Net Air Emissions from Electric Vehicles:

The Effect of Carbon Price and Charging Strategies

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Abstract

Plug-in hybrid electric vehicles (PHEVs) may become part of the transportation fleet on time scales of a decade or two. We calculate the electric grid load increase and emissions due to vehicle battery charging in PJM and NYISO with the current generation mix, the current mix with a $50/tonne CO_2 price, and this case but with existing coal generators retrofitted with 80% CO_2 capture. We also examine all new generation being natural gas or wind+gas. PHEV fleet percentages between 0.4 and 50% are examined. Vehicles with small (4 kWh) and large (16 kWh) batteries are modeled with driving patterns from the National Household Transportation Survey. Three charging strategies and three scenarios for future electric generation are considered. When compared to 2020 CAFE standards, net CO_2 emissions in New York are reduced by switching from gasoline to electricity;, coal-heavy PJM shows somewhat smaller benefits unless coal units are fitted with CCS or replaced with lower CO_2 generation. NO_X is reduced in both RTOs, but there is upward pressure on SO_2 emissions or allowance prices under a cap.

Introduction

Mass-market electric vehicles have recently been introduced in the USA, following the introduction in China of the BYD plug-in hybrid electric vehicle (PHEV) in 2008. Here we use the term PHEV to denote both plug-in hybrid vehicles and extended-range electric vehicles (EREVs). Vehicle gasoline consumption can be displaced by electric power generation. The net air emissions of such displacement depend on the fleet gasoline mileage, PHEV fleet electric mileage, and electric generation mix at the time vehicle charging takes place. Moving emissions to the electricity sector has advantages, but the resulting environmental quality depends on net changes in emissions.

Existing electricity generation assets can likely support a significant number of PHEVs (*1*-*3*). Previous work has predicted reductions in NO_X and CO_2 emissions when comparing PHEVs to conventional vehicles (CVs), but the magnitude varies and depends on PHEV and generation mix assumptions (*4*-*9*). Pollutant concentration has been estimated to decline in densely populated areas, but may increase near generators (*6*, *7*). The majority of these models suggest an increase in SO_2 emissions; however one comes to a contrasting conclusion based on assumptions that rely on aggressive new emissions control technology (*8*). SO_2 emissions from USA power plants in 2008 and 2009 respectively were 7.9 and 5.6 million short tons, well under the Acid Rain Program cap of 8.95 MT for 2010 (*10*).

In modeling PHEV effects on the electric grid, it is important to know when vehicles will charge, and how much energy they will need. Only one of the previous analyses (*5*) uses driving data to predict the energy needed for recharging and the time when that recharging will likely take place. Those that do not use driving data make assumptions that strongly influence their results (e.g. assuming that a specific percentage of miles are driven using only battery energy, or that all vehicles require the same charge and arrive at designated times at charging points). Variation in assumptions can lead to significant changes in conclusions. For example, if the required charge is changed from 4.8 to 12 kWh and the charge rate is changed from 1.2 to 7.2 kW (variations that are within reasonable ranges) then the peak-added load from all vehicles arriving at specific assumed hours could more than double system load (*1*). Another simplification is modeling only one type of PHEV; if all SUVs were replaced with small cars, emissions would decline significantly regardless of whether those small cars were PHEVs or CVs.

Use of data from surveys of travel that log vehicle type and driving data allows both time and energy requirements to be predicted. We use publicly-available data to predict net emissions from PHEVs under different CO_2 scenarios. Vehicle electricity use is predicted using multiple PHEV types, different charging strategies, battery sizes, CV efficiencies, charge depleting (CD, all-electric mode) efficiencies and charge sustaining (CS, gasoline mode) efficiencies of the vehicles.

To model the electric power generation fleet, we consider four approaches. First, we model a scenario in which the generation capacity needed to charge PHEVs has the same attributes as the generation capacity currently available. Second, we model replacement or retrofit of current coal generators with CO_2 capture and sequestration (CCS). Third, we model all new generation as natural gas (assuming 45% efficiency, a heat rate of 7600 BTU/kWh) (*11*). Finally, we model all new generation as 30% wind, 70% natural gas by energy. We also consider the implications of a binding cap on SO_2 emissions.

We estimate that PHEVs are likely to have lower net emissions of NO_X and CO_2 than a conventional vehicle fleet, given current (10.7 liters/100 km) efficiencies. When compared to 2020 CAFE standards (6.7 liters/100 km), net CO_2 emissions in New York are greatly reduced by switching from gasoline to electricity, but coal-heavy PJM shows lower benefits unless coal units are fitted with CCS or replaced with lower CO_2 generation. NO_X is reduced in both RTOs, but SO_2 increases unless a cap binds (discussed below). A $50/tonne CO_2 price applied only to combustion emissions in the electric sector will have a negligible short-term effects on net CO_2 emissions from PHEVs.

Methods

Estimating the additional electric load from electric vehicles

To model the incremental increase in electricity load from the addition of PHEVs, we used the day trip file from the 2009 national household travel survey (NHTS) (*12*). This file was analyzed to enumerate the trips taken by vehicles in the survey. The NHTS data file contains trip frequency, length, start and end time, mode, and vehicle attributes (make, model, year) from 150,000 USA households. We used the data to model vehicles trips taking into account the battery state of charge. To reflect the range of the current U.S. federal subsidy structure for reported battery capacity, we modeled a small battery of 4 kWh and a large battery of 16 kWh for passenger cars (*13*). Batteries for other vehicle classes were scaled by their charge depleting (CD) mode efficiencies resulting in "small" batteries of 4, 5.27, and 5.58 kWh and “large" batteries of 16, 22.1, and 22.3 kWh for cars, vans, and SUVs/light trucks respectively. Using the trip distances from the NHTS data, we modeled the amount of electricity necessary to move the vehicle assuming two different sets of CD efficiencies. The first, referred to as 2005, assumes 0.19, 0.24, and 0.34 kWh/km for cars, vans, and SUVs/light trucks respectively. The second, referred to as 2020, assumes 0.12, 0.16, and 0.23 kWh/km for cars, vans, and SUVs/light trucks respectively. These values include losses in transmission and are consistent with estimates from other sources *(14-17)*. The lower efficiency case was compared to current conventional vehicles, and the higher case to a fleet meeting 2020 CAFE standards of 35 mpg. Charge rate was assumed to be 7.2 kW, but a lower charge rate (1.4 kW) was not found to change load characteristics significantly for small battery PHEVs (supporting information).

The total distance travelled in electric mode was constrained by a limit that allowed vehicles to use 75% of battery capacity. Once the battery was depleted, gasoline was assumed to provide motive force for the charge sustaining (CS) mode travel. The arrival times for vehicles were then used to predict the times of day when grid load from PHEVs would occur, given different charging strategies (described in the displaced gasoline section below). More information about this method is available in the supporting information.

Since the boundary of PJM is not coincident with state boundaries, we estimated the number of vehicles in PJM by using statewide vehicle registrations for states that are mostly in PJM (*18*). The ratio of vehicles per GWh of annual load for each state was combined in a weighted average to yield an estimate of 30 million vehicles in PJM. We used 10.5 million vehicles in NYISO (*18*). The PHEV market share of this fleet was modeled at three levels: 0.45% (corresponding to a goal of 1 million PHEVs nationwide (*19*)) 10, and 25%.

Generator dispatch

We used the method described in (*20*) to construct monthly short-run marginal cost (SRMC) curves for each electric power generator in PJM and NYISO from EPA eGRID data (*21*) and DOE fuel cost and heat content data (*22*). The monthly SRMC curves allow seasonal NO_X emission calculations. The effects of a price on CO_2 were modeled as in (*20*). Here we do not model the effects of transmission constraints, nor of the additional emissions when generators are started and ramped to full power. We also modeled the effects of replacing all coal generation with coal generators that capture 80% of emitted CO_2, using a 20% energy penalty to de-rate the nameplate capacity. We adopted the assumption that coal plants equipped with CCS reduced SO_2 emissions by 98% (*23*).

The hourly load with and without electric vehicles was combined with the SRMC curve to determine the market clearing price. The generators predicted to bid in at or below the market clearing price make up the generation fleet that in each hour. Once the dispatched generators were determined in each hour, CO_2, NO_X, and SO_2 emissions from the eGRID database for each generator were used to predict emissions from the additional load in response to PHEVs.

Displaced gasoline

Reductions in gasoline consumption from using a PHEV depend on the CD and CS mode efficiencies and the miles travelled in each mode. The miles travelled in CD mode depends on the size of the PHEV battery. The net change in gasoline usage can then be determined, using the efficiency of conventional vehicles. Given large batteries, petroleum consumption could be reduced by 65-90% for every conventional vehicle replaced with a PHEV, depending on the number of charges in the day and the efficiency of the vehicle in charge depleting mode. Small batteries could reduce consumption by 25-50%.

Subtracting the distance travelled in CD mode from the total distance travelled by the vehicle yields the distance travelled in CS mode and the miles displaced from regular gasoline travel. We assume that the efficiency in CS is equal to that of the CV fleet so any increase in CV fleet efficiency increases the CS efficiency. This efficiency determines the amount of fuel used by PHEVs and CVs. This choice was made because, although PHEVs have the ability to use regenerative braking to increase efficiency, they carry additional weight compared to conventional cars, and thus will likely be less efficient in CS mode than a hybrid electric vehicle (HEV) such as the Prius. When a consumer chooses a PHEV instead of a conventional vehicle both will likely have similar technology and therefore more efficient PHEVs will coexist with more efficient conventional vehicles. Because of this the lower efficiency CD mode values are combined with 2005 new vehicle efficiency, and the higher efficiency CD values are compared to 2020 new car efficiency (assumed to be 35mpg). This assumption is used throughout this work.

The changes that will allow the CV fleet to meet the 2020 CAFE standards will also increase efficiency of PHEVs. Advances in aerodynamics and body weight reduction are as applicable to PHEVs as CVs. Drive train and engine efficiency improvements will also increase PHEV efficiency, though improvements will not necessarily yield identical efficiency increases in CVs and PHEVs. If a lighter, more efficient engine is developed for CVs it could be incorporated in PHEVs as a range extender.

Net Emissions

The net emissions associated with displacing CVs with PHEVs depend on the generators used to supply the PHEV load and the efficiency of the conventional vehicle fleet. The emission of CO_2, NO_X, and SO_2 from displaced gasoline were estimated based on EPA data as 2.32 kg/L, 5.80 g/L, and 0.114 g/L respectively (*24, 25*). We calculated the displaced emissions by multiplying the emissions rates by the liters avoided in charge depleting mode electric drive. We also modeled emissions from a hypothetical pure natural gas generation fleet operating at 45% efficiency and with emissions of 378 kg CO_2/MWh, 340 g NO_X/MWh, and 12 g SO_2/MWh (*26*).

We considered three charging strategies. In the "home charging" strategy a vehicle charges after the last trip of the day when it reaches home. Load is added near peak system load. In the "smart charging" scenario a vehicle charges during periods of predicted low load after the last trip of the day. Because the dispatch model is based on SRMC, these periods also have the lowest cost. In the "work charging" scenario a vehicle charges the first time it arrives at work until it leaves and then again after the last trip of the day at home. Thus, the first two strategies (home charging and smart charging) require the same amount of energy and result in only a single charge, while work charging uses more grid energy and results in two separate charges. Both small and large battery sizes are considered for PHEVs in addition to three CD efficiencies. All net emissions in CO_2 scenarios are calculated using the difference in emissions from the load with PHEVs under a given CO_2 scenario and the no-PHEV load under the same CO_2 scenario.

Results

We show results for a 10% PHEV market share of the light-duty vehicle fleet. Other PHEV market shares are included in the supporting information, but results are similar except for the lowest 0.45% level (with fewer PHEVs charging, the specific plant used to charge them becomes uncertain).

Compared to 2005 gasoline fleet efficiency levels, all charging strategies and CD mode efficiencies yield reduction of CO_2 emissions. If the 2020 conventional vehicle fleet efficiency target of 35 MPG is compared to the 2020 CD efficiency, net CO_2 emissions drop significantly in switching from gasoline to electricity in NYISO, but less in PJM because of the differences in generation, unless CCS generation is used.

Home charging occurs near peak system load, smart charging near minimum system load, and work charging occurs both near peak system load (at the same time as home charging) and earlier in the day when most vehicles are arriving at work. These differences in timing result in changes in generator mix and thus emissions. In PJM, home charging results in the greatest CO_2 reductions with no CO_2 price and relies more on natural gas generation. In NYISO, smart charging results in greater CO_2 reductions because of the large number of natural gas generators predicted to be used to meet demand.

Few qualitative changes are observed between small and large battery sizes. Large batteries increase the magnitude of emissions changes, but do not change the sign except in the case of NO_X emissions in NYISO with work or home charging. Large batteries are also more sensitive to charge rate (see supporting information).

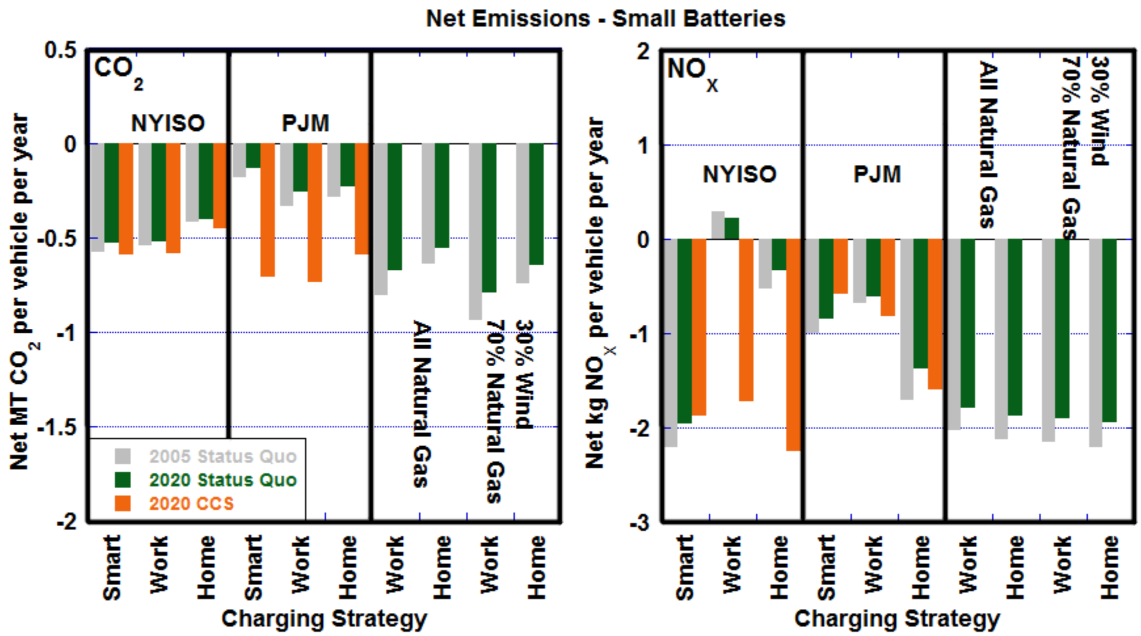

Figure 1 Net metric tons of CO_2, and net kg of NO_X emitted per vehicle-year given PJM and NYISO generation mix and all natural gas and 30% wind / 70% natural gas (in the latter two cases the charging strategy is not relevant because the emissions are independent of the time a vehicle charges and represent charging twice or only once). For comparison, the predicted emissions per conventional vehicle using 2005 (22 mpg) and 2020 (35 mpg) efficiencies are 4.1 and 2.6 MT CO_2, and 10 and 6.4 kg NO_X. Emissions for 2005 fleet and 2020 fleet are compared given the status quo (no CO_2 price) as well as a $50/tonne CO_2 price in conjunction with CCS installed on coal plants given 2020 efficiencies. A similar figure for large batteries is included in the supporting information.

CO_2 emissions

Without a CO_2 price there is no incentive to use a generator with lower CO_2 emissions. Both current and future PHEVs are predicted to result in net decreases of emissions in all charging strategies and both RTOs. In NYISO home charging does not decrease CO_2 emissions as much as smart or work charging because it is displacing gasoline with plants near the peak, often using oil (discussed below). Smart charging relies on 86% natural gas in NYISO, whereas home charging uses only 44% natural gas. In NYISO work and smart charging have similar CO_2 emissions. PJM shows nearly the opposite result with smart charging having significantly lower reductions in CO_2 emissions (relying on 98% coal). Home and work charging in PJM exhibit similar levels of CO_2 emissions.

Adding a $50/tonne CO_2 price does not significantly alter the plants used to meet a given load. The no-PHEV load is adjusted using a -0.1 price elasticity of demand. By itself, this causes a significant decrease in emissions (*20*). No price elasticity was applied to demand associated with PHEVs, since it is likely that in an era with large penetration of PHEVs that the combination of gasoline price, electricity price, battery price, and (possibly) subsidies that encourage large-scale adoption will make the substitution of electricity for gasoline attractive. Emissions associated with PHEVs are compared to emissions given the no-PHEV load and a $50/tonne CO_2 price (supporting information); there was very little effect.

We modeled the effects of converting only coal plants to CCS. Under the CCS scenario, smart charging in PJM relies on 91% coal, and 4% natural gas, with 5% oil and biomass. The percentage from coal is smaller than the non-CCS cases because CCS reduces the net capacity of coal plants. In NYISO, the generation mix for PHEV load is 6.4% coal, 88% natural gas, 2.7% oil, 0.4% biomass, and 2.3% renewable. In PJM, CO_2 emissions savings are roughly doubled from the no-CCS case, while in NYISO there is only a slight reduction compared to the status quo.

Using only natural gas generators (at 45% efficiency) to charge PHEVs, means that charging time does not affect emissions. Thus, the smart charging scenario is not included. Net emissions of CO_2 are reduced by 0.55-0.69 tonnes compared to 2005 CVs and by 0.47-0.57 tonnes compared to 2020 CVs. Reductions in the wind case are larger. In PJM net emissions of CO_2 are likely to be reduced 4-62%. In NYISO, net emissions of CO_2 are likely to be reduced 9-42%.

NO_X emissions

At the outset, we note that there is insufficient experience with PHEVs to reliably predict certain aspects of their operational NO_X emissions (e.g. cold starts). Thus, our results apply to vehicles in the CD mode, but CS mode operations require additional data (such as the chosen control strategy of manufacturers). CO_2 price does not directly affect NO_X emissions. However, coal generators emit more NO_X per MWh produced on average than other generators (*27*), so any increase in natural gas compared to coal reduces NO_X. Emissions of NO_X decline in all scenarios except work charging in NYISO because high-emission generators being used at a specific time in the day to charge PHEVs in NYISO. Both home and work charging increase peak demand because the uncontrolled charge after vehicles arrive home closely coincides with system peak load. Smart charging in NYISO results in the greatest reductions of NO_X. This relies heavily on natural gas that has low NO_X emission rates. Home charging uses the same energy as smart charging, but takes place largely in the evening near peak load (supporting information). In PJM home charging based on the current generation mix and short-run marginal costs would be 55% coal, 33% natural gas, 10% oil and 2% biomass. Using the 2005 generation mix of NYISO. this load would be met with a mostly oil generators: the marginal units for home charging in NYISO would be 1% coal, 44% natural gas, 54% oil and 0.5% biomass. Oil use in New York reached a 15-year high in 2005 (16% of generation). Dual-fuel generation represents the majority of marginal units in New York City, Long Island, and Albany (28). In 2008, high oil price and low natural gas price drove these units to use 6 times more gas than in 2005 (supporting information), and oil represented only 3% of generation. It is reasonable to expect that recent shale gas exploitation will keep oil use low in New York in the next decade, Thus, our "all natural gas" scenario is likely to better represent future NYISO emissions from charging PHEVs than the 2005 data.

Adding a \$50/ton CO_2 price significantly decreases the no-PHEV load. This is especially important in NYISO. Instead of seeing increases of NO_X ranging from 0.22-0.29 kg per vehicle-year as in the status quo case reduction of 1.5-1.6 kg per vehicle-year are expected.

In the CCS scenario there is little change in NO_X emissions. For amine-based carbon capture (added to coal plants in our model) to function ,the amount of SO_2 and NO_2 must be below 10 ppm, but NO_2 makes up very little of the NO_X emissions from a power plant (*23*). IGCC and chilled ammonia systems also require low SO_2. CCS decreases the electricity output of coal plants per MMBTU of fuel (due to the energy penalty of CCS), but the NO_X/MMBTU remains roughly constant decreasing only 1% (*21*). Thus, the NO_X/MWh generated by coal plants would increase without additional emission controls. This is especially noticeable in the PJM smart charging scenario that relies heavily on coal. NO_X emissions are still reduced compared to a CV.

Using only natural gas causes significant reductions in NO_X emissions. This model does not reflect any increase in emissions from gas generators ramping to follow wind (29), so NO_X emissions from the electricity generation fall by 30%. NO_X emissions will decline between 7 and 43% in PJM and 5-70% in NYISO except in the work charging scenario. In either case NO_X emissions are likely to decrease significantly for each PHEV that displaces a CV.

SO_2 emissions

Unlike the other pollutants, net SO_2 emissions increase in most scenarios (figure 2a). National 2005 electric sector emissions were 9.4 million tonnes of SO_2, compared to combined emissions for highway vehicles of 0.13 million tonnes (*25*), reflecting the low sulfur content of motor fuels in the United States. Even with 25% PHEVs, neither RTO would exceed current SO_2 emissions caps established under the Acid Rain Program, because the annual SO_2 emissions have declined in 2008 and 2009 (*30*) to 88% and 63% of the 2010 cap, respectively. The decline is likely due to actions taken in anticipation of the now-voided Clean Air Interstate Rule and demand reductions associated with the recent recession. The highest increase in SO_2 emissions from the electricity sector from our model was 0.17 million tonnes in PJM (with smart charging, large batteries, low efficiency CD mode, and 25% PHEVs), comparable to the current total emissions from highway vehicles using liquid fuels.

The proposed Clean Air Transport Rule (CATR) would greatly reduce the allowable SO_2 emissions in both NYISO and PJM, making results such as those in figure 2a unlikely in the 28 capped states unless the CATR is not implemented. We now consider the introduction of PHEVs when generators have complied with the 2014 CATR. SO_2 emissions must decrease below those in 2005 by 77% in NYISO to comply. PJM is not made up of a single state; the weighted average of reductions necessary in Pennsylvania, Ohio, Maryland, Virginia, West Virginia, Delaware, and New Jersey was estimated to be 83%. These reductions were then applied to SO_2 emissions factors for plants in each RTO and the model was rerun (figure 2b). With the electric generation reductions necessary to meet the CATR, net vehicle emissions in NYISO are near zero and those in PJM are always lower than 0.9 kg per vehicle-year for small batteries.

We emphasize that under CATR, while per-vehicle net SO_2 emissions increase, total emissions from electric generating units in the capped states cannot. Thus, if CATR goes into effect as proposed, and we assume emissions in the RTOs are just under the cap without PHEVs, the additional generation would cause an upward pressure on SO_2 allowance prices. EPA estimates that the marginal cost of SO_2 allowance prices in Pennsylvania near the cap limit will be ~$22 per additional thousand tonnes (*31*). Thus, for 0.9 kg/vehicle-year, the approximately 840 tonnes of additional SO_2 emissions from charging vehicles in Pennsylvania would increase the SO_2 allowance prices by ~$19/tonne (EPA estimates that the allowance price will be ~$2300/tonne at the proposed Pennsylvania 2014 cap limit of 128,542 tonnes).

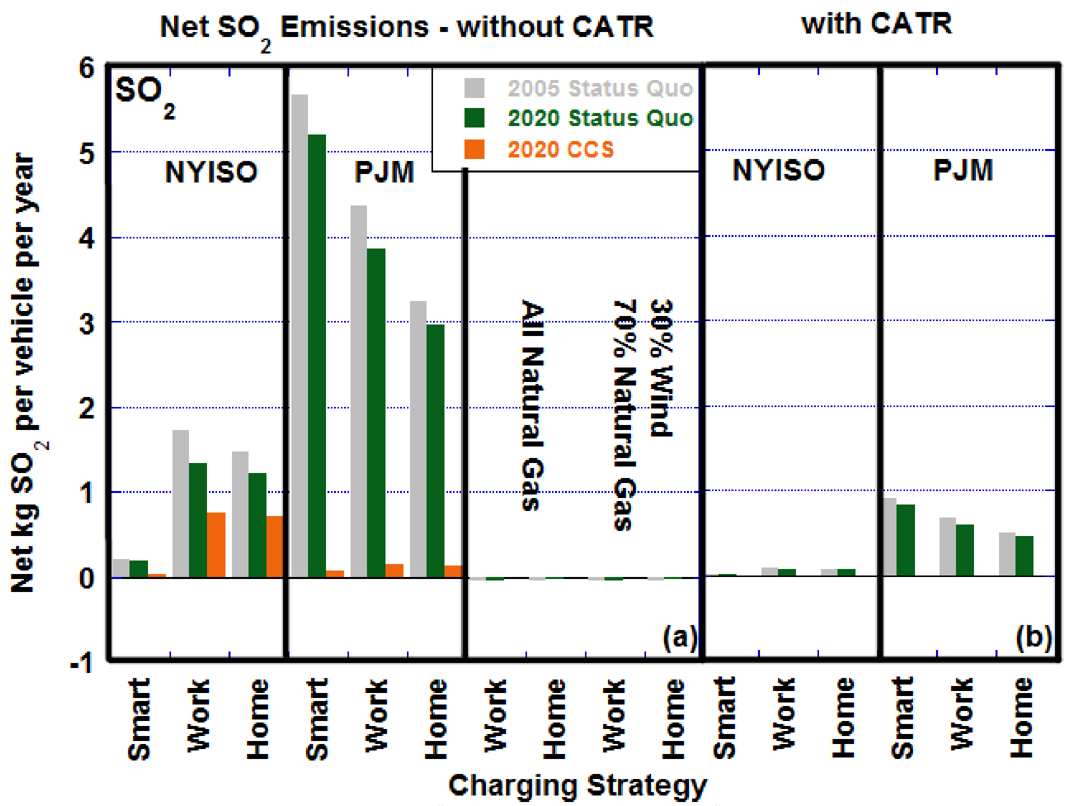

Figure 2: Net kg SO_2 emitted per vehicle-year given (a) PJM and NYISO generation mix of 2005, as well as all natural gas and 30% wind / 70% natural gas, and (b) PJM and NYISO with generator emissions factors for SO_2 reduced to comply with CATR. For comparison, the predicted annual emissions per conventional vehicle using 2005 (22 mpg) and 2020 (35 mpg) efficiencies are 0.20 and 0.13 kg SO_2. Emissions for 2005 fleet and 2020 fleet are compared given the status quo (no CO_2 price) as well as a \$50/tonne CO_2 price in conjunction with CCS installed on coal plants. Different charging strategies are modeled to determine the timing of PHEV charging. A similar figure for large batteries is included in the supporting information.

SO_2 emissions would not change significantly in response to a CO_2 price alone except for an increase in the NYISO smart charging case. However, CCS will require SO_2 emissions to be reduced significantly to avoid contamination during portions of the capture process for IGCC or amine capture. Thus, the net SO_2 emissions in the CCS cases are closer to zero (*23*). Using only natural gas or a combination of natural gas and wind both results in essentially no change to net SO_2 emissions.

Discussion

Net emissions from PHEVs depend on the efficiency of the conventional vehicle fleet, PHEV CD (charge depletion, all-electric mode) mode efficiency, charging strategy, battery size, driving patterns, and generator mix used for charging. In all cases, net CO_2 emissions decline. In most cases, NO_X emissions decline (NO_X emissions in NYISO increase when combined with work charging, because of the heavy reliance during 2005 on oil to accomplish this charging and specific plants being used; natural gas has supplanted oil in most NYISO units recently). With large batteries, NO_X emissions are unchanged. Even in a RTO with cleaner generation overall, the marginal units might have higher emissions factors; in PJM, the plants charging near peak emit less NO_X than those in NYISO. Using only natural gas, or gas and wind combined, will result in significant decreases to CO_2 and NO_X emissions. It is also possible that there would be some improvements to grid stability and a decreased need for balancing fluctuations in wind generation if variable charging of PHEVs is coordinated with changes in wind output.

Electric vehicles will place upward pressure on net SO_2 emissions. With the Clean Air Interstate Rule vacated by the courts and the final rule promulgation of CATR delayed by EPA, there is uncertainty about the level of capped emissions. Net SO_2 emissions caused by vehicles will be less than 6% in NYISO and 2% in PJM, of the proposed 2014 CATR cap on electric generators under any of the reduced SO_2 scenarios. We note that the upstream (largely refinery) emissions displaced by decreasing gasoline use are ~ 0.45 kg SO_2 per vehicle-year (supporting information). This is more than half of the SO_2 emissions reduction required to comply with CATR. However, it is possible that the associated upstream refining emissions will also decrease when CATR is implemented.

Choosing a charging strategy can change the resulting net emissions associated with PHEVs. In NYISO, the smart charging scenario generally resulted in lower or equal net emissions than home charging and lower than work charging, resulting in lower emissions. In PJM, smart charging generally causes higher emissions because coal is often on the margin at night. In PJM there is a tradeoff between use of off-peak charging and increased emissions. RTOs and LSEs should be aware of possible tradeoffs between cost and emissions before encouraging particular charging strategies. Information about generation resources should be used in concert with pricing data to find the optimal charging strategy in individual RTOs.

Conclusion

There are strong arguments in favor of electrification of the transportation sector in addition to net emissions. Combining numerous mobile emission sources into a far small number of stationary sources offers opportunities for cost-effective emissions reduction that may not otherwise be feasible in the transportation sector, and the location of emissions is likely to be moved farther from densely populated areas. If PHEV cars displace light trucks, SUVs, and vans from the fleet, emissions will be further reduced from the values reported here.

Enacting a CO_2 price of \$50/tonne will not be effective at reducing net CO_2 emissions from a PHEV fleet. PHEVs are likely to place upward pressure on SO_2 allowance prices if emission caps bind, or to increase emissions if the caps do not bind.

PHEVs will probably reduce net CO_2 and NO_X emissions, but are unlikely to reduce net SO_2 emissions.

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Supporting Information Available

Additional information is available free of charge via the Internet at http://pubs.acs.org.

Brief:

Net emissions of CO_2 and NO_X from PHEVs in PJM and NYISO are significantly reduced, but there is upward pressure on SO_2 emissions.

Literature Cited

1 Lemoine, D. M.; Kammen, D. M.; Farrell, A. E. An innovation and policy agenda for commercially competitive plug-in hybrid electric vehicles. *Environ. Resour. Lett*. **2008**, 3 (1), 1-10.

2 Kintner-Meyer, M; Schneider, K.; Pratt, R. Impact assessment of plug-in hybrid vehicles on electric utilities and regional US power grids. Part I: Technical analysis. Pacific Northwest National Laboratory, Richland, WA, 2007.

3 Denholm, P.; Short, W. An evaluation of utility system impacts and benefits of optimally dispatched plug-in hybrid electric vehicles. National Renewable Energy Laboratory: Golden, CO, 2006.

4 Samaras, C,; Meisterling, K. Life cycle assessment of greenhouse gas emissions from plug-in hybrid vehicles: Implications for policy. *Environ. Sci. Technol.* **2008**, *42* (9), 3170-3176.

5 Sioshansi, R.; Denholm, P. Emissions impacts and benefits of plug-in hybrid electric vehicles and vehicle-to-grid services, *Environ. Sci. Technol.* **2009**. *43* (4), 1199-1204.

6 Stephan, C. H.; Sullivan, J. 2008. Environmental and energy implications of plug-in hybrid-electric vehicles. *Environ. Sci. Technol.* **2008**. 42 (4), 1185-1190.

7 Thompson, T.; Webber, M; Allen, D. T. Air quality impacts of using overnight electricity generation to charge plug-in hybrid electric vehicles for daytime use. *Environ. Resour. Lett.* **2009**. 4 (1): 014002.

8 Environmental assessment of plug-in electric hybrid vehicles, vol. 2 United States air quality analysis based on AEO-2006 assumptions for 2030. Electric Power Research Institute Report 1015326, Palo Alto, CA, 2007.

9 Environmental assessment of plug-in electric hybrid vehicles vol 1 nationwide greenhouse gas emissions. Electric Power Research Institute, Palo Alto, CA, 2007.

10 Table of Emissions, Emission Rates, Heat Input: 2008 vs. 2009. U.S. Environmental Protection Agency: Washington, DC, 2010; http://www.epa.gov/airmarkets/images/ARPCoal08v09annual.xls

11 11 Average Operating Heat Rate for Selected Energy Sources, Energy Information Administration: Washington, DC, 2010.

12 *National Household Travel Survey*, U.S. Department of Transportation: Washington, DC, 2010; http://nhts.ornl.gov/download.shtml

13 The American Recovery and Reinvestment Act of 2009. Public Law. 111-5, Congress, 2009; http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=111_cong_bills&docid=f:h1enr.pdf

14 Peterson, S. B.; Apt, J.; Whitacre, J. F. Lithium-ion battery cell degradation resulting from realistic vehicle and vehicle-to-grid utilization. *J. Power Sources.* **2010**, 8, 2385-2392.

15 Comparing the benefits and impacts of hybrid electric vehicle options for compact sedan and sport utility vehicles. Electric Power Research Institute, Palo Alto, CA, 2001.

16 Elgowainy, A; Han, J; Poch, L.; Wang, M.; Vyas, A.; Mahalik, M.; Rosseau, A. Well-to-wheels analysis of energy use and greenhouse gas emissions of plug-in hybrid electric vehicles. Argonne National Labs, Argonne, IL 2010.

17 Shiau, C-S; Kaushal, N.; Hendrickson, C.T., Peterson S. B.; Whitacre J. F.; Michalek, J. J. Optimal plug-in hybrid electric vehicle design and allocation for minimum life cycle cost, petroleum consumption, and greenhouse gas emissions. *ASME J. Mech. Design*, **2010**, 132, 1-11.

18 State motor vehicle registrations – 2006, Table MV-1, U.S. Department of Transportation, Federal Highway Administration: Washington, DC, 2007.

19 New Energy for America. http://www.barackobama.com/pdf/factsheet_energy_speech_080308.pdf

20 Newcomer, A; Blumsack S. A.; Apt, J; Lave, L. B.; Morgan, M. G. Short run effects of a price on carbon dioxide emissions from U.S. electric generators. *Environ. Sci. Technol*. **2008**. *42* (9), 3139-3144.

21 Emissions & generation resource integrated database (eGRID), U.S. Environmental Protection Agency: Washington, DC, 2007 http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html

22 Cost and quality of fuels for electric plants 2004 and 2005, U.S. Department of Energy: Washington, DC, 2006.

23 Integrated Environmental Control Model (IECM), Version 6.2.4, Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh; http://www.cmu.edu/epp/iecm/.

24 Emission facts: average annual emissions and fuel consumption for passenger cars and light trucks, U.S. Environmental Protection Agency: Washington, DC, 2000; http://www.epa.gov/otaq/consumer/f00013.htm.

25 National emissions inventory, U.S. Environmental Protection Agency: Washington, DC, 2005. http://www.epa.gov/ttn/chief/eiinformation.html

26 AP 42, Fifth Edition, Volume I, Chapter 3: Stationary internal combustion sources, U.S. Environmental Protection Agency: Washington, DC, 2000.

27 Jaramillo, P.; Griffin, 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* (17), 6290-6296.

28 Fuel diversity in the New York electricity market. NYISO, 2008; http://www.nyiso.com/public/webdocs/documents/white_papers/fuel_diversity_11202008.pdf.

29 Katzenstein, W.; Apt, J. Air Emissions Due To Wind And Solar Power. *Environ. Sci. Technol.* **2009**. 43(2): 253-258.

30 Emission, compliance, and market data. U.S. Environmental Protection Agency: Washington, DC, 2010; http://www.epa.gov/airmarkets/progress/ARP_1.html

31 Table IV.D-2 of Federal implementation plans to reduce interstate transport of fine particulate matter and ozone. U.S. Environmental Protection Agency: Washington, DC, 2010.

Net Air Emissions from Electric Vehicles:
The Effect of Carbon Price and Charging Strategies

Scott B. Peterson, J.F. Whitacre, and Jay Apt

Supporting Information

Table of Contents

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Timing and magnitude of additional load from PHEVs

The national household transportation survey (NHTS) was used as the basis for estimating the timing and magnitude of additional load from PHEVs (*1*). The NHTS day trip file was divided according to month, and by weekday and weekend. Then the resulting trip data was reorganized to list the vehicle trips for the day. Estimation of the driving distribution was conducted for weekday (Monday-Friday) and weekend days due to significant changes in driving patterns. These data were used to list vehicle trips by trip length (some are zero length for cars not used during a day), for each month, with weekend days separated from work-week days. We modeled that the vehicles operate entirely on electric propulsion until they reach the design limit of energy in the pack (assumed as 75% of the rated capacity). Thereafter the vehicle continues in charge sustaining mode for the rest of the driving, using gasoline for propulsion (PHEV) or charge sustaining (EREV). The NHTS data on use of cars, vans, and light trucks allowed us to model the charging load based on the relative proportions of those vehicle types. The electricity use for all trips was based on vehicle efficiency. Added load is based on battery state and an assumed 7.2 kW circuit infrastructure (240V single-phase, 40A de-rated for continuous use). The charger is assumed to by 92% efficient. A separate run was conducted assuming 1.4 kW rate charging and similar emissions results were achieved for small batteries.

Not all vehicles are driven on a given day so all vehicles, whether driven or not, were included in the total number. The vehicle trips were modeled on a monthly basis. Therefore it was assumed that the load added by PHEVs was identical on weekdays throughout a given month and also that all weekends in a month are identical.

Four different levels of PHEV market penetration were modeled. The first is based on the goal of having 1 million PHEVs nationwide (0.45%) (2). The others are 10%, 25%, and 50%. For every number of PHEVs modeled the entire NHTS day trip file was run. To model a specific percentage the file was looped multiple times until the desired number of vehicles to constitute the correct percentage was reached or surpassed. This was done to avoid omitting the vehicles near the end of the dataset on the last loop in each case otherwise. In all cases the charging time is limited both by the time the vehicle is available to charge and the charge needed based upon the reported distance driven prior to charging.

The timing of vehicle charging varies depending on the strategy modeled. An example is shown (figures S1 and S2) for the highest and lowest load days in PJM. The example includes a fleet of 50% PHEVs to illustrate the timing. The timing of smart charging is based on the average load during the given month and therefore may not perfectly flatten load during every night. The lowest load day of the year was a weekend and therefore it is unsurprising that the PHEV load leads to an increase over existing load.

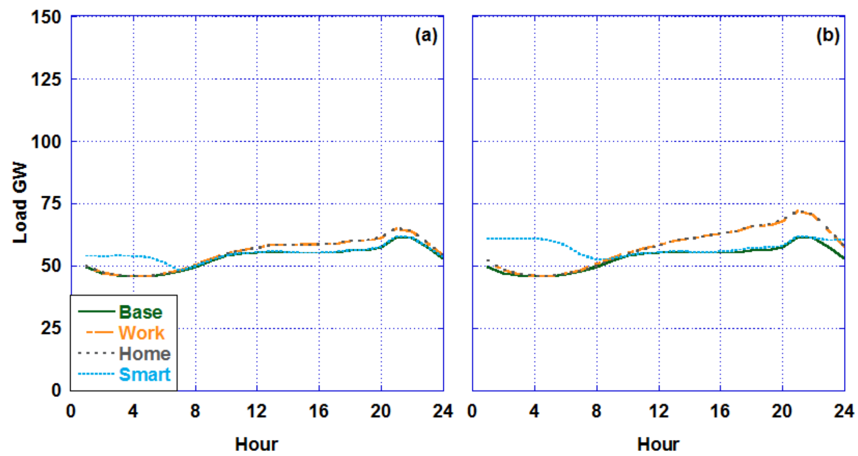

Figure S1: Load on day of minimum hourly demand (Sunday, April 10, 2005) in PJM, 50% PHEVs with (a) small batteries and (b) large batteries

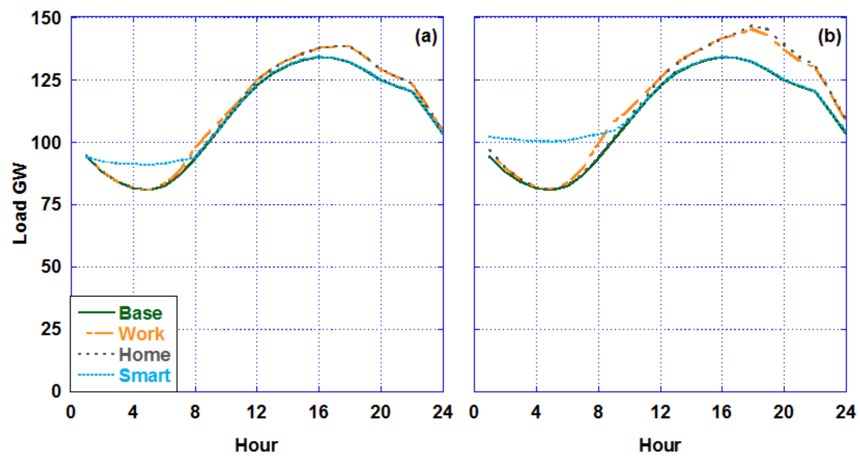

Figure S2: Load on day of maximum hourly demand (Tuesday, July 26, 2005) in PJM, 50% PHEVs with (a) small batteries and (b) large batteries

Work and home charging are quite similar throughout the year so it is possible to show the average added load per PHEV used. Results for home charging are shown in figure S3. The average hourly load per PHEV driven is shown given different charge depleting mode efficiencies, battery sizes (a and b for small, c and d for large) and separating weekends and weekdays (a and d for weekday, b and c for weekend). It is clear from the figure that many of the small battery PHEVs are depleted upon arrival at their destination. This can be observed by noting the small difference between current and 2020 efficiencies. With large batteries the difference is much greater because a significant number of vehicles do not entirely deplete their battery.

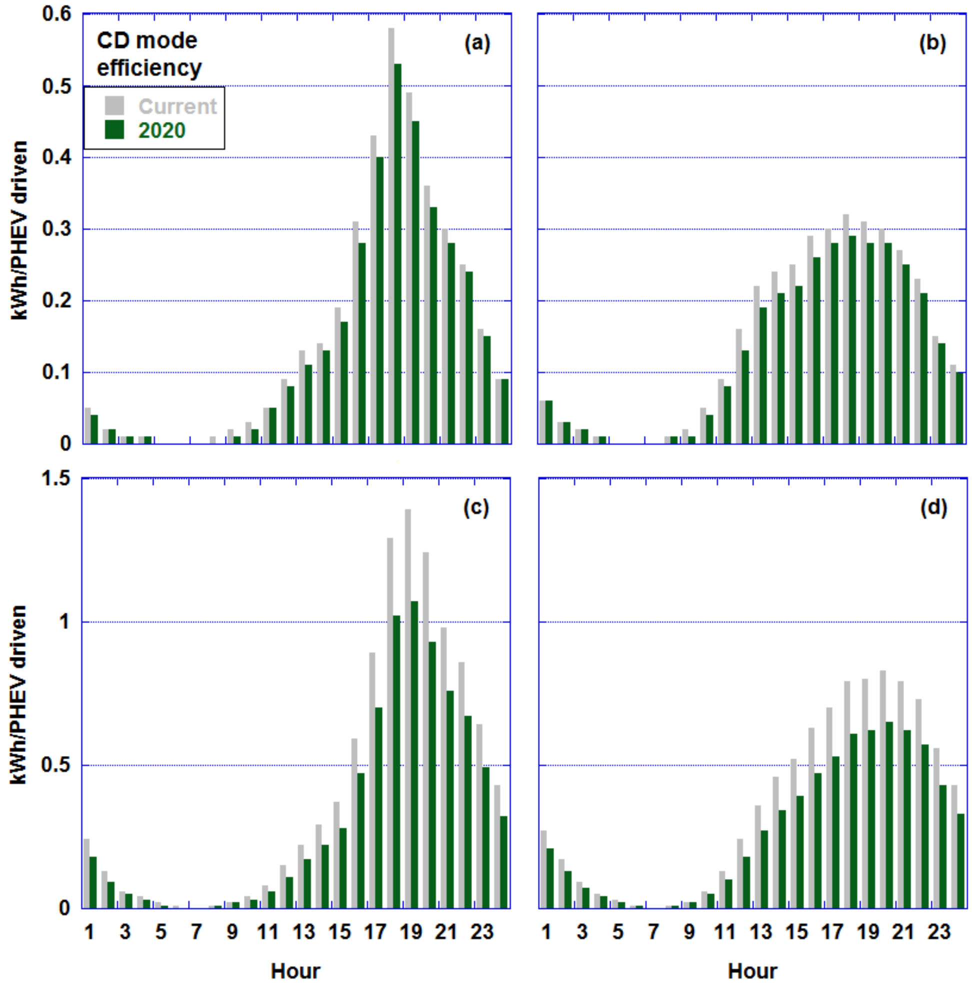

Figure S3: Load per PHEV driven given home charging for (a) small batteries on a weekday, (b) small batteries on a weekend, (c) large batteries on a weekday, (d) large batteries on a weekend.

Figure S4 shows results for work charging and is otherwise similar to figure S3. It is notable that the small battery cases can charge the battery in one hour so the magnitude of load is also indicative of the timing of vehicle arrival. With large batteries this is no longer the case.

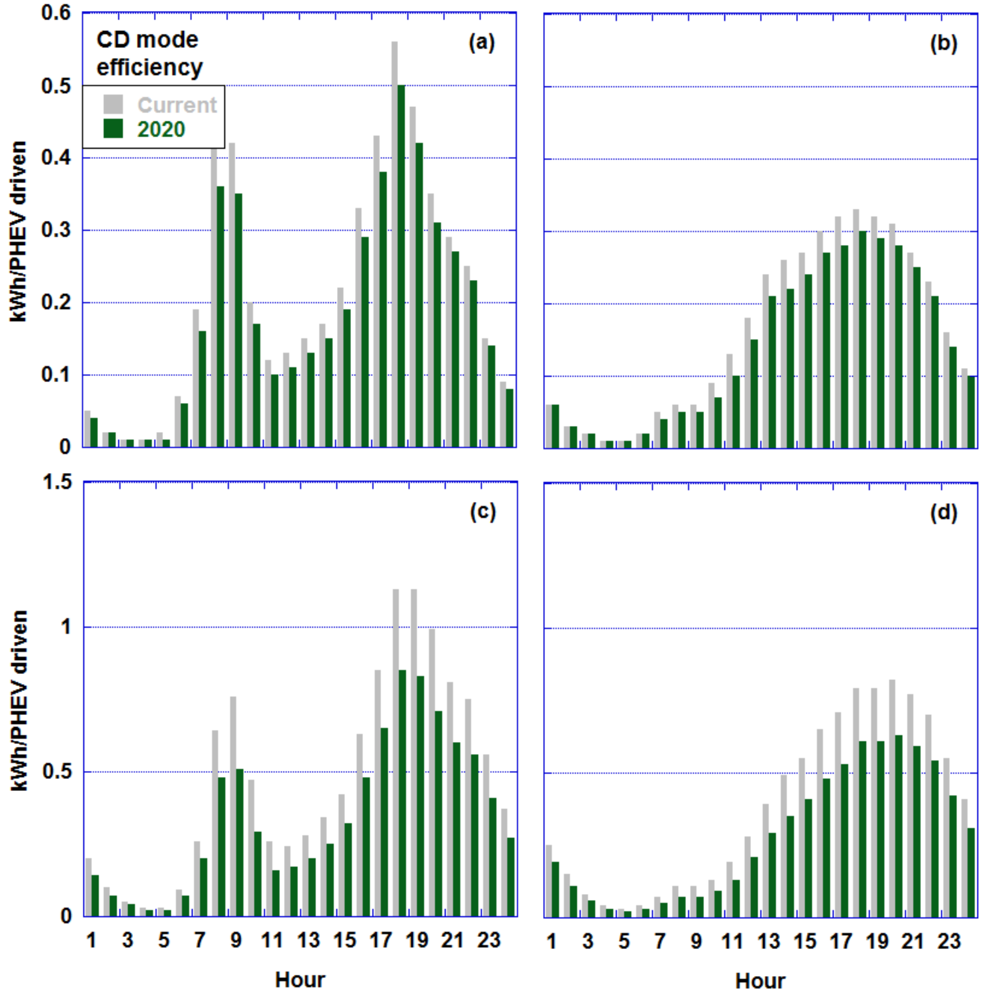

Figure S4: Load per PHEV driven given work charging for (a) small batteries on a weekday, (b) small batteries on a weekend, (c) large batteries on a weekday, (d) large batteries on a weekend.

If a slower charge rate is used then the load curves do change. Figure S5-S6 shows load changes when charging infrastructure is varied. What is most notable is the load given small batteries is very similar. This results in similar emissions and means that charge rate is not greatly relevant for small batteries. This is a response to the varied nature of vehicle arrival times. The natural distribution means that peaks from arrival and short charge times largely do not matter. With large batteries a low charge rate does greatly change the load profile by lowering peak additional load and spreading it across the day. However such low charge rates are unlikely with large batteries. In some cases this limits the ability of vehicles to actually charge their battery. The lower efficiency rate is used to maximize demand associated with PHEVs.

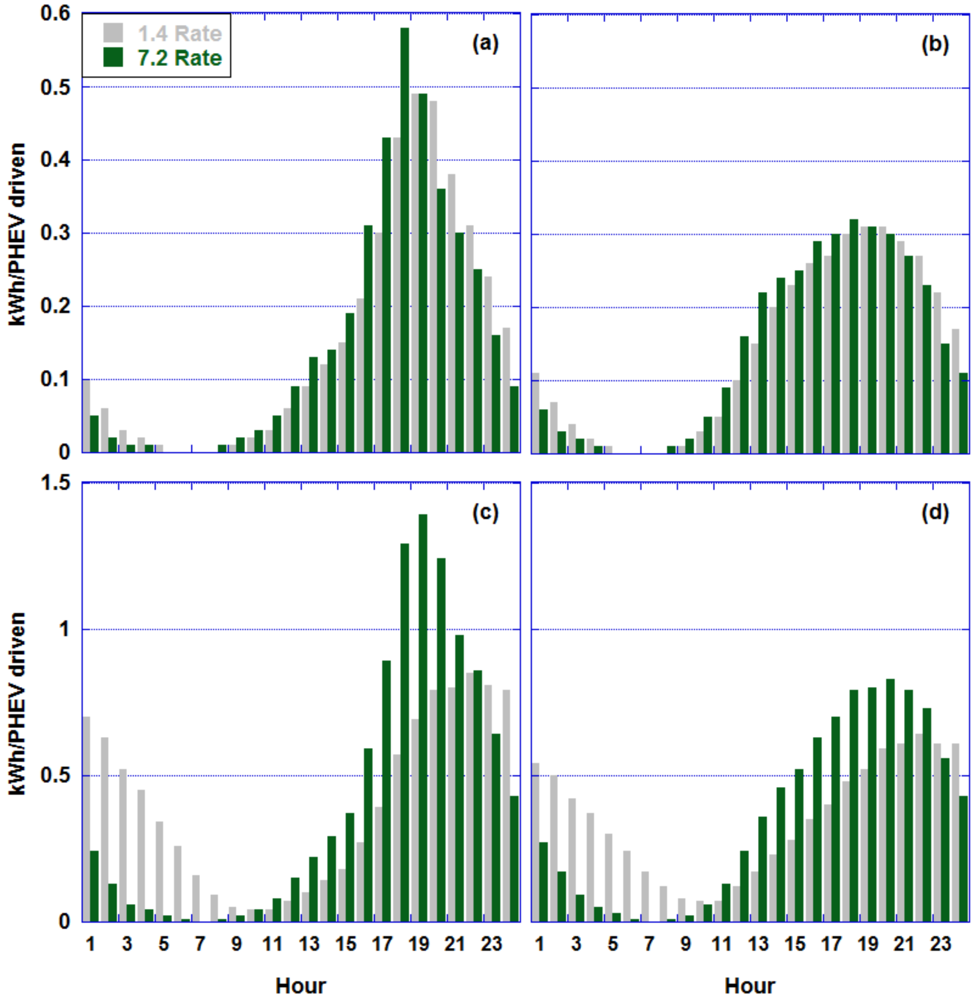

Figure S5: A comparison of load given home charging with lower efficiency vehicles and two separate charge rates for (a) small batteries on a weekday, (b) small batteries on a weekend, (c) large batteries on a weekday, (d) large batteries on a weekend.

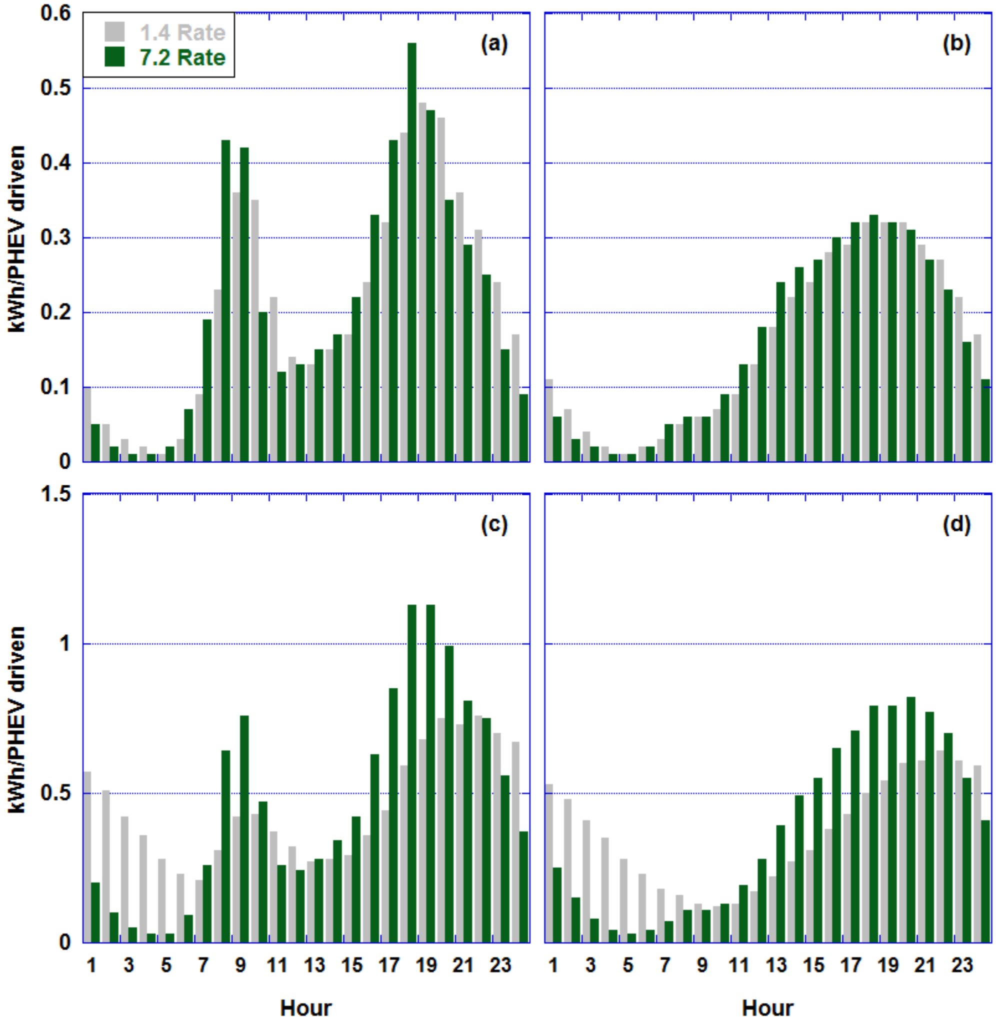

Figure S6: A comparison of load given work charging with lower efficiency vehicles and two separate charge rates for (a) small batteries on a weekday, (b) small batteries on a weekend, (c) large batteries on a weekday, (d) large batteries on a weekend.

Generator dispatch

We used the method described in (*3*) to construct monthly short-run marginal cost (SRMC) curves for each electric power generator in PJM and NYISO from EPA eGRID data (*4*) and DOE fuel cost and heat content data (*5*). We combined that with regionally appropriate fuel cost and quality data from the same year. A dispatch order curve was created for PJM and NYISO using the 2005 data and reported annual generator availability.

We modeled the effect of a CO_2 price using the CO_2 emissions data included in the eGRID database. Adding a CO_2 price increases the short run marginal cost (SRMC) of generators with listed CO2 emissions and can change the dispatch order slightly. The change is more noticeable in PJM where a large part of the generation mix is low cost coal than in NYISO. We also modeled the effect of a CO_2 price on dispatch mixes where the coal generators are replaced with coal generators that capture 80% of their CO_2 and sequester it. The effects of the plant use of electric power for capture, compression, pipeline shipment, and injection of the carbon dioxide were modeled by de-rating the plant output by 20% of current nameplate generation capacity. We assume there are no forced or unforced outages, and no constraints due to NO_X seasonal shutdowns to simplify modeling. The monthly SRMC curves allow seasonal NO_x emission calculations (for plants that repot separate emissions factors in eGRID database). An example SRMC curve created based on the yearly average capacity for PJM is shown in figure S7. Given a scheduled no-PHEV load the plants with minimal SRMC that meet the load are used. PHEV load is then added onto the no-PHEV load for each hour and the additional plants needed are determined along with their related emissions.

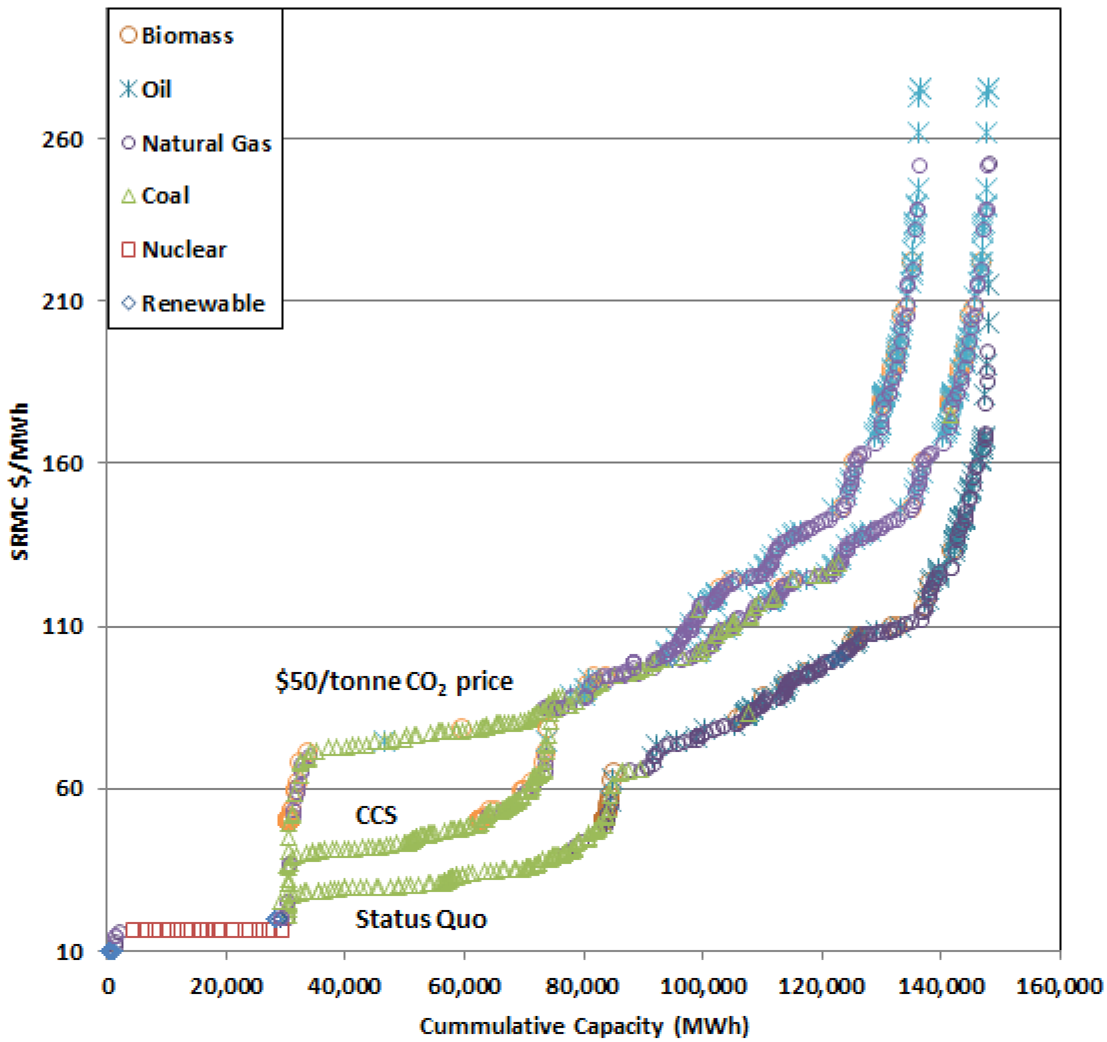

Figure S7: SRMC curve for PJM based on yearly averages. Three different curves are shown for the three different carbon scenarios. Adding CCS decreased the SRMC of coal plants compared to a $50/tonne CO_2 price, but also results in a decrease in overall system capacity.

The effects of a price on CO_2 were modeled as in (3). The hourly load with and without electric vehicles was combined with the SRMC curve to determine the market clearing price. The generators predicted to bid in at or below the market clearing price make up the generation fleet that in each hour. Once the dispatched generators were determined in each hour, CO_2, NO_x, and SO_2 emissions from the eGRID database for each generator were used to predict emissions from the additional load in response to PHEVs.

Here we do not model the effects of transmission constraints, nor of the additional emissions when generators are started and ramped to full power. However eGRID records emissions from plants throughout the year and thus should include emissions associated with ramping plants up and down. Plants that ramp up and down, or start often should have relatively higher emissions rates. The predicted number of plant starts does not increase a great deal in response to the added load from PHEVs and is shown in table S1 for large batteries in NYISO and PJM. It is possible given smart charging the number of plants starts will actually likely decline. With smaller batteries the changes in plant starts are also smaller.

Table S1: Generator starts with large batteries

Charging Strategy	%PHEVs	Percent Change	
		NYISO	PJM
Work Charging	0.44%	0.12%	0.16%
	10%	1.9%	9.4%
	25%	7.6%	29.3%
Home Charging	0.44%	0.11%	0.12%
	10%	2.8%	8.4%
	25%	9.0%	25.6%
Smart Charging	0.44%	-1.7%	-0.9%
	10%	-13%	-10%
	25%	-28%	-23%

Figures S8-9 show the modeled plants starts with and without PHEVs in PJM. The eGRID data should reflect actual emissions from plants. As seen in the figures the plants that are cycling due to changes in load throughout the day are the same plants that are cycling more or less often in response to PHEVs. Because of this it is assumed that their emissions factors already largely take into account the cycling that the plants undergo.

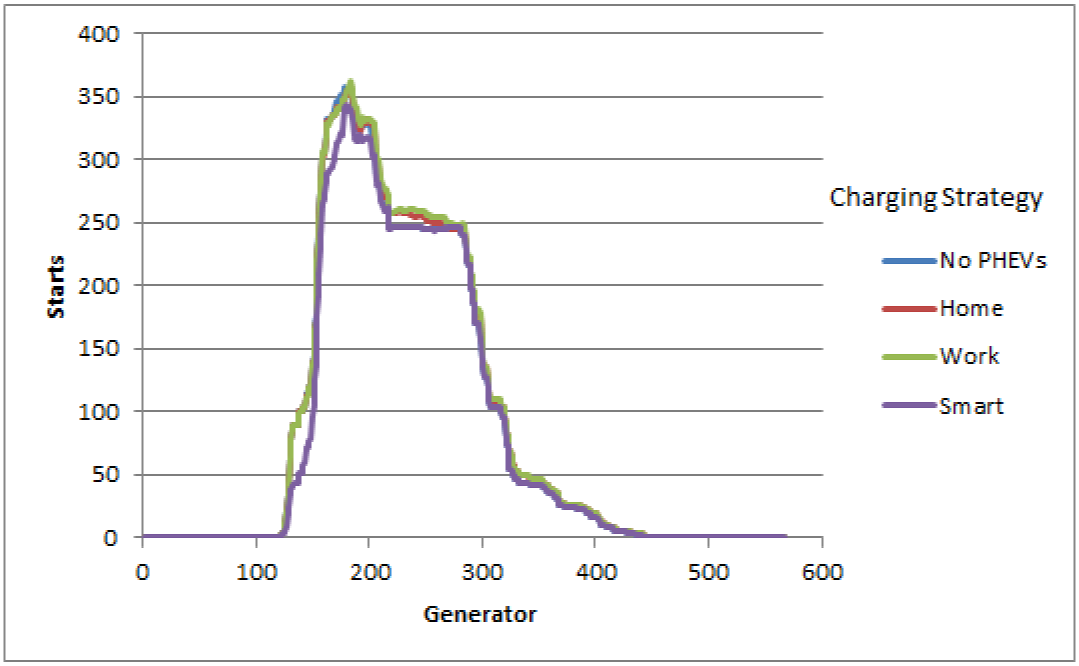

Figure S8: Modeled plant starts in PJM given 10% PHEVs and small batteries

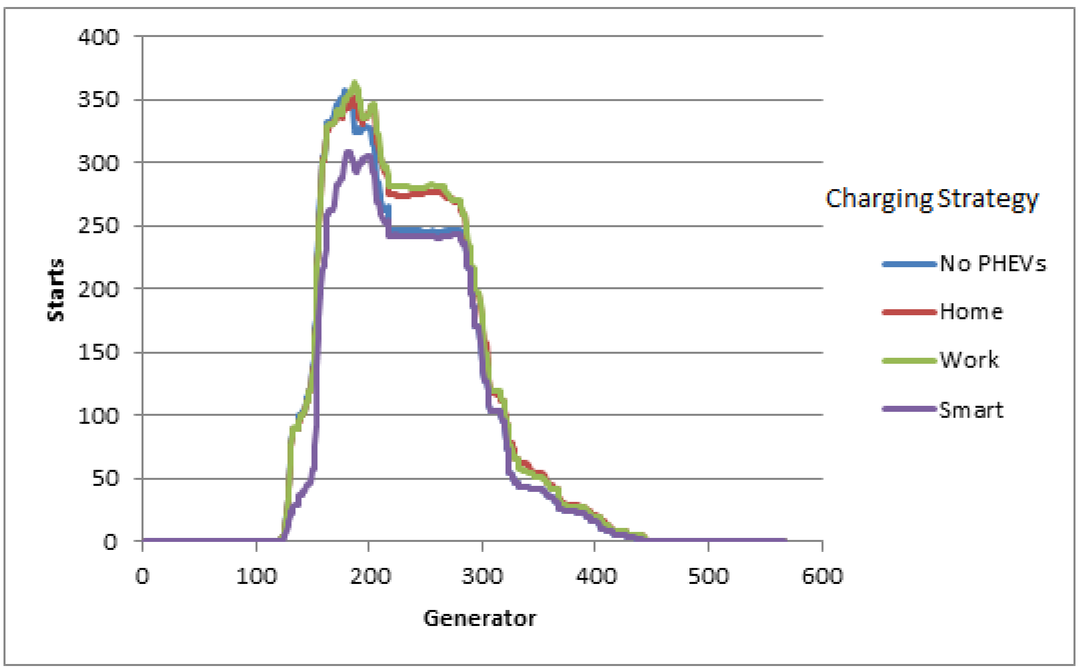

Figure S9: Modeled plant starts in PJM given 10% PHEVs and large batteries

This model does not account for regional flows between power control areas. In 2005 net imports accounted for 10% of NYISO load (4). Net exports accounted for 6% of PJM generation (4). Because only the load in each area was accounted for, the model under or over estimates the amount of pollution depending on where the excess generation occurred. This difference explains a great deal of the variation between the reported and modeled emissions in each power control area. The two did not solely transfer power between markets though. So the emissions characteristics of the imports and exports are not clear. According to a letter from the director of system and resource planning for NYISO the majority of imports came from Canada and were mostly hydroelectric and nuclear generation (*6*).

Table S2: Comparison of modeled emissions and reported emissions in 2005

	Million Tons CO_2	Tons SO_2	Tons NO_X
PJM reported	460	2,900,000	740,000
PJM modeled	410	2,900,000	670,000
Diff	-10%	-1%	-9%
NYISO reported	61	180,000	66,000
NYISO modeled	59	200,000	74,000
Diff	-3%	11%	12%

We also modeled the effects of replacing all coal generation with coal generators that capture 80% of emitted CO_2, using a 20% energy penalty to de-rate the nameplate capacity. We adopted the assumption that coal plants equipped with CCS reduced SO_2 emissions by 98% (*7*).

Generator fuel mix used for charging

The generation mix used to charge PHEVs depends on the charging time of day shown previously. The specific plants used were estimated following a previously described method (8). Figures S10 through S12 show the mix of fuel types predicted to be used for charging PHEVs given different numbers of PHEVs, charging strategies, and carbon scenarios. Only the medium charge depleting mode efficiency values are shown since there were only negligible changes in response to changing the charge depleting efficiency.

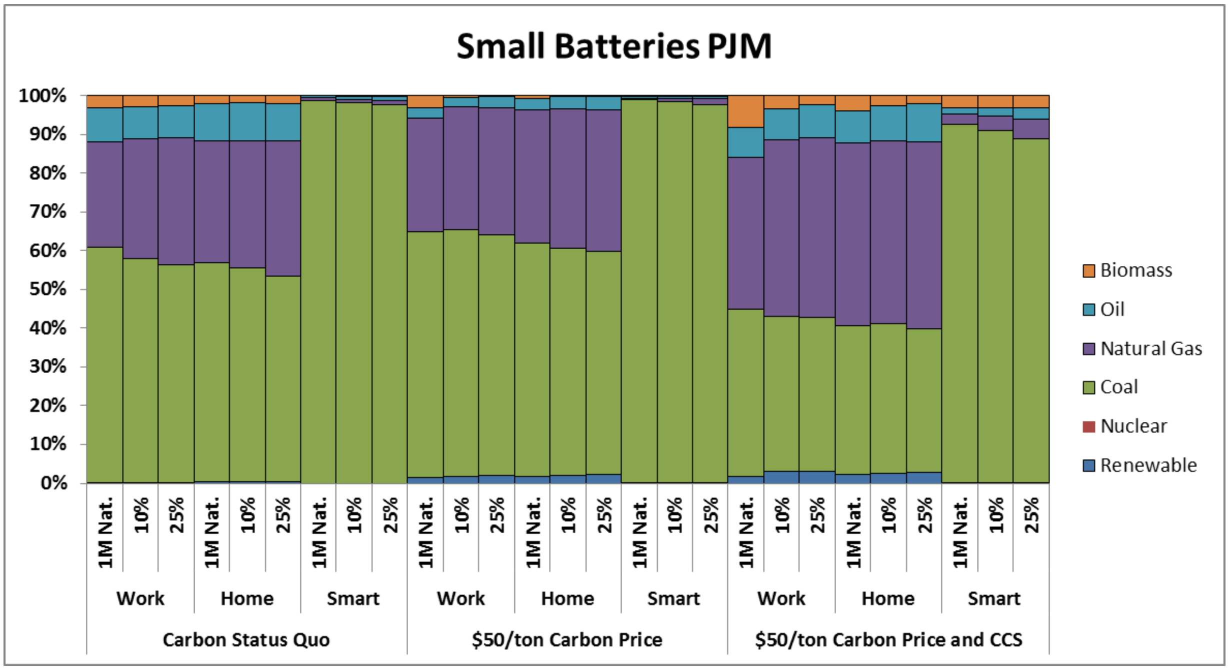

Figure S10: Generation mix used to charge in PJM given small batteries and PHEV numbers ranging from 1 million nationwide to 50% of the fleet. Coal declines as number of PHEVs grows because coal generators are already used to their capacity. 2005 generation mix assumed.

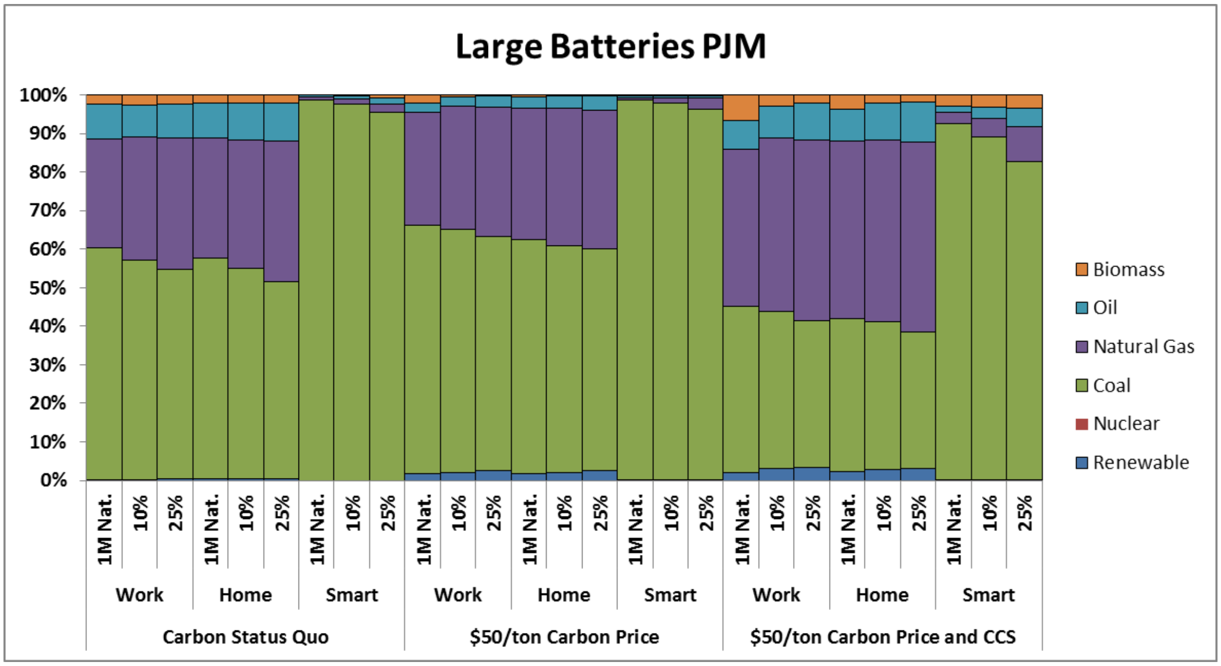

Figure S11: Generation mix used to charge in PJM given large batteries and PHEV numbers ranging from 1 million nationwide to 50% of the fleet. Introduction of a carbon price increases the amount of coal used for PHEVs because generators previously used to meet the no-PHEV load are now available for charging PHEVs due to predicted declines in load associated with increased prices. 2005 generation mix assumed.

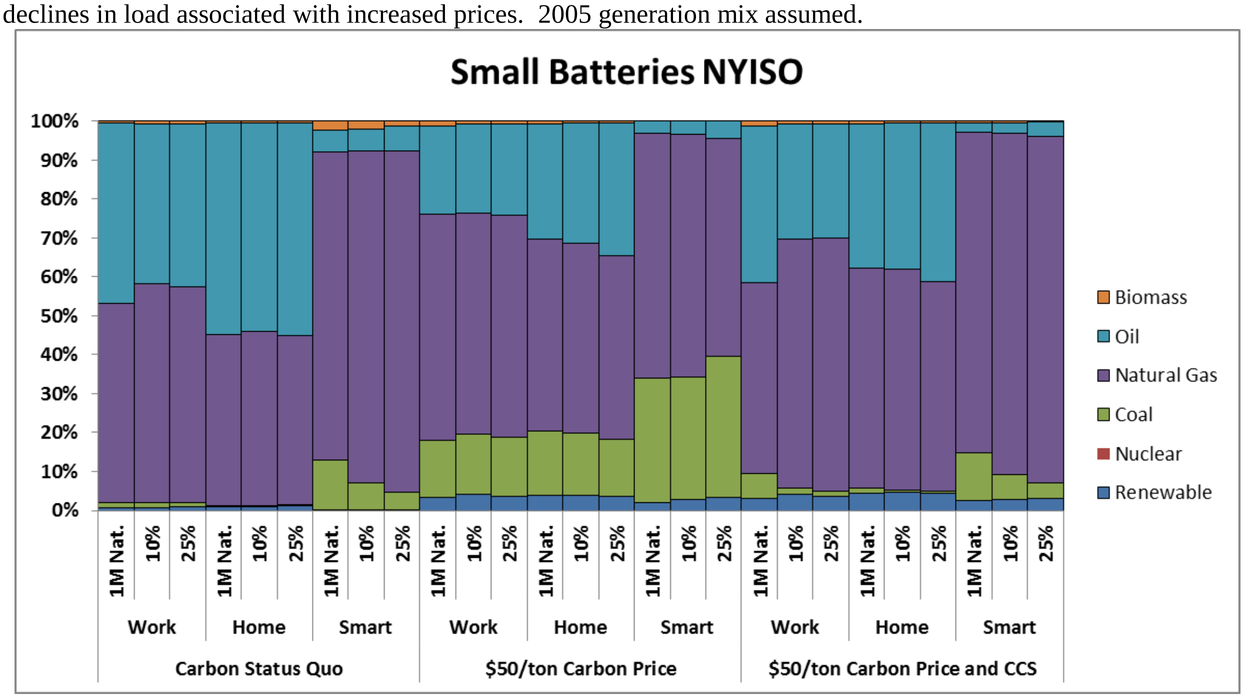

Figure S12: Generation mix used to charge in NYISO given small batteries. Coal use for PHEVs predicted to increase given a carbon price. 2005 generation mix assumed.

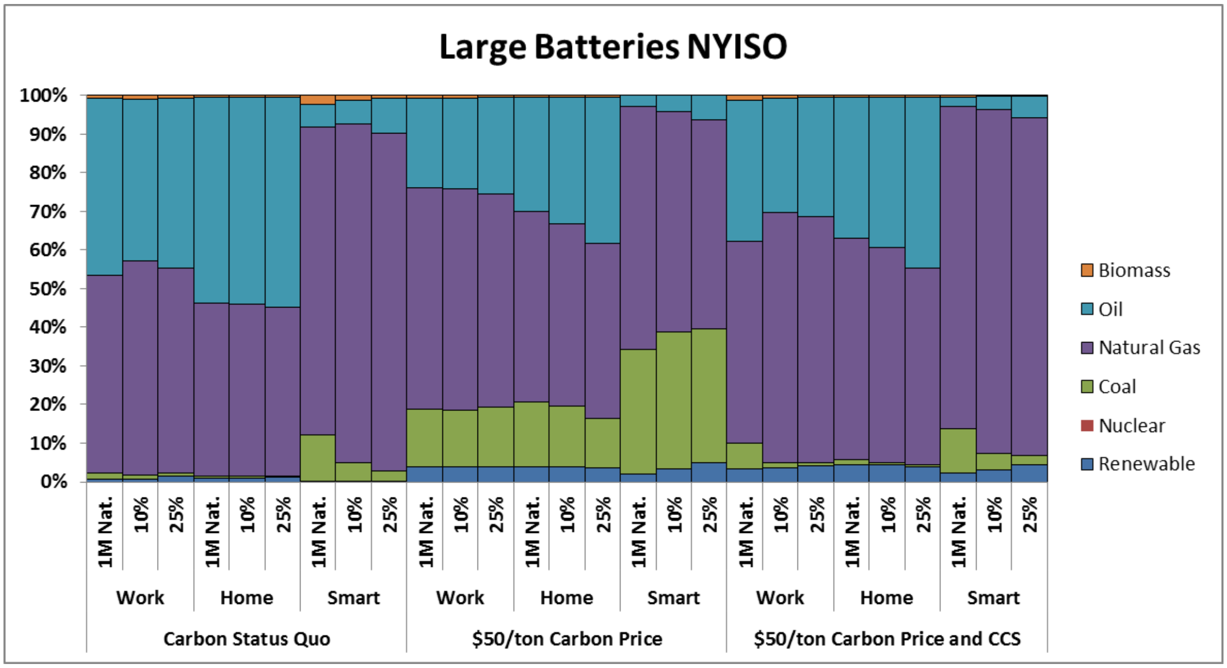

Figure S13: Generation mix used to charge in NYISO given large batteries. Coal use for PHEVs predicted to increase given a carbon price. 2005 generation mix assumed.

The marginal fuel postings for PJM in 2005 were used to compare with these results (figure S14). These include imports which were not taken into account in the dispatch model. They also include the effects of congestion in the grid which dictates each power plant cannot necessarily serve each load. Overall the results indicate that coal is on the margin a good deal of the time throughout the year.

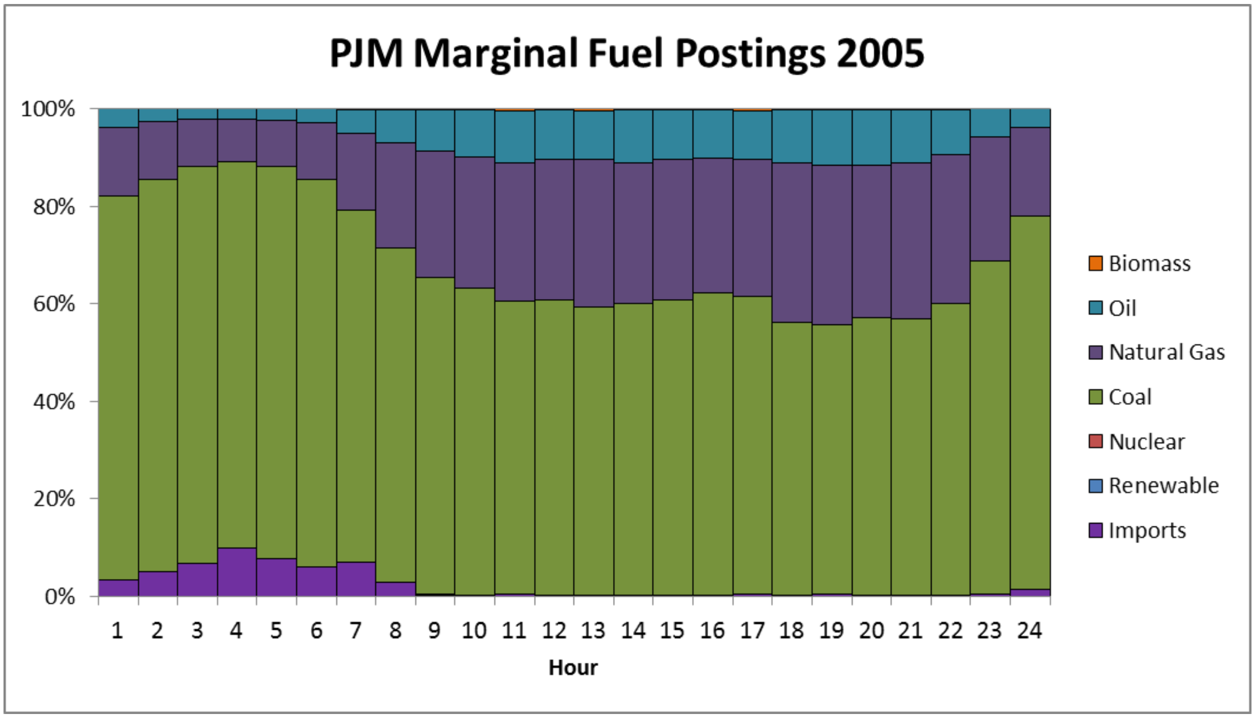

Figure S14: Marginal fuel postings from 2005 in PJM showing high percentage of time coal is on the margin. The marginal fuel is coal more than 50% of the time throughout the day.

Effect of a carbon price on emissions

The effect of a carbon price was modeled assuming that the price elasticity of demand is -0.1. The changes predicted in response to a carbon price for load, and emissions are shown in tables S3- S4. In both the CCS and carbon price no-PHEV load decreases in response to price changes. A carbon price results in decreased emissions (predictable given a decreased load), but with CCS some pollutants increase due to the lower electricity output per BTU of fuel consumed by coal plants. NYISO has fewer coal plants so the increase of emissions from coal plants with CCS does not outweigh other emissions savings.

Table S3: Comparison of no-PHEV load and emissions under carbon scenarios in PJM

Carbon Scenario	Change in Load	Change in CO_2	Change in NO_x	Change in SO_2	Change in CH_4	Change in N_2O	Change in Hg
$50/ton Carbon Price	-8.3%	-23%	-24%	-19%	-11%	-23%	-26%
$50/ton Carbon Price and CCS	-4.9%	-79%	5.3%	-83%	17%	6.3%	3.6%

Table S4: Comparison of no-PHEV load and emissions under carbon scenarios in NYISO							
Carbon Scenario	Change in Load	Change in CO_2	Change in NO_x	Change in SO_2	Change in CH_4	Change in N_2O	Change in Hg
$50/ton Carbon Price	-3.5%	-18%	-40%	-34%	-16%	-29%	-34%
$50/ton Carbon Price and CCS	-3.4%	-47%	-32%	-76%	-11%	-19%	-2.9%

Additional emissions from the electricity sector due to charging

Figures S15 –S17 emissions per additional MWh of load from PHEVs and include pollutants not discussed in the main text. The increase is measured from the no-PHEV case. This distinction is important because the emissions overall for the carbon price or CCS case might be lower than the status quo case for a given number of PHEVs, but the increase in emissions in response to adding PHEVs might be larger for those cases than the carbon status quo case. This section does not reflect net emission changes including offset petroleum usage. The charts show the average emissions per additional MWh of load combining small batteries, large batteries, and all three different charge depleting efficiencies. Uncertainty bars indicate the maximum and minimum among those options. The x-axis is labeled to indicate the percent of vehicles that are PHEVs and the charging strategy used for PHEVs. By normalizing the emissions to the MWh of load the difference in charging twice in work charging and other charging strategies which only charge one time is reduced. It is apparent that emission rates in some combinations of charging strategies, carbon scenarios, are more sensitive to the number of PHEVs being charged than others.

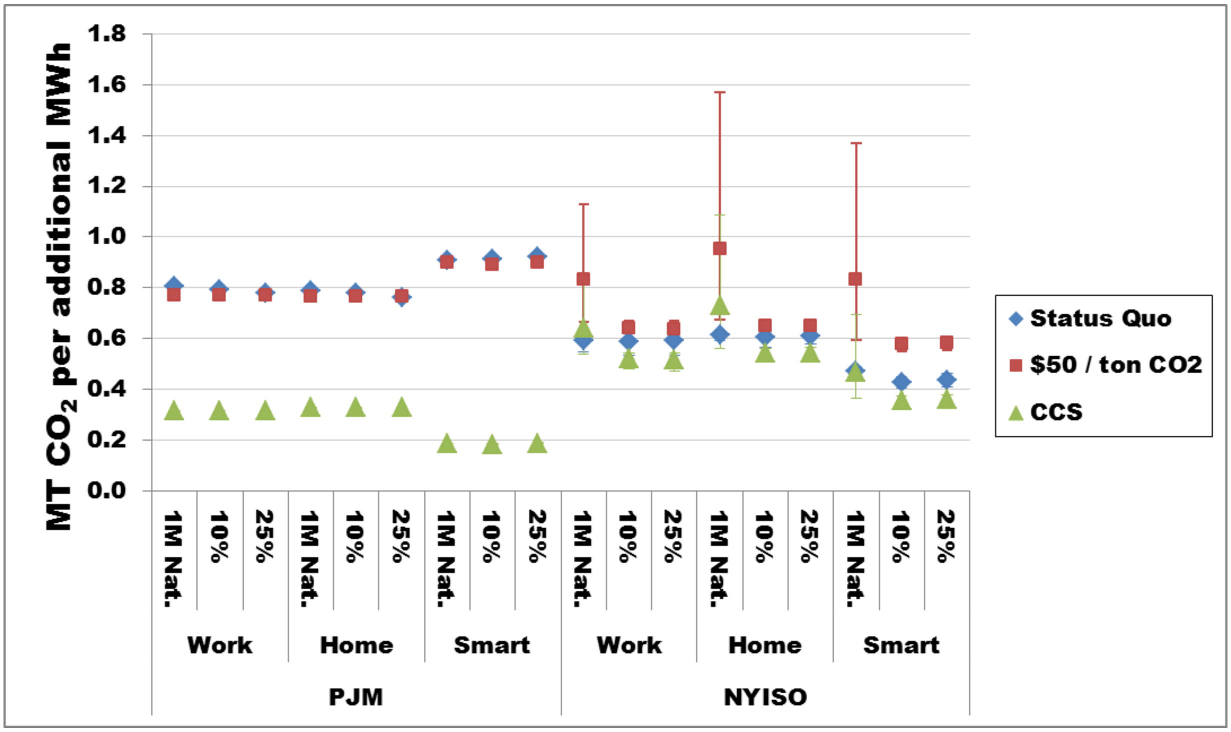

Figure S15: Metric tons carbon dioxide emitted to charge various numbers of PHEVs in PJM and NYISO. Markers indicate average value while error bars indicate the minimum and maximum value predicted given any combination of battery size and charge depleting efficiency covered in the paper. 2005 generation mix assumed.

The emissions of CO_2 shown here are reflected in the net emissions results in the main paper which found higher net emission of CO_2 with a $50/ton carbon price. Different numbers of PHEVs do not appear to influence the emissions given either a carbon price or CCS in PJM.

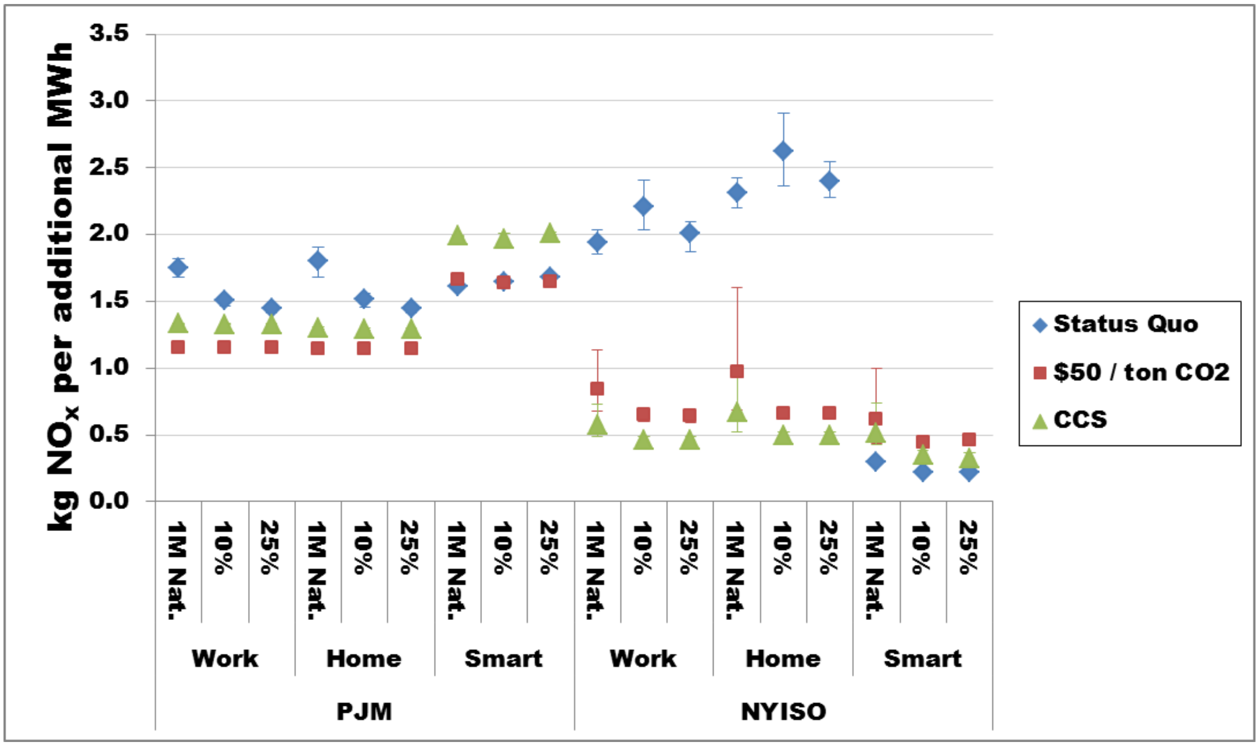

Figure S16: Kilograms of NOx emitted per MWh to charge various numbers of PHEVs in PJM and NYISO. Markers indicate average value while error bars indicate the minimum and maximum value predicted given any combination of battery size and charge depleting efficiency covered in the paper. 2005 generation mix assumed.

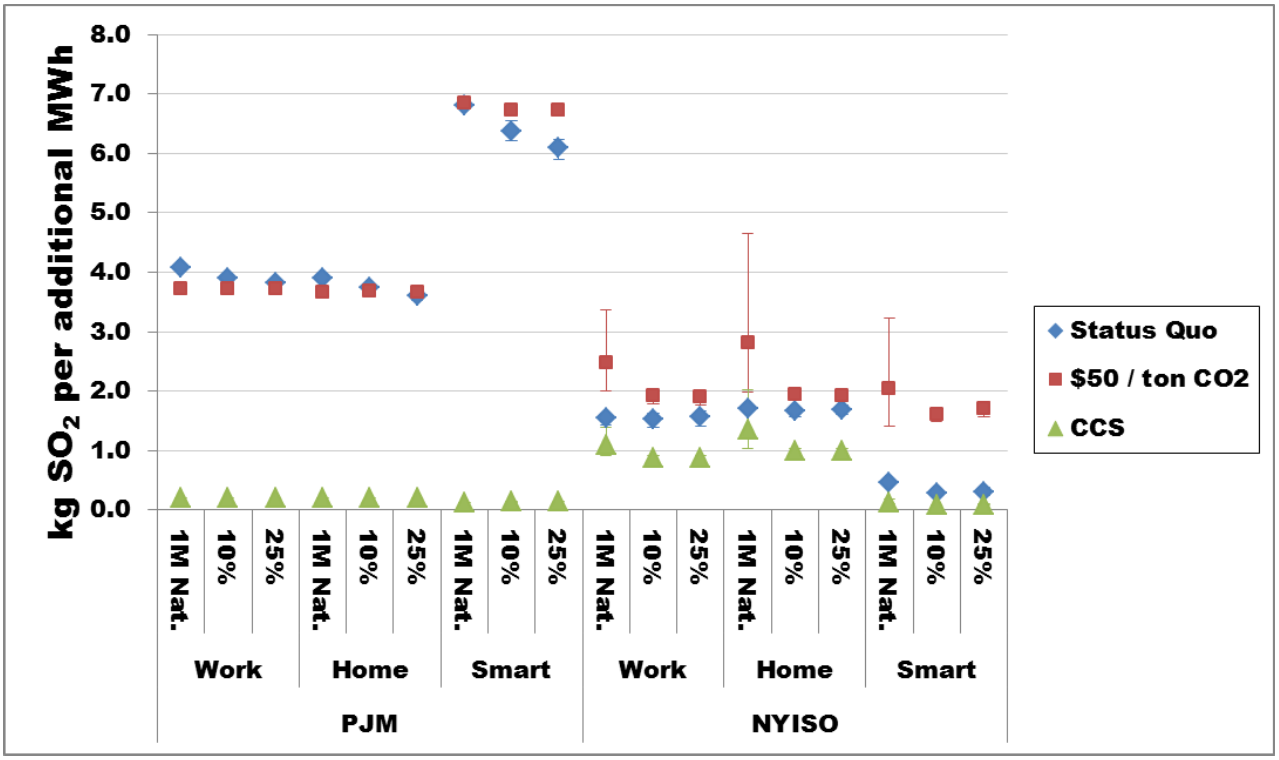

Figure S17: Kilograms of SO_2 emitted per MWh to charge various numbers of PHEVs in PJM and NYISO. Markers indicate average value while error bars indicate the minimum and maximum value predicted given any combination of battery size and charge depleting efficiency covered in the paper. 2005 generation mix assumed.

Emissions from gasoline

The distance traveled in CS mode is recorded for each vehicle along with the total distance travelled by vehicles. The total distance can be considered the conventional fleet and gasoline consumption is calculated based on the efficiencies described in the main text and shown below (table S5). The same is done for PHEVs using the distance in CS mode to calculate gasoline consumption by PHEVs. The same efficiency values are used for CS mode travel and vehicles that PHEVs replace. This is done for a number of reasons. The increase in weight associated with creating a PHEV will decrease efficiency to some extent. Also the comparison does not exclude hybrids. Hybrids will get boosts from regenerative braking and effectively run in CS mode constantly. Hybrids will also be more efficient than similar PHEVs running in CS mode. To achieve the 2020 CAFE standards it will likely be necessary to have a significant number of hybrids in the fleet. This does mean that the estimates of displaced emissions may be lower than actually observed especially if PHEVs are replacing CVs instead of HEVs.

Table S5: Fuel efficiency (l/100km)		
Vehicle Type	Current	2020 (35 MPG fleet)
Car	9.1	5.9
Van	12	7.6
SUV	13	7.8
Truck	13	7.8

The liters of gasoline consumed are multiplied by the factors reported in the EPA documents cited in the main text and reported again in table S6.

Table S6: Emissions Factors	
Pollutant	kg/l gasoline
CO_2	2.3
SO_2	1.1e-4
NO_x	5.8e-3

The difference between emissions from total and CS miles can be used to find the reduction in pollution from mobile sources attributable to partial electrification of the distance travelled.

Net emissions per PHEV

Figures S18 through S21 show net emissions of CO_2, NO_x, and SO_2 per vehicle-year given PJM and NYISO generation mix. The number of PHEVs modeled varies from 0.4% to 50% of the vehicle fleet. For comparison, the predicted emissions per conventional vehicle using 2005 and 2020 efficiencies are 3.7 and 2.3MT CO_2, 9.3 and 5.8 kg NOx, and 0.18 and 0.11 kg SO_2. Columns represent medium charge depleting (CD) mode efficiency and uncertainty bars represent high and low CD efficiency. Emissions for 2005 fleet and 2020 fleet are compared given the status quo (no carbon price) as well as a \$50/ton CO_2 price and a \$50/ton CO_2 price in conjunction with CCS installed on coal plants. Different charging strategies are modeled to determine the timing of PHEV charging as discussed previously in the supporting information.

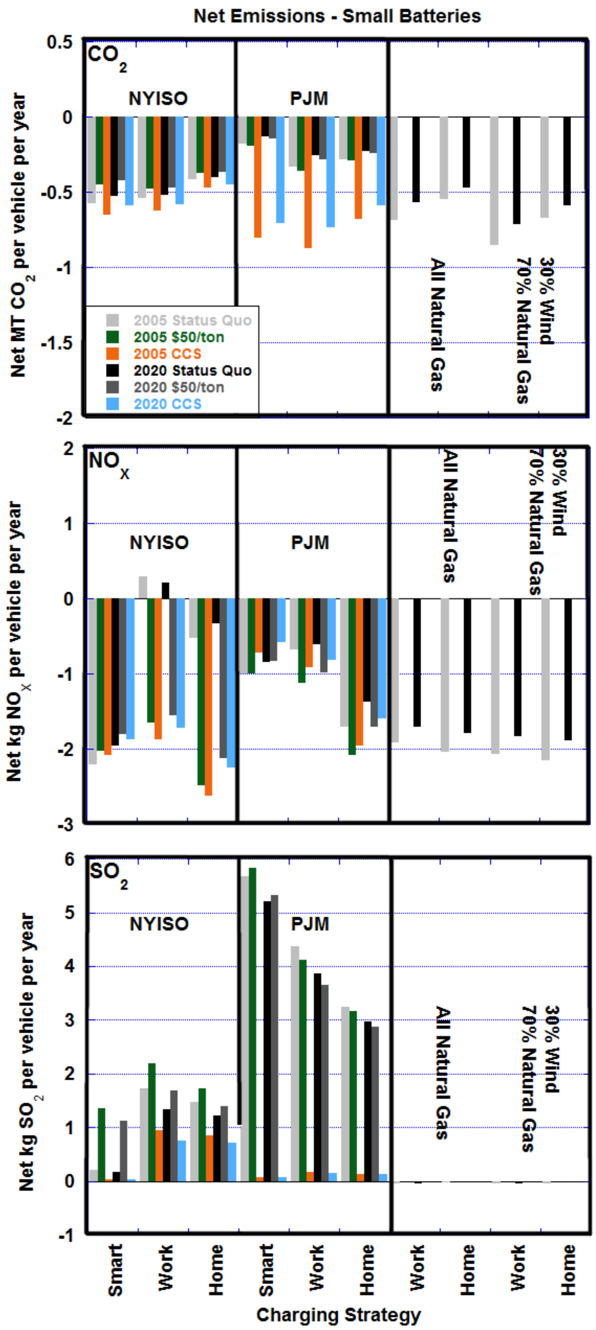

Figure S18: Net emissions given 10% PHEVs and small batteries. Net metric tons of CO_2, and net kg of NO_x and SO_2 emitted per vehicle-year given PJM and NYISO generation mix as well as all natural gas and 30% wind combined with natural gas. For comparison, the predicted annual emissions per conventional vehicle using 2005 (22 mpg) and 2020 (35 mpg) efficiencies are 4.1 and 2.6 MT CO_2, 10 and 6.4 kg NO_x, and 0.20 and 0.13 kg SO_2. Emissions for 2005 fleet and 2020 fleet are compared given the status quo (no carbon price) as well as a $50/ton CO2 price and a $50/tonne CO2 price in conjunction with CCS installed on coal plants. Different charging strategies are modeled to determine the timing of PHEV charging. 2005 generation mix assumed.

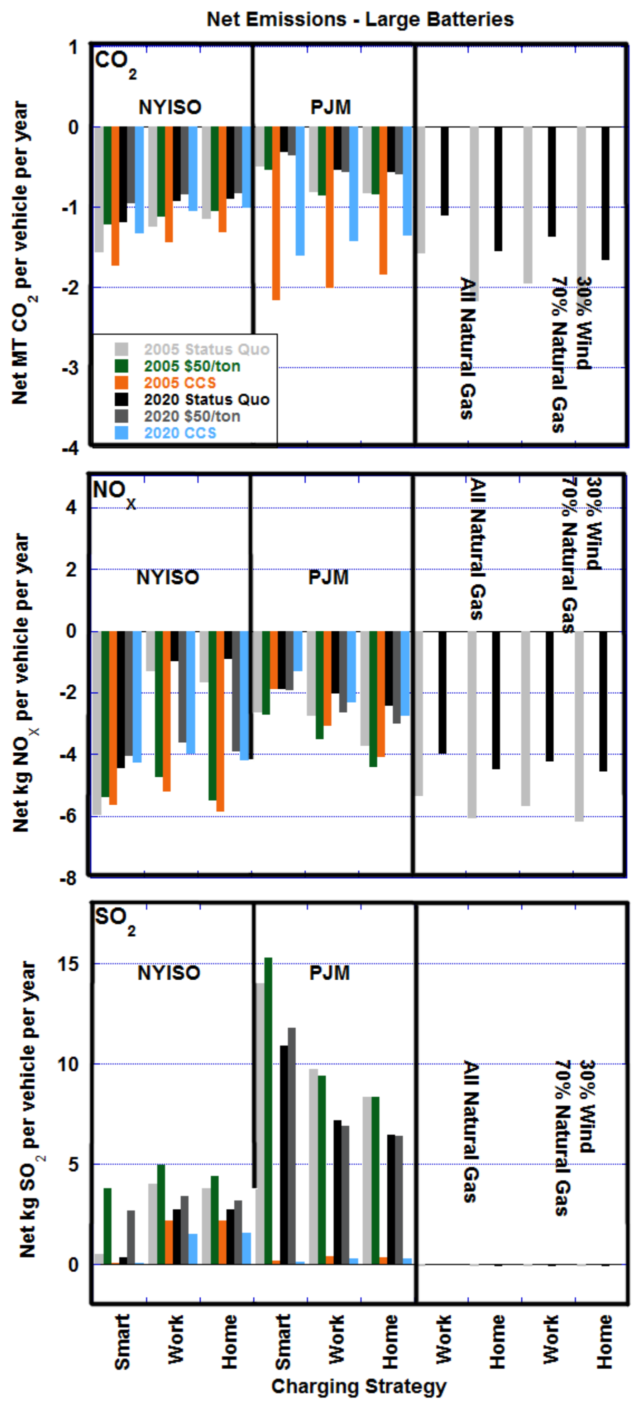

Figure S19: Net emissions given 10% PHEVs and large batteries. Net metric tons of CO_2, and net kg of NO_x and SO_2 emitted per vehicle-year given PJM and NYISO generation mix as well as all natural gas and 30% wind combined with natural gas. For comparison, the predicted annual emissions per conventional vehicle using 2005 (22 mpg) and 2020 (35 mpg) efficiencies are 4.1 and 2.6 MT CO_2, 10 and 6.4 kg NO_x, and 0.20 and 0.13 kg SO_2. Emissions for 2005 fleet and 2020 fleet are compared given the status quo (no carbon price) as well as a $50/ton CO2 price and a $50/tonne CO2 price in conjunction with CCS installed on coal plants. Different charging strategies are modeled to determine the timing of PHEV charging. 2005 generation mix assumed.

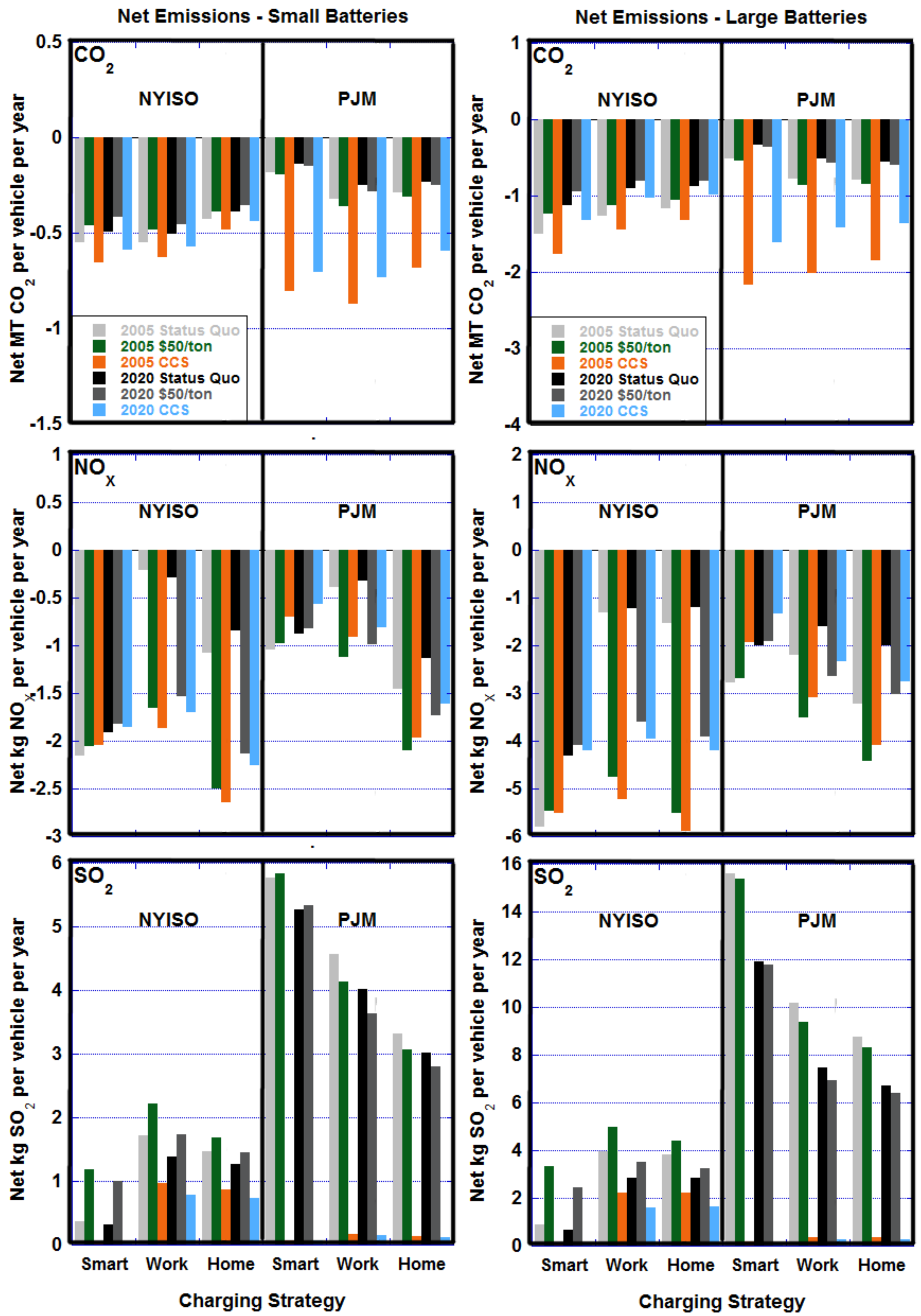

Figure S20: Net emissions per vehicle given 0.44% PHEVs 2005 generation mix assumed.

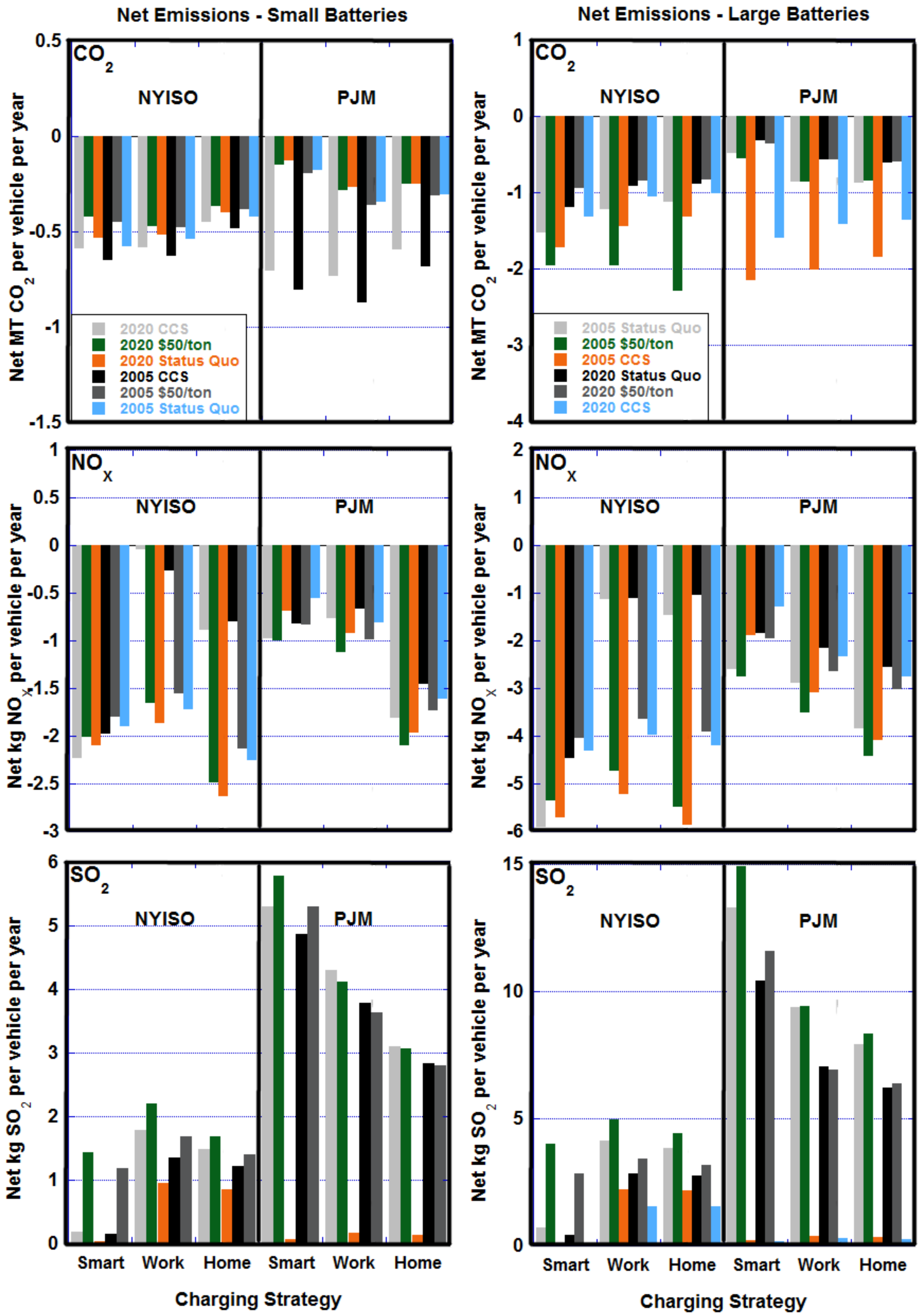

Figure S21: Net emissions per vehicle given 25% PHEVs 2005 generation mix assumed.

Sensitivity to natural gas prices

The high petroleum use in NYISO was likely a response to low prices for petroleum relative to natural gas prices (figure S22). Natural gas prices have fluctuated more than coal prices recently. Because of this the model was also run assuming gas cost $4.90 / mmbtu.

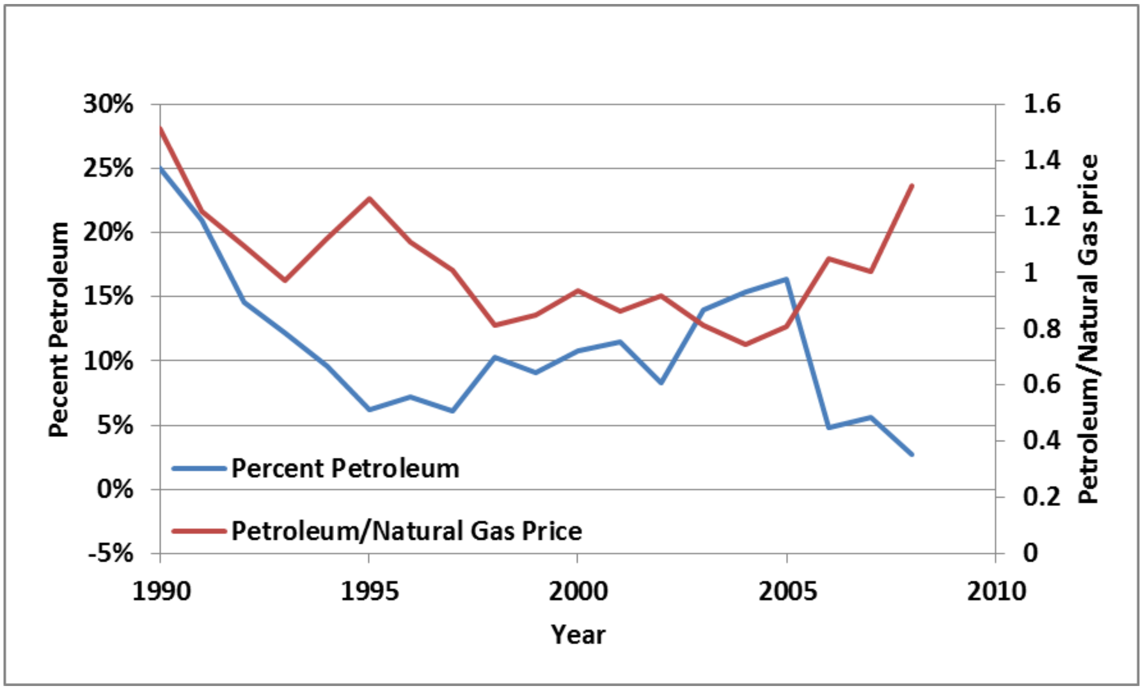

Figure S22: Percent petroleum used for generation in NYISO compared to the ratio of petroleum to natural gas prices per BTU. There is clearly anti-correlation between the ratio of petroleum to natural gas prices and the percent petroleum (9, 10).

The results are shown below for the 2005 gas prices and lower gas prices assuming a 10% PHEV fleet.

Table S7: Net CO_2 emissions MT/vehicle-year in PJM given 2005 natural gas prices

Battery		2005 Status Quo	2005 $50/tonne	2005 CCS	2020 Status Quo	2020 $50/tonne	2020 CCS
Small	Smart	-0.18	-0.19	-0.81	-0.13	-0.15	-0.71
	Work	-0.33	-0.36	-0.87	-0.26	-0.28	-0.73
	Home	-0.28	-0.29	-0.68	-0.23	-0.24	-0.59
Large	Smart	-0.49	-0.55	-2.2	-0.32	-0.36	-1.6
	Work	-0.82	-0.86	-2.0	-0.54	-0.57	-1.4
	Home	-0.83	-0.84	-1.8	-0.57	-0.59	-1.4

Table S8: Net CO_2 emissions MT/vehicle-year in PJM given 490 cents/Mbtu natural gas price							
Battery		2005 Status Quo	2005 $50/tonne	2005 CCS	2020 Status Quo	2020 $50/tonne	2020 CCS
Small	Smart	-0.23	-0.34	-0.80	-0.18	-0.28	-0.70
	Work	-0.44	-0.30	-0.85	-0.35	-0.23	-0.71
	Home	-0.35	-0.24	-0.66	-0.29	-0.19	-0.58
Large	Smart	-0.65	-0.90	-2.1	-0.44	-0.64	-1.6
	Work	-1.0	-0.72	-1.9	-0.74	-0.47	-1.4
	Home	-1.0	-0.72	-1.8	-0.72	-0.49	-1.3

Table S9: Net CO_2 emissions MT/vehicle-year in NYISO given 2005 natural gas prices							
Battery		2005 Status Quo	2005 $50/tonne	2005 CCS	2020 Status Quo	2020 $50/tonne	2020 CCS
Small	Smart	-0.58	-0.45	-0.65	-0.53	-0.42	-0.59
	Work	-0.54	-0.48	-0.63	-0.52	-0.47	-0.58
	Home	-0.41	-0.37	-0.47	-0.40	-0.37	-0.45
Large	Smart	-1.6	-1.2	-1.7	-1.2	-0.95	-1.3
	Work	-1.2	-1.1	-1.4	-0.93	-0.84	-1.1
	Home	-1.2	-1.1	-1.3	-0.90	-0.83	-1.0

Table S10: Net CO2 emissions MT/vehicle-year in NYISO given 2005 natural gas prices							
Battery		2005 Status Quo	2005 $50/tonne	2005 CCS	2020 Status Quo	2020 $50/tonne	2020 CCS
Small	Smart	-0.39	-0.58	-0.64	-0.33	-0.50	-0.56
	Work	-0.47	-0.47	-0.65	-0.38	-0.37	-0.54
	Home	-0.38	-0.35	-0.50	-0.32	-0.29	-0.42
Large	Smart	-1.1	-1.6	-1.7	-0.75	-1.1	-1.3
	Work	-1.1	-1.1	-1.5	-0.76	-0.74	-1.0
	Home	-1.1	-1.0	-1.4	-0.76	-0.72	-1.0

With no carbon price net emissions of CO_2 generally decline in response to a lower natural gas prices in PJM. In NYISO the opposite holds true because the no-PHEV load then uses more of the natural gas leaving the PHEV load to relying on dirtier plants. Cheaper natural gas would also allow a CO_2 price to be more effective as seen in PJM, however it is unlikely natural gas prices will remain low compared to coal if demand significantly increases. In NYISO where many plants are dual fuel plants running on petroleum or natural gas it is likely that natural gas will continue to be cheaper and the preferred fuel.

Upstream emissions

The paper focuses only on use phase emissions. Upstream emissions from both PHEVs and the vehicles they will be displacing are significant. Data on upstream emissions associated with lithium-ion batteries being used in PHEVs is not yet common. For example in the GREET model the description of the battery data states the following (11):

> We collected data from another source and calculated the energy required for assembly and testing of an Ni-MH battery to be approximately 35.2 million Btu/ton of battery material; the data revealed that battery testing requires significant amounts of electricity (Gaines 2006). The large discrepancy between the values for Ni-MH batteries is troubling, and even the other values have been questioned because the energy required for vehicle assembly is much lower. We decided to use the Li-ion value from Ishihara et al. (1999) and the Ni-MH value from Gaines (2006) as default values for GREET 2.7, but we hope to find publicly available data that could replace these sources. By using our default values, the resulting energy requirement for Pb-Ac assembly is 27.5 million Btu/ton of battery material

This highlights some of the problems associated with attempting to specify the emissions associated with a relatively new product. Testing of batteries need not require using huge amounts of energy as it is entirely feasible to feed energy back into the grid when discharging batteries instead of simply wasting the energy as heat. Then the only losses are the efficiency losses associated with charge and discharge cycles and conversion and synchronization to the grid. Using the GREET data and assuming 140Wh/kg energy density the emissions associated with battery assembly are shown below (tables S11-S12).

Table S11: Emissions associated with battery assembly for small batteries

Battery size kWh	Tons CO2	kg NOX	kg SO2
4	0.08	0.09	0.20
5.16	0.11	0.12	0.25
5.33	0.11	0.12	0.26
5.33	0.11	0.12	0.26

Table S12: Emissions associated with battery assembly for small batteries

Battery size kWh	Tons CO2	kg NOX	kg SO2
16	0.34	0.36	0.79
20.65	0.44	0.46	1.02
21.33	0.45	0.48	1.05
21.33	0.45	0.48	1.05

These emissions increases from battery creation are quite small in comparison to the emissions savings for CO_2 and NO_X. In one year it is likely the emissions savings over gasoline will surpass the additional emissions associated with battery creation. Emissions of SO_2 are likely to increase, and increase further according to this, but once again the magnitude is similar to one year's use phase emissions. These emissions will likely decrease as the electricity grid becomes cleaner since many are associated with electricity use. The yearly gallons of gasoline displaced per PHEV depends on the number of charges and battery size and is shown below.

Table S13: Liters saved per vehicle and upstream emissions (well–to-pump)

Battery Size	Charging strategy	Annual liters gasoline saved	kg SO2	kg Nox	MT CO2
Small	Home	580	0.45	0.91	0.32
	Work	740	0.58	1.16	0.41
Large	Home	1550	1.2	2.43	0.86
	Work	1690	1.3	2.65	0.94

The annual upstream emissions from gasoline production are significant and the savings associated with displacing the gasoline are as well, but there are upstream emissions from the electricity produced to displace the gasoline. A complete life cycle assessment is beyond the scope of this work and will not be conducted.

1 *National Household Travel Survey*, U.S. Department of Transportation: Washington, DC, 2010; http://nhts.ornl.gov/download.shtml

2Remarks of Senator Barack Obama—as prepared for delivery, New Energy for America, Michigan State University, Monday, August 4th, 2008, Lansing, Michigan

3 Newcomer, A; Blumsack S. A.; Apt, J; Lave, L. B.; Morgan, M. G. Short Run Effects of a Price on Carbon Dioxide Emissions from U.S. Electric Generators. *Environ. Sci. Technol.* **2008**. *42* (9), 3139-3144.

4 *Emissions & Generation Resource Integrated Database (eGRID),* U.S. Environmental Protection Agency: Washington, DC, 2007 http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html

5 *Cost and Quality of Fuels for Electric Plants 2004 and 2005*, U.S. Department of Energy : Washington, DC, 2006.

6 Chao, H. New York state department of environmental conservation comments of the NYISO on initial report of the RGGI emissions leakage multi-state staff working groups to the RGGI agency heads. 2007.

7 Integrated Environmental Control Model (IECM), Version 6.2.4, Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh. Available: http://www.cmu.edu/epp/iecm/.

8 Newcomer, A; Blumsack S. A.; Apt, J; Lave, L. B.; Morgan, M. G. Short Run Effects of a Price on Carbon Dioxide Emissions from U.S. Electric Generators. *Environ. Sci. Technol.* **2008**. *42* (9), 3139-3144.

9 Electric power industry generation by primary energy source, 1990 through 2008 (megawatthours). available http://www.eia.doe.gov/cneaf/electricity/st_profiles/sept05ny.xls

10 Electric power delivered fuel prices and quality for coal, petroleum, natural gas, 1990 through 2008. available http://www.eia.doe.gov/cneaf/electricity/st_profiles/sept06ny.xls

11 Burnham, A.; Wang, M; Wu, Y. Development and applications of GREET 2.7 – the transportation vehicle-cycle model. Argonne National Labs, Argonne, IL 2006.

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