Clean truck deployment consistent with President Biden’s climate commitment can save $1 trillion for consumers and avoid 70,000 premature deaths by 2050

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Abstract: Zero emission freight trucks are critical to improving public health, reducing global greenhouse gas emissions, and meeting President Biden’s commitment of the U.S. reaching net-zero emissions by 2050. In this study, we estimate the techno-economic feasibility of battery electric trucks in the US. We also assess the economic and environmental benefits of widespread truck electrification consistent with the President’s climate commitment and compare those with EPA’s 2022 proposed truck rules. We find that electric trucks have 10-20% lower per mile TCO than the equivalent diesel trucks across all categories, generating large savings for truck owners and operators. For example, a Class-8 electric truck with 375-mile maximum range would save over $300,000 over its lifetime. We find that the EPA proposed truck rules fall significantly short of meeting the President’s climate commitment, would result in ~57% of the on-road truck stock to be diesel powered in 2050. A stronger rule that required at least 20% of the new truck sales in 2027, at least 50% in 2030 and 100% of the new truck sales in 2035 are electric will save truck owners / operators about $1 trillion through 2050, while avoiding over 70,000 premature deaths. These numbers are on top of any benefits that EPA proposed rules would generate. If environmental benefits such as avoided air pollution and greenhouse gas emissions are monetized, the TCO of electric trucks would be 30% lower than diesel equivalents, resulting in even higher savings ($1.5 trillion higher than EPA proposed rules through 2050). We find that reduction of the truck payload due to battery weight is only 5%, reduced to zero through cost-effective lightweighting. This is an issue affecting only a small fraction of trucks that utilize the maximum payload limit. The average distance traveled between a required 30-minute truck rest stop is 150 miles and 190 miles for regional-haul and long-haul trucks respectively. Vehicle battery charging during rest stops is sufficient to add over 200 miles of range when fast charging at rates greater than 500 kilowatt. These facts show that electric trucks are ready to meet the cost and performance demands for a substantial share of regional and long-haul trucking today. Lastly, given the transition towards a low or zero-carbon US power grid, electric trucks offer a pathway for near elimination of air pollution and GHG emissions from trucks. The air quality benefits of a stronger EPA rule will be especially strong for environmental justice communities living near ports, warehousing and freight logistics centers. Strong policy support and well-coordinated investments in vehicle technologies and charging infrastructure will be critical to harness the true potential of battery electric trucks.

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This is a working paper intended to facilitate discussion on research in progress and has not been peer reviewed. Working papers published under this series may subsequently be published elsewhere.
1 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. Disproportionately high levels of air pollution in low-income communities also give rise to equity concerns. Decarbonizing freight trucking is therefore indispensable to managing air pollution and global climate change. Current U.S. policies are inadequate to meet President Biden’s commitment of economy-wide net-zero emissions by 2050, at the Glasgow Climate Summit, and reduce air pollution emissions.

Recent advances in electric vehicle (EV) battery cost and performance, range, and recharging—along with a proliferation of vehicle models and a rapidly expanding charging network—have readied EVs to overtake gasoline and diesel vehicles as the dominant on-road technology. Now that the plummeting cost of wind and solar power have enabled a rapid and cost-effective expansion of a clean electricity grid, a cost-effective pathway to decarbonize the transportation sector is within reach. For example, battery costs have fallen drastically to levels unforeseen just a few years back. By 2022, lithium-ion battery costs (LFP) have fallen more than 90%—to roughly $100/kWh—relative to their cost in 2010, and are expected to reduce by another 40% by 2030 due to intense competition, economies of scale, and improved processes to reduce production costs (Figure 1).

Also, 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 just the operational cost of most gas based power plants in the country. 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. For example, Volvo has committed to sell 50% zero-emission trucks globally by 2030 and Daimler Trucks is planning a full zero-emission product line-up by 2027. Several recent studies have also shown that zero-emission heavy-duty vehicles are ready for widespread commercial deployment. Fleet owners are also making strong commitments to electrify their vehicles. For example, Amazon has pledged to make 50% of shipments carbon-neutral by 2030, and FedEx recently announced plans to fully electrify last-mile deliveries by 2040. Policymakers in several major vehicles markets in the world such as California, U.K., France, Germany etc have enacted policies for ensuring 100% sale of zero emission electric vehicles, including trucks, by 2035-2040. The time, therefore, seems ripe for a thorough reassessment of the techno-economic case for electric trucking in the U.S., 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. 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 and has already deployed chargers capable of charging at rates greater than 2C for their cars. A 30-minute (2C) fast charging session would fuel up to 4-6 hours of driving time.

Several studies, including one from the California Air Resources Board (CARB), have shown that 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 (2024) and somewhat higher in the long term (2030). We do not estimate the TCO of hydrogen fuel cell trucks in this analysis, but compare our electric truck TCO with that of the hydrogen fuel cell truck. Natural gas based trucks only marginally reduce greenhouse gas (GHG) emissions and hence are not considered in the analysis.

Data from China, which has the most amount of heavy duty electric vehicles (primarily buses) shows that battery prices for buses commercial vehicles are somewhat lower than the average battery prices for EVs in China and Globally (BNEF, 2020). While it is true that the battery prices for buses and commercial vehicles are higher in other regions of the world likely because of low volumes, they are expected to be similar to those for passenger EV at scale as is the case in China and in line with analysis assumed in other studies (California Air Resources Board, 2019; Hall & Lutsey, 2019).

Another major development is related to battery weight, an especially important for long-haul trucks given maximum gross vehicle weight limits. In the US, federal laws limit maximum gross vehicle

\begin{figure}
\centering
\includegraphics[width=\textwidth]{image.png}
\caption{Historical and projected EV battery pack prices, including the price projection used in our analysis}
\end{figure}
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. Any substantial reduction in payload capacity on account of heavier batteries discourages EV adoption. Here, as with battery cost, energy density at the cell-level (and by extension at the pack level) has also been increasing steadily with time and is projected to continue to grow.(Field, 2020) That said, while the lower energy density of batteries immediately comes to the fore as a barrier, it is less widely known that the power train which includes the engine and cooling system, transmission and accessories accounts for about a quarter of the weight of the tractor, which battery packs will nearly eliminate. Additionally, data from the North American Council for Freight Efficiency shows that the average truck payload is less than 45,000 tonnes (~70% of the maximum payload capacity) (North American Council for Freight Efficiency & Rocky Mountain Institute, 2018).

2 Methods and Data

Our work in this paper draws extensively on our previous works on bottom-up cost modeling and market data to improve on the existing long-haul electric truck literature. See for example, Phadke et al (2021a) and Phadke et al (2021b). 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. We also use a stock turnover model for all truck categories in the US to estimate truck population each year and estimate the aggregate environmental and economic impacts of truck electrification. Using the high level highway traffic flow information and charging energy needs, we also estimate the charging infrastructure needed to support electric truck deployment. 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. Please refer to Phadke et al (2021a and 2021b) for additional information on our modeling and other methods.

2.1 Scenarios

Our analysis evaluates the following two scenarios:

EPA Proposed Case, a scenario that is very similar to the EPA proposed truck rule, in which MDV and HDV electrification proceeds slowly as envisaged in the proposed EPA rules. In this scenario, electric trucks constitute about 8% of new medium-duty vehicle (MDV) sales in 2027, 14% in 2030, 28% in 2035, and 57% in 2050. EVs constitute about 3% of new heavy-duty truck (HDT) sales in
2027, 5% in 2030, 12% in 2035, and 33% by 2050. The electric grid is assumed to decarbonize based on current state and federal power-sector policy, which closely mirrors the projections of the National Renewable Energy Laboratory’s (NREL’s) standard scenarios, in which the clean electricity (carbon-free) share reaches approximately 45% by 2035 (Cole 2020).

**President’s Climate Commitment Case**, which models new EV sales penetration consistent with President Biden’s climate commitment of reaching economy-wide net-zero emissions by 2050. EVs constitute 100% of new MDV and HDT sales by 2035. This scenario assumes new policies are adopted and market forces shift to overcome EV-related barriers quickly. EV sales scale logarithmically to 100% between 2022 and 2035. Also, we assume all truck classes reach 100% ZEV sales in the same year, making no distinction between tractors and non-tractors or pickup trucks. On the electricity grid side, all coal-fired power plants retire by 2030, no new natural gas plants are built, and the electric grid reaches a national 90% clean electricity share by 2035.

### 2.2 Key Assumptions

Our key assumptions are summarized in the following table. For additional details, please refer to Phadke et al (2021a and 2021b).

**Table 1: Summary of Key Assumptions**

<table>
<thead>
<tr>
<th>Data</th>
<th>Value</th>
<th>Source / Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel price (national average)</td>
<td>$3.3/gal [diesel, 2022] $3.3/gal [gasoline, 2022] Held fixed in the future</td>
<td>Average price before the 2022 fuel price surge</td>
</tr>
<tr>
<td>Electricity price</td>
<td>$0.115/kWh [2022] Held fixed in the future</td>
<td>EIA National Average Retail Electricity Price (2022)</td>
</tr>
<tr>
<td>Charging infrastructure cost (amortized, average)</td>
<td>$0.02/kWh [2020] Changes based on utilization</td>
<td>Phadke et al (2019)</td>
</tr>
<tr>
<td>Vehicle Miles Traveled (VMT)</td>
<td>~30,000–45,000 mi/year for MDVs ~90,000 mi/year for HDTs (375-mile range) ~130,000 mi/year for HDTs (500-mile range) Decreasing over vehicle lifetime</td>
<td>Phadke et al (2021a and 2021b)</td>
</tr>
<tr>
<td>Vehicle economic life</td>
<td>12–15 years</td>
<td>Phadke et al (2021a and 2021b)</td>
</tr>
<tr>
<td>Interest rate</td>
<td>7%</td>
<td>Phadke et al (2021a)</td>
</tr>
<tr>
<td>Maintenance costs</td>
<td>$0.21/mi for HDTs [ICE]</td>
<td>ICE value from ATRI (2019)</td>
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</tbody>
</table>
### 3 Results

#### 3.1 Electric Trucks Are Less Expensive to Own and Operate than Diesel Trucks, Resulting in Large Consumer Savings

Our results show that electric trucks already hold a TCO advantage today over diesel powered trucks, across all categories. Although electric trucks’ upfront price (i.e. purchase cost) is more than diesel trucks today, they will approach upfront price parity by mid-2030s — eliminating the final, and most important, barrier to adoption.

### Table: Electric Truck Costs

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Upfront price</strong></td>
<td>Class 2b-3 (MDV):</td>
<td>$61k (EV), $50k (ICE) [2020]</td>
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<td></td>
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<td>$45k (EV), $50k (ICE) [2030]</td>
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<td>Class 4–5 (MDV):</td>
<td>$71k (EV), $55k (ICE) [2020]</td>
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<td></td>
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<td>$55k (EV), $55k (ICE) [2030]</td>
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<td></td>
<td>Class 6–7 (MDV):</td>
<td>$109k (EV), $85k (ICE) [2020]</td>
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<td></td>
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<td>$93k (EV), $85k (ICE) [2030]</td>
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<td></td>
<td>Class 7–8 tractor (HDT):</td>
<td>$210k (EV), $125k (ICE) [2020]</td>
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<tr>
<td></td>
<td></td>
<td>$146k (EV), $125k (ICE) [2030]</td>
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<tr>
<td><strong>Tax</strong></td>
<td></td>
<td>8% of purchase price</td>
</tr>
<tr>
<td><strong>Fuel economy</strong></td>
<td>EVs:</td>
<td>0.5–1.8 mi/kWh for MDVs [2020]</td>
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<td></td>
<td></td>
<td>0.5–1.9 mi/kWh for MDVs [2030]</td>
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<td></td>
<td></td>
<td>0.47 mi/kWh for HDTs [2020]</td>
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<tr>
<td></td>
<td></td>
<td>0.49 mi/kWh for HDTs [2030]</td>
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<tr>
<td></td>
<td>ICE vehicles:</td>
<td>6.6–7.5 mpg for MDVs [2020]</td>
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<tr>
<td></td>
<td></td>
<td>6.8–8.1 mpg for MDVs [2030]</td>
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<td></td>
<td></td>
<td>6.1 mpg for HDTs [2020]</td>
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<td></td>
<td></td>
<td>6.3 mpg for HDTs [2030]</td>
</tr>
<tr>
<td><strong>Cost of carbon</strong></td>
<td></td>
<td>$49/MT [2020]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$66/MT [2030]</td>
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<tr>
<td><strong>Non-GHG environmental cost of</strong></td>
<td></td>
<td>$0.165–0.158/mi for MDVs/HDTs [2020–2030]</td>
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<tr>
<td>ICE vehicles**</td>
<td></td>
<td>National average mortality factors from Thakrar et al. (2020) using damage costs from Holland et al. (2020)</td>
</tr>
</tbody>
</table>

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Phadke et al (2021a and 2021b)

HDT details provided in the subsequent sections

Phadke et al (2021b)

Ricke et al. (2018); Caldeira et al (2016)
significant, consumer-cost barrier to EV ownership. Given this economic shift, accelerating EV deployment will yield large consumer-cost savings. Figure 2 compares the total cost of ownership (TCO) for EVs and ICE trucks between 2020 and 2035.

Figure 2a: Total Cost of Ownership (TCO) EV and Diesel Trucks. TCO for electric trucks is lower than diesel trucks for all truck categories already. A 375-mile class-8 truck electric would save more than $300,000 over its life compared to an equivalent diesel truck.

Class 8 truck electric truck with 375-mile range (300-mile range at 80% maximum DoD of battery) offers about 15% lower per mile TCO ($1.44/mi for electric compared to $1.69 for diesel, including the driver and operational costs, indicating a net saving of $0.25/mile)\(^1\). This implies a net savings of over $300,000 over the truck lifetime all for a less than 4% increase in the tractor weight given currently available light-weighting options. Given the continued decline in the battery prices, for Model Year 2030 or so, the electric truck TCO would be 21% lower than diesel truck (a saving of $0.35/mile, or >$400,000 over the life of the truck). Also note that, these TCOs and economic

\[^1\] For comparison, the American Transportation Research Institute estimates the 2018 diesel truck TCO to be $1.821/mile (ATRI, 2019).
benefits are estimated using a conservative highway diesel price of $3.3/gallon. At current highway diesel prices of over $5/gallon, Class-8 electric truck TCO would be more than 30-35% cheaper than that of an equivalent diesel truck.

If the environmental benefit of avoided local air pollution and CO2 emissions are also included, the TCO of electric trucks would be 30% lower than diesel trucks saving nearly $0.5/mile (Figure 2b).

![Bar chart showing TCO of Class-8 Truck](image)

**Figure 2b:** Impact of accounting for environmental benefits on class-8 electric truck TCO (375-miles). If the environmental benefits of electric trucks are monetized, their TCO becomes 30% lower than the Diesel trucks.
Figure 3 shows how we arrive at our estimate of the upfront cost of the electric truck, with the examples of two class-8 trucks (375 mile range and 500-mile range). 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 ($18000). 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.
3.2 Sensitivity Analysis

The mean baseline payback period for truck electrification is 3.3 years (Figure 4). Our sensitivity analysis suggests that electric trucks remain cost-effective even when different assumptions affect their TCO adversely relative to ICE vehicles. When annual mileage (50,000-130,000 miles/yr) and battery price ($80 - $250/kWh) are varied individually, payback period ranges between 2.2 and 7 years. When charging cost is varied individually ($0.075 – 0.24/kWh), payback period ranges between 1.8 and 10 years. When diesel price is changed to $6.6/gallon, the payback period of electric truck reduces to 1 year. The Discussion section addresses variation in charging cost further.

Baseline payback period = 3.3 years

Figure 4: 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 1. Baseline values are 90,000 miles/year driven, $135/kWh battery cost, $3.3/gal diesel, and $0.135/kWh charging cost (which includes both the electricity cost of $0.115/kWh and the levelized cost of charger of $0.02 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 2026 prices;

3.3 EPA Proposed Truck Rules Fall Significantly Short of Meeting President’s 2050 Climate Commitment

In the EPA Proposed Case, because of the slow stock turnover of trucks (average life of ~12-15 years or so), nearly 57% of the on-road truck stock would still be diesel powered by 2050. In contrast, in the President’s Climate Commitment consistent case, only about 7% of the truck stock in 2050 would be diesel powered, while ~93% would be electric (Figure 5). As a result, the EPA Proposed Case will fall significantly short of meeting the President’s Climate Commitment by 2050.
3.4 Electric trucks can generate a total consumer savings of more than $1 trillion

The magnitude of national consumer savings from widespread electric truck deployment becomes clear when comparing the President’s Climate Commitment scenario with the EPA Proposed Case. The President’s Climate Commitment scenario results in cumulative economic savings of approximately $1 trillion through 2050 compared to the EPA Proposed Case (figure 6). These savings represent roughly $100,000-300,000 per truck over its lifetime. Note that these savings do not include the monetary value of human health and environmental benefits due to accelerated electrification, which make the electric truck economics even more attractive.

Figure 5. On-road truck stock 2020-2050

Figure 6. Annual consumer savings in the President’s Climate Commitment case relative to the EPA Proposed Case (cumulative savings of $1 trillion through 2050)
3.5 Accelerating EV Adoption Saves 70,000 Lives, Avoids $500 billion in Health and Environmental Damages Through 2050

Gasoline- and diesel-powered vehicles harm human health and the environment via emissions of pollutants such as NO\textsubscript{x} and SO\textsubscript{2} as well as GHG emissions that contribute to climate change. Accelerating EV adoption reduces both sources of damage dramatically. Compared with the EPA Proposed Case, by 2050 the President’s Climate Commitment scenario reduces transportation sector emissions of NO\textsubscript{x} by 96% and SO\textsubscript{2} by 99%, which dramatically reduces PM\textsubscript{2.5} exposures and avoids 70,000 premature deaths (Figure 7). The health benefits would notably benefit low-income communities and communities of color, where vehicle pollution is worst. For example, African American, Latino, and low-income households in California are exposed to 43%, 39%, and 10% more PM\textsubscript{2.5} pollution, respectively, than white households (Reichmuth 2019). Broadly speaking, communities of color face higher risk from particulate pollution, and living or working near highways or heavy traffic is particularly risky (ALA 2020). Heavy-duty trucks contribute a disproportionate share of vehicle emissions. They constitute only 5% of U.S. on-road vehicles but are responsible for 36% of particulate emissions, suggesting that electrifying trucks can have an outsized influence on emissions and human exposure to pollutants (Kodjak 2015). When combined with the local air pollution reductions associated with a 90% clean electricity grid, the President’s Climate Commitment scenario avoids an additional 40,000 premature deaths through 2050.

![Figure 7. Cumulative premature deaths in the EPA Proposed Case and President’s Climate Commitment Case, 2020–2050. The President’s Climate Commitment scenario avoids 70,000 more premature deaths due to air pollution through 2050, compared with the EPA proposed case.](image-url)
The President’s Climate Commitment scenario slashes CO\(_2\) emissions from trucks (including any electricity used by trucks for charging) by 50% in 2035—putting this sector on a path to meet its share of the net-zero emissions and global 1.5°C goal—and by 90% in 2050, relative to 2020 levels (Figure 8). On the contrary, the EPA proposed rules would reduce the CO\(_2\) emissions form trucks only by 10% by 2035 and 33% by 2050, relative to the 2020 levels. In total, the pollutant and CO\(_2\) emissions reductions in the President’s Climate Commitment scenario equate to nearly $500 billion in health and environmental savings through 2050, compared with the EPA Proposed Case. **The net economic and environmental benefit of the President’s Climate Commitment case over the EPA proposed case is over $1.5 trillion through 2050.** Combined with a 90% clean electricity grid by 2035, the aggressive electrification in the President’s Climate Commitment scenario would accelerate U.S. climate change mitigation efforts.

![Figure 8](Figure 8. Total CO\(_2\) emissions from trucks in the President’s Climate Commitment Case and EPA Proposed Case through 2050.  

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

### 3.6 Most Electric Trucks Won’t Require Any Compromise on Payload due to Battery Pack Weight

One of the key criticisms of electric trucks is the high battery weight resulting in some loss of the truck payload. In this section, we describe 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. 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 10 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 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.
Further, since most trucks reach their volume limit before reaching their weight limit, accepting a

Figure 10. 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 20% (~ 2200 kg) heavier to diesel truck. However, with moderate lightweighting options which leading to less than 2% reduction in total net payload capacity. For 500-mile electric trucks, the weight is about 27% higher (10% 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.

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 [1-ton Vs 3-ton] compensates for the additional weight of the battery. Lightweighting [reduction up to 1.5 ton] 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 in line with recent claims by Tesla. Combined with the fact that distance traveled by trucks between mandatory 30-minute rest stops is 190 miles and 150 miles for a long haul and regional haul trucks respectively, we argue that charging during rest stops will give electric trucks sufficient range for most applications in the near future (Phadke et al. 2021).

### 3.7 Required Charging Infrastructure Can Be Built Cost-Effectively to Serve the Envisioned EV Fleet

To enable the widespread electric truck adoption in the President’s Clean Commitment scenario, U.S. electric vehicle charging infrastructure must provide drivers with at least as much convenience as provided by existing gasoline and diesel fueling stations. A 2019 poll suggests the largest roadblock to increased EV sales is the unavailability of or distance to charging stations (Toth/Morning Consult 2019). As fast charging and longer battery ranges become more ubiquitous, this dynamic may change. A 500-kW charger could fully charge a 375-mile range truck in 30 minutes, and faster charging speeds are possible. The speed of charging and commensurate added range are important for a number of vehicle classes. Fortunately, many MDV and HDT applications require frequent stops or short trips and can be covered with the range available in new electric MDVs and HDTs. For example, many delivery vans, busses, or regional haul trucks will drive less than 100 miles before stopping, well within the range of forthcoming electric MDV/HDT battery range (Figure 11).

![Figure 11](image-url). Electric trucks can add sufficient range without compromising payload weight across many MDV and HDT classes (recreated from Smith 2019).
Under the President’s Climate Commitment scenario, about 1.05 million chargepoints will be needed for trucks between 2020 and 2050 – about 900,000 for HDTs and 150,000 for MDVs (Table 4). This equates to a combined average of 35,000 chargepoints each year during 2020–2050, including an average of 19,000 chargepoints per year in the 2020s and 53,000 chargepoints per year in the 2030s.

Table 2. Total MDV and HDT chargepoint installations in the President’s Climate Commitment scenario

<table>
<thead>
<tr>
<th></th>
<th>Total Installations</th>
<th>Average Annual Installations</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDV</td>
<td>85,000</td>
<td>82,000</td>
</tr>
<tr>
<td>HDT</td>
<td>300,000</td>
<td>590,000</td>
</tr>
</tbody>
</table>

The combination of 125-, 350-, and 1,000-kW HDT chargepoints will be spread across about 2,700 truck stops. We model every existing U.S. highway truck stop and site charging stations such that every long-haul freight mile a truck will travel is covered with a chargepoint (Figure 12). Siting HDT charging along existing rights-of-way simplifies installation. However, new fast-charging stations will require upgraded power infrastructure, which could slow deployment.

Another challenge for electrifying trucks is the availability of fast charging at intervals appropriate to an electric HDT’s range. Currently, the average distance to a 30-minute truck stop is approximately 190 miles (Figure 11). However, if a national high-speed charging network is built along existing trucking routes, with 500-kW or better fast-chargers capable of fully charging a 375-mile-range truck in 30 minutes, these range concerns will be allayed for most long-haul trucking use cases.

A combination of 50-, 125-, and 300-kW medium-duty vehicle chargepoints will be spread across the country, primarily sited at MDV parking depots and warehouses so vehicles can charge overnight or when they park between shifts.

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2 Federal law requires a 30-minute break for long-haul truck drivers after 8 hours of continuous travel.
**Figure 12.** Optimal siting of HDT charging infrastructure, 2050. Most of the charging infrastructure could be sited at the existing truck stops. Every long-haul freight mile along major highways is electrified.

### 3.8 Charging Infrastructure Investment

In the President’s Climate Commitment case, annual heavy-duty truck and medium-duty vehicle public charging infrastructure investments through 2035 are $3.6 billion and $390 million, respectively (Phadke and Abhyankar et al, 2021). Beyond 2035, annual charging infrastructure investments for HDTs and MDVs increases to $6.3 billion and $520 million, respectively (ibid). The cumulative investment in public charging infrastructure makes up a small portion of EV TCO. As another point of comparison, U.S. utilities invest about $30 billion annually in new electricity distribution system upgrades (Figure 13) (EEI 2021). Still, the United States must commit to accelerating project-development timelines—already a major hurdle in charging infrastructure deployment—to reach President’s Climate Commitment levels on time.

The distribution grid will require upgrades to support new electric loads from vehicle charging. For aggressive truck electrification envisaged in the President’s Climate Commitment case, Phadke and Abhyankar et al (2021b) estimate a cumulative $116 billion of distribution system investments over the next 30 years, or approximately $3.7 billion per year. The cost of public charging, including the estimated distribution upgrade costs, will not increase rates, however, as the increased electricity sales helps increase throughput for utilities in order to cover the additional expenses. In fact, distribution rates ($/kWh) would actually fall by 2% through 2035 due to increased electricity sales.
4 Discussion

The comparison of diesel and electric trucks based both on a bottom-up estimation and market-data suggests the following.

1) The TCO for an electric truck is 10-20% lower for all truck categories, 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, as shown in our examples for 300- and 500-mile-range electric Class-8 trucks. We therefore conclude that replacing diesel trucks with electric trucks is both technically feasible and economically viable.

In this study, we do not estimate the TCO of hydrogen fuel cell trucks. Although more work is needed to compare TCO of battery electric with hydrogen fuel cell trucks, prima facie, several studies have shown that battery electric trucks are substantially more economical than hydrogen fuel cell based trucks such as CARB (2019) and ICCT (2020). 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) clean, low-cost generation has become abundant across many hours of the day in most regions of the country.
Dynamic electricity tariffs are necessary for the trucking industry to take full advantage of potentially low wholesale electricity prices during hours of high solar and wind generation. 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 $0.135/kWh is based on the average national retail electricity price ($0.115/kWh) and amortized infrastructure costs with high (33%) station utilization ($0.02/kWh).³ We believe such a cost—and even lower costs—are achievable today by customers in areas that support dynamic electricity pricing. However, charging costs in areas with static electricity 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 4 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 static electricity pricing and low utilization. Supportive electricity policy is critical to benefiting both truck charging and the electricity grid.

We hold diesel and electricity prices fixed in this analysis. In fact, we hold our diesel prices constant at $3.3/gallon, a very conservative assumption given the recent volatility in the fuel prices. In the long run, we assume no increase in electricity prices due to 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 that reduced petroleum demand will cause falling diesel 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. 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

³ 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.
charging infrastructure needs to support an electrified trucking network and developing strategies for charging under different fleet performance criteria and grid conditions.

Lastly, this work highlights the role for public policy to stimulate and facilitate the transition from diesel to electric long-haul trucking. It is important to rationalize electricity tariffs those 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 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 and funding for incentives, low cost financing and other measures to defray upfront ZEV vehicle purchase costs for small and medium sized trucking firms.
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