Demand Side Emissions Policies*

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Abstract

When implementing a Pigouvian tax to address an externality, a general principle is that the effectiveness of the policy is independent on where the tax is implemented. This would suggest that pricing the emissions associated with the generation, transmission, and distribution of electricity would be equally effective where the electricity is produced, or where it is consumed by residential, industrial, or commercial customers. I use hourly data on power plant generation and pollution emissions from 2010 to 2015 to evaluate alternative policies for addressing emission externalities associated with electricity generation. I show that the second best demand side policies, focusing on all generation within a given hour, are extremely ineffective in capturing the total variation in emission externalities. Conversely, a simple second best supply side policy can capture most of variation in emission externalities. This suggests that policies designed to address emission externalities should focus on wholesale markets operations and the generation of electricity, not utility retail pricing or demand response programs.

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1 Introduction

One of the preferred methods to address a market externality, going back to Pigou (1932), is to impose a tax on the transaction equal to the marginal external cost. Conventional wisdom suggests the physical incidence, on producer or consumers, should not impact the effectiveness of the externality correcting policy in competitive markets, as elucidated by Weyl and Fabinger (2013). In the electricity industry, where there is a large potential for unpriced pollution emission externalities, there has been an abundance of policy proposals that depart from the ideal externality correcting tax, many of which focus primarily on changing consumer behavior. These policies that push for consumer responsibility include energy efficiency investments, retail rate design, and structuring demand response, are driven by utilities in the vacuum of State or Federal policy addressing emissions. While wide-spread, the ability of these demand side policies to address supply side emission externalities is not well characterized.

In this paper, I show the 'second best' demand side policies are not nearly as effective in addressing the emission externalities associated with the generation of electricity as the second best supply side policy. This is because there is significant heterogeneity in the marginal emissions across electricity generators within an hour, and consumers of electricity can not differentiate between different sources of electricity when they are making their consumption decision. Any policy that addresses the price paid by consumers, or the total demand within the electricity system, will not be able to directly address this heterogeneity. Instead, simple plant specific policies can address almost all of the variation in marginal external damages.

I show this using detailed data on plant-level hourly emissions in the United States from 2010 to 2015, and a new technique for evaluating alternative pricing structures as developed by Jacobsen et al. (2018). With these data and procedure, I am able to estimate the second best policy aimed at addressing emission externalities as a function of fundamental characteristics of electricity, such as it's origin or the time of day that it is consumed. After making relatively weak assumptions about the substitution across electricity plants, the R^2 from the least-squares estimation of the second best policy represents the proportion of welfare that can be recovered by the second best policy relative to a benchmark policy that does not differentiate across product attributes. One benefit of this measure of relative policy effectiveness is that it doesn't depend on the elasticity of demand or supply, or structural assumptions on pass-through.

These results are policy relevant. For one, these marginal external damages are large, surpassing the private marginal cost at times. If the policy design has significant implications on policy effectiveness, it is important to design the best possible policy. Second, there is a current debate on which type of agent should address these externalities. Largely, utilities are pushing demand response and energy efficiency type programs while emphasizing consumer responsibility. Conversely, the wholesale electricity markets, like the New York Independent System Operator, are considering incorporating carbon damages into its decision to dispatch different units. My results suggest wholesale electricity market operators would be vastly more effective in addressing emission externalities than a distribution utility, and as such their role in policy making should be emphasized.

The impetus for related literature is Holland and Mansur (2008), which quantifies how real time electricity pricing would impact the average hourly emissions from producing electricity. Leveraging the fact that real time emissions policies will reduce variance in demand, they evaluate how less load variance impacts the *average* marginal emissions within a given area. Unsurprisingly, they find the relative effectiveness of real time electricity pricing on emission externalities depends on the local fuel mix. If the marginal units emit more pollution than the average unit, then real time electricity pricing reduced emission externalities. They find the effects to be small in magnitude, however by only looking at averages within a particular time frame, they are overlooking the cross-sectional variance of emission externalities. This paper revisits the effectiveness of retail pricing in addressing emissions externalities using a new technique, a richer and more recent data set.[1]

In this paper, I not only evaluate how retail rates can impact emissions, but also explicitly recover retail rates that would be most effective in addressing emission externalities. This contributes

[1] Since Holland and Mansur (2008) there has be a rapid change in the mix of fuels used to generate electricity as natural gas prices have remained low and there has been more invest in renewable generation.

to a more general, important, dialog on how can we design electricity rates to be more efficient.[2] Borenstein and Bushnell (2018) highlight the significant heterogeneity is hourly marginal social cost in generating electricity, as well as the incongruence of these real cost with the price paid by consumers. This hour-to-hour variation is primarily due to changes in the private marginal cost, not marginal emission damages. Despite this, there still is significant heterogeneity in marginal external damages per unit of electricity and part of this paper is highlighting this feature of the US electricity grid.[3]

Ideally, the price paid by a consumer would equal to the social marginal cost at any given time and any given location.[4] My results suggest the only way to address the heterogeneity in emission externalities is to expose consumers to location specific retail rates, to have the ability to contract with specific electricity generators, or to have a supply side policy directed at each plant. Of these three, the supply side policy is the easiest to implement, and I recover the second best supply side policy which can address over 80% of the variation in marginal external damages.

The paper proceeds as follows. Section 2 considers the theory behind second best policies to address emission externalities at both the demand and supply side. Section section 3 describes the data used in the analysis. Section 4 presents the second best emission policies, as well as the R^2 values representing the relative performance of the different second best policies. Section 5 explicitly calculates the absolute dead weight loss (DWL) associated with alternative policies with generous assumptions on supply and demand. Section 6 concludes the paper.

[2]Relevant papers for this discussion include Blonz (2016); Burger et al. (2019)

[3]Commonly, when evaluating the impact of alternative policies on emissions, the approach is to average the emissions in a geographic area across all electricity used in that area and referring to this as the average marginal emissions rate. For example (Boomhower and Davis, 2018; Holland et al., 2016; Fowlie and Muller, 2017; Zivin, Kotchen, and Mansur, 2014). This averaging of the emissions greatly reduces the variance in emissions per MWh.

[4]The idea of location based retails rates is termed Distributed Locational Marginal Price. For example, Li, Wu, and Oren (2014).

2 Modeling Second Best Emission Policies

The following closely resembles the theory presented by Jacobsen et al. (2018). Instead of the consumer choosing their optimal consumption bundle across multiple products, they choose a single amount to consume at a given time period and demand is independent across time periods. Importantly, this independence of consumption across periods excludes any inter-temporal substitution which is a critical assumption in the results that follow. Given the context of electricity markets, this is a reasonable assumption given the empirical evidence that consumers do not substitute across periods (Jessoe and Rapson, 2014; Gillan, 2017; Ito, Ida, and Tanaka, 2018; Allcott, 2011), as pointed out and emphasized by Jacobsen et al. (2018). My contribution is to model the heterogeneity on the supply side in the marginal external emissions per unit produced. I assume there is independence of costs of production across periods, but not within periods.

With the assumption about independence across periods, I proceed considering the optimal choice of the producer, consumer, and social planner in a single period, then aggregate across periods. There is a representative consumer which consumes X_j units of the good at time j with $j = 1, ..., J$. This is produced from different production resources, denoted by the the subscript $i = 1, .., I$, each of which produces a quantity x_{ij} such that $X_j = \sum_i^I x_{ij}$. The costs of production are specific to the production resource, $c_i(x_{ij})$, and are additive across resource and over time. I assume cost are increasing for all i, $c_i' > 0$. In the context of electricity markets, X_j is the total amount of electricity consumed in a given hour, and x_{ij} is the amount of electricity produced by a particular plant.

Generating electricity creates pollution, SO_2, $PM2.5$, NO_X, and CO_2 which can cause damage to human health and reduce productivity. I specify the total external damages associated with producing x_{ij} units of the commodity as the value $\phi_{ij} x_{ij}$ so that ϕ_{ij} represents the marginal external damages of the good at time j from producer i.[5] I assume that the damages are linear so that the

[5]The marginal external damages clearly depends depend on the resource type, i, because each resource might invest in different production or abatement technologies. Having the marginal external damages vary over time, j, represents other determinants of economic damages from pollution including the heat rate of the plant, the temperature outside, rain, and the size of the exposed population.

total damages during all time periods equals $\phi = \sum_j \sum_i \phi_{ij} x_{ij}$. In what follows, I assume the externality is ignored by the producers and consumers, however the social planner decides to address the externality through demand or supply side policies.[6]

In a single periods, the representative consumer chooses the quantity X_j according to their utility $U_j(X_j)$ for good X. I assume that utility is increasing and concave, $U_j' > 0, U_j'' < 0$ and that $U_j'(0) = \infty$. The consumer is endowed with a fixed income of M, and they can purchase an outside good n which is the numeraire and enters their utility linearly. If the social planner introduces a tax, the revenue is returned to the consumer with a lump sum transfer of D.

While the setup of this model is motivated by the market for electricity, this general setting can be seen elsewhere. A consumer will choose how much to consume of a particular good, however the good is composed of a number of inputs each with a different marginal external damages. Importantly, the consumer can not contract for the inputs of which the final good is composed.

2.1 Consumer's and Producers' Problem

The consumer solves the following problem when there is a per-unit demand side tax, t_j^d:

$$\max_{X_j} \quad U_j(X_j) \tag{1}$$

$$s.t. \quad (p_j - t_j^d)X_j + n \leq M + D \tag{2}$$

The first order condition states the consumer will choose the optimal amount of X_j so that the marginal utility is equal to the unit price plus the per-unit tax given there is an interior solution: $\frac{\partial U_j}{\partial X_j} = p_j + t_j^d$. If there is no demand side tax, the consumer will set the marginal utility equal to the per-unit price: $\frac{\partial U_j}{\partial X_j} = p_j$.

Producers are competitive price taking profit maximizers in the short run.[7] For every hour,

[6] In reality, some producers do care about emissions externalities when there are existing policies in place such as SO_2 trading, or a CO_2 cap and trade program.

[7] I do not consider entry or exit. Instead of profit maximizing, it is possible the supply side is determined by a central planner that is minimizing the cost of production across all resources. This is very close to reality in the setting of wholesale electricity markets.

they choose the quantity to maximize their profits for a given equilibrium price. If there is a unit production tax, t_{ij}^{s}, this will increase their cost of production. Each producer i will choose x_{ij} at time j to solve

$$\max_{x_{ij}} \quad p_j x_{ij} - c_i(x_{ij}) - t_{ij}^{s} x_{ij} \tag{3}$$

So they will choose to produce x_{ij} such that the marginal cost of production equals the price per unit less the unit production tax: $\frac{\partial c_i(x_{ij})}{\partial x_{ij}} = p_j - t_{ij}^{s}$. If there is no production tax, they will produce where price is equal to the marginal cost of production: $\frac{\partial c_i(x_{ij})}{\partial x_{ij}} = p_j$.

The equilibrium is defined by a market price, p_j, such that the consumer is maximizing their utility, the producers are maximizing their profits, and the markets clear: $X_j = \sum_i x_{ij}$. In what follows, I let $\tilde{x}_{ij}$ and $\tilde{X}_j$ denote these equilibrium quantities.

2.2 Social Planner

The goal of the social planner is to maximize welfare, which is utility minus the cost of production and the damages from the externalities. Total welfare is the sum of per-period welfare across all periods:

$$W = \sum_j W_j = \sum_j^J \left[U(\tilde{X}_j) + M - \sum_i^I c_i(\tilde{x}_{ij}) - \sum_i^I \phi_{ij} \tilde{x}_{ij} \right]$$

The planner has the ability to introduce a tax t which can vary over time j, and across units i. They choose this tax to maximize the total welfare W such that total demand is equal to total supply $\tilde{X}_j = \sum_i \tilde{x}_{ij}$.

If the social planner is unconstrained by the type of tax they introduce, they would choose to have a policy that is the most flexible, a separate tax per period, differentiated by the producer. As such the optimal supply side tax would be a set of t_{ij}^{*} that would maximize total welfare, W_j. The first order conditions for this problem are

$$
\begin{aligned}
\frac{\partial W}{\partial t^*_{ij}} = \sum_j^J \frac{\partial W_j}{\partial t^*_{ij}} =& \sum_j^J \left[\frac{\partial U_j}{\partial X_j} \sum_{m=1}^I \frac{\partial \tilde{x}_{mj}}{\partial t^*_{ij}} - \sum_{m=1}^I \frac{\partial c_m(x_{mj})}{\partial x_{mj}} \frac{\partial \tilde{x}_{mj}}{\partial t^*_{ij}} - \sum_{m=1}^I \phi_{mj} \frac{\partial \tilde{x}_{mj}}{\partial t^*_{ij}} \right] \\
=& \sum_j^J \left[\sum_{m=1}^I \left[\frac{\partial U}{\partial X_j} - \frac{\partial c_m(x_{mj})}{\partial x_{mj}} - \phi_{mj} \right] \frac{\partial \tilde{x}_{mj}}{\partial t^*_{ij}} \right] = 0
\end{aligned}
$$

in this expression, a tax on unit i will impact the equilibrium quantity produced by that unit through $\frac{\partial \tilde{x}_{mj}}{\partial t^*_{ij}}$ when $m = i$, and all other units when $m \neq i$. In the presence of a supply side tax, $\frac{\partial c_m(x_{mj})}{\partial x_{mj}} = p_j - t^*_{mj}$ and $\frac{\partial U}{\partial X_j} = p_j$, implying

$$
\frac{\partial W}{\partial t^*_{ij}} = \sum_j^J \sum_m^I \left[t^*_{mj} - \phi_{mj} \right] \frac{\partial \tilde{x}_{mj}}{\partial t^*_{ij}}
$$

which will equal to zero when $t^*_{mj} = \phi_{mj}$ for all m and all j. This is first best, also referred to as the Pigouvian Benchmark. It is optimal to set the tax equal to the marginal external damages per unit of electricity from source i at time period j.

2.3 Second Best Policies

If the social planner can only price the externality over time, as a demand side policy, or across plants, as a supply side policy, they will not be able to achieve the Pigouvian Benchmark. In this subsection, I consider alternative second best policies. If there is a demand side tax, t^d_j, which can not differentiate between plants, we have a similar first order condition

$$
\begin{aligned}
\frac{\partial W_j}{\partial t^d_j} =& \frac{\partial U_j}{\partial X_j} \sum_m^I \frac{\partial \tilde{x}_{mj}}{\partial t^d_j} - \sum_m^I \frac{\partial c_m(x_{mj})}{\partial x_{mj}} \frac{\partial \tilde{x}_{mj}}{\partial t^d_j} - \sum_m^I \phi_{mj} \frac{\partial \tilde{x}_{mj}}{\partial t^d_j} \\
=& \sum_m^I \left[\frac{\partial U_j}{X_j} - \frac{\partial c_m(x_{mj})}{\partial x_{mj}} - \phi_{mj} \right] \frac{\partial \tilde{x}_{mj}}{\partial t^d_j} = 0
\end{aligned}
$$

where $\frac{\partial \tilde{x}_{mj}}{\partial t^d_j}$ denotes how the per unit tax on demand impacts the equilibrium quantity produced by plant i through the market clearing condition. This relates to the combined supply and demand derivatives, as well as assumptions about pass-through. For the demand side policy, $\frac{\partial U_j}{\partial X_j} = p_j + t_j^d$, and $\frac{\partial c_i(x_{ij})}{\partial x_{ij}} = p_j$, so that

$$\frac{\partial W}{\partial t_j^d} = \sum_j^J \sum_m^I \left[t_j^d - \phi_{mj} \right] \frac{\partial \tilde{x}_{mj}}{\partial t_j^d}$$

Here, it is impossible to set all $t_j^d = \phi_{mj}$, instead, the social planner with set $t_j^d = \frac{\sum_m \phi_{mj} \frac{\partial \tilde{x}_{mj}}{\partial t_j^d}}{\sum_m \frac{\partial \tilde{x}_{mj}}{\partial t_j^d}}$ which equals the weighted average marginal external damages across all electricity generating plants, with the weight equal to the plant's responsiveness to the demand side tax. A higher tax will be set if dirtier plants are more responsive to the implementation of the tax.

If the planner can only choose a supply side policy, some t_i^s, which depends on the origin of the electricity but not on the time, the first order condition will be identical to the ones above however the policy is,

$$\frac{\partial W}{\partial t_i^s} = \sum_j \frac{\partial W_j}{\partial t_i^s} = \sum_j \sum_m \left[t_m^s - \phi_{mj} \right] \frac{\partial \tilde{x}_{mj}}{\partial t_i^s}$$

To maximize total welfare the first order conditions imply the social planner will choose to have $t_m^s = \frac{\sum_j \phi_{mj} \frac{\partial \tilde{x}_{mj}}{\partial t_i^s}}{\sum_j \frac{\partial \tilde{x}_{mj}}{\partial t_i^s}}$. Similarly to the demand side policy, when the planner is constrained they will set the tax equal to some average of the marginal external damages. The tax for unit m will be larger if they pollute more during hours in which they are more responsive to a tax. If the plant's responsiveness to the tax is independent over time, this second best policy would just be the average marginal emissions rate for the plant.

Noticing that t_{ij}^* does not equal t_j^d or t_i^s, both limited supply and demand side policies are second best, there will be some welfare loss from this pricing imperfection.

2.4 Dead-Weight Loss and Regression Statistics

Consider the optimal supply side policy, $t^*_{ij} = \phi_{ij}$, and some deviation from that policy τ_{ij}. Jacobsen et al. (2018) show how to recover an expression for dead weight loss. Consider a weighted average of the optimal policy, and the generic policy $t_{ij} = (1-\rho)\phi_{ij} + \rho\tau_{ij}$. Taking the derivative of total welfare with respect to the weight, ρ, provides

$$\frac{\partial W}{\partial \rho} = \sum_j \sum_i \sum_m \left[t_{ij} - \phi_{ij}\right] \frac{\partial \tilde{x}_{ij}}{\partial t_{mj}} \frac{\partial t_{mj}}{\partial \rho}$$

Substituting $t_{ij} = (1-\rho)\phi_{ij} + \rho\tau_{ij}$ and $\frac{\partial t_{mj}}{\partial \rho} = \tau_{mj} - \phi_{mj}$

$$\frac{\partial W}{\partial \rho} = \rho \sum_j \sum_i \sum_m \left[\tau_{ij} - \phi_{ij}\right] \frac{\partial \tilde{x}_{ij}}{\partial t_{mj}} \left[\tau_{mj} - \phi_{mj}\right]$$

The change in total welfare, or dead weight loss from some tax $\tau_{ij} \neq \phi_{ij}$, equals the integral from $\rho = 0$ to $\rho = 1$. Assume that change in equilibrium output $\tilde{x}_{ij}$ in response to a tax, and the externality ϕ_{ij}, are independent of ρ.

$$DWL(t_{ij} = \tau_{ij}) = -\frac{1}{2} \sum_{j=1}^{J} \sum_{i=1}^{I} \sum_{m=1}^{I} \left[\tau_{ij} - \phi_{ij}\right] \left[\tau_{mj} - \phi_{mj}\right] \frac{\partial \tilde{x}_{ij}}{\partial t_{mj}}$$

Define the tax error, e_{ij}, as $\tau_{ij} - \phi_{ij}$. Dead weight loss can be re-expressed as

$$DWL(t_{ij} = \tau_{ij}) = -\frac{1}{2} \sum_{j=1}^{J} \sum_{i=1}^{I} e_{ij}^2 \frac{\partial \tilde{x}_{ij}}{\partial t_{ij}} + \sum_{j=1}^{J} \sum_{i=1}^{I} \sum_{m \neq i} e_{ij} e_{mj} \frac{\partial \tilde{x}_{ij}}{\partial t_{mj}}$$

At this point, the expression will simplify greatly if a few conditions are met. Consider the following assumptions: (1) the tax error, e_{ij} is independent of the own-tax derivative $\frac{\partial \tilde{x}_{ij}}{\partial t_{ij}}$ (2) The product of the tax errors, $e_{ij}e_{mj}$, are independent of the cross derivatives, $\frac{\partial \tilde{x}_{ij}}{\partial t_{mj}}$. If (1) and (2) are met, the expression for dead weight loss simplifies to

$$DWL(t_{ij} = \tau_{ij}) = -\frac{1}{2}\left(\overline{\frac{\partial \tilde{x}_{ij}}{\partial t_{ij}}} - \overline{\frac{\partial \tilde{x}_{ij}}{\partial t_{mj}}}\right)\sum_{j=1}^{J}\sum_{i=1}^{I} e_{ij}^2$$

where $\overline{\frac{\partial \tilde{x}_{ij}}{\partial t_{ij}}}$ is the average change in the equilibrium quantity in response to the tax and $\overline{\frac{\partial \tilde{x}_{ij}}{\partial t_{mj}}} = \frac{1}{I(I-1)}\sum_{i=1}^{I}\sum_{m\neq i}\frac{\partial \tilde{x}_{ij}}{\partial t_{mj}}$. This shows that the dead-weight loss is proportional to the sum of the squared tax error.

Before proceeding, it is important to evaluate the extent to which assumption (1) and (2) are met in the context of emission externalities associated with electricity generation. Although the total emissions per unit of production at a plant might be associated with the equilibrium response of that plant to a tax, it is reasonable to state that the residual emissions that are not addressed by the tax are independent of the plant's responsiveness to the tax. In the context of a supply side policy, this assumption is stating that the plant is not more or less responsive to the tax when they are polluting more or less than their average amount per unit. For a demand side tax, this suggest that a plant is not more of less responsive when its emissions per unit deviate more or less from the average emissions in that hour.[8] For assumption (2) to hold, it is necessary that two products that have (dis-)similar tax errors are not also more or less substitute-able.

We can think of a general tax policy that is linear in observable product attributes, $\tau_{ij} = f(z_{ij}|\theta) = \alpha + \beta z_{ij}$, where the tax error would be equal to $\phi_{ij} - f(z_{ij}|\theta)$. Finding the parameters values that minimize total dead-weight loss is equivalent to minimizing the sum of the squared tax errors, and can be found using ordinary least squares to project ϕ_{ij} onto z_{ij}. This dead weight loss minimizing tax policy, $f(z_{ij}|\hat{\theta})$, is the second best policy. Moreover, the R^2 from this regressions represents the percent of welfare that is recovered from the second best policy relative to a policy that does not differentiate over z_{ij}, as the R^2 from this regression is equivalent to

[8] Violation of this assumption might be reasonable for demand side policies. If so, the second best policy can still be recovered using a weighted least squares estimation procedure, where the weights are equal to the unit's responsiveness to the tax.

$$
\begin{aligned}
R^2 =& 1 - \frac{SSR^{SecondBest}}{TSS^{SecondBest}} \\
=& 1 - \frac{SSR^{SecondBest}}{SRR^{Uniform}} \\
=& 1 - \frac{DWL(t_{ij} = f(z_{ij}|\hat{\theta}))}{DWL(t_{ij} = \bar{t})}
\end{aligned}
$$

where $\bar{t}$ is an average of all ϕ_{ij}, SSR stands for the Sum of Squared Residuals and TSS stands for the total sum of squares.

3 Data

The primary data are on the hourly operation of electricity generators from the EPA's Continuous Emission Monitoring System (CEMS) from 2010 to 2015.[9] These data report the hourly emissions of SO_2, CO_2, and NO_x, as well as as gross generation and net generation for each generator. These data are widely used.[10] In what follows, I aggregate the generator level observations to the plant level. Particulate matter, like $PM2.5$, is a by product of burning fuel to generate electricity and can have an impact on human health, however is not reported in the CEMS database.[11]

The CEMS data are hourly observations on 1482 electricity generating plants in the Continental United States structured as an unbalanced panel. When the electricity plant is not operating and not generating any pollution, the quantity of electricity generated and emissions are not reported.[12] Table 1 tabulates the number of plants of each fuel type, as well as the average name plate capacity of the plants in Megawatts by fuel type.

[9] This includes all electricity generating generators in the United States over 25 megawatts that are not powered by Nuclear, Hydro, and Renewable resources.

[10] See Davis and Hausman (2016) for a good outline on the accuracy of this data, as well as a list of publications that use these data.

[11] It is possible to account for hourly $PM2.5$ emissions by calculating the average $PM2.5$ emissions per MWh according to annual data from the EPA National Emission Inventory, then calculating the hourly emissions as the average emission times the amount of MWh produced.

[12] There are also times when the electricity generator is not producing any electricity, but emitting a large amount of pollution because it is still burning fuel to produce heat, but is not connected to the electricity grid.

Table 1: Plant Type and Size

Main Fuel Type	Mean Capacity, MW	Number of Plants
Coal	844.4	353
Gas	486.9	918
Other	1037.9	108
Petro	222.8	103

Table 2 presents summary statistics for the average emissions per MWh for each plant. For context, one MWh is the average amount of electricity consumed by a household in the US in one month. Significant heterogeneity in the average emissions per MWh across plants is evident. In particular, there is a long right tail, with a few plants emitting much more emissions per MWh on average than the rest. This across plant heterogeneity is important for the results that follow.

Table 2: Mean Plant Damages per MWh

Emission	Min	Q1	Mean	Median	Q3	Max
CO2 ton per MWh	0	0.56	0.81	0.77	1.03	11.41
NOX lbs per MWh	0	0.01	2.03	0.01	1.40	66.86
SO2 lbs per MWh	0	0.33	1.58	0.91	2.12	35.65

The hourly emissions in the CEMS data are converted to economic damages using county-pollutant specific damages from the AP2 developed by Nick Mueller, as in Holland et al. (2016). This model is an integrated assessment air pollution model, and calculates the impact of a unit increase in SO_2, NO_X, and $PM2.5$ on human health, crop and timber yields, degradation of buildings and materials, and reduced visibility and recreation for every county in the US (Muller and Mendelsohn, 2007). This cross-sectional variation in pollution damages is driven primarily by population density, but is good in capturing how similar emissions profiles from plants located in different areas will have different impacts. Figure 1 shows the distribution of damages by county within the United States for one additional pound of SO_2 and NO_X, in 2011 USD. To account for the externalities of carbon emissions, I use the central estimate for the social cost of carbon developed by the Intergovernmental Working Group, \$41/ton of CO_2 in 2007 USD, inflated to \$43.31

2011 USD (IWG, 2016). Because CO_2 is a greenhouse gas with global damages, I do not consider any cross-sectional variance in the damages from a ton of CO_2.

The county specific SO_2 damages range from \$2.02 to \$374.56 per pound, with a mean of \$14.10 per pound. Likewise, county specific NO_x damages range from \$0.04 to \$22.03 per pound, with a mean of \$2.12. Taking the mean emissions per MWh across all plants, and the mean damages, this suggest the average consumption of electricity in a month (one MWh) has a total external damages of \$61.85 on average.[13] Given the average wholesale price of electricity ranges for \$30 to \$60 per MWh, this suggests the marginal external damages associated with electricity generation are large. The social costs of one unit of electricity can be twice as large as the private costs in a given time period.

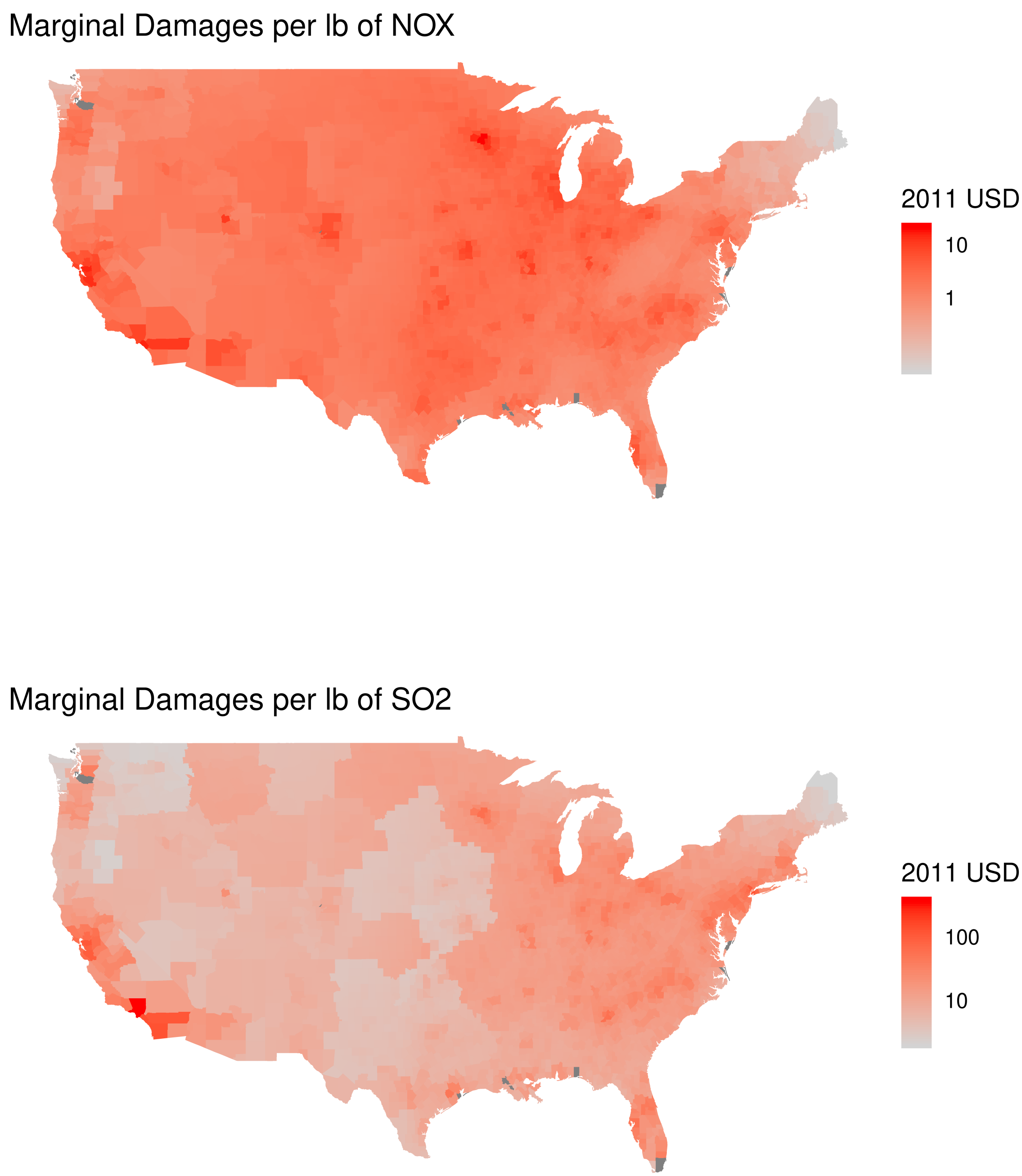
For every hour I calculate the total damages at an electricity generating plant as the sum of the marginal external damages from CO_2, SO_2, and NO_X. I denote the total damages at plant i in hour j as $TotDamages_{ij}$, with

$$TotDamages_{ij} = NO_xDamages_c \cdot NO_xlbs_{ij} + SO_2Damages_c \cdot SO_2lbs_{ij} + CO_2Damages \cdot CO_2tons_{ij}$$

The distribution on hourly plant damages per MWh, $TotDamages_{ij}/GrossGeneration_{ij}$, separated by NERC region are presented in Figure 2. The data in this figure represent the observations when electricity plants are producing more than 10 MWh of electricity, and only for the plants with more than 1000 observations. This subsample is what is used in the analysis that follows. Evident from these density plots is the heterogeneity in external damages per MWh, with multiple peaks and a wide spread. The values used to create the density plots are truncated to fit between 0 and 100 \$/MWh.

[13]This comes from 0.81*43.31+2.03*2.21+1.58*14.10.

Figure 1: A map of marginal external damages per pound of pollutant by county.



Data on marginal external damages per county comes from Holland et al. (2016).

Figure 2: Damages per MWh by Plant-Hour

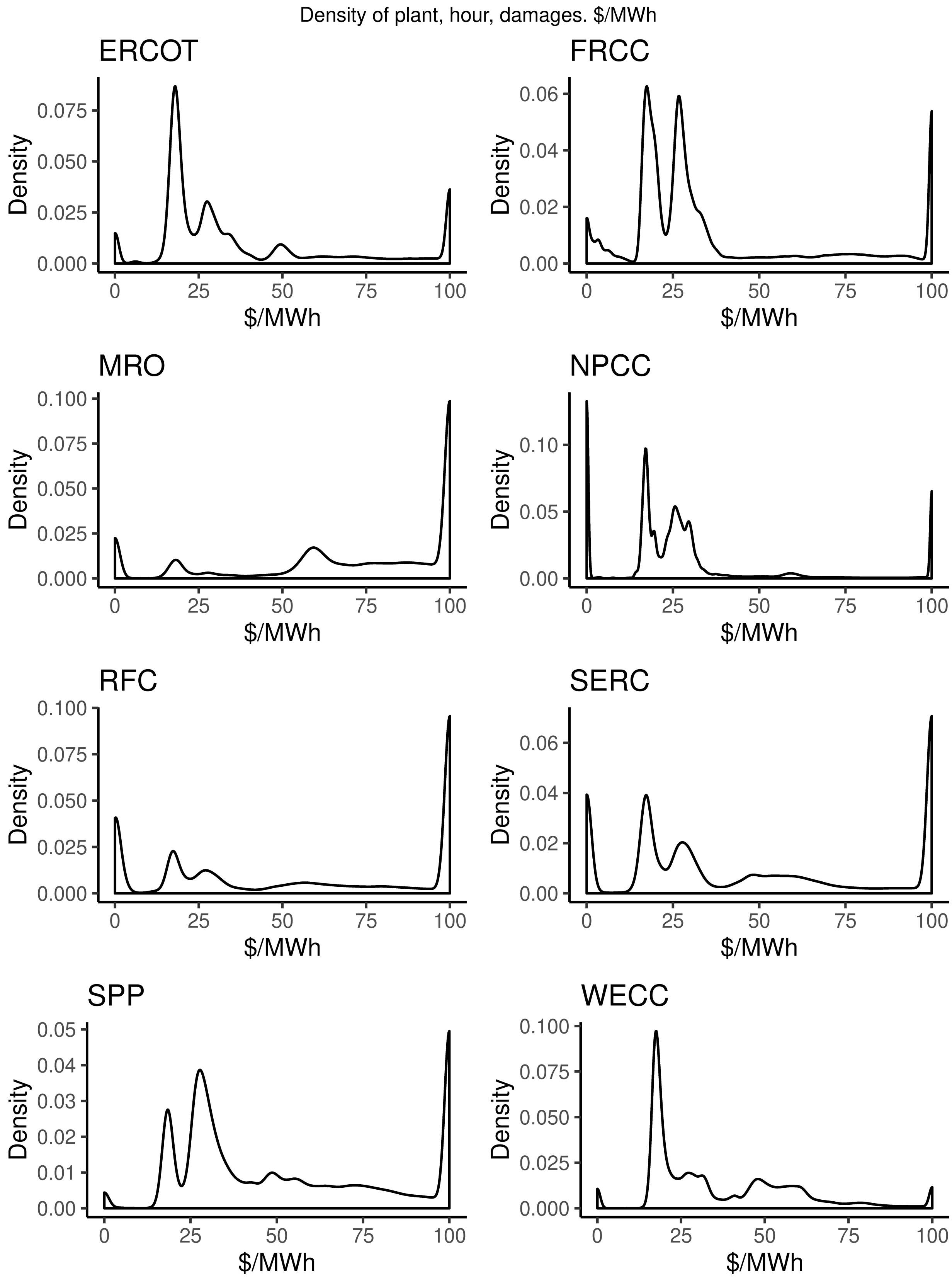
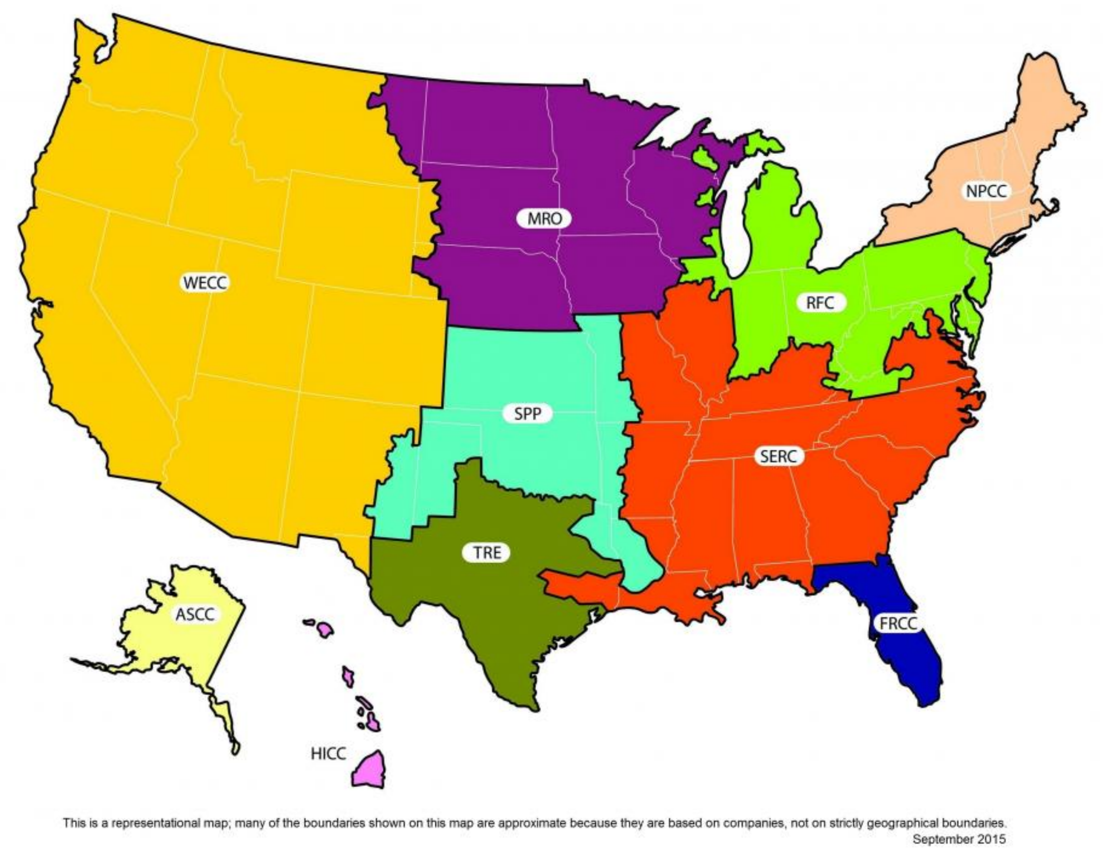


Figure 3: Map of NERC regions.



Source: EPA.gov. Broadly these regions can be matched to wholesale electricity markets. The TRE and SPP regions match with the Energy Reliability Council of Texas (ERCOT) and Souther Power Pool (SPP) wholesale markets respectively. MRO, matches with the most of the Midcontinent Independent System Operator's (MISO) footprint prior to 2013. RFC is similar to the Pennsylvania-New Jersey-Maryland wholesale market. NPCC region consists of two market, the New England ISO and the New York ISO. Finally WECC includes the California wholesale market, CAISO, and the remaining western states. While MISO and PJM are partially within SERC, there are no wholesale markets in the South Eastern United States.

4 Second Best Emission Policies

In this section I consider alternative second best policies to address emission externalities associated with electricity generation. This builds off of the framework of evaluating imperfect pricing, first outlined by Jacobsen et al. (2018) and modified in section 2. I consider alternative functions of product attributes to estimate the total damages from emission externalities. The results from ordinary least squares estimation represents the second best policy to address the emission externalities, and the R^2 from that regression is the percentage of the total welfare that is captured by this second best policy relative to flat tax that doesn't differentiate across product attributes.

The second best policy is found by regressing the marginal external damages in an hour onto product attributes. Given true marginal external damages ϕ_{ij} and some product attributes z_{ij}, the second best policy based off of the product attributes is some function of the product attribute $f(z_{ij}|\theta)$ that tries to address the emission externalities ϕ_{ij}, choosing $\hat{\theta}$ that minimize $\left(\phi_{ij} - f(z_{ij}|\theta)\right)^2$.

In what follows, I consider z_{ij} to be product attributes such as the time of day the electricity is produced or consumed as well as where the electricity was generated. In particular, when I consider *demand* side policies, I consider forms of z_{ij} which depend only on the index j, as the consumer can not differentiate between the source of electricity. In variantly, these take the form of time periods fixed effects. For on-peak emission charges I let $f(z_{ij}|\theta) = \theta_p$ where $p \in \{\text{offPeak}, \text{onPeak}\}$, and the mapping between time period j and peak p is such that

$$p = \begin{cases} \text{onPeak, if } 15 < Hour_j < 21 \\ \text{offPeak, otherwise} \end{cases}$$

One of the environmental factors that most impacts electricity plant operation is the temperature outside. To account for this I also consider a policy function that allows for a different emission price depending on if the hour is in a summer month. That is $f(z_{ij}|\theta) = \theta_{p,s}$ where $s = \text{onSummer}$ if the month associated with time period j is in June, July, or August, and $s = \text{offSummer}$ otherwise.

The tax is differentiated across summer periods within a year and peak periods within a day.[14]

Although less rare in practice, I consider demand side charges that are much more flexible including a separate per unit charge for every hour of the day by month of year $f(z_{ij}|\theta) = \theta_{m,h}$, where m is the month associated with time period j and h is the hour of day associated with time periods j.[15] In the limit, I consider the most flexible demand side emission charges, a separate emissions price for every single hour of sample: $f(z_{ij}|\theta) = \theta_j$, where j represents a year-month-day-hour unit of observation.

In terms of a *supply* side policy I consider one policy, a separate emissions charge for every single electricity plant that is time invariant. This is $f(z_{ij}|\theta) = \theta_i$. In practice, this would be simple for a wholesale market operator to implement by adjusting the unit's bid into the wholesale market. Alternative policies that can be considered include policies based on total load within the system, as well as retail rate policies that are based on the wholesale price.

In practice, I do not directly observe the marginal emissions per plant per hour. I observe the total emission, and the corresponding $TotDamages_{ij}$, as well as the gross generation, $GrossGen_{ij}$. To recover an estimate for the marginal external damages per unit I note that $TotDamages_{ij} = \phi_{ij} x_{ij}$ and $GrossGen_{ij} = x_{ij}$, so that taking the ratio $TotDamages_{ij}/GrossGeneration_{ij}$ is a good approximation for ϕ_{ij}. In reality, this is the average emissions per unit per hour. In what follows I minimize the sum of the squared difference between $TotDamages_{ij}/GrossGeneration_{ij}$ and $f(z_{ij}|\theta)$.[16]

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[14]This second best policy could consist of some base tax θ_0, then a modifier depending summer periods within a year and peak periods within a day, however I do not incorporate a fixed amount so I can recover a separate value for every instance of s and p. This affects the R^2 in that a model with no intercept will have an inflated R^2. I correct for this by calculating the R^2 manually using the total sum of squared difference from the average as the total sum of squares.

[15]This is a total of 12*24=288 parameters.

[16]An alternative approach is to notice that minimizing the sum of the squared difference between ϕ_{ij} and $f(z_{ij|\theta})$ is similar to minimizing the difference between $TotDamages_{ij}$ and $f(z_{ij}|\theta) \cdot GrossGen_{it}$. This works when $f(z_{ij}|\theta) = \theta_j$, but not when $f(z_{ij}|\theta)$ is across plants. In the latter case, the second best policy will be biased upward relative to the estimates I provide when dirtier plants are producing relatively more electricity.

4.1 Estimation Results

With the hourly plant-level data on electricity generation and emissions from 2010 to 2015, I estimate the second best policy functions outlined above separately for all 8 NERC regions in the continental United States.[17] The recovered parameters represent the second best policy that can be used to address emission externalities associated with electricity generation. Looking at the simple demand side policies, $\hat{\theta}_{p,s}$ presented in Table 3, the second best emission charge per hour depends largely on the market. Interestingly, the second best policy to address emission externalities indicate that off peak prices should be lower than on peak prices, contra to conventional wisdom regarding peak pricing. This is because more electricity is generated from *relatively* cleaner resources, like natural gas plants relative to coal, during peak periods. This general result extends to summer periods, overall, the second best emission policy is a lower tax during the summer.

Table 3: Second Best Peak/Summer

market	OffPeak,OffSummer	OffPeak,OnSummer	OnPeak,OffSummer	OnPeak,OnSummer
ERCOT	45.15	42.40	42.05	38.76
FRCC	43.08	40.79	42.83	40.46
MRO	98.55	96.50	93.25	87.46
NPCC	35.67	34.42	34.45	33.64
RFC	129.72	125.39	124.90	116.72
SERC	78.31	76.67	76.98	72.15
SPP	63.48	61.90	63.91	60.08
WECC	37.27	35.68	36.10	34.07

Looking at more flexible demand side policies Figure 4 shows the average values of $\hat{\theta}_{m,h}$ across hour of day and across months of the year for each NERC region separately. Similar to the results presented in Table 3, there is significantly more heterogeneity across markets than within markets. The second best hourly price is lowest during the peak of the day, and varies over the course of the year depending on the NERC region. Throughout the day, or over the course of the year, the

[17] I estimate it separately for each NERC region to reduce the computational intensity of the estimation.

second best policy to address the emission externalities doesn't change considerably, which might suggest that there isn't much to be gained from hourly policies to address emission externalities.

From the supply side estimation, I recover a set of plant specific $\hat{\theta}_i$ which are time invariant taxes used to address emission externalities. The densities of these plant specific tax rates, across NERC regions, are shown in Figure 5. In this diagram the largest 5% of values were winsorized so the tail of the distribution does not distort the image, and the color of the density represents the average value of $\hat{\theta}_i$ within the region. We see significant heterogeneity across plants within a NERC region. Largely, the plant specific emissions rate is centered around \$25/MWh, however there are some regions with a more even distribution. Almost all of the regions have a long right tail, suggesting some plants create an exceptional amount of damage per MWh.

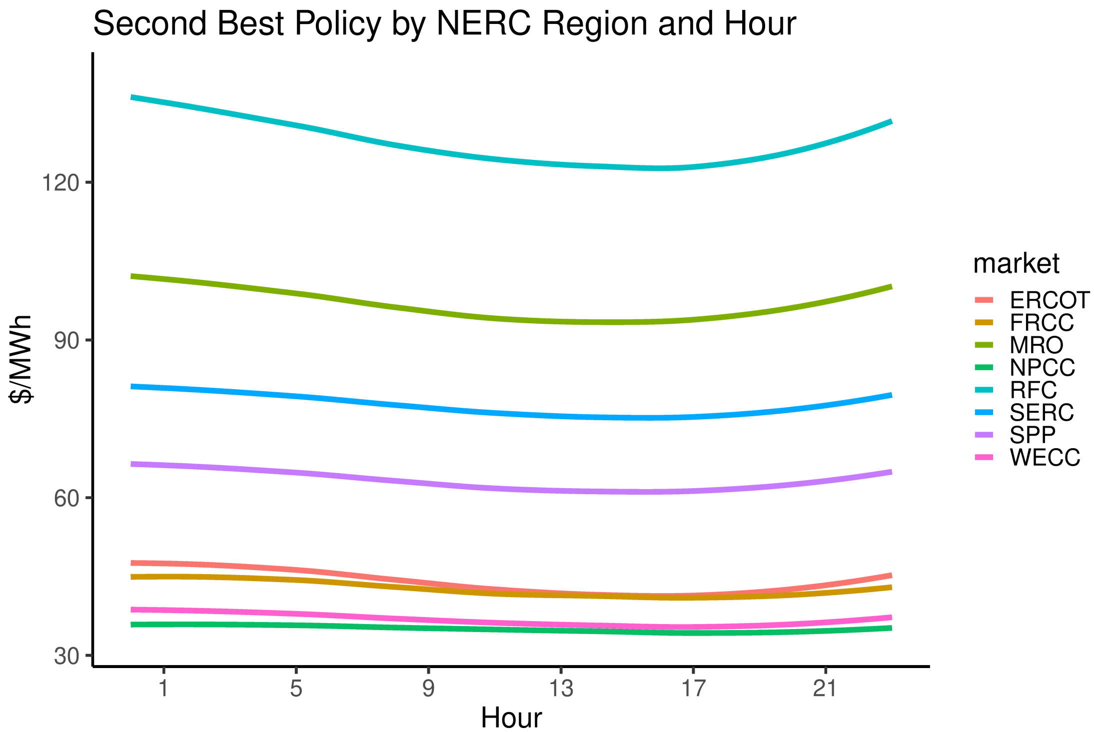
Given the connection to the model presented in section two, the R^2 from the OLS regressions represents the percentage of total welfare that is captured by the these second best policies relative to a policy that doesn't differentiate across product attributes. Table 4 presents this information for four policies and by NERC region. We see that the demand side policies, $\theta_{s,p}$, $\theta_{m,h}$, and θ_j effectively address none of the large heterogeneity in emissions externalities. Even the policy that has a separate per unit tax for every single hour in the sample address at most 4% of the total variation in emissions. Given these are the *best* policies that price electricity over the course of the day, any other demand side policy would perform even worse. In contrast, the supply side policy, that simply charges each plant a separate time-invariate tax per unit can addresses 57 to 86% of the dead weight loss that remains after a uniform per unit tax.

5 Discussion

5.1 Dead-weight loss comparison

Similar to Borenstein and Bushnell (2018), it is possible to directly calculate the total dead weight loss from imperfectly pricing electricity if you are willing to make assumptions on the elasticity of

Figure 4: Second Best Demand Policies.



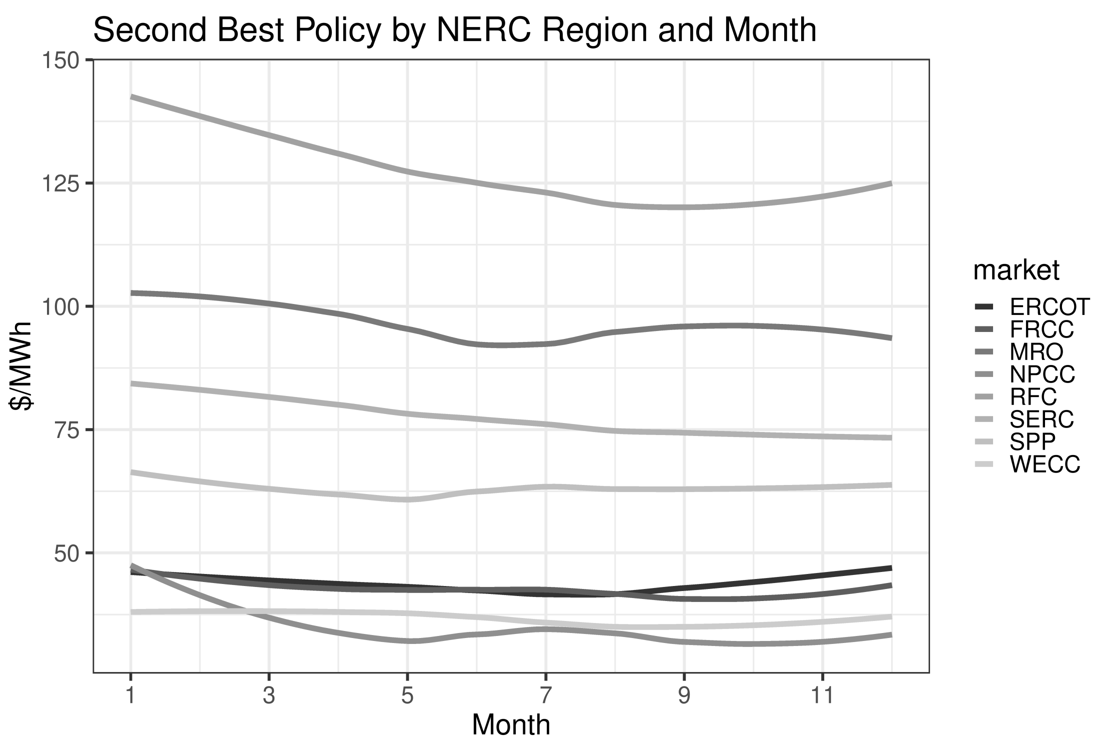


Figure 5: Second Best Supply Policies.

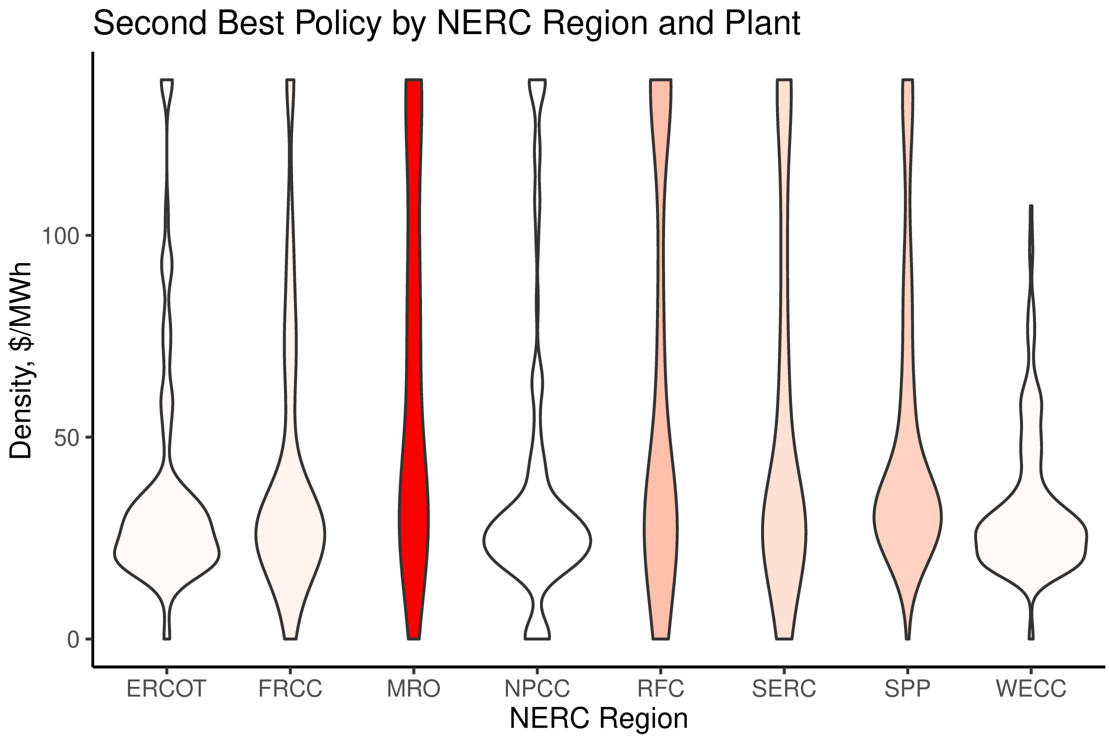


Table 4: R-squared from Second Best Regressions

NERC Region	Summer Peak	Month by Hour	Day by Hour	Plant Specific	N obs.
ERCOT	0	0.00	0.01	0.77	3115739
FRCC	0	0.00	0.03	0.57	1881911
MRO	0	0.00	0.04	0.60	2651015
NPCC	0	0.01	0.04	0.60	3363451
RFC	0	0.00	0.02	0.71	7749748
SERC	0	0.00	0.02	0.63	8305699
SPP	0	0.00	0.01	0.86	2957715
WECC	0	0.01	0.02	0.80	6453583

demand and supply as well as pass-through. Although the method presented above is informative in which policy is *relatively* better in addressing the variation in emission externalities, there is no reference point for what is *absolute* dead weight loss associated with these alternative policies. More specifically, what is the dead weight loss associated with a uniform tax rate? If it is small, then the need to address the heterogeneity in emissions is small. In this section I will make generous assumptions on how the tax rate affects the production from each plant and overall all demand to answer this question.

First I assume that there are no cross effects, so that the dead weight loss associated with some policy τ_{ij} can be represented by

$$DWL\left(\tau_{ij}\right) = -\frac{1}{2}\sum_{j}\sum_{i}\left[\tau_{ij} - \phi_{ij}\right]^{2}\frac{\partial x_{ij}}{\partial \tau_{ij}}$$

If I am willing to assume constant marginal cost, $\frac{\partial x_{ij}}{\partial \tau_{ij}}$ represents the average change in quantity demanded from plant i in response to the tax. Assuming a constant elasticity of demand function, this expression can be re expressed as $\frac{\partial x_{ij}}{\partial t_{ij}} = \varepsilon^{d}\frac{x_{ij}}{price_{ij}}$. Following Borenstein and Bushnell (2018), I assume an elasticity of demand equal to 0.2, which is in line with many empirical estimates.[18] For each hour, I let $GrossGen_{ij}$ equal x_{ij} and use a fixed price of \$50/MWh.

I consider three alternative values of t_{ij} motivated by the analytical second best policies derived in section 2. The first is an average emissions $\tau = I^{-1}J^{-1}\sum_{i}\sum_{j}\phi_{ij}$ in the entire sample period, this represents the baseline dead weight loss which the policy differentiated by product attribute is improving over. Next, I consider a hour of sample specific policy, $\tau_{j} = I^{-1}\sum_{i}\phi_{ij}$ and a plant specific policy $\tau_{i} = J^{-1}\sum_{j}\phi_{ij}$. These are not the second best hour specific policy, as it doesn't take into account how plant might be more responsive to the tax, however it is a close approximation. Finally, I consider the total dead-weight loss when there is no tax, $\tau_{ij} = 0$. I normalize the total dead weight loss to a per MWh value by dividing the sum by the total amount of electricity generated in the NERC region during the sample period.

Table 5 shows the total dead weight loss per MWh associated with a base policy of a flat tax. Given that this policy *is* addressing the externality, it is surprising that its inability to address the heterogeneity in emission externalities per MWh still results in dead weight loss on the order of 1 to \$50/MWh. Importantly, doing this calculation shows which regions a differentiated policy could do the most benefit, e.g. RFC, and where it would do the least amount of benefit, e.g. WECC. In Table 5 I also calculate the % of the dead weight loss that is recovered from the differentiated

[18] This is a central estimate for the elasticity of demand. See **?**

supply side and demand side policy. Although not identical, the numbers are similar in magnitude to Table 4.

Figure 6 shows the total dead weight loss calculations for the four separate policies, across NERC regions, in absolute value. We see that going from no policy to an average tax can address around half of the total dead weight loss associated with electricity emission externalities. This amount, per MWh, is quite large. In RFC for example, an average price could reduce dead weight loss by \$30 per MWh. Going from an average price to a extremely flexible demand side policy (one price for each hour of the sample), does very little to address the residual variation in emission externalities after an average emission price is imposed. Conversely, a plant specific price can address almost all of the dead-weight loss from emission externalities.

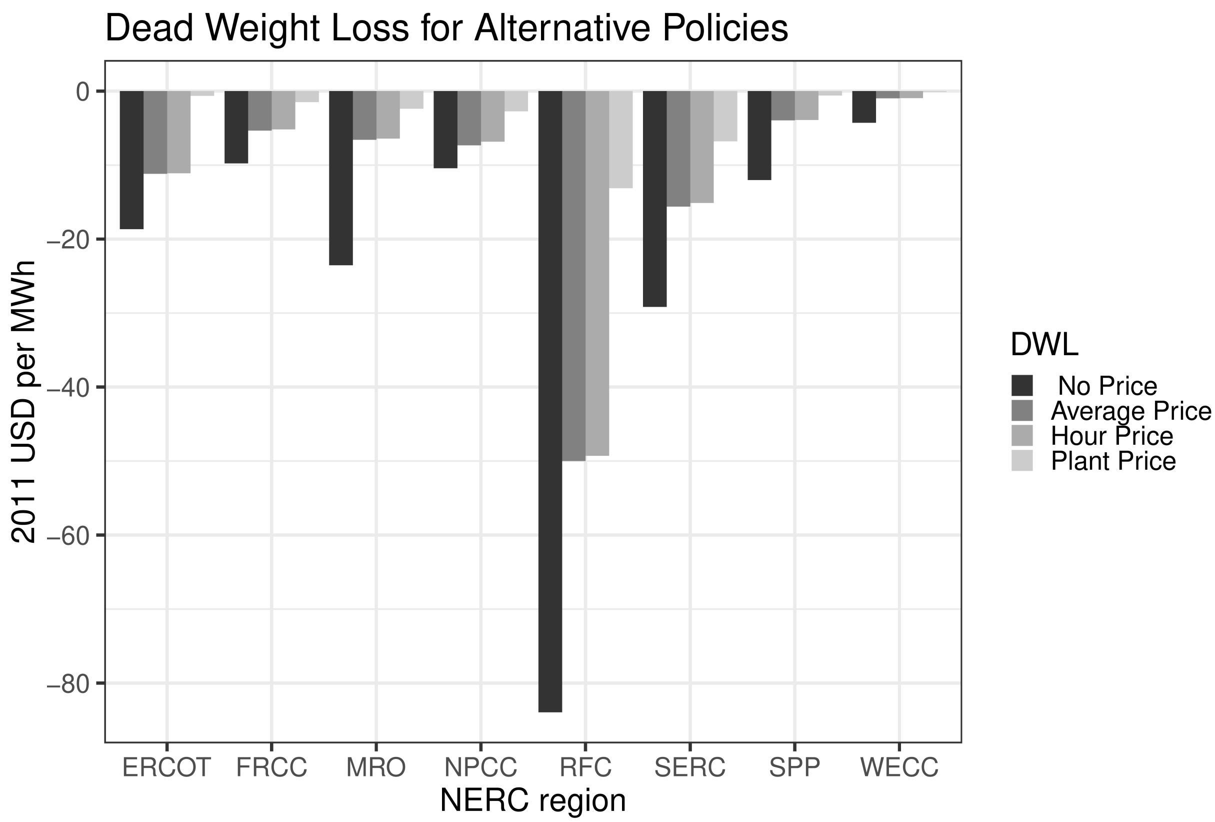
Table 5: DWL per MWh and % Welfare Recovered

NERC	DWL, average policy	\% Recovered, hour policy	\% Recovered, plant policy
ERCOT	-11.16	0.01	0.94
FRCC	-5.32	0.03	0.72
MRO	-6.57	0.02	0.64
NPCC	-7.31	0.07	0.63
RFC	-49.99	0.01	0.74
SERC	-15.60	0.03	0.57
SPP	-3.94	0.01	0.85
WECC	-0.96	0.02	0.90

6 Conclusion

In this paper I show that demand side emissions policies do not do a good job in capturing the cross-sectional variance in emission externalities. Instead, supply side policies that take into account the average emissions of an electricity generating plant can address almost all of the variation in marginal external damages. As a result, policy makers concerned with the large emission externalities associated with electricity generation should focus on incorporating supply side policies,

Figure 6: Total DWL for Alternative Policies.



that differentiate across resources, instead of demand side policies such as real time pricing or demand response.

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