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Impact Assessment of Plug-in Hybrid Vehicles on the U.S. Power Grid

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Abstract— The US electricity grid is a national infrastructure that has the potential to deliver significant amounts of the daily driving energy for the US light duty vehicle (cars, pickups, SUVs, and vans) fleet. This paper discusses a 2030 scenario with 37 million plug-in hybrid electric vehicles (PHEVs) on the road in the US demanding electricity for an average daily driving distance of about 33 miles (53 km). The paper addresses the potential electrical grid impacts of the PHEVs fleet relative to their effects on the production cost of electricity, and the emissions from the electricity sector. The results of this analysis indicate significant regional difference for the cost impacts and the CO_2 emissions. Battery charging during the day may have twice the cost impacts than charging during the night. The CO_2 emissions impacts are very region-dependent. In predominantly coal regions (Midwest), the new PHEV load may reduce the CO_2 emission intensity (ton CO_2/MWh), while in others regions with significant clean generation (hydro and renewable energy), the CO_2 emission intensity may increase. These results may change with the valuation of carbon emissions because the carbon value may shift the generator dispatch toward cleaner fuels. *Copyright Form of EVS25.*

Keywords— Plug-in hybrid electric vehicles, production cost of electricity, emissions, charging profiles

1 INTRODUCTION

The U.S. electricity infrastructure has the potential to provide a significant portion of the driving energy to millions of electric vehicles. The electrification of transportation offers a tremendous opportunity to meet national and global energy security and emission objectives that reduces the dependence of petroleum and lower national and global CO_2 emissions.

Previous work has shown that the existing US generation and transmission infrastructures have the technical potential to supply power to 73% of the U.S. light duty vehicle (LDV) fleet [1]. The level of 73% is a national average, with the actual values varying significantly by regions. Because of the large regional differences in the generation mix across the US and the varying available electricity capacity to accommodate the new transportation load, a very detailed analysis was performed that studied at high temporal and regional resolution the likely grid impacts of defensible penetration scenario in the US for the 2030. This study addresses some of the questions by regional energy planners who were interested in the likely cost impacts of generating electricity, which then in turn has electric rate impacts to rate payers. In addition, several questions by the automotive industry and policy makers emerged regarding the emissions profile of the electricity supply for electric vehicles. Of particular interest were questions that explore the time periods when the electricity is the cleanest and to understand the effect of day-charging versus night-charging strategies on the overall emission reduction potential of electric transportation.

The analysis generated very regionally detailed results with an hourly time resolution. This paper summarizes the massive amount of data at an aggregated level of 13 regions covering the entire contiguous US LDV and electric power sectors.

The paper discusses insights to the following set of questions:

- What are the impacts of a plausible penetration of plug-in hybrid electric vehicles (PHEVs) on the electricity production cost at a regional level?
- What are the impacts on CO_2 intensity at a regional level for a set of selected charging strategies?

To explore these questions, this analysis employed an economic dispatch of electric generators to meet the new load. The economic dispatch was performed with a production cost model called PROMOD[1]. PROMOD performs a security constrained unit commitment with optimal power flow modeling to minimize the operating cost for meeting load.

This analysis is unique because of its level of temporal (hourly) and regional (by service territories) resolution for the US grid as well as the representation of individual generator units and detailed modeling of the US transmission system. This provides significant insights into the likely effects of the new transportation load on the generation dispatch and power transfers across regions and their influence on electricity production cost and emissions. Other excellent studies have been performed with less resolution most notably the study by Oakridge National Laboratory [2].

2 PHEV PENETRATION ASSUMPTION

The number of PHEVs that are likely to be on the road in the year 2030 is currently the subject of several

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[1] PROMOD is developed by Ventyx. http://www.ventyx.com

analytical research efforts using various modeling techniques to capture the customer acceptance and consumer choices for purchasing PHEVs [3][4][5]. We applied the Delphi approach to establish a defensible market adoption projection for this analysis. In this approach we interviewed relevant industry professionals in the fields of automotive manufacturers, automotive supplier, battery, and research communities to ascertain a defensible projection of PHEVs likely to be on road in the US in 2030 [6].

We used the medium penetration scenario that assumes that all of the DOE cost targets for mass-produced PHEVs will be realized [7]. The adoption trajectory for PHEVs is shown in Figure 1. It is defined by a logit function describing a commonly observed market penetration of new technologies. The adoption rate is expressed in terms of a market share in percent of annual sales in the US. We derived the number of available PHEV in the fleet by inventorying old vehicles leaving the market and being replaced by new vehicles and an overall annual growth of the vehicles stock of 1.4%. Using these assumptions, a total of about 37 million vehicles are presumed to be in the US fleet in 2030.

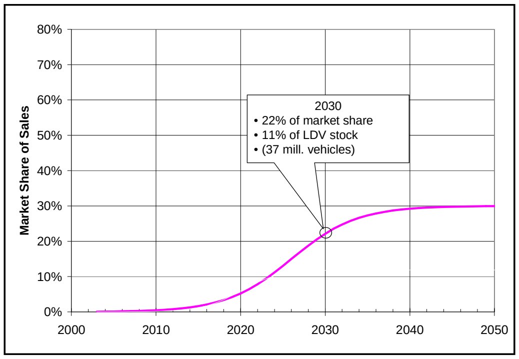

Figure 1: PHEV Penetration Projections

The total PHEV fleet was regionally distributed according to the today's proportion of light-duty vehicles registrations. Regions were defined based on the North American Electric Reliability Corporation's (NERC's) definition prior to 2006 redefinition of the regions.

The analysis employed the following definition of 13 regions, also shown in Figure 2:

ECAR: East Central Area Reliability Coord. Agreement
ERCOT: Electric Reliability Council of Texas
MAAC: Mid-Atlantic Area Council
MAIN :Mid-America Interconnected Network
MAPP: Mid-Continent Area Power Pool
NPCC: Northeast Power Coordination Council
    NYISO: New York ISO
    ISONE: ISO New England
FRCC: Florida Reliability Coordinating Council
SERC: Southeastern Electric Reliability Council
SPP: Southwest Power Pool
NWP: Northwest Power Pool Area
AZN&RMP: Arizona-New Mexico-Nevada Power Area and the Rocky Mountain Power Area
CNV: California and Southern Nevada.

Table 1 shows the regional distribution of PHEV adoption by NERC region for the year 2030. The source for the U.S. vehicle stock data is the 2001 motor vehicle registration, by states, as published by the U.S. Department of Transportation [8]. Registration figures were chosen for cars, light trucks, SUVs, and vans, generally referred to as LDVs. Motorcycles are not included. Approximately 217 million vehicles were registered in the LDV category in 2001. Registrations for cars, pickup trucks, and SUVs alone amounted to 198 million. Other heavier vehicles, such as busses and trucks, are not considered in this study, although there are no technical reasons that would prevent busses and trucks from adopting plug-in hybrid electric technology. This analysis strictly focuses on LDVs, excluding motorcycles.

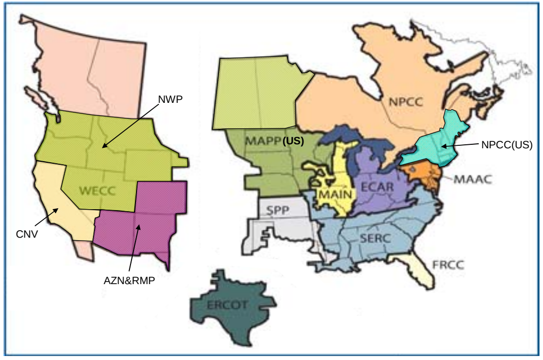

Figure 2: Definition of Regions Used in this Study—13 Modified NERC Sub-Regions Based on the Pre-1/1/2006 Regional Council Structure[2]

Table 1: Assumed PHEV Stock by NERC Regions in 2030

Region	Number of PHEVs in Mill.	Annual Electric Energy Consumption [TWh]
ECAR	4.9	22.9
ERCOT	2.1	9.7
MAAC	3.4	16.0
MAIN	2.9	13.5
MAPP	1.6	7.5
NYISO	1.6	7.5
ISONE	1.9	8.9
FRCC	2.3	10.7
SERC	6.3	29.3
SPP	1.3	6.3
NWP	2.2	10.4
AZN&RMP	1.6	7.6
CNV	4.6	21.4
US total	36.8	171.6

3 CHARGING PROFILES

The charging profiles were based on the US Department of Transportation's 2001 National Household

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(2) After 1/1/2006, the Regional Reliability Councils—ECAR and MAAC—were aggregated into Reliability First Corporation. Sections of the MAIN merged into SERC and into the Midwest Reliability Organization (MRO). More information can be found at: http://www.nerc.com/~org/entities/.

Travel Survey [12]. Of the approximately 70,000 individual travel logs in the survey about 30,000 pertained to drives with a personal vehicle. These 30,000 observations of travel events were simulated assuming a population of LDV representing the proportion of the US vehicle classes (car, pickup, van, SUV) with an assumed PHEV configuration and an electric drive range of 33 miles, similar to a PHEV33 [9][10]. The efficiency assumptions of PHEVs by vehicle classes were based on EPRI studies [11]. Three charging scenarios were assumed.

- Scenario 1: charging at home (A4)
- Scenario 2: charging at home and work (A5). This scenario assumed ubiquitous charging infrastructure supporting opportunity charging whenever the vehicle is parked. This scenario is also referred to as *day charging* because it has the highest energy demand during day time
- Scenario 3: charging at home, delayed to after 10 p.m. with randomized onset of charging over a 2-hour period (A6). This scenario is also referred to as *night charging*. It maximizes the use of off-peak power.

Following the emerging industry trends of dual 120 Volt and 240 Volt charging capabilities in both the announcements of PHEV offerings and charging station infrastructure developments, we assumed an equal share of 120 Volt and 240 Volt charging. The resulting charging profiles are shown in Figure 3. The electric energy requirements (area under the profiles) are approximately 12 kWh for home charging (A4), 15.6 kWh for home and work (A5), and 11 kWh for home delayed charging (A6) to an average of approximately 12.8 kWh per day per vehicle. The (A5) charging strategy require higher energy requirements because the battery was partially cycled several times during the day and partially charged up whenever the opportunity arose.

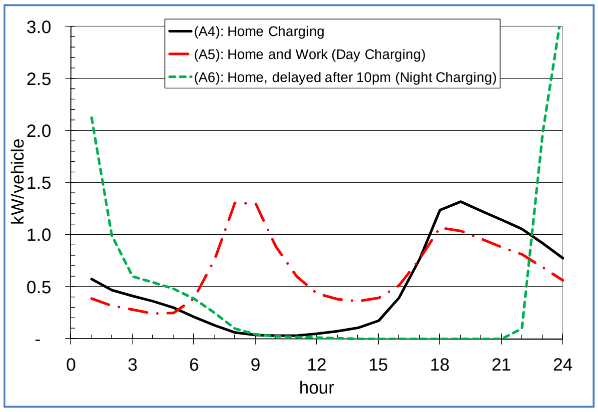

Figure 3: Charging profiles used

4 ELECTRIC GRID SIMULATIONS

The impacts of the additional electric load were studied using a commercial grade software tool called PROMOD. This tool is used for infrastructure planning and grid operations purposes and provides detailed representation of the electric power system including the economics of individual generator units and the transmission transfer limits. It is based on optimization techniques that minimize the operating cost of the entire system to deliver electric power to the customers. The model provides hourly results over 1 year for operating conditions and cost of each power plant and each transmission line. This very detailed information was aggregated to a state level and then further to a regional level to manage the massive amount of data output.

The model represented the US electric power system as of the year 2009 with some projections of future power plant constructions that were sufficiently far advanced in the permitting or construction process. However, to represent a future grid for the year 2030, additional infrastructure expansion assumptions were necessary to accommodate the anticipated load growth from non-transportation loads. Projections of electric generation capacity expansions by the US Energy Information Administration’s Annual Energy Outlook 2009 (AEO2009) were used to augment the power plant fleet to represent a future grid scenario for 2030 [13].

5 SIMULATION RESULTS

5.1 Marginal Generation to support PHEVs

The marginal generation that would support PHEVs is the electric generation beyond what the grid would have consumed without the electric vehicles. It is the key driver for determining cost and emissions. It is determined by the available installed capacity in a region and the net transfer of electricity across regions. The generation on the margin will determine how expensive and how ‘green’ the additional generation will be to fuel the future electric vehicle fleet. The literature shows that the average generation mix is often used to assess the emissions associated with the production of electricity for electric transportation. This method is misleading. The average generation mix is an indicator of the emissions profile for the existing electricity use today and the expected use of electricity using “business as usual assumptions”. With the emergence of new technologies, such as PHEVs and electric vehicles (EVs), the relevant emission profile depends on what power plant will be used beyond the existing end-use loads to fuel electric vehicles.

In all regions, we found that natural gas generation technologies were the key contributor to the marginal generation, followed by coal steam technology. Within the natural gas fuels technology, combined-cycle plants dominated in most regions, particularly when charging occurs at night. Single-cycle steam plants fueled by natural gas were dispatched after the combined-cycle plants reached their maximum capacity, followed by combustion turbines, which were primarily used to meet peak demand because of their lower efficiency. When comparing the marginal generation difference between day charging (A5) in Figure 4 and night charging (A6) in Figure 5, the use of combustion turbines is fairly dominant as a supplier of electricity on the margin during the day when all lower cost plants (coal, natural gas combined and single cycle) are fully dispatched. Coal plants contribute a significant amount to the night charging supply of electricity. During the day, very little coal capacity remains to be dispatched to meet the PHEV load. The category “Other Single Cycle” in Figure 5 represents steam turbines with mix fuel capabilities. In most cases they are operated with natural gas.

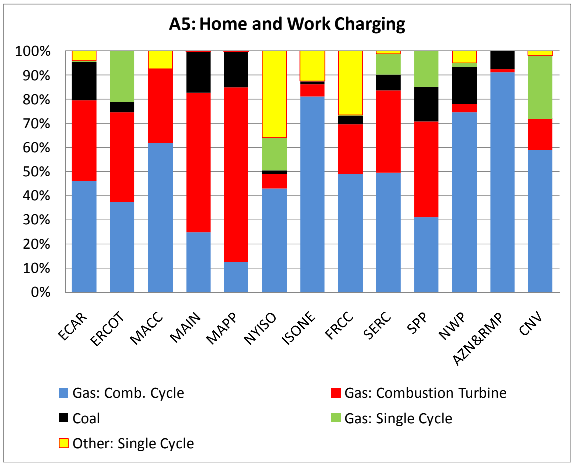

Figure 4: Marginal Generation for Day Charging at Home and Work (A5)

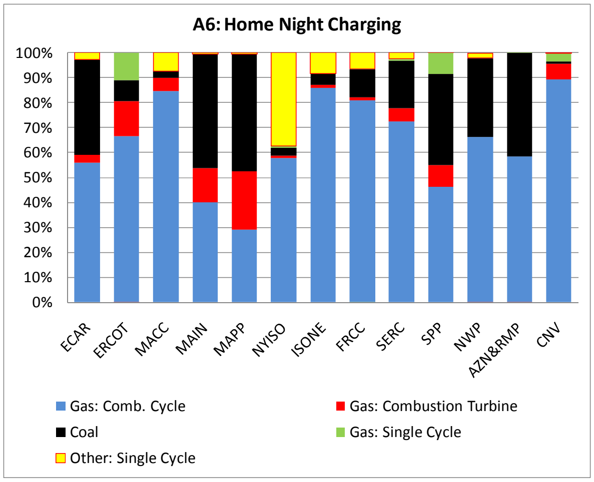

Figure 5: Marginal Generation for Night Charging at Home (A6)

Renewable energy (such as geothermal, solar, wind, and biomass) was not assumed to contribute to the daily driving energy of PHEVs. This was primarily determined by the fact that renewable energy plants are unlikely to be the marginal resource (especially not wind and solar technologies) because all of the electricity production will fully be utilized to meet the Renewable Portfolio Standards (RPS) or otherwise - by statute - required to be fully utilized and dispatched. The only time that wind could be on the margin would be if there are too much wind resources for a given load, in which case wind electricity production will need to be ‘spilled’. This condition was, however, not observed in our analysis. Furthermore, nuclear power plants did not contribute to the electricity supply for the electric vehicles because the nuclear capacity in the US is already fully utilized as a baseload resource, with virtually no remaining capacity to meet additional load.

Two key insights drawn from the results in Figure 4 and Figure 5 are:

Regional differences: there are significant regional differences in the composition of the marginal electricity generation across the US that is likely to ‘fuel’ the emerging electric vehicle fleet. The majority of the generation is likely to be contributed by natural gas technologies. The extent to which coal resources can contribute depends on the available capacity at the time when vehicles are charged, which is primarily at night when the output of coal plants is reduced in relation to the lower load requirements. The regional contribution to the marginal generation is linked to the installed capacity and its availability to meet the additional load. For coal technology, the Midwestern regions (ECAR, MAPP, MAIN) indicate significant contribution by coal for the night charging (A6). In contrast, California (CNV) shows no contribution from coal resources. Northeastern regions (NPCC) shows only small coal contribution, which in most cases stems from imports from the Midwestern region, primarily ECAR. The Northwestern region (NWP) is rich in hydro electric resources, however, because of limited water resources, the hydro electric capacity is fully utilized, leaving no additional generation possible unless new hydro capacity is built or the regulatory framework for water rights is changed.

Differences based on charging time: there are significant differences between day and night charging (A5 and A6, respectively). Day charging requires high-cost combustion turbines and single-cycle natural gas plants to meet the vehicle load. At night, higher efficient and lower-cost natural gas combined-cycle and coal units are likely to supply the electricity for the vehicles.

The different generation mix for day versus night charging is more pronounced when one analyzes the monthly and hourly generation. Figure 6 shows the hourly technology dispatch for an average summer day in the MAIN region.

The key driver for determining the type of marginal generation is the cost for dispatching the next increment of electricity production. During the day, the native load (non-electric vehicle) is significantly higher than during the night. As a consequence, higher cost generators are dispatched during the day, which in most cases are single-cycle gas and combustion turbine technologies.

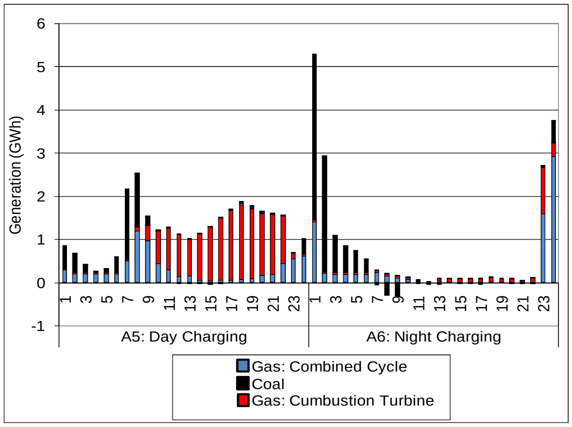

Figure 6: Hourly Marginal Generation for Summer, in MAIN for Day- and Night-Charging

5.2 Impacts on Average Electricity Production Cost

Production cost is the total operating cost for generating electricity. Often the production cost is expressed as average cost in $/MWh. The question is often posed of how much may the average cost change as the total generation increases to serve the PHEV load? Judging by the overall increase in the electric energy demand of about 3% of the total generation, the cost impacts are expected to remain small.

Figure 7 shows the regional distribution of production cost impacts of the electric vehicle fleet, expressed as the percent difference to a case without electric vehicles. The results clearly indicate that charging during the day causes twice the impact of night charging. As discussed in the previous section, expensive combustion turbine and single-cycle natural gas units are key reasons for the cost increase. Charging at night utilizes low-cost coal and natural gas combined-cycle technologies. Across the regions, the highest cost impacts are in already high-cost regions of California and the Northeast. The relatively high impact (on a percent basis) for the Northwest region (NWP) must be seen in the context that the production cost is one of the lowest in the nation. The average cost increases in absolute terms are comparable with those in other western regions. When expressed as percentage change, they appear large.

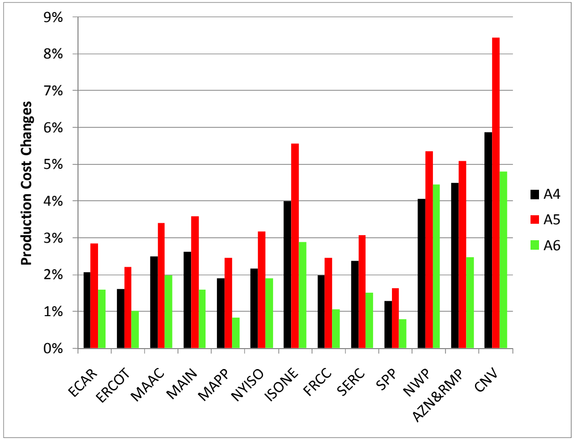

Figure 7: Changes in the Production Cost of Electricity by Charging Profiles

5.3 Impacts on CO_2 Intensity

Similar to the cost impact discussion above, emissions impacts are determined by how much the marginal generation for supporting the electric vehicle fleet shifts the emission profile of the generation to meet the non-transportation load. The specific CO_2 emissions or CO_2 emission intensity is generally used to express the CO_2 emissions output associated with the generation of 1 MWh (ton CO_2/MWh).

Figure 8 shows the regional CO_2 emission changes by charging profiles. The Eastern regions (ECAR, MAAC, MAIN, SERC, SPP), Rocky Mountain (AZN&RMP), and Texas (ERCOT) show a net reduction in the intensity. California and the NWP, which are rich in renewable energy resources, are likely to increase their CO_2 emission intensity with a growing electric vehicle fleet. This result is fully plausible when recognizing that the non-transportation load is met by a high portion of renewable resources (hydro in the NWP and hydro, wind, geothermal in California), and that the generation for meeting the future transportation load (marginal generation) is primarily fossil-fuel based.

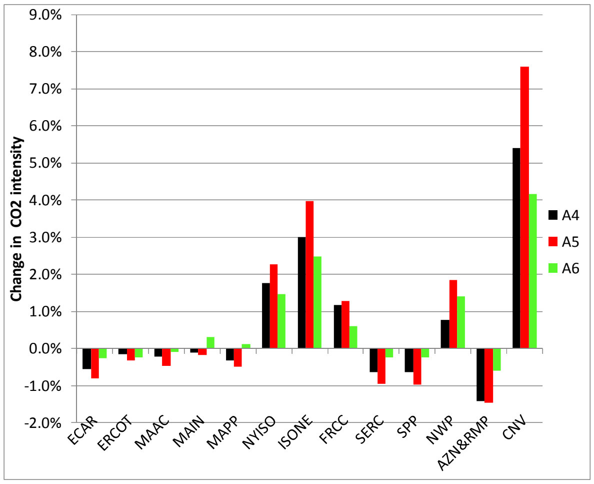

Figure 8: Changes in the CO_2 Intensity by Charging Profiles

6 DISCUSSION

The detailed modeling results clearly indicate that from an economic perspective, the recommendation should be to charge at night utilizing the lower-cost generation capabilities. From a CO_2 emissions point of view, this policy recommendation is not quite as clear. For the regions such as MAAC, MAIN, MAPP, SERC, SPP, and AZN&RMP, the lowest emission intensity can be reached with day charging strategies (A5), when gas generation shifts the average CO_2 emissions per MWh produced toward slightly ‘greener’ generation. Of course with the monetization of carbon emissions, the marginal generation will change and with that the cost and emission impacts. The degree that a moderate carbon valuation of $25/ton CO_2 impacts the CO_2 intensity is shown in Figure 9.

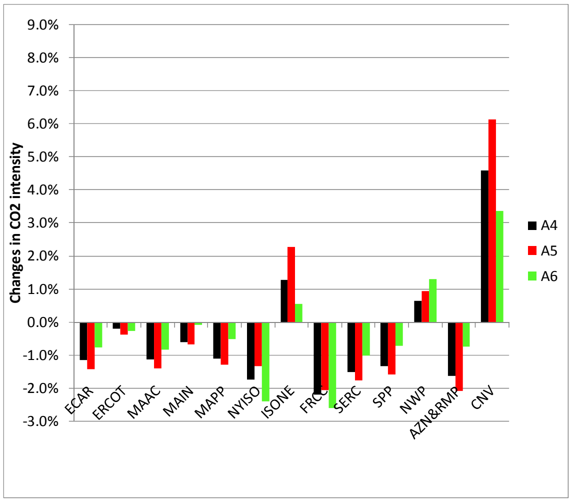

Figure 9: Changes in the CO_2 intensity with a $25/ton CO_2 cost adder

With a moderate CO_2 emissions value, the night charging may swing the trade-off between lower-cost and higher CO_2-emitting coal units to higher-cost and less CO_2-emitting natural gas units. This switch in the economic dispatch was observed in the NWP region. For the other regions, the moderate cost adder for CO_2 emission may not have been sufficient to replace coal with natural gas units at night.

This result has an important policy implication. It suggests that the valuation of carbon emission may better align the environmental with the economic objectives for PHEV charging. The off-peak (night) charging strategy that would be incentivized through time-of-use or real-time electricity rates, would clearly maximize the economics of the entire infrastructure by increasing the overall utilization of the power system as well as maximizing the CO_2 reduction potential of electric transportation. By aligning the emission reduction potential with economics, the potential for a conflicting message about the cleanest fuel for electric transportation given our current and expected generation mix can be avoided.

To put things in perspective, however, it should be noted that the net differences between day charging and night charging remain relatively small. They may amount to between 10 and 30 kg of CO_2 per vehicle per year, which is relatively small compared to the total emissions of a gasoline light duty vehicle of 150 to 200 g of CO_2 per kilometer.

7 SUMMARY AND CONCLUSIONS

A detailed grid analysis was performed to address the two key questions of what are the likely electric supply cost impacts of an emerging electric vehicle fleet, and what are the detailed emissions impacts from the electric supply system across the regions in the US and as a function of battery charging strategies. The electric vehicles assumed in this analysis were a PHEV with an assumed electric driving range of 33 miles. About 37 million PHEVs were assumed to be on the road in the US in 2030, which presumes a market share of about 22% of annual sales in 2030. The total electric energy requirement for the entire electric vehicle fleet was relatively modest compared to the total electricity production for non-transportation users. As the consequence, the impacts were expected to be relatively small. On the cost impact side, the electricity production cost impacts reflected a high cost sensitivity in the high-cost regions, where supply is already tight, such as California and the Northeast. In Midwestern regions that traditionally had sufficient capacity for even large power exports to eastern regions, smaller cost impacts were indicated in response to the new PHEV load. The cost impacts are double in size for day charging than for night charging. The marginal generation, which is the generation that is expected to be used in the emerging electric vehicle fleet, will be produced primarily from natural gas resources and secondarily from coal.

The CO_2 emissions impacts were expressed in terms of CO_2 intensity (ton CO_2/MWh). The results indicated a diverse picture across the US regions. In some regions, the regional CO_2 emissions intensity is expected to go down for all charging strategies investigated. In those regions, the marginal generation is predominately from natural gas combined-cycle plants shifting the overall fossil-fueled generation toward a cleaner fueled with high efficiency. In other regions, particularly in those with high contributions of the renewables energy resources (California and the Pacific Northwest), the overall CO_2 intensity is likely to go up, recognizing that a fossil fuel-based generation type will be the supply for the vehicles.

The charging strategies (night charging versus day charging) have a noticeable impact on the CO_2 emissions intensity. Each charging strategies has a regional specific emissions profile based on the margin generation in that region and for the time period when charging occurs. Charging electric vehicles is cleaner from a CO_2 emissions point of view at night in the Northeast, the West, and Florida. Predominantly in the Midwestern region, charging during the day is cleaner because of the use of gas technologies. These results may change with the valuation of carbon emissions because the carbon value may shift the generator dispatch toward cleaner fuels.

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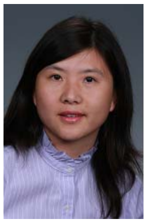

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