Environmental Science & Technology

Article

pubs.acs.org/est

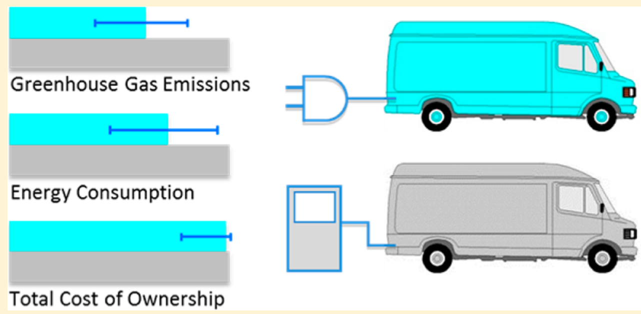
Electric Urban Delivery Trucks: Energy Use, Greenhouse Gas Emissions, and Cost-Effectiveness

Dong-Yeon Lee,*[†] Valerie M. Thomas,[‡,§] and Marilyn A. Brown[§]

[†]School of Civil and Environmental Engineering, [‡]School of Industrial and Systems Engineering, and [§]School of Public Policy, Georgia Institute of Technology, Atlanta, Georgia 30332, United States

Supporting Information

ABSTRACT: We compare electric and diesel urban delivery trucks in terms of life-cycle energy consumption, greenhouse gas (GHG) emissions, and total cost of ownership (TCO). The relative benefits of electric trucks depend heavily on vehicle efficiency associated with drive cycle, diesel fuel price, travel demand, electric drive battery replacement and price, electricity generation and transmission efficiency, electric truck recharging infrastructure, and purchase price. For a drive cycle with frequent stops and low average speed such as the New York City Cycle (NYCC), electric trucks emit 42−61% less GHGs and consume 32−54% less energy than diesel trucks, depending upon vehicle efficiency cases. Over an array of possible conditions, the median TCO of electric trucks is 22% less than that of diesel trucks on the NYCC. For a drive cycle with less frequent stops and high average speed such as the City−Suburban Heavy Vehicle Cycle (CSHVC), electric trucks emit 19−43% less GHGs and consume 5−34% less energy, but cost 1% more than diesel counterparts. Considering current and projected U.S. regional electricity generation mixes, for the baseline case, the energy use and GHG emissions ratios of electric to diesel trucks range from 48 to 82% and 25 to 89%, respectively.



1. INTRODUCTION

Urban delivery trucks may be a suitable application for electrification. These medium-duty postal and parcel delivery trucks operate in an urban environment in which a significant portion of their trip time is spent idling,[1] resulting in low fuel economy. Urban delivery trucks have low average driving speed,[2] and electric motors provide higher efficiency at low speeds. Also, frequent deceleration and stops in urban driving are well suited to utilization of regenerative braking.[3] And since these trucks typically operate on almost the same route every day and return to a company garage at the end of every operation,[4] systematic central recharging is feasible.

Although electric vehicles have been identified as a way to increase energy security and reduce air pollution,[5] fleet operators may not see electric trucks as an attractive alternative to conventional internal combustion engine (ICE) trucks if electric trucks are not cost-effective.[6,7] Some recent studies have concluded that electric trucks may not yet be cost-competitive, mostly depending upon vehicle utilization level, purchase price, diesel fuel price, and diesel truck fuel economy.[8,9]

The relative merits of electric and diesel trucks also depend on the life-cycle environmental impacts. Although electric trucks do not produce tail-pipe emissions, greenhouse gas (GHG) emissions from electricity generation could be substantial.[10,11] And even though electric trucks may have greater tank-to-wheels (TTW) efficiency than ICE trucks in city delivery operation, the overall energy efficiency of electric trucks depends on life-cycle energy use including upstream electricity generation and transmission efficiency. Here we explore the GHG emissions, energy saving potential, and cost-effectiveness of electric urban delivery trucks over their lifetime for urban delivery operation. The objective is to provide answers and insights to the following questions: Which type of truck, under what conditions, consumes more energy? Which emits more GHGs? Is the electric truck cost-effective in comparison with the diesel truck? Which factors are the most and least significant when evaluating the total cost of ownership? This analysis can provide a basis for medium-duty fleet operators and policy makers to better understand the promises and limitations of electric urban delivery trucks.

2. DATA AND ANALYSIS

To compare medium-duty electric and diesel delivery trucks, we define the system boundary[12,13] and then clarify the vehicle characteristics. We calculate life-cycle energy use and GHG emissions including vehicle operation, vehicle production and end-of-life management, electric drive battery, and electric vehicle supply equipment (EVSE in short or charging

Received: May 15, 2012
Revised: May 6, 2013
Accepted: June 20, 2013
Published: June 20, 2013

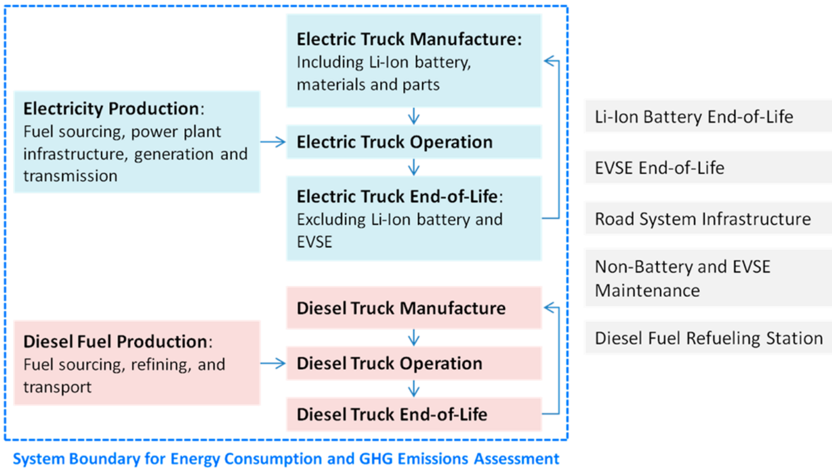


Figure 1. System boundary diagram.

equipment). We evaluate the total cost of ownership parameters with all monetary values in 2011 constant dollars.

2.1. System Boundary. Figure 1 illustrates the system boundary for the life-cycle energy use and GHG emissions assessment, which includes vehicle manufacture, operation, and end-of-life; Li-ion battery and EVSE production; and diesel fuel and electricity production and distribution. GHG emissions are evaluated using a 100-year time horizon with the Intergovernmental Panel on Climate Change (IPCC) 2007 evaluation of the global warming potentials of non-CO_2 GHGs.[14] The functional unit for evaluating primary energy consumption and GHG emissions is the transport of one metric ton of urban delivery freight a distance of one kilometer, i.e., MJ/t·km and $kgCO_2e$/t·km.

2.2. Vehicle Characteristics and Data. For urban delivery, vehicles of gross vehicle weight (GVW) class 4−6 (6350−11800 kg or 14001−26000 lbs) are normally used.[15] We use vehicle operation data from a FedEx Express parcel delivery diesel truck of GVW class 5 (16001−19500 lbs)[2] and from 219 SEV Newton electric trucks in 63 cities across the U.S.[16] Baseline data on the diesel and electric trucks and the vehicle operational characteristics are shown in Table 1.

2.3. Vehicle Operation Energy Use and GHG Emissions. The life-cycle energy use of the electric truck consists of three upstream components and two downstream components. The first upstream component accounts for indirect energy input ($E_{\mathrm{In\_Indirect}}$) for the production and distribution of power generation fuel and the construction, maintenance, decommissioning, and waste disposal of the power plant. Energy efficiency associated with this component can be expressed as the energy payback ratio (EPR), defined as a ratio of total energy output to the indirect energy input. EPRs have been reported as 4.7 for coal, ranging from 1.6 to 11; 3.8 for natural gas, ranging from 2.5 to 5; 15 for nuclear ranging from 14 to 16; 230 for hydro-electric ranging from 170 to 280; 2.9 for petroleum; and 25 for other fuels (mostly wind) ranging from 18 to 34.[18,19] The second upstream efficiency component is the electric power plant's generation efficiency (η_{PP}) related to direct energy input ($E_{\mathrm{In\_Direct}}$) for electricity generation and total energy output (E_{Out}). As of 2011, the U.S. national average coal power plant efficiency was 34%, while that of natural gas plants was 47% and petroleum 38%.[20] Generation efficiencies for other types of generation fuels are 33% for nuclear, 90% for hydro-electric, and 46% for wind[21−23]—see Table 2. These first two upstream components can be characterized by the upstream generation efficiency of the power plant, η_{LC}, as follows:

$$\eta_{\mathrm{LC}} = \frac{E_{\mathrm{Out}}}{E_{\mathrm{In\_Indirect}} + E_{\mathrm{In\_Direct}}} = \frac{\eta_{\mathrm{PP}}}{1 + \frac{\eta_{\mathrm{PP}}}{\mathrm{EPR}}} \quad (1)$$

Electric grid transmission and distribution efficiency (from power plants to end-use customers) is the third component of upstream efficiency, characterized here as 93%[24] (see SI Section 16). The downstream energy use of the electric truck is composed of electric drivetrain (DC−DC converter, inverter, and electric motor) efficiency and the loss in charging/discharging. We use the tank-to-wheels (TTW) efficiency (2.8 MJ/km) of the electric truck based on vehicle dynamic simulator result (SI Table 2S). In the case of the diesel truck, the overall energy use is composed of upstream efficiency of diesel fuel production and vehicle operation efficiency. We use observed diesel truck fuel economy (10.7 MJ/km, 3.38 km/L, or 8 mpg). The diesel fuel density and lower heating value are 835 kg/m^3 and 43.2 MJ/kg, respectively.[25]

GHG emissions from vehicle operations (gCO_2e/t·km) are derived from life-cycle GHG emissions per unit of energy

Table 1. Medium-Duty Electric and Diesel Truck Baseline Characteristics

	electric truck (SEV Newton)[16,17]	diesel truck (FedEx)[2]
chassis manufacturer	N/A	Freightliner
engine manufacturer	-	Cummins
model year[a]	2011	2006
GVW (kg)	7490	7260
curb weight (w/o cargo) (kg)	4260	4400
payload (kg)	3230	2860
electric motor (kW)	120	
battery capacity (kWh)	80	
electric drive range (km)	160 (100 miles)	
daily distance traveled (km)	50 (31 miles)	65 (41 miles)
average speed (km/h)	32	32
number of stops per km	1.7	1.9
kinetic intensity[a] (km^{-1})	1.0	1.15

[a]Model year difference and the definition of kinetic intensity are discussed in the Supporting Information (SI).

dx.doi.org/10.1021/es400179w | Environ. Sci. Technol. 2013, 47, 8022−8030

Table 2. Vehicle Operation Energy Use and GHG Emissions: Baseline Case

	GVW class 5 electric truck						
generation fuel	coal	natural gas	nuclear	hydro	petroleum	other[a]	
life-cycle generation efficiency η_{LC} (%)	31.7	41.8	32.3	89.6	33.6	44.7	
U.S. average generation mix[26] (%)	39.8	26.9	19.3	7.9	0.6	5.5	
aggregate generation efficiency				39.8			
transmission & distribution efficiency (%)				93[24]			GVW class 5 diesel truck
aggregate upstream efficiency (%)				37			87.3[27]
tank-to-wheel (TTW) energy use (MJ/km)				2.8[16]			10.7[2,28]
overall energy use[b] (MJ/t·km)				2.34			4.3
life-cycle generation GHG emissions (gCO_2e/MJ_e)	279[29]	158[30,31]	8.2[29,32]	2.4[29,33]	230[34]	6.2[17,29,33]	-
life-cycle GHG emissions (gCO_2e/MJ)				169[b]			90[34,35]
overall GHG emissions[b] ($kgCO_2e/t·km$)				0.15			0.34

[a]Other renewables; mostly wind.[26] [b]For detailed calculation methods and parameters, see SI Section 13.

(gCO_2e/MJ), as shown in Table 2. GHG emissions of electricity are based on generation fuel, percentage of each fuel in the generation mix, and life-cycle emissions of each fuel (Table 2). The generation fuel mix varies over the course of a day, and the marginal emissions will depend on when the vehicle is charged. In addition, generation mix differs by region and will change over time; this spatiotemporal variation is addressed in a later section. For the baseline calculation, we use the January 2011–July 2012 U.S. average generation mix.[26] The total vehicle operation GHG emissions of the diesel truck can be decomposed into the fuel-chain carbon intensity of diesel fuel ($kgCO_2e/MJ$), fuel economy, and total travel demand (km).[36]

2.4. Vehicle Manufacture Energy Use and GHG Emissions. As shown in SI Table 4S, our manufacturing calculation is based on data for both medium-duty trucks and passenger cars. The relationship between electric and ICE passenger car manufacturing energy use and GHG emissions is used to infer electric truck data from diesel truck manufacturing data. For the calculation of the total vehicle-cycle energy use and GHG emissions of the FedEx diesel truck manufacture, we utilize economic input–output life cycle assessment (EIO-LCA) data.[37] Because data on GVW class 5 diesel trucks are not specified in the EIO-LCA database, we infer from energy use and GHG emissions per curb weight and vehicle price for passenger cars and tractor-trailers. Detailed calculations are presented in SI Table 5S.

For the electric truck, we divide our calculation into three parts: nonbattery vehicle production, battery production, and electric vehicle supply equipment (EVSE) production and installation. We use the ICE truck manufacture data for the nonbattery electric vehicle production, adjusted to reflect the difference between the ICE truck and electric truck (SI Table 4S and Figure 2S).

Battery weight is estimated by multiplying the battery capacity (80 kWh) of electric trucks by the ratio of battery weight to battery capacity (11.4 kg/kWh). The ratio is determined from the electric truck maker's data,[17] the battery manufacturer's data,[38] and personal communication with an electric truck mechanic. The calculation procedure is shown in SI Figure 2S.

With regard to the EVSE, three charging rates are available. Level 1 is the slowest but normally requires no special equipment other than a connector or cord set. Level 2 takes less time than Level 1 but requires installation of charging equipment along with a dedicated electric circuit.[5] Using Level 2, fleet operators can recharge the 80 kWh battery from 0% state of charge (SOC) to 100% SOC within 5–8 h.[5,17] Level 3 provides even faster (approximately 72 kW) charging than Level 2 (10–16 kW), but it is expensive, ranging from \$20,000 to \$50,000 per unit.[5] Here we assume that fleet operators will use either Level 1 or 2. Our assumption is supported by electric truck activity data in which the average charging rate is reported to be about 4 kW.[16,17] According to Lucas et al.,[39] life-cycle energy use and GHG emissions for charging equipment production are 638 MJ and 34 $kgCO_2e$ for Level 1 and 4290 MJ and 250 $kgCO_2e$ for Level 2.

For the end-of-life vehicle (ELV) energy use and GHG emissions, we include vehicle recycling without Li-ion battery and EVSE. Currently, automotive Li-ion batteries are not recycled, even though it has been reported that recycling of automotive Li-ion batteries would reduce energy requirements and greenhouse gas emissions for battery manufacture.[40] Also, given the small contribution of EVSE manufacture in total energy use and GHG emissions, we assume EVSE recycling or other end-of-life effects would be small. As illustrated in the SI, for the single truck considered in our study, we estimate that 25% of energy consumption and 17% of GHG emissions savings can be recouped by recycling automotive metals. Detailed information on life-cycle energy use and GHG emissions calculation methods and parameters is presented in the SI.

2.5. Total Cost of Ownership. The total cost of ownership (TCO) for electric and diesel trucks is composed of purchase cost, maintenance cost, fuel or electricity cost, EVSE cost, and battery cost.[41,42] Other costs such as insurance, purchase incentives, tax credits, or penalties may exist,[43] but for comparison without subsidies or regulatory effects, we exclude those factors in our calculation. Insurance cost is assumed to be the same for both electric and diesel trucks, and thus excluded from the comparison.

The time horizon of the vehicle technology comparison is mainly determined by the maximum achievable lifetime vehicle kilometers traveled (VKT) and daily or annual VKT demand. Based on actual electric and diesel truck operation data,[2,16] here we test a 48–96 km (30–60 mile) range of daily distance traveled. With this VKT demand set, vehicle lifetime ranges from 11 to 20 years. It is assumed that the vehicle retires in the year when the accumulated VKT reaches 240000 km (150000 miles).

Electric trucks have higher capital cost than conventional diesel trucks mostly because of the battery cost, which increases

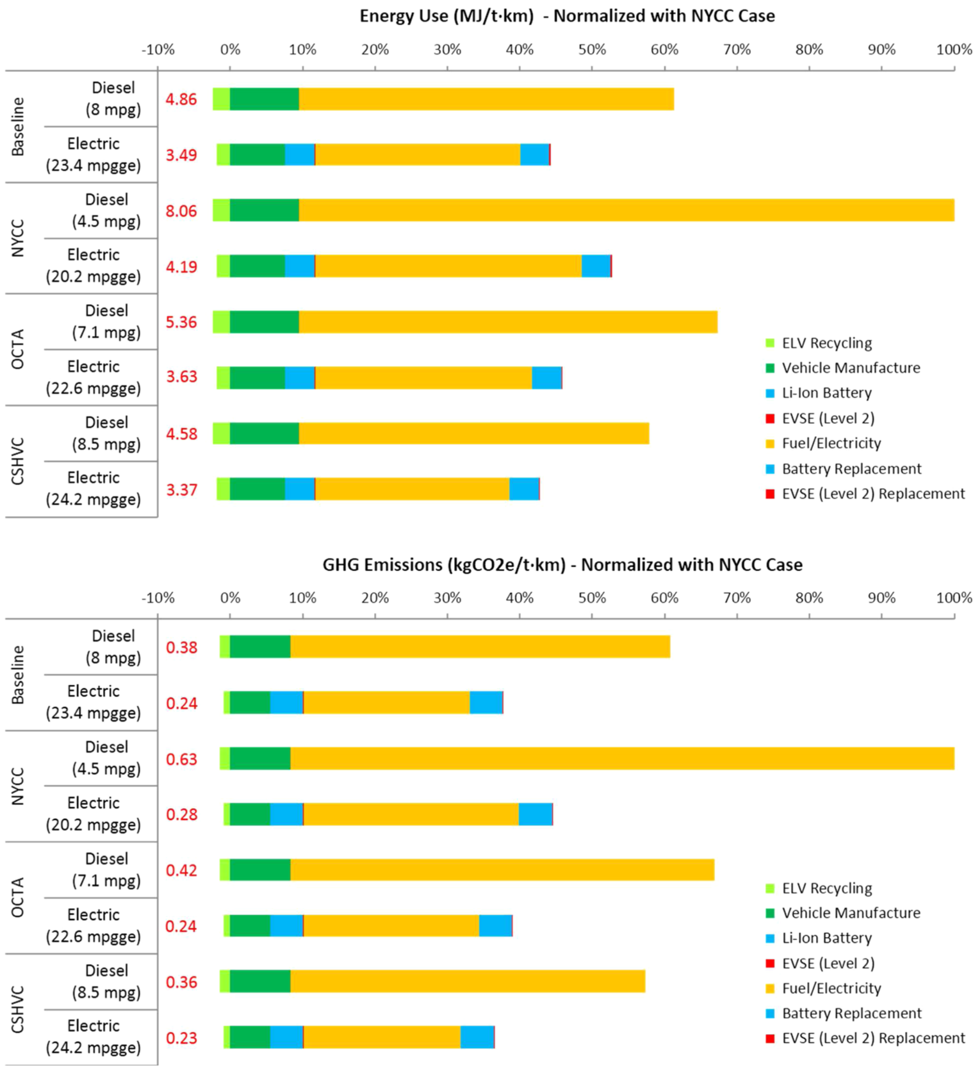


Figure 2. Life-cycle energy use and GHG emissions normalized with NYCC case (8.06 MJ/t·km and 0.63 $kgCO_2e$/t·km). Numbers in red are net total including recycling effect.

with battery capacity.[6,7] Unlike passenger cars that have a standard window sticker price, commercial vehicle prices can vary depending upon negotiation between fleet operators and truck manufacturers, and truck volumes to be purchased. We estimate the purchase price for diesel and electric trucks based on data reported in newspapers and government reports. We assume that the purchase price difference between electric and diesel trucks ranges from \$25,000 to \$37,000, corresponding to the smallest SEV Newton, with the comparable diesel truck price of \$60,000 (SI Table 10S).

For the diesel truck maintenance cost, we use data from the FedEx delivery truck experiment (0.139 \$/km or 0.223 \$/mile).[2] Electric trucks are reported to have 35% lower total maintenance cost than diesel trucks due to the absence of engine and transmission-related maintenance (e.g., timing belt, water pump, fuel filter, oil change, engine air filter, and coolant replacement).[44] Also, brake pads for electric vehicles can last twice as long as those for diesel trucks, owing to regenerative braking; this can reduce maintenance costs another 20−30%. The SEV Newton maintenance cost has been reported to be only about 10% of its diesel truck counterpart.[45] Nonetheless, here we assume that the electric truck's maintenance will cost 25−50% of the diesel truck, because some of the electric powertrain parts may have reliability issues due to yet-to-be-proved technological maturity (0.035−0.069 \$/km). Li-ion battery and EVSE replacement is not included in the maintenance cost, but dealt with separately in our study. We assume annual maintenance cost is evenly distributed over the vehicle lifetime, except for the battery and EVSE.

As of 2011, the battery price of the electric truck is estimated to be \$625 per kWh as shown in SI Table 8S, which falls within the range of prices projected or reported in previous studies (SI Figure 4S). Given the battery cycle life (2800 cycles at 100% depth of discharge)[46,47] and operation range (48−96 km daily and 11520−23040 km annually), it is estimated that no battery replacement is needed over the vehicle lifetime (240000 km or 150000 miles) (SI Table 11S). Nonetheless, because the automotive Li-ion battery is a relatively new technology, in addition to the no-replacement case, we also consider the case of one replacement in 6−10 years, regardless of annual VKT. Replacement during the first 5 years would be covered by the manufacturer's 5-year warranty for the battery.[17] For the one-replacement case, it is assumed that no further replacement is needed. With regard to the future battery price for the replacement, we assume that the electric truck's Li-ion battery price will decline linearly from 625 \$/kWh in 2011 to 230

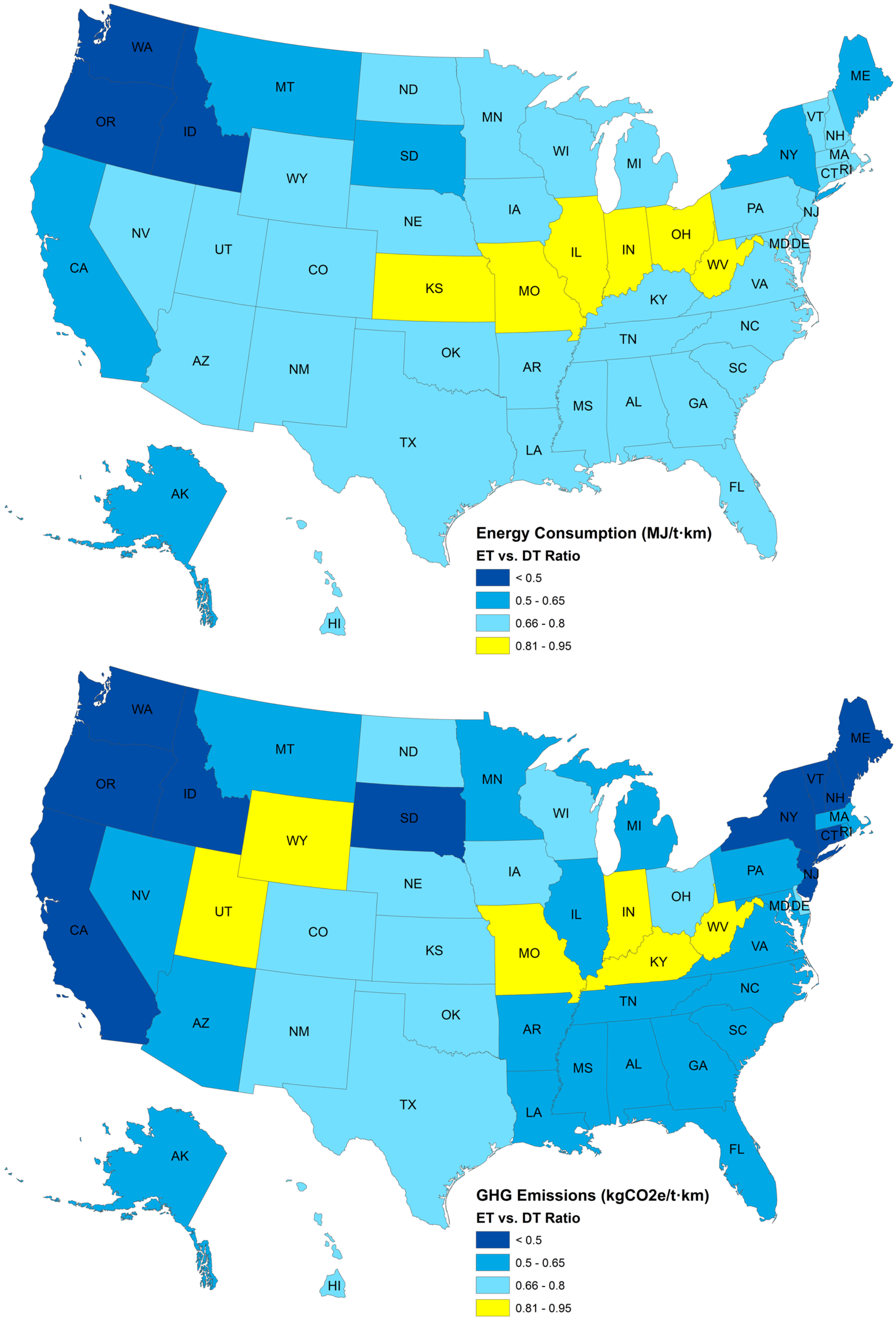


Figure 3. State-by-state variation of life-cycle energy use and GHG emissions with 2011−2012 generation mix and baseline vehicles: ratio of electric truck (ET) to diesel truck (DT).

\$/kWh in 2020. Detailed battery price estimates and projections are provided in SI Figure 4S.

As mentioned previously, fleet operators will use either Level 1 or Level 2 EVSE. The connector and cord for Level 1 EVSE

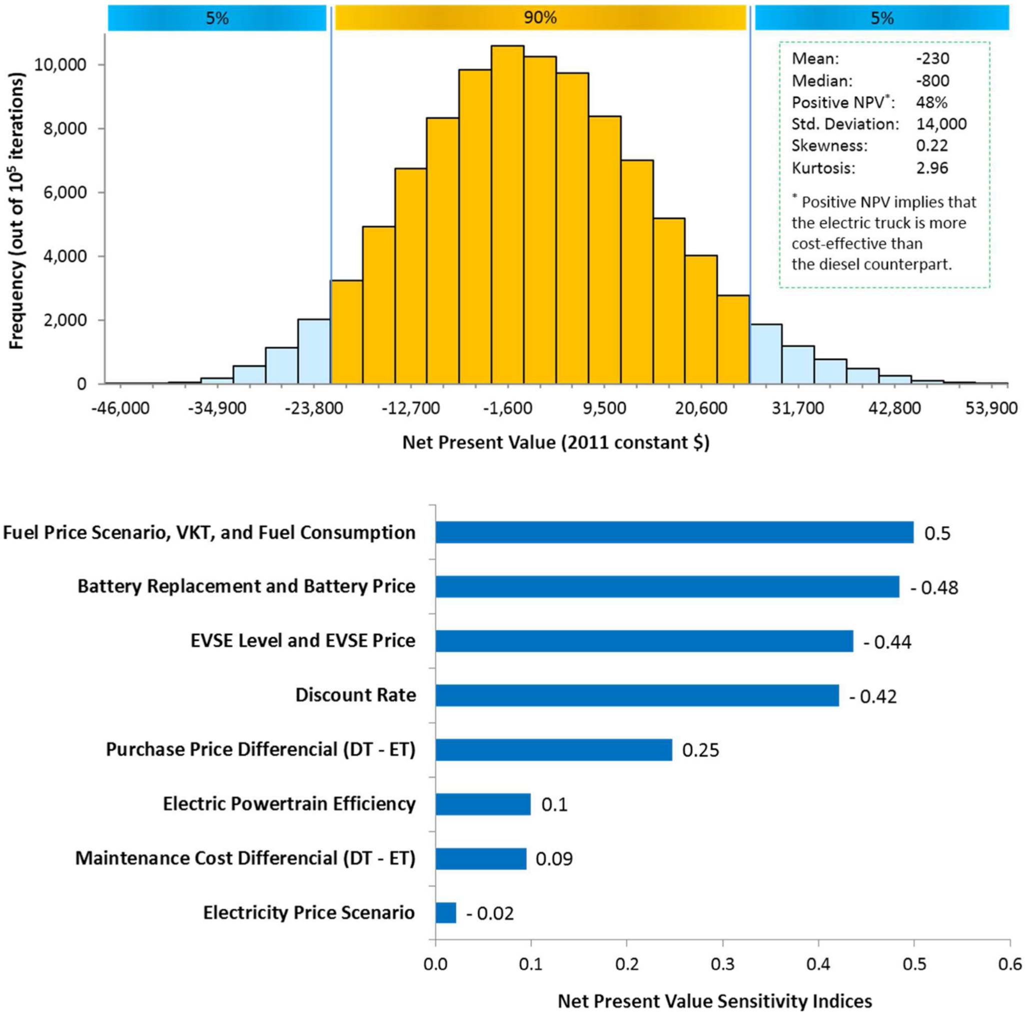


Figure 4. Monte Carlo simulation and linear regression-based sensitivity analysis result of the net present value of the difference between the TCO of an electric versus a diesel delivery truck.

comes with the electric truck, and thus there is no initial upfront cost associated with the EVSE. For Level 2, the price of the available equipment including installation will range from \$1,860 to \$14,400 (SI Table 12S). Based on the reported EVSE lifetime (15 years for Level 1 and 6 years for Level 2),[39] we assume one replacement of EVSE over the vehicle lifetime: in the 16th year for Level 1 and in the seventh year for Level 2. Level 1 EVSE replacement is relatively low cost and assumed to be 0. The future Level 2 EVSE price is assumed to be 50% of current price due to economies of scale with a wider adoption of electric vehicles and the corresponding expansion of charging infrastructure.

Since fuel costs could be critical in the TCO of diesel trucks and thus the adoption of electric trucks,[48] we test four diesel fuel price forecasts (SI Figure 6S).[49] The initial fuel price value used in this study is the July 2011 diesel fuel price (3.87 \$/gallon),[50] while the EIA forecast's initial value is the price in 2009, and the fuel price change pattern in our calculation is exactly the same as that forecast by the EIA.[49] The same principle is applied to electricity price forecasts. We consider two scenarios: a constant real electricity price and the EIA forecast (SI Figure 6S). Another key factor contributing to total fuel or electricity cost is efficiency of the electric and diesel trucks. In addition to the baseline case summarized in Table 1, average fuel economy data[2] from the dynamometer test on three different drive cycles (drive schedule of vehicle speed vs time) were considered. In so doing, a full-load correction factor was applied (see SI Table 1S). The three drive cycles considered are New York City Cycle (NYCC), Orange County Transit Authority Bus Cycle (OCTA), and City−Suburban Heavy Vehicle Cycle (CSHVC). One may recall that the model year of the diesel truck is 2006 (Table 1), whereas that of the electric truck is 2011. The maximum fuel economy improvement of the diesel truck between 2006 and 2011 is assumed to be 12% based on an industry report and fuel efficiency-related vehicle technology advances over the same period of time.[51,52] As a result, the diesel truck fuel economy in our calculation ranges from 4.6 mpg or 1.93 km/L (for baseline NYCC) to 9.6 mpg or 4.05 km/L (for CSHVC with 12% improvement). According to vehicle dynamic simulator results, the electric truck efficiency varies from 16.7 mpgge (for the lowest electric truck efficiency on NYCC) to 34.3 mpgge (for the highest on CSHVC) SI Table 2S. Based on the electric truck activity data,[18] we assume ±20% vehicle efficiency variation (2.2−4.5 MJ/km or 16.7−34.3 mpgge for baseline case in Table 2) in the sensitivity analysis. More detailed information can be found in the Supporting Information.

The net cost of an electric truck can be represented by the net present value (NPV), expressed by eq 2, where i stands for i-th year; d is the discount rate (5−15%); Y is vehicle lifetime

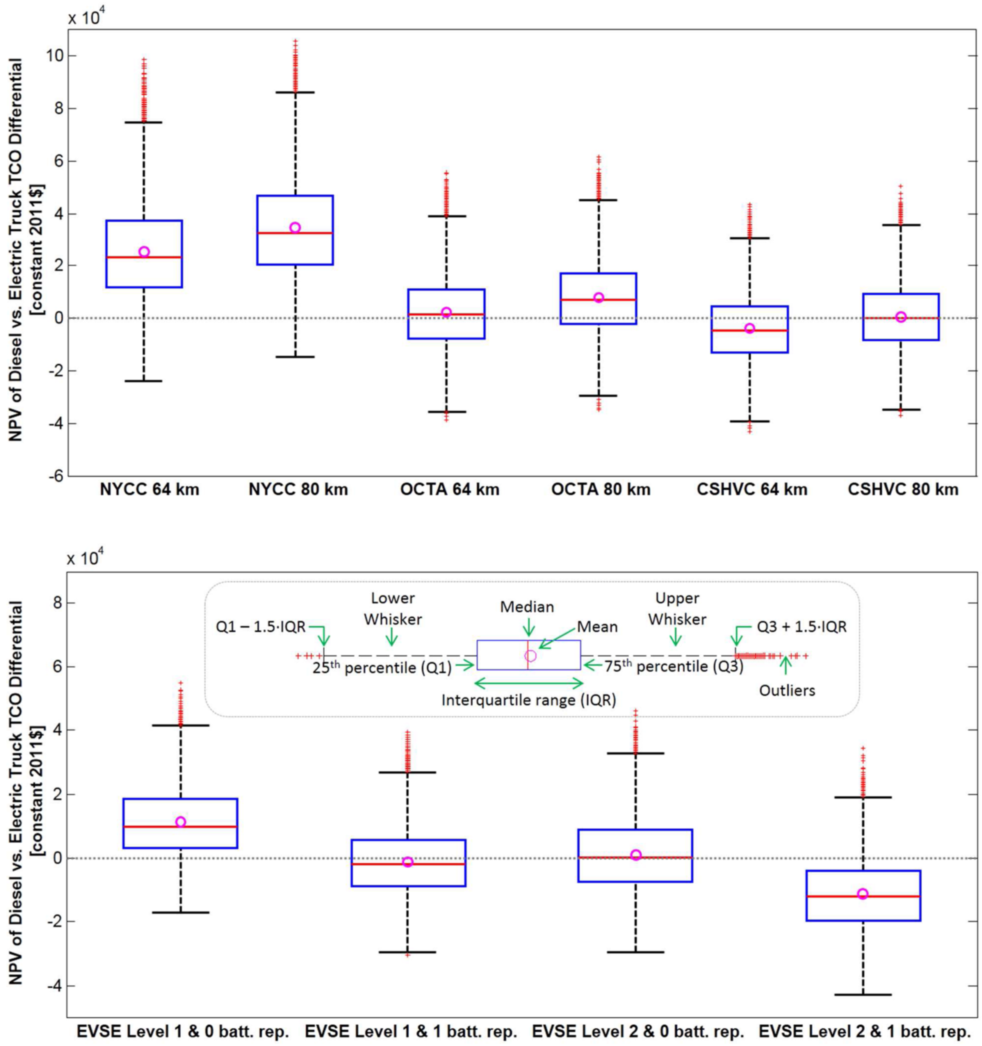


Figure 5. Monte Carlo simulation results for different drive cycles (as a proxy for fuel economy), operational ranges (64 or 80 km; 40 or 50 miles), EVSE Level 1 or 2, and battery replacement (0 or 1) scenarios.

(11–20 years depending upon daily/annual VKT demand); and TCO_i is the annual TCO of each type of truck in year *i*.

$$\mathrm{NPV} = \sum_{i=0}^{Y} \left\{ \frac{\mathrm{TCO}_{\mathrm{diesel},i} - \mathrm{TCO}_{\mathrm{electric},i}}{(1+d)^i} \right\} \tag{2}$$

To evaluate the uncertainty of the costs of diesel and electric trucks, we used Monte Carlo simulation, assuming a uniform distribution for each of the variables. Using 100000 samples, we conducted regression analysis to determine the sensitivity of the NPV results with respect to the independent variables. Full equations of TCO_i and a list and description of the independent variables are presented in the Supporting Information.

3. RESULTS

As can be seen in Figure 2 and SI Figure 8S, over the life-cycle the electric truck consumes 28% less energy (3.49 vs 4.86 MJ/t·km) and emits 38% less GHGs (0.24 vs 0.38 $kgCO_2e$/t·km) than the diesel truck in the baseline case for both the 2011–2012 and the 2025 projected U.S. average electricity mix. The difference in GHG emissions is larger than the difference in energy use due to diesel fuel's larger fuel-cycle energy use and emissions per unit VKT and payload. We show final results not only by VKT but also by payload of each truck, assuming that both diesel and electric delivery trucks are operated at full load.

The comparative energy consumption and GHG emissions vary depending upon the drive cycles and the electric powertrain efficiency for the baseline diesel truck efficiency case. For the NYCC drive cycle, for which the diesel truck achieves only 4.6 mpg (or 1.9 km/L; see SI Table 1S), life-cycle energy use and GHG emissions are 39–54% and 48–61% less for the electric truck than the diesel truck, depending upon the electric powertrain efficiency. In contrast, for the CSHVC drive cycle, for which the diesel truck achieves 8.6 mpg (or 3.6 km/L), the energy use of the electric truck is 14% and 34% less than the diesel truck for the lowest and highest electric truck efficiency, respectively. For the same drive cycle, the GHG emissions of the electric truck are 27% lower than the diesel truck for the lowest electric truck efficiency and 43% less for the highest.

The results vary with the carbon-intensity of regional electricity generation (Figure 3). For the baseline case (Tables 1 and 2) with the 2011–2012 U.S. electricity mix, electric trucks have an energy efficiency advantage in most parts of the U.S., with the largest advantage in the Pacific Northwest. For GHG emissions, electric vehicles have the lowest relative emissions in the Pacific Northwest, the West, and in the

Northeast. In the states of Utah, Wyoming, Missouri, Kentucky, West Virginia, and Indiana, electric trucks emit 5−19% less GHGs than diesel trucks. For generation mix data, see SI Table 13S. State-by-state variation by drive cycles can be found in SI Figure 7S. Here we do not consider potential changes in power generation mix as a consequence of electric truck adoption; our analysis is on attributional basis.

The relative importance of individual variables is evaluated by a sensitivity analysis: for the detailed method and formula, see the SI. Whether the battery is replaced or not over the vehicle lifetime makes a big difference in the relative diesel versus electric truck energy use and GHG emissions: 82% for energy use and 34% for GHG emissions (SI Table 19S). Other than the battery replacement, TTW efficiency of both types of trucks, diesel fuel's upstream efficiency, electric grid transmission efficiency, and coal power plant generation efficiency and GHG emissions are the top five variables with the most significant influence.

The total costs of ownership (TCO) of the electric and diesel trucks are similar (Figure 4). For separate Monte Carlo simulation results for diesel and electric trucks, see SI Figure 9S. Based on the Monte Carlo simulation output, regression analysis can be utilized for sensitivity analysis.[53,54] The tornado chart in Figure 4 illustrates a sensitivity index of input variables, which is derived from standardized/normalized regression coefficients (see the SI). Among diverse uncertainty factors, Figure 4 shows that the relative TCO is most sensitive to the diesel truck's fuel consumption (or fuel economy), VKT, and diesel fuel price scenario. Almost in the same degree, the NPV of TCO differential is sensitive to battery replacement, battery price, and EVSE price. The interpretation of the positive sign of the sensitivity index is that a higher value of the variable leads to a higher TCO differential and thus higher probability of cost-effectiveness of the electric truck. Considering that future fuel price and battery replacement are not something that can be controlled, here we focus on more predictable factors that fleet operators might know or could select: daily or annual VKT demand, fuel economy of the diesel truck as a function of drive cycle, and EVSE.

As can be seen in Figure 5, the electric truck is relatively more cost-effective on the NYCC and when VKT demand is higher. However, the cost-competitiveness of the electric truck is expected to diminish in drive cycles with higher average speed, as indicated in Figure 5. Furthermore, battery replacement along with EVSE will greatly affect the relative TCO of the electric truck. To reduce costs, fleet operators may choose EVSE Level 1. However, this could limit vehicle operation flexibility, because electric trucks should be plugged in and recharged whenever they are back in the fleet's garage, which may take 7−8 h.[16]

All in all, the life-cycle energy use and GHG emissions of the electric truck are lower than that of the diesel truck, particularly for the frequent stop and low average speed (NYCC- and OCTA-type) drive cycles. For both types of trucks, vehicle efficiency is important from the perspective of energy consumption, GHG emissions, and TCO over the vehicle lifetime. The TTW efficiency of the truck depends strongly on the drive cycle, and the electric truck is more likely to provide higher benefits with the NYCC-style driving conditions than with the CSHVC or similar conditions. Given the same drive cycle and thus the same vehicle efficiency, the electric truck would be more attractive to fleet operators with high truck utilization (VKT demand), of course within the electric drive range. Battery replacement is another key factor; to maximize the benefits from electric trucks, the durability and reliability of the automotive Li-ion battery are crucial, which might be advanced with technological development. Recycling of the EV Li-ion battery could also improve life-cycle energy consumption and GHG emissions. There is also variation by state in the electric truck's comparative energy consumption and GHG emissions. For the baseline case, recent and projected future generation mixes result in similar or less energy consumption and GHG emissions of the electric truck compared to the diesel truck in most parts of the U.S.

■ ASSOCIATED CONTENT

Supporting Information

Additional detail of calculations, methods, and data (text, 20 tables, 9 figures; 35 pages). This information is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*Phone: 404-894-2236; e-mail: dlee348@gatech.edu; mail: Lamar Allen Sustainable Education Building, Room 215, 788 Atlantic Drive, Atlanta, GA 30332.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We thank Alexander Smith and John Bustamante for initial participation, and Frank Kreikebaum for comments on the manuscript.

■ REFERENCES

(1) *Heavy-Duty Truck Activity Data*; U.S. DOT, Federal Highway Administration: Washington, D.C., 1999.

(2) *FedEx Express Gasoline Hybrid Electric Delivery Truck Evaluation: 12-Month Report*; U.S. DOE, National Renewable Energy Laboratory: Golden, CO, 2011.

(3) Hellgren, J. Life cycle cost analysis of a car, a city bus and an intercity bus powertrain for year 2005 and 2020. *Energy Policy* **2007**, 35 (1), 39−49.

(4) Martin, C. Battery-Powered Trucks: Toys No More. *Bloomberg Businessweek*, January 25, 2011.

(5) *Plug-In Electric Vehicle Handbook for Fleet Managers*; U.S. DOE, Office of Energy Efficiency and Renewable Energy, 2012; www.afdc.energy.gov/pdfs/pev_handbook.pdf (accessed July 25, 2012).

(6) Offer, G. J.; Howey, D.; Contestabile, M.; Clague, R.; Brandon, N. P. Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system. *Energy Policy* **2010**, *38* (1), 24−29.

(7) van Vliet, O.; Brouwer, A. S.; Kuramochi, T.; van den Broek, M.; Faaij, A. Energy use, cost and CO_2 emissions of electric cars. *J. Power Sources* **2011**, *196* (4), 2298−2310.

(8) Feng, W.; Figliozzi, M. An economic and technological analysis of the key factors affecting the competitiveness of electric commercial vehicles: A case study from the USA market. *Transp. Res., Part C* **2013**, 26135−145, DOI: 10.1016/j.trc.2012.06.007.

(9) Davis, B.; Figliozzi, M. A methodology to evaluate the competitiveness of electric delivery trucks. *Transp. Res., Part E* **2013**, 498−23, DOI: 10.1016/j.tre.2012.07.003.

(10) Doucette, R. T.; McCulloch, M. D. Modeling the CO_2 emissions from battery electric vehicles given the power generation mixes of different countries. *Energy Policy* **2011**, *39* (2), 803−811.

(11) Doucette, R. T.; McCulloch, M. D. Modeling the prospects of plug-in hybrid electric vehicles to reduce CO_2 emissions. *Appl. Energy* **2011**, *88* (7), 2315−2323.

(12) *International Standard 14040: Environmental Management — Life Cycle Assessment — Principles and Framework*; International Organization for Standardization (ISO): Geneva, Switzerland, 2006.
(13) *International Standard 14044: Environmental Management — Life Cycle Assessment — Requirements and Guidelines*; International Organization for Standardization (ISO): Geneva, Switzerland, 2006.
(14) *IPCC Fourth Assessment Report: Climate Change* 2007; World Meteorological Organization, Intergovernmental Panel on Climate Change: Geneva, Switzerland; http://www.ipcc.ch/publications_and_data/ar4/wg1/en/tssts-2-5.html (accessed March 25, 2012).
(15) *Transportation Energy Data Book*, 29th ed.; U.S. DOE, Oak Ridge National Laboratory: Oak Ridge, TN, 2010.
(16) *Vehicle Technologies Program — Smith Newton Vehicle Performance Evaluation*; U.S. DOE, National Renewable Energy Laboratory, 2013; http://www.nrel.gov/docs/fy13osti/58108.pdf (accessed April 28, 2013).
(17) Smith Electric Vehicles. Technical Specifications; http://www.smithelectricvehicles.com (accessed June 15, 2011).
(18) White, S. W.; Kulcinski, G. L. Birth to death analysis of the energy payback ratio and CO_2 gas emission rates from coal, fission, wind, and DT-fusion electrical power plants. *Fusion Eng. Des.* **2000**, *48* (248), 473−481.
(19) Gagnon, L. Civilisation and energy payback. *Energy Policy* **2008**, *36* (9), 3317−3322.
(20) *eGRID2012 Version 1.0*; U.S. EPA; www.epa.gov/egrid (accessed July 27, 2012).
(21) White, S. W. *Net Energy Payback and CO_2 Emissions from Helium-3 Fusion and Wind Electrical Power Plants*. Ph.D. Dissertation, University of Wisconsin, Madison, WI, 1998.
(22) *Reclamation: Managing Water in the West*; U.S. DOI, Bureau of Reclamation, Power Resources Office: Washington, DC, 2005.
(23) Pope, K.; Dincer, I.; Naterer, G. F. Energy and exergy efficiency comparison of horizontal and vertical axis wind turbines. *Renewable Energy* **2010**, *35*, 2102−2113.
(24) *Annual Energy Review 2011*; U.S. DOE, Energy Information Administration: Washington, DC, 2012.
(25) Ma, H.; Riera-Palou, X.; Harrison, A. Development of a new tank-to-wheels methodology for energy use and green house gas emissions analysis based on vehicle fleet modeling. *Int. J. Life Cycle Assess.* **2011**, *16* (4), 285−296.
(26) *Electric Power Monthly — April 2012*; U.S. DOE, Energy Information Administration: Washington, DC, 2011; http://205.254.135.24/electricity/monthly (accessed April 8, 2012).
(27) Schafer, A.; Heywood, J.; Weiss, M. Future fuel cell and internal combustion engine automobile technologies: A 25-year life cycle and fleet impact assessment. *Energy* **2006**, *31* (12), 2064−2087.
(28) Huai, T.; Shah, S. D.; Wayne Miller, J.; Younglove, T.; Chernich, D. J.; Ayala, A. Analysis of heavy-duty diesel truck activity and emissions data. *Atmos. Environ.* **2006**, *40* (13), 2333−2344.
(29) Meier, P.; Wilson, P.; Kulcinski, G.; Denholm, P. US electric industry response to carbon constraint: A life-cycle assessment of supply side alternatives. *Energy Policy* **2005**, *33* (9), 1099−1108.
(30) *Annual Energy Outlook 2011*; U.S. DOE, Energy Information Administration: Washington, DC, 2011.
(31) Jaramillo, P.; Griffin, W. M.; Matthews, H. S. Comparative life-cycle air emissions of coal, domestic natural gas, LNG, and SNG for electricity generation. *Environ. Sci. Technol.* **2007**, *41*, 6290−6.
(32) Fthenakis, V. M.; Kim, H. C. Greenhouse-gas emissions from solar electric- and nuclear power: A life-cycle study. *Energy Policy* **2007**, *35* (4), 2549−2557.
(33) Raadal, H. L.; Gagnon, L.; Modahl, I. S.; Hanssen, O. J. Life cycle greenhouse gas (GHG) emissions from the generation of wind and hydro power. *Renewable Sustainable Energy Rev.* **2011**, *15* (7), 3417−3422.
(34) *Development of Baseline Data and Analysis of Life Cycle Greenhouse Gas Emissions of Petroleum-Based Fuels*; U.S. DOE, National Energy Technology Laboratory: Golden, CO, 2008.
(35) *Well-to-Tank Energy Use and Greenhouse Gas Emissions of Transportation Fuels — North American Analysis*; General Motors Corporation; U.S. DOE Argonne National Laboratory; BP; ExxonMobil; Shell; http://www.transportation.anl.gov/pdfs/TA/165.pdf (accessed June 20, 2011).
(36) Creutzig, F.; McGlynn, E.; Minx, J.; Edenhofer, O. Climate policies for road transport revisited (I): Evaluation of the current framework. *Energy Policy* **2011**, *39* (5), 2396−2406.
(37) *Economic Input-Output Life Cycle Assessment (EIO-LCA) US 2002 (428) Model*; Carnegie Mellon University Green Design Institute; www.eiolca.net (accessed April 23, 2012).
(38) Valence. Valence Battery Modules Spreadsheet; http://www.valence.com (accessed February 6, 2012).
(39) Lucas, A.; Silva, C. A.; Neto, R. C. Life cycle analysis of energy supply infrastructure for conventional and electric vehicles. *Energy Policy* **2012**, *41*, 537−547.
(40) Sullivan, J. L.; Gaines, L. Status of life cycle inventories for batteries. *Energy Convers. Manage.* **2012**, *58*, 134−148.
(41) Carlsson, F.; Johansson-Stenman, O. Costs and benefits of electric vehicles: A 2010 perspective. *J. Transport Econ. Policy* **2003**, *37* (1), 1−28.
(42) Thiel, C.; Perujo, A.; Mercier, A. Cost and CO_2 aspects of future vehicle options in Europe under new energy policy scenarios. *Energy Policy* **2010**, *38* (11), 7142−7151.
(43) Motavalli, J. Frito-Lay Adds Electric Trucks to Its Fleet. *The New York Times*, September 8, 2010; http://wheels.blogs.nytimes.com/2010/09/08/frito-lay-adds-electric-trucks-to-its-fleet (accessed June 20, 2011).
(44) Werber, M.; Fischer, M.; Schwartz, P. V. Batteries: Lower cost than gasoline? *Energy Policy* **2009**, *37* (7), 2465−2468.
(45) Ramsey, M. As Electric Vehicles Arrive, Firms See Payback in Trucks. *The Wall Street Journal*, December 7, 2010; http://online.wsj.com/article/SB10001424052748704584804575644773552573304.html (accessed October 22, 2012).
(46) Valence. U-Charge® XP Specifications; http://www.valence.com (accessed October 10, 2012).
(47) Valence. U-Charge® U1−12RT Specifications; http://www.valence.com (accessed October 10, 2012).
(48) Diamond, D. The impact of government incentives for hybrid-electric vehicles: Evidence from US states. *Energy Policy* **2008**, *37*, 972−983.
(49) *Gasoline and Diesel Fuel Update*; U.S. DOE, Energy Information Administration: Washington, DC, 2011; http://www.eia.gov/petroleum/gasdiesel (accessed August 10, 2011).
(50) *Short-Term Energy and Summer Fuels Outlook*; U.S. DOE, Energy Information Administration: Washington, DC, 2011; http://205.254.135.7/forecasts/steo/report/electricity.cfm (accessed August 10, 2011).
(51) *Fuel Economy Improves Notably in Medium-Duty Engines, Driving an Increase in Owner Satisfaction*; J.D. Power and Associates; JDPower.com (accessed December 20, 2012).
(52) *Transportation Demand Module*; U.S. DOE, Energy Information Administration: Washington, DC, 2012; www.eia.gov/forecasts/aeo/assumptions/pdf/transportation.pdf (accessed December 21, 2012).
(53) Saltelli, A.; Annoni, Paola. How to avoid a perfunctory sensitivity analysis. *Environ. Modell. Software* **2010**, *25*, 1508−1517.
(54) Baveye, P.; et al. Recommended practices in global sensitivity analysis. In *Uncertainties In Environmental Modelling & Consequences For Policy Making*; Saltelli, A., Vidoni, D., Mascherini, M., Eds.; Springer: Published in cooperation with NATO Public Diplomacy Division; pp 183−202; doi:10.1007/978-90-481-2636-1_8.