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Transmission network-based energy and environmental assessment of plug-in hybrid electric vehicles

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ABSTRACT

The introduction of plug-in hybrid electric vehicles (PHEVs) is expected to have a significant impact on regional power systems and pollutant emissions. This paper analyzes the effects of various penetrations of PHEVs on the marginal fuel dispatch of coal, natural gas and oil, and on pollutant emissions of CO_2, NO_x, SO_2 in the New York Metropolitan Area for two battery charging scenarios in a typical summer and winter day. A model of the AC transmission network of the Northeast Power Coordinating Council (NPCC) region with 693 generators is used to realistically incorporate network constraints into an economic dispatch model. A data-based transportation model of approximately 1 million commuters in NYMA is used to determine battery charging pattern. Results show that for all penetrations of PHEVs network-constrained economic dispatch of generation is significantly more realistic than unconstrained cases. Coal, natural gas and oil units are on the margin in the winter, and only natural gas and oil units are on the margin in the summer. Hourly changes in emissions from transportation and power production are dominated by vehicular activity with significant overall emissions reductions for CO_2 and NO_x, and a slight increase for SO_2. Nighttime regulated charging produces less overall emissions than unregulated charging from when vehicles arrive home for the summer and vice versa for the winter. As PHEVs are poised to link the power and transportation sectors, data-based models combining network constraints and economic dispatch have been shown to improve understanding and facilitate control of this link.

1. Introduction

Plug-in hybrid electric vehicles (PHEVs) utilize advanced batteries to obtain between 20 and 60 miles of fully-electric driving and afterwards uses a traditional hybrid electric power train for range extension [1,2]. In the future, PHEVs will likely shift the transportation network's dependence away from petroleum and towards the electric grids, thus inducing a significant transformation within the electric power and transportation sectors [3–5]. Moreover, the pollutant emission changes from mobile sources of vehicles to point sources of power plants as a result of PHEVs will affect air quality, especially at urban centers.

Recently studies have begun to investigate fuel mixtures, emission changes and grid reliability issues associated with PHEV usage [3–9]. The findings from those studies have advanced our understanding on the energy and environmental impacts of PHEVs. Overall, the penetration of PHEVs into the automobile market is expected to reduce tailpipe emissions as well as the total emissions accounting for the increased emissions from coal, natural gas and oil power plants [5,6]. A unit commitment model without transmission constraints was incorporated into an economic dispatch model of the Electricity Reliability Council of Texas (ERCOT) region to evaluate the change in generator dispatches resulting from PHEV deployment [7]. Researchers also analyzed the potential impacts of PHEVs on electricity demand, supply, generation mixture and emissions in 2020 and 2030 in 13 regions specified by the North American Electric Reliability Corporation (NERC) and the U.S. Department of Energy's Energy Information Administration. Modeled without transmission constraints of the electric power network, the study further assumed a uniform fuel mixture for electricity generation within the region [8]. Using a 10-bus reduced model for the Ontario transmission system, a study in 2010 analyzed the optimality of PHEV's off-peak charging on the reliability of the region's power system [9].

This paper shows the need to incorporate realistic engineering and operational constraints of the power transmission network into an economic dispatch model when assessing the regional impact of PHEVs on the varying fuel mixture and emissions of power generation. We show that these network constraints noticeably alter the dispatch of generation from that based purely on economics of

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Table 1
Vehicle emission factors in NYMA.

Vehicle type	VOC (g mile^{-1})	NO_x (g mile^{-1})	CO (g mi^{-1})	$PM_{2.5}$ (g mile^{-1})	PM_{10} (g mile^{-1})	CO_2 (g mile^{-1})
LDGV	0.51	0.45	11.19	0.12	0.25	504.0

individual generators. Consequently, an economic dispatch model with network constraints can more realistically model the regional impact of PHEVs.

In this paper, we present our study on the energy and environmental impacts of PHEV-40 (PHEV with a 40-mile all electric range) with various market penetrations (replacing the corresponding conventional vehicles with PHEVs) in the New York Metropolitan Area (NYMA) using an economic dispatch model subject to realistic engineering and operational constraints of the reduced NPCC AC power network [10]. Moreover, every generator in our model has an associated fuel type (coal, nuclear, hydro, natural gas and oil), cost function for power generation and emissions characteristics (CO_2, NO_x and SO_x), which we obtained from corresponding Independent System Operators (ISOs). Based on driving patterns of commuters working in New York City (NYC), we aim to evaluate the effects of different PHEV penetrations and charging scenarios on generation fuel mixture and emissions in the Northeast Power Coordinating Council (NPCC) region for the summer and winter seasons.

2. Methodology

2.1. Transportation system modeling

This study of the transportation system in NYMA focuses on vehicles commuting in-and-out of NYC. The U.S. Department of Transportation's 2000 Census Transportation Planning Package (CTPP), which contains data specifically designed for transportation planners, reveals that approximately 1,040,000 people within NYMA commute daily to NYC by personal vehicles [11]. These vehicles usually congest the city's main roads and highways, thereby contributing to the high pollution levels near the freeways within and around NYC.

2.1.1. Commuting patterns

We assume that the NYMA commuters with PHEVs travel to their workplaces in NYC starting with a fully-charged battery and that battery recharge occur immediately after returning home from work. This is known as the "unregulated charging" scenario in this analysis. The increased hourly electricity demand from PHEVs is modeled using the number of commuters, PHEV market penetrations, the times when commuters leave work, the speeds at which they travel, and the daily commuting distance. Unregulated charging of many PHEVs at high demand hours presents significant challenges to the power system such as increased peak demand and decreased grid reliability. Thus, this scenario represents a worst case where PHEV charging is not systematically controlled. Due to the flexibility of charging PHEVs at off-peak hours, a systematically "regulated" charging scenario is introduced in Section 2.3 in order to help alleviate the challenges to the power system from unregulated charging.

Our model of the commuting patterns is based on data from two transportation patterns surveys. The Journey-to-Work data in the 2000 CTPP is used to determine the number of commuters that drive daily to NYC from every county in the NYMA. The Regional Travel Household Interview Survey (RT-HIS) itemizes the time when a random NYMA commuter leaves work for home [12].

A Monte Carlo (MC) method was used to generate a realistic hourly electricity demand profile in a typical weekday from unregulated charging. From RTHIS and CTPP, a time profile of commuters leaving work, a distance profile of their commuting distances and driving speeds at various commuting segments were derived. Accordingly, the MC method generates a time a random commuter leaves work, the corresponding commute distance, and the driving speeds inside and outside NYC. During rush hours, a traffic congestion factor known as Travel Time Index (TTI) is applied to reduce the speed out of NYC. TTI is estimated to be 1.44 from 6 AM to 9 AM, 1.63 from 3 PM to 6 PM and is 1.00 for other hours [13].

The random commuter's daily energy requirement for PHEV charging is then calculated by assuming a linear relationship between mileage and the electric energy for light-duty gasoline vehicles (LDGVs). This relationship ranges from 0.26 kWh mile^{-1} to 0.46 kWh mile^{-1} within the 40-mile electric-drive range [4]. The charging time of standard PHEV-40 batteries is approximated at 6 h on a standard 120 V outlet. Repeating this algorithm for a thousand random commuters produces an electricity demand profile for unregulated charging for each hour of the day.

2.1.2. Vehicle emissions

The commuting distances in the transportation modeling and a fuel economy of 17.5 mile gal^{-1} were used to calculate the amount of gasoline that commuters driving LDGVs consume per day [14]. Combined with the emissions rates for VOC, NO_x, CO, $PM_{2.5}$, PM_{10} and CO_2 in g mile^{-1}, shown in Table 1, baseline vehicle emissions were found and compared to reductions from PHEV penetrations [15].

2.2. Power systems modeling

We model the power system by applying an optimal power flow model (MATPOWER) onto a reduced 36-bus Northeast Power Coordinating Council (NPCC) AC network [16]. MATPOWER simulates power flow while minimizes generation costs, transmission losses and costs for required reserves subject to realistic grid constraints taken from ISOs, such as thermal limits on transmission lines, real and reactive generation capacities, bus voltages and generator voltage settings.

The geographic area of the NPCC region totals approximately one million square miles and includes New York State, the six New England states, Ontario, Québec and the Maritime Provinces. The total population served is approximately 56 million people, and 20% of the Eastern Interconnection load is served within the NPCC region.

The 36 buses are located at geographic points around the Northeast; 19 of which represent the entire state of New York and its corresponding generating facilities. The loads from PHEV activity in NYMA largely affect 13 buses: Farragut, Dunwoodie, Newbridge, Ramapo, Rochestor, Massena, New Scotland, Marcy and Pleasant Valley in New York; Millstone, Norwalk Harbor and Southington in New England; Alburtis in PJM. For this study, we have individually matched the fuel type and emission rates for CO_2, SO_2, and NO_x for 693 generators in the NPCC network according to existing public data in order to simulate the emissions changes due to PHEV penetrations [17].

The baseline load profiles in the NPCC region are taken from the corresponding ISOs: PJM, NYISO, ISONE and Ontario [18–23]. Moreover, to model PHEV's power demands we heterogeneously incorporated different marginal loads to the different buses affected based on PHEV penetration and commuter volume to that bus.

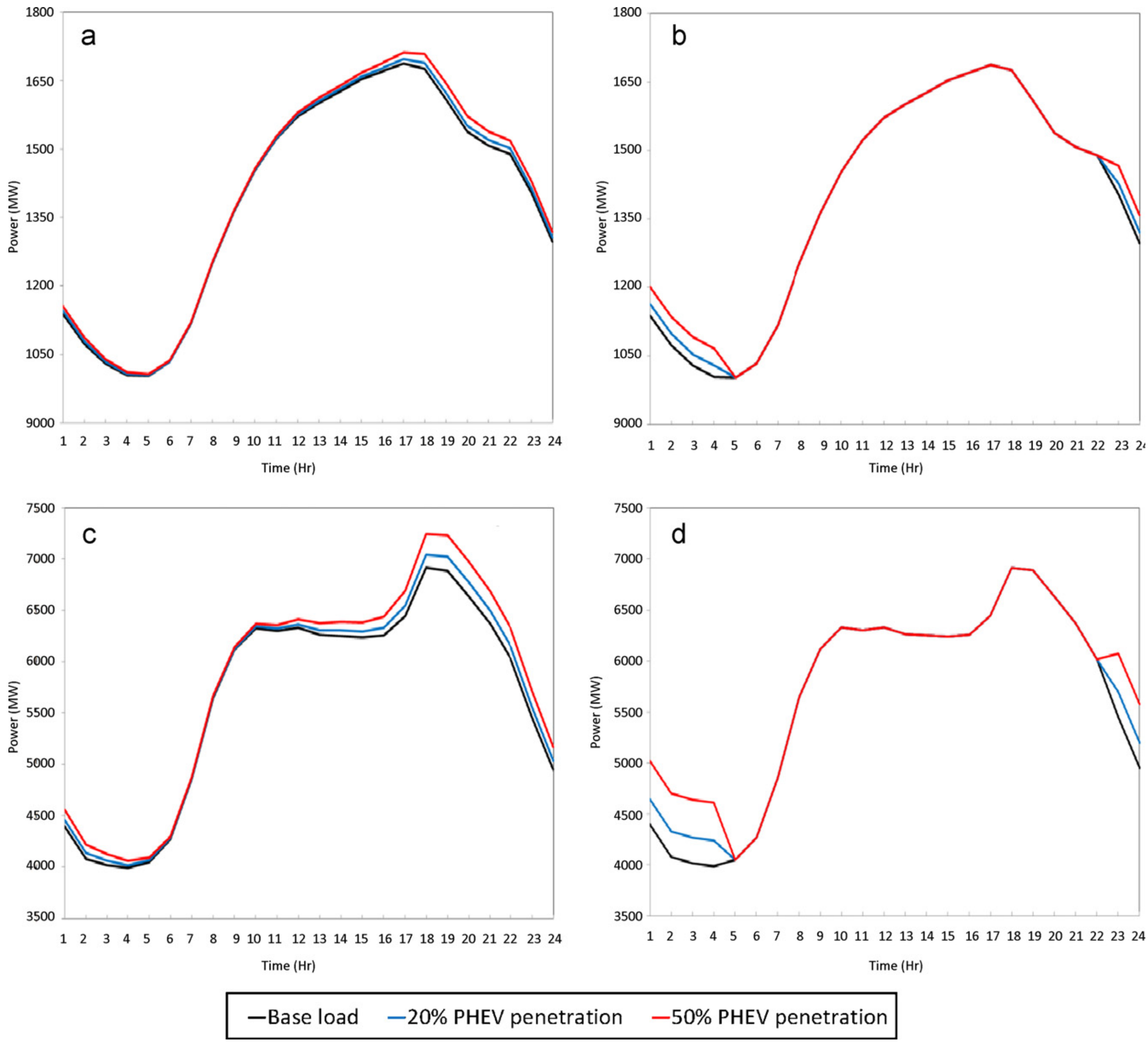

Fig. 1. Load profiles in NYMA with 20% and 50% penetrations of PHEVs for the scenarios: (a) unregulated charging in summer, (b) regulated charging in summer, (c) unregulated charging in winter, and (d) regulated charging in winter.

2.3. Scenarios

Five different PHEV market penetrations were used based on the potential market dispersion of these vehicles [24]. The penetrations are 1%, 5%, 10%, 20%, and 50% of the entire Light Duty Vehicle (LDV) fleet, where results for 20% and 50% are reported in detail. Results for 1–10% penetrations are briefly discussed.

Two seasonal scenarios were analyzed: one in the summer when demand for electricity peaks and another in the winter with low baseline loads. There are significant differences in the hourly aggregate loads and spatial distribution of these loads between the two seasons. These differences can significantly vary the impact of PHEVs in terms of marginal generation dispatch, fuel mixture, and emissions characteristics. For each season, real-time data from ISOs were taken during a select 24-h period to represent the base load profile of that season.

Furthermore, beyond the "unregulated charging" described in Section 2.1.1, a "regulated charging" scenario was developed to study the impact of a potential charging regulation. This scenario requires PHEV owners to charge their vehicles at night when base load is low. This scenario creates a uniform power demand from 11 PM to 5 AM, where most vehicles are available for charging while at home [12]. The regulated charging approach can avoid increasing the costly peak loads where generators must ramp up to meet ever larger loads while potentially reducing network reliability. Moreover, regulated charging can avoid additional pollution during peak load by not using the notoriously polluting peaking units.

3. Results and discussion

3.1. Load profiles

Fig. 1 represents the electric demand profiles for the NYMA during a 24-h period in two different seasons and under various penetration scenarios. The unregulated charging of PHEVs aggravates the late afternoon and early evening peak electric demand because the additional load coincides with residents turning on their home appliances. In contrast, with regulated charging the additional demand will help to fill the valley of the demand curve in the late night and early morning, particularly in the winter season.

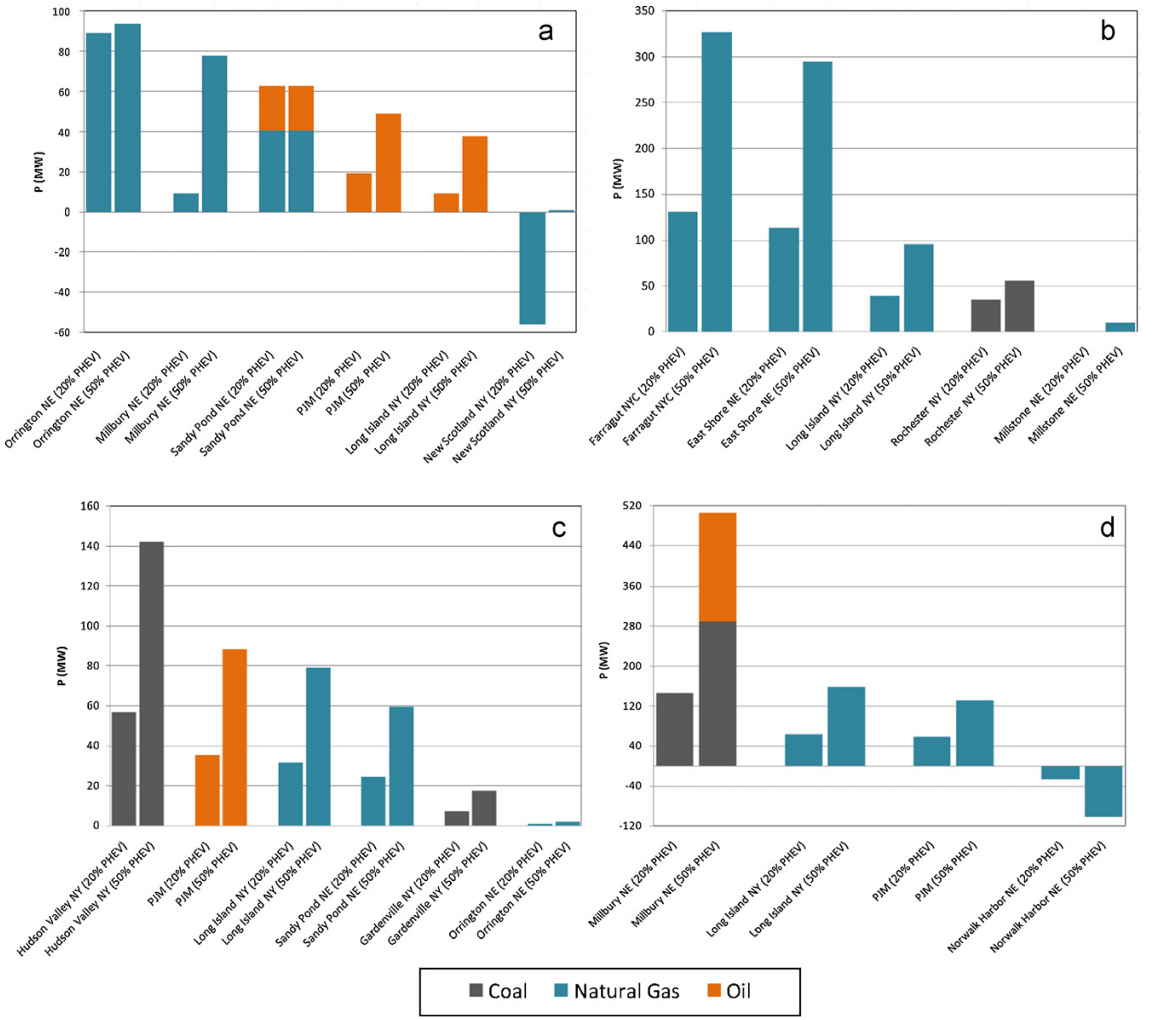

Fig. 2. Location-specific marginal fuel mixture at 20% and 50% penetrations of PHEVs for the scenarios: (a) summertime unregulated charging at peak load (5 PM), (b) summertime regulated charging at valley load (4 AM), (c) wintertime unregulated charging at peak load (8 PM), and (d) wintertime regulated charging at valley load (4 AM).

The changes in electric demand will cause the ISOs to re-dispatch the power generators, particularly for the regulated charging case in the winter when significant load from PHEVs is added. This would alter the emission characteristics from the power plants. In real network operations, the sharp increase and decrease of the load profiles at 11 PM and 5 AM in regulated charging would not exist. However, schemes to smooth the profile at 11 PM and 5 AM would not significantly alter the fuel mixture and emission characteristics at the other 22 h. Consequently, potential schemes to smooth the load profiles for regulated charging are beyond the scope of this study.

3.2. Marginal capacity

In this section, we will investigate how the fuel mix for power generation changes with PHEV penetration. Since the operating costs of electricity generated from hydropower and nuclear power plants are the lowest among different generation types and that these units have slow ramping rates, these power plants typically provide the base-load power. In our model, nuclear and hydro units have zero operating cost per MW produced. These units are already dispatched at their respective full capacities due to base case loads prior to the incorporation of PHEV loads. Therefore, these units are unable to generate additional power when PHEV loads are incorporated. Moreover, nonlinear engineering and operational constraints of the grid modeled were insufficient to reduce the dispatch of nuclear and hydro units when PHEV loads are added. Consequently, the dispatch of nuclear and hydro units does not change with the additional PHEV loads investigated.

At the current regulatory environment, the electricity generated from coal-fired power plants is still relatively inexpensive compared to natural gas and oil plants and therefore maximized at a lower demand. As a result, remaining coal units not used for base load, natural gas plants, and to a less extend, oil-fired plants will provide the marginal capacity.

Our power systems simulations yield quantitative results on the marginal capacity. We compare the fuel mix in the NPCC region with different PHEV penetrations in the NYMA. Fig. 2 illustrates the location specific marginal fuel mix for 20% and 50% PHEV penetration scenarios at peak and valley load hours.

Overall, natural gas plants located in or around the urban centers of NYMA provide the largest portion of the marginal capacity. How-

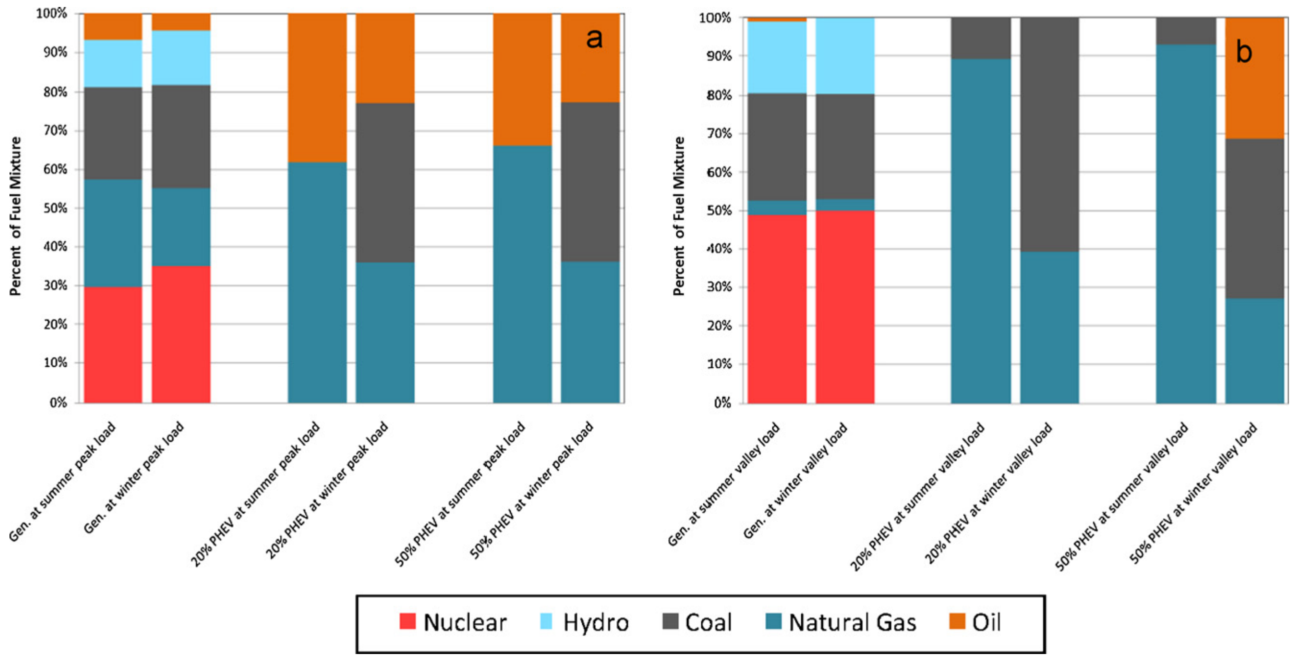

Fig. 3. Percent-wise marginal fuel mixture for 20% and 50% penetrations of PHEV at summer peak and winter valley base loads using: (a) unregulated charging, and (b) regulated charging.

ever, the specific combination of marginal fuel dispatch depends on the season and charging scenario. Despite the differences in the exact marginal dispatch pattern, a few of the buses are affected across multiple PHEV penetrations for most seasonal and charging scenarios, e.g. Long Island and PJM. This is due to the fact that these buses have a compilation of lower cost generators and topological advantage (e.g. lower line flow losses and higher thermal limits) over other buses. Thus for other scenarios these same advantages will likely remain, causing the same buses to be marginal dispatched again.

In the summer, natural gas and oil-fired power plants are dispatched to meet the additional load for unregulated charging scenario, because almost all of the coal plants are already fully dispatched for base load. Furthermore, at peak load peaking oil units in or near NYMA are present in the marginal fuel dispatch due to amount of total load and network constraints. For the regulated charging scenario, natural gas generators provide almost all of the marginal dispatch due to its lower base load at nighttime compared to unregulated charging at daytime peak load. At nighttime, most of the coal units are dispatched for base load, while natural gas is sufficient to provide marginal power without oil units.

In wintertime, coal, natural gas and oil units are all marginally dispatched for both charging scenarios. Coal is used because there is an available coal capacity after serving base load. Natural gas and oil-fired power plants are dispatched to serve the remaining marginal load. Fig. 3 shows the fuel mixture in percentage for base load and marginal load from 20% to 50% penetration of PHEV.

Fuel mixture for base load in the NPCC network is dominated by nuclear, natural gas and coal in the summer and by nuclear, coal and hydro in the winter. Marginal fuel mixture is dominated by coal, natural gas and oil, whose specific compilations depend on season and load conditions as shown. More significantly, as base load fuel mixture for the NPCC region uses more clean energy (nuclear and hydro) than the nation currently uses, the NPCC generation mixture can be used as a model representing the future fuel compilation for the national power system [17]. Consequently, the marginal fuel mixture from charging PHEVs in the NPCC region can be representative of the marginal fuel mixture for the nation in aggregate.

Overall, the non-intuitive negative marginal dispatches at summer peak and winter valley loads, and marginally dispatched oil units in Figs. 2 and 3 are caused by power flows deviating significantly from pure economic dispatches without network constraints. Consequently, realistic marginal dispatches are not only subject to generator cost but also transmission constraints. These effects of network constraints are further explained in Section 4.

3.3. Emissions

3.3.1. Vehicle emissions

Fig. 4 shows significant reductions in CO_2 and NO_x emissions from the transportation sector as a result of PHEV penetration in the NYMA. The hours of 6 AM and 6 PM account for the times when there is significant vehicle traffic and hence when the greatest reductions take place. Spatially, these emissions reductions will occur within the NYMA, particularly in NYC and the immediate surrounding areas. Twenty percent penetration scenarios are enumerated in Table 2. Seasonal variations, heavy-duty vehicles, or transient drivers are not considered in the analysis. At 20% PHEV penetration, daily CO_2 and NO_x emissions in the transportation sector are reduced by nearly 4860 tons and 7 tons, respectively.

3.3.2. Power plant emissions

It is expected that all types of the emissions from power plants will increase as a result of PHEV penetration with the most sig-

Table 2
Daily baseline emissions from commuters and emissions reduction from 20% penetration of PHEV in the NYMA.

	CO (ton day^{-1})	VOC (ton day^{-1})	NO_x (ton day^{-1})	$PM_{2.5}$ (ton day^{-1})	PM_{10} (ton day^{-1})	CO_2 (ton day^{-1})
Baseline	609.8	24.5	25.9	6.6	13.7	29198.9
Emissions reduction (20% PHEV)	156.5	6.3	6.7	1.7	3.5	4858.6

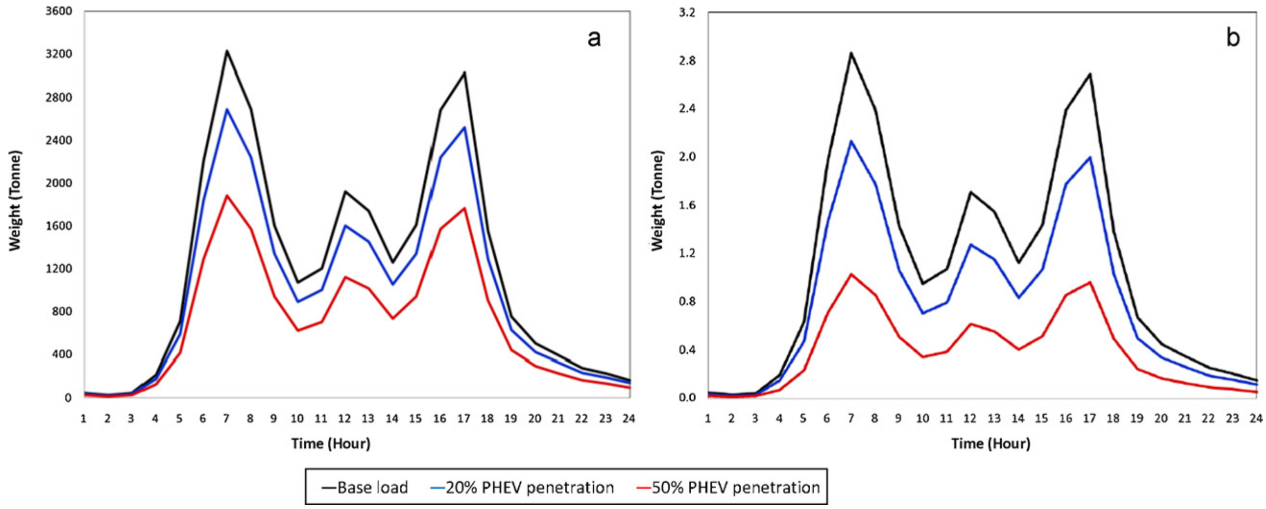

Fig. 4. Hourly emissions from commuter traffic with 20% and 50% penetration of PHEVs in the NYMA for: (a) CO_2 and (b) NO_x.

nificant increase coming from CO_2. Moreover, marginal emissions are dependent only on the specific fuel type and emission characteristics of those marginally dispatched generators. Therefore, quantitative and qualitative differences in the marginal dispatch of generation modeled with and without network constraints will be reflected in the marginal emissions.

In the unregulated charging scenarios the additional increases occur from the peak demand hours of the day to early hours of the next morning as commuters come back home from work with PHEV batteries needing charge. During the regulated charging scenarios the emission increase will occur during the allotted charging times from late night to early morning before commuters leave for work.

Table 3 expresses the modeling results over four demand scenarios and at 0% and 20% PHEV penetration. Table 3 illustrates that unilaterally the emissions of all pollutants from power plants will increase due to the introduction of PHEVs, but the magnitude of the increases vary with the level of PHEV penetration, charging scenarios and seasons.

Since coal units are among the heaviest emitters of CO_2, NO_x, and SO_2, the significant marginal dispatch of coal in wintertime produces higher marginal SO_2 emissions than in the summertime. Moreover, more marginal power from coal in the winter regulated case produces more emissions across the board compared to unregulated charging in the winter as well as unregulated and regulated charging in the summer. Marginal CO_2 and NO_x emissions results for unregulated charging are similar betweem summer and winter seasons. This is due to coal units marginally dispatched in winter and peaking oil units marginally dispatched in the summer have similar CO_2 and NO_x emissions characteristics. Regulated charging in summer using natural gas plants produces the least marginal emissions, because coal is not extensively used due to their commitment to high base loads and peaking oil units are not deployed for valley loads at night.

3.3.3. Net emissions

Net emissions are calculated from the sum of emissions from tailpipe and smoke stacks. Table 4 tabulates the results that net CO_2 emissions decrease significantly, NO_x emissions decrease noticeably and SO_2 emissions increase slightly. The decrease in vehicle CO_2 and NO_x emissions clearly offset the increase resulting from power plants in the region.

Fig. 5 shows the hourly net CO_2 emissions with 20% and 50% penetration of PHEVs in the NYMA for unregulated and regulated charging.

From early morning to late night, net emissions profile is largely dictated by vehicle activity. This again shows that vehicle emissions reduction is the dominant factor compared to power plant emissions during these hours. This is due to the fact that power plants are cleaner than vehicle engines in producing energy for transportation. The increase in net emissions from late night to early morning hours for unregulated and regulated charging cases show that at these times, power plant emissions increase is the dominant factor compared to vehicle emissions reductions. This is due to the fact that at these hours, there is little vehicle activity overall such that the percentage substitution of PHEV makes little difference in vehicle emissions reduction. Simultaneously however, the continual charge of PHEV batteries at home are still drawing large amount of power from the grid. Consequently, emissions from producing power for charging PHEVs are higher than the emissions reduction from PHEVs on the road, resulting in positive net emissions at the late night to early morning hours. This net emissions increase is more noticeable in the regulated charging cases,

Table 3
Daily power plant emissions increase in the NPCC region for unregulated and regulated charging scenarios in the summer and winter.

Season	PHEV penetration	Unregulated charging				Regulated charging			
		Electricity generation (GWh)	CO_2 (ton day^{-1})	NOx (ton day^{-1})	SO_2 (ton day^{-1})	Electricity generation (GWh)	CO_2 (ton day^{-1})	NO_x (ton day^{-1})	SO_2 (ton day^{-1})
Summer	0%	2420.8	975,052	786.7	4148.6	2,420.8	975,052	786.7	4148.6
	20%	2422.7	976,344	787.7	4149.1	2,422.7	976,135	787.3	4149.2
	Δ	1.9	1292	1.0	0.5	1.9	1083	0.6	0.6
Winter	0%	2175.8	809,205	671.1	4007.7	2,175.8	809,205	671.1	4007.7
	20%	2177.7	810,493	672.0	4010.3	2,177.7	810,649	672.5	4013.9
	Δ	1.9	1,288	0.9	2.6	1.9	1,444	1.4	6.2

Table 4
Daily net emissions in the NPCC region for both unregulated and regulated charging scenarios in the summer and winter.

Season	PHEV penetration	Unregulated charging		Regulated charging	
		CO_2 (ton day^{-1})	NO_x (ton day^{-1})	CO2 (ton day^{-1})	NO_x (ton day^{-1})
Summer	0%	1,004,251	812.6	1,004,251	812.6
	20%	1,000,684	806.9	1,000,475	806.5
	Δ	−3567	−5.7	−3776	−6.1
Winter	0%	838,404	697.1	838,404	697.1
	20%	834,833	691.2	834,989	691.8
	Δ	−3571	−5.9	−3415	−5.3

because the same batteries charging energy requirements are allotted in a smaller time window in regulated charging. This increases the corresponding power requirement from the grid, and thereby increases emissions from the power sector while vehicle emissions reduction remains unchanged between unregulated and regulated charging.

Moreover, as vehicle emissions reduction remains constant in regulated and unregulated cases in both summer and winter seasons, trends in net emissions mimic the same trend from power plant emissions. Namely, regulated charging of PHEVs in the summer produces the most marginal net emissions reduction; unregulated charging in summer and winter produces similar marginal net emissions reduction; regulated charging in winter produces the least marginal net emissions reduction.

3.4. Summary of results for 1%, 5% and 10% penetrations of PHEVs

Daily energy demand for 1%, 5% and 10% penetrations of PHEVs are 0.1 GWh, 0.5 GWh and 1.0 GWh, respectively. The marginal generation for and net CO_2 and NO_x reductions from 1%, 5% and 10% penetrations of PHEVs are dominated by coal units in the winter and natural gas units in the summer. At 10% penetration, there is minimal increase of generation and emissions from oil units at summer peak demand. In general, net CO_2 and NO_x reductions from the three penetrations are approximately the corresponding fractions of the reductions from the 20% penetration. Overall, net CO_2 and NO_x reductions in wintertime average about 5% less than those in summertime due to the use of coal versus the cleaner natural gas units. Finally, regulated charging marginally reduces more net emissions than unregulated charging in the summer and vice versa in the winter. This trend is consistent with that in higher PHEV penetrations and consistent with the use of different marginal fuels.

4. Effects of network constraints

As described at the beginning of this paper, many existing PHEV assessments do not contain network transmission constraints. However, the power to charge PHEVs must be delivered by the grid, and therefore such power flows must adhere to transmission constraints. Using our reduced model of the NPCC grid, we show that engineering and operational constraints in a realistic US power grid, such as line impedance, line flow and bus voltage limits, significantly alter the generation dispatch from a pure economic dispatch without network constraints. Consequently, an economic dispatch model with grid constraints is a more realistic approach to analyze the energy and environmental impacts of PHEVs.

Fig. 6 shows the difference in generation dispatch between economic dispatches with and without grid constraints using a 50% penetration of PHEVs with base load. Results are calculated from economic dispatches with network constraints less those without network constraints.

The effects of network constraints are significant at daytime summer peak load and at nighttime winter valley loads as shown. Network impedance, not congestion, has the foremost influence on the generation dispatch pattern in our summer peak and winter valley load cases. This suggests that I^2R line loss minimization is an economic priority with network constraints. Moreover, the aggregation of the differences between grid and no-grid results over all the buses gives the total power losses of the network due to network impedance. (This is about 1 GW in our cases.) However, generation difference at individual buses can be 10 times the aggregate difference. Particularly, the large difference in the generation at Alburtis (PJM, Bus 1) with and without network constraints suggests the importance of analysis using the grid. Fig. 6 shows that reducing the overall impedance of the network dramatically decreases the dispatched generation at Alburtis, i.e. this generation

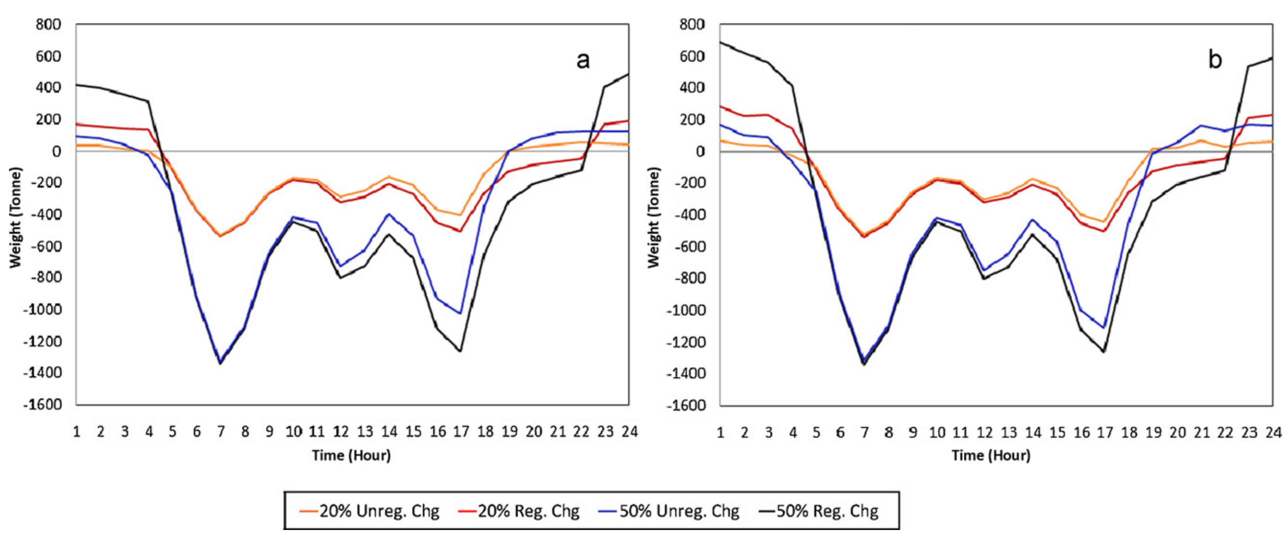

Fig. 5. Net hourly CO_2 emissions from the unregulated and regulated charging of PHEVs in the NYMA during: (a) summertime and (b) wintertime.

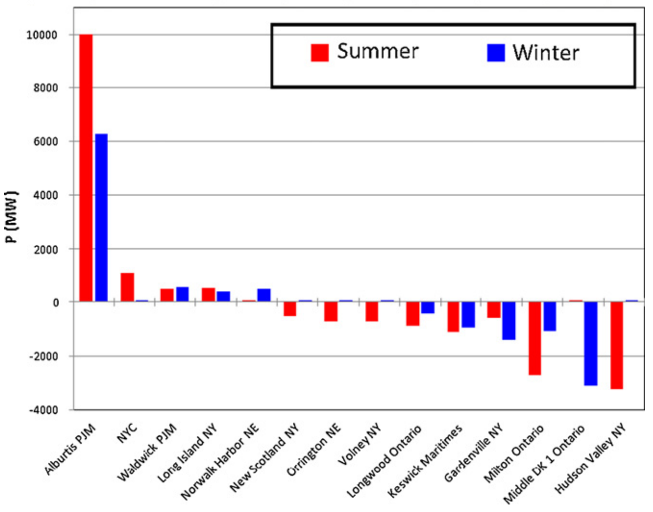

Fig. 6. Difference between economic dispatch of total generation with and without grid constraints with 50% penetration of PHEVs in the summer and winter.

with network impedance is much greater than that without. This result and direct topology inspection show the impedance of the topological region around Alburtis is smaller than other regions in the network. Thus, this bus is economically dispatched with less transmission losses to provide power to loads at other buses. On the other hand, when the impedance of the entire network is eliminated, the topological advantage of Alburtis is eliminated. This results in a reduction of power output from this bus and an increase of power output from other buses as shown.

These large generation differences at individual buses can cause significant differences in marginal fuel dispatch and emissions between economic generation dispatches with and without grid constraints. An example of such differences in marginal dispatch is obtained by comparing Fig. 2a (with grid constraints) and Fig. 7 (without grid constraints).

The difference between this marginal dispatch with grid constraints and a pure economic dispatch is significant. Pure economics without network constraints would only dispatch natural gas units

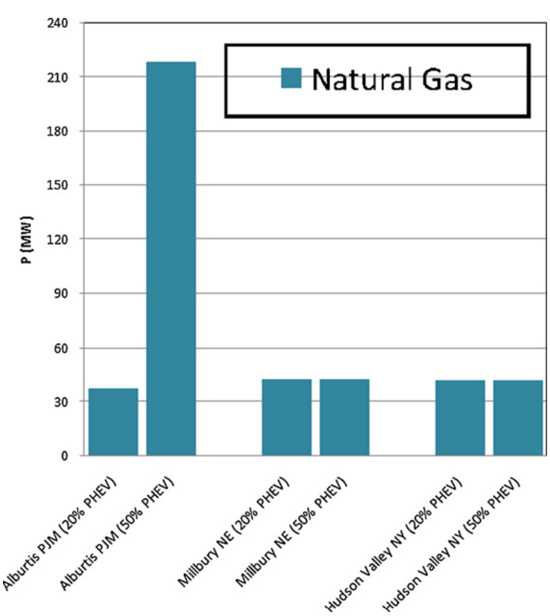

Fig. 7. Marginal economic dispatch at summer peak load for 20% and 50% penetrations of PHEVs using unregulated charging without grid constraints.

at the three locations for 20% and 50% penetration of PHEVs as shown in Fig. 7. Since these units at Millbury (New England) and Ramapo (Hudson Valley) are the cheapest, they are dispatched first to their capacities with the rest of the marginal load served by the next cheapest units at Alburtis.

As our power system model realistically represents the physical NPCC grid, the difference between generation with and without network constraints in the model are manifested in the physical system. Compared to without grid constraints the marginal dispatch with grid constraints increases generation at certain buses and decreases generation at other buses (e.g. New Scotland in New York and Norwalk Harbor in New England). These behaviors lead to uneconomic dispatches, which cannot not be observed in a dispatch model without grid constrains. In addition, there are multiple topological causes for the negative marginal dispatches depicted in Fig. 7. For example, one cause is a thermal limit on a line from Waldwick in PJM to Ramapo in Hudson Valley. Moreover, the relaxation of grid constraints need not be topologically close to a bus for that bus to uneconomically dispatch significant generation. Consequently, the effects of grid constraints on economic dispatch are nonlinear and generally widespread when realistically assessing PHEVs' influence on regional power consumption and emissions.

5. Conclusions

This paper demonstrates that network-constrained economic generation-dispatch models add significant realism in assessing the impact of PHEVs on regional power systems and the associated pollutant emissions. Using a model of the AC transmission network of the Northeast Power Coordinating Council region and a data-based transportation model of commuters in the New York Metropolitan Area, this paper shows that (1) coal, natural gas and oil units are on the margin in the winter, and natural gas and oil units are on the margin in the summer, (2) commuter hourly driving behavior dominates changes in emissions from transportation and power production, (3) there is significant overall emissions reductions for CO_2 and NO_x, and a slight increase for SO_2, and (4) regulated charging from 11 PM to 5 AM produces less overall emissions than unregulated charging occurring whenever drivers arrive home for the summer and vice versa for the winter.

Future work in the assessment of PHEVs is to incorporate unit commitment of generators into the network-constrained economic dispatch model such that generator start-up time is modeled. Moreover, as volatile renewable power sources such as wind and solar enter the generation mix, batteries of PHEVs have the potential to interact with the grid as distributed storage to help maintain network reliability and increase the capacity factors of these renewable power sources. Consequently, system planning models such as the one described in this paper which incorporates network topology will be important in assessing the value and determining the operations of PHEVs as storage units.

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