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Spatial and Temporal Heterogeneity of Marginal Emissions: Implications for Electric Cars and Other Electricity-Shifting Policies

Joshua Graff Zivin, Matthew J. Kotchen and Erin T. Mansur

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UC Center for Energy and Environmental Economics
2547 Channing Way, # 5180
Berkeley, California 94720-5180
www.uce3.berkeley.edu

Spatial and Temporal Heterogeneity of Marginal Emissions: Implications for Electric Cars and Other Electricity-Shifting Policies

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Abstract

In this paper, we develop a methodology for estimating marginal emissions of electricity demand that vary by location and time of day across the United States. The approach takes account of the generation mix within interconnected electricity markets and shifting load profiles throughout the day. Using data available for 2007 through 2009, with a focus on carbon dioxide (CO_2), we find substantial variation among locations and times of day. Marginal emission rates are more than three times as large in the upper Midwest compared to the western United States, and within regions, rates for some hours of the day are more than twice those for others. We apply our results to an evaluation of plug-in electric vehicles (PEVs). The CO_2 emissions per mile from driving PEVs are less than those from driving a hybrid car in the western United States and Texas. In the upper Midwest, however, charging during the recommended hours at night implies that PEVs generate more emissions per mile than the average car currently on the road. Underlying many of our results is a fundamental tension between electricity load management and environmental goals: the hours when electricity is the least expensive to produce tend to be the hours with the greatest emissions. In addition to PEVs, we show how our estimates are useful for evaluating the heterogeneous effects of other policies and initiatives, such as distributed solar, energy efficiency, and real-time pricing.

JEL Codes: H23, L94, Q5

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* Graff Zivin: University of California, San Diego and NBER, Department of Economics and Graduate School of International Relations & Pacific Studies, 9500 Gilman Drive, MC 0519 La Jolla, CA 92093, jgraffzivin@ucsd.edu; Kotchen: Yale University and NBER, School of Forestry & Environmental Studies, 195 Prospect Street, New Haven, CT 06511, matthew.kotchen@yale.edu; Mansur: Dartmouth College and NBER. Department of Economics, 6106 Rockefeller Hall, Hanover, NH 03755, erin.mansur@dartmouth.edu. We thank Daniel Knudsen for excellent research assistance and seminar participants at Cornell, Berkeley, and the UC Energy Institute for useful comments.

1. Introduction

Electricity generation is the primary source of carbon dioxide (CO_2) emissions worldwide and accounts for more than 40 percent of domestic emissions in the United States (U.S. EPA 2012). Climate policies designed to reduce these emissions from electricity generation include those that seek to change the sources of energy toward lower carbon intensities (*e.g.*, coal to natural gas, fossil fuels to renewables) and those that attempt to reduce demand for electrical power (*e.g.*, efficiency standards, building energy codes). In contrast, the recent focus on climate policies that promote plug-in electric vehicles (PEVs) aim to increase demand for electricity, but the claim is that electricity used for charging PEVs will generate less CO_2 emissions at power plants than at the tailpipes of conventional gasoline-powered vehicles.

Despite such claims, quantifying the change in emissions for any activity that affects electricity demand is more complicated than it might first appear. There is significant variation in the types of electric power plants across the United States, and the emission rates differ greatly among them. Coal-fired units emit considerable CO_2 compared to natural gas units, and even these have significantly higher emission rates than units based on wind, solar, hydro, or nuclear energy. The change in emissions due to a change in electricity demand thus depends on which plant is providing the power—that is, the plant "on the margin." But several factors complicate the task of identifying the marginal plant that corresponds to a change in electricity demand at a particular time and place. Not only is the composition of electricity generating units highly variable both across and within regions of the United States; the utilization of many units fluctuates with aggregate load on the electricity grid, which changes through the day (peak versus off-peak) and times of year (seasonal differences). Importantly, the electricity grid is also comprised of interconnected networks where electricity is traded over large distances, and there is no definitive way of locating where the electricity demanded at a particular time and place is actually generated.

Attempting to overcome these challenges, the present paper makes two primary contributions. First, we develop and implement a methodology for estimating marginal emissions of electricity demand across the United States. The method produces estimates that vary by location and time of day. The results, as we will discuss, are essential inputs for understanding the environmental implications of many climate and energy policies. We focus on CO_2 emissions throughout the paper but also provide an appendix with results for sulfur dioxide and nitrogen oxides. Second, we demonstrate the usefulness of our estimates with a detailed application to PEVs. In particular, we evaluate the implications of PEVs on CO_2 emissions and find that greater caution is warranted when considering the supposed environmental benefits: given current technology and patterns of electricity generation, PEVs in some regions will generate more CO_2 emissions per mile traveled than the average vehicle currently on the road.[1]

Our approach for estimating the marginal emissions of electricity demand exploits several government datasets on hourly emissions, consumption, and generation across the United States. For each hour between January 2007 and December 2009, we aggregate CO_2 emissions up to three broad regions based on grid interconnections that account for all possible sources of emissions associated with a change electricity demand at a particular location. We then regress the hourly emissions of each interconnection on the hourly electricity consumption of its sub-regions based on the North American Electric Reliability Corporation (NERC) classifications, controlling for different combinations of fixed effects.

The results indicate how marginal changes in electricity consumption within a NERC region affect emissions at the interconnection level, and we find substantial variation among locations and times of day. While the average across all regions and hours of the day is 1.21 pounds of CO_2 per kilowatt hour (lbs CO_2/kWh) consumed, the marginal emissions for the upper Midwest is 2.30 lbs CO_2/kWh, which is almost three times the magnitude of that for the Western United States. Throughout hours of the day, there is an overall 26-percent increase in marginal emissions from 7:00 PM compared to 3:00 AM, while among regions the rate ranges by as much as 0.66 to 2.80 lbs CO_2/kWh for the same hour of the day.

These estimates have important implications for understanding the environmental consequences of many electricity-shifting policies. If, for example, the expansion of electricity generated from renewables displaces existing generation sources, the estimates of marginal

[1] A complete environmental accounting would require an analysis of all power plant and tailpipe emissions that occur in addition to CO_2. This challenge is discussed in more detail later in the paper.

emissions can be used to quantify the avoided pollution and how it differs by location and time of day. Similarly, to the extent that policies for energy efficiency, smart grids, and more stringent building codes reduce demand for electricity, estimates of the marginal emissions will help to understand the impacts and quantify the heterogeneous effects of uniform policies. The estimates are also relevant for understanding the impacts of activities and policies that increase electricity demand, as with PEVs, the application upon which we focus.

The charging of PEVs increases demand for electricity and its associated emissions while simultaneously reducing emissions from the tailpipes of substitute vehicles. Given current technologies, we show how the emissions of charging PEVS differ by region and time of day. The CO_2 emissions per mile from driving PEVs are less than those from driving a hybrid car in the western United States and Texas. In the upper Midwest, however, charging during the recommended hours at night implies that PEVs generate more emissions per mile driven than even the average car currently on the road. Other regions have marginal emission rates that place PEVs somewhere between a hybrid and a comparable economy car. Underlying many of our results is a fundamental tension between electricity load management and environmental goals, as the hours when electricity is the least expensive to produce tend to be the hours with the greatest emissions. In addition to PEVs, we show how our estimates of marginal emissions are useful for evaluating the heterogeneous effects of other policies and initiatives related to residential solar, energy efficiency, and real-time pricing.

2. Background

Studies of the environmental impacts of electricity consumption have increasingly recognized the importance of variability in the “footprint” of electricity generated at different points in space and time. Emissions from power plants on the margin are often exceedingly different from average emissions over the entire load-generating base. Moreover, the electricity grid’s interconnectedness means that those sources on the margin often lie beyond the boundaries of a particular state or political entity considering policy changes (Marriott and Matthews 2005). While no accepted methodology for addressing flows across the US grid has emerged, it is clear that different approaches yield significantly different estimates of emissions associated with load shifting in a particular location (Weber *et al*. 2010). Reliable estimates of marginal emissions are nevertheless critical for evaluating a range of climate and energy policies, some of which we have mentioned and discuss in more detail later in the paper. At this point, however, we focus more specifically on our application to PEVs and the policies that seek to promote them.

2.1. Plug-in Electric Vehicles

Pure PEVs are battery-driven automobiles that derive all of their energy (with the exception of that harnessed from deceleration during driving) from an external source of electricity. They have been promoted worldwide as a tool for reducing emissions and mitigating climate change. In Europe, the UK Climate Change Committee has recently made electric vehicles a centerpiece of its climate change policy (Adam 2009). The electrification of the transportation sector has also been identified as an important tool in battling climate change in the United States (Lehmann 2011). Indeed, California, which is often a pioneer of US environmental policy, recently adopted the Advanced Clean Cars Program that will require manufacturers to offer PEVs for sale in the state as part of the effort to reach state-level goals in reducing greenhouse gas (GHG) emissions over the next twenty years.

Significant financial incentives for consumer adoption have also accompanied the enthusiasm for PEVs in the United States. At the federal level, there is a consumer tax credit of $2,500 per vehicle plus an additional $417 for each kWh of battery capacity in excess of five kWhs. The total credit allowed per vehicle is capped at $7,500, and all vehicles currently on the market qualify for the full credit.[2] A wide and varying range of additional incentives are offered at the state level. These include rebates and tax credits for the purchase of vehicles and charging infrastructure, as well as access to carpool lanes and free public parking in some municipalities.[3] While some states offer no incentives, at least four offer incentives of at least

[2] See IRS Notice 2009-89. Also, the credit begins to phase out for a manufacturer's vehicles when at least 200,000 qualifying vehicles have been sold for use in the United States. The count is determined based on a cumulative basis for sales after December 31, 2009.

[3] A comprehensive listing of both state and federal incentives is available online through the Plug in America website at http://www.pluginamerica.org/incentives.

$5,000, which when combined with the federal program accounts for somewhere between one-quarter and one-third of the manufacturer's suggested retail price of the two most popular models on the market, the Nissan Leaf and Chevrolet Volt.

Conventional automobiles generate several key pollutants as a byproduct of gasoline combustion. In addition to CO_2, these include nitrogen oxides, volatile organic compounds, carbon monoxide, and particulate matter. PEVs also generate pollution notwithstanding their misleading classification as "zero-emissions vehicles." PEVs simply trade tailpipe emissions for emissions generated at the smokestack of electric power plants. For some pollutants, the switch may be beneficial because the technologies and economies of scale are such that the costs of pollution control are cheaper at power plants. Moreover, the fact that emissions for the criteria pollutants under the Clean Air Act are more tightly regulated in the power sector might further ensure some environmental benefits of purchasing a PEV instead of a comparable substitute vehicle.

The benefits of PEVs are less clear, however, when it comes to CO_2 emissions, which are currently unregulated in the US electricity sector. The net effect on CO_2 emissions of switching to PEVs will depend, in part, on the carbon intensities of the power plants supplying the electricity for charging. It follows that any emission benefits will necessarily differ across charging locations because of the wide variability of emission intensities among power plants. Policies that promote charging during certain hours will also have differing effects because of the way that plants are utilized differently throughout the day during peak and off-peak times of electricity demand.[4] Our methodology for estimating marginal emissions accounts for these features, and we will use the estimates to make explicit comparisons between PEV emissions at different locations relative to comparable substitute vehicles. We will also make comparisons among choices based on the electricity generation costs and the social cost of carbon. While our analysis is not a comprehensive benefit-cost analysis, which would entail other considerations, many of which are difficult to measure, we do discuss the broader policy context later in the paper. At this point, we briefly review the existing literature on estimating marginal emissions with applications to PEVs.

[4] The same issues arise when evaluating how the expansion of renewables affects emissions (Borenstein, 2012).

2.2. Literature Review

Despite the widely recognized importance of distinguishing between marginal and average electricity generating units and electricity flows across regions, nearly all of the limited literature on the environmental impacts of PEVs, most of which has an engineering orientation, takes a rather narrow approach. Several studies analyze the benefits of PEVs assuming that a particular type of power plant is generating the electricity to charge the vehicles (EPRI 2002; Kliesch and Langer 2006; Stephan and Sullivan 2008). As one might expect, these studies find that cleaner power plants yield greater environmental benefits. While the magnitudes of the differences are illustrative, the analyses are not especially informative for answering questions about changes in PEV penetration at particular locations or in the timing of charging during the day. Other studies take a less hypothetical approach, yet rely on average emissions rates across regions to assess environmental impacts (Samaras and Meisterling 2008; Michalek *et al*. 2011; Anair and Mahmassani 2012). While these studies conduct sensitivity analyses around the estimates, they eschew efforts to directly assess the emissions profiles associated with the marginal power sources that would be used to charge PEVs.

Several studies do attend to electricity generation on the margin. McCarthy and Yang (2010) and Blumsack, Samaras, and Hines (2008) use engineering models to simulate merit-order dispatch (*i.e*., least cost allocation) of electricity. McCarthy and Yang (2010) focus on California, where they conclude that PEVs reduce CO_2 emissions relative to conventional gasoline vehicles and hybrids. Blumsack *et al*. (2008) conduct their analysis at the level of regional transmission organizations (excluding the Western United States), while also considering the life-cycle CO_2 emissions of battery manufacturing. They conclude that PEVs are generally better, though no worse, than conventional cars in terms of GHG emissions.

In contrast to these simulation models, a regression approach to estimating marginal emissions can account for details of the electricity industry that might otherwise be ignored, including market power, transmission and operating constraints, and imperfect information about market conditions. In one study, Siler-Evans, Azevedo, and Morgan (forthcoming) use a regression approach to estimate marginal emissions by region and time of day. They use the US

Environmental Protection Agency's (EPA) Continuous Emission Monitoring System (CEMS) data (described below) and regress each NERC region's hourly change in aggregate emissions on its hourly change in gross fossil-fuel generation. While this approach is an improvement on other methods, it is only valid under the following assumptions: (a) all consumption in a region is met by power plants in the same region; (b) only power plants in the CEMS data supply marginal electricity output; (c) aggregate fossil-fuel generation is exogenous; and (d) the method's *ad hoc* corrections for line losses are constant over location and time. In contrast, the approach that we apply in this paper is based directly on the relationship between aggregate emissions and end-use consumption, and we allow the marginal producer to be located anywhere in the corresponding grid interconnection.

Finally, two other studies are worth mentioning in tandem because they comprise what is perhaps most closely related to our analysis here. In addition to considering specific electricity-generation technologies, Stephan and Sullivan (2008) apply the estimates of marginal emissions from Holland and Mansur (2008) to analyze PEVs. Holland and Mansur (2008) focus on the environmental effects of real-time pricing, and they regress daily emissions at the NERC level on the first and second moments of the within-day distribution of consumption in the same NERC region. While the validity of these estimates are subject to some of the same assumptions as those in Siler-Evans *et al*. (forthcoming), Stephan and Sullivan's (2008) use of them suggests that PEVs have emission rates between 50 and 75 percent that of hybrid vehicles (not plugged in).

In what follows, we describe our method, which differs from the existing literature in several important ways. Unlike previous analyses, we estimate hour-of-day marginal emission rates. Moreover, the aggregation of emissions at the level of grid interconnections means that the estimates account for how demand shocks in some regions may affect marginal emissions in others. Finally, we discuss how the estimates for CO_2 (along with sulfur dioxide and nitrogen oxides) can be used to evaluate a variety of policies, in addition to our primary focus on PEVs.

3. Data and Preliminaries

This section describes the various data sets used in our analysis, presents basic summary statistics, and makes preliminary comparisons between the emission rates of electric power plants that might charge PEVs relative to comparable vehicles currently on the road.

3.1. Data on Emissions and Electricity

Using data over the three year period of 2007 through 2009, the most recent period for which all data are available, we combine data sets from several federal agencies: the EPA, the Energy Information Administration (EIA), and the Federal Energy Regulatory Commission (FERC). The EPA's CEMS data is our primary source of emissions data for all fossil-fuel generating units with at least 25 megawatts (MW) of generating capacity.[5] These data include information on CO_2, sulfur dioxide, and nitrogen dioxide emissions and are available hourly for the most recent period of January 2007 through December 2009. Also included in the CEMs data, which we use here, is each unit's hourly gross generation, *i.e*., the total amount of electrical power that a unit produces for internal use and for sale. We obtain hourly electricity consumption data for the same time period from FERC Form 714, which is reported at the level of 200 planning areas across the nation.[6] We also use data from Form 714 on the Hourly System Lambda, which is an estimate of the marginal cost of electricity generation for a given hour in each planning area.[7] Two other sources of data are useful for some basic calculations of summary statistics. One is EIA Form 923 that includes net generation (only electricity for sale) at the power plant level by month for 2007 through 2009.[8] The other is EPA's Emissions & Generation Resource Integrated

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[5] Technically, a generating unit is a subset of a power plant that typically consists of a boiler, generator, and smoke stack. Detailed information about the CEMS program and more specifics about which units are included in the data can be found online at http://www.epa.gov/airmarkets/emissions/continuous-factsheet.

[6] These data are available online at http://www.ferc.gov/docs-filing/forms/form-714/overview.asp.

[7] In restructured competitive electricity markets, the lambdas are simply market prices. The system lambdas are not available for one of the interconnection/NERC regions (ERCOT), so for this one we use reported prices as the measure of marginal generation costs, available at http://www.ercot.com/mktinfo/prices/mcpea.

[8] These data are available online at http://www.eia.gov/electricity/data/eia923/.

Database (eGRID), which contains data on the emissions rates of power plants based on net generation for the corresponding period from 2007 and 2009.[9]

The unit of observation varies widely among these data sources. For instance, the EPA data are available at the level of generating units, while the FERC data are reported for planning areas that range in size from the city of St. Cloud, Minnesota to all of the Pennsylvania, Jersey, Maryland (PJM) Power Pool, the largest control area covering 13 states from New Jersey to Chicago. At various points of our analysis, and to different degrees, we aggregate and merge the data sets to make them comparable and account for important institutional features about electricity grid interconnections.[10]

Figure 1 provides a general overview of the US electrical grid with an illustration of how the United States is partitioned into three interconnections (Western, ERCOT, and Eastern) and eight NERC regions (FRCC, MRO, NPCC, RFC, SERC, SPP, TRE, WECC).[11] Interconnections are important because they identify the entire regions over which electricity is traded, so changes in demand at any location—from, for example, a new PEV—could affect the generation of a marginal plant anywhere within the corresponding interconnection. Note that the Western and ERCOT interconnections each have only one NERC region, and we will follow convention and refer to the different designations interchangeably as WECC and ERCOT, respectively. In contract, the Eastern interconnection encompasses six NERC regions, and we will decompose parts of our analysis accordingly to obtain greater spatial resolution in our results.

Table 1 provides summary statistics at the level of interconnections and NERC regions, and looking across them gives a sense of the regional heterogeneity. The first three columns report average hourly CO_2 emissions, electricity consumption, and net electricity generation.

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[9] Data is not available for 2008, and information about eGrid and the data sets are available online at http://www.epa.gov/cleanenergy/energy-resources/egrid/.

[10] All of the emissions and consumption data are for the United States only. Canada (and Mexico to a much smaller degree) does trade power with the United States (see Figure 2). But most of the power coming from Canada is hydroelectric and sold over large direct current lines that are at capacity most hours. This suggests that changes in consumption in the United States would have a small effect on production decisions in Canada, and any changes in production would have negligible effects on short-run CO_2 emissions, which is the focus of our analysis.

[11] The acronyms correspond with the following full names: Electric Reliability Council of Texas (ERCOT), Florida Reliability Coordinating Council (FRCC), Midwest Reliability Organization (MRO), Northeast Power Coordinating Council (NPCC), Reliability*First* Corporation (RFC), SERC Reliability Corporation (SERC), Southwest Power Pool (SPP), Texas Regional Entity (TRE), and Western Electricity Coordinating Council (WECC).

Looking first at the three interconnections, we see that the Eastern interconnection is more than four times the size of WECC, which is approximately twice the size of ERCOT. It is also the case that consumption tends to be lower than generation, and the difference can be explained by line losses due to the transport of electricity over power lines. The similarity of consumption and net generation for the Eastern interconnection is because of imports from Canada at a magnitude of roughly three MW/hour on average. Among the NERC regions of the Eastern interconnection, the differences between consumption and net generation indicate which regions are importers or exporters of electric power. The pattern is such that Florida (FRCC), the upper Midwest (MRO) and NPCC are importers, the Mid-Atlantic region (RFC) and the Southeast (SERC) are exporters, and the Oklahoma region (SPP) is close to neutral.

Figure 2 illustrates graphically and in more detail the pattern of how electricity tends to flow around the United States. Although the graph is based on 2010 data and finer NERC sub-regions, a similar energy import-export pattern is evident. The important point of the figure for the purposes of our analysis is to recognize how electric power flows substantially within the grid interconnections, as this is critical for estimating the marginal emissions of changes in electricity demand at a particular location.

Table 1 also reports several measures of the CO_2 emissions rate for each region. First is the consumption-based emission rate, which is simply the first column divided by the second. The ERCOT and Eastern interconnections have similar rates, just under 1.3 lbs CO_2/kWh, while WECC is substantially lower at 0.85. Within the Eastern interconnection NERC regions, the rates range from a high of 1.64 in SPP to a low of 0.57 in NPCC. These rates are somewhat misleading, however, because they do not account for electricity being traded across regions: a region that imports power will have an artificially low rate, while an exporter's rate will be too high. The generation-based emissions rates, which are the first column divided by the third, take such trading into account, and for this reason, they are the ones typically used when evaluating electricity emissions. We now see that the generation-based emissions rate in MRO is quite close to that of SPP, as the rates in importing (exporting) regions have risen (fallen). As a simple point of comparison, we report in the last column of Table 1 eGRID's emissions rates by region based on net generation. While the time period differs because 2008 is missing, the numbers are quite similar to our generation-based estimates. In both cases, the rates are informative, but they are not especially useful for understanding how changes in electricity demand will affect emissions—as they both represent average rather than marginal emission rates.

3.2. Preliminary Comparisons Among Vehicles

When plugging in a PEV, or engaging in other activities that increases demand for electricity, any power plant in the same interconnection could, in principle, provide the marginal power. Yet, as mentioned previously, the CO_2 emissions associated with power plants differs greatly, ranging from zero for hydropower and nuclear plants to substantial for many coal-fired plants. To determine how the heterogeneity of emissions affect the environmental implications of PEVs, we consider the emission rates of particular plants and make preliminary comparisons between the potential emissions from charging PEVs and driving substitute vehicles.

We begin with the EPA CEMS data on hourly CO_2 emissions and gross generation for the fossil-fired units over the entire sample period 2007-2009. Because we are interested in the marginal emissions of consumption (rather than generation), we make two adjustments to gross generation to derive consumption-based emission rates. First, we convert gross to net generation based on the reported difference between the two for units in the EIA Form 923 data of 2008, a year for which both numbers are available. We find that approximately 4.59 percent of the gross generation is consumed on-site, and we make this constant adjustment to all units and hours to obtain an estimate of hourly net generation. Second, to focus on consumption, we must also account for electricity that is lost through transmission and distribution, and we use Stephan and Sullivan's (2008) estimate of 9.6 percent to make this conversion. Hence, the emissions rate of interest for our analysis is a unit's hourly CO_2 emissions divided by its net transmitted generation, defined as (gross generation)/(1.0459×1.096).

Figure 3 plots the cumulative distribution and probability density functions for the hourly net transmitted (*i.e.*, consumption-based) emissions rates for all of the fossil-fired units in the CEMS data. The mean emissions rate is 2.10 lbs CO_2/kWh with upper and lower quartiles of 1.42 and 2.40. The peaks of the probability density function illustrate the different emissions rates among the three primary technologies of fossil units, which, from low to high emissions rates, are combined-cycle gas turbines, single-cycle gas turbines, and coal-fired boilers.

We now consider how this distribution of emission rates can be used to compare the CO_2 emissions of electric cars against those of substitute vehicles currently in use. The two most popular PEVs on the market are the Chevrolet Volt and the Nissan Leaf, and these vehicles use approximately 36 kWh and 34 kWh per 100 miles, respectively.[12] Taking the midpoint and normalizing per mile, we summarize the current PEV technology as requiring 0.35 kWh/mile. This number multiplied by any one of the emission rates illustrated in Figure 3 yields the emission rates of PEVs in terms of lbs CO_2/mile if charging occurred with electricity from that particular unit in a given hour. For the purposes of comparison with other vehicles, however, we use the 0.35 kWh/mile as a conversion to report all vehicle emissions in terms of lbs CO_2/kwh, as this make makes comparisons straightforward using Figure 3.

The average fuel economy of the US fleet of light-duty, gasoline-powered vehicles is 21.7 miles per gallon (mpg) (Department of Transportation 2009). Because combusting a gallon of gasoline releases 19.6 lbs CO_2 (EPA 2011), the average light-duty gasoline vehicle emits 0.90 lbs CO_2/mile. To make this number comparable with the emission rates of PEVs in Figure 3, we simply multiply by 1/0.35 miles/kWh to obtain 2.58 lbs CO_2/kWh. This number is shown as the right-most vertical reference line in Figure 3, and it represents the average emissions rate of light-duty gasoline vehicles in the 2009 US fleet. One way to interpret the cumulative distribution function in Panel A is that a PEV will emit less CO_2 than the average light-duty vehicle assuming the PEV's charge comes from a fossil-fired unit that is below the 87th percentile in emissions. In contrast, and more importantly, a PEV could emit more CO_2 if its charge comes from a fossil-fired unit above that percentile in emissions—roughly 13 percent of all electricity-generating units. While these numbers illustrate how PEVs might compare with other vehicles in terms of their emissions, the comparisons are potentially misleading for several reasons. First, they are not informative about the probability of which units might be on

[12] The US Department of Energy reports fuel economy statistics for both conventional and electric cars, and these statistics are available online at www.fueleconomy.gov.

the margin. Second, they do not distinguish among hours of the day, over which there is substantial variation in emissions rates. Third, they imply that only one unit could be on the margin, when in fact several could be on the margin simultaneously or over the course of a PEV's charge of several hours. Finally, the numbers assume that the substitute for a PEV is a random draw from the population of all light-duty vehicles. While we address the first three of these concerns in our subsequent empirical analysis, we first make comparisons with vehicles that are more likely to be substitutes for PEVs.

We consider the alternatives of a comparable economy car and a hybrid. Using characteristics of the Nissan Leaf, a set of comparable gasoline vehicles is the Toyota Corolla, Honda Civic, Chevrolet Cruze, and Ford Fiesta, and this set has a 2012 fuel economy average of 31 mpg.[13] Converting these units, as described above, implies an emissions rate of 1.79 lbs CO_2/kWh, corresponding to the middle reference line in Figure 3, and the interpretation is that approximately 41 percent of the fossil units that might charge PEVs over any hour have higher emission rates. Turning to the hybrids, we consider the leading seller of a Toyota Prius, which for 2012 has a combined fuel economy rating of 50 mpg, or for purposes of comparison an emissions rate of 1.13 lbs CO_2/kWh. As shown by the left-most reference line in Figure 3, only 12 percent of the fossil-fired units over all hours have emission rates lower than this, implying much scope for PEVs to have higher emission rates than hybrid vehicles. In sum, these comparisons demonstrate the importance of identifying the marginal power plant for evaluating the environmental implications of PEVs, as well as the choice of substitute vehicles.[14]

4. Estimating Marginal Emissions

[13] The six characteristics of the Leaf are head room (41.2 inches front/ 37.3 inches rear), hip room (51.5 in. front / 50 in. rear), leg room (42.1 in. front / 31.1 in. rear), shoulder room (54.4 in. front / 52.5 in. rear), 5 seating capacity, and 14.5 cubic feet of cargo volume. The combined fuel economy is 30 mpg for the Corolla and Cruze, 32 mpg for the Civic, and 33 mpg for the Fiesta.

[14] Here we have simply chosen likely alternatives to PEVs, but a more formal empirical approach could be used to identify the most likely substitutes. While we leave these estimates to future research, it is worth remarking that the value of such an exercise will increase with more data if and when electric vehicles become more common.

We begin with models to estimate the marginal rate of CO_2 emissions from electricity consumption within each of the three interconnections (WECC, ERCOT, Eastern).[15] Considering each interconnection separately, c_t denotes an interconnection's CO_2 emissions in hour of sample t, and the contemporaneous quantity of electricity demanded in the interconnection is q_t.[16] Our general approach is to regress each interconnection's hourly emissions on its hourly consumption. While in most markets that one might study, quantity demanded and thereby emissions would depend on price, we can treat q_t as exogenous in this case because wholesale electricity prices are not borne by consumers. Hence, the derived demand for wholesale electricity is perfectly inelastic, with few minor exceptions that pose no difficulty for our analysis.

The specific models that we estimate, one for each of the three interconnections, have the form

$$(1) \qquad c_t = \beta_h q_{th} + \alpha_{hm} + \varepsilon_t ,$$

where h denotes hour of day (24 in total) and m denotes month of sample (36 in total). The term α_{hm} represents a fixed-effect for each hour of day by month of sample.[17] We estimate equation (1) using ordinary least squares, and we report Newey-West standard errors based on a 24-hour lag to account for serial correlation. The coefficients of interest are $\beta_1,...,\beta_{24}$, which provide estimates of the marginal emissions of consumption for each hour of the day within an interconnection. When estimating equation (1), along with others reported here, we include data for only weekdays. We exclude weekends for two reasons. First, patterns of electricity demand and therefore generation differ between weekends and days of the week, meaning

[15] While we focus on CO_2 emissions throughout the paper, the approach generalizes to sulfur dioxide and nitrogen oxides as well. We estimate these results and report them in appendix tables.

[16] Prior to aggregating emissions and demand for all econometric models, we convert all data into eastern standard time for the Eastern interconnection, central standard time for ERCOT, and western standard time for WECC.

[17] We also estimated models with different sets of fixed effects to test robustness of our results. Specifically, we estimated models with fixed effects based on day of sample, day of sample by hour of day, day of sample by seasonal hour of day, and hour of day by week of sample. In general, the results display qualitatively similar patterns across hours of the day and regions. In cases where they differ, the results are statistically insignificant.

that hourly coefficients may systematically differ. Second, our primary application to PEVs is more suited to days of the week, when commuting patterns are more regular.[18]

We also provide a decomposition analysis for the Eastern interconnection, as it consists of six distinct NERC regions that we denote with subscripts i. Specifically, we estimate more spatially explicit relationships between where consumption takes place and its associated marginal emissions. Accordingly, for only the Eastern interconnection, we estimate the following model:

$$(2) \qquad c_t = \sum_{i=1}^{6} \beta_{ih} q_{ith} + \alpha_{hm} + \varepsilon_t .$$

The only difference is that we include right-hand-side variables for electricity demand separately for each NERC region, while keeping the aggregate Eastern interconnection emissions on the left-hand-side. As a result, within the same model, we estimate marginal emissions for each hour of the day separately for each of the six NERC regions in the Eastern interconnection. A useful feature of the model is that marginal emissions are calculated for each NERC region while controlling for electricity consumption in other regions. The reason for keeping emissions aggregated at the interconnection level is to account for the trading of electricity that occurs between NERC regions within the interconnection.[19]

Table 2 reports the results of all regression models for marginal CO_2 emissions.[20] The first three columns are the estimates of specification (1) for each interconnection. To facilitate interpretation and comparison, we also illustrate results of these three models in Figure 4, which plots the marginal emissions (with 95-percent confidence intervals) against the hour of day for the WECC, ERCOT, and Eastern interconnections. Figure 4 shows substantial variation in

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[18] We did estimate parallel models that include data for all days of the week, and the results do not differ in meaningful ways. These other results are available upon request.

[19] In terms of other disaggregated analyses, one could explore how hourly demand shocks in each planning area affect hourly emissions at each generating unit, but such an approach would suffer from omitted variable biases or multicollinearity. For example, if one were to regress a power plant's emissions on the local planning area demand alone, this would ignore the fact that neighboring region's consumption is correlated with the local demand. The bias could be in either direction, depending on the region's net importing status. At the other extreme, a regression of US aggregate emissions on consumption in each of the planning areas may be noisy given the high correlation among consumption variables.

[20] Analogous results for sulfur dioxide and nitrogen oxides are reported in Appendix Tables 1 and 2, respectively.

the marginal emissions rates over both location and time of day. Within interconnections, the unweighted average across hours of the day are 0.80 for WECC, 0.96 for ERCOT, and 1.29 for Eastern. The largest difference is that Eastern has a CO_2 emissions rate more than 60 percent larger than WECC, reflecting a greater reliance on coal in the East. The variation in marginal emissions throughout the day tends to follow a familiar pattern in all interconnections: high during off-peak hours and low during on-peak hours. This pattern occurs because coal-fired units, which have higher emission rates, are most commonly used to meet base-level and off-peak electricity demand; whereas, natural gas units, which have relatively low emissions rates, are often brought online to meet peak demand. This pattern of fuel shifting explains why emission rates tend to be higher at night (midday for WECC) and lower during periods of peak demand in the morning and evening.

Returning to Table 2, the next six columns report the coefficient estimates of specification (2) for each of the NERC regions within the Eastern interconnection. These estimates indicate even greater variability in marginal emissions by location. The highest rates occur in MRO (the upper Midwest), which at 2.3 lbs CO_2/kWh is nearly three times the emissions rate of WECC. Among the Eastern NERC regions, the variation over time of day also tends to follow the general pattern of high (low) emissions rates during off-peak (on-peak) hours. The last column of Table 2 reports an average of the coefficients across all NERC regions weighted by the hourly electricity consumption in each region. These numbers provide a sense for the variation in marginal emissions among hours of the day for the entire United States. We find, for example, a 26-percent increase in marginal emissions from 7:00 PM (1.09 lbs CO_2/kWh) to 3:00 AM (1.37 lbs CO_2/kWh).

In the next section, with our application to electric cars, we will take advantage of all the hourly estimates of marginal emissions rates for each NERC region. We will also discuss how they are useful for other applications as well. At this point, however, we turn to some more general observations about the importance of considering the marginal emissions of electricity consumption rather than the average emissions of electricity generation.

Panel A of Figure 5 illustrates the unweighted daily average of marginal emissions for all eight NERC regions, along with a total estimate that is an average weighted by the hourly electricity consumption in each region. The total is a national average, marginal emissions rate of 1.21 lbs CO_2/kWh. We also show 95-percent confidence intervals for these estimates. Here again we see that the marginal rates are low in WECC and high in MRO. For the purposes of comparison, Panel A also includes the generation-based average emissions rates from Table 1, along with confidence intervals. Because generation-based, average emissions rates are the most readily available, they are the ones most commonly used to evaluate the environmental impacts of changes in electricity demand. Yet they are conceptually incorrect because the real measure that matters is the marginal (rather than average) emission rate for consumption (rather than generation). The comparisons in Panel A of Figure 5 show the bias associated with using the average, generation-based emission rates. An important finding is that the bias is not always in the same direction. While, over the course of the entire day, marginal emissions are greater than average emissions (with statistical significance) in FRCC, MRO, and NPCC, the opposite result holds in SERC and SPP. The magnitude of the differences is also quite substantial in MRO, NPCC, and SPP.

In Panel B of Figure 5, we summarize Siler-Evans *et al*.'s (forthcoming) results as a further point of comparison. Recall that their approach differs from ours; for each NERC region, they regress the hourly change in aggregate emissions on the hourly change in gross generation measured by the CEMS data. Hence, their estimates focus on how local changes in generation affect local emissions, and thereby do not account for how electricity is traded with the Eastern interconnection. In general, we find greater differences between marginal and average emission rates, and the levels themselves differ by meaningful amounts in some cases.

There are also several reasons why the emission rate estimates based on CEMS gross generation may be biased for consumption-based applications. First, gross generation by a power plant includes power used by the plant that is not sold, so the emissions rate of pounds of pollutant per MWh produced will understate the rate based on what is sold. Second, generation does not account for transmission line losses that are approximately nine percent of total generation. This implies that the gross-generation-based rate will further understate the consumption-based rate. Third, small fossil-fired power plants are not included in CEMS, implying that the true effect will be larger still. Note that this potential bias is present in our results as well. Fourth, non-fossil generation could be on the margin and is not captured by either analysis.[21]

5. Electric Vehicles

We now use our estimates of the marginal emissions rates for a more careful analysis of the CO_2 emissions associated with electric cars. Automobile manufacturers and electric utilities suggest charging PEVs between midnight and 5 AM.[22] Calculating the average marginal emissions over this time period for all NERC regions using the coefficient estimates in Table 2 yields rates of 0.82 for WECC, 1.10 for ERCOT, 1.21 for SPP, 1.24 for FRCC, 1.25 for NPCC, 1.38 for SERC, 1.47 for RFC, and 2.64 for MRO. The overall mean based on the Total column is 1.35 lbs CO_2/kWh. For purposes of comparison, recall that the emissions rates of the potential substitute vehicles are 1.13 for the hybrid, 1.79 for the economy car, and 2.58 for the light-duty fleet average. These numbers imply that a PEV charging in MRO between midnight and 5 AM will generate more CO_2 emissions than driving a comparable distance with a car representing the light-duty fleet average. Moreover, for all regions with the exceptions of WECC and ERCOT—that is, the entire Eastern interconnection—charging a PEV at the recommended time will generate greater emissions than driving a comparable hybrid car.

Figure 6 enables a broader set of comparisons with the total CO_2 emissions of charging a PEV at different times of the day in each region. The figure is based on the assumption that the PEV charges for four hours and draws 13 kWh to drive 35 miles, as these are the specifications for the Chevrolet Volt. The figure illustrates, for example, that charging a PEV in the WECC between midnight and 4 AM would emit an average of just over 10 lbs of CO_2. While we consider non-overlapping 4-hour intervals throughout the day for illustrative purposes, other intervals and durations are straightforward to derive using the results in Table 2. Figure 6 illustrates the heterogeneity of emissions that PEVs will have both among regions and within a

[21] Some technologies—nuclear, solar, run-of-river hydro, and wind—are unlikely to be on the margin as they have low marginal costs. Yet, hydroelectric reservoirs (the largest renewable) are used to follow load (i.e., are marginal), but they have a constraint on cumulative production during a dry season. In the West, for example, precipitation is stored over the winter, spring, and early summer to be used when prices are highest in the late summer.

[22] For example, see http://sdge.com/clean-energy/electric-vehicles/ev-rates.

region over times of the day. WECC and MRO are on opposite ends of the range with the low and high emissions, respectively. While emissions tend to be higher with charging at night in most regions, this pattern does not always hold, as in NPCC where there are many oil-fired units used to meet peak demand. Importantly, the figure shows that the recommended charging in the hours after midnight, which are those when electricity demand is the lowest, tend to be the hours with the greatest emissions in most NERC regions. Also shown in Figure 6 are the reference lines for the emissions associated with driving the substitute vehicles 35 miles. WECC is the only region where PEVS have lower emissions than a hybrid for charging over all hours of the day. The national average numbers imply that hybrids emit less CO_2 than a PEV for charging over all hours expect for 5 – 8 PM, which is a time of peak demand.

Beyond accounting for the CO_2 emissions of PEVs are economic considerations about the costs of electricity generation and emissions. Knowing these costs is essential for setting optimal policy about where to deploy PEVs and when to charge them. As part of a more comprehensive analysis, we consider two components of the social costs of charging PEVs. First is the marginal external cost of the CO_2 emissions itself. We value these costs using the marginal damage estimates of $21 per metric ton of CO_2 as recommended by the Interagency Working Group on the Social Cost of Carbon (2010) for regulatory impact analysis (see also Greenstone *et al*. 2011). Second is the marginal generation costs of producing the electricity. We estimate these costs with the Hourly System Lambdas (or prices in the case of ERCOT) described in Section 3.1. These marginal generation costs are reported for each hour of the day and NERC region in Appendix Table 3. Note that we are not including residential retail prices for electricity in these partial social cost calculations, as they represent transfers rather than economy-wide opportunity costs. We nevertheless make some simple comparisons below based on residential prices for electricity, as they do matter for individuals deciding whether to purchase a PEV. Moreover, we refer to these as partial social cost calculations because not included are the costs of other pollutants, which would matter in ways that we also discuss below.

Figure 7 shows the social costs of daily electricity generation and CO_2 emissions of different charging times and NERC regions. The bottom part of each bar represents the costs of generation (13 kWh multiplied by the average marginal costs over that period). The top part of each bar is the social cost of carbon (SCC) ($21 per metric ton converted to lbs and multiplied by the emissions for the corresponding times and regions in Figure 6). Several things are worth noting. First, the generation costs of charging a PEV are substantially larger than the social costs of carbon (at least at $21 per metric ton) for all time periods and regions with the exception of MRO, where generation costs are relatively low in addition to emissions being relatively high. Second, within regions, the time profile of generation costs for charging a PEV tends to be the opposite of that for emissions: it is substantially more costly to generate electricity for charging during the day and peak times when demand is high and emissions are low. Third, the time periods that minimize generation costs are generally those that minimize the sum of generation and CO_2 damage costs, emphasizing again the relatively small magnitudes of the costs of CO_2 emissions.

The preceding analysis underscores the fundamental tradeoff of PEVs as a cost-effective approach to reducing GHG emissions. The regions and times of day when electricity generation is relatively less expensive—and therefore more favorable for charging PEVs—are also the regions and times of day with the greatest CO_2 emissions. What is more, even accounting for the environmental damage, the estimate of the SCC is not enough to change the fact that minimizing costs tends to mean maximizing CO_2 emissions. This does, however, raise the question of how high the SCC would need to be in order to align the objectives of minimizing both costs and emissions. To make this comparison, we consider results for the national average. While minimizing costs implies a recommended charging time of midnight to 4 AM (Figure 7), minimizing emissions implies a recommended charging time of 4 to 8 PM. Only if the SCC were at least $250 per metric ton would the recommended charging time be 4 to 8 PM for both objectives. This number is indeed quite high.

It is important to emphasize that while these calculation focus on CO_2 emissions, they do not account for other externalities (positive and negative) of driving an electric car. These would include the reduction of local pollutants generated on roadways, which themselves exhibit substantial regional heterogeneity (Muller and Mendelsohn, 2009). While power plants also contribute pollutants like sulfur dioxide and nitrogen oxides, these pollutants are regulated under a cap-and-trade system, meaning that any change in emissions at one location would be offset by a change in emissions elsewhere. The environmental effects would thus depend on the spatial distribution of the marginal costs and benefits of abatement (Burtraw and Mansur, 1999). A further factor to consider is that driving behavior may change if the marginal cost of driving falls (*i.e*., the rebound effect). The per gallon equivalent cost of driving an electric car is estimated at approximately $2/gallon.[23] It follows that, as with the Corporate Average Fuel Economy Standards, the rebound effect may occur and cause increased congestion, local emissions, and accidents (Portney *et al*. 2003).[24] While a comprehensive benefit-cost analysis of electric cars would need to take account of these different effects, they are beyond the scope of our analysis here, which is to demonstrate how our estimates of marginal emissions provide a novel and important input to the process.

6. Other Applications

The basic framework that we developed in Section 4 allows empirical estimation of the marginal emission rates of electricity consumption at different times of day and geographic locations across the United States. We have shown how these estimates are critical for understanding the environmental and economic implications of PEVs. We now consider how the same estimates can be used to examine the impacts of other policies and technologies that shift electricity demand: distributed solar, energy efficiency, and real-time pricing. In each case, we apply the empirical estimates of marginal emissions to provide illustrative calculations. While the approach is "back-of-the-envelope" and therefore abstracts from many important features and nuances of each case, our primary purpose is not to offer comprehensive analyses of each policy or technology. Instead, our aim is to show how one might apply our methodology more generally to a range of research questions.

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[23] EIA (2011) reports an average residential electricity rate of $0.12/kWh. For the average electric car, this is $0.042 per mile. For a gasoline car to pay this rate, gasoline prices would need to be $0.86/gallon for an average car, $1.38 for a commuter car, or $2.10 for a Prius.

[24] A careful life-cycle analysis that tends to the embodied carbon in both PEVs and their substitutes is also needed to ensure comprehensiveness.

6.1. Distributed Solar

Much like PEVs, renewable sources of energy are promoted as an important tool for addressing climate change and other environmental problems associated with the combustion of fossil fuels. Among the different alternatives, solar photovoltaic systems convert solar energy into electricity with virtually no emissions, ignoring those associated with the production and installation of the hardware. Distributed solar installations are those of smaller scale located at or near the site of primary consumption, such as arrays placed on residential or commercial rooftops. Of particular interest here are the "behind-the-meter" installations because they serve on-site electricity consumption rather than production that is fed directly onto the grid. The aggregate capacity of these installations has grown significantly in recent years, increasing 1,400 percent between 2000 and 2010 (Barbose *et al.*, 2011).

The environmental and economic implications of reducing electricity demand—from PEVs as well as solar installations—depends on where and when the shifts occur. In the case of photovoltaics, the timing of these reductions will follow the trajectory of the sun, ramping up in the morning, peaking by mid-afternoon, and tapering off in the evening. Thus, the benefits of distributed solar deployment will depend importantly on the marginal emissions and costs of electricity generation in the relevant electricity market during daylight hours, and our methodological approach is well suited for quantifying these effects.

Consider a simple, illustrative example of a residential solar system that homogenously produces 1 kWh of electricity for consumption from 7 AM to 7 PM. Using the hourly coefficients from Table 2, we can readily estimate the reduction in CO_2 emissions that would occur because of displaced electricity demand in various parts of the country. By simply summing coefficients over the relevant hours, we find, for example, that the solar installation would avert 9.8 lbs of CO_2/day for a household in the WECC, while the comparable number is 14.7 lbs of CO_2/day for the Eastern interconnection. Scaling emissions to the annual level, this yields 3,359 and 5,347 lbs for the two regions, respectively.[25] While in both regions the solar generated electricity

[25] Recall that our estimates of marginal emissions are based on data for weekdays only. It is, however, straightforward to replicate our analysis using all days of the week or by estimating separate coefficients for weekdays and weekends and taking a weighted average. This might be a more reasonable approach for understanding the implications of distributed solar and other possible applications. While the full set of these

occurs during hours when marginal emissions are relatively low, the differences indicate that the environmental benefits of distributed solar (assuming comparable generation) are significantly higher in the East, where the marginal emissions are greater from electricity on the grid. Monetizing these benefits, using the social cost of carbon estimate of $21 per metric ton (discussed previously), we value the emission reductions at $34 and $51 per year in the WECC and Eastern interconnections, respectively. These benefits are, however, lower than the additional benefits of avoided generation costs, which can be derived in similar fashion using the hourly marginal generation costs in Appendix Table 3. Interestingly, the cost savings in the Eastern interconnection are also larger than those in the WECC, with magnitudes of $251 versus $227 per household per year.[26]

Thus, this simple example shows how our methodology can be used to estimate regional differences in the benefits of distributed solar installations. While our comparisons suggest that the benefits may be significantly larger in the East compared to the West, more detailed analyses would also need to account for regional differences in generation based on the amount of sunshine.[27]

6.2. Energy Efficiency

Policies that seek to promote energy efficiency in residential and commercial buildings are playing an increasingly important role in the portfolio of initiatives designed to address energy and climate challenges. The methodology and estimates in this paper can further the understanding of the heterogeneous benefits that arise from such policies. Unlike the charging of PEVs and solar power, investments in energy-efficiency affect energy consumption patterns over the course of an entire day. Let us assume for simplicity that investments in efficiency

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results is available upon request, it is worth mentioning that pooling all days of the week has little affect on the results. For example, with estimates based on all seven day per week, comparable numbers for the emission reductions are 3,173 and 5,252 for the WECC and Eastern interconnections, respectively.

[26] These estimates of the cost savings are also based on weekdays only, but using estimates based on all seven days of the week make little to no difference ($251 and $227 for Eastern and WECC, respectively).

[27] Though we do not discuss it explicitly, the steps outlined here can apply to wind power that is used for behind the meter consumption as well. For recent analyses that do consider wind power, but with very different methodologies and for generation that connects directly to the grid, see Cullen (2011), Kaffine, McBee, and Lieskovsky (forthcoming), and Novan (2011).

reduce household electricity consumption by a homogenous 10 percent throughout all hours of the day and night.[28] It follows that for the average residential home in the United States, which consumes approximately 30 kWh/day, the savings would be a 0.125 kW reduction in electricity consumption each hour. Using our estimates of the hourly marginal benefits in terms of reduced CO_2 emissions and avoided generation costs, we can see how the benefits differ by region. Under the admittedly strong assumption about homogeneity of energy savings across varied climates, we see that efficiency investments again have greater benefits in the East. In the WECC the stylized investment in energy efficiency reduces CO_2 emissions by 2.4 lbs per household per day (880 lbs per year, valued at $8.38), while the same investment for a residence in the Eastern interconnection reduces emissions 3.9 lbs per household per day (1,408 lbs per year, valued at $13.42). Note that the environmental return is more than 50 percent greater in the East. The two regions are, however, more similar with respect to the avoided generation costs, with an annual estimated savings of $52.10 for the WECC and $55.28 for the East.

6.3. Real-Time Pricing

Real-time electricity pricing has long been a focus of economists and electric utilities as an effective market-based tool for smoothing generation by shifting demand from peak to off-peak hours.[29] Our previous analysis shows, however, that reducing generation costs with a shift from peak to off-peak times of the day leads to increased CO_2 emissions in many parts of the country.[30] Indeed, incorporating our estimates of marginal emissions and generation costs into the design of price schedules would facilitate the use of real-time pricing to balance reductions in generation costs with environmental externalities, and thus promote overall social welfare.

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[28] In reality, the strong relationship between temperature and energy consumption suggests that temporal patterns will be an important feature in a more complete evaluation of energy efficiency investments. See Jacobsen and Kotchen (forthcoming) for evidence on how energy savings from efficiency vary over the course of a year in a given location.

[29] See, for example, Borenstein (2005), Borenstein and Holland (2005), and Wolak (2010).

[30] This point has been made in other studies with more specialized contexts. See, for example, Kotchen *et al*. (2006) for a study of how the differences between peak and off-peak emissions affect the environmental benefits of converting hydroelectric dams from peaking to run-of-river flows.

While a complete analysis of real-time pricing is beyond the scope of our paper, we illustrate the core tradeoffs with another simple comparison between the WECC and Eastern interconnections. Consider a simple scenario in which real-time pricing moves 1 kWh of a household's electricity demand from 6 PM to 4 AM. That is, the pricing is such that demand moves from one of the peak hours with the highest generation costs to one of the off-peak hours with the lowest generation costs. Using our estimates in Appendix Table 3, we find that the cost savings per household on an annual basis would be $5.68 for the WECC and $9.97 in the East. But along with these changes in generation costs are changes in CO_2 emissions. For the WECC, emissions remain virtually unchanged, increasing 3.65 lbs/year, valued at 3.5 cents; whereas, for the East, emissions increase more substantially by 105.85 lbs/year, valued at approximately 1 dollar.

The design of optimal real-time pricing from a social welfare perspective should thus account for such different effects across all hours of the day and within each region. Only in this way can price signals be sent that balance the real-time social costs and benefits. This is important because, as we have shown, increases in demand in the off-peak hours at night generally increase emissions outside of the West, where dirtier electricity sources tend to be on the margin at those times of day. Despite the differences across the illustrative policies and technologies that we have considered, each serves to highlight some of the fundamental tensions between the objectives of load management on the electrical grid, minimizing generation costs, and minimizing environmental externalities.

7. Conclusion

Electricity generation is responsible for more CO_2 emissions and other air pollutants than any other sector in the US economy. Accordingly, a primary focus of existing and proposed environmental policy is to change patterns of electricity supply and demand in ways that reduce emissions. There is, however, substantial geographic and temporal variation in the emission rates of power plants. This heterogeneity combined with the electricity grid's interconnected networks for trading and distributing electricity pose difficult challenges for quantifying the environmental and economic implications of electricity-shifting policies. The difficulty arises because there is no definitive way to identify which power plants are generating electricity on the margin to meet demand at a particular location and time.

Our primary contribution in this paper is the development of a methodology to estimate marginal emissions of electricity demand that vary by location and time of day across the United States. The basic approach is to regress hourly emissions at the grid interconnection level on hourly electricity consumption for subsets of the corresponding NERC sub-regions. This level of aggregation takes into account the generation mix within interconnected electricity markets and the shifting load profiles throughout the day. Applying the methodology to emissions and consumption data for 2007 through 2009 (the most recent available), we find substantial variation among locations and times of day. For example, marginal CO_2 emission rates are more than three times as large in the upper Midwest compared to the western United States. Moreover, within regions, marginal emission rates for some hours of the day are more than twice those for other hours. While we focus our analysis on CO_2, which is a uniformly mixing GHG, we report the results for sulfur dioxide and nitrous oxides as well.

Estimates of the spatially and temporally heterogeneous marginal emission rates are critical for evaluating a range of energy and environmental policies and initiatives. We apply our results to an evaluation of PEVs in particular. The charging of PEVs increases demand for electricity and its consequent emissions, while simultaneously reducing emissions from the tailpipes of substitute vehicles that otherwise would have been driven. Our results show how the emissions of charging PEVS differs by region and hours of the day. In some regions (the west and Texas), the CO_2 emissions from driving PEVs are less than those from driving a hybrid. However, in other regions (the upper Midwest), charging during the recommended hours of midnight to 4 AM implies that PEVs generate more emissions than even the average car currently on the road. Underlying this result is a fundamental tension between load management of electricity and achieving environmental goals. The hours when electricity is the least expensive to produce tend to be the hours with the greatest emissions. In addition to PEVs, we show how our estimates of marginal emissions are useful for evaluating other polices and initiatives related to distributed solar, energy efficiency, and real-time pricing.

Finally, while our estimates and applications provide new insight, there are caveats and limitations that should be recognized. The general methodology holds the fuel mix for electricity generation constant and as such should be used for short- to medium-run analyses. While it is straightforward to replicate our approach as new data becomes available, a long run analysis should also attend to the endogenous changes in fuel mix as well as upgrades and replacements of existing electricity generating units that may be induced by policy changes intended to alter current energy consumption patterns. In terms of our application to PEVs and other electricity-shifting policies, the analyses are admittedly incomplete for full policy evaluations. We focus on CO_2 emissions, their valuation, and comparisons with electricity generation costs. But other pollutants, along with important features and nuances in each case, should be taken into account to make these analyses more comprehensive. Doing so will require careful attention to the heterogeneity of marginal damages and locations of other pollutants across space and time, as well as a clear understanding of the institutional structures and constraints under which those pollutants are regulated (*e.g.*, under a cap-and-trade regime). These concerns comprise a future research agenda.

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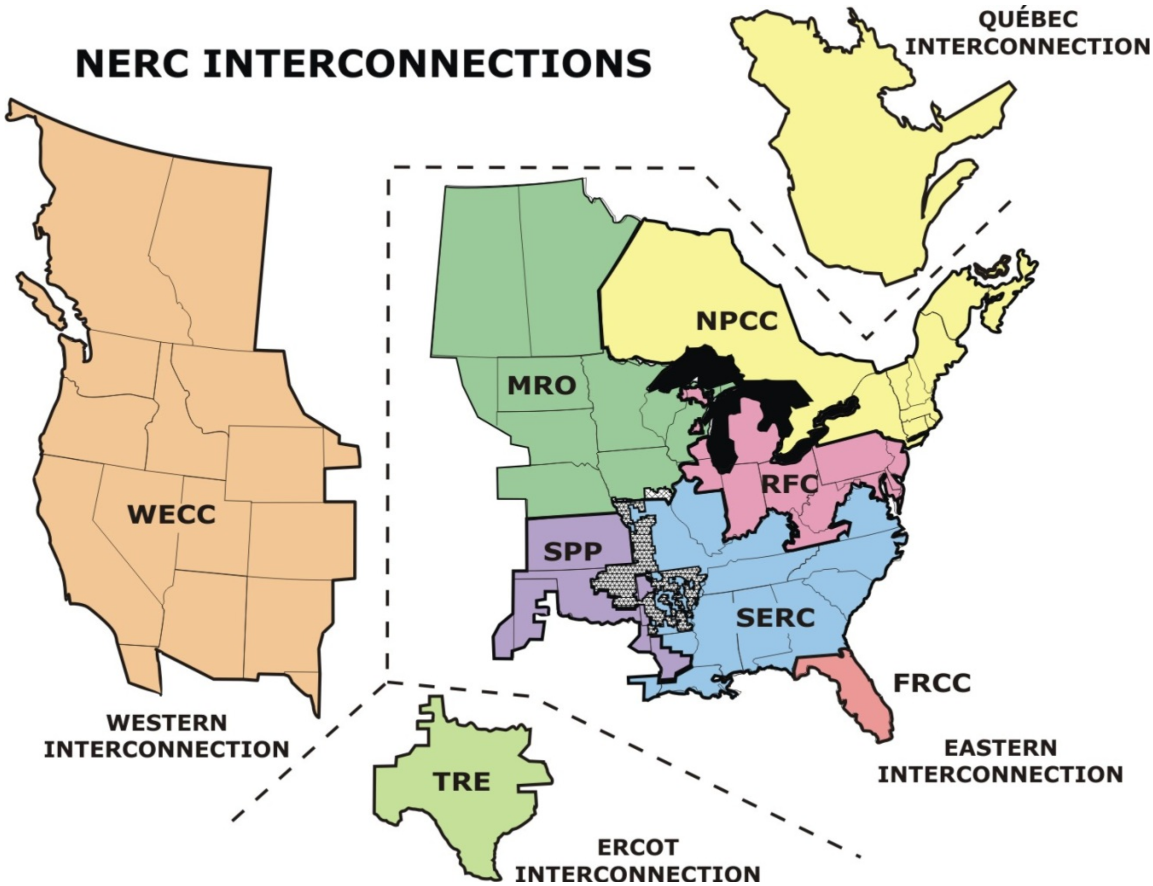


Figure 1: Grid interconnections and NERC regions, acronyms defined in the main text (source: NERC website at www.nerc.com)

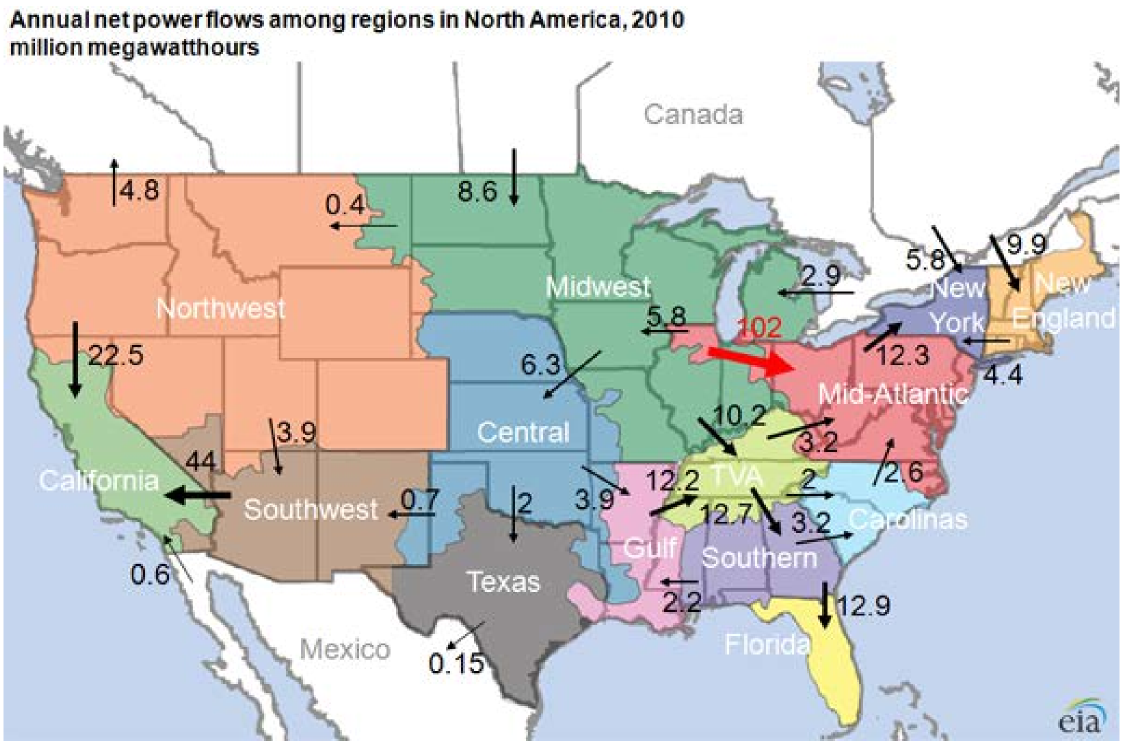


Figure 2: Annual 2010 net power flows for across NERC sub-regions
(source: EIA figure based on FERC Form 714 data, http://www.eia.gov/maps/)

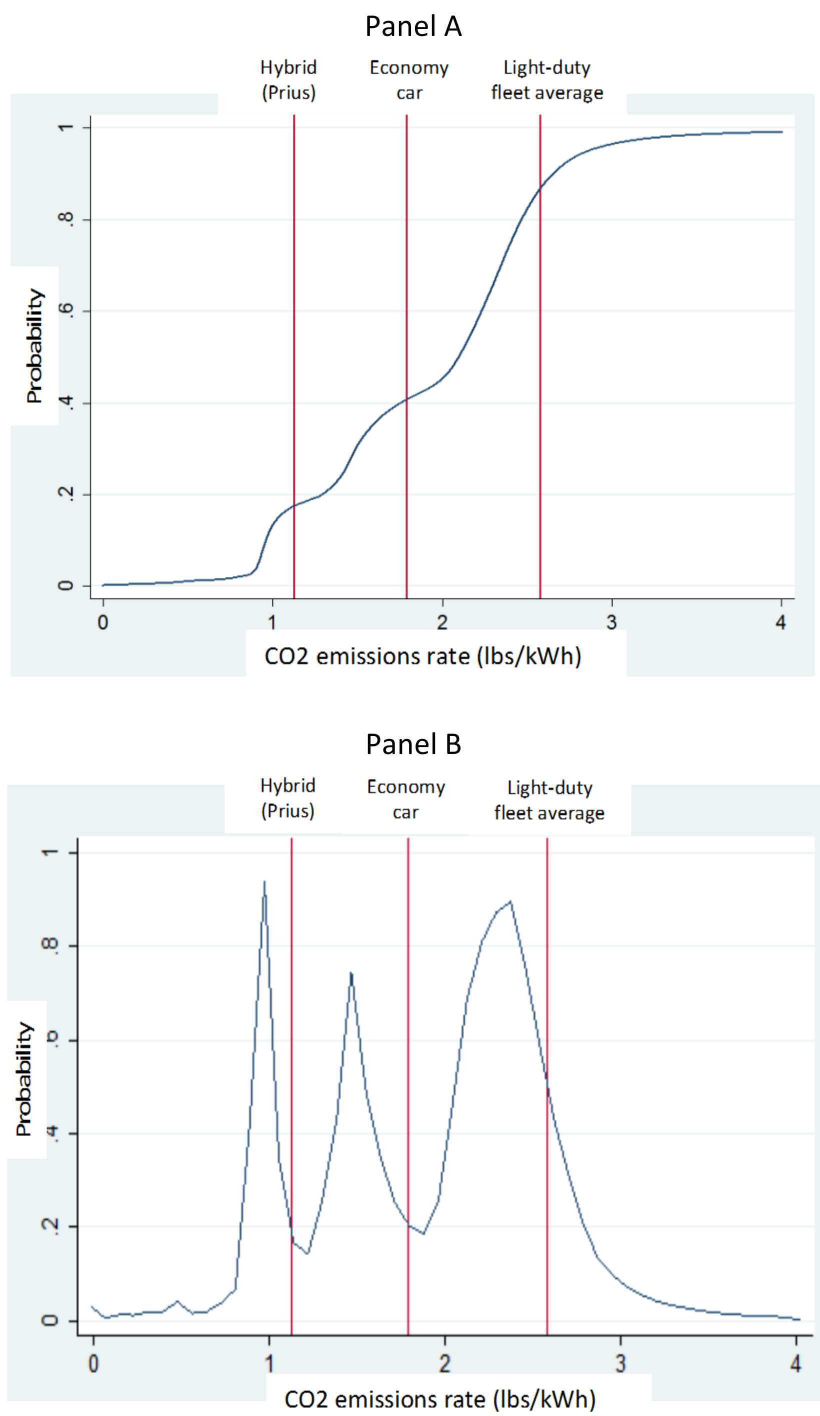


Figure 3: Cumulative distribution function (Panel A) and kernel probability density function (Panel B) of fossil-fired power, net transmitted generation (*i.e.*, consumption-based) CO_2 emission rates, in comparison with light-duty average, economy, and hybrid vehicle alternatives

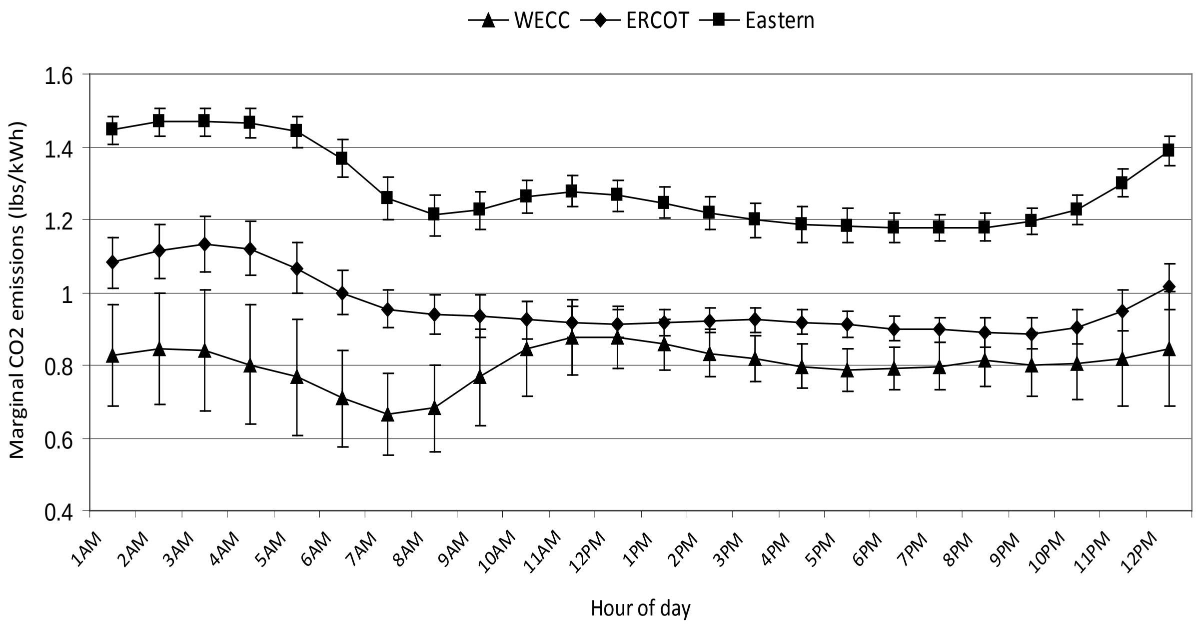
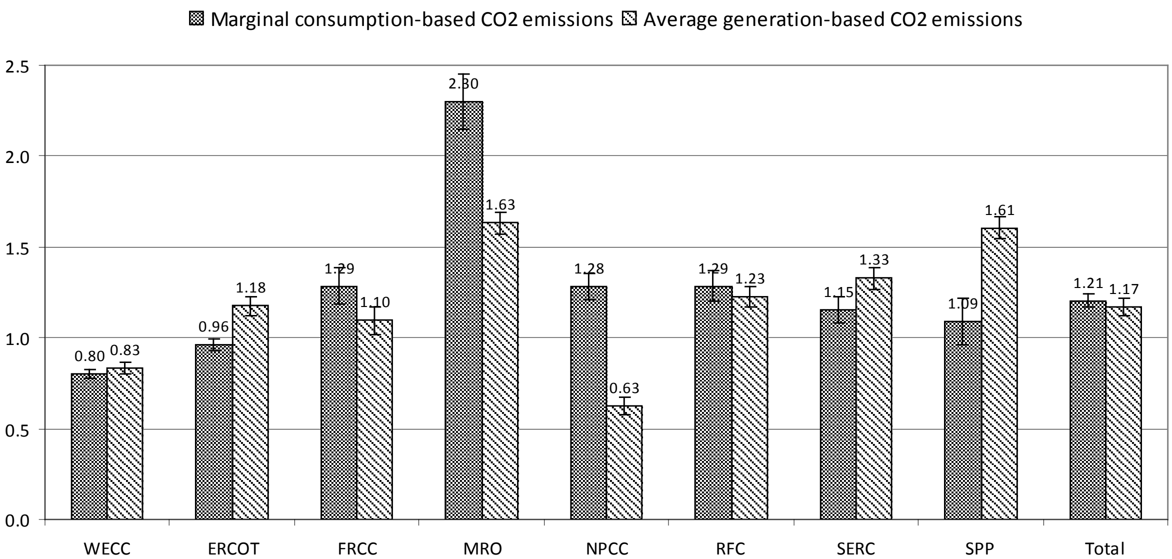


Figure 4: Marginal CO_2 emissions (lbs/kWh) and 95-percent confidence intervals, by interconnection and hour of day

Panel A: Marginal estimates for NERC regions based on unweighted average of hourly coefficients in Table 2 (and 95-percent confidence intervals), marginal estimate for the total derived using weighted average by hourly regional electricity consumption, average generation-based estimates taken from Table 1



Panel B: Generation-based estimates from Siler-Evans *et al*. (forthcoming) and total category derived from authors' calculation using weighed average by regional electricity consumption

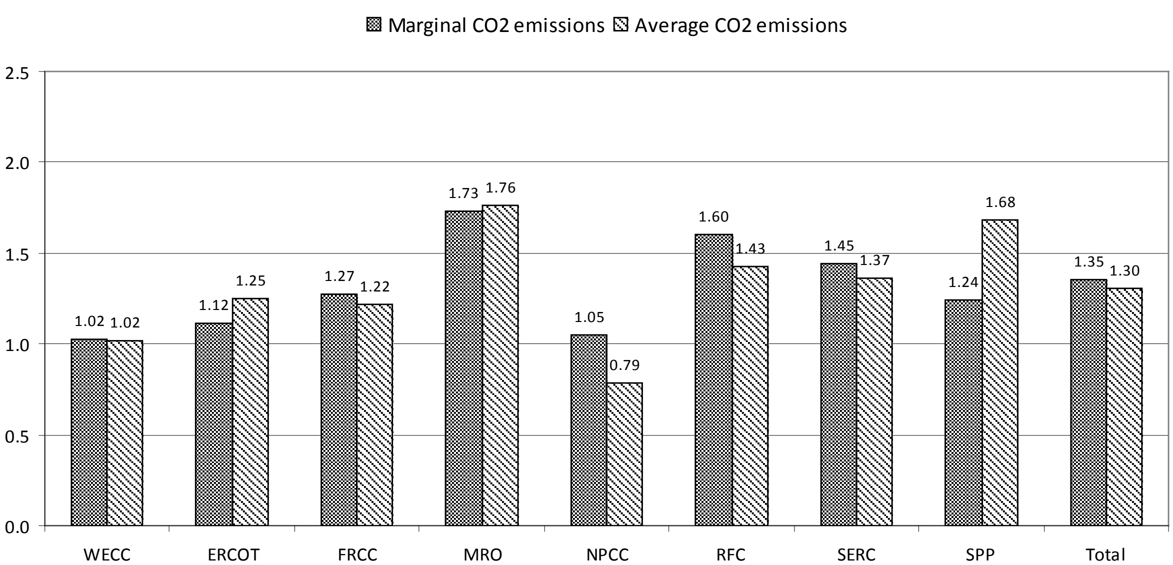


Figure 5: Comparison of marginal and average CO_2 emission rates by NERC regions

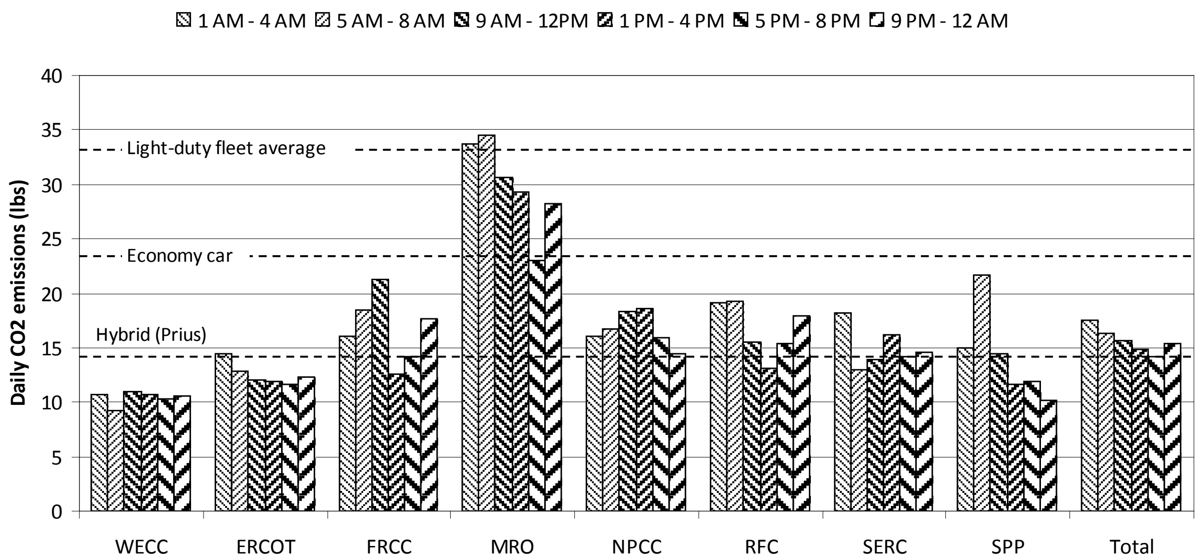


Figure 6: Daily CO_2 emissions of different charging times and NERC regions for a PEV to drive 35 miles, with comparisons to possible substitute cars

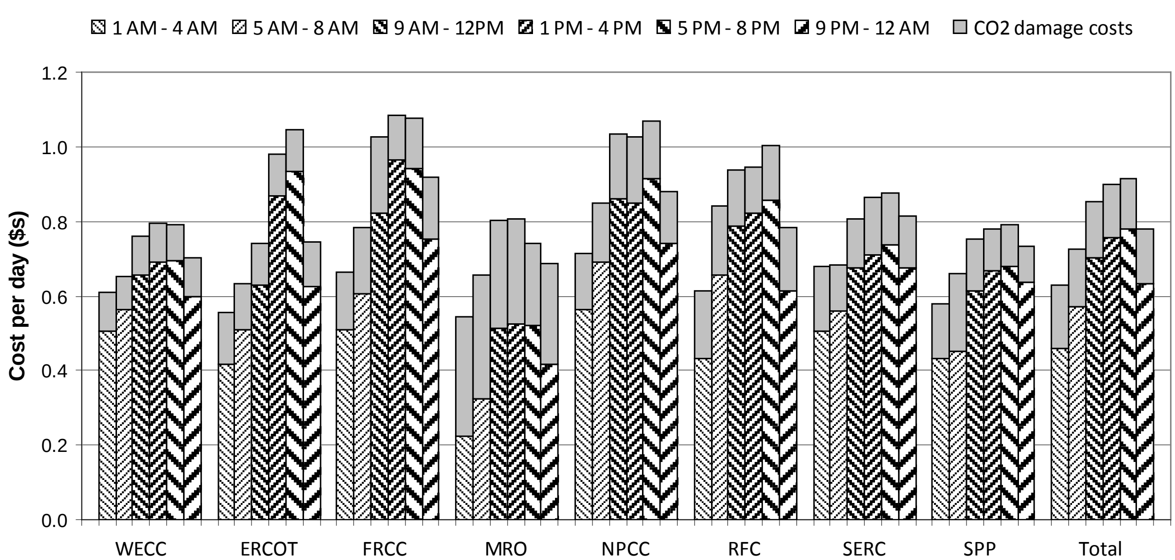


Figure 7: Social costs of daily electricity generation and CO_2 emissions of different charging times and NERC regions for a PEV to drive 35 miles

Table 1: Summary statistics by interconnection and NERC regions

Region	CO_2 Emissions (million lbs/hour)	Electricity Consumption (million kWhs)	Net Electricity Generation (million kWhs)	Emissions Rate (lbs/kWh) Consumption-Based	Generation-Based	eGRID (2007, 2009)
WECC	70.5	82.7	84.7	0.852	0.832	0.974
	(10.4)	(13.2)	(6.6)	(0.071)	(0.103)	
ERCOT	45.0	35.3	38.3	1.278	1.176	1.217
	(8.6)	(8.2)	(5.3)	(0.065)	(0.164)	
Eastern	427.4	339.4	339.5	1.261	1.257	1.329
	(71.7)	(58.0)	(30.3)	(0.063)	(0.163)	
FRCC	26.4	25.9	24.0	1.016	1.097	1.199
	(7.0)	(6.7)	(3.3)	(0.043)	(0.231)	
MRO	40.0	33.8	24.5	1.204	1.632	1.671
	(5.5)	(6.8)	(1.9)	(0.168)	(0.187)	
NPCC	19.2	33.6	30.4	0.568	0.627	0.724
	(5.3)	(6.2)	(2.7)	(0.062)	(0.147)	
RFC	138.0	109.9	112.3	1.256	1.227	1.400
	(24.0)	(18.8)	(10.3)	(0.079)	(0.170)	
SERC	163.9	111.8	123.3	1.472	1.327	1.308
	(28.9)	(23.7)	(12.2)	(0.059)	(0.180)	
SPP	39.8	24.4	24.8	1.640	1.606	1.675
	(6.8)	(5.1)	(3.2)	(0.123)	(0.190)	
Total	542.9	457.4	462.5	1.190	1.172	1.255
	(86.1)	(76.4)	(40.4)	(0.063)	(0.142)	

Notes: Reported numbers are means and standard deviations (in parentheses), with the exception of the last column. Rows above the first dotted line are interconnections, and those below are the separate NERC regions for the Eastern interconnection. CO_2 emissions are hourly from EPA's CEMS data; electricity consumption is hourly from FERC Form 714; and net electricity generation is average hourly generation based on monthly reports from EIA Form 923. The consumption- and generation-based emissions rates are simply the ratio of the first column over the other respective column. The eGrid emissions rate is based on simply aggregating the data set's emissions and net generation over both 2007 and 2009.

Table 2: Regression results of marginal CO_2 emissions (lbs/kWh), by interconnection, NERC regions, and time of day

	Interconnection			Eastern NERC region						Total
Hour	WECC	ERCOT	Eastern	FRCC	MRO	NPCC	RFC	SERC	SPP	US
1 AM	0.83	1.08	1.45	1.33	1.91	0.73	1.73	1.28	1.35	1.31
	(0.07)	(0.04)	(0.02)	(0.18)	(0.58)	(0.31)	(0.18)	(0.09)	(0.47)	
2 AM	0.84	1.11	1.47	1.22	2.83	1.32	1.40	1.44	0.92	1.36
	(0.08)	(0.04)	(0.02)	(0.16)	(0.24)	(0.25)	(0.11)	(0.06)	(0.27)	
3 AM	0.84	1.13	1.47	1.19	2.82	1.41	1.37	1.45	1.11	1.37
	(0.08)	(0.04)	(0.02)	(0.15)	(0.24)	(0.26)	(0.11)	(0.06)	(0.28)	
4 AM	0.80	1.12	1.47	1.21	2.81	1.46	1.38	1.43	1.24	1.36
	(0.08)	(0.04)	(0.02)	(0.15)	(0.25)	(0.27)	(0.11)	(0.06)	(0.29)	
5 AM	0.77	1.07	1.44	1.26	2.81	1.35	1.47	1.30	1.44	1.35
	(0.08)	(0.04)	(0.02)	(0.15)	(0.28)	(0.35)	(0.13)	(0.07)	(0.33)	
6 AM	0.71	1.00	1.37	1.44	2.67	1.18	1.58	1.05	1.75	1.30
	(0.07)	(0.03)	(0.03)	(0.16)	(0.31)	(0.45)	(0.16)	(0.08)	(0.36)	
7 AM	0.66	0.95	1.26	1.48	2.80	1.36	1.41	0.87	1.74	1.22
	(0.06)	(0.03)	(0.03)	(0.17)	(0.39)	(0.45)	(0.18)	(0.09)	(0.39)	
8 AM	0.68	0.94	1.21	1.52	2.35	1.24	1.46	0.76	1.74	1.17
	(0.06)	(0.03)	(0.03)	(0.16)	(0.37)	(0.35)	(0.16)	(0.09)	(0.40)	
9 AM	0.77	0.94	1.23	1.75	2.15	1.21	1.46	0.79	1.41	1.18
	(0.07)	(0.03)	(0.03)	(0.18)	(0.31)	(0.28)	(0.12)	(0.09)	(0.37)	
10 AM	0.85	0.92	1.26	1.81	2.37	1.42	1.25	0.99	1.16	1.21
	(0.07)	(0.03)	(0.02)	(0.21)	(0.29)	(0.23)	(0.10)	(0.07)	(0.34)	
11 AM	0.88	0.92	1.28	1.65	2.49	1.50	1.08	1.20	0.97	1.22
	(0.05)	(0.02)	(0.02)	(0.22)	(0.24)	(0.20)	(0.08)	(0.06)	(0.29)	
12 PM	0.88	0.91	1.27	1.33	2.43	1.52	0.99	1.32	0.91	1.20
	(0.04)	(0.02)	(0.02)	(0.20)	(0.21)	(0.16)	(0.07)	(0.06)	(0.27)	
1 PM	0.86	0.92	1.25	1.12	2.38	1.45	0.99	1.32	0.86	1.18
	(0.04)	(0.02)	(0.02)	(0.18)	(0.18)	(0.16)	(0.06)	(0.06)	(0.25)	
2 PM	0.83	0.92	1.22	0.97	2.28	1.41	1.01	1.27	0.87	1.15
	(0.03)	(0.02)	(0.02)	(0.17)	(0.17)	(0.17)	(0.06)	(0.07)	(0.23)	
3 PM	0.82	0.92	1.20	0.89	2.17	1.45	1.01	1.21	0.95	1.12
	(0.03)	(0.02)	(0.02)	(0.16)	(0.17)	(0.18)	(0.07)	(0.07)	(0.21)	
4 PM	0.80	0.92	1.19	0.89	2.18	1.40	1.03	1.18	0.92	1.11
	(0.03)	(0.02)	(0.02)	(0.15)	(0.17)	(0.18)	(0.07)	(0.07)	(0.20)	
5 PM	0.79	0.91	1.18	0.93	1.99	1.33	1.09	1.16	0.89	1.10
	(0.03)	(0.02)	(0.02)	(0.15)	(0.16)	(0.17)	(0.07)	(0.07)	(0.19)	
6 PM	0.79	0.90	1.18	1.04	1.78	1.31	1.14	1.11	0.96	1.09
	(0.03)	(0.02)	(0.02)	(0.14)	(0.14)	(0.17)	(0.06)	(0.06)	(0.18)	
7 PM	0.80	0.90	1.18	1.15	1.69	1.16	1.22	1.07	0.92	1.09
	(0.03)	(0.02)	(0.02)	(0.14)	(0.15)	(0.17)	(0.06)	(0.05)	(0.19)	
8 PM	0.81	0.89	1.18	1.23	1.64	1.11	1.27	1.04	0.90	1.09
	(0.04)	(0.02)	(0.02)	(0.15)	(0.18)	(0.21)	(0.07)	(0.05)	(0.22)	
9 PM	0.80	0.89	1.19	1.28	1.81	1.28	1.21	1.07	0.87	1.11
	(0.05)	(0.02)	(0.02)	(0.15)	(0.17)	(0.20)	(0.07)	(0.05)	(0.21)	
10 PM	0.81	0.91	1.23	1.35	2.03	1.05	1.35	1.05	0.77	1.14
	(0.05)	(0.03)	(0.02)	(0.15)	(0.18)	(0.20)	(0.07)	(0.05)	(0.24)	
11 PM	0.82	0.95	1.30	1.46	2.27	1.06	1.43	1.12	0.72	1.21
	(0.07)	(0.03)	(0.02)	(0.16)	(0.19)	(0.23)	(0.08)	(0.06)	(0.26)	
12 AM	0.84	1.02	1.39	1.34	2.59	1.06	1.51	1.23	0.75	1.28
	(0.08)	(0.03)	(0.02)	(0.17)	(0.21)	(0.25)	(0.09)	(0.06)	(0.26)	
R^2	0.95	0.97	0.99	0.99	--	--	--	--	--	

Notes: The dependent variable in all models is hourly CO_2 emissions. The three interconnection models are estimates of specification (1). The Eastern NREC region columns are coefficient estimates from the same model, specification (2). All models include 18,792 hourly observations and hour-of-day by month-of-sample fixed effects. Newey-West standard errors with a 24-hour lag are reported in parentheses, and all coefficients are statistically significant at the 99-percent level. The total US column is an average of the coefficients across all sub-regions weighted by the region's hourly electricity demand.

Appendix Table 1: Regression results of marginal sulfur dioxide emissions (lbs/kWh), by interconnection, NERC regions, and time of day

	Interconnection			Eastern NERC region					
Hour	WECC	ERCOT	Eastern	FRCC	MRO	NPCC	RFC	SERC	SPP
1 AM	0.53	1.46	6.11	4.62	3.73	0.69	10.22	4.78	1.18
	(0.08)	(0.19)	(0.17)	(1.30)	(2.42)	(1.61)	(0.83)	(0.62)	(1.99)
2 AM	0.58	1.71	6.19	4.47	5.11	2.75	9.40	5.22	0.68
	(0.09)	(0.20)	(0.18)	(1.18)	(1.66)	(1.47)	(0.71)	(0.55)	(1.62)
3 AM	0.63	1.83	6.17	4.38	4.25	3.08	9.34	5.12	2.32
	(0.09)	(0.21)	(0.19)	(1.24)	(1.89)	(1.53)	(0.74)	(0.51)	(1.73)
4 AM	0.52	1.77	6.11	4.73	3.73	3.76	9.24	4.91	3.22
	(0.08)	(0.20)	(0.19)	(1.20)	(2.12)	(1.66)	(0.78)	(0.49)	(1.82)
5 AM	0.47	1.44	5.96	5.30	4.33	4.79	8.74	4.57	4.29
	(0.08)	(0.18)	(0.18)	(1.17)	(2.17)	(1.77)	(0.77)	(0.42)	(1.89)
6 AM	0.36	1.11	5.45	6.24	3.93	6.12	8.09	3.49	5.65
	(0.07)	(0.15)	(0.17)	(1.18)	(2.24)	(1.98)	(0.76)	(0.43)	(2.01)
7 AM	0.34	0.84	4.73	6.71	4.35	5.59	7.77	1.92	5.89
	(0.06)	(0.12)	(0.18)	(1.19)	(2.55)	(2.48)	(1.02)	(0.49)	(2.06)
8 AM	0.26	0.68	4.36	6.23	5.30	6.09	7.41	1.16	5.55
	(0.07)	(0.13)	(0.17)	(1.04)	(2.33)	(2.45)	(0.98)	(0.46)	(2.14)
9 AM	0.22	0.55	4.35	6.79	7.59	5.52	6.64	1.64	1.89
	(0.07)	(0.13)	(0.17)	(1.21)	(2.02)	(2.06)	(0.75)	(0.48)	(2.01)
10 AM	0.27	0.46	4.43	6.99	10.73	5.75	4.97	2.83	-0.60
	(0.08)	(0.13)	(0.16)	(1.32)	(1.99)	(1.88)	(0.74)	(0.54)	(1.88)
11 AM	0.23	0.40	4.31	6.27	12.38	5.20	3.56	3.95	-1.97
	(0.06)	(0.12)	(0.17)	(1.33)	(1.89)	(1.90)	(0.82)	(0.57)	(1.78)
12 PM	0.23	0.35	4.04	4.79	11.99	4.58	2.76	4.49	-2.07
	(0.07)	(0.11)	(0.20)	(1.24)	(1.80)	(1.76)	(0.82)	(0.62)	(1.83)
1 PM	0.20	0.33	3.81	3.96	10.85	4.47	2.57	4.29	-1.10
	(0.06)	(0.10)	(0.21)	(1.17)	(1.71)	(1.68)	(0.77)	(0.70)	(1.96)
2 PM	0.15	0.32	3.64	3.45	9.65	4.42	2.71	3.80	0.11
	(0.06)	(0.09)	(0.22)	(1.10)	(1.70)	(1.52)	(0.73)	(0.73)	(1.86)
3 PM	0.14	0.34	3.56	3.17	9.03	4.72	2.71	3.48	1.30
	(0.05)	(0.10)	(0.23)	(1.08)	(1.68)	(1.37)	(0.67)	(0.70)	(1.71)
4 PM	0.14	0.31	3.52	3.10	8.78	4.40	2.76	3.45	1.28
	(0.05)	(0.10)	(0.23)	(1.03)	(1.61)	(1.31)	(0.67)	(0.67)	(1.50)
5 PM	0.16	0.29	3.52	3.35	7.81	3.95	3.08	3.41	1.08
	(0.05)	(0.09)	(0.23)	(1.00)	(1.60)	(1.29)	(0.68)	(0.66)	(1.39)
6 PM	0.19	0.26	3.56	4.04	6.84	3.96	3.55	3.10	1.25
	(0.05)	(0.09)	(0.20)	(0.99)	(1.47)	(1.23)	(0.65)	(0.60)	(1.30)
7 PM	0.17	0.26	3.62	4.88	6.97	4.08	3.92	2.80	0.65
	(0.05)	(0.10)	(0.17)	(0.99)	(1.33)	(1.21)	(0.58)	(0.51)	(1.26)
8 PM	0.17	0.24	3.69	5.34	6.83	2.76	4.58	2.74	0.00
	(0.06)	(0.11)	(0.16)	(1.06)	(1.37)	(1.26)	(0.61)	(0.51)	(1.30)
9 PM	0.20	0.29	3.85	5.69	7.28	2.21	5.11	2.74	-0.82
	(0.06)	(0.12)	(0.16)	(1.18)	(1.53)	(1.36)	(0.72)	(0.56)	(1.35)
10 PM	0.29	0.39	4.22	5.67	7.53	0.88	6.39	2.88	-1.28
	(0.08)	(0.13)	(0.16)	(1.20)	(1.48)	(1.38)	(0.70)	(0.54)	(1.49)
11 PM	0.37	0.61	4.93	5.51	8.00	1.65	7.36	3.74	-1.95
	(0.09)	(0.15)	(0.15)	(1.27)	(1.52)	(1.48)	(0.76)	(0.56)	(1.51)
12 AM	0.43	0.92	5.65	4.74	7.31	2.03	8.50	4.64	-1.56
	(0.10)	(0.16)	(0.15)	(1.29)	(1.69)	(1.48)	(0.73)	(0.54)	(1.55)
R^2	0.81	0.67	0.98	0.98	--	--	--	--	--

Notes: The dependent variable in all models is hourly sulfur dioxide emissions. The three interconnection models are estimates of specification (1). The Eastern NREC region columns are coefficient estimates from the same model, specification (2). All models include 18,792 hourly observations and hour-of-day by month-of-sample fixed effects. Newey-West standard errors with a 24-hour lag are reported in parentheses.

Appendix Table 2: Regression results of marginal nitrogen oxides emissions (lbs/kWh), by interconnection, NERC regions, and time of day

	Interconnection			Eastern NERC region					
Hour	WECC	ERCOT	Eastern	FRCC	MRO	NPCC	RFC	SERC	SPP
1 AM	0.71	0.56	1.87	0.48	2.29	-1.27	2.80	1.95	0.04
	(0.08)	(0.03)	(0.10)	(0.43)	(0.55)	(0.66)	(0.43)	(0.29)	(0.61)
2 AM	0.78	0.58	1.93	0.29	2.12	-0.79	2.76	2.08	0.33
	(0.10)	(0.03)	(0.11)	(0.41)	(0.75)	(0.70)	(0.42)	(0.26)	(0.70)
3 AM	0.79	0.59	1.95	0.24	1.90	-0.68	2.72	2.12	0.77
	(0.11)	(0.03)	(0.11)	(0.42)	(0.82)	(0.71)	(0.39)	(0.25)	(0.74)
4 AM	0.73	0.60	1.97	0.32	1.86	-0.51	2.67	2.11	1.29
	(0.10)	(0.03)	(0.11)	(0.41)	(0.88)	(0.69)	(0.35)	(0.23)	(0.81)
5 AM	0.64	0.57	1.95	0.43	2.13	0.10	2.40	2.08	1.90
	(0.10)	(0.04)	(0.11)	(0.41)	(0.97)	(0.78)	(0.30)	(0.21)	(0.86)
6 AM	0.55	0.55	1.83	0.98	2.15	0.85	2.07	1.79	3.06
	(0.09)	(0.04)	(0.09)	(0.39)	(0.95)	(0.70)	(0.25)	(0.17)	(0.82)
7 AM	0.44	0.63	1.65	1.40	1.99	1.11	1.80	1.48	3.48
	(0.08)	(0.03)	(0.07)	(0.44)	(0.97)	(0.64)	(0.27)	(0.16)	(0.82)
8 AM	0.39	0.63	1.59	1.66	2.10	1.50	1.49	1.42	3.51
	(0.07)	(0.03)	(0.06)	(0.45)	(0.85)	(0.56)	(0.26)	(0.15)	(0.80)
9 AM	0.40	0.55	1.57	1.67	2.56	2.09	1.09	1.55	2.92
	(0.07)	(0.03)	(0.06)	(0.46)	(0.73)	(0.56)	(0.25)	(0.16)	(0.79)
10 AM	0.41	0.52	1.53	1.44	3.17	2.40	0.67	1.82	2.14
	(0.07)	(0.03)	(0.07)	(0.43)	(0.68)	(0.53)	(0.25)	(0.17)	(0.77)
11 AM	0.41	0.55	1.46	1.21	3.68	2.42	0.44	1.93	1.35
	(0.06)	(0.03)	(0.07)	(0.45)	(0.67)	(0.52)	(0.26)	(0.17)	(0.67)
12 PM	0.43	0.60	1.38	0.89	3.64	2.26	0.45	1.86	1.02
	(0.05)	(0.04)	(0.07)	(0.44)	(0.62)	(0.45)	(0.23)	(0.19)	(0.60)
1 PM	0.43	0.72	1.32	0.91	3.19	2.13	0.56	1.66	1.30
	(0.04)	(0.05)	(0.07)	(0.43)	(0.58)	(0.42)	(0.20)	(0.21)	(0.58)
2 PM	0.43	0.85	1.28	0.98	2.87	2.16	0.71	1.38	1.50
	(0.04)	(0.06)	(0.07)	(0.42)	(0.57)	(0.37)	(0.20)	(0.22)	(0.56)
3 PM	0.43	0.92	1.26	1.09	2.68	2.24	0.79	1.19	1.75
	(0.04)	(0.07)	(0.07)	(0.42)	(0.55)	(0.34)	(0.20)	(0.24)	(0.54)
4 PM	0.41	0.94	1.24	1.06	2.70	2.21	0.82	1.12	1.49
	(0.04)	(0.07)	(0.07)	(0.41)	(0.55)	(0.33)	(0.20)	(0.25)	(0.53)
5 PM	0.40	0.91	1.24	1.11	2.23	1.96	1.01	1.07	1.46
	(0.04)	(0.06)	(0.07)	(0.39)	(0.51)	(0.32)	(0.21)	(0.26)	(0.50)
6 PM	0.40	0.81	1.25	1.29	2.01	1.91	1.12	1.03	1.37
	(0.04)	(0.05)	(0.07)	(0.37)	(0.49)	(0.35)	(0.22)	(0.26)	(0.46)
7 PM	0.40	0.72	1.28	1.50	1.95	1.82	1.28	1.02	1.10
	(0.04)	(0.04)	(0.06)	(0.37)	(0.47)	(0.38)	(0.27)	(0.26)	(0.47)
8 PM	0.39	0.66	1.32	1.53	2.28	1.90	1.20	1.17	0.67
	(0.05)	(0.04)	(0.06)	(0.39)	(0.49)	(0.38)	(0.24)	(0.24)	(0.48)
9 PM	0.40	0.60	1.34	1.33	2.49	1.42	1.25	1.30	0.44
	(0.06)	(0.04)	(0.06)	(0.42)	(0.57)	(0.38)	(0.29)	(0.26)	(0.49)
10 PM	0.47	0.53	1.40	1.06	2.05	-0.01	1.94	1.23	0.56
	(0.07)	(0.03)	(0.06)	(0.43)	(0.59)	(0.52)	(0.40)	(0.27)	(0.53)
11 PM	0.55	0.51	1.54	0.80	2.11	-0.37	2.27	1.45	0.07
	(0.08)	(0.03)	(0.07)	(0.44)	(0.61)	(0.62)	(0.48)	(0.29)	(0.55)
12 AM	0.64	0.51	1.73	0.33	2.29	-0.52	2.48	1.81	-0.15
	(0.09)	(0.03)	(0.08)	(0.46)	(0.67)	(0.66)	(0.51)	(0.31)	(0.61)
R^2	0.90	0.90	0.99	0.99	--	--	--	--	--

Notes: The dependent variable in all models is hourly nitrogen oxides emissions. The three interconnection models are estimates of specification (1). The Eastern NREC region columns are coefficient estimates from the same model, specification (2). All models include 18,792 hourly observations and hour-of-day by month-of-sample fixed effects. Newey-West standard errors with a 24-hour lag are reported in parentheses.

Appendix Table 3: Marginal generation costs of electricity ($s/MWh), by NERC region and hour of day

	Interconnection			Eastern NERC region						Total
Hour	WECC	ERCOT	Eastern	FRCC	MRO	NPCC	RFC	SERC	SPP	US
1 AM	39.88	41.08	37.15	42.18	19.01	47.31	35.54	40.27	37.28	37.92
2 AM	38.81	32.22	35.39	40.00	17.11	43.97	33.20	40.07	33.84	35.76
3 AM	38.25	28.30	33.56	37.82	16.22	41.73	31.37	38.19	31.90	34.01
4 AM	38.60	27.08	33.38	36.97	15.95	40.22	32.65	37.42	30.49	33.85
5 AM	39.88	29.22	35.33	39.55	17.24	42.01	37.42	37.17	30.00	35.70
6 AM	42.19	37.01	41.54	44.62	21.42	46.84	48.86	40.10	31.44	41.31
7 AM	44.97	40.94	48.90	48.07	27.66	60.31	58.49	44.94	35.44	47.55
8 AM	46.58	50.00	51.94	54.19	33.87	63.45	57.48	49.83	42.11	50.81
9 AM	48.33	42.63	52.32	56.55	36.80	63.39	55.98	50.71	44.20	50.85
10 AM	49.90	49.31	55.19	61.93	38.25	65.49	61.25	51.37	46.12	53.77
11 AM	51.28	50.86	56.94	65.44	40.63	68.13	62.88	52.13	48.57	55.44
12 PM	52.55	50.37	57.49	69.18	41.77	67.17	62.44	52.97	50.19	56.04
1 PM	52.54	52.00	58.31	72.47	42.07	66.10	63.39	53.75	51.03	56.76
2 PM	53.24	63.57	58.92	74.41	41.43	67.03	63.83	54.60	51.08	58.26
3 PM	53.57	74.12	58.23	74.81	39.84	64.19	62.53	54.96	51.35	58.66
4 PM	53.62	77.32	58.37	75.15	38.67	64.08	63.07	55.00	51.96	59.03
5 PM	53.99	85.85	58.59	73.49	37.76	68.64	62.66	55.39	51.71	59.92
6 PM	54.18	77.64	60.71	71.95	38.61	73.04	66.62	56.78	51.62	60.84
7 PM	53.27	68.99	61.36	71.72	41.23	70.51	67.50	57.88	52.64	60.48
8 PM	51.74	54.55	61.15	72.55	42.25	69.55	67.37	57.24	52.65	58.93
9 PM	49.55	51.15	58.18	68.73	41.12	68.03	61.04	56.33	52.11	56.10
10 PM	47.27	43.44	51.36	62.46	35.86	59.47	48.06	54.18	51.14	50.05
11 PM	45.24	56.27	45.62	53.72	28.31	51.99	41.69	50.10	48.98	46.34
12 AM	42.50	41.90	41.71	46.32	23.19	49.03	37.99	47.29	43.72	41.86

Notes: The system lambda data are from FERC Form 714, with the exception of those for ERCOT, which are market clearing prices (http://www.ercot.com/mktinfo/prices/mcpea). The eastern and total columns are an average across all of the corresponding sub-regions weighted by the hourly electricity demand.