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Lawrence Berkeley National Laboratory

Long-haul battery electric trucks are technically feasible and economically compelling

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Abstract

Zero emission freight trucks are critical to meet global climate goals and reduce air pollution. Technological constraints and economic conditions have generally suggested that electrifying this sector is challenging; however, the emerging reality is different. We assess how recent dramatic improvements in battery technology make it technically feasible and potentially economically attractive to electrify heavy-duty trucking if charging infrastructure needs are met and cost-effective electricity pricing is available. We use the latest data on battery technology and detailed component-level cost and performance data for trucks to estimate the total cost of ownership of electric trucks. We estimate the TCO of an electric truck to be $1.27/mile, 20% less than that of a diesel truck, assuming trucks can access average industrial electricity prices of about $0.07/kWh which require reforms in electricity tariffs to make demand and transmission charges peak-coincident. We find that if environmental externalities, such as air pollution and greenhouse gas emissions are monetizable, the TCO of an electric truck could be as low as $0.95/mile, 40% lower than a diesel truck. We also show that electric trucks with a 250-mile range can have the same weight as diesel trucks with realistic improvements to battery packing fractions, and that weight parity for 500-mile-range trucks is achievable with commercially available lightweighting options and about 3.5% reduction in maximum payload capacity. We conclude that adequate fast charging infrastructure and electricity prices that reflect true system costs can unlock a major environmental and economic opportunity by enabling electrification of freight. If battery prices continue to fall and battery pack density continues to increase at even half the current rates, long-haul battery electric trucks will become dramatically more attractive.

Introduction

In the U.S., medium- and heavy-duty trucking, which is almost entirely diesel-based, accounts for 23% of direct greenhouse gas (GHG) emissions from transportation, and, by 2025, a third of NOx emissions from transportation[1,2]. Heavy-duty trucking's contribution to the environmental footprint of developing countries is even greater. For instance, in India, it accounts for 41% of CO_2 and 55% of NO_x emissions from transportation[3]. Disproportionately high levels of air pollution in low-income communities also give rise to equity concerns.[4] Decarbonizing freight trucking is therefore indispensable to managing air pollution and global climate change.

However, high battery cost and weight as well as the high cost of electricity generation have meant truck electrification is beyond immediate reach. But today the situation is different.

For one, battery costs have fallen drastically to levels unforeseen just a few years back. By 2018, lithium-ion battery costs had fallen more than 80%—to roughly $175/kWh—relative to their cost in 2010 (Figure 1). Battery prices are expected to continue decreasing due to intense competition, economies of scale, and improved processes to reduce production costs[5,6]. A cost of $100/kWh is expected by 2026 according to BloombergNEF[7], and by 2020 according to Tesla[8]. Second, the cost of electricity from clean renewables such as solar and wind has also fallen so steeply that it is cheaper than or in parity with the levelized cost of generation from new coal plants[9]. Perhaps recognizing that these trends will not go unnoticed by policy makers, several truck original equipment manufacturers (OEMs) are making substantial investments in electric trucks[10]. The time, therefore, seems ripe for a thorough reassessment of the techno-economic case for electric trucking, which is presented here.

Another factor supporting the substitution of electric trucks for diesel is that recent technology developments indicate that electric trucks, like electric cars, can be almost fully charged in 30 minutes, likely without causing significant battery degradation. Studies comparing the impact of fast charging (2C, 30-minute charging) and slow charging (<2C) on battery cells degradation demonstrate a significant decrease in cycle life with fast-charging compared to slow charging only at temperatures of <30C[13–15]. This result suggests the importance of controlling battery temperature during fast charging, which is already widespread in commercial EVs. We argue that 30-minute charging is likely to be feasible for larger truck battery packs because constraints on charge rate exist at the cell level. Since larger battery packs typically simply have a larger number of battery cells, there ought to be no additional constraint on fast charging for a truck battery pack relative to those that exists for a car. Commercially, Tesla claims 30-minute charging for the Tesla Semi truck[11] and has already deployed chargers capable of charging at rates greater than 2C for their cars[12]. A 30-minute (2C) fast charging session would fuel up to 4-6 hours of driving time.[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).[16] We do not estimate the TCO of hydrogen fuel cell trucks in this analysis, instead compare our TCO estimates for battery electric with hydrogen fuel cell trucks. Natural gas based trucks only marginally reduce greenhouse gas (GHG) emissions and hence are not considered in the analysis.

[1] Assumes 60 mph average driving speed; 240-400 mile operating range.

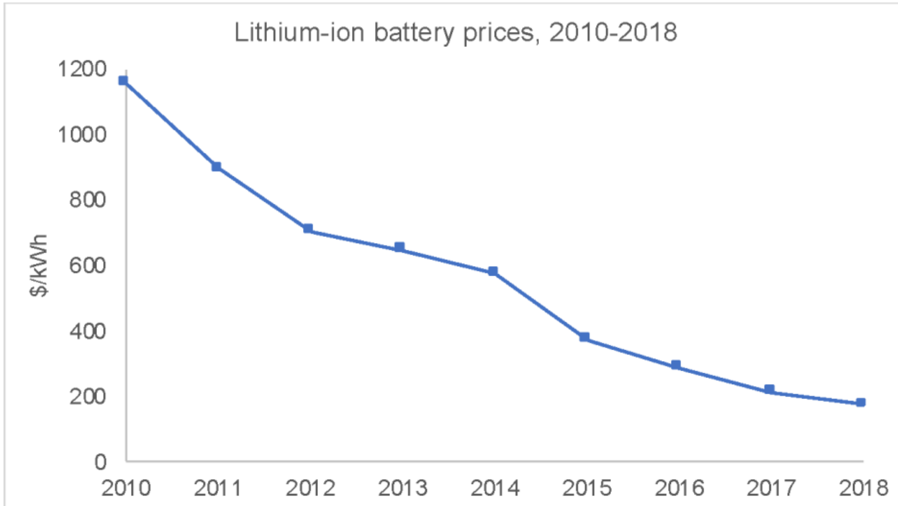

Figure 1. Reduction in lithium-ion battery price, 2010–2018. Prices are from a BloombergNEF survey[7].

Multiple studies have examined the potential for electrification[5,6,16–30] 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[5,18,21,24–29]. Of studies that actually evaluate the economic performance of electric trucks[5,6,16–20,27–29], 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 [5,17,24,27–29]. 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[23–25]. Only a few recent studies discuss battery-electric trucks as an option for long-haul transportation[6,17–20]. Table 1 summarizes key aspects of studies that address the economics of long-range trucks.

Existing techno-economic analyses of battery-electric trucks have several limitations. First, most studies only assess trucks with low ranges--studies of long-range trucking are limited. Studies that do assess long-range trucks discuss charging issues and lack of fast charging and high battery weight as the main barrier to deployment of long haul battery electric trucks. Among those that find electric truck total cost of ownership (TCO) less than that of diesel trucks, only one accounts for the cost of fast charging infrastructure as part of the TCO[6], while none consider the implication of demand charges which could be a significant portion of the overall cost for fast charging. Next, some studies do not capture the recent trend of low battery prices, and some do not transparently specify their input assumptions. None, except Sen et al. (2017)[20], account for the cost of environmental externalities such as air pollution and greenhouse gas emissions. Finally, most studies only account for the weight increase due to batteries and not weight savings from eliminating the diesel powertrain components from electric trucks. Our analysis fills these gaps.

Table 1. Studies Evaluating the Economics of Long-Range Battery-Electric Trucks

Study	Region	TCO ($/mi)*	~ΔTCO, compared to diesel truck	Battery price ($/kWh)	Range (mi)	Battery capacity (kWh)	Gross vehicle weight	Truck model year
Mareev et al. (2017)[6]	Germany	$1.19-1.30	(-8.30)%	$225-335	450	600	40t	2012
		$1.42-1.75	(-11)-33%		430-450	825	40t	2012
		$1.53-1.89	(-5)-18%		450	900	40t	2012
Tanco et al. (2019)[17]	Latin America	$3.54-4.67	60-74%	$250 (reduces to $100 by 2031)	310	961	40t	2010
Earl et al. (2018)[18]	Europe	$1.89	(-3.70)%	$170	500	~1000	40t	2021
		$1.79	(-9.20)%		300	~1000	40t	2018
Sripad and Viswanathan (2019)[19]	U.S.	$1.22	(-18)%	$90-120	500	~1000	>16.5t	2015
Sen et al. (2017)[20]	U.S.	$1.03-1.56	(-25)%	$600	330	270	>16.5t	N.A.
		$0.74-1.11	(-15)%		520	400		

Note:

(1) Daily ranges are reported where possible. If not, 90% utilization rate is used to convert annual mileage to daily mileage.
(2) Some of the data presented in this table were obtained from visual figures and charts, and may not be 100% accurate.
(3) The data reported for Sen et al. (2018) excludes environmental costs.
(4) To enable comparison across papers, euros were converted to USD (at a rate of 1€ : $1.12) and kilometers were converted to miles. For readability, battery prices and ranges were rounded to the nearest 5.

Our work draws on bottom-up cost modeling and 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 amortized fast-charging infrastructure costs—which are key to addressing range anxiety for long-range freight—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 lightweighting options. The results provide the most comprehensive techno-economic analysis of long-haul electric trucking to date.

Results

A: Total Cost of Ownership

We estimate the TCO of a Class 8 truck with a 400-mile operating range electric truck to be $1.27/mile--20% lower than the comparable diesel truck TCO of $1.60/mile[2] (Figure 2). This TCO is based on the battery pack size generated by the vehicle dynamic model for a 500-mile-range[3] truck, which is 1179 kWh.[4]

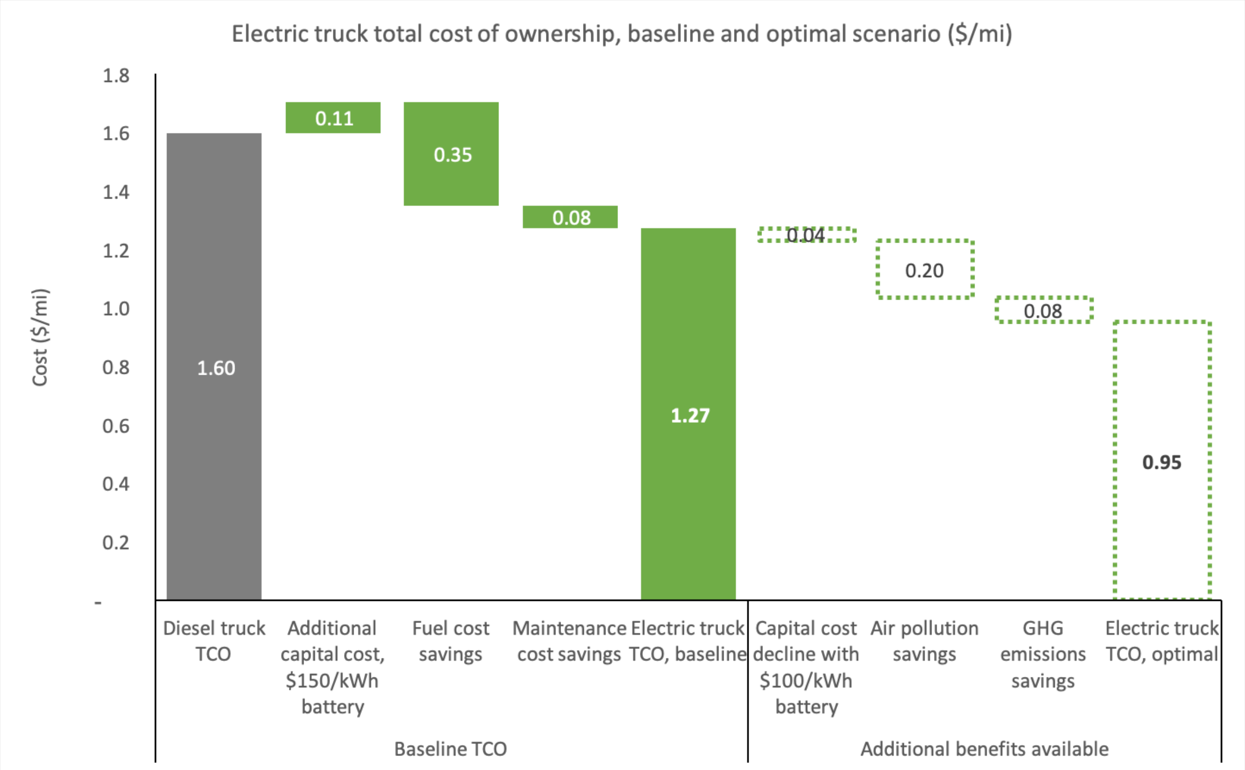

Figure 2. TCO per mile for diesel vs. electric truck with component-level breakdown of the cost differential. The baseline battery cost is $150/kWh. Additional benefits available represent further improvements in TCO if battery costs are $100/kWh and if air pollution/GHG emissions benefits can be monetized. These figures reflect trucks driving 400 miles/day, 260 days/year.

[2] For comparison, the American Transportation Research Institute estimates 2018 diesel truck TCO to be $1.69/mile.

[3] Range is the theoretical maximum distance a truck can go with 100% depth of discharge while the operating range is the actual distance a truck is expected to travel on a daily basis.

[4] We also compared results from the vehicle dynamic model to industry fuel efficiency claims. The results of the VDM gave an electric fuel efficiency of 2.4 kWh/mi for the base case, and 1.4 kWh/mi for the most efficient case (i.e., exploiting all possible lightweighting options). This range encompasses the claim of <2 kWh/mi given by Tesla for its semi.

The modeled total capital cost of the 500-mile electric truck is 124% higher than the diesel truck's capital cost ($279,800 vs. $125,000 at battery prices of $150/kWh) (Figure 3)—equivalent to an additional $0.11/mile in capital cost for electric trucks. At a battery cost of $100/kWh, the capital cost for the 500-mile truck drops to $220,854 or 77% higher than the diesel truck.

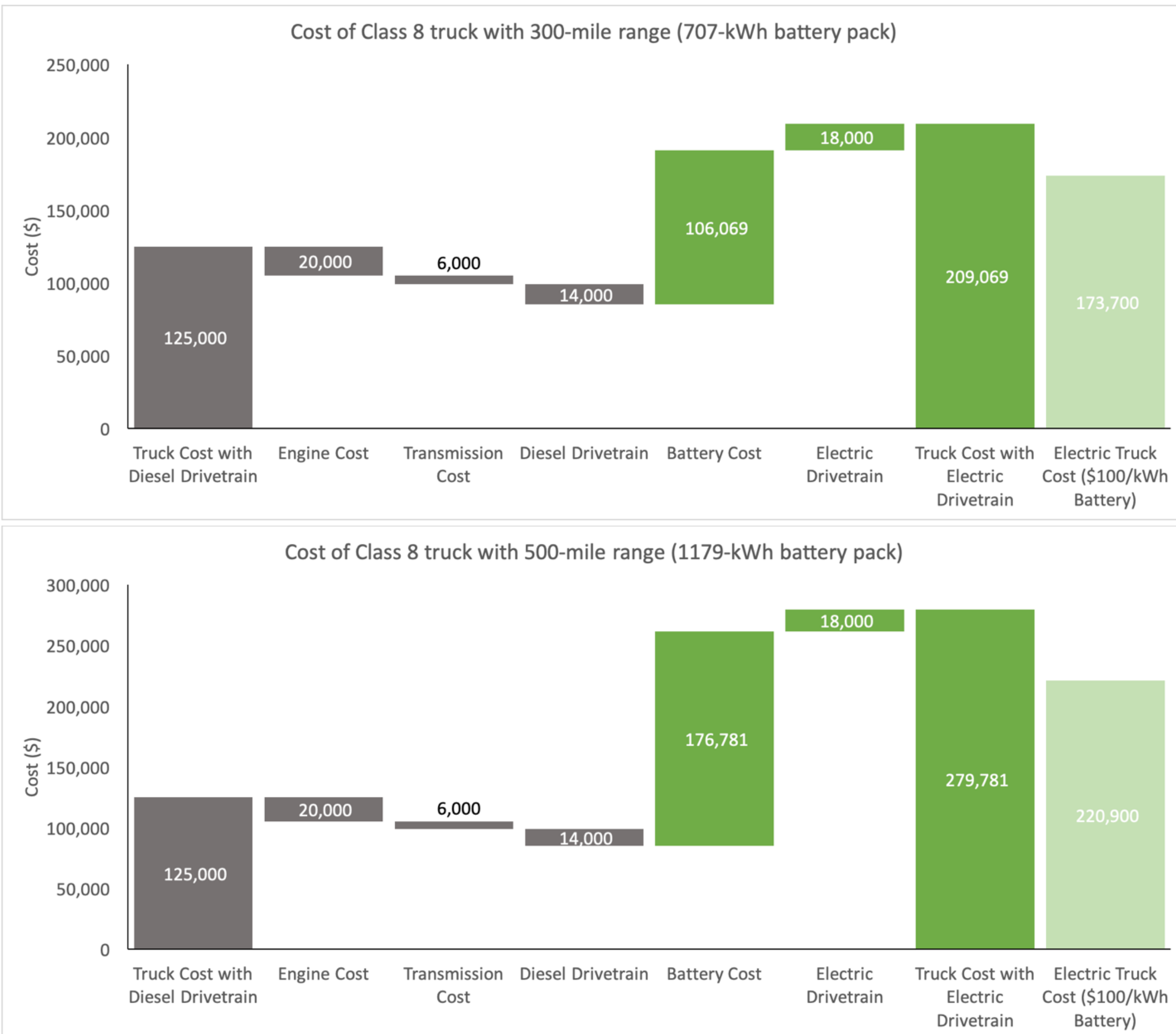

Figure 3. Capital cost of a Class 8 diesel truck compared with a Class 8 battery-electric truck with 300-mile range and 707-kWh battery (top) and 500-mile range and 1,179-kWh battery (bottom), with battery costs of $150/kWh (dark green) and $100/kWh (light green).

However, electric trucks save $0.08/mile on maintenance costs and $0.35/mile on fuel costs. Note that battery electric trucks have TCO parity with diesel even if diesel prices drop by 58% (to $1.39/gal).We do not estimate a difference in general operation costs between electric and diesel trucks (i.e., cost of the cab, driver wages, insurance, tire replacements, permits, and tolls). As such, the higher capital cost of electric trucks is more than offset by lower lifetime fuel and maintenance costs. Additional benefits of lower battery costs, air pollution savings, and GHG emissions savings could eventually mean an electric truck TCO as low as \$0.95/mile, 40% lower than the diesel TCO (Figure 2). This result assumes \$100/kWh battery costs (which are expected by 2020–2026), electricity sources powering trucks that are 90% free of GHG and air pollutant emissions ("90% clean"), and monetization of air pollution and GHG reductions.

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 4).

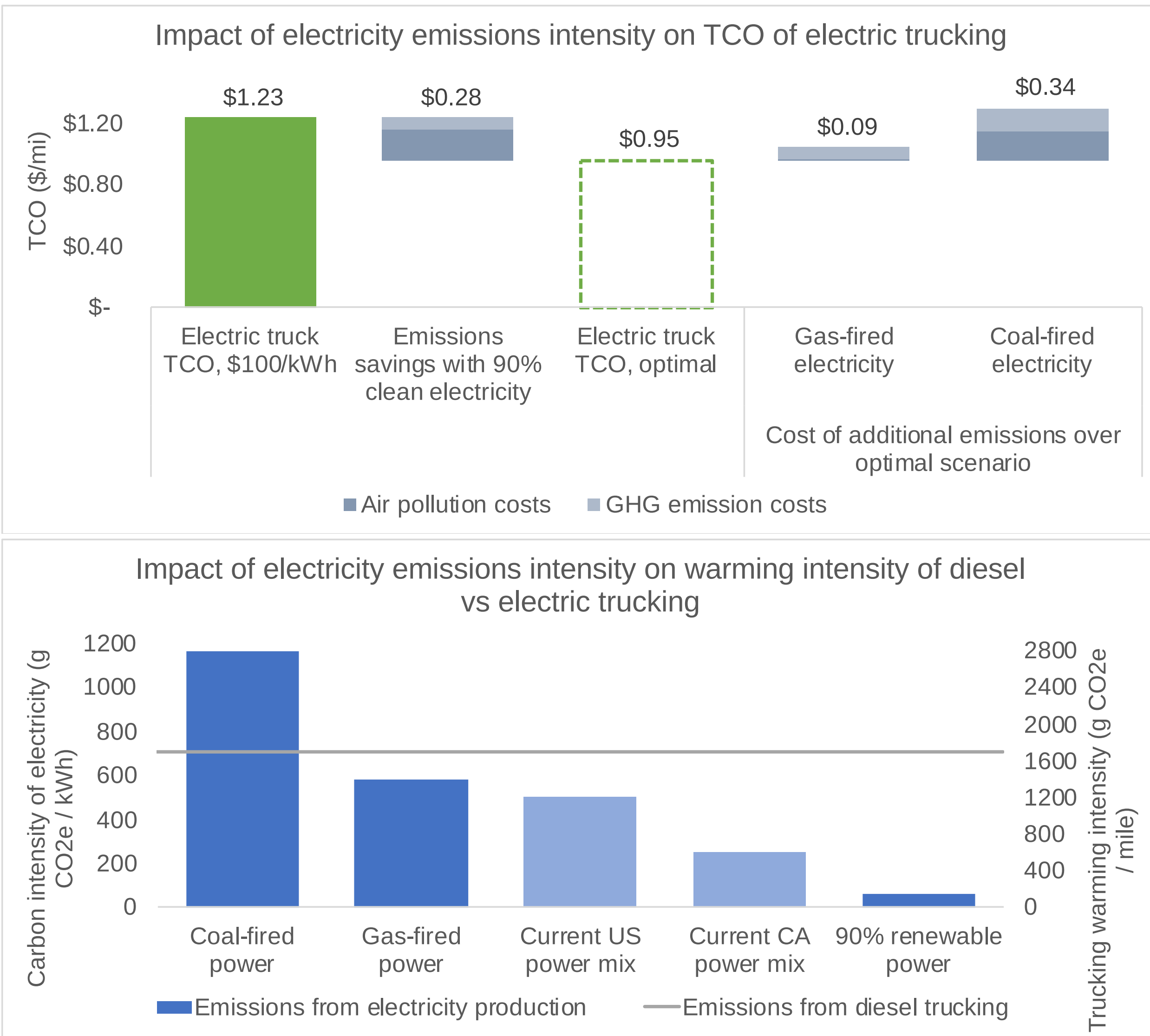

Figure 4. (Top) Impact of electricity emissions intensity (from 90% clean electricity, gas-fired electricity, and coal-fired electricity) on electric truck TCO, assuming air pollution and GHG emissions costs can be monetized. (Bottom) Comparison of warming intensity of trucking for diesel trucking and 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.

The mean baseline payback period for truck electrification is 3.4 years (Figure 5). Figure 5 also shows the sensitivity of payback period to key parameters. When annual mileage, battery price, or diesel price are varied individually, payback period ranges between 1.5 and 9.9 years. When charging cost is varied individually, it ranges between 2.9 and 20.4 years. The Discussion section addresses variation in charging cost further.

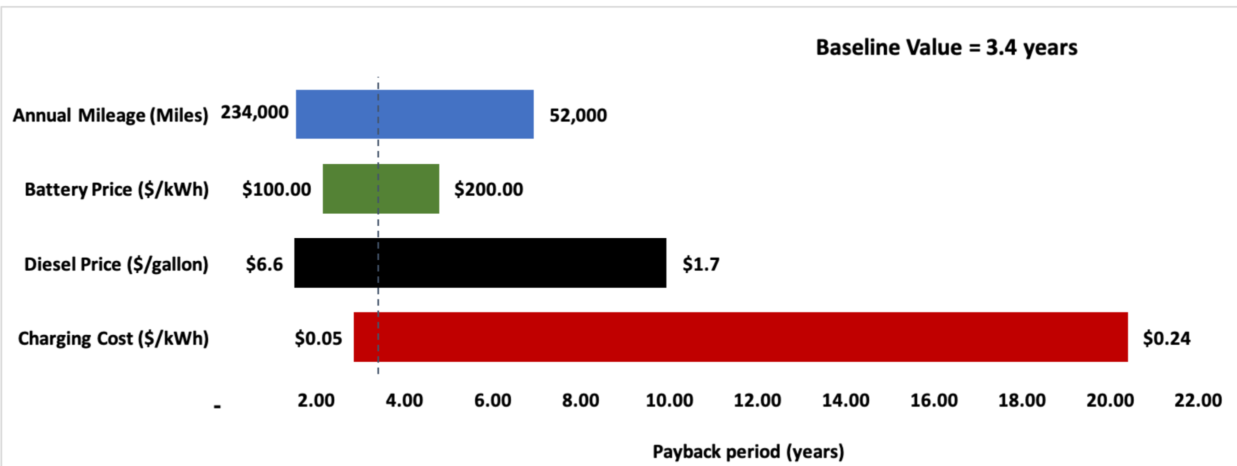

Figure 5. Sensitivity of the electrification payback period, not including any additional environmental benefits, to different parameters: each parameter is varied individually while the other parameters are held at their baseline values listed in Table 6. Baseline values are 104,000 miles/year driven, $150/kWh battery cost, $3.3/gal diesel, and $0.09/kWh charging cost. 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; and for annual mileage is based on driving 200-900 miles/day for 260 days/year.

The bottom-up TCO analysis uses battery-weight estimates generated from the vehicle dynamic model (see Methods section), which suggests a 1179-kWh battery powering a truck with an operating range of 400 miles at 2.4 kWh/mile efficiency. This estimate is more conservative relative to claims made by OEMs. The next section describes the bottom-up estimates using battery weight and other drivetrain component data obtained through market research and specifications provided by Volvo and Tesla for their Class 8 trucks.

B: Industry-Based Estimations: Battery Pack Weight

We break down truck weight for vehicles commercially available on the market based on Tesla's 300- and 500-mile range (707- and 1,179-kWh battery capacity) trucks with our conservative efficiency assumption of 2.4 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 300-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 3 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.

The figure shows that the weights 300-mile electric truck is 6% higher than a comparable diesel truck, leading to less than 2% reduction in total net payload capacity. We also find that 250 mile range truck has the same weight as a diesel truck. For 500-mile electric trucks, the weight is about 20% higher (8% reduction in payload capacity) but can be reduced by about 15% by applying commercially available light weighting options resulting into only a minor reduction payload capacity. Note that if trucks can achieve fuel efficiency similar to those claimed by Tesla, then the battery size, weight, and cost will be about 20% lower than assumed in this analysis.

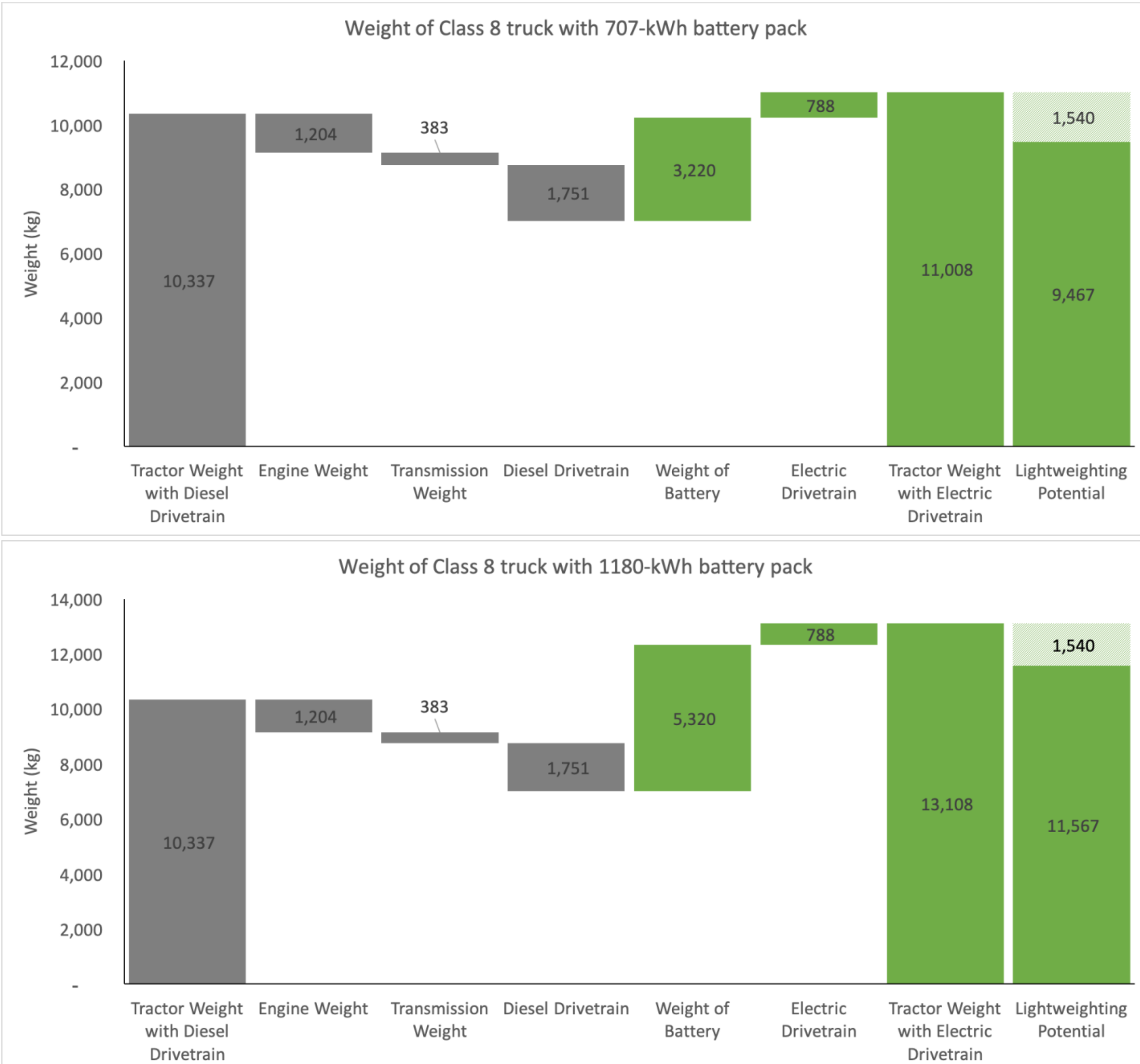

Figure 6. Weight of a Class 8 diesel truck compared with a Class 8 battery-electric truck with 300-mile range and 707-kWh battery (top) and 500-mile range and 1,180-kWh battery (bottom), cell specific energy of 250 Wh/kg and packing fraction of 0.88.

Discussion

The comparison of diesel and electric Class 8 long-haul trucks based both on a bottom-up estimation and market-data suggests the following. 1) The TCO for an electric long-haul truck is 20% lower, with potential to be 40% lower based on projected future battery cost and with monetization of reductions in environmental externalities. 2) Approximate weight parity with diesel trucks is achievable for both 300- and 500-mile-range electric trucks. We therefore conclude that replacing long-haul diesel trucks with electric trucks is both technically feasible and economically viable.

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).10 Although we do not estimate the TCO of hydrogen fuel cell trucks in this analysis, our TCO estimates for long haul electric trucks ($1.27/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). Although more work is needed to assess to compare TCO of battery electric with hydrogen fuel cell trucks, prima facie, it appears that battery electric trucks are substantially more economical. Given that we have shown that long haul battery electric trucks are technically feasible, they are likely to have clear advantages over hydrogen fuel cell based trucks.

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 7, 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 7). 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.

Our baseline charging cost of $0.09/kWh is based on the average national industrial tariff and amortized infrastructure costs with high (33%) station utilization[5]. We believe such a cost—and even lower costs—are achievable today by customers in ERCOT, which has regulations supporting dynamic electricity pricing. However, charging costs in areas with static pricing may be much higher, especially if stations face low (10%) utilization when electric vehicle demand is still relatively low—up to $0.24/kWh in Southern California Edison territory, for instance. The sensitivity analysis in Figure 5 reflects this skew: the range of charging costs reflects the low value achievable with policy support and the large range of higher costs that could ensue with

[5] Station utilization rate is the fraction of the time that all charging stalls are occupied—thus, a charging station with a 33% utilization rate would be charging the maximum number of trucks it can 33% of the time. For more detail, see Phadke et al., 2019.

static electricity pricing and low utilization. Supportive electricity policy is critical to benefiting both truck charging and the electricity grid.

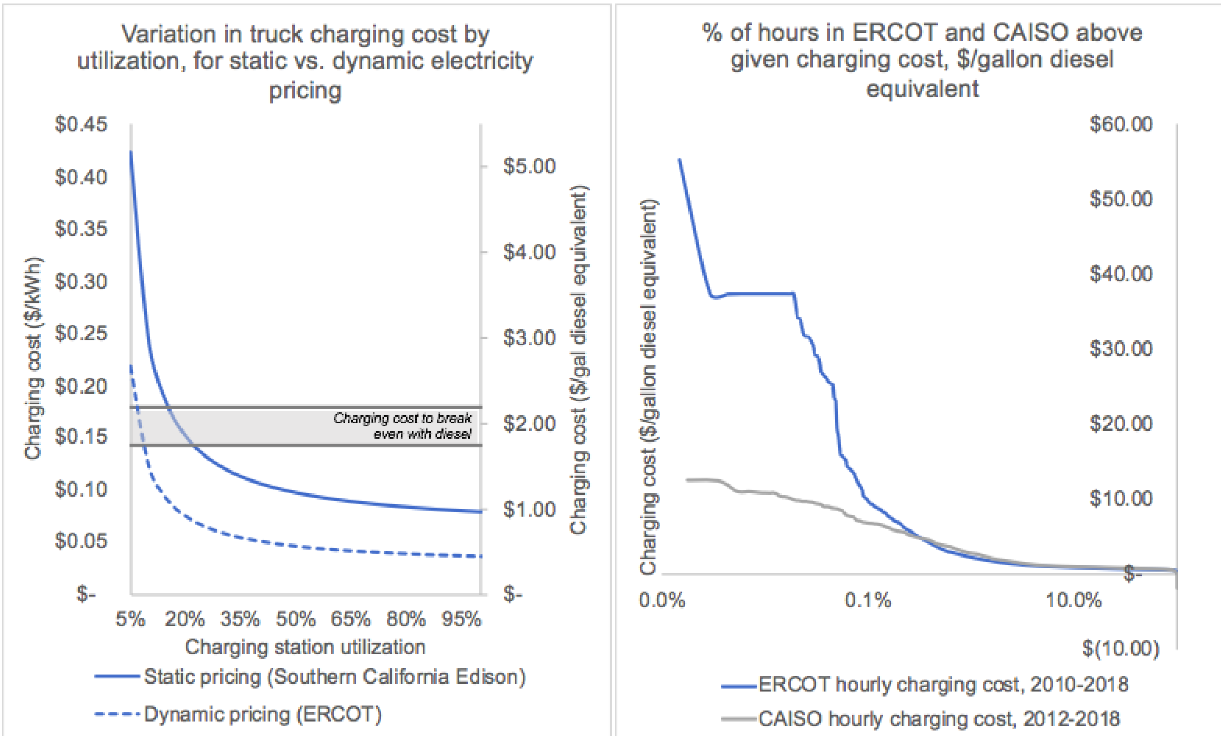

Figure 7. Variation in truck charging cost by utilization, for static vs. dynamic, system-reflective electricity pricing (left). Proportion of hours in ERCOT (2010–2018) and CAISO (2012–2018) above given charging cost (right). *Note: diesel breakeven range is based on $3.30/gal diesel, battery costs 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).*

We hold diesel and electricity prices fixed in this analysis. While one could expect modest real increases in diesel prices[31], 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. We do not assume falling diesel prices either, given the high degree of uncertainty under a future high-electric-vehicle scenario. 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, we have shown that benefits of truck electrification can be substantial, but that they vary with 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.

Lastly, this work highlights the role for public policy in stimulating and facilitating the transition from diesel to electric long-haul trucking. For one, there is a need for rationalization of electricity tariffs that send the right price signals for truck charging without imposing undue burden on the rest of the system. Second, in the absence of proper pricing of environmental externalities, achieving a lower TCO for electric trucks hinges on both realizing scale economies in the production of electric trucks and high utilization of charging infrastructure, which is necessary for low cost of charging. Third, due to substantially higher costs of manufacturing the truck, strong policies that ensure supply and demand of zero emission trucks are critical in the next decade. Attaining each of these mature end states requires surviving a long period of infancy of this industry marked by low demand for vehicles and charging and consequently, unprofitability. Faced with such prospects, private investments will voluntarily occur at a level that is lower than is optimal socially. While this is characteristic of any infant industry, given the importance of addressing pollution from trucking, there exists a case for intervention in the form of mandates on zero emissions trucks production complemented by a large public investment in building a robust charging infrastructure along a nations’ highways.

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 (Oak Ridge National Laboratory, 2017)[6]. In addition, Tesla has announced an electric variant of the Class 8 truck, and reference performance and cost numbers are available for comparison with our modeling. The diesel truck model for this estimation is the Volvo VNL 400[34] truck, and the electric truck model is the Tesla Semi[35].

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).

A: 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 defines the parameters and shows the values that we use for estimating battery pack size.

[6] Heavy-duty trucks are defined by Oak Ridge National Laboratory as Class 7 and 8 trucks; 96% of the fuel consumed by this group of trucks is consumed by Class 8 trucks{Updating}

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

Body[36]	Gross vehicle weight (including payload and battery pack)	W_T	36,000	kg
	Coefficient of drag	C_d	0.63	
	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	400	miles
	Average velocity[27]	v	19	m/s
	Root mean square velocity[27]	v_{rms}	22	m/s
	Average acceleration/deceleration[27]	a	0.112	m/s^2
	Road grade[27]	r	1%	
	Fraction of time driven on road grade r[27]	t_f	15%	
	Average road gradient (r/100)[27]	Z	0.0001	
Environmental Characteristics	Air density	ρ	1.20	kg/m^3
	Acceleration due to gravity	g	9.8	m/s^2

B: 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 incremental capital cost of the battery and electric power train.

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

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

$$\begin{aligned}\textit{Unit capital cost (electric truck)} &= \textit{unit capital cost (diesel truck)} + \\ &\quad \textit{unit battery cost} + \textit{unit incremental powertrain cost} \qquad (4)\end{aligned}$$

The incremental capital cost of an electric truck over a diesel truck is the additional cost of the battery and electric powertrain less the cost of a diesel powertrain. 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 6 summarizes the parameters used for estimating all the components of Equation 2.

To estimate electric truck fuel costs, we draw on a complementary bottom-up estimate of charging cost (from Phadke et al., 2019[37]) that includes electricity and fast-charging infrastructure costs. We also consider alternative tariff structures that impact the electricity price, particularly by varying demand charges. 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 results of Phadke et al., 2019. These results, which comprise the components of Equation 3, are summarized in Table 3.

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, gas, and 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 4.

Table 3. Input Parameters for TCO Model

Unit capital cost components		
Battery pack cost[8]	$150, sensitivity case of $100	$/kWh
Battery life[7]	2,000	cycles
Daily driving distance	400	miles
Life of truck[38]	15	years
Annual mileage[8]	104,000	miles/yr
Cost of truck without battery and allied drivetrain	$85,000	$
Real discount rate[9]	0.9%	
Unit fuel cost components		
Fuel efficiency of electric truck[10]	2.4	kWh/mile
Fuel efficiency of diesel truck[39]	5.9	miles/gallon
Amortized charging infrastructure cost[37]	$0.023	$/kWh
Electricity price[40]	$0.066	$/kWh
Diesel price[31]	$3.30	$/gallon
Unit maintenance cost components		
Diesel maintenance cost[41]	$12,000–$30,000	$/yr
Electric maintenance cost[11]	$6,500	$/yr
Battery replacement cost (year 7)[8]	$100	$/kWh
Unit operation cost components		
General operation costs	$0.76	$/mile

7 Based on expert input
8 Derived based on Sripad and Viswanathan (2017)
9 Derived based on Sripad and Viswanathan (2019)
10 Result of VDM; validated by industry numbers
11 Estimated based on Cannon (2016)

Table 4. Input Parameters for Additional Benefits of Electrification

Unit air pollution cost components		
Air pollution damages from heavy diesel on-road vehicles[42]	$58	$billion/year
Air pollution damages from coal-based electricity generation[42]	$118	$billion/year
Air pollution damages from gas-based electricity generation[42]	$5	$billion/year
Coal-fired generation[43]	1733	billion kWh/year
Gas-fired generation[43]	1014	billion kWh/year
Fraction of on-road pollution contributed by Class 8 trucks[12]	56%	
Miles driven by Class 8 trucks[45]	164	billion miles/year
Unit GHG emissions cost components		
Diesel consumed by Class 8 trucks[45]	28,884	million gallons/year
Social cost of carbon[46]	$52	$/tonne CO2, 2019 dollars
Emissions intensity from coal-fired electricity[47,48]	210	lb CO2/million btu
Emissions intensity from gas-fired electricity[49]	117	lb CO2/million btu
Emissions intensity of US power mix[50]	943	lb CO2/MWh
Emissions intensity of CA power mix[51]	474	lb CO2/MWh
Coal plant heat rate[52]	10,465	Btu/kWh
Gas plant heat rate[52]	7,707	Btu/kWh
Methane leakage rate[53]	2.3%	% of US gas production
Total electricity losses across T&D system[54] and in AC/DC power conversion[13]	14.5%	

C: 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 707- and a 1,180-kWh pack, which are estimated to be the size of the battery pack used to power the 300- 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 3 battery pack (Table 5).

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

[13] Industry interview

Table 5. Input Parameters for Battery Pack Weight Estimate

Battery pack size[55]	100	kWh
Tesla Model 3 battery pack weight	619	kg
Tesla Model 3 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[56]	26.1	kg
Energy stored per module[56]	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 6. 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
- 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 7 shows the resulting battery pack component weights for a 707- and 1,180-kWh pack.

Table 7. Component Weights for a Semi Truck Battery Pack

	707-kWh pack	1180-kWh pack	
Cells	2,828	4,714	kg
Cooling tubes	59	99	kg
Busbars	31	52	kg
Protective case	301	456	kg
Total weight	**3,220**	**5,320**	**kg**

A final element of our weight calculation was to estimate the impact of lightweighting on total truck weight. Truck lightweighting is a set of technologies that help improve fuel efficiency of trucks by 1) reducing the rolling resistance of the tractor, 2) increasing payload capacity due to reduced gross vehicle weight, and 3) allowing the adoption of other fuel efficiency technologies that may add weight to the tractor.

The main lightweighting 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 lightweighting is to combine different components to reduce the need for fasteners and other material interfaces. While lightweighting may not improve individual truck efficiency dramatically, it has driven a significant improvement in operational efficiency of fleets wherein larger payload capacity per truck has led to smaller fleet sizes for delivering the same quantity of payload according to the North American Council for Freight Efficiency[57].

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