long routes while remaining on schedule. The average length of a US Class I freight haul is 1,662 km (ref. ³). Class I freight rail routes include 30- to 45-min stops for crew changes every 240–400 km, at which point batteries could be recharged. Longer routes also include a refuelling stop at the midpoint for 1–2 h (rail representative, personal communication). Technological advances enable charging rates of 30 min to 1 h for fully charging each cell (1–2C charging) for commercially available LFP batteries, although LFP technology can theoretically achieve 4C charging²⁵. Although not considered in this analysis, the potential ability to swap a discharged battery car with a charged battery car could provide additional flexibility at stations that are well-staffed and receive sufficient through-traffic each day. There appears to be notable downtime during which charged cars can be swapped with discharged cars as boxcars typically sit idle for up to 25 h at a time³⁶.

Table 1 | Historical wholesale energy prices in ERCOT and CAISO

	Historical (2017–2019)	
	CAISO ³⁸	ERCOT ³⁷
Percentage of hours under US\$30 MWh ⁻¹	60	76
Percentage of hours under US\$45 MWh ⁻¹	87	91
Average price of eight cheapest hours of the day (US\$ MWh ⁻¹)	17.5	16.9
Average price of 12 cheapest hours of the day (US\$ MWh ⁻¹)	20.3	18.4
Average price of eight cheapest hours on the most expensive day (US\$ MWh ⁻¹)	69.4	44.3

These prices reflect only the price of generation and do not include fast-charging infrastructure, T&D or demand charges. The percentage of hours observed under a specific price point is calculated as the average hourly wholesale price observed for all days in the timeframe.

The centralized and scheduled nature of freight rail operation and dispatch can enable high use of fast-charging infrastructure, leading to lower costs. We estimate the cost of a 72-MW charging station connected at the transmission level that can charge eight tender cars at a time (for example, two trains with four tender cars each). Using historical prices from the Electric Reliability Council of Texas (ERCOT³⁷) and California Independent System Operator (CAISO³⁸), we estimate the levelized cost of electricity-plus-charging to be between US\$0.051 kWh⁻¹ (60% use, ERCOT) and US\$0.185 kWh⁻¹ (10% use, CAISO) (Fig. 1). Phadke et al. discuss the effect of rate design on charging costs³⁹. Because these costs are shared across the number of trains using the charging stations, stations with higher travel volumes have potential to be the most cost-effective locations.

Table 2 | Input parameters for levelized unit charging costs in existing ERCOT and illustrative CAISO market for 72 MW station

Cost component	ERCOT		CAISO		Units
Electricity generation	Price a retail electricity provider would pay to pass through the real-time price to a retail customer, on the basis of ERCOT prices 2017–2019 ³⁷ and ERCOT day-ahead market clearing prices for capacity ⁵⁴	26.5	Illustratively modelled as the price an energy service provider would pay to pass through the real-time price to a direct-access customer, not including resource adequacy payments, on the basis of CAISO real-time prices 2017–2019 ³⁸ , California renewable portfolio standards ⁵⁵ , renewable energy certificate prices ⁵⁶ and CAISO fees ⁵⁷	32.9	US\$ MWh ⁻¹
Transmission and distribution	T&D charges paid by a transmission-connected customer in Oncor service territory, charging only at non-critical-peak times ⁵⁸	0.3	T&D charges paid by a transmission-connected customer in Oncor service territory, charging only at non-critical-peak times ⁵⁸	0.3	US\$ MWh ⁻¹
Electrical equipment	Average of best-case electric vehicle supply equipment (EVSE) costs, taken to be (1) the balance of system (BOS) costs of grid-tied storage and (2) industry-projected EVSE costs, on the basis of utility-scale solar plus storage BOS costs ⁴⁸ and inverter lifetime ⁵⁹			34.8	US\$ MWh ⁻¹
Grid connection	Average levelized US grid connection cost for utility-scale solar photovoltaic (PV) projects ⁶⁰			2.4	US\$ MWh ⁻¹
Operations and maintenance	Cost of (1) inverter maintenance for a PV plant, (2) preventive maintenance and inspection, averaged for both an existing electric bus charging station and the electrical/wiring inspection costs of a PV plant and (3) estimated structural maintenance ⁵⁹			4.8	US\$ MWh ⁻¹
Installation	Installation costs associated with grid-tied storage, grid-connected storage cost of installation, labour and equipment, engineering, procurement and construction (EPC), overhead and interconnection ⁴⁸			7.5	US\$ MWh ⁻¹
Capital	Return owed on capital investment, on the basis of California investor-owned utility rates of return ⁵³			7%	

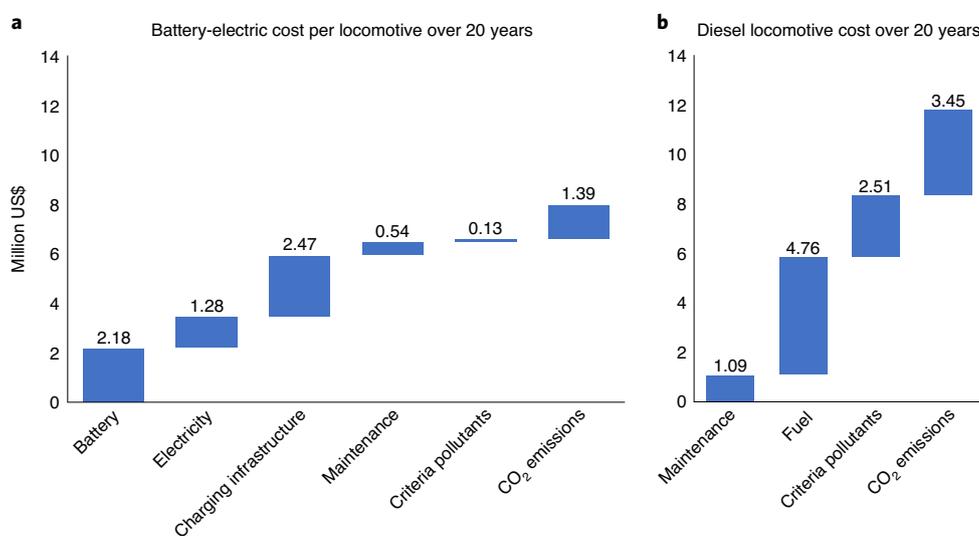


Fig. 3 | TCO of locomotives by propulsion technology over 20 years for the average US Class I line-haul freight locomotive. a, Depiction of the TCO for battery-electric propulsion. **b**, Depiction of the TCO for diesel propulsion. Both technologies are estimated using a 9.1-MWh battery with a 241-km range for a 3.3-MW locomotive pulling 1,090 revenue-tonnes. Assumptions include: US\$0.61⁻¹ diesel price, US\$100 kWh⁻¹ battery price (US\$50 kWh⁻¹ replacement price), 30% station use rate and 3% discount rate. Environmental damages are estimated using the ReEDs model for the US electricity mix under the CE590 scenario for battery-electric. Diesel damages are estimated under the assumption of continued roll-out of the EPA Tier 4 rule. The social cost of carbon emissions starts at US\$125 t⁻¹ in 2021 and increases to US\$226 t⁻¹ by 2040.

Achieving parity with diesel

At near-future battery prices (US\$100 kWh⁻¹), battery-electric trains can achieve parity with diesel-electric trains if environmental costs are included or if rail companies can access wholesale electricity prices and achieve 40% use of fast-charging infrastructure. The charging cost for a battery-electric train includes the cost of charging infrastructure and electricity. The cost of charging infrastructure is mainly driven by its use factor. We assume use of 30–50%, owing to centralized train scheduling and high volumes of traffic on

most routes¹³. Electricity costs can be reduced by avoiding charging when electricity prices are high. In certain markets, such as ERCOT, demand and fixed transmission charges can be avoided by avoiding charging during critical peak pricing (CPP) hours, which occur during fewer than 50 h per year³⁷. Average wholesale generation prices in key organized US markets for the last 3 years are less than US\$0.021 kWh⁻¹ during the lowest-priced 12 h in a day (Table 1). We use these values for the base case in the total cost of ownership (TCO) and net present value (NPV) calculations^{37,38}.

Table 3 | Input parameters for battery pack size

Train characteristics		
Power rating of locomotive ²¹	3.3	MW
Power rating of train (four locomotives)	13.2	MW
Train payload ²¹	6,806	revenue-tonnes
Locomotive payload	1,701	revenue-tonnes
Efficiency of diesel engine ²¹	0.39	
Energy intensity of freight rail sector ³⁵	212	kJ revenue-tonne-km ⁻¹
Energy requirements for diesel-powered train ³⁵	0.059	kWh revenue-tonne-km ⁻¹
Range	241	km
Volume of standard 14.6-m boxcar ²³	129	m ³
Payload capacity of standard boxcar ²³	114	t
Energy requirements for battery-powered train		
Heat value of diesel ⁶¹	10.6	kWh l ⁻¹
Battery pack assumptions (LFP)		
Cell-specific energy ⁶²	210	Wh kg ⁻¹
Packing fraction ³³	0.76	
Pack specific energy ⁶²	160	Wh kg ⁻¹
Cell energy density ⁶³	470	Wh l ⁻¹
Battery roundtrip efficiency ⁶⁴	0.95	
Efficiency relative to diesel	2.44	
Depth of discharge ⁶⁵	0.8	
Cooling requirements		
Battery tender car floor area	52.7	m ²
Temperature change	15	°C
Operating time	12	h d ⁻¹
Cooling load	20,045	kJ h ⁻¹

Using the energy requirement of 0.0345 kWh revenue-tonne-km⁻¹ for LFP batteries, we estimate electricity prices necessary to achieve parity with diesel for a battery-powered train with a 241-km range pulling 1,090 revenue-tonnes. We estimate the capital cost of required battery capacity and the associated cost of charging, inclusive of battery weight, cooling requirements and inverter. Figure 2 depicts the relationships among battery prices, diesel prices and electricity prices needed to motivate a switch to battery-powered trains. To achieve parity with 2019 diesel prices reported by the rail industry (averaging US\$0.56 l⁻¹ of diesel (ref. ⁴⁰)), all-inclusive electricity prices (electricity generation plus amortized charging costs) must reach US\$0.056 kWh⁻¹ with near-future LFP technology priced at US\$100 kWh⁻¹; this calculation excludes environmental costs. At average US diesel prices (US\$0.66 l⁻¹), electricity prices must reach US\$0.072 kWh⁻¹ with US\$100 kWh⁻¹ batteries. For context, average US industrial tariffs are US\$0.064 kWh⁻¹, excluding infrastructure costs⁴¹. If major markets followed tariff rules like ERCOT's CPP structure, freight railroads could realize electricity costs (including charging-infrastructure costs) under US\$0.07 kWh⁻¹ if they reach 40% use of charging infrastructure—thus achieving parity with diesel-powered trains. Including environmental costs relaxes the requisite price of electricity-plus-charging infrastructure to break even with diesel. Table 2 describes the inputs used to estimate unit charging costs for the ERCOT market for a 72-MW charging station that could accommodate two trains charging simultaneously at 1C.

Table 4 | Input parameters for TCO model

Unit capital cost components		
Battery life ⁶⁶	5,000	cycles
Cost of battery pack ⁶⁷	50–200	US\$ kWh ⁻¹
Cost to replace battery	50	US\$ kWh ⁻¹
Cost of inverter ⁴⁸	70	US\$ kWh ⁻¹
Cost of standard boxcar ⁶⁸	135,000	US\$
Inverter size	3.3	MW
Variable operations and maintenance cost of diesel engine (full-time use) (rail representative, personal communication)	200	US\$ d ⁻¹
Variable operations and maintenance cost of diesel engine (backup use) (rail representative, personal communication)	100	US\$ d ⁻¹
Unit fuel cost components		
Electricity generation price ³⁷	0.023	US\$ kWh ⁻¹
Levelized cost of fast-charging infrastructure ³⁹	0.02–0.09	US\$ kWh ⁻¹
Cycles per day	1	
Diesel price ⁴⁰	0.8	US\$ l ⁻¹
Average daily locomotive fuel consumption ²⁶	1,454	l d ⁻¹
Unit air pollution costs		
Air pollution damages per diesel locomotive ⁶	1,458	US\$ d ⁻¹
Median marginal damages of NO _x emissions from locomotives ⁶	12,420	US\$ t ⁻¹
Median marginal damages of PM _{2.5} emissions from locomotives ⁶	45,586	US\$ t ⁻¹
Unit GHG emissions cost components		
Marginal damage of CO ₂ emissions (2020–2040) ⁶⁹	125–226	US\$ t ⁻¹
CO ₂ emissions rate of diesel ⁷⁰	2.7	kg CO ₂ l ⁻¹
Median marginal damages of NO _x emissions from coal-fired electricity ⁶	10,579	US\$ t ⁻¹
Median marginal damages of SO ₂ emissions from coal-fired electricity ⁶	26,672	US\$ t ⁻¹
Median marginal damages of NO _x emissions from natural gas electricity ⁶	10,292	US\$ t ⁻¹
Median marginal damages of SO ₂ emissions from natural gas electricity ⁶	21,951	US\$ t ⁻¹
CO ₂ , NO _x and SO ₂ emissions rates of US power mix (2020–2040) ⁵¹	varies	kg MWh ⁻¹
All prices are listed in 2019 US\$.		

Locomotive total cost of ownership. Figure 3 displays the TCO per locomotive over 20 years for the baseline scenario. Here, we apply the energy intensity derived from the California representative line-haul train (0.0345 kWh revenue-tonne-km⁻¹) to the US average class I line-haul train so that the results can be scaled up to approximate the nationwide costs of a transition to battery-electric freight rail. Over 20 years, battery-electric tender cars (including maintenance of the existing diesel engine) cost US\$6.47–8 million and diesel locomotives cost US\$5.85–11.83 million, depending on whether environmental damages are included. Table 3 describes the input parameters for battery pack size.

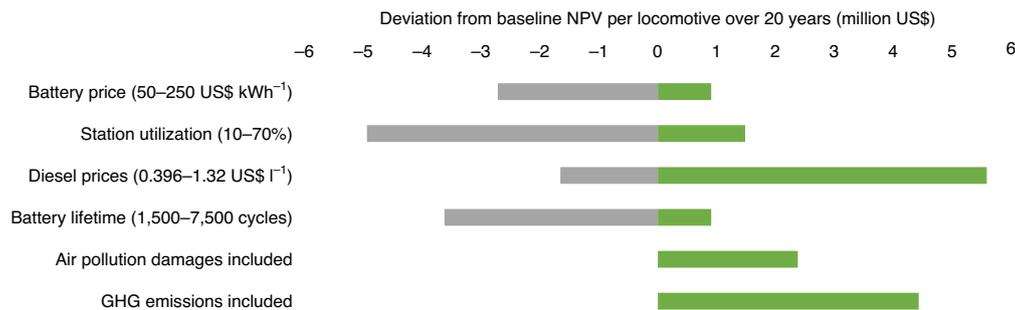


Fig. 4 | Sensitivity of battery-electric locomotive NPV over 20 years to changes in input assumptions. Baseline battery-electric NPV is -US\$598,602. Baseline assumptions include a 9.1-MWh battery, US\$100 kWh⁻¹ battery price, 30% station use rate, US\$0.61 l⁻¹ diesel price, battery life of 5,000 cycles and zero cost of environmental damages. Values are estimated as changes from baseline battery-electric scenario NPV for each input, holding baseline assumptions equal across all other components. The ranges to the inputs are in parentheses. Grey bars depict a decrease in locomotive NPV, relative to baseline assumptions. Green bars depict an increase in locomotive NPV relative to baseline assumptions.

Table 4 describes the key input parameters used in the TCO analysis, which represent current and near-term forecasted technology and prices. We use a diesel price of US\$0.61 l⁻¹, halfway between 2019 rail-reported fuel costs⁴⁰ and US average prices. We include diesel engine maintenance costs in the TCO for battery-electric locomotives to maintain flexibility of dual fuel capability should train operators choose to dispatch battery tender cars to relieve power constraints on the grid. Even a modest price on external environmental damages would be sufficient to make battery-electric locomotives cost-competitive with diesel-electric locomotives at near-future battery prices (US\$100 kWh⁻¹) and current electricity-plus-charging-infrastructure prices (US\$0.070 kWh⁻¹).

Sector-wide net present value. We investigate the NPV over 20 years to the freight rail sector of converting diesel-electric locomotives to battery-electric, comparing the capital and operating costs along with costs of damages from CO₂ and criteria air pollutants. Whereas the TCO compares each propulsion technology separately, the NPV compares the sector-wide savings of battery-electric relative to diesel. The NPV of the baseline battery-electric scenario leads to a US\$15 billion cost without environmental considerations, US\$44 billion in savings when accounting for criteria pollution abatement and US\$94 billion in savings with CO₂ emissions reductions. The main determinants of the economic returns are the station use rates and the price of diesel fuel. Our analysis shows that battery-electric trains are cost-effective today if diesel-electric trains internalize the costs of environmental damages, even at battery prices of US\$250 kWh⁻¹ and low station use rates of 25%.

We analyse the sensitivity of our results from the baseline battery-electric scenario to changes in battery price, charging station capacity use, diesel price, battery lifetime and the inclusion of environmental damages. Figure 4 depicts the range of NPV per locomotive over 20 years for each input category. The largest uncertainty in NPV is driven by charging station use rates and the price of diesel.

Comparison with alternative zero-emissions technologies

Electrification via catenary is widespread in Europe and Asia. However, the context is not directly transferable because US freight trains tend to pull ten times more payload than European freight trains, dramatically increasing the average electricity infrastructure requirements³². Historically, electrification has been estimated to be about twice as expensive in the United States compared with Europe but these costs are highly uncertain owing to the limited number of observations⁴². Furthermore, the frequent use of double-stack containers in the United States makes catenary requirements

problematic; infrastructure would need to be 7 m higher than the tracks to accommodate such trains³². Recent US cost estimates for catenary construction range from US\$5.1 million km⁻¹ (ref. ⁴³) to US\$31 million km⁻¹ (ref. ²¹), excluding the cost of the locomotives. However, these estimates are only available for passenger rail. International estimates are notably lower, with the Norwegian government paying US\$1.76 million km⁻¹, for example, for freight rail electrification¹³. One advantage of battery-electric diesel locomotives is that batteries could simply be attached to existing locomotives with an extra tender car, rather than purchasing new locomotives or upgrading tracks. However, the cost of charging infrastructure makes up a substantial portion of initial capital expenditure. The most recent estimates find that hydrogen fuel cell locomotives are nearly half the price of battery-electric locomotives in the United States today but would cost the same by 2050, using more conservative assumptions for the battery tender cars (US\$320 kWh⁻¹ battery prices, 1,500-cycle battery lifespan and 5.1 MWh maximum capacity per tender car)¹³.

Discussion

Our analysis provides initial evidence that—given near-future battery prices and access to wholesale electricity tariffs—retrofitting diesel-electric locomotives with battery-electric technology could save the US freight rail sector billions of dollars while yielding environmental, health and grid-resilience benefits. The average emissions intensity of the US power mix is 383 kg CO₂ MWh⁻¹ (ref. ⁴⁴), which is projected to decrease to 90% by 2035⁴⁵. Because battery cars can charge predominantly when renewable electricity is available, they can exploit low-cost, zero-emission energy. The ability of tariff policies, such as real-time pricing, to enable use of low-cost renewable electricity for battery-electric trains must be evaluated further. To achieve diesel parity in the short run, such low-cost tariffs are necessary. Alternatively, a commensurate air pollution damage charge or strict air pollution standards that minimize these damages could enable a transition toward battery-electric trains. Such policy options must be evaluated in more detail.

The vast pool of locomotive batteries could be deployed to address location-specific grid constraints during extreme events. Even locations with electrified rail could stand to benefit from mobile grid storage provided by battery tender cars if they experience locationally constrained grid stress. A battery-electric rail sector will have over 200 GWh of modular and mobile storage, providing four advantages over typical grid-scale storage. First, locomotives will still have their diesel engines, so their batteries can be available to the power system to manage extreme events. Second, unlike typical grid-scale storage, trains can be moved to address

location-specific power system constraints. Third, because the batteries sit on railcars, which can be attached to or detached from freight trains, they can be flexibly deployed to charge and discharge in optimal locations—charging where prices are low and discharging where the grid is most constrained. Fourth, the four major players in the freight rail industry have maintained a market share of 85% (ref. ⁴⁶) and each could control large amounts of mobile energy storage, in contrast to fragmented storage ownership that requires highly efficient markets for optimal use. Large-scale modular and mobile storage from trains could support the power system in several ways with appropriate vehicle-to-grid infrastructure, including supplying power to the grid during extreme price or demand events, supporting temporary decommissioning of the transmission and distribution (T&D) infrastructure during wildfire events and providing emergency backup power to critical loads in the case of outages. Preliminary estimates of the most expensive 90 hours per year in the ERCOT market, for example, show that batteries could be discharged at US\$200 kWh⁻¹, potentially generating enough revenue to pay for the upfront battery cost in a single year³⁷. Planning and deploying bidirectional charging infrastructure to optimize grid services via charging and discharging of battery-electric tender cars will be required to capture the full economic and environmental value of battery-electric trains. Further research is needed on the deployment and operation of such infrastructure.

Although we estimate battery sizes for average daily freight train ranges, much smaller batteries can substantially mitigate air pollution damages. Assuming most damages result from concentrated populations around railyards, train operators may wish to add just enough capacity to run trains on battery power in these areas. BNSF Railway is currently pursuing this approach as part of a project funded by the California Air Resources Board to reduce emissions around railyards⁴⁷. Additional battery tender cars could be added to the consist (sequence of cars) to increase the range of the locomotive. Further research could provide insight into optimal ranges for different trip lengths and locations.

Methods

Scenario. We estimate the levelized TCO to convert the US freight rail sector from diesel to battery-electric locomotives over 20 years. We begin with a baseline scenario of average charging costs (which capture both electricity tariffs and costs of installing fast-charging infrastructure), no consideration of environmental benefits and no further decline in battery prices. This scenario represents the economics without any policy intervention in approximately the year 2023. We then consider the sensitivity of our results to changes in charging costs (reflecting cases in which low-cost renewable electricity can be used), forecasted battery price declines and inclusion of the value of environmental benefits. Low renewable electricity prices can be achieved by implementing policies such as real-time pricing, with tariffs linked to wholesale market prices and environmental regulations that capture the economic value of environmental benefits³⁹. Such prices are already observed, for example, in California during certain times of the day.

Battery size. We estimate battery size on the basis of the specifications of trains currently operating in California, representative of line-haul trains consisting of four 3.3-MW locomotives carrying 6,806 revenue-tonnes²¹. Using the average energy requirements of the diesel baseline at 0.059 kWh revenue-tonne-km⁻¹ and the relative efficiency of battery power over diesel engines, we estimate that each locomotive requires a 14-MWh battery to pull 1,701 revenue-tonnes for 241 km with LFP technology. Batteries incur an efficiency loss due to the need to cool the battery system. We upsize the battery to accommodate air conditioning requirements for the battery tender car. We estimate the energy required to cool the entire volume of the boxcar by 15°C over 12 h of the day.

Charging cost. We adapt the method from previous research on TCO of electrifying the trucking sector³⁹ to the rail sector, estimating the unit cost of charging as the total of the levelized cost of equipment, the cost of generation and the cost of T&D. We model the unit charging cost for a retail customer who is able to access wholesale energy prices in ERCOT territory. This scenario is realistic under current regulations. The levelized cost of equipment is defined as the minimum price per unit of energy delivered (kWh) that a charging service provider should charge the consumer to break even on the investment in charging equipment and grid interconnection³⁹.

Sector-wide cost of ownership. We use a straightforward energy balance approach using national data on train revenue-tonne-km and diesel fuel consumption to estimate the energy required to transport the same payload under battery-electric propulsion. To ensure that our sector-wide results do not overestimate electricity requirements, we use the national average estimates to calculate sectoral costs, benefits and emissions. Whereas the California representative line-haul locomotive used to estimate energy requirements pulls 1,701 revenue-tonnes, the national average line-haul Class I freight locomotive carries only 1,090 revenue-tonnes. We estimate that this load requires a 9.1-MWh battery per locomotive, after adjusting for battery weight and cooling requirements.

Each locomotive with an a.c. traction motor requires an onboard inverter for the 3.3-MW traction motor at US\$70 kWh⁻¹ (ref. ⁴⁸). We borrow existing methods to estimate charging costs that include electricity and fast-charging-infrastructure costs, where the equipment cost per kWh decreases as a function of capacity use, defined as the number of hours the station is used each day³⁹. Assuming a capacity use rate of 50%, amortized fast-charging-infrastructure costs plus energy are US\$0.048 kWh⁻¹. We estimate a low-cost scenario of US\$0.048 kWh⁻¹ (50% capacity use) and a high-cost scenario of US\$0.07 kWh⁻¹ (25% capacity use) inclusive of the levelized cost of fast-charging infrastructure. Given the flexibility in charging times, we expect that train operators would have access to the lowest energy prices.

We estimate our baseline scenario at battery prices of US\$100 kWh⁻¹. Data from China, which has the highest amount of heavy-duty electric vehicles (HDEV), show that battery prices for buses and other HDEVs are somewhat lower than the average battery prices for light-duty electric vehicles (LDEV) in China and globally¹⁹. While some of this difference in the average battery pack price for HDEVs in China and rest of the world is attributable to their use of different types of battery chemistries, China's production of HDEVs is much greater than that of any other country in the world. Hence, the price of battery packs for HDEVs in the United States is likely to come close to the price of battery packs for LDEVs with economies of scale. Others have similarly suggested that such economies of scale could soon emerge within the HDEV sector^{49,50}. We calculate environmental impacts by comparing diesel emissions to baseline emissions from electricity generation using projected US emissions. Nationwide emissions are modelled using National Renewable Energy Laboratory's Regional Energy Deployment System (ReEDS) model⁵¹ under the 90% clean energy by 2035 scenario⁴⁵. Using median marginal damages from locomotives estimated in 2011⁶, combined with EPA's projected NO_x and PM_{2.5} emissions reductions under the existing Tier 4 requirements for locomotives⁵², we project the total damages from criteria pollutants assuming a constant linear reduction in PM_{2.5} and NO_x, which corresponds to existing forecasted trajectories⁷.

Data availability

The data that support the results of this study are provided as Supplementary Data. Source data are provided with this paper.

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Author contributions

A.P. conceived the idea and guided the project. N.P. conducted the analysis, refined the methods, curated data and wrote the draft. D.P. developed the methods for leveled costs of charging infrastructure. E.T. collected the preliminary data and conducted the initial analysis of the working paper version of this manuscript.

Competing interests

The authors declare no competing interests.

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