Title

Why Regional and Long-Haul Trucks are Primed for Electrification Now

Permalink

https://escholarship.org/uc/item/3kj8s12f

Authors

Phadke, Amol
Khandekar, Aditya
Abhyankar, nikit
et al.

Publication Date

2021-03-01

Peer reviewed

International Energy Analysis Department
Energy Analysis and Environmental Impacts Division
Lawrence Berkeley National Laboratory

Why Regional and Long-Haul Trucks are Primed for Electrification Now

Amol Phadke*, Aditya Khandekar*, Nikit Abhyankar*, David Wooley#, Deepak Rajagopal&%

* Lawrence Berkeley National Laboratory
\# Goldman School of Public Policy, UC Berkeley
& Institute of Environment and Sustainability, UCLA
% Corresponding author: rdeepak@ioes.ucla.edu

March 2021

This work was supported by the Hewlett Foundation under Lawrence Berkeley National Laboratory Contract No. DE-AC02-05CH11231.

Disclaimer

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor The Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or The Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, or The Regents of the University of California.

Ernest Orlando Lawrence Berkeley National Laboratory is an equal opportunity employer.

Copyright Notice

This manuscript has been authored by an author at Lawrence Berkeley National Laboratory under Contract No. DE-AC02-05CH11231 with the U.S. Department of Energy. The U.S. Government retains, and the publisher, by accepting the article for publication, acknowledges, that the U.S. Government retains a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for U.S. Government purposes.

Why regional/long-haul trucks are primed for electrification now

A. Phadke[*], A. Khandekar[*], N. Abhyankar[*], D. Wooley[#], D. Rajagopal[&,%]

Abstract

Zero emission freight trucks are needed to both improve public health and reduce global greenhouse gas emissions but at the same time are generally believed to be uneconomical. However, recent dramatic declines in battery prices and improvement in their energy density have created opportunities for battery-electric trucking today that were seldom anticipated just a few years ago. At the current global average battery pack price of $135 per kilowatt-hour (kWh) (realizable when procured at scale), a Class 8 electric truck with 375-mile range and operated 300 miles per day when compared to a diesel truck offers about 13% lower total cost of ownership (TCO) per mile, about 3-year payback and net present savings of about US $200,000 over a 15-year lifetime. This is achieved with only a 3% reduction in payload capacity. Even this small penalty can be reversed cost-effectively through light-weighting, in any case, only matters for a small fraction of trucks which regularly utilize their maximum payload. Electric trucks appear poised to also meet the performance demands for a large share of regional and long-haul trucking today. The estimated average distance traveled between 30-minute driver breaks is 150 miles and 190 miles for regional-haul and long-haul trucks respectively in the US. Thirty minutes of charging using 500 kW or mega-Watt scale fast-chargers would add sufficient range without impairing operations and economics of freight movement. However, as with almost any clean technology, higher upfront capital costs of both vehicles and charging infrastructure are major barriers when electric trucking is in its infancy. Without strong policy support, coordinated investments in both vehicle manufacturing and fuel infrastructure will not be forthcoming on the scale needed to harness the true potential of battery electric trucks.

---

[*] Lawrence Berkeley National Laboratory
[#] Goldman School of Public Policy, University of California Berkeley
[&] Institute of Environment and Sustainability, University of California, Los Angeles
[%] Corresponding author: rdeepak@ioes.ucla.edu

Table of Contents

Executive Summary 3
1. Introduction 7
2. Methods and Data 13
3. Results 21
4. Discussion 28
5. References 32

Executive Summary

Globally, heavy-duty vehicles (primarily trucks) are estimated to comprise only about 11% of the motor vehicles, yet account for close of half the total CO_2 emissions from motor vehicles and 71% of vehicle particulate emissions (PM) (Kodjak, 2015). The latter are responsible for the vast majority of air pollution related deaths worldwide (Landrigan et al., 2017) . Furthermore, low-income communities everywhere bear a disproportionate proportion of the health burden from freight movement. For instance, it is estimated that in California, African American, Latino, and Asian Californians experience respectively 43, 39, and 21% higher level of $PM_{2.5}$ pollution from cars, trucks, and buses relative to white Californians (Union of Concerned Scientists, 2019). Zero emission freight trucks are critical to both reducing global greenhouse gas emissions and improving public health. This paper shows that recent dramatic improvements in battery technology have primed heavy-duty trucks for near-term electrification.

At the current global average battery pack price of $135 per kilowatt-hour (kWh) (realizable when procured at scale), a Class 8 electric truck with 375-mile range and operated 300 miles per day when compared to a diesel truck offers about 13% lower total cost of ownership (TCO) per mile, about 3-year payback and net present savings of about US $200,000 over a 15-year lifetime. This is achieved with only a 3% reduction in payload capacity. Even this small penalty can be reversed cost-effectively through light-weighting, which in any case, only matters for a small fraction of trucks which regularly utilize their maximum payload. This accounts for a 3% reduction in payload capacity, though that loss can be avoided cost-effectively through light-weighting and is only consequential for a small fraction of operations that regularly utilize the truck's maximum payload. Battery prices are projected to decline to about $60 per kWh by 2030 accompanied by further improvement in energy density and efficiency. These advances, combined with state or federal polices to monetize pollution reduction benefits, could make electric truck TCO over 40% lower relative to TCO for diesel today.

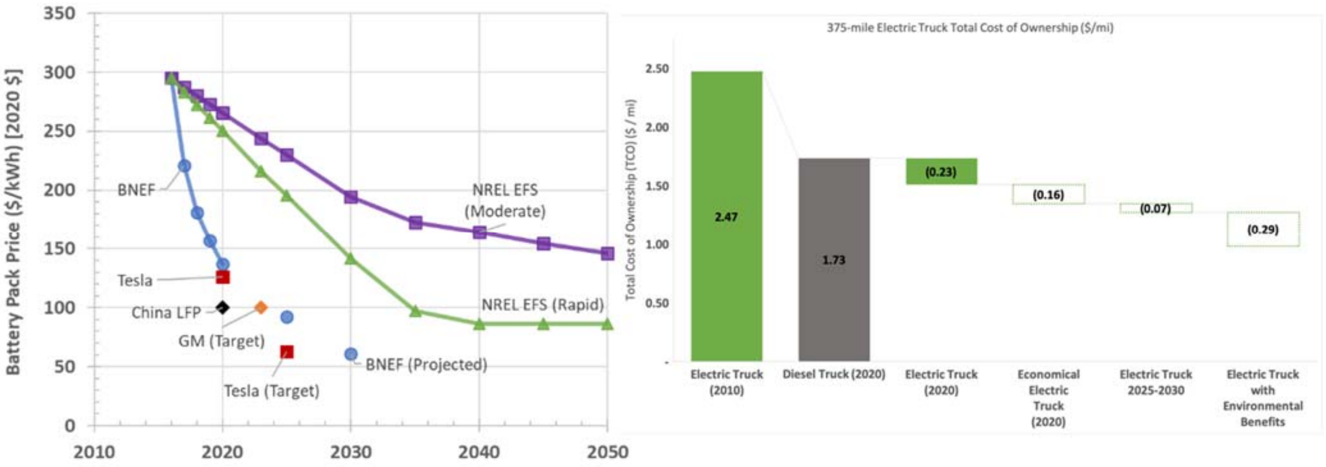
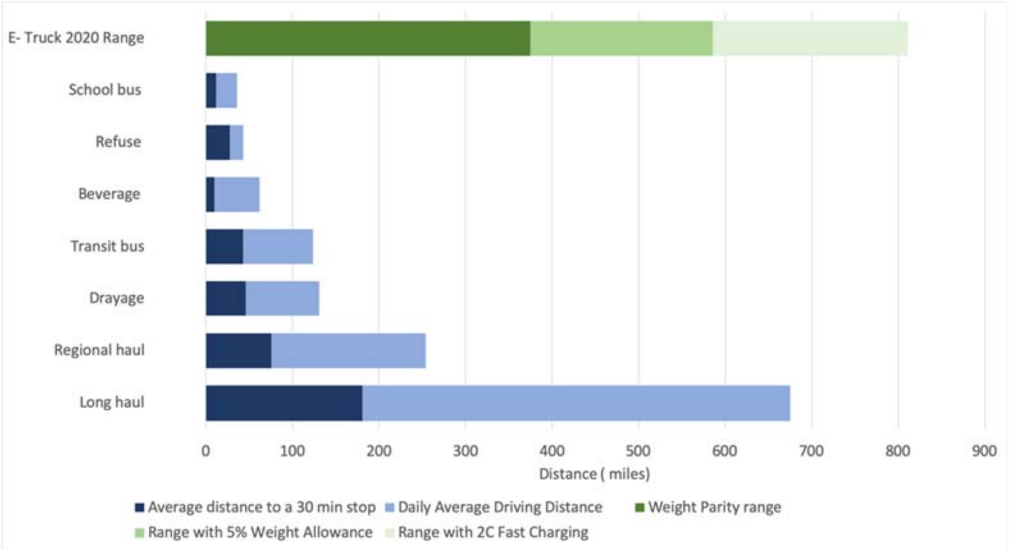


Figure ES1: Electric trucks can offer significant savings due to dramatic decline battery prices and opportunities for economical charging. The graph on left shows the estimated actual prices from 2010 to 2020 by BNEF (solid blue line with circular markers) and projections by BNEF going forward (blue circular markers without a solid line). It also shows projections made by National Renewable Energy Laboratory (NREL) as of 2017 looking into the future under two different scenarios of cost reduction (Moderate and Rapid) as well as a few additional data points such as individual targets for GM and Tesla. Figure on the right shows the total cost of ownership under different scenarios we estimate in this report. ***Data Sources***: Battery pack prices - National Renewable Energy Laboratory, Electrification Futures Study [EFS] (Jadun et al., 2017) and (BNEF, 2020).



ES2: Electric trucks can have sufficient range for most applications without materially compromising payload. Figure depicts a comparison of average daily distance for different

vehicle types, their average distance to a 30-minute or longer stop and our estimate of potential range for a 375-mile Class 8 Truck with 5% additional weight allowance for the battery and 2C fast charging availability Source: For data on driving distances refer (Oak Ridge National Laboratory, 2019).

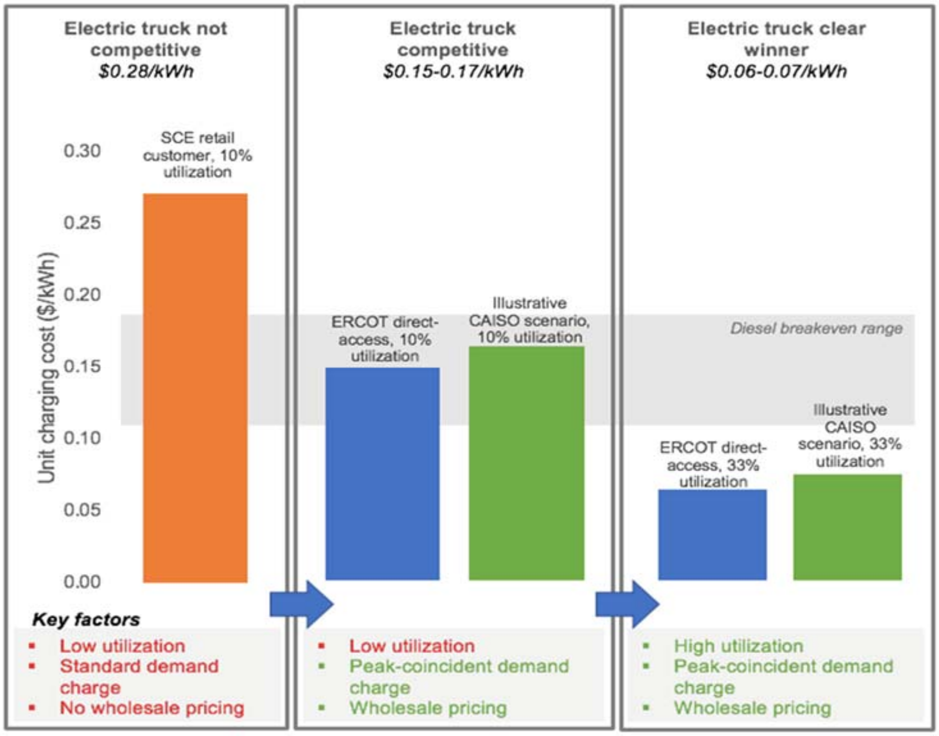
As vehicle battery costs have fallen, so has their weight and size. These physical changes accompany a steadily rising energy density. As a result, electric trucks with a range up to 375 miles (300 miles at 80% maximum depth of discharge (DoD)) might entail little to no reduction in payload carrying capacity. An often-overlooked fact is that the electric drive train is substantially lighter relative to a diesel drive train, which offsets a significant amount of battery pack weight. Lightweighting and improved aerodynamics using commercially available technology can enable additional range up to 450 miles. (North American Council for Freight Efficiency, 2015). Further, since most truck trips tend to be limited by volumetric capacity of payload as opposed to payload weight, a 5% payload weight penalty for reducing fuel cost significantly is likely to be acceptable for most trucks. Additionally, the Federal Motor Carrier Safety Administration (FMCSA) has several restrictions on the hours of driving by truck drivers (FMCSA 2015). For example, the maximum continuous driving without a 30 minute mandatory break is 8 hours (which translates to a distance of about 450 miles) and a range of 500 miles will be sufficient to cover the maximum allowed continuous driving. Additional FMCSA driving limits include the 14-hour “driving window” limit, 11-hour driving limit, and 60-hour/7-day and 70-hour/8-day duty limits. The maximum driving allowed in a 14-hour driving window is 11 hours, after which a mandatory break of 10 hours is required. Range of 200 to 400 miles can be added (with 1C and 2C charging rate) in a 30-minute break sufficient to cover the remaining allowed three hours of driving (distance of about 170 miles). Note the scenario described above is to show that a 500-mile range electric truck has sufficient range to enable the maximum allowed driving. For a typical driving schedule, a 300-mile range might be sufficient. For example, a representative duty cycle for long haul trucks estimated by DOE-NREL indicates more than a 30-minute break after 3-4 hours (less than 250 miles) of driving which is followed by another 3-4 hours of driving after which there is more than 10-hour break with a total distance of about 500 miles. ORNL 2019 finds that the average distance to a 30-minute stop which can be used to add significant range with fast charging is 190 miles and 150 miles for a long haul and regional haul trucks, which constitute the majority (about 70%) of the diesel consumed and emissions by trucking. For these reasons, we argue that electric trucks can have sufficient range for most applications in the near future.

Although electric trucks present an enormous opportunity both from economic, environmental, and environmental justice standpoints, major barriers need to be addressed to fully realize their potential and an appropriate policy ecosystem is required to stimulate and facilitate the transition from diesel to electric long-haul trucking. First, as is often the case in early stages of clean energy technology commercialization, electric trucks carry higher up-front costs than conventional trucks (for both vehicles and charging infrastructure). This is due to lack of scale economies and market uncertainty. For instance, simple calculations suggest that the 13% lower TCO notwithstanding, at the current battery price of $135/kWh, a 375-mile range truck with a 797-kWh battery pack has an upfront cost that is 75% greater relative to a diesel truck, which experience suggests is a major barrier to adoption. This price differential is not expected to last long, but strongly suggests the need for early-adopter subsidies to drive sales, and lower capital costs through manufacturing economies of scale.

Second, as battery costs decline, charging related costs are beginning to loom larger. Whereas a decade ago, when battery costs were in excess of $1000/kWh, charging-related costs would have accounted for about 15% to 18% of the TCO, today they account for 25% to 30% and increase further as battery prices decline. Figure ES3 shows the effect of electricity price retail price demand charges and at wholesale prices without “demand” charges which are levied based maximum instantaneous power consumption during a specified billing period and are distinct from energy charges. Electricity prices, especially demand charges, but also energy charges, that do not reflect the true cost to the system is a barrier to electrification of commercial vehicle fleets in general but especially for long-haul trucks. There is a need for electricity tariffs that send the right price signals for truck charging and avoid without imposing unfair costs or truck owners or other customers

Third, it will take time to achieve high utilization rates for vehicle charging infrastructure, which is essential to realizing a low levelized cost of infrastructure per unit of delivered electricity to vehicles. Figure ES3 shows the effect of low and high utilization of charge infrastructure on total cost of charging, which is the sum of the cost of electricity and the levelized cost of infrastructure.

Realizing the full economic potential of electric trucks therefore requires surviving a long period of infancy marked by low demand for vehicles and charging, and consequently, higher cost of new vehicles and slow return on charging infrastructure. Faced with such barriers, absent public intervention, private investments in electric trucks will occur at a level lower than is socially optimal. Given the importance of addressing pollution from trucking, strong policy support for the coordinated and large-scale investments in vehicle technologies and fuel infrastructure is warranted to harness the economic and environmental potential of battery electric trucks. Binding targets for vehicle sales, supported by targeted subsidies indexed both to international battery prices and cumulative sales can deliver the scale of adoption needed to launch this new industry on a sustainable future trajectory.



ES3: Rational electricity tariffs and improved charging infrastructure utilization can significantly improve the economics of electric trucks (Phadke et al., 2019).s

1. Introduction

Globally, heavy-duty vehicles are estimated to comprise only about 11% of the motor vehicles, yet account for close of half the total CO2 emissions from motor vehicles and 71% of vehicle particulate emissions (PM) (Kodjak, 2015). The latter are responsible for the vast majority of air pollution related deaths worldwide (Landrigan et al., 2017). For instance, in the U.S., heavy duty trucks comprise 5% of the on-road traffic but account for 30% and 36% of vehicle CO2 emissions and particulate emissions respectively (Kodjak, 2015) while trucking as a whole account for 83% of all freight related CO2 emissions (Schipper et al., 2011). Heavy-duty trucking's share to the environmental footprint of developing countries is even greater. For instance, in India which has low car ownership per capita relative to higher income countries, the such truck comprise 5% of the vehicle fleet but comprise 71% of CO_2, 74% of PM and 55% of NO_x emissions from on-road vehicles (Apte et al., 2017; Guttikunda & Mohan, 2014; Kodjak, 2015). Furthermore, world over low-income groups world-wide bear a disproportionate proportion of the environmental burden from freight movement. For instance, it is estimated that in California, African American, Latino, and Asian Californians experience respectively 43, 39, and 21% higher level of $PM_{2.5}$ pollution from cars, trucks, and buses relative to white Californians (Union of Concerned Scientists, 2019). Zero emissions trucks can significantly improve health outcomes for vulnerable populations.

Of the two leading zero emissions vehicle (ZEV) technologies – battery electric vehicles and hydrogen fuel cell vehicles, the focus here is on the former, which has experienced the most dramatic improvements on multiple fronts.[1] Battery cost and energy density have historically been barriers for heavy-duty battery electric vehicles (including medium and heavy-duty trucks and transit buses). But today the situation is dramatically different.

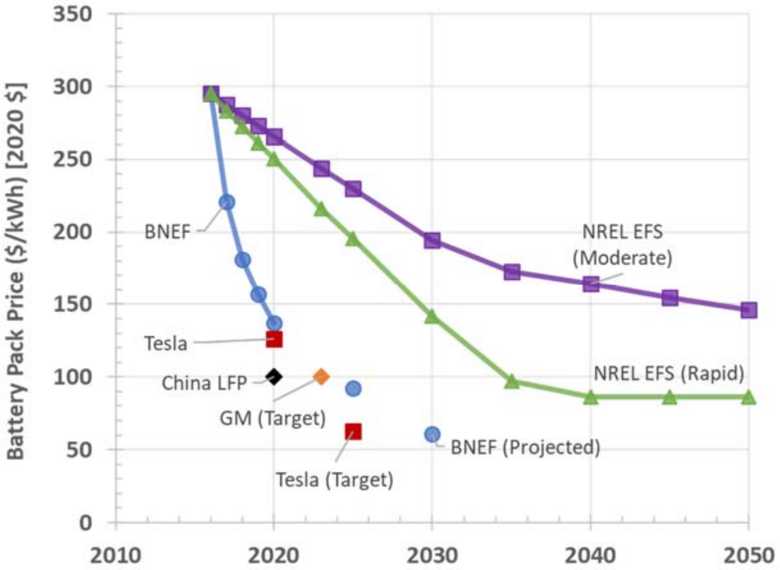


Figure 1. Battery prices have been consistently reducing more rapidly than projections(Jadun et al., 2017), (BNEF, 2020). Figure shows the estimated actual prices from 2010 to 2020 by

---

[1] According to the California Air Resources Board (CARB), for short and medium haul trucks, the total cost of ownership (TCO) for battery electric trucks is less than half that of hydrogen fuel cell trucks in the short to medium term (2018-24) and somewhat higher in the long term (2030) (California Air Resources Board 2019). Although we do not estimate the TCO of hydrogen fuel cell trucks in this analysis, our TCO estimates for 375-mile long-haul electric trucks ($1.51/mile) is substantially lower than CARB TCO estimate for hydrogen fuel cell trucks for regional delivery ($2.3/mile and $1.5/mile) for the short and medium term (2018-24)

BNEF (solid blue line with circular markers) and projections by BNEF going forward (blue circular markers without a solid line). It also shows projections made by National Renewable Energy Laboratory (NREL) as of 2017 looking into the future under two different scenarios of cost reduction (Moderate and Rapid) as well as a few additional data points such as individual targets for GM and Tesla. ***Data Sources***: Battery pack prices - National Renewable Energy Laboratory, Electrification Futures Study [EFS] (Jadun et al., 2017) and (BNEF, 2020).

One major recent development is the decline in battery prices. By 2020, lithium-ion battery costs had declined to roughly $136/kWh, an 85% decline relative to prices in 2010 (Figure 1) and are projected to reach a price of $55 per kWh in 2030 (Holland, 2018). Data from China, which has the most amount of heavy-duty electric vehicles (primarily buses) shows that battery prices for buses and other heavy duty vehicles are somewhat lower than the average battery prices for light-duty EVs in China and globally (BNEF, 2020). While some of this difference in the average price of battery pack price for HDVs in China and rest of the world is attributable to use of different types of battery chemistries[2] the production of heavy-duty EVs in China is much greater than any other country in the world. Therefore, with economies of scale the price of battery packs for HDVs is likely to come close price of battery packs for passenger EVs as is the case in China, as pointed out by others as well (See California Air Resources Board, 2019; Hall & Lutsey, 2019).

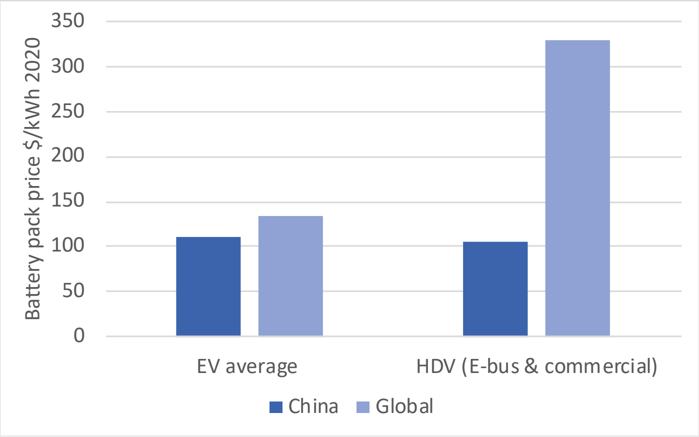


Figure 2: A comparison of average EV battery prices globally and in China across all vehicle types and specifically, prices for batteries in heavy-duty vehicles. Source: (BNEF, 2020)

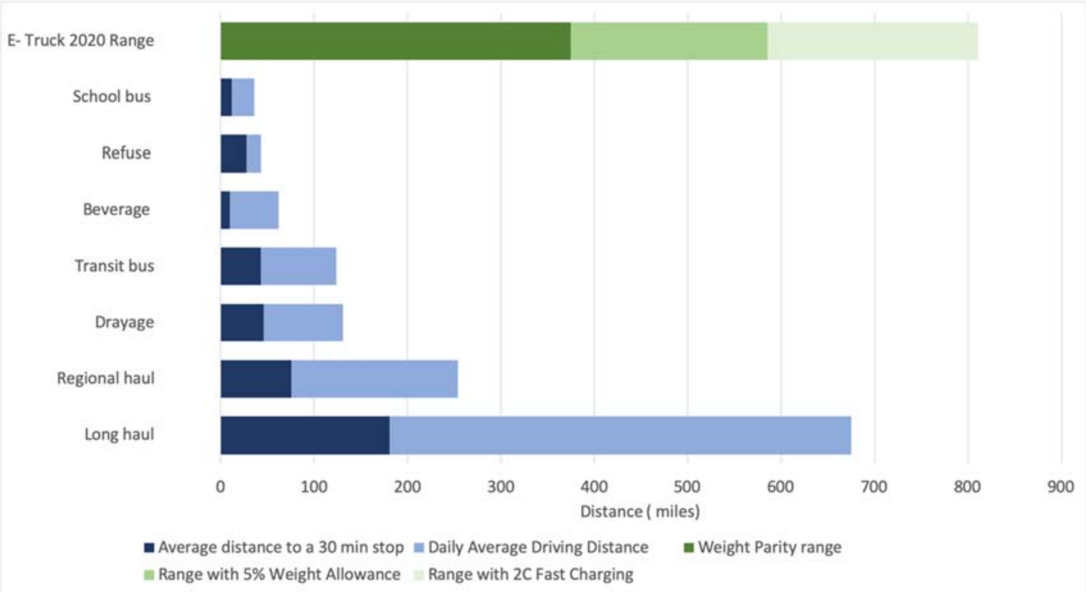
---

[2] China currently relies more on Lithium Iron Phosphate (LFP) which is among the cheaper types of chemistries in use today when compared to say, Lithium Nickel Cobalt Aluminum Oxide (NCA) or Lithium Nickel Manganese Cobalt (NMC))

A second related development concerns battery weight, an especially significant factor for long-haul trucks, which are subject to maximum gross vehicle weight limits. In the US, federal laws limit maximum gross vehicle weights to 80,000 pounds on interstate highways (Federal Highway Administration, 2019) of which the tractor itself accounts for about 17,000 pounds (US Department of Energy, 2010), thus leaving about 63,000 pounds for revenue-generating payload. A widespread concern is that battery weight of an EV results in a reduction in allowed payload capacity, a factor that discourages EV adoption. As with battery cost, however, energy density at the cell-level (and by extension at the pack level) has also been improving steadily, resulting in significant reductions in battery weight. (Field, 2020). While the lower energy density of batteries and higher weight (relative to diesel engine and fuel) is perceived as a market barrier, critics of battery electric trucks often overlook the offsetting weight reduction from elimination of engine, cooling system, transmission and accessories. These parts account for about a quarter of the weight of a diesel tractor, which battery packs nearly eliminate. As described below, the weight difference between and battery electric and diesel trucks is small (resulting in a potential payload loss of about 5%) and is likely to fall lower as light-weighting techniques are employed. Moreover, data from the North American Council for Freight Efficiency shows that the average truck payload is less than 45,000 pounds (~70% of the maximum payload capacity) (North American Council for Freight Efficiency & Rocky Mountain Institute, 2018). Hence, for most cargo movement, payload is no longer a constraint for battery electric trucks.

A reason that attracts attention to battery electric trucks is the decreasing cost and carbon emissions of electric power. While electric trucks certainly reduce exposure of vulnerable populations to diesel pollution, their life cycle environmental benefits depend in large part on the source of electricity used for charging the batteries. In this context, a third key development is the fact that decline in battery prices is complemented by the steep drop in cost of electricity generation from clean renewables such as solar and wind, and the corresponding decline in GHG pollution of the average grid electricity. In fact, costs of renewable electricity have declined to such an extent that it is cheaper than or in parity with the levelized cost of generation from new coal plants (Lazard, 2018). Given current national and international ambitions to decarbonize the electric grid and growing prospects for deep CO2 reduction by the 2030's, electric trucks offer a pathway to near elimination of air pollution and GHG emissions from road freight operations. However, as we point of later aligning retail tariffs with generation prices is an area that needs policy attention.

There is also growing evidence that fast charging can be accomplished without significant impact on battery life. Studies comparing the impact of fast charging[3] and slow charging on battery cells degradation found a significant decrease in cycle life with fast-charging relative to slow charging only at temperatures above 30 degree Centigrade (Den Boer et al., 2013; Teslarati, 2017; The Tesla team, 2019). Controlling battery temperature through battery management systems and better cooling, a practice that is becoming widespread in commercial EVs, mitigates battery degradation concerns. A 1 Megawatt (MW) fast charger can deliver about 500 kilowatt-hours (kWh) in 30 minutes which at an energy economy of 2 kWh per mile amounts to 250 miles worth recharge. Additionally, actual data on commercial fleet operations reported by National Renewable Energy Laboratory's (NREL) Fleet DNA tool suggests that the 80th percentile of daily distance travelled by long-haul tractors is about 600 miles and that the average distance to a 30-minute stop is less than 200 miles (Oak Ridge National Laboratory, 2019). As heavy-duty battery electric trucks continue to improve it is likely that even faster charging rates and range improvement will become common (due to gradually increasing battery energy-density and decreasing HDV vehicle weight). Extreme fast charging is one important aspect that is still in its infancy that needs targeted investments and incentives at this stage.



---

[3] Charging and discharging rates are often referred to in terms of C-rates. Basically, the C-rate denotes the number of times it can be fully charged in 1 hour. A 50kWhr battery when charged from zero to full charge in 1hour is said to be charged at the 1C rate while if it is fully charged in only 30 minutes it is referred to as 2C charging because it can be fully charged twice in 1 hour. If it is charged from zero to full in 2 hours it is 0.5C charging. Charging a 500kWhr battery at 0.5C 1C, and 2C rates will require 250KW, 500kW and 1MW fast charger respectively. Charging a 1000 kWh battery at 0.5C 1C, and 2C rates will require 500kW, 1MW and 2 MW fast charger respectively.

Figure 3: Comparison between average daily distance for different vehicle types, their average distance to a 30-minute or longer stop and our estimate of potential range for a 375-mile Class 8 Truck with 5% additional weight allowance for the battery and 2C fast charging availability. Source: For data on driving distances refer (Oak Ridge National Laboratory, 2019).

Multiple studies have examined the potential for electrification (Çabukoglu et al., 2018; California Air Resources Board, 2019; B. A. Davis & Figliozzi, 2013; Den Boer et al., 2013; Earl et al., 2018; Gopal et al., 2017; Karali et al., 2019; Lee & Thomas, 2017; Liimatainen et al., 2019; Mareev et al., 2017; Moultak et al., 2017; Sen et al., 2017; Sripad & Viswanathan, 2019; Taefi et al., 2017; Talebian et al., 2018; Tanco et al., 2019; Zhou et al., 2017). Several assume battery-electric trucks to be an infeasible option for replacing conventional diesel trucks, particularly long-haul trucks on account of large battery capacity requirements, range anxiety, and uncertainty related to availability of charging infrastructure (Çabukoglu et al., 2018; Den Boer et al., 2013; Earl et al., 2018; Lee & Thomas, 2017; Liimatainen et al., 2019; Moultak et al., 2017; Taefi et al., 2017; Talebian et al., 2018; Zhou et al., 2017). Of studies that actually evaluate the economic performance of electric trucks (California Air Resources Board, 2019; Den Boer et al., 2013; Earl et al., 2018; Lee & Thomas, 2017; Mareev et al., 2017; Sen et al., 2017; Sripad & Viswanathan, 2019; Taefi et al., 2017; Tanco et al., 2019; Zhou et al., 2017), several consider or conclude battery-electric trucks to be a solution for only light- and medium-duty trucks with a low daily range of less than ~250 miles (Den Boer et al., 2013; Lee & Thomas, 2017; Moultak et al., 2017; Taefi et al., 2017; Tanco et al., 2019; Zhou et al., 2017). Certain studies deem long-haul electric trucks, which have greater than 250-mile daily range, unviable specifically because of range anxiety due to a lack of fast charging (Karali et al., 2019; Moultak et al., 2017; Talebian et al., 2018). However, a few more recent studies analyze battery-electric trucks as an option for long-haul transportation (California Air Resources Board, 2019; Sripad & Viswanathan, 2019; Tanco et al., 2019).

Different from many earlier studies, this work relies on bottom-up cost, weight and performance estimation and latest market data to improve on the existing long-haul electric truck literature. We estimate the TCO of an electric truck compared to a diesel truck based on bottom-up truck technical specifications generated from a vehicle dynamic model (detailed in the methods and data section). We fully account for recent trends toward lower-cost, higher-energy-density batteries. We include additional cost reduction potential from monetizing air pollution and GHG reductions. Our charging costs account for levelized cost of fast-charging infrastructure and demand charges as part of electricity cost. Finally, we provide detailed comparisons of the weights of diesel versus electric long-haul trucks based on the Tesla semi, with consideration of commercially available light weighting options. The results provide the most comprehensive techno-economic analysis of long-haul electric trucking to date.

2. Methods and Data

We investigate the potential for a Class 8 electric truck to seamlessly replace a Class 8 diesel truck based on economics and performance. Class 8 trucks were chosen as the reference model for this analysis because they consume nearly 20% of all energy consumed by the U.S. transport sector(S. C. Davis et al., 2017). Furthermore, the CALSTART Zero-emissions technology inventory list up to 31 existing models of heavy-duty battery electric trucks with 23 more announced to be launched. For reference, there are 3 existing models and 6 announced models of hydrogen fuel-cell electric trucks (CALSTART 2020). The diesel truck model for this estimation is the Volvo VNL 400 (Legacy Truck Centers, 2019) truck, and the electric truck model is the Tesla Semi (Tesla, 2019).

Below, Section A describes the battery pack capacity estimation for a Class 8 electric truck using our vehicle dynamic model. Section B describes our TCO estimation. Section C shows the analysis for estimating the weight of the battery pack for a commercially available Class 8 truck. It is worth emphasizing that our study draws on both bottom-up estimations and industry claims: we analyze TCO based on a bottom-up battery pack size estimate from the vehicle dynamic model, whereas the battery pack weight estimation is based on existing commercial trucks (in this case the Tesla Semi). The entire set of calculations is carried out in a spreadsheet and is available for download along with this report.

2.1 Vehicle Dynamic Model

We use the vehicle dynamic model represented in Equation 1 to estimate required battery pack size (E_p, in kWh) based on the standard performance requirements of a Class 8 diesel truck.

$$E_p = \left[\frac{\left(\frac{1}{2}\rho * C_d * A * v_{rms}^3 + C_{rr} * W_T * g * v + t_f * W_T * g * v * Z\right)}{\eta_{bw}} + \left(\frac{1}{2} W_T * v * a\left(\frac{1}{\eta_{bw}} - \eta_{bw} * \eta_{brk}\right)\right)\right] * \frac{D}{v} \quad (1)$$

Table 2 lists the parameters used to estimate the battery pack size.

Table 2. Vehicle Dynamic Model Input Parameters (Derived from Sripad and Viswanathan, 2017)

Category	Parameter	Representation in Equation 1	Value	Unit
Body (Alternative Fuels Data Center, 2020)	Gross vehicle weight (including payload and battery pack)	W_T	36,000	kg
	Coefficient of drag	C_d	0.45	
	Coefficient of rolling resistance	C_{rr}	0.0063	
	Braking efficiency	η_{brk}	0.97	
	Drivetrain efficiency	-	0.90	
	Battery discharge efficiency	-	0.95	
	Battery-to-wheels efficiency (product of battery discharge efficiency, drivetrain efficiency, and braking efficiency)	η_{bw}	0.83	
	Frontal area of truck	A	7.20	m^2
Use Characteristics	Daily driving distance	D	300 or 400	miles
	Average velocity (Sripad & Viswanathan, 2017)	v	19	m/s
	Root mean square velocity (Sripad & Viswanathan, 2017)	v_{rms}	22	m/s
	Average acceleration/deceleration (Sripad & Viswanathan, 2017)	a	0.112	m/s^2
	Road grade (Sripad & Viswanathan, 2017)	r	1%	
	Fraction of time driven on road grade r (Sripad & Viswanathan, 2017)	t_f	15%	
	Average road gradient (r/100) (Sripad & Viswanathan, 2017)	Z	0.0001	
	Air density	ρ	1.20	kg/m^3

Category	Parameter	Representation in Equation 1	Value	Unit
Environmental Characteristics	Acceleration due to gravity	g	9.8	m/s^2

2.2 Total Cost of Ownership Model

We address TCO primarily on a per-mile basis, summing the unit capital cost, unit maintenance cost, unit fuel cost, and unit general operation costs (Equation 2). We assume the fuel cost of an electric truck comprises electricity cost and the levelized cost of the charging equipment (Equation 3). We compute the unit capital cost of an electric truck as the unit capital cost of a diesel truck plus the capital cost of the battery and electric power train minus the cost of the avoided diesel truck components such as the power train, fuel and fuel tank etc.

$$\textit{Unit cost of ownership} = \textit{unit capital cost} + \textit{unit fuel cost} + \textit{unit maintenance cost} + \textit{unit operation costs} \qquad (2)$$

$$\textit{Unit fuel cost (electric truck)} = \textit{unit electricity cost} + \textit{unit cost of charging equipment} \qquad (3)$$

$$\textit{Unit capital cost (electric truck)} = \textit{unit capital cost (diesel truck)} + \textit{Battery and related component costs} - \textit{avoided diesel truck component costs} \quad (4)$$

The cost of electric powertrains is less than one third the cost of diesel powertrains—savings that are not considered by previous studies. The major component of the incremental capital cost of an electric truck is the battery cost, which we base on the battery pack size generated from the vehicle dynamic model. We amortize incremental capital cost to estimate per-mile incremental capital cost, which is primarily driven by battery prices and the range of electric trucks (which determines the battery size). We estimate operations, maintenance, and diesel fuel costs based on empirical data. Table 3 summarizes the parameters used for estimating all the components of Equation 2. We account for depreciation of battery and factor in the cost of replacement cost, but we ignore the depreciation of the vehicle as a whole. This is likely conservative with respect to EVs given that they incur lower maintenance and repair expenses and consequently a potentially longer asset life. In any case, there has been insufficient experience to estimate a distinct EV depreciation schedule except for the battery pack alone which can be approximated based on total charge and discharge cycles.

To estimate electric truck fuel costs, we draw on a complementary bottom-up estimate of charging cost (Phadke et al., 2019) that includes electricity and fast-charging infrastructure costs. The unit cost of the charging equipment is the minimum price per unit of energy delivered (kWh) that a charging service provider should charge consumers to break even on the investment in charging equipment and grid interconnection. The unit cost is a function of 1) the useful service life of the charging equipment, and 2) the utilization rate in terms of average kWh/day delivered. We do not explicitly conduct these analyses in this paper but rather draw on the model of Phadke et al., 2019. These results, which comprise the components of Equation 3, are summarized in Table 3.

In addition to a base case scenario, which uses current international battery pack price (as estimated and reported by BNEF), we evaluate cost and performance given plausible future developments on multiple fronts. We consider the effects of an aerodynamically superior design of the truck with a 45% lower drag co-efficient (declining from 0.45 to 0.25) which improves fuel economy by about 10% from 2.1 kWh/mi to 1.9 kWh/mi. We also consider the potential for charging at lower cost by ~60% ($0.1/kWh as opposed to $0.16/kWh in the base case) by procuring electricity at prices that more closely track wholesale electricity price as opposed to cost of retail service. We also evaluate the effect of a decline in battery price from $135 per kWh to $60 per kWh. Lastly, we allow for the monetization of air pollution/GHG emissions benefits from avoided emissions, which further reduces the TCO.

Table 3. Input Parameters for TCO Model

Unit capital cost components[4]		
2020 Battery pack cost (Holland, 2018)	$135 (2030 Price $60)	$/kWh
Battery life[5]	2,000	cycles
Battery size	375 or 500	kWh
Annual mileage[6]	78,0000 or 104,000	miles/year
Life of truck (Ritter, 2018)	15	years
Cost of truck without battery and allied drivetrain	$85,000	$
Real discount rate[7]	6.9%	
Unit fuel cost components		
Fuel efficiency of electric truck[8]	2.1	kWh/mile
Fuel efficiency of diesel truck (Alternative Fuels Data Center, 2020)	5.9[9]	miles/gallon
Amortized charging infrastructure cost[10]	$0.03	$/kWh
Electricity price[10]	$0.13	$/kWh
Diesel price (EIA, 2019)	$3.30	$/gallon
Unit maintenance cost components		
Diesel maintenance cost	$12,000–$30,000	$/year
Electric maintenance cost[11]	$6,500	$/year
Battery replacement cost (year 7) (Holland, 2018)	$100[12]	$/kWh
Unit operation cost components		
General operation costs	$0.76	$/mile

---

[4] Taxes on vehicles and components are excluded from this analysis and recognize that with higher upfront cost and component costs, electric vehicles could come out a bit costlier, but our sensitivity analyses will show that taxes are unlikely to change the basic conclusions.

[5] Based on expert input

[6] Assuming an average daily driving distance of 300 miles for a 375-mile range truck and 400-miles for a 500-mile range truck so as to achieve an average daily depth of discharge of battery of 80% and 260 days of driving for any truck

[7] Derived assuming nominal discount rate of 9%

[8] Result of VDM; validated by industry numbers

[9] Latest models of diesel trucks have high fuel economy but we anticipate such trucks to be costlier as well and we intend to addressed this in sensitivity analysis.

[10] Derived from Phadke et. al. 2019

[11] Estimated based on Cannon (2016)

[12] It is worth pointing out that diesel trucks need an engine rebuild after about 500,000 miles which makes our estimate conservative

2.3 Class 8 Truck Battery Pack Weight Estimation

Four components contribute to the weight of a standard battery pack module used in vehicles: 1) cells, which store energy; 2) busbars, which act as the transmission system for the battery pack; 3) cooling tubes, which maintain optimal ambient temperature within the pack; and 4) an outer case for protecting the pack against physical damage. Here we estimate the weight of a 797- and a 1,062-kWh pack, which are estimated to be the size of the battery pack used to power the 375- and the 500-mile-range Tesla Semi models. To derive the weight of the semi packs, we use the component weights for a 100-kWh Tesla Model S battery pack (Table 4).

Table 4. Input Parameters for Battery Pack Weight Estimate

Battery pack size (Carbuzz, 2019)	100	kWh
Tesla Model S battery pack weight	619	kg
Tesla Model S battery pack dimensions	91 x 59 x 4.5	in
Specific energy of each cell	250	Wh/kg
Total number of battery modules	16	
Individual battery module weight(HSR Motors, 2019)	26.1	kg
Energy stored per module(HSR Motors, 2019)	5.2	kWh

The difference between the total module weight (418 kg) and the total cell weight (400 kg) gives the total weight of the busbars and cooling tubes (18 kg). The difference between the total pack weight (619 kg) and the total module weight (418 kg) gives the weight of the protective case (201 kg). Assuming that 50% of the busbar and cooling tube weight is from busbars and 50% is from cooling tubes, we calculate the per-unit weights of individual battery pack components (Table 6).

Table 5. Per-Unit Weight of Individual Battery Pack Components

Cooling tubes	0.09	kg/kWh
Busbars	0.09	kg/kWh
Battery cell	4	kg/kWh

To estimate the weight of our semi battery packs, we make the following assumptions:

- Weight of battery cells is scaled by battery pack capacity
- Weight of cooling tubes is scaled by battery pack capacity with a 5% weight reduction from design changes
- Weight of busbars is scaled by battery pack capacity and then reduced by 50% to account for higher voltage[13]
- Weight of the protective case is scaled with battery pack surface area (semi battery pack dimensions are 99x78x20 in, giving a surface area ratio of 2.14)

Table 6 shows the resulting battery pack component weights for a 797- and 1,062-kWh pack.

Table 6. Component Weights for a Semi Truck Battery Pack

	797-kWh pack	1062-kWh pack	
Cells	3,187	4,250	kg
Cooling tubes	67	89	kg
Busbars	35	47	kg
Protective case	127	202	kg
Total weight	**3,416**	**4,587**	**kg**

A final element of our weight calculation was to estimate the impact of light-weighting on total truck weight. The main light-weighting strategy that is suitable and currently available for Class 8 trucks is to convert components from a heavier material to a lighter material. There are many possibilities for such conversion--for example, converting cab sheet metal from steel to aluminum or lightweight steel, or converting aerodynamic roof hoods from aluminum to plastic. Another strategy for light-weighting is to combine different components to reduce the need for fasteners and other material interfaces. While light-weighting may not improve *individual* truck efficiency dramatically, it has driven a significant improvement in operational efficiency of *fleets*, where larger payload capacity per truck led to smaller fleet sizes needed to deliver the same quantity of payload (North American Council for Freight Efficiency, 2015).

---

[13] [consider dropping a footnote to explain why the weight of the busbars drop in half due to higher voltage - seems counterintuitive]

Although we focus on determining TCO from the truck owner's point of view, we also analyze additional benefits that could be realized if environmental externalities from diesel trucking can be monetized. In this paper the externalities we consider are costs of air pollution and greenhouse gas (GHG) emissions. Depending on existing markets or compensation mechanisms, such externalities may or may not be able to be included in the TCO. The degree to which truck electrification mitigates diesel trucking externalities depends on the fuel used for electricity generation. Here we primarily consider scenarios with electricity entirely powered by coal and gas, compared to 90% renewable energy (with the remaining 10% of electricity assumed to be powered by gas), as well as scenarios incorporating the current power mix of the United States and of California. These elements are summarized in Table 7.

Table 7. Input Parameters for Additional Benefits of Electrification

Unit air pollution cost components		
Air pollution damages from heavy diesel on-road vehicles (Goodkind et al., 2019)	$58	$billion/year
Air pollution damages from coal-based electricity generation (Goodkind et al., 2019)	$118	$billion/year
Air pollution damages from gas-based electricity generation (Goodkind et al., 2019)	$5	$billion/year
Coal-fired generation (EIA, 2020e)	1733	billion kWh/year
Gas-fired generation (EIA, 2020e)	1014	billion kWh/year
Fraction of on-road pollution contributed by Class 8 trucks[14]	56%	
Miles driven by Class 8 trucks (Bureau of Transportation Statistics, 2017)	164	billion miles/year
Unit GHG emissions cost components		
Diesel consumed by Class 8 trucks (Bureau of Transportation Statistics, 2017)	28,884	million gallons/year
Social cost of carbon (EPA, 2017)	$52	$/tonne CO2, 2019 dollars
Emissions intensity from coal-fired electricity (EIA, 2020c, 2020a)	210	lb CO2/million btu

---

[14] Estimated based on Goodkind et al. and California ARB[44]

Emissions intensity from gas-fired electricity (EPA Center for Corporate Climate eadership, 2018)	117	lb CO2/million btu
Emissions intensity of US power mix (Carnegie Mellon University, 2019)	943	lb CO2/MWh
Emissions intensity of CA power mix (EIA, 2019)	474	lb CO2/MWh
Coal plant heat rate (EIA, 2020d)	10,465	Btu/kWh
Gas plant heat rate (EIA, 2020d)	7,707	Btu/kWh
Methane leakage rate (Alvarez et al., 2018)	2.3%	% of US gas production
Total electricity losses across T&D system(EIA, 2020b) and in AC/DC power conversion[15]	14.5%	

3. Results

3.1 Total Cost of Ownership

Figure 4 shows the TCO comparison for both the 375-mile range and 500-mile range Class-8 electric truck relative to diesel. At the current international battery pack price of $135 per kilowatt-hour, a Class 8 truck electric truck with 375-mile range (300-mile range at 80% maximum DoD of battery) with a 797-kWh battery pack offers about 13% lower per mile TCO ($1.51/mi for electric compared to $1.73 for diesel) (Figure 2). This implies a net savings of about $200,000 over its lifetime for a less than 3% increase in the tractor weight given currently available light-weighting options.

---

[15] Industry interview

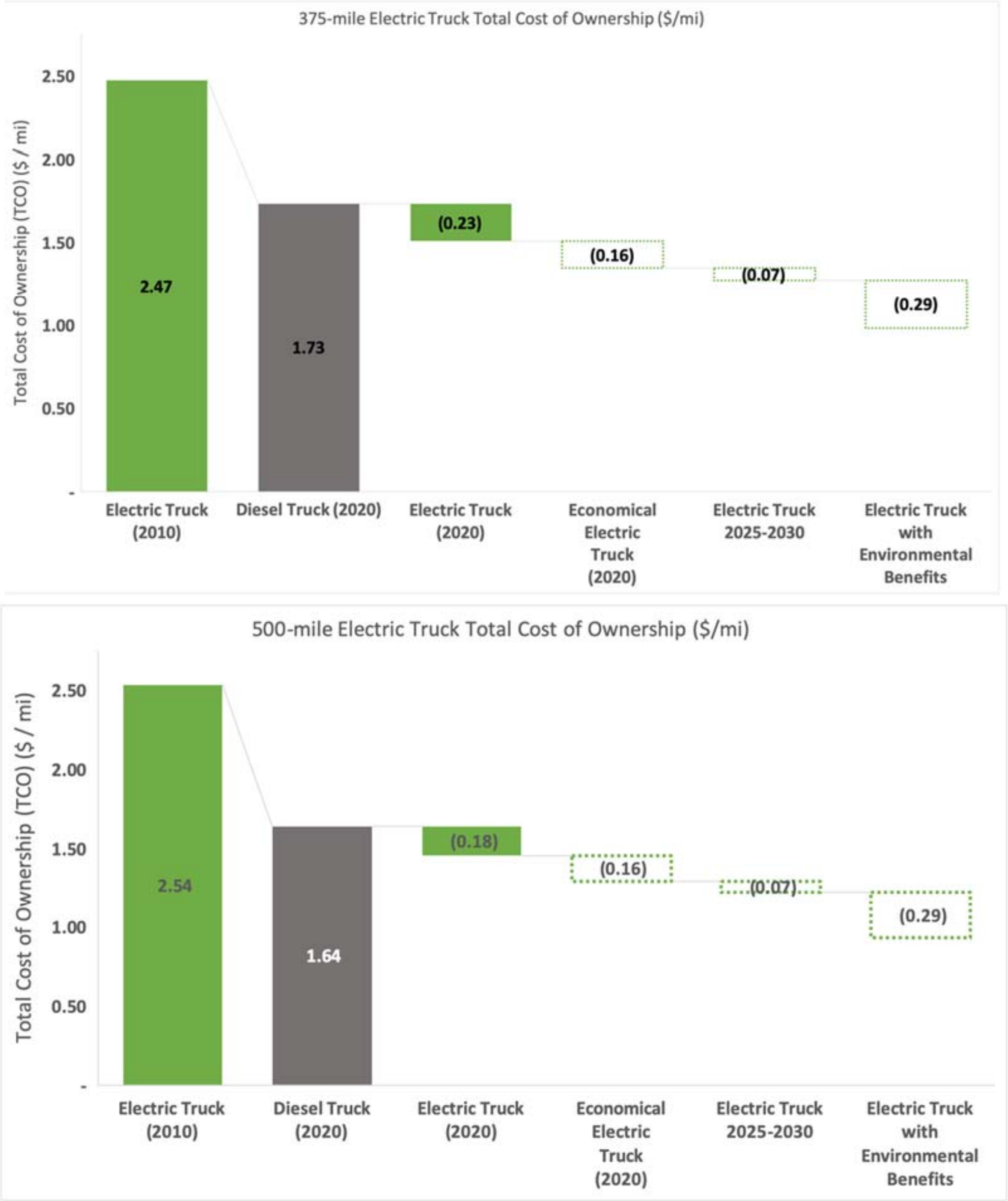


Figure 4 (Top) TCO comparison for 375-mile (797 kWh battery pack truck) operated 300 miles per day for 260 days per year. (**Bottom**) TCO comparison for 500-mile (1062 kWh battery pack truck) operated 400 miles per day for 260 days per year. The battery cost in 2020 is $135/kWh. The economical electric truck scenario assumes an aerodynamically better design which improves fuel economy coupled with a lower total charging cost ($0.1/kWh compared to $0.16 in base case). The electric truck in 2025-30 scenario tacks a decline in battery prices to $60 per kWh from the $135 per kWh on to the economical truck scenario. Lastly, this is combined with monetization of air pollution/GHG emissions benefits from avoided emissions, which further reduces the TCO.

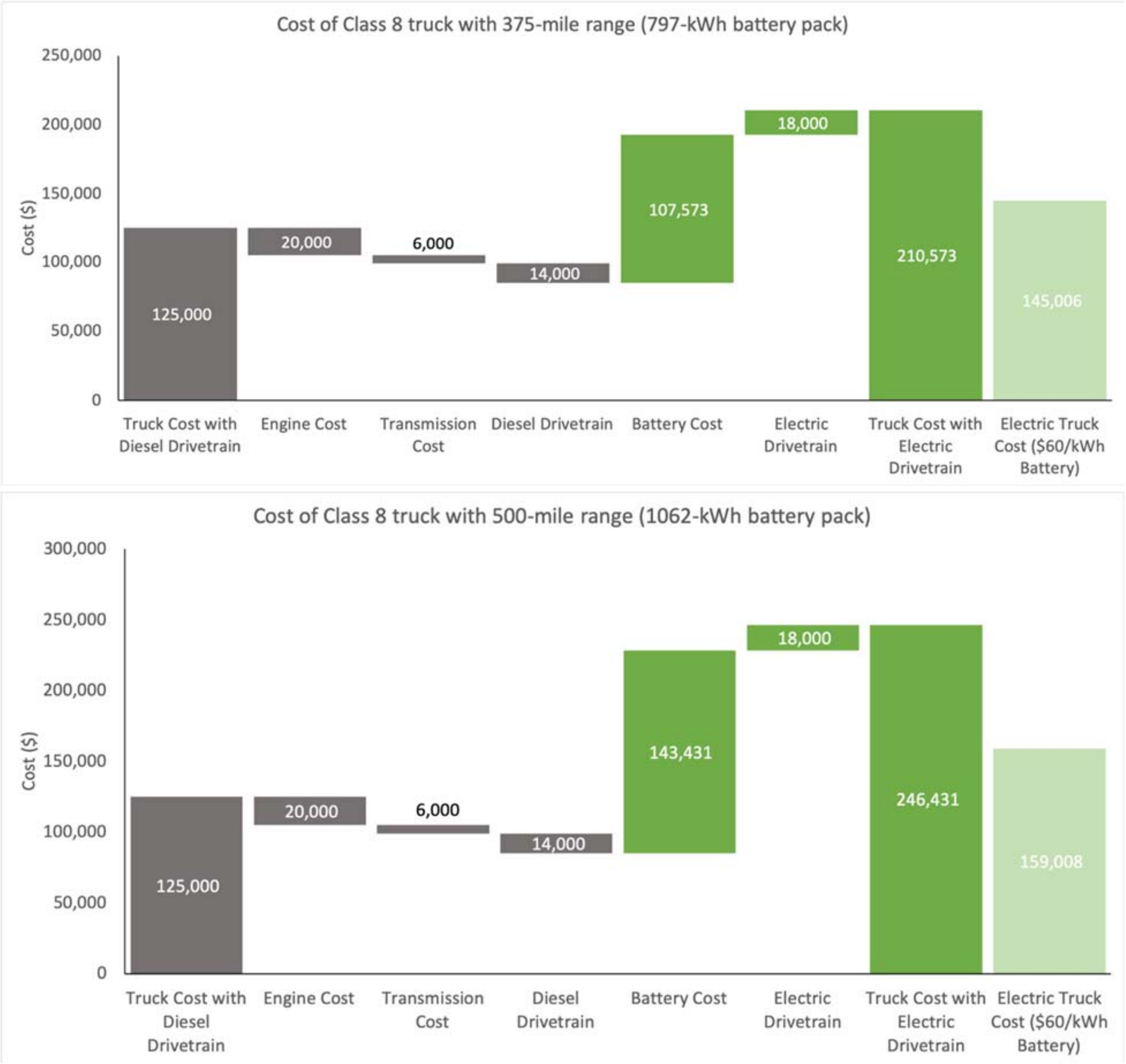


Figure 5 Capital cost of a Class 8 diesel truck compared with a Class 8 battery-electric truck with 375-mile range and 797-kWh battery (top) and 500-mile range and 1,062-kWh battery (bottom), with battery costs of $135/kWh (dark green) and $60/kWh (light green).

Figure 5 shows how we arrive at our estimate of the upfront cost of the electric truck. We begin with a diesel truck price of $125,000 and first subtracting out the cost of engine, transmission and drive train ($20,000, $6000 and $14000 respectively) which are not required in an electric truck. Next, we add to this the battery cost, which is simply the product of battery price per kWh and battery size ($107,753 and $143,341 for the 375-mile (797 kWh) and 500-mile (1062 kWh) trucks @ $135/kWh) and drive train cost ($18,000). This yields an estimated cost of $210,573 and $246,431 respectively for the 375- and 500-

mile trucks. These are respectively 69% and 97% greater relative to the upfront cost of the diesel truck.

For the 375-mile truck, the excess upfront cost translates to about $0.12 per mile (levelized). However, electric trucks save $0.11/mile on maintenance costs and $0.23/mile on fuel costs, yielding a net reduction of $0.23 per mile which explains the about 13% reduction relative to $1.73 per mile TCO of diesel, which can be seen in Figure 4. We assume other costs such as general operation costs such as driver wages, insurance, tire replacements, permits, and tolls are identical for diesel and EVs and ignore difference in end-of-life value.

We next describe our bottom-up weight estimates for battery and other drivetrain components based on the publicly available specifications for Volvo and Tesla for their Class 8 trucks. We break down truck weight for vehicles commercially available on the market based on Tesla's 375- and 500-mile range (797- and 1,062-kWh battery capacity) trucks with our conservative efficiency assumption of 2.1 kWh/mile (Tesla claims less than 2 kWh/mile). Figure 6 compares the weight of a Class 8 diesel truck and the weight of Class 8 electric trucks with 375-mile (top) and 500-mile (bottom) ranges. The figure assumes a packing fraction (ratio of cell weight to battery weight) of 0.88, which represents an improvement over the 100-kWh Tesla Model S packing fraction (0.65) owing to the lower surface-area-to-volume ratio of higher-capacity battery packs. The incremental truck weights are estimated by adding the weight of the battery and electric powertrain and subtracting the weight of the diesel powertrain components. The light green bar segments show the potential for reducing truck weight using lighter materials, such as aluminum, instead of steel for the truck body.

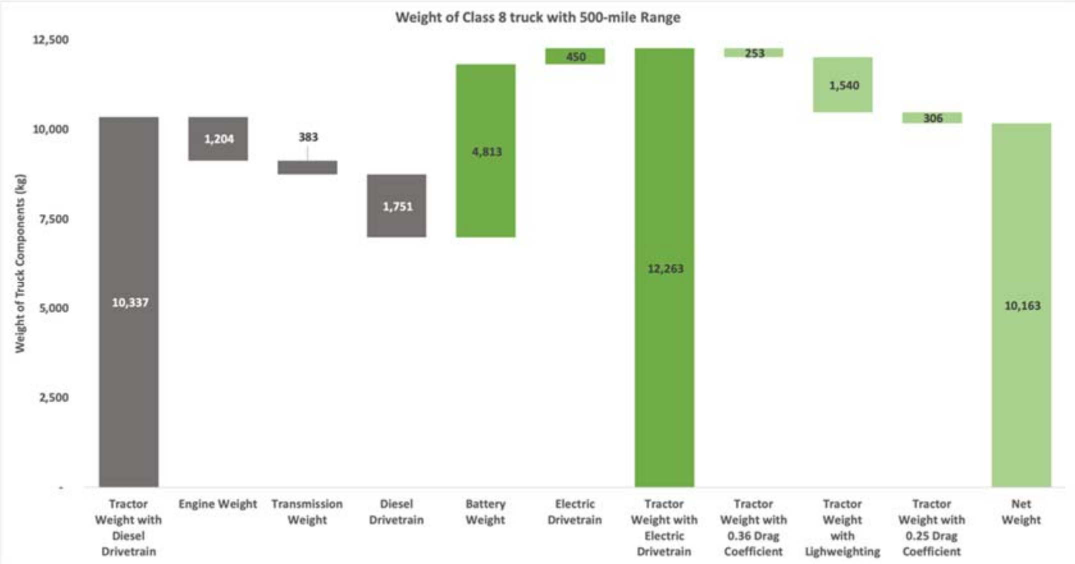


Figure 6. Weight of a Class 8 diesel truck compared with a Class 8 battery-electric truck with 375-mile range and 797-kWh battery (top) and 500-mile range and 1,062-kWh battery (bottom), cell specific energy of 250 Wh/kg and packing fraction of 0.88.

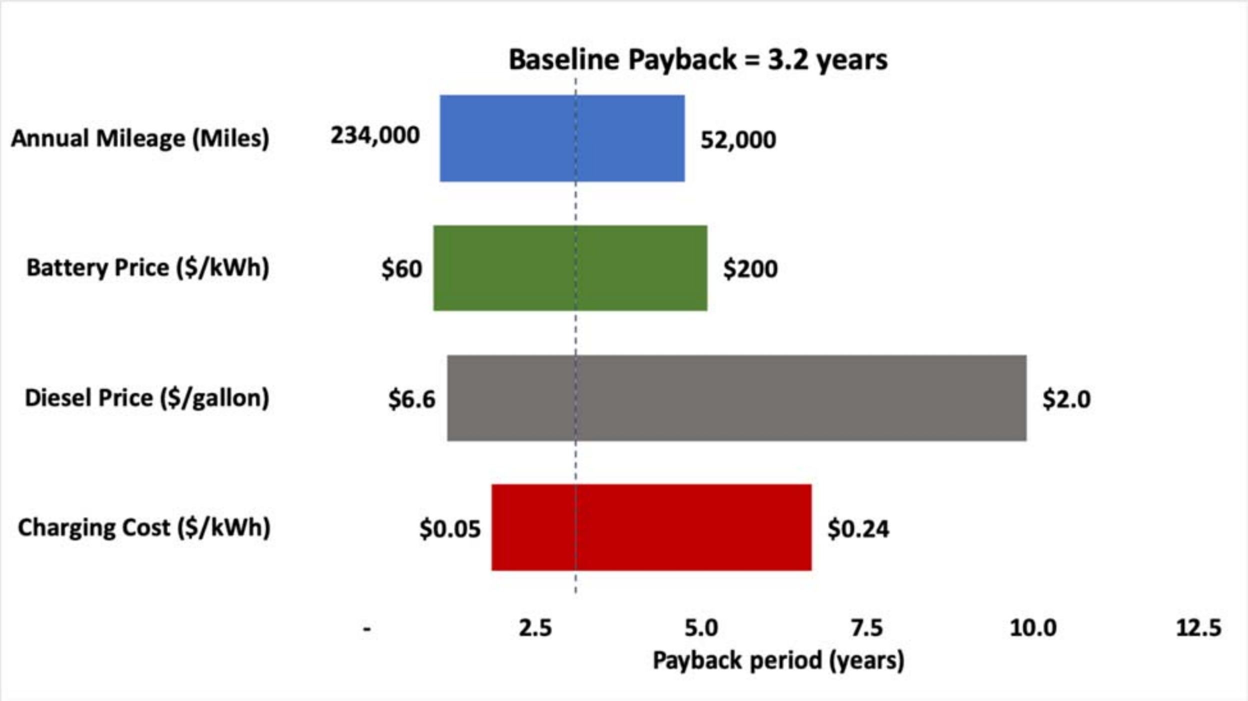
Our calculations suggest that the tractor of 375-mile range electric truck is about 3% (~ 300 kg) heavier relative to a diesel truck. However, adoption of even moderate light-weighting options can lead to an increase of 9% in total net payload capacity. For 500-mile electric trucks, the tractor is about 19% heavier relative to diesel tractor but which can be reduced to only 2% heavier by applying commercially available light weighting options resulting into only a minor reduction payload capacity.[16]

Electric trucks with a range up to 300 miles will not require any compromise of the payload capacity because lower weight of the electric powertrain compared to diesel compensates for the additional weight of the battery. Light-weighting (reduction up to 1.5 metric tonnes) and improved aerodynamics using commercially available technology can enable additional range up to 450 miles. Further, since most trucks reach their volume limit before reaching their weight limit, accepting a 5% weight penalty for reducing fuel cost significantly is likely to acceptable for most trucks; together this will allow for large enough batteries to reach ranges up to 600 miles (see ES2). Fast charging during 30-minute driver rest stop can add significant battery range (a 30-minute break is taken every 190 miles and 150 miles for a long haul and regional haul trucks respectively). For these reasons we believe that electric trucks will have sufficient range for most applications in the near future (see ES2 B).

---

[16] If trucks were to indeed achieve a fuel efficiency similar to those claimed by Tesla, then the battery size, weight, and cost could be about 20% lower than estimated here.

The mean baseline payback period for truck electrification for a 375-mile truck is 3.2 years (Figure 8). Figure 8 also shows the sensitivity of payback period to key parameters. When annual mileage and battery price are varied individually, payback period ranges between 1.0 and 5.1 years. When charging cost is varied individually, it ranges between 1.8 and 6.7 years. When diesel price is varied individually, it ranges between 1.2 and 9.9 years The Discussion section addresses variation in charging cost further.



*Battery price range $200 - $60

Figure 8. Sensitivity of the electrification payback period, not including any additional environmental benefits, to different parameters: each parameter is varied individually while the other parameters are held at their baseline values listed in Table 6. Baseline values are 78,000 miles/year driven, $135/kWh battery cost, $3.3/gal diesel, and $0.16/kWh charging cost (which includes both the electricity cost and the levelized cost of charger per kWh of electricity delivered). Sensitivity range for charging cost is based on Phadke et al. 2019; for diesel is based on 50% and 200% of baseline; for battery price is based on 2017 prices and projected 2020-26 prices;

Indeed, electricity emissions intensity (in terms of both air pollution and GHGs) determines the level of net environmental benefits for electric trucks relative to diesel (see Figure 9).

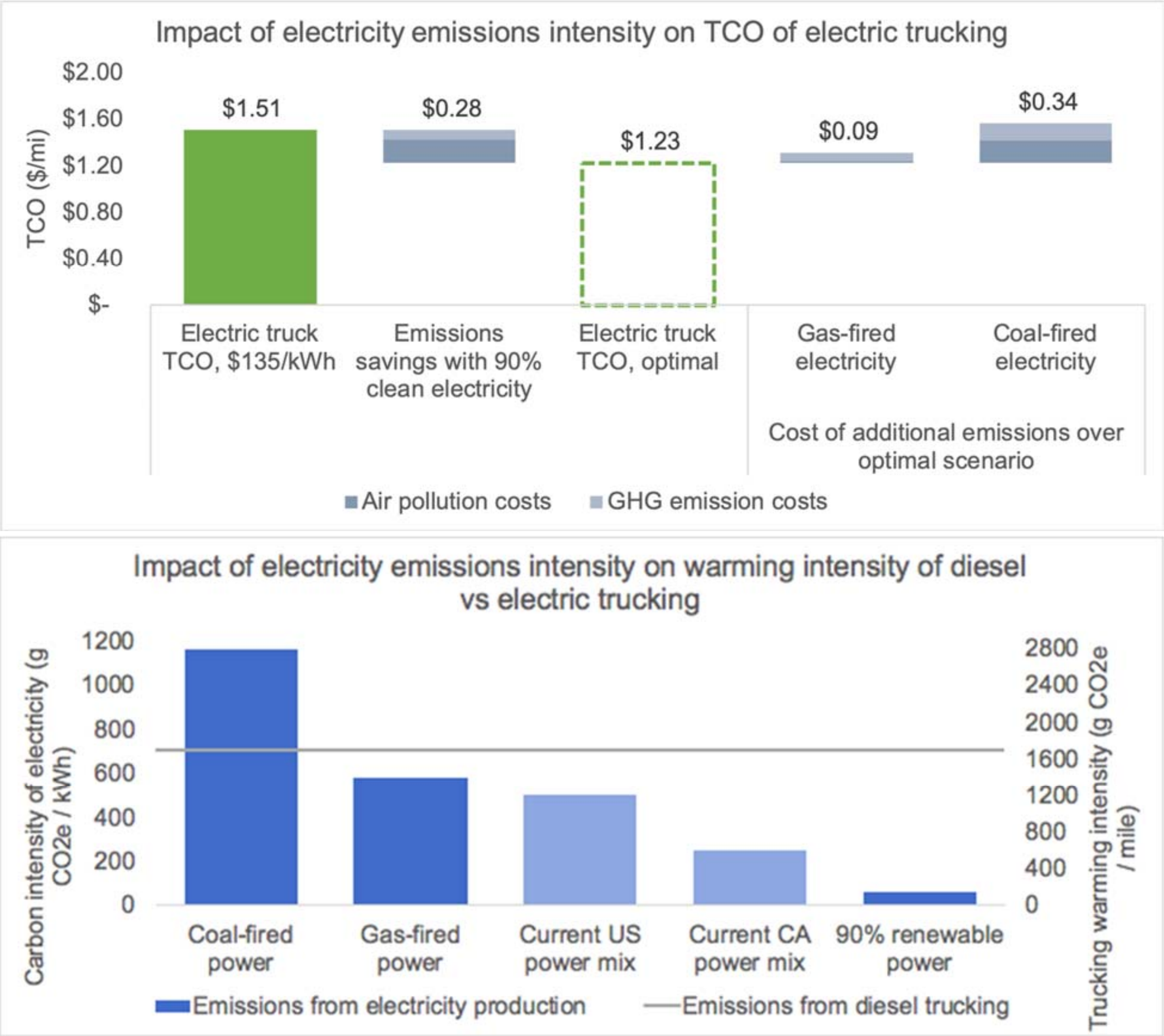


Figure 9. (Top) Impact of electricity emissions intensity (from 90% clean electricity, gas-fired electricity, and coal-fired electricity) on 375-mile electric truck TCO, assuming air pollution and GHG emissions costs can be monetized. (Bottom) Comparison of warming intensity of trucking for diesel trucking and electric trucking powered by electricity from coal, gas, and 90% renewable energy, and by the current power mix in the US and in California.

While savings on air pollution and GHGs from electrification are $0.28/mi in a scenario where electricity sources are 90% clean, savings drop to $0.20/mi when electricity comes from gas, and savings become negative (costs rise) by $0.05/mi when electricity comes from coal. In terms of global warming, diesel trucking contributes more warming (in terms of g CO2e/mile) than electrified trucking powered by either gas or 90% clean energy. However, electric trucks powered by gas-fired electricity only save 18% of GHG emissions over diesel trucking, and electric trucking powered by coal produces 64% more GHG emissions than diesel trucking on a per-mile basis.

4. Discussion

The comparison of diesel and electric Class 8 long-haul trucks based both on a bottom-up estimation and market-data shows the following. A Class 8 truck electric truck with 375-mile maximum range with a daily average utilization of 300 miles offers about 13% lower per mile TCO and a 3- to 4-year payback for a net savings of about $200,000 over its lifetime, all for about a 3% reduction in payload capacity. Even this reduction in payload capacity could be avoided cost-effectively through light-weighting, and is not a major concern beyond the small fraction of operators which consistently use the trucks maximum payload limit. Based on this our primary conclusion is that that replacing long-haul diesel trucks with electric trucks is both technically feasible and economically viable.

A key lesson is that a low cost of fast-charging (both the amortized cost of charging infrastructure and cost of electricity combined) is central to the economic case for truck electrification, and therefore, getting the charging cost right is critical. As detailed in Phadke et al. 2019 and illustrated in Figure 10, clean, low-cost generation is become abundant across several hours of the day. For instance, most hours of the year in both ERCOT and CAISO have low wholesale electricity prices (see Figure 10). Dynamic electricity tariffs are necessary for the trucking industry to take full advantage of those prices. While static tariffs have fixed price schedules and non-peak-coincident demand charges, dynamic tariffs track wholesale electricity prices, and more importantly, have demand charges coincident with system peak demand. Dynamic tariffs align pricing with the real-time state of the grid and incentivize trucks to charge during low-priced times when the grid is unconstrained. Static tariffs—particularly non-peak-coincident demand charges—can unnecessarily impede truck charging by imposing a high per-kW charge even when charging happens when the grid is unconstrained and generation prices are low.

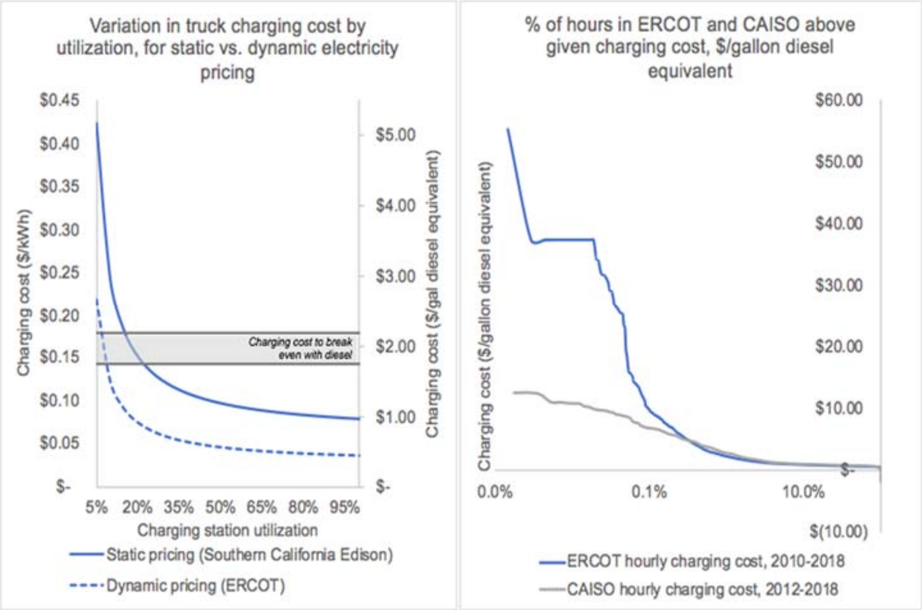


Figure 10. *Excerpt from Phadke et al. (2019)* Variation in truck charging cost by utilization, for static vs. dynamic, system-reflective electricity pricing (left). Proportion of hours in ERCOT (2010–2018) and CAISO (2012–2018) above given charging cost (right). Note: Diesel breakeven range is based on $3.30/gal diesel, battery costs are between $150/kWh (top of range) and $100/kWh (bottom of range), and truck efficiency is assumed to be 5.9 mi/gal (diesel) or 2.1 kWh/mi (electric).

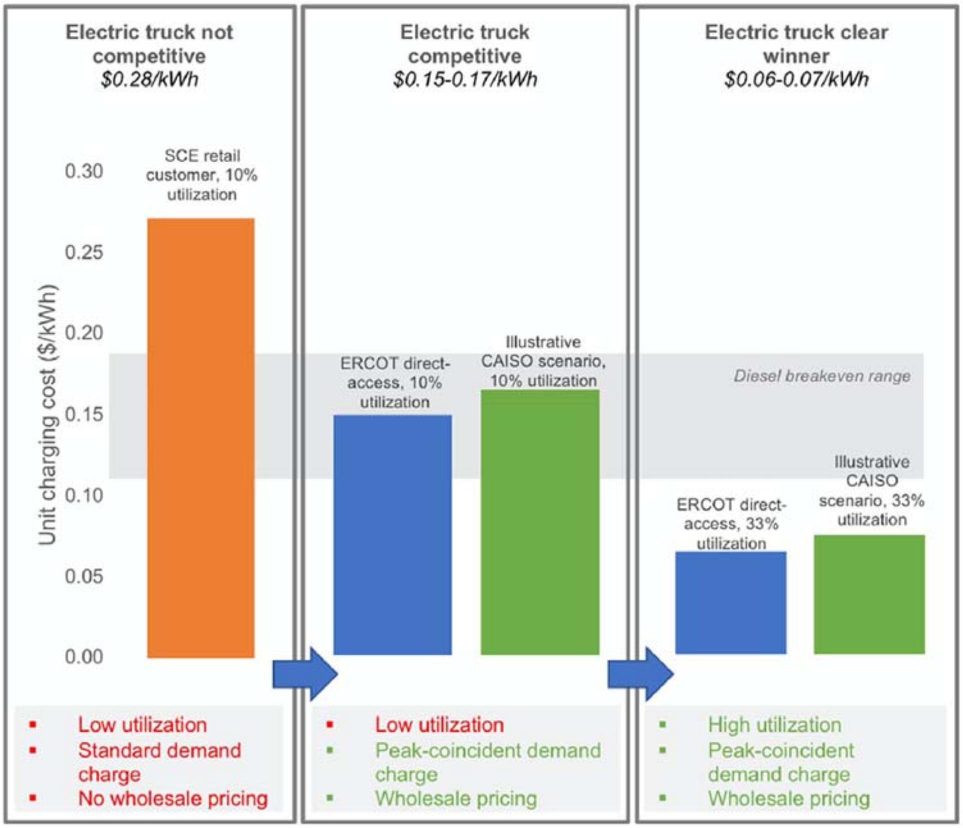


Figure 9. Pathway from conditions that result in non-competitive electric trucks (low utilization, standard non-peak-coincident demand charges, and no wholesale pricing) to conditions that result in increasingly competitive electric trucks (peak-coincident demand charges, wholesale pricing, and—eventually—high utilization). Diesel breakeven figures reflect battery costs between $170/kWh and $100/kWh, and $3.16/gal diesel costs.

Figure 11: ***Excerpt from Phadke et al. 2019*** Rationale electricity tariffs and improved charging infrastructure utilization can significantly improve the economics of electric trucks

We held diesel and electricity prices fixed in this analysis. While modest real increases in diesel prices are being projected (EIA, 2019), we assume no increase on account of high rates of vehicle electrification—the scenario we implicitly address in this paper—could reduce petroleum demand enough to decrease diesel prices. For similar reasons, we do not assume escalating electricity prices. Given uncertainties surrounding grid decarbonization scenarios, falling renewables prices, electrification rates, and electricity policy, we do not attempt to predict changes in electricity prices over time and instead compare electricity to diesel on today's terms.

Environmentally, the benefits of truck electrification can be substantial, but depend on the emissions intensity of electricity. The only scenario in which truck electrification has negative incremental environmental benefits relative to diesel is when the electricity is entirely from coal-based generation while, and not surprisingly, maximum benefits accrue when electricity is exclusively from clean renewables. Gas-fired power, while substantially less emitting than coal and diesel in terms of air pollution, is only marginally better than diesel trucking in terms of GHG emissions when accounting for methane leakage.

The investment trend in the US electricity sector is away from coal and towards increasing renewable energy and natural gas. From 2008-2018, 45% of new capacity additions were gas, and 44% were wind or solar. Only 7% of new capacity in this period was coal, and no new coal capacity has been added since 2015. Looking forward, 50% of capacity under construction is gas, and 44% is wind or solar; similar ratios hold for permitted capacity. (Wind and solar account for over 60% of capacity in earlier stages of development, with gas only 17-26%.)[32] Furthermore, 10 states, as well as Washington, D.C., and Puerto Rico, have 100% clean energy or renewable energy targets.[27] As such, new trucking load will likely be met with increasing investment in gas and renewables, meaning that long-run marginal emissions from electric trucking are expected to be less than that of diesel trucking.

In sum, today there is reason for optimism that long-haul truck electrification can be achieved at a TCO lower than diesel truck TCO without compromising on payload capacity. Future technical research needs to focus on estimating charging infrastructure needs to support an electrified trucking network and developing strategies for charging under different given fleet performance criteria and grid conditions.

An appropriate policy ecosystem is required to stimulate and facilitate the transition from diesel to electric long-haul trucking. As is the case with almost any clean technology, higher upfront costs (for both vehicles and charging infrastructure), due to lack of scale economies and market uncertainty, are greater at the early stages of adoption and are a major market barrier. For instance, notwithstanding the 13% lower TCO of electric trucks (for a 375-mile range truck with a 797-kWh battery pack), they are costlier upfront by 75% upfront, which is major barrier. As battery costs decline, charging related costs are beginning to loom larger. Whereas a decade ago, when battery prices were close $1000/kWh, charging-related cost would have accounted for about 15% to 18% of the TCO of heavy-duty trucks, today they account for 25% to 30%. Recall Figure ES3 which shows how the utilization of charge infrastructure determines the total cost of charging (the sum of cost of electricity and levelized cost of infrastructure) and early stage of adoption will necessarily be characterized by low utilization of charging infrastructure.

Realizing the full economic potential of electric trucks requires surviving a period of infancy of this industry marked by low demand for vehicles and charging, and consequently, higher cost of new vehicle manufacturing and slower return on charging infrastructure. Faced with such barriers, absent public intervention, private investments in electric truck will occur at a level lower than is socially optimal. While this is characteristic of any infant industry, given the importance of addressing pollution from trucking, without strong policy support the coordinated and large-scale investments in vehicle technologies and fuel infrastructure will not be forthcoming on the scale needed to harness the true potential of battery electric trucks. Binding targets for vehicle sales supported by targeted incentives that are indexed both to international battery prices and cumulative sales can help in this regard. There is also a need to rationalize electricity tariffs so that they send the right price signals for truck charging without imposing undue burden on the rest of the system.

Acknowledgements
We thank Bill Van Amburg, Cristiano Facanha, Nihan Karali, and Ray Minjares for comments and suggestions which improved the report and also acknowledge the support of Hewlett Foundation for funding this work. The views expressed herein are however solely those of the authors.

5. References

Alternative Fuels Data Center. (2020). *Average Annual Vehicle Miles Traveled of Major Vehicle Categories*. https://afdc.energy.gov/data/10309

Alvarez, R. A., Zavala-Araiza, D., Lyon, D. R., Allen, D. T., Barkley, Z. R., Brandt, A. R., Davis, K. J., Herndon, S. C., Jacob, D. J., Karion, A., Kort, E. A., Lamb, B. K., Lauvaux, T., Maasakkers, J. D., Marchese, A. J., Omara, M., Pacala, S. W., Peischl, J., Robinson, A. L., Hamburg, S. P. (2018). Assessment of methane emissions from the U.S. oil and gas supply chain. *Science*. https://doi.org/10.1126/science.aar7204

Apte, J. S., Messier, K. P., Gani, S., Brauer, M., Kirchstetter, T. W., Lunden, M. M., Marshall, J. D., Portier, C. J., Vermeulen, R. C. H., & Hamburg, S. P. (2017). High-Resolution Air Pollution Mapping with Google Street View Cars: Exploiting Big Data. *Environmental Science & Technology*, *51*(12), 6999–7008. https://doi.org/10.1021/acs.est.7b00891

BNEF. (2020). Battery Pack Prices Cited Below $100/kWh for the First Time in 2020, While Market Average Sits at $137/kWh. In *Bloomberg New Energy Finance*. https://about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh/?utm_medium=Twitter_BNEF&utm_campaign=BNEF&utm_source=Social-o&utm_content=organic&tactic=331602&sf134474242=1

Bureau of Transportation Statistics, U. D. of T. (2017). *National Transportation Statistics*. http://www.princeton.edu/ alaink/Orf467F17/NTS_Entire_2017Q2.pdf

Çabukoglu, E., Georges, G., Küng, L., Pareschi, G., & Boulouchos, K. (2018). Battery electric propulsion: An option for heavy-duty vehicles? Results from a Swiss case-study. *Transportation Research Part C: Emerging Technologies*, *88*, 107–123. https://doi.org/10.1016/j.trc.2018.01.013

California Air Resources Board. (2019). *Advanced Clean Trucks Total Cost of Ownership Discussion Document*.

CALSTART (2020): Drive to Zero's Zero-emission Technology Inventory (ZETI) Tool Version 5.9. Available online at https://globaldrivetozero.org/tools/zero-emission-technology-inventory/

Carbuzz. (2019). 2018 Tesla Model S P100D. In *CarBuzz*. https://carbuzz.com/cars/tesla/model-s-p100d

Carnegie Mellon University. (2019). *Power Sector Carbon Index*. https://emissionsindex.org

Davis, B. A., & Figliozzi, M. A. (2013). A methodology to evaluate the competitiveness of electric delivery trucks. *Transportation Research Part E: Logistics and Transportation Review*, *49*(1), 8–23. https://doi.org/10.1016/j.tre.2012.07.003

Davis, S. C., Susan E Williams, & Robert G Boundy. (2017). *Transportation Energy Data Book: Edition 36* (p. 400). Oak Ridge National Laboratory.

Den Boer, E., Aarnink, S., Kleiner, F., & Pagenkopf, J. (2013). Zero emissions trucks: An overview of state-of-the-art technologies and their potential. *Ω*, 151.

Earl, T., Mathieu, L., Cornelis, S., Kenny, S., Ambel, C. C., & Nix, J. (2018). *Analysis of long haul battery electric trucks in EU: Marketplace and technology, economic, environmental, and policy perspectives.*

EIA. (2019). *State Electricity Profiles: California*. State Electricity Profiles. https://www.eia.gov/electricity/state/california/

EIA. (2019). *Table 11. Petroleum and Other Liquids Supply and Disposition.* https://www.eia.gov/outlooks/aeo/tables_ref.php

EIA. (2020a). How much carbon dioxide is produced when different fuels are burned? In *Frequently Asked Questions*. https://www.eia.gov/tools/faqs/faq.php?id=73&t=11

EIA. (2020b). How much electricity is lost in electricity transmission and distribution in the United States? In *Frequently Asked Questions*. https://www.eia.gov/tools/faqs/faq.php?id=105&t=3

EIA. (2020c). Subbituminous and bituminous coal dominate U.S. coal production. In *Today in Energy*. https://www.eia.gov/todayinenergy/detail.php?id=2670

EIA. (2020d). *Table 8.1. Average Operating Heat Rate for Selected Energy Sources*. https://www.eia.gov/electricity/annual/html/epa_08_01.html

EIA. (2020e). What is U.S. electricity generation by energy source? In *Frequently Asked Questions*. https://www.eia.gov/tools/faqs/faq.php?id=427&t=3

EPA. (2017). *The Social Cost of Carbon*. https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon_.html

EPA Center for Corporate Climate eadership. (2018). *Emission Factors for Greenhouse Gas Inventories*. https://www.epa.gov/sites/production/files/2018-03/documents/emission-factors_mar_2018_0.pdf

Federal Highway Administration. (2019). *Compilation of Existing State Truck Size and Weight Limit Laws*. US Department of Transportation. https://ops.fhwa.dot.gov/freight/policy/rpt_congress/truck_sw_laws/app_a.htm

Field, K. (2020, February). *BloombergNEF: Lithium-Ion Battery Cell Densities Have Almost Tripled Since 2010*. https://cleantechnica.com/2020/02/19/bloombergnef-lithium-ion-battery-cell-densities-have-almost-tripled-since-2010/

Goodkind, A. L., Tessum, C. W., Coggins, J. S., Hill, J. D., & Marshall, J. D. (2019). Fine-scale damage estimates of particulate matter air pollution reveal opportunities for location-specific mitigation of emissions. *Proceedings of the National Academy of Sciences*, *116*(18), 8775–8780. https://doi.org/10.1073/pnas.1816102116

Gopal, A. R., Karali, N., Sharpe, B., Delgado, O., Bandivadekar, A., & Garg, M. (2017). *Improved heavy-duty vehicle fuel efficiency in India, benefits, costs and environmental impacts* (No. 1398495; p. 1398495). https://doi.org/10.2172/1398495

Guttikunda, S. K., & Mohan, D. (2014). Re-fueling road transport for better air quality in India. *Energy Policy*, *68*, 556–561. https://doi.org/10.1016/j.enpol.2013.12.067

Hall, D., & Lutsey, N. (2019). *Estimating the Infrastructure Needs and Costs for the Launch of Zero Emission Truck*. https://theicct.org/publications/zero-emission-truck-infrastructure/

Holland, M. (2018). $100/kWh Tesla Battery Cells This Year, $100/kWh Tesla Battery Packs In 2020. In *CleanTechnica*. https://cleantechnica.com/2018/06/09/100-kwh-tesla-battery-cells-this-year-100-kwh-tesla-battery-packs-in-2020/

HSR Motors. (2019). Battery Modules: Tesla Battery Modules \textgreater 85-TYPE. In *HSR Motors*. https://hsrmotors.com/products/battery_modules

Jadun, P., Colin McMillan, Daniel Steinberg, Matteo Muratori, Laura Vimmerstedt, & Trieu Mai. (2017). *Electrification Futures Study: End-Use Electric Technology Cost and Performance Projections through 2050*. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy18osti/70485.pdf

Karali, N., Abhyankar, N., Sharpe, B., & Bandivadekar, A. (2019). *Improving fuel efficiency for heavy-duty vehicles of 3.5–12 tonnes in India: Benefits, costs, and environmental impacts* (No. 1498692; p. 1498692). Energy Analysis and Environmental Impacts Division Lawrence Berkeley National Laboratory. https://doi.org/10.2172/1498692

Kodjak, D. (2015). *Policies to reduce fuel consumption, air pollution, and carbon emissions from vehicles in G20 nations*. https://theicct.org/sites/default/files/publications/ICCT_G20-briefing-paper_Jun2015_updated.pdf

Landrigan et al., P. J. (2017). *The Lancet Commission on pollution and health.* The Lancet. http://ugspace.ug.edu.gh/bitstream/handle/123456789/31420/The%20Lancet%20Commission%20on%20pollution%20and%20health.pdf?sequence=1

Lazard. (2018). *Levelized Cost of Energy and Levelized Cost of Storage 2018*. https://www.lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2018/

Lee, D.-Y., & Thomas, V. M. (2017). Parametric modeling approach for economic and environmental life cycle assessment of medium-duty truck electrification. *Journal of Cleaner Production*, *142*, 3300–3321. https://doi.org/10.1016/j.jclepro.2016.10.139

Legacy Truck Centers, I. (2019). *2018 Volvo Trucks VNL 400 Sleeper*. https://www.legacytruckcenters.com/inventory/v1/Current/Volvo-Trucks/VNL-Series/2018-VNL-400/Sleeper—8266161

Liimatainen, H., van Vliet, O., & Aplyn, D. (2019). The potential of electric trucks – An international commodity-level analysis. *Applied Energy*, *236*, 804–814. https://doi.org/10.1016/j.apenergy.2018.12.017

Mareev, I., Becker, J., & Sauer, D. (2017). Battery Dimensioning and Life Cycle Costs Analysis for a Heavy-Duty Truck Considering the Requirements of Long-Haul Transportation. *Energies*, *11*(1), 55. https://doi.org/10.3390/en11010055

Moultak, M., Lutsey, N., & Hall, D. (2017). *Transitioning to zero-emission heavy-duty freight vehicles* (p. 59). The International Council on Clean Transportation.

North American Council for Freight Efficiency. (2015). *Confidence Report: Light-weighting*. https://nacfe.org/technology/light-weighting-2/

North American Council for Freight Efficiency, & Rocky Mountain Institute. (2018). *Electric Trucks: Where they make sense*. https://nacfe.org/emerging-technology/electric-trucks/

Oak Ridge National Laboratory. (2019). *Medium- and Heavy-Duty Vehicle Electrification: An Assessment of Technology and Knowledge Gaps*. https://info.ornl.gov/sites/publications/Files/Pub136575.pdf

Phadke, Amol A., Margaret McCall, & Deepak Rajagopal. (2019). Reforming electricity rates to enable economically competitive electric trucking. *Environmental Research Letters*.

Ritter, K. (2018). The Tesla Semi Costs—Part 4. In *InsideEVs*. https://insideevs.com/news/336275/the-tesla-semi-costs-part-4/

Schipper, L., C. Saenger, & A. Sudardshan. (2011). Transport and Carbon Emissions in the United States: The Long View. *Energies*, *4*, 563–581.

Sen, B., Ercan, T., & Tatari, O. (2017). Does a battery-electric truck make a difference? – Life cycle emissions, costs, and externality analysis of alternative fuel-powered Class 8 heavy-duty trucks in the United States. *Journal of Cleaner Production*, *141*, 110–121. https://doi.org/10.1016/j.jclepro.2016.09.046

Sripad, S., & Viswanathan, V. (2017). Performance Metrics Required of Next-Generation Batteries to Make a Practical Electric Semi Truck. *ACS Energy Letters*, *2*(7), 1669–1673. https://doi.org/10.1021/acsenergylett.7b00432

Sripad, S., & Viswanathan, V. (2019). Quantifying the Economic Case for Electric Semi-Trucks. *ACS Energy Letters*, *4*(1), 149–155. https://doi.org/10.1021/acsenergylett.8b02146

Taefi, T. T., Stütz, S., & Fink, A. (2017). Assessing the cost-optimal mileage of medium-duty electric vehicles with a numeric simulation approach. *Transportation Research Part D: Transport and Environment*, *56*, 271–285. https://doi.org/10.1016/j.trd.2017.08.015

Talebian, H., Herrera, O. E., Tran, M., & Mérida, W. (2018). Electrification of road freight transport: Policy implications in British Columbia. *Energy Policy*, *115*, 109–118. https://doi.org/10.1016/j.enpol.2018.01.004

Tanco, M., Cat, L., & Garat, S. (2019). A break-even analysis for battery electric trucks in Latin America. *Journal of Cleaner Production*, *228*, 1354–1367. https://doi.org/10.1016/j.jclepro.2019.04.168

Tesla. (2019). *Tesla Semi Truck*. Tesla Semi. https://www.tesla.com/semi

Teslarati. (2017). Close-up look at the Tesla Semi "Megacharger" charging port. In *Teslarati*. https://www.teslarati.com/tesla-semi-megacharger-charging-port-close-up-look/

The Tesla team. (2019). Introducing V3 Supercharging. In *Tesla*. https://www.tesla.com/blog/introducing-v3-supercharging

Union of Concerned Scientists. (2019). *Factsheet: Inequitable Exposure to Air Pollution from Vehicles in California*. https://www.ucsusa.org/resources/inequitable-exposure-air-pollution-vehicles-california-2019

US Department of Energy. (2010). *Class 8 Truck Tractor Weight by Component*. US Department of Energy. https://www.energy.gov/eere/vehicles/fact-620-april-26-2010-class-8-truck-tractor-weight-component

Zhou, T., Roorda, M. J., MacLean, H. L., & Luk, J. (2017). Life cycle GHG emissions and lifetime costs of medium-duty diesel and battery electric trucks in Toronto, Canada. *Transportation Research Part D: Transport and Environment*, *55*, 91–98. https://doi.org/10.1016/j.trd.2017.06.019