

# Big Batteries on Wheels

## The economic, environmental, and resilience case for rapidly converting diesel locomotives to battery-electric

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**Abstract:** The U.S. rail sector is responsible for significant air pollution damages due to its dependence on diesel-based propulsion. One pathway to a zero-emission rail sector involves electrifying railway tracks and using emission-free electricity which requires significant storage combined with renewable electricity on the grid. We consider an alternate pathway, adding battery storage cars to diesel-electric trains. This approach would enable the rail sector to store and run on renewable electricity while obviating the need to electrify tracks. We show that the dramatic declines in the cost of battery storage and renewable energy present an opportunity to eliminate rail emissions cost effectively. We build a bottom-up cost model to explore the technical feasibility and costs of retrofitting diesel-electric trains with large batteries. We show that a single railcar carrying a 9-MWh battery is sufficient to power an average Class I freight train for 150 miles, the average distance traveled in a day. We establish a baseline scenario with high charging costs, no consideration of environmental benefits, and no further decline in battery prices, and we compare it against scenarios with lower charging costs, lower battery prices, and valuation of environmental benefits. Across these scenarios, the 20-year net present value of savings for the U.S. freight rail sector ranges from a cost of \$54 billion to savings of \$250 billion. In addition, a battery-electric rail sector would provide more than 200 GWh of modular and mobile storage, which could provide grid services and improve the resilience of the power system.

The U.S. rail sector transports roughly a third of the country's freight and is nearly entirely dependent on diesel fuel. More than 87% of freight railways in the United States use diesel-based propulsion, a share much greater than in most other countries with large rail sectors.<sup>1,2</sup> Although the rail sector represents a small share (less than 3%) of energy consumption and emissions from transportation, it nonetheless produces significant air pollution damages. In 2011, air pollution from locomotives caused about 1,500 premature deaths, accounting for \$12 billion in health damage costs.<sup>3</sup> For comparison, these damages are almost three times those associated with all natural gas-based power generation in the United States.<sup>4</sup> Per gallon of diesel consumed, locomotives produce close to twice the air pollution damages as heavy-duty trucks.<sup>5</sup> In addition, these railways cost consumers about \$10 billion in diesel fuel every year and emit roughly 39 million metric tons of CO<sub>2</sub>.<sup>6</sup>

One pathway to a zero-emission rail sector involves electrifying railway tracks and using carbon-free electricity. However, track electrification entails significant expenditure, and achieving carbon-free electricity will require significant grid-scale storage of renewable energy (RE).<sup>7,8</sup> We consider an alternate pathway to decarbonizing the rail sector: adding battery cars to diesel-electric trains. This approach would enable the rail sector to store and run on renewable electricity while obviating the need to electrify tracks.

Recent and ongoing declines in lithium-ion battery and RE costs can enable the transition to battery-electric rail. Lithium-ion battery costs fell by more than 80% between 2010 and 2017 and are currently about \$170 per kWh. Costs are expected to continue falling; a cost of \$100/kWh is expected by 2024 according to BloombergNEF and by 2020 according to Tesla.<sup>9,10</sup> As costs have fallen, the energy density of these batteries has increased. Furthermore, electricity from solar and wind technologies is now at half the long-run costs of fossil fuel-based plants.<sup>11</sup>

Given these changes in the economics of batteries and RE, retrofitting diesel-electric locomotives with electrically connected battery cars could enable the rail freight sector to reduce pollution and realize economic gains. Further, battery-electric trains would introduce a vast pool of large mobile batteries to the grid. These batteries could be deployed to address location-specific grid constraints in extreme events. Next, we assess the technical feasibility, costs, and benefits of battery-electric trains.

## Technical feasibility

Retrofitting trains is straightforward, because an electric drivetrain already exists.

The vast majority of locomotives in the United States are diesel-electric, meaning a diesel engine drives a generator that provides power to traction motors. Because an electric drivetrain is already in place, it is feasible to convert such a train to battery-electric by adding one or more battery cars with wiring to deliver power to the locomotive's powertrain.

Charging time is unlikely to pose logistical constraints given fast-charging and ease of battery swapping.

Recent developments in battery technology enable charging rates of 30 minutes to 1 hour for a full charge at the cell level. In addition, swapping of depleted battery cars with charged battery cars can be implemented at charging stations. Assuming a charging time of 1 hour, about 5% additional battery cars (given that they are charging for less than 5% of the time in a 24 hour

period) would enable train operators to use trains without requiring any idling time for charging with battery car swapping.

## Battery weight and volume are not obstacles.

We estimate that 9 MWh of battery storage can provide sufficient energy to power an average U.S. Class I freight train for 1 day of travel (about 150 miles).<sup>12</sup> Our approach to estimating battery capacity is further explained in the next section and in Table 1.

Using cell-specific energy figures for Tesla lithium-ion batteries and a typical packing fraction (i.e., cell weight/ pack weight) of 0.45, we estimate the total weight of a 9-MWh battery at about 74,300 kg. An average Class I train's weight per car load is about 51,300 kg, but freight railcars are commonly rated to carry more than twice this capacity.<sup>13,14</sup> Furthermore, range is hardly limited by battery weight. A typical 50 foot boxcar can carry about 90,000 kg.<sup>15</sup> A single railcar carrying a battery of this weight would enable a range of 400 miles, more than 2.5 times the daily distance traveled by an average locomotive.

Estimating pack volume is difficult, but a crude approach—assuming the ratio of pack energy density (kWh/L) to pack specific energy (kWh/kg) is the same as at the cell level—yields a total battery volume of about 30 cubic meters, which is less than 0.5% of the volume of a typical boxcar.<sup>16</sup> Hence, neither battery weight nor volume presents a serious obstacle to battery-electric retrofitting.

## Battery-electric powertrains have better grade capability than diesel-electric.

Any vehicle's grade performance depends on its ability to increase power output. In an electric powertrain, higher power outputs can be achieved by adding additional motors. Thus, the cost of delivering high peak power for an electric powertrain is much less than it is for a diesel engine. For example, among freight truck powertrains, diesel engines cost about six times as much as an electric motor for an equivalent amount of power.<sup>17</sup>

## Costs and benefits

Here we investigate the net present value (NPV) to the U.S. freight rail sector of converting diesel-electric locomotives into battery-electric. First, we estimate required battery capacity—assuming one cycle per day—as the product of the heat value of diesel and average diesel consumption per day per locomotive. We then multiply battery capacity by \$/kWh of battery storage to obtain the capital cost of the battery. The other major cost of retrofitting is the cost of fast-charging. We use estimates by Phadke et al. (2019) of the per kWh cost of truck charging that could be obtained through demand charge reform, off-peak charging, and an average charger utilization of about 33%.<sup>18</sup> These estimates include the levelized cost of charging infrastructure over its lifetime.

We compare costs with savings from avoided diesel spending and avoided damages from CO<sub>2</sub> and local air pollutants. Table 1 lists the key baseline input parameters used in this analysis. This baseline scenario reflects the current price of lithium-based batteries, the highest of three charging cost estimates by Phadke et al. (2019), and no consideration of environmental benefits.

Table 1. Baseline input parameters.

Battery type	Lithium iron phosphate	
Avg. diesel consumption per locomotive per day <sup>19</sup>	1,640	L
Heat value of diesel <sup>20</sup>	10.6	kWh/L
Efficiency factor of battery over diesel engine & generator <sup>21</sup>	2	
Battery life <sup>22</sup>	4,000	cycles
Battery price <sup>23</sup>	170	\$/kWh
Charging cost (inclusive of infrastructure) <sup>24</sup>	0.1139	\$/kWh
Diesel to CO <sub>2</sub> conversion factor <sup>25</sup>	2.7	kg/L
Marginal damage of CO <sub>2</sub>	40	\$/metric ton CO <sub>2</sub> emitted
Air pollution damages per locomotive <sup>26</sup>	1,280	\$/day

We also consider scenarios that progressively improve the case for battery-electric locomotives, altering one parameter at a time. In the first non-baseline scenario, we assume current battery price and no valuation of environmental benefits—as in the baseline—but replace charging cost with \$0.06/kWh, Phadke et al. (2019)’s lowest estimate, which assumes access to ERCOT wholesale prices of about \$0.03/kWh (rest is charging infrastructure cost). In the next scenario, we replace the battery price with the 2020-2025 forecasted battery price of \$100/kWh. Next, we account for savings from avoided air pollution damages but not from CO<sub>2</sub>. Finally, we account for savings from avoided CO<sub>2</sub> damages.

Our results are illustrated in Figures 1–3. Switching to battery-electric is profitable for the freight rail sector when the calculation accounts for health and/or climate damages from existing diesel-electric rail. When excluding these damages, switching to battery-electric is still profitable with current battery technology assuming either \$0.06/kWh charging or forecasted near-future battery prices of \$100/kWh.

The incremental Total Cost of Ownership (TCO) over a 20-year time period ranges from a cost of \$2 million per locomotive in the baseline scenario to savings of \$9.5 million per locomotive in the best-case scenario. Over the same time period, the NPV of savings for the freight rail sector ranges from a cost of \$54 billion to savings of \$250 billion. Whereas no payback is attained in the baseline scenario, the intervention scenarios have payback periods of one to seven years. In summary, this analysis provides initial evidence that switching from diesel-electric to battery-

electric locomotives in the United States may save the rail sector billions of dollars while yielding environmental, health, and grid resilience benefits.

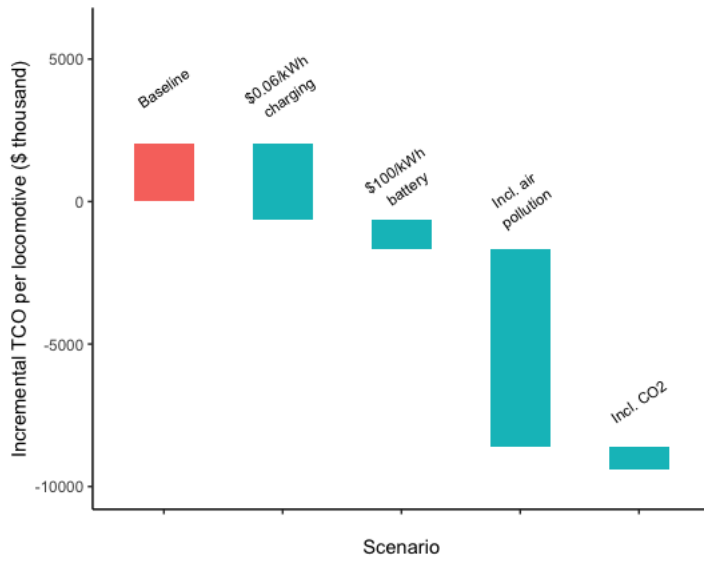


Figure 1. Worst- to best-case incremental TCO over 20 years for the average locomotive.

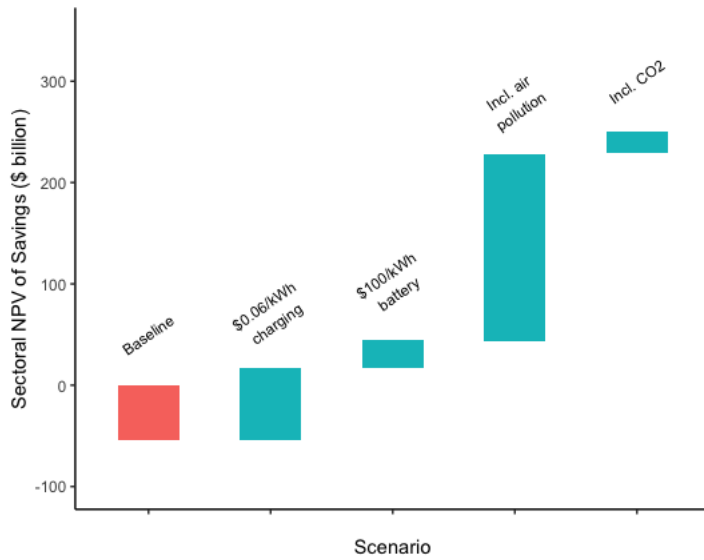


Figure 2. Worst- to best-case NPV of savings over 20 years for the rail freight sector.

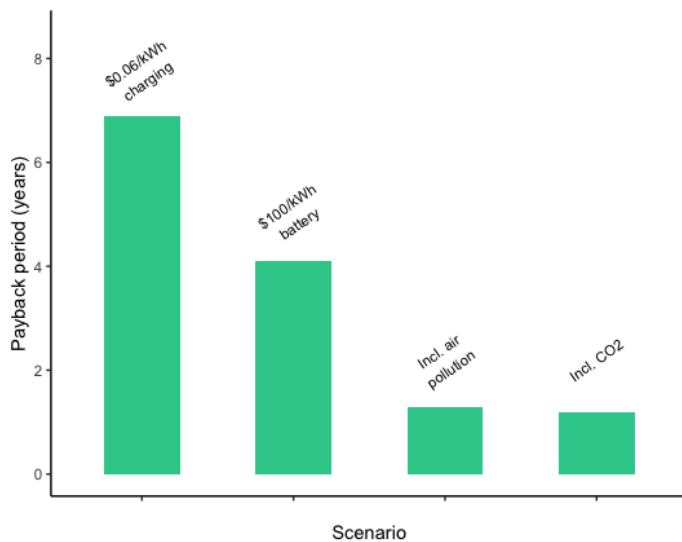


Figure 3. Payback period for non-baseline scenarios.

Although we estimate that a 9-MWh battery can fully power an average train for one day, even much smaller batteries can substantially mitigate air pollution damages. Assuming most damages result from the concentration of populations around railyards, train operators may wish to add just enough capacity to run trains on battery power only 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 railyards.<sup>27</sup>

Our estimation approach faces various limitations. First, we do not offset our estimates of avoided air pollution and CO<sub>2</sub> damages by the additional damages incurred from increased electricity generation. Our reasoning is that we expect charging will occur primarily during hours when renewable energy is dispatched on the margin. The consolidated nature of the freight rail sector make it ripe for corporate procurement of renewables through PPAs, which have dropped to \$0.02/kWh for wind and to below \$0.03/kWh for solar PV.<sup>28,29</sup> Developers do not expect these offer prices to change significantly in 2020.<sup>30</sup> Thus, we expect that the competitiveness of renewables, combined with the ease of swapping battery railcars for charging during peak solar and wind production hours, will enable near-zero emissions charging. Given charging infrastructure costs of about \$0.03/kWh based on estimates from Phadke et al. 2019, cost of charging will be about \$0.06/kWh.

Nonetheless, we estimate an upper bound on the amount by which avoided damages would be offset if all charging were to occur with electricity produced from coal and natural gas, respectively. With no offsetting, gross avoided damages from air pollution and CO<sub>2</sub> are \$12.4 billion and \$1.4 billion, respectively. Supposing that coal is the source of all electricity consumed by trains, we find that net avoided air pollution damages for the locomotive sector are \$6.65 billion per year and net avoided CO<sub>2</sub> damages are \$300 million per year. Replacing coal with natural gas, net damages are \$12 billion and \$800 million per year, respectively.

In addition, our analysis does not account for the cost of additional railcars to store batteries or the loss in fuel efficiency due to the extra weight of battery cars. The cost of railcars is modest, however, and a 9-MWh battery increases the total weight of an average freight train only by about 2%.<sup>31,32</sup> Furthermore, these weight increases will be offset by the elimination or large reduction in



diesel fuel being stored in the locomotive's fuel tank. As such, these factors are unlikely to impact fuel consumption or costs significantly.

Finally, we do not claim that retrofitting to battery-electric is a least-cost pathway to decarbonizing the rail sector, because we have not assessed the costs of electrifying U.S. rail by catenary or third rail—forms of propulsion commonly used in other countries—or by other means.

## Value of modular and mobile storage to the power system

If every U.S. locomotive were equipped with a 9-MWh battery, the rail sector would possess more than 200 GWh of modular and mobile storage. Such storage offers four unique advantages over the typical grid-scale storage or storage in on-road vehicles. First, because trains will still have their diesel engines, they can make their batteries available to the power system to manage extreme events. This is not the case with typical electric vehicles (EVs), which do not have dual-fuel capacity. Second, unlike typical grid-scale storage, train-based storage can be moved to address location-specific power-system constraints. Third, because the batteries are housed in railcars, which can be attached to or detached from a freight train seamlessly, the train-based approach provides significant logistical flexibility in deploying mobile storage and charging/discharging it in optimal locations (charge where prices are low or negative, discharge where constraints are largest). Finally, the four major players in the U.S. freight rail industry have maintained a market-share of above 80%, and each could control and dispatch a large amount of mobile storage—in contrast to fragmented storage ownership that requires highly efficient markets for optimal use.<sup>33</sup> Large-scale modular and mobile storage might 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 transmission and distribution infrastructure in wildfire events, and providing emergency backup power to critical loads in the case of outages. Further research is needed to evaluate such possibilities and enabling infrastructure and policy.

## Enabling policy and infrastructure for a battery-electric rail sector

Our analysis shows that battery-electric trains are cost-effective today if diesel-electric trains internalize the costs of the health damages they cause. 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.

RE prices have dropped to about 1.5–3 cents/kWh, which is less than half of the long-run marginal cost of fossil-based power plants. Battery cars can predominantly charge when RE is available, enabling them to provide low-cost, zero-emission power. Further research should evaluate how tariff policies (such as real-time pricing) might promote the use of low-cost RE for battery-electric trains.

Lastly, planning and deploying bidirectional charging infrastructure to enable optimal charging and discharging of battery-electric cars (to provide grid services) will be required to capture the full economic and environmental value of battery-electric trains. Deployment and operation of such infrastructure is another area for further research.

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- <sup>5</sup> Used damage estimates from Goodkind et al. (2019) and diesel fuel consumption statistics in *National Transportation Statistics 2018 4th Quarter*.
- <sup>6</sup> According to our analysis.
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<sup>21</sup> Batteries have round-trip efficiencies of around 90% whereas, according to CARB, the newest diesel-electric freight locomotives have engine efficiencies of 40-50%. Source: California Environmental Protection Agency Air Resources Board. (2016). *Technology Assessment - Freight Locomotives*.

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<sup>26</sup> Based on estimated air pollution damages from the locomotive sector in 2011. Source: Goodkind et al. (2019).

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<sup>31</sup> A new boxcar costs about \$135,000 according to <https://www.marketwatch.com/story/shortage-of-railroad-boxcars-has-shippers-fuming-2015-06-21>.

<sup>32</sup> Assuming the ratio of cars to locomotives and average carload tonnage reported by BTS (2018) 'Class I Rail Freight Fuel Consumption and Travel' and 'Energy Intensity of Class I Railroad Freight Service'.

<sup>33</sup> IBISWorld Industry Report 48211 December 2018, Rail Transportation in the US- <https://clients1.ibisworld.com/reports/us/industry/default.aspx?entid=1133>