

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

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S Supporting Information

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 CO₂ price, and this case but with existing coal generators retrofitted with 80% CO₂ 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 CO₂ 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 CO₂ generation. NO_x is reduced in both RTOs, but there is upward pressure on SO₂ 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 CO₂ 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 SO₂ emissions; however, one comes to a contrasting conclusion based on assumptions that rely on aggressive new emissions control technology.⁸ SO₂ 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 analyses⁵ 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 CO₂ 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, gaso-line 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 CO₂ 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 SO₂ emissions.

We estimate that PHEVs are likely to have lower net emissions of NO_x and CO₂ than a conventional vehicle fleet, given current (10.7 L/100 km) efficiencies. When compared to 2020 CAFE standards (6.7 L/100 km), net CO₂ emissions in New York are

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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 CO₂ generation. NO_x is reduced in both RTOs, but SO₂ increases unless a cap binds (discussed below). A \$50/tonne CO₂ price applied only to combustion emissions in the electric sector will have a negligible short-term effects on net CO₂ 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 traveled 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 nationwide¹⁹) 10, and 25%.

Generator Dispatch. We used the method described in ref 20 to construct monthly short-run marginal cost (SRMC) curves for each electric power generator in PJM and NYISO from EPA eGRID data²¹ 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 CO₂ were modeled as in ref 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 CO₂, using a 20% energy penalty to derate the nameplate capacity. We adopted the assumption that coal plants equipped with CCS reduced SO₂ 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 in each hour. Once the dispatched generators were determined in each hour, CO₂, NO_x, and SO₂ 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 traveled in each mode. The miles traveled 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 traveled in CD mode from the total distance traveled by the vehicle yields the distance traveled 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 vehicle efficiency (assumed to average 35 mpg). 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 CO₂, NO_x, and SO₂ 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 CO₂/MWh, 340 g NO_x/MWh, and 12 g SO₂/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 CO₂ scenarios are calculated using the difference in emissions from the load with PHEVs under a given CO₂ scenario and the no-PHEV load under the same CO₂ 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, emissions are more sensitive to the specific plant used to charge them).

Compared to 2005 gasoline fleet efficiency levels, all charging strategies and CD mode efficiencies yield reduction of CO₂ emissions. If the 2020 conventional vehicle fleet efficiency target of 35 MPG is compared to the 2020 CD efficiency, net CO₂ 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 CO₂ reductions with no CO₂ price and relies more on natural gas generation. In NYISO, smart charging results in greater CO₂ 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 the Supporting Information).

CO₂ Emissions. Without a CO₂ price there is no incentive to use a generator with lower CO₂ 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 CO₂ 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 CO₂ emissions. PJM shows nearly the opposite result with smart charging having significantly lower reductions in CO₂ emissions (relying on 98% coal). Home and work charging in PJM exhibit similar levels of CO₂ emissions.

Adding a \$50/tonne CO₂ 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 CO₂ 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, CO₂ 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 CO₂ 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 CO₂ are likely to be reduced 4–62%. In NYISO, net emissions of CO₂ 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). CO₂ 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.

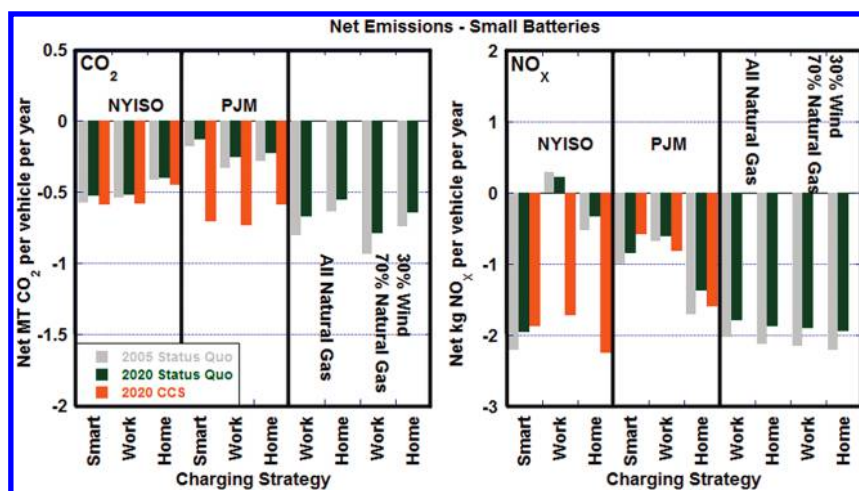


Figure 1. Net metric tons of CO₂ and net kg of NO_x emitted per vehicle-year given PJM and NYISO generation mix and all natural gas and 30% wind/70% natural gas (in the latter two cases the charging strategy is not relevant because the emissions are independent of the time a vehicle charges and represent 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 CO₂ and 10 and 6.4 kg NO_x. Emissions for 2005 fleet and 2020 fleet are compared given the status quo (no CO₂ price) as well as a \$50/tonne CO₂ price in conjunction with CCS installed on coal plants given 2020 efficiencies. A similar figure for large batteries is included in the Supporting Information.

Adding a \$50/ton CO₂ price significantly decreases the no-PHEV load²⁰ and thus emissions. This is especially important in NYISO. Instead of seeing increases of NO_x ranging from 0.22 to 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 SO₂ and NO₂ must be below 10 ppm, but NO₂ makes up very little of the NO_x emissions from a power plant.²³ IGCC and chilled ammonia systems also require low SO₂. 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.

SO₂ Emissions. Unlike the other pollutants, net SO₂ emissions increase in most scenarios (Figure 2a). National 2005 electric sector emissions were 9.4 million tonnes of SO₂, 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 SO₂ emissions caps established under the Acid Rain Program, because the annual SO₂ emissions have declined in 2008 and 2009³⁰ 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 SO₂ emissions from the electricity sector from our model was 0.17 million tonnes in PJM (with smart charging, large batteries, low

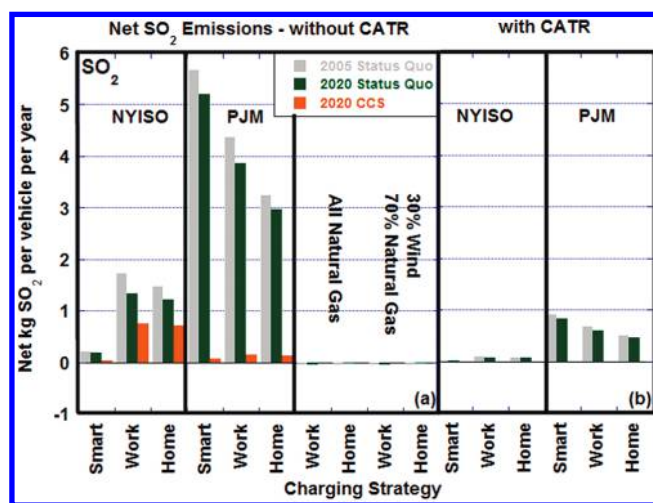


Figure 2. Net kg SO₂ emitted per vehicle-year given (a) PJM and NYISO generation mix of 2005 as well as all natural gas and 30% wind/70% natural gas and (b) PJM and NYISO with generator emissions factors for SO₂ reduced to comply with CATR. For comparison, the predicted annual emissions per conventional vehicle using 2005 (22 mpg) and 2020 (35 mpg) efficiencies are 0.20 and 0.13 kg SO₂. Emissions for 2005 fleet and 2020 fleet are compared given the status quo (no CO₂ price) as well as 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. A similar figure for large batteries is included in the Supporting Information.

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 SO₂ 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. SO₂ 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 SO₂ 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 SO₂ 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 SO₂ allowance prices. EPA estimates that the marginal cost of SO₂ 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 SO₂ emissions from charging vehicles in Pennsylvania would increase the SO₂ 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).

SO₂ emissions would not change significantly in response to a CO₂ price alone except for an increase in the NYISO smart charging case. However, CCS will require SO₂ emissions to be reduced significantly to avoid contamination during portions of the capture process for IGCC or amine capture. Thus, the net SO₂ 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 SO₂ 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 CO₂ 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 CO₂ 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 SO₂ 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 SO₂ 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 SO₂ scenarios. We note that the upstream (largely refinery) emissions displaced by decreasing gasoline use are ~0.45 kg SO₂ per vehicle-year (Supporting Information). This is more than half of the SO₂ 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 resulted in lower net emissions than work charging and lower or equal emissions compared to home charging. In PJM, smart charging generally causes higher emissions because coal is often on the margin at night. In PJM there is a trade-off between use of off-peak charging and increased emissions. RTOs and LSEs should be aware of possible trade-offs 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 CO₂ price of \$50/tonne will not be effective at reducing net CO₂ emissions from a PHEV fleet. PHEVs are likely to place upward pressure on SO₂ allowance prices if emission caps bind or to increase emissions if the caps do not bind. PHEVs will probably reduce net CO₂ and NO_x emissions but are unlikely to reduce net SO₂ emissions.

ASSOCIATED CONTENT

S Supporting Information. Additional information. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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