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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 and real-time pricing.

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 (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.*,

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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." 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 in 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. The marginal effect, averaging across all regions and hours of the day, is 1.21 pounds of CO_2 per kilowatt hour (lbs CO_2/kWh) consumed. However, we find substantial variation among locations and times of day. For example, for the average hour of the day, the marginal effect in the upper Midwest is 2.30 lbs CO_2/kWh, which is almost three times the magnitude of that for the Western United States. For some hours, this spatial difference is even larger. Similarly, we see variation in emissions rates by hour of the day. For the average American, the cleanest consumption occurs when electricity demand is at its peak (7:00 PM). In contrast, emissions rates are about 26 percent greater during low demand hours (3:00 AM). 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 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 and real-time pricing.

[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.

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