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

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9 September 2019

Full working paper and all citations are available at https://ies.lbl.gov/publications/working-paper-005-long-haul-battery
Background (1/3)

Truck electrification presents an opportunity to mitigate GHG and NOx emissions

- The imperative to decarbonize long-distance trucking is clear
  - Road freight accounted for ~8% of global GHG emissions in 2015
  - More than 90% of global emissions growth from road freight vehicles from 2000-2015 was in emerging economies; the majority of this growth is attributable to large trucks

- Electrification also has potential to mitigate NOx emissions, which are disproportionately emitted by heavy-duty trucking
  - In the US, heavy-duty trucking is expected to contribute 1/3 of NOx emissions from the transportation sector by 2025
  - In India, heavy-duty trucking emits 55% of NOx from the transportation sector
The electrification of trucking is becoming more feasible for many reasons, including advances in fast-charging technology

Electrification of this sector has been seen as challenging, but recent developments suggest that it is becoming more feasible:

- **Battery costs are falling**: At the end of 2017, lithium-ion battery prices had fallen to $175/kWh, an 80% drop from their cost in 2010; BNEF projects $100/kWh by 2026
- **Generation costs are falling**: The cost of electricity generation is dropping as wind and solar prices have become cheaper than coal

Recent technology developments also indicate that electric trucks can be fully charged in 30 minutes, likely without significant battery degradation:

- **Temperature control is important**: Studies comparing the impact of fast charging (2C, 30-minute) and slow charging (<2C) on battery degradation only show a significant decrease in cycle life with fast charging at temperatures of <30C; battery temperature control during fast charging is already widespread in commercial EVs
- **Constraints on charge rate exist at the cell level**, which implies no greater constraint on charging rate for a larger battery pack, given cells connected in parallel
- **Tesla claims 30-minute charging** for the Tesla Semi and has already deployed chargers capable of >2C charging for their cars
Multiple studies examine truck electrification, but they have several distinct limitations

- Many studies examine electrification as an option for truck decarbonization (see appendix for summary of studies specific to the economics of long-range battery-electric trucks)

- There are several limitations to existing studies
  - Several assume battery-electric trucks to be infeasible for replacing diesel trucks due to battery capacity requirements, range anxiety, and charging infrastructure uncertainties
  - Studies of long-range trucking are limited
  - Only one study considers the cost of fast-charging infrastructure in the TCO, and none consider the impact of demand charges
  - Some do not capture low battery price trends
  - Most do not account for the costs of environmental externalities such as air pollution and greenhouse gas emissions
  - Most account only for weight increases from the battery but not weight savings from eliminating diesel powertrain components
Research objectives

Our work seeks to evaluate an electric truck’s incremental TCO using bottom-up modeling, and incremental weight using market data

In this work, we investigate the potential for a Class 8 electric truck to seamlessly replace a Class 8 diesel truck based on economics and performance*

- We estimate the TCO of an electric truck compared to a diesel truck based on bottom-up truck technical specifications generated by a vehicle dynamic model
- We compare the weights of diesel versus electric long-haul trucks based on the Tesla Semi and the Volvo VNL 400

We seek to improve on the existing electric truck literature by providing the most comprehensive techno-economic analysis of long-haul electric trucking to date

- We use both bottom-up cost modeling and market data
- We account for recent trends towards lower-cost, higher-energy-density batteries
- We include additional cost reduction potential from monetizing air pollution and GHG reductions
- We include fast-charging infrastructure and demand charges in our charging costs

*See working paper for details on methodology
We estimate the TCO of an electric truck to be 20% lower than that of a comparable diesel truck

- We estimate the TCO of a Class 8 truck to be $1.27/mi
  - This is 20% less than the TCO of a comparable diesel truck: $1.60/mi
  - Based on battery size calculated for truck with a 400-mile operating range: 1,179 kWh

- Electric trucks incur an additional $0.11/mi in capital cost over diesel, but save $0.08/mi on maintenance and $0.35/mi on fuel

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.
Key findings: total cost of ownership (2/5)

Additional benefits from lower battery costs and air pollution/GHG savings could drive electric truck TCO up to 40% less than diesel

- Electric truck TCO could eventually be as low as $0.95/mi, 40% lower than diesel TCO
- Achieving this TCO assumes
  - $100/kWh battery costs (expected by 2020-26)
  - Electricity sources that are 90% free of GHG and air pollutant emissions
  - The ability to monetize environmental benefits

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.
Key findings: total cost of ownership (3/5)

Electricity emissions intensity determines environmental benefits of electrification, with coal-powered trucks emitting 64% more CO2 than diesel

- Savings on air pollution and GHG emissions from electrification are $0.28/mi when electricity is 90% clean, but are only $0.20/mi with gas-fired electricity and are ($0.05)/mi (costs rise) with coal-fired electricity.

- An electric truck powered by gas-fired electricity emits less GHGs per mile than a diesel truck, but only by 18%.

- If electricity comes from coal, per-mile GHG emissions are 64% higher than from diesel trucking.
The capital cost of an electric truck is estimated to be 77-124% higher than that of a diesel truck, depending on battery price

- The modeled capital cost of a Class 8 electric truck is **124% higher** than a diesel truck’s capital cost (~$280,000 vs. $125,000) at battery prices of $150/kWh
- At battery prices of $100/kWh, the incremental cost of an electric truck is ~$96,000, or **77% higher** than a diesel truck.
Key findings: total cost of ownership (5/5)

The mean baseline payback period for truck electrification is 3.4 years

- The mean baseline payback period for truck electrification is 3.4 years
- When four key variables are varied individually, charging cost has a greater impact on payback than any other

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.
Key findings: weight parity (1/2)

We find that a 250-mile-range electric truck achieves weight parity with diesel, and that 300-/500-mile-range trucks can achieve weight parity while sacrificing 3.5% or less of payload capacity

- We analyze truck weight for vehicles commercially available on the market—the Tesla Semi (300- and 500-mile range models)—as well as shorter-range trucks
  - Our assumption of 2.4 kWh/mi is more conservative than Tesla’s claim of <2 kWh/mi
- We assume improvement in battery packing fractions (from 0.65 in the 100-kWh Tesla Model 3 battery pack to 0.88 in the Semi battery packs) due to lower surface-area-to-volume ratio of higher-capacity battery packs
- We also consider commercially available lightweighting options
- We find that:
  - Electric trucks with a 250-mile range can have the same weight as diesel trucks with realistic improvements to battery packing fractions
  - Weight parity for 300-mile-range trucks is achievable with a <2% reduction in payload capacity
  - Weight parity for 500-mile-range trucks is achievable with lightweighting and a 3.5% reduction in payload capacity
We find that a 250-mile-range electric truck achieves weight parity with diesel, and that 300-/500-mile-range trucks can achieve weight parity while sacrificing 3.5% of less of payload capacity.

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.
Low charging costs are key to the economic case for truck electrification, and dynamic tariffs are important to unlocking low costs

- Low charging costs (both charging infrastructure costs and electricity costs) are critical to the economic case for truck electrification
- Periods with low-cost electricity are abundant (see righthand panel), but dynamic electricity tariffs are needed to take advantage of low prices (see lefthand panel)

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).
Dynamic electricity tariffs can incentivize trucks to charge at low-cost times that are beneficial to both trucks and the grid

- Dynamic electricity tariffs **align electricity pricing with the real-time state of the grid**
- This incentivizes trucks to charge at low-cost times when the grid is unconstrained
- Electricity cost ties in with **infrastructure cost**, since higher electricity prices may impede electrification, **driving up unit infrastructure cost**
- Supportive electricity policy is critical to benefiting both truck charging and the electricity grid

<table>
<thead>
<tr>
<th>Dynamic electricity tariffs</th>
<th>Static electricity tariffs</th>
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<tbody>
<tr>
<td>Track wholesale prices</td>
<td>Fixed price schedules</td>
</tr>
<tr>
<td>Demand charges coincident with system peak demand</td>
<td>Non-peak-coincident demand charges</td>
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</tbody>
</table>
Discussion: long-run emissions

Long-run marginal GHG emissions of electric trucking are expected to be less than that of diesel trucking

- The environmental impact of truck electrification can be substantial, but it depends on the emissions intensity of the electricity powering the trucks
  - Renewable power delivers substantial emissions savings with electrification
  - Gas-fired power delivers some emissions savings over diesel trucking
  - Coal-fired power drives substantially higher GHG emissions than diesel trucking

- The investment trend in the US away from coal power and towards increasing investment in renewable energy and gas-fired power
  - From 2008-18, 45% of new capacity was gas, 44% wind/solar, and 7% coal (with no new coal added since 2015)
  - ~50% of capacity under construction or permitted is gas, and ~44% is wind/solar
  - Wind/solar account for over 60% of capacity in earlier stages of construction

- 10 states, as well as Washington, D.C., and Puerto Rico, have 100% clean energy or renewable energy targets

- New trucking load will likely be met with increasing investment in renewables and gas, meaning that long-run marginal emissions from electric trucking are expected to be less than that of diesel trucking
Discussion: conclusions

Long-haul truck electrification has economic and technical potential, but policy support will be important to realize it

- There is reason for optimism that long-haul truck electrification can be achieved at a TCO lower than a diesel truck’s TCO without compromising on payload capacity

- Future technical research areas
  - Estimating charging infrastructure needs to support electrified trucking network
  - Developing strategies for charging under different fleet performance criteria or grid conditions

- Public policy will play a crucial role in stimulating and facilitating the transition from diesel to electric trucking
  - There is a need to set electricity tariffs that provide appropriate price signals for truck charging without imposing an undue burden on the rest of the system
  - Without proper pricing of environmental externalities, low TCO depends on achieving scale and a low cost of charging, which in turn depends on high utilization—reaching these mature end stages will require a long period of gestation with incomplete cost recovery → private investment will occur at a level that is less than socially optimal
### Summary of studies evaluating the economics of long-range battery-electric trucks

<table>
<thead>
<tr>
<th>Study</th>
<th>Region</th>
<th>TCO ($/mi)*</th>
<th>~ΔTCO, compared to diesel truck</th>
<th>Battery price ($/kWh)</th>
<th>Range (mi)</th>
<th>Battery capacity (kWh)</th>
<th>Gross vehicle weight</th>
<th>Truck model year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mareev et al. (2017)5</td>
<td>Germany</td>
<td>$1.19-1.30</td>
<td>(-8.30)%</td>
<td>$225-335</td>
<td>450</td>
<td>600</td>
<td>40t</td>
<td>2012</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.42-1.75</td>
<td>(-11)-33%</td>
<td></td>
<td>430-450</td>
<td>825</td>
<td>40t</td>
<td>2012</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.53-1.89</td>
<td>(-5)-18%</td>
<td></td>
<td>450</td>
<td>900</td>
<td>40t</td>
<td>2012</td>
</tr>
<tr>
<td>Tanco et al. (2019)11</td>
<td>Latin America</td>
<td>$3.54-4.67</td>
<td>60-74%</td>
<td>$250 ($100 by 2031)</td>
<td>310</td>
<td>961</td>
<td>40t</td>
<td>2010</td>
</tr>
<tr>
<td>Earl et al. (2018)12</td>
<td>Europe</td>
<td>$1.89</td>
<td>(-3.70)%</td>
<td>$170</td>
<td>500</td>
<td>~1000</td>
<td>40t</td>
<td>2021</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.79</td>
<td>(-9.20)%</td>
<td></td>
<td>300</td>
<td>~1000</td>
<td>40t</td>
<td>2018</td>
</tr>
<tr>
<td>Sripad and Viswanathan (2019)13</td>
<td>U.S.</td>
<td>$1.22</td>
<td>(-18)%</td>
<td>$90-120</td>
<td>500</td>
<td>~1000</td>
<td>&gt;16.5t</td>
<td>2015</td>
</tr>
<tr>
<td>Sen et al. (2017)14</td>
<td>U.S.</td>
<td>$1.03-1.56</td>
<td>(-25)%</td>
<td>$600</td>
<td>330</td>
<td>270</td>
<td>&gt;16.5t</td>
<td>N.A.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$0.74-1.11</td>
<td>(-15)%</td>
<td></td>
<td>520</td>
<td>400</td>
<td></td>
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</tr>
</tbody>
</table>

(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.