Supporting Information: Quantifying the Economic Case for Electric Semi-Trucks

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Methods

Vehicle Dynamics: The power demands of the electric semi-truck are estimated using a parametric relationship between the vehicle design parameters, the road conditions and the drive cycle in consideration, as shown by:

$$\mathrm{P(t)} = \left(\frac{1}{2}\rho.\mathrm{C_d.A.v(t)^3} + \mathrm{C_{rr}.W_T.g.v(t)} + \mathrm{t_f.W_T.g.v(t).Z} + \mathrm{W_T.v(t)}.\frac{d\mathrm{v}}{d\mathrm{t}}\right)\frac{1}{\eta_{\mathrm{bw}}} \quad ,$$

$$\mathrm{P_{reg}(t)} = \left(\mathrm{W_T.v(t)}.\frac{d\mathrm{v}}{d\mathrm{t}}\right)\eta_{\mathrm{bw}}.\eta_{\mathrm{brk}} \quad ,$$

The drive cycle provides information on the instantaneous speed, (v(t)), and the various drive cycles used in this study are shown in Figure (S2). Vehicle design parameters like the frontal area, (A), coefficient of rolling resistance, (C_{rr}), are obtained from current datasets of the fleet of Class 8 trucks in the U.S.[1,2] The road gradient, (Z), and the fraction of the trip for which positive road gradients exist, (t_f), are fixed based on the case in consideration. The total weight of the truck, (W_T), is fixed at 80,000 lbs (∼36,000 kg) which is the gross-weight limit for Class 8 vehicles. The other variables include the battery-to-wheels efficiency, (η_{bw}), and the efficiency of the brakes, (η_{bw}). The regenerative power, ($P_{reg}(t)$), represents segments of deceleration. Charge rates at the regenerative segments is limited to 2C. The power load profile obtained form the above-mentioned relationships for a given case is then applied on the battery pack model to study the pack performance.

Battery Model: The battery pack is modeled within AutoLion-ST[3] which uses a thermally coupled electrochemical battery model for each cell. The mathematical relationships for the Pseudo two-dimensional battery model used within the framework can be found elsewhere.[4–6] The cells are assembled into the battery pack but no cell-to-cell variation is considered. The degradation model which accounts for the loss of Li-ions over cycling due to various parasitic processes is implemented as a sub-model within the battery pack model.[7] The rate constants of the degradation reactions/ processes are fit to a specific cell chemistry based on NMC-622 ($LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$) cathode and Graphite anode. Additional details on the degradation model can be found in the following sections.

Cost Model: Total operational costs including the fuel costs are calculated over the total lifetime distance traveled for each discrete value of the variables within the bounds from the baseline scenario. All the operational costs are expressed per unit distance. Using the values and bounds of the annual mileage, the annual cash flow distributions for each case are obtained. The present value factors are calculated using a fixed discount rate. Applying the present value factors on the annual cash flows and other investments, we obtain the levelized annual costs. Finally, the operational cost per unit distance (US$ per mile) distribution is obtained based on the same annual mileage values used to annualize cash flows for the respective cases.

The payback period, which is the time span over which the fuel savings from the electric semi-truck are able to recover the initial price differential, is studied using an approach similar to the cost per mile calculations. The sensitivity analysis for the payback is performed by fixing the variable in consideration while the rest of the variables remain at baseline scenario values.

Price of Electricity and Diesel:

One of the major advantages of electric powertrains is the higher efficiency. If we examine the cost of energy contained in the fuel itself, based on the energy density of diesel which translates to about 37.7 kWh/ga. Comparing the price of electricity and diesel using a common scale, we arrive at the comparison shown in Figure (S1).

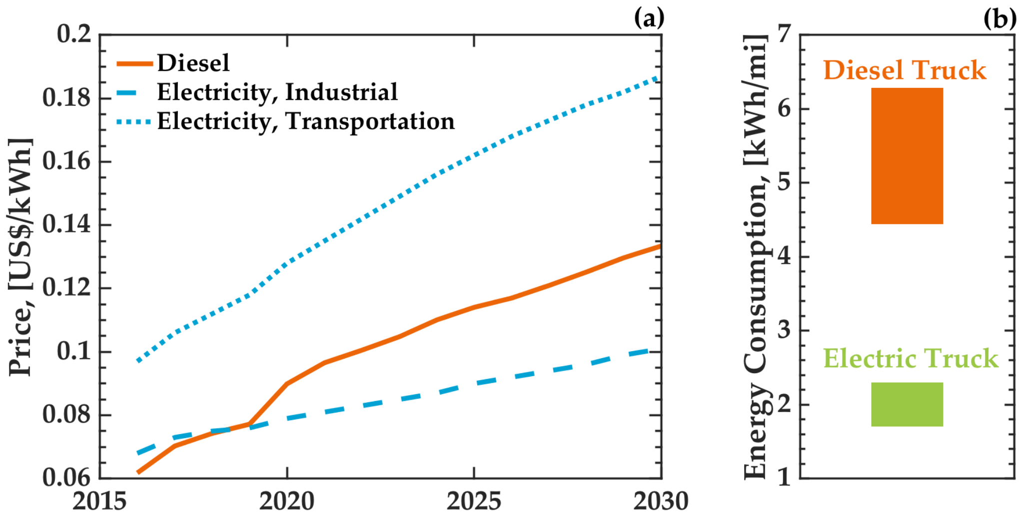

Figure S1: A comparison of the nominal price of fuel per unit of energy of diesel and electricity (transportation and industrial) with known projections[8] is shown in Part (a). While the price per unit energy is very similar, the efficiency of the electric powertrain is several times higher than one powered by diesel. As shown in Part (b), for the baseline scenario consideration, if the price per unit energy of electricity and diesel and equal, it is about 2.5-4 times more expensive to power a diesel truck than a well-designed electric truck.

Realistic Use Cases and Drive Cycles:

The drive cycles used to simulate the operation of semi-trucks as seen in Figure 1 are shown below in Figure (S2). The drive cycles are based on data from NREL DriveCAT[9] and modified for the purpose of this study.

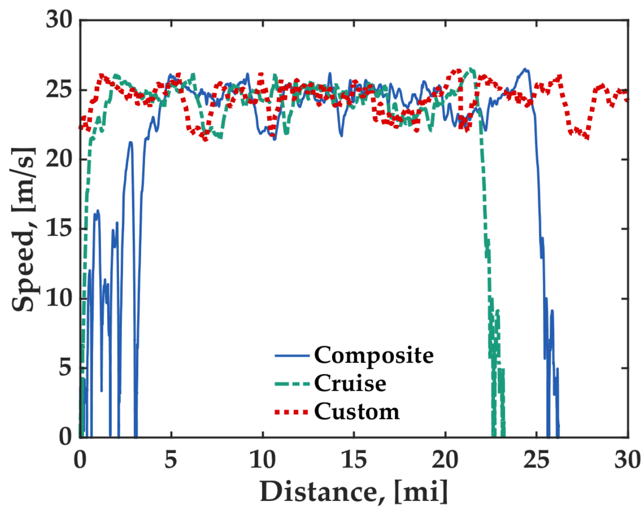

Figure S2: The Composite, Cruise and Custom drive cycles used to study the performance of the electric semi-truck is shown over a small representative distance. The drive cycles are repeated over the total trip distance. The Composite and the Cruise drive cycles are segments of the CARB-HHDDT from NREL DriveCAT[9] and the Custom drive cycle is based on the Cruise drive cycle without the acceleration from stop and deceleration to stop segments. The Custom drive cycle is representative of long-haul duty cycles where speed remains close to a mean value for most of the trip.

Payload Capacity of Electric Semi-Trucks

The total weight of Class 8 Semi-trucks is about 32,493±892 lbs,[10] the diesel powertrain is about 24% of the total weight of the tractor cab[2,11] including the transmission and accessories. The empty vehicle weight excluding the diesel engine and the fuel tank is estimated to be about ∼26,000 lbs with the trailer. The 1,000 kWh battery pack is about 5,000—6,600 kg or 11,000—14,600 lbs at 200—150 Wh/kg at the pack-level where the cells themselves have a much higher specific energy.[12] The resulting maximum payload capacity is between 39,400—43,000 lbs (Considering 95% bounds). The average payload carried by Class 8 trucks is about 32,000—39,000 lbs depending on the hauling distance,[2,13] however, the data for the on-road weight of Class 8 semi-trucks[2,11] shows that 93% of the trucks are under a gross on-road weight of 72,800 lbs which translates to about ∼39,800 lbs of payload assuming a truck empty weight of about 33,000 lbs, which translates to the electric truck being capable of meeting the demands of 93% of the payload demands.

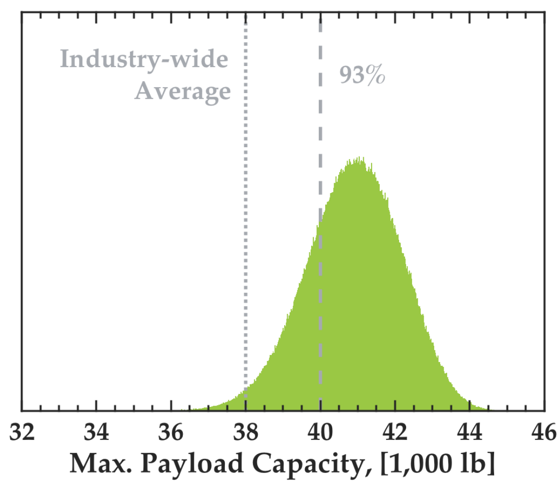

Figure S3: The maximum payload capacity distribution of the electric semi-truck with a 1,000 kWh battery pack considered for this study with a drag coefficient of 0.36 and a battery pack specific energy of 200—150 Wh/kg. The industry-wide average payload demand and the 93% bound of the payload demand are overlaid on the distribution. We can observe that the mean payload capacity is over the 93% bound of the payload demand.

Battery Degradation Modeling and Simulation:

The degradation processes are modeled within the battery pack model[4–7] degradation sub-model[7] shown below:

$$j_{SEI} = -k_{o,SEI}.\ c^{s}_{solvent}.\ \exp\Big[-\frac{\alpha_{c,SEI}.F}{RT}.\big(\phi_s - \phi_e - I.R_{film} - U_{SEI}\big)\Big]$$

$$j_{PL} = -i_{o,PL}.\ \exp\Big[-\frac{\alpha_{c,PL}.F}{RT}.\big(\phi_s - \phi_e - I.R_{film}\big)\Big]$$

$$\frac{d\epsilon_{AM}}{dt} = -k_{AMI}.I_{total}$$

where the side currents for each of the degradation processes for Solid-Electrolyte Interphase (SEI), (j_{SEI}), for the Lithium plating, (j_{PL}), and the last rate equation captures the Active Material Isolation along with the total current, (I). The other constants from the degradation sub-model are the rate constants ($k_{o,SEI} = 1 \times 10^{-12}$ m/s)[7], ($k_{AMI} = 2 \times 10^{-14}$m/s) and the exchange current density, ($i_{o,PL} = 0.001 A/m^2$)[7]. The (α's) are the cathodic transfer coefficients. ($c^{s}_{solvent}$), is the concentration of the solvent. The (ϕ's) are the potentials of the electrode and liquid phases. (R_{film}) is the resistance of the SEI layer.

Power Profiles:

The day-long load profiles generated using the vehicle dynamics model in conjunction with the drive cycles are shown in Figure S4. Cases A-C run for a distance of 270 miles while Cases D-F run for 400 miles. Case A and D are for 3 truck platoons with the Composite drive cycle, 500 kW charging in a flat road. Case B and E are single trucks under the Cruise drive cycle at a charging rate of 1.5 MW at flat road conditions as well. Case C and F are single trucks with the Custom duty-cycle at a 1% road grade and 1.5 MW fast charging.

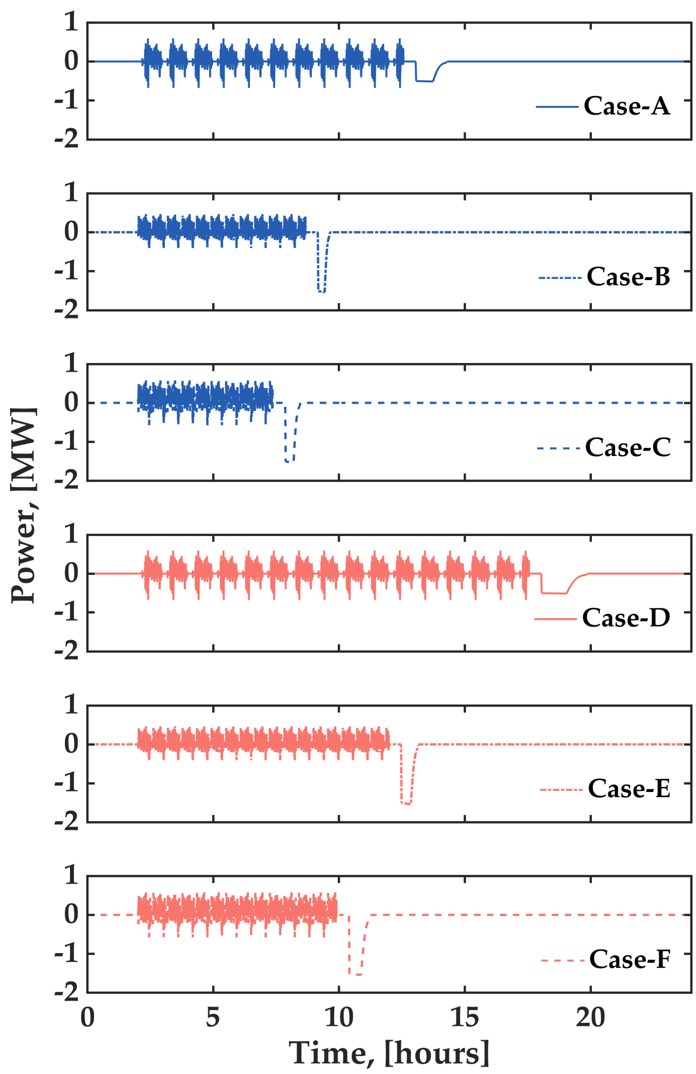

Figure S4: The various power profiles corresponding to each of the cases used for estimating the cycle life of the battery pack as discussed in Figure 1(b). Each power profile spans 24 hours and is repeated to simulate the performance of the battery pack over its lifetime.

Payback Period Distributions:

The distributions for the payback periods corresponding to the sensitivity bounds shown in Figure 3 are compiled below with the mean values and the standard deviations for each case.

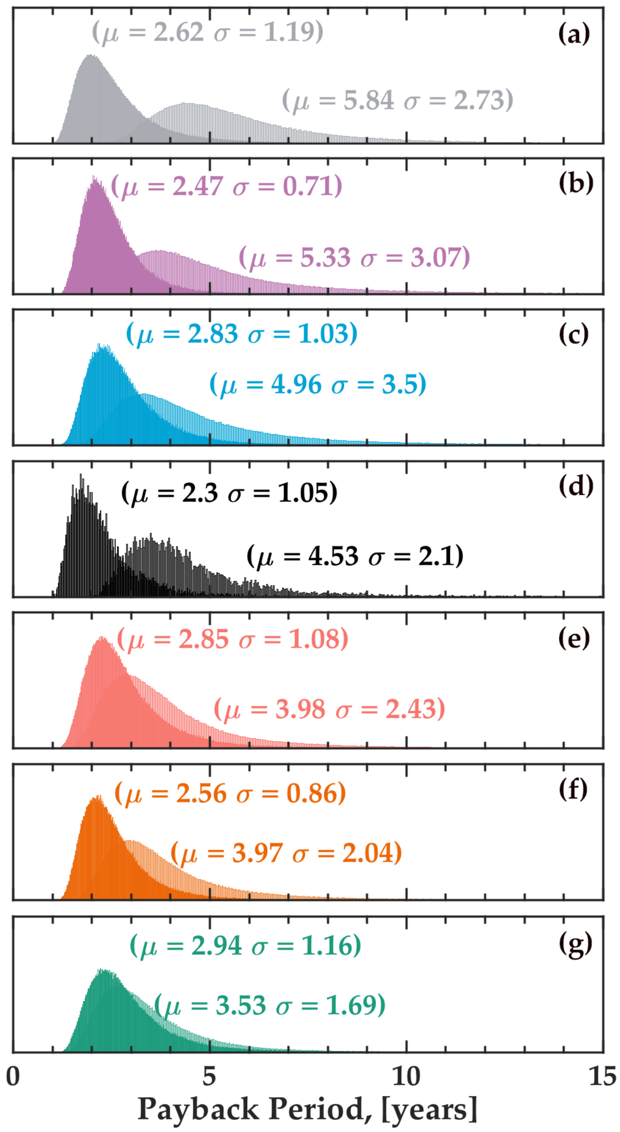

Figure S5: The distributions for the payback period corresponding to the bounds of the sensitivity analysis shown in Figure 3. (a) Initial Price Differential, [$1,000] (b) Diesel Price, [US$/ga] (c) Electricity Price, [US$/kWh] (d) Annual Mileage, [1,000 mi] (e) D-Truck Additional Repairs [US$/mi] (f) D-Truck Efficiency, [mpg] (g) E-Truck Efficiency, [kWh/mi]

Vehicle Design Considerations:

The price of fuel (electricity and diesel) coupled with the efficiency of electric powertrains would generally result in lower operational costs for electric trucks. However, an aerodynamically inefficient truck electric truck design would result in a higher energy consumption and require a larger battery pack for a fixed range.[12] As shown in Figure (S6), for a 500 mile rated range semi-truck, the required battery pack would be about 1,300kWh resulting in a much higher initial price differential resulting in a mean payback period of 5.11±2.79 years. Also, it is worth noting that at a drag coefficient of 0.63, the battery pack would be extremely heavy and resulting in reduced payload capacity unless very high specific energy battery packs. The effect of reduced payload capacity is not accounted for in Figure (S6), albeit, it highlights the importance of vehicle design for the feasibility of electric semi-trucks.

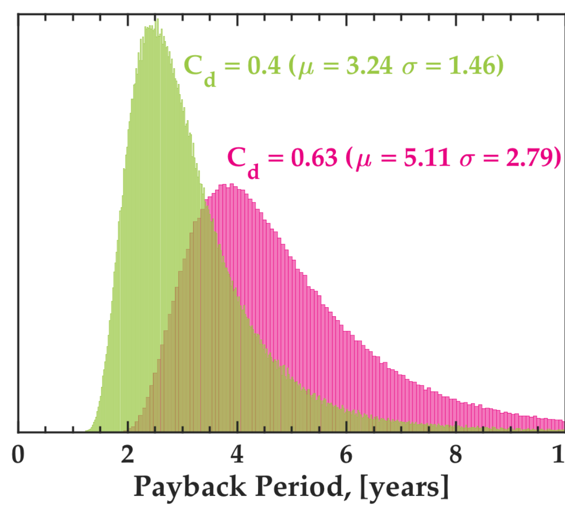

Figure S6: The exterior design and the effective drag coefficient of the electric semi-truck plays a crucial role in the economic case, where a lower drag coefficient which results in a lower energy consumption and effectively a smaller battery pack which in-turn decreases the initial price differential. We identify a drag coefficient, C_d, of 0.63 to represent the threshold beyond which there is a very high probability of the payback period being higher than the lifetime of the trucks.

Price of Electricity and the Charging Infrastructure:

One of the key drivers for the economic case of electric semi-trucks is the low operating costs, however, the final operating costs, specifically the 'fuel' costs hinge the price of electricity. For large battery packs—such as the ones proposed to be used in semi-trucks with driving ranges of about 500 miles—the charging power required is over 500kW to ensure charging times shorter than 4 hours for a full charge. Very low power would result in increased charging time resulting in the need to account for the value-of-travel-time-savings (VTTS) within the operational costs.[14,15] On the other hand, a high power demand for charging would lead to 'demand charges' and hence effectively a higher price of electricity.[14] As the price of electricity increases, the operational costs for electric trucks increase and once the price of electricity is close to US$0.25/kWh, as shown in Figure (S7), there are no scenarios where the operational costs for the electric trucks are 'certainly' lower than that of diesel trucks. Further, if the price of electricity were about US$0.85/kWh, there would be no scenarios where the operational costs for the electric truck are lower than that of the diesel truck. This leads to a situation where no favorable scenarios for a payback period with electric trucks exist, and such a price of electricity would represent a threshold for the commercial feasibility of electric trucks. It should also be noted that the values for the price of electricity quoted here are the effective price the truck fleet operator pays and it includes the cost of the charging infrastructure along with any subsidies that need to be accounted for.

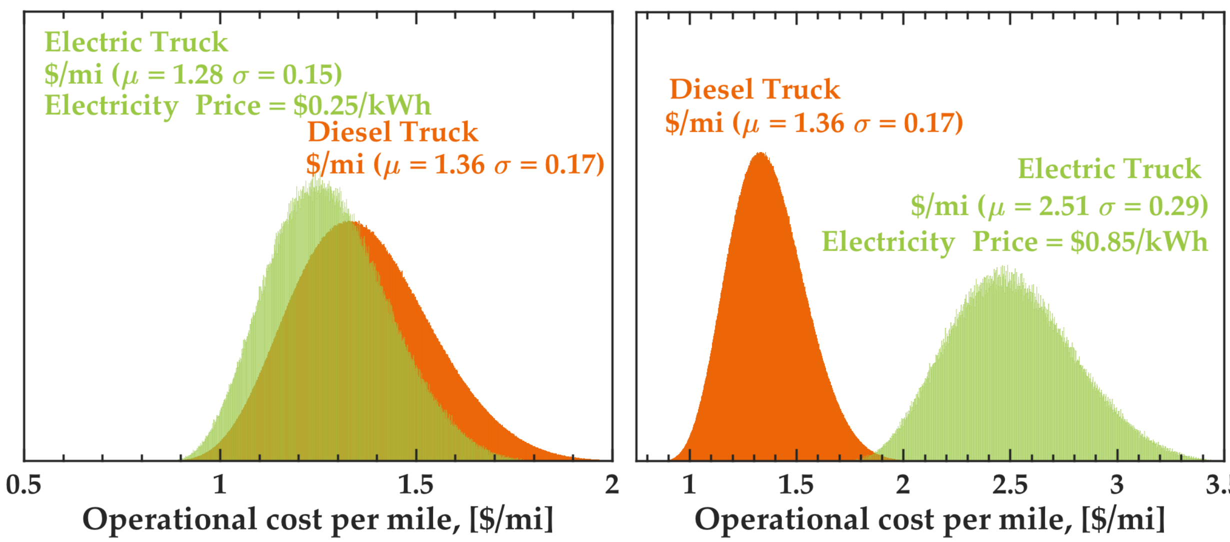

Figure S7: The operational costs for the electric and diesel trucks if the price of electricity is US$0.25/kWh and US$0.85/kWh. At US$0.85/kWh, there are no case scenarios where the operational costs of the electric semi-truck are lower than the diesel semi-truck.

Battery Pack Replacement:

In order to account for the battery pack replacements, the fraction of cases that require replacement is randomly sampled from the ideal distribution with no replacement and replaced with another random sample with the same number of cases from the limiting distribution with all battery packs replaced. This process is captured in Figure (S8).

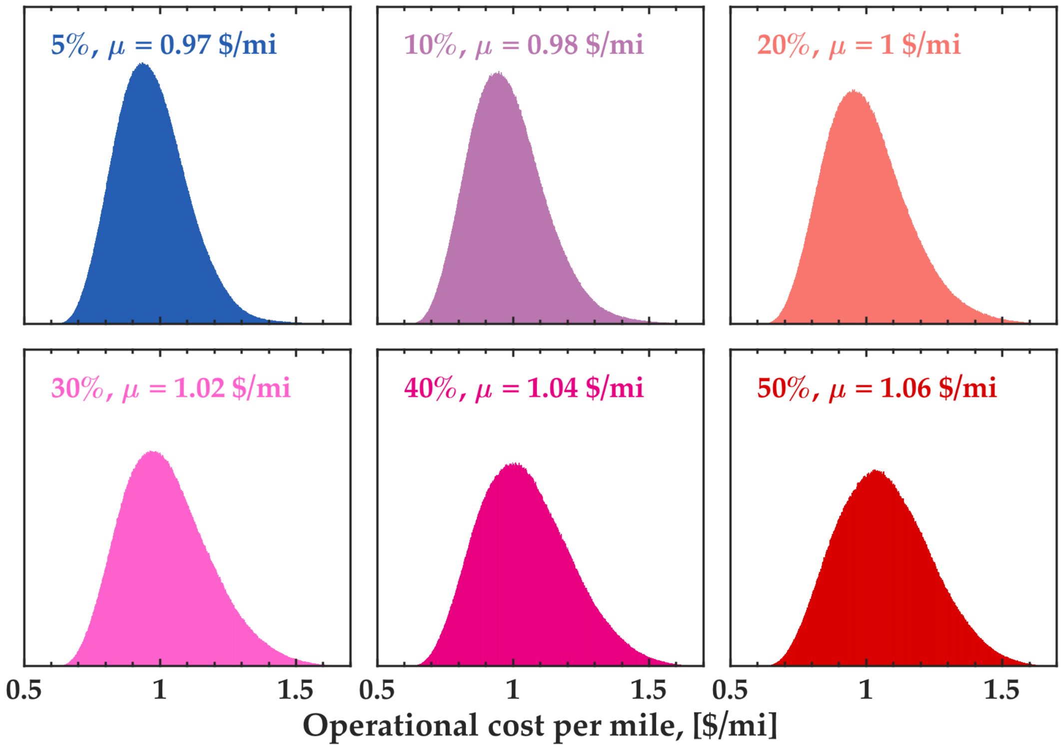

Figure S8: The extent to which the distributions are skewed by the replacement fraction is shown above. The mean value shows a steady increase with the increase in the battery pack replacement fraction as the distributions tend to become bi-modal in nature.

Sensitivity of the Payback Period to the Choice of Battery Chemistry:

Throughout this study, we have considered the battery pack to be based on cells that use an NMC-622 ($LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$) cathode and Graphite anode. The baseline battery pack price is considered to be about \$150/kWh, however, changes in the battery chemistry would change the pack price and thereby change the payback period. All changes in the battery pack price affect the variable considered to represent the initial price differential. Similar to the analysis discussed in the manuscript, we can estimate the sensitivity of the payback period to changes in the battery pack price. In order to perform such an analysis, BatPaC[16] was used to estimate the difference in the cell costs between NMC-333 and NMC-811 . The changes in the cell manufacturing costs were found to be about \$10/kWh higher for NMC-333 and \$10/kWh lower for NMC-811 compared to NMC-622. These changes are assumed to result in an equivalent change in the battery pack price which leads to an increase or decrease in the initial price differential. The sensitivity of the payback period to these changes are shown in Figure (S9).

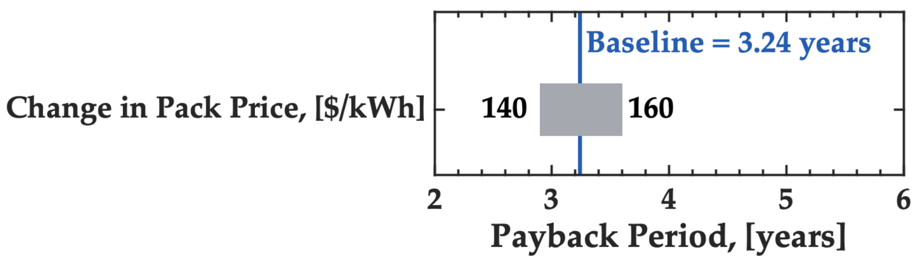

Figure S9: Sensitivity of the payback period to change in the battery pack price.

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