Carbon Tax Incidence and Household Energy Demand in the U.S.

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Abstract

This paper develops a model based on the general equilibrium framework to evaluate household's excess burden of carbon tax levied on energy goods (electricity and natural gas). The model accounts for tax distortion on labor market and cross-price effects between energy goods. With data from the U.S. Residential Energy Consumption Survey, own price and cross-price elasticities of energy goods are estimated. Substitution effects are found between electricity and natural gas, and omitting such effects will overestimate the excess burden of carbon tax. The results indicate that carbon tax performs differently on affecting excess burden of low, middle and high income households. With a low pre-set labor tax rate, higher income households have lower excess burden comparing to lower income households, but with a high pre-set labor tax rate, the effect is reverse. Our empirical results also suggest excess burden differs across 9 U.S. regions, and minor natural gas price variation does not affect excess burden significantly.

1 Introduction

According to the U.S. Energy Information Administration (EIA) (2011), in 2009, 81.5% of U.S. greenhouse gas emissions are due to the consumption of energy-related carbon dioxide. With the increasing concern about environmental related issues due to greenhouse gas, such as global warming and climate change, more attention has been drawn to the reduction of greenhouse gas and efficient use of energy. Most recently, the U.S. Environmental Protection Agency (EPA) released proposed standards for the Clean Power Plan to reduce carbon dioxide emissions from power sectors. Under market-based mechanisms of the Clean Power Plan, carbon pricing which is the charge to those who emit carbon dioxide (CO_2) can perform as a simple and effective way to achieve the goal of reducing greenhouse gas. Carbon pricing generally takes the form of carbon tax and allowance. In the 1990s, carbon taxes have already existed in European countries and Finland is the first country to enact carbon tax with a tax rate of \$30 per metric ton of CO_2. In 2012, Australia started to use carbon tax and set the tax rate as \$23.78 per metric ton of CO_2 which increases 2.5% annually.

To address the drawbacks of energy consumption on environment at the household level, a carbon tax on energy goods can be a promising way. Carbon tax belongs to environmental tax which carries "double dividend" resulting from an improvement in environment and reduction of tax distortionary effects. Referring to energy goods, adding carbon tax on energy good will reduce consumption, thus yield less carbon emissions which can potentially reduce environmental damages. However, the increase of price by levying carbon tax will still yield excess burden, though the excess burden is alleviated by the second dividend. In addition, if we consider the interaction between environmental tax and pre-existing taxes, such as income tax, the double dividend hypothesis may not be valid, thus the excess burden will be greater. To deal with policy maker's concerns on the impact of tax on consumers in terms of excess burden, a comprehensive understanding of household energy demand is crucial.

Electricity and natural gas are two primary energy goods that are commonly consumed by households in the developed countries. In the U.S. residential sector, electricity is consumed by 100% of the households, natural gas is used by about 60% of the households, and other fuels are consumed by less than 10% of the households (U.S. Energy Information Administration 2009). To provide a sound incentive for a more efficient use of energy, a potential carbon tax should be added to the consumption of electricity and natural gas at the household level. In order to investigate the effectiveness of a tax on energy consumption it is vital to know how the demand for energy good responds to its price. Therefore, correctly estimating price elasticities is necessary. In recently years, the energy market of natural gas has been disrupted by innovation, and the price of natural gas fluctuates a lot around year 2008, thus taking consideration of substitution effects between electricity and natural gas is important when estimating price elasticities.

There is extensive theoretical and empirical literature on household energy demand, and most of these studies concentrate exclusively on either electricity or natural gas, few have taken consideration of both at the same time. Ignoring cross-price effects between electricity and natural will yield biased estimates, especially for the period that the price of natural gas is not stable. In addition, the majority of previous studies of energy demand are just focusing on the estimation of price elasticities without further consideration of consumers' welfare changes due to incidences of price change or carbon tax. Moreover, from the perspective of general equilibrium, the price change of energy goods will distort energy market as well as other markets, thus the effect on consumers' welfare caused by price change of energy goods will be larger. This paper will fill the gap of knowledge by giving a comprehensive analysis on the implications for household energy consumption (electricity and natural gas) and excess burden of carbon taxes.

2 Review of Literature

A large number of studies have estimated the long run and short run price elasticities of electricity demand using aggregate nationwide or state-level data (Houthakker 1980; Baltagi, Bresson, and Pirotte 2002; Kamerschen and Porter 2004; Dergiades and Tsoulfidis 2008). With aggregate panel data, unobservable heterogeneity can be controlled by applying fixed or random effects along with appropriate instrumental variables. However, the use of aggregated data for electricity consumption and prices inevitably carries the misspecification error generated by an aggregation bias Dubin and McFadden (1984). Among studies with household level data, Metcalf and Hassett

(1999) modeled the electricity demand with U.S. Residential Energy Consumption Survey (RECS) using instrumental variable approach and estimated the price elasticity as 0.78. Fell, Li, and Paul (2014) develop an empirical strategy employing Generalized Methods of Moment (GMM) to estimate electricity demand with Consumer Expenditure Survey (CEX), and find a price elasticity of electricity demand close to 0.5. Recently Reiss and White (2005) develop a model focusing on the heterogeneity in households' demand elasticities, their relation to electric appliance holdings and how households respond to nonlinear price changes. Focusing on Californian households with data from the RECS, they find considerable heterogeneity in households' price and income elasticities. On the contrary, Alberini, Gans, and Velez-Lopez (2011) find no evidence of significantly different elasticities across households. They use a dynamic model with average electricity price which is instrumented by state-level and lagged prices to estimate the electricity demand in the 50 largest metropolitan areas in the United States of as 2008. In terms of studies out of U.S., Boogen, Datta, and Filippini (2014) estimate the long run and short run electricity price elasticities in Switzerland by constructing an index of the household appliances stock. To deal with the potential endogeneity with average price, an instrumental variable approach is adopted and their results suggest that Swiss households are price inelastic in electricity prices. McRae (2015) uses a structural model to study the change in electricity demand from upgrading low-quality electricity connection in Colombia. His electricity demand model is similar to Reiss and White (2005) and incorporates the nonlinearity in the price schedule and heterogeneity across households characteristics and appliance holdings. The mean price elasticity is 0.32 which is close to estimates of Reiss and White (2005).

Considering household natural gas demand, previous studies in literature use different econometric techniques for estimating elasticities of natural gas from panel data to cross-sectional data. Back to the 1960s, Balestra and Nerlove (1966) have developed a dynamic demand model involving appliance stock choice to estimate residential and commercial natural gas demand in the U.S. With the combination of time-series and cross-sectional data from 1957-1962, they estimate an own price elasticity range of 0.58 to 0.69. They find natural gas had negligible income elasticities in the residential and commercial sector, and a long-run income elasticity of 2.86 in the industrial sector. Focusing on data from 12 European countries, Asche, Nilsen, and Tveteras (2008) find an inelastic own price elasticity of natural gas in the short run.

Since electricity and natural gas may be substitutes, and many households consume both at the same time, the unobserved factors that affect electricity and natural gas consumptions are very likely to be correlated. If this is true, modeling demand equations separately may yield biased coefficients. In addition, structural equation system provides a better identification strategy in the presence of endogenous prices. Not much literature has drawn attention to the potential correlation of electricity and natural gas demand equations, few exceptions include Beierlein, Dunn, and McConnon (1981), Labanderia, Labeage, and Rodriguez (2006) and Guta (2012). With state level aggregated data in the U.S., Beierlein, Dunn, and McConnon (1981) use a seemingly unrelated regression approach to deal with the potential correlated unobservable factors among 6 natural gas and electricity demand equations. Labanderia, Labeage, and Rodriguez (2006) develop a quadratic demand model which is an extension of Deaton and Muellbauer (1980)'s Almost Ideal Demand System to estimate household energy demand in Spain. The commodity portfolio includes electricity and natural gas, and their results suggest electricity and natural gas are weak substitutes.

Comparing to taxes such as income tax, environmental tax may generate double dividend that improves social welfare and yields lower excess burden, but the validity of double dividend relies on specific assumptions and conditions (Bovenberg and Mooij 1994; Parry and Bento 2000; Schneider 1997; Goulder 2013). For the estimation of consumer's excess burden, Harberger (1964) gives a comprehensive measure which incorporates distortion of all markets. The full measure is impossible to use in reality because the second term of this measure requires the calculation of derivatives of all commodities with respect to tax. Ignoring the second term, Harberger (1964)'s measure reduces to the simpler "Harberger triangle", which is widely used. However, without considering the impact of tax on other markets, the "Harberger triangle" will underestimate the excess burden of tax. To deal with the effect of tax on other markets, Goulder and Williams (2003) develop an applicable formula to approximate the excess burden. Their framework is derived from a general equilibrium model involving commodity markets and labor market. With data from the 1995 U.S. survey and incorporating elasticities from previous literature, numerical simulations suggest their formula is unbiased and performs well.

3 The Model

The theoretical model for excess burden of carbon tax is derived from the general equilibrium framework which involving energy markets (electricity and natural gas), commodity market (numeraire good) and labor market. Since tax not only distorts commodity market but also labor market, ignoring the effect of tax distortion on labor market will underestimate consumer's excess burden. Household demand equations for energy goods (electricity and natural gas) come from the utility maximization framework, and the formula for excess burden of carbon tax is derived in terms of own price, cross-price elasticities of energy goods, and labor supply elasticities.

3.1 The General Equilibrium Framework

The demand for energy is modeled with the framework of households production theory suggested by Deaton and Muellbauer (1980). Suppose in the short run, households demand electricity and natural gas through the following production function for energy services

$$S = S(C_e, C_g; A_e, A_g), \tag{1}$$

where S denotes energy services, C_e and C_g is the consumption for electricity and natural gas respectively, A_e and A_g are given stocks of electric and natural gas appliances. We assume these appliance stocks are predetermined and do not change in the short run.[1] This equation describes how electricity and natural gas are used with appliances to provide energy services. Suppose each household get utility from energy services S, a composite good (numeraire) C_m, leisure l, and a set of exogenous household and socio-demographic characteristics Z. The utility function can be

[1] Deaton and Muellbauer (1980) suggest a model for household's simultaneous demands for electricity and appliances which allows for the changes of appliance stock over time. However, dealing with endogenous demand for appliances is not our concern, for simplicity, in this paper we just take appliance stocks as given and exogenous.

expressed as

$$U = U(S, C_m, l; Z). \tag{2}$$

Since appliance stocks are fixed, the cost function of energy services is linear in the demand of electricity and natural gas, which is defined as

$$C(S) = p_e C_e + p_g C_g, \tag{3}$$

where p_e and p_g are the prices of electricity and natural gas. Suppose households facing budget and time constraints as below:

$$\begin{aligned} C(S) + p_m C_m &= w(1 - t_l)L + G \\ T - L - l &= 0, \end{aligned} \tag{4}$$

where p_m is the price of numeraire good which is normalized to 1. w is the wage rate (normalize to 1) and G is the government subsidy or lump-sum transfer. T is the total available time and L denotes the time allocated to labor. t_l is tax on labor which is equivalent to income tax.

Incorporating the energy service function in (1) and cost function in (3), the household utility maximization problem can be written as

$$\begin{aligned} \max_{C_e, C_g, C_m, l} \quad & U(S(C_e, C_g; A_e, A_g), C_m, l; Z) \\ \text{subject to} \quad & p_e C_e + p_g C_g + p_m C_m = w(1 - t_l)L + G \\ & T - L - l = 0. \end{aligned} \tag{5}$$

Solving the optimization problem yields the demand functions for electricity and natural gas as

$$\begin{aligned} C_e^* &= C_e(p_e, p_g, Y; Z) \\ C_g^* &= C_g(p_e, p_g, Y; Z), \end{aligned} \tag{6}$$

where Y denotes the right hand-side term of household budget constraint in (5), which is approximate to household income.

To simplify our analysis, we assume electricity, natural gas and numeraire is produced by a single input process.[2] Suppose the production function of each good is specified as following:

$$y_i = F_i(L_i), \qquad i = e, g, m \tag{7}$$

where y_i is the output of each good, L_i is the amount of input (labor) used to produce each good. Consider a producer's profit maximization framework

$$\begin{aligned} &\max_{L_i} && p_i(1+t_i)y_i - L_i \\ &\text{subject to} && \sum_i L_i = L, \end{aligned} \tag{8}$$

where t_i is the tax levied on each good i. Let $f_i(L_i) = \frac{dF_i}{dL_i}$, by solving the producer's optimization problem and rearranging the first order conditions we have

$$p_i = t_i + \frac{1}{f_i(L_i)}\ , \qquad i = e, g, m. \tag{9}$$

In order to reach a general equilibrium, the markets of government income, labor and commodities must clear, which yield constraints below:

$$\begin{aligned} &G = t_l L + t_e C_e + t_g C_g + t_m C_m \\ &T = L_e + L_g + L_m + l \\ &y_i = C_i\ , && i = e, g, m. \end{aligned} \tag{10}$$

To simplify the derivation of carbon tax excess burden formula, in this model, we assume that there is no government spending on public goods, thus government spending G is only the form of subsidy or lump-sum transfer.

[2]Electricity is used as input for almost every product, and natural gas is also used to generate electricity. Since we are focusing only on the residential markets of electricity and natural gas, it is reasonable to take electricity and natural gas as final goods.

3.2 Carbon Taxes and Excess Burden

A carbon tax is usually levied on the metric ton of carbon dioxide emissions. To be consistent with existing carbon tax rule, in this paper, carbon tax t_c is defined as the amount of dollars per metric ton of CO_2 emission. In fact, the taxes on per unit electricity t_e and natural gas t_g are linear functions of carbon tax t_c, which can be denoted as $t_e(t_c)$ and $t_g(t_c)$ respectively. Therefore, the derivation for excess burden of carbon tax can be decomposed into two parts: excess burden of carbon tax in terms t_e and t_g.

Totally differentiating consumer's utility function with respect to energy tax (t_e and t_g) yields

$$\frac{\partial U}{\partial t_i} = \frac{\partial U}{\partial S}\frac{\partial S}{\partial C_e}\frac{\partial C_e}{\partial t_i} + \frac{\partial U}{\partial S}\frac{\partial S}{\partial C_g}\frac{\partial C_g}{\partial t_i} + \frac{\partial U}{\partial C_m}\frac{\partial C_m}{\partial t_i} + \frac{\partial U}{\partial l}\frac{\partial l}{\partial t_i}\,, \qquad i = e, g. \tag{11}$$

Following Goulder and Williams (2003)'s approach, incorporating first order conditions from general equilibrium framework, employing Slutsky equation, the excess burden of energy tax (t_e and t_g) in terms of elasticities can be expressed as

$$\frac{1}{\lambda}\frac{\partial U}{\partial t_i} \approx \frac{\frac{t_i C_i}{p_i}\epsilon_i + \frac{t_k C_k}{p_i}\epsilon_{k,i} - \frac{t_l Y}{p_i}\epsilon_L s_i}{1 - \frac{t_e C_e}{Y}\epsilon_{e,Y} - \frac{t_g C_g}{Y}\epsilon_{g,Y} - t_l \epsilon_{L,Y}}\,, \qquad i = e, g; k \neq i, \tag{12}$$

where λ is the marginal utility of income, s_i is budget share of energy goods i, Y denotes household income with government lump-sum transfer. ϵ_i is own price elasticity of energy good i and $\epsilon_{k,i}$ is cross-price elasticity; $\epsilon_{i,Y}$ and $\epsilon_{k,Y}$ are corresponding income elasticities of energy goods; ϵ_L is labor supply elasticity and $\epsilon_{L,Y}$ is income elasticity of labor supply.[3]

The (12) above applies only for a marginal change in energy tax, with larger tax changes, the more general excess burden formula can be expressed as

$$\frac{1}{\lambda}\Delta U_i \approx \frac{\frac{t_i^2 C_i}{2p_i}\epsilon_i + \frac{t_i t_k C_k}{p_i}\epsilon_{k,i} - \frac{t_i t_l Y}{p_i}\epsilon_L s_i}{1 - t_l \epsilon_{L,Y}}\,, \qquad i = e, g; k \neq i. \tag{13}$$

[3]Due to the length of paper, detailed derivations for the all excess burden formulas are presented in the appendix A and B.

Both (12) and (13) incorporates income effect, which increases labor supply and reduces the tax distortion in the labor market, thus offsets excess burden. Similar to the excess burden caused by energy tax levied on electricity or natural gas in (13), the excess burden formula with marginal carbon tax change can be derived as

$$\frac{1}{\lambda}\frac{\partial U}{\partial t_c} = \frac{1}{\lambda}\frac{\partial U}{\partial t_e}\frac{\partial t_e}{\partial t_c} + \frac{1}{\lambda}\frac{\partial U}{\partial t_g}\frac{\partial t_g}{\partial t_c}. \tag{14}$$

For a larger change in t_c, the more general carbon tax excess burden formula can be approximately expressed as

$$\frac{1}{\lambda}\Delta U_c \approx \frac{\tau_e[\frac{\tau_e t_c^2 C_e}{2p_e}\epsilon_e + \frac{\tau_g t_c^2 C_g}{2p_e}\epsilon_{g,e} - \frac{t_c t_l Y}{p_e}\epsilon_L s_e] + \tau_g[\frac{\tau_g t_c^2 C_g}{2p_g}\epsilon_g + \frac{\tau_e t_c^2 C_e}{2p_g}\epsilon_{e,g} - \frac{t_c t_l Y}{p_g}\epsilon_L s_g]}{1 - t_l \epsilon_{L,Y}}, \tag{15}$$

where τ_e is ratio of t_e and t_c, τ_g is ratio of t_g and t_c. This formula measures excess burden caused by carbon tax (per metric ton of CO_2 emissions) in terms of elasticities, and the calculation of this formula requires own price, cross-price elasticities of electricity and natural gas, and labor supply elasticities.

4 Demand Estimation

This section describes the model of household demand for electricity and natural gas, the dataset and empirical results. Previous studies of Parti and Parti (1980), Reiss and White (2005) and McRae (2015) use similar procedures which are called "conditional demand analysis" to estimate household electricity and further calculate the own price and income elasticities. Driven by their econometric specification on electricity, we further apply the econometric specification to natural gas. By jointly modeling demand for electricity and natural gas, cross-price elasticities will be better captured which are necessary for our theoretical model analyses.

4.1 Econometric Specification

Energy is not consumed by people directly, instead, the demand for energy is derived from the demand for services provided by corresponding appliances. The empirical model is derived from the theoretical model is previous section. According to (6), the demand for electricity and natural gas is a function of prices, income and a set of exogenous socio-demographic and weather variables, thus the electricity and natural gas consumption from each appliance j in household i in a year can by express as

$$\begin{aligned} q_{ij}^{e*}(p_i^e, p_i^g, y_i, z_i^e) &= \alpha_j^e + \beta_{1j}^e p_i^e + \beta_{2j}^g p_i^g + \delta_j^e y_i + \gamma_j^e \mathbf{z}_i + \eta_{ij}^e \\ q_{ij}^{g*}(p_i^g, p_i^e, y_i, z_i^g) &= \alpha_j^g + \beta_{1j}^g p_i^g + \beta_{2j}^e p_i^e + \delta_j^g y_i + \gamma_j^g \mathbf{z}_i + \eta_{ij}^g \end{aligned} \tag{16}$$

where superscripts e and g denote electricity and natural gas respectively, p measures household level prices and y is the household annual income. $\mathbf{z}$ is a set of household characteristics and local weather conditions. η_{ij} is household level error term of appliance j, α_j, β_j, δ_j and γ_j are coefficients.

Following Reiss and White (2005), we treat total household demand as electricity (natural gas) used by J_e (J_g) distinct appliances. Thus the total household demand for electricity (natural gas) is the sum of its appliances' consumption, which is aggregated to obtain

$$\begin{aligned} q_i^{e*}(p_i^e, p_i^g, y_i, z_i^e) &= \sum_j^{J_e} A_{ij}^e(\alpha_j^e + \beta_{1j}^e p_i^e + \beta_{2j}^g p_i^g + \delta_j^e y_i + \gamma_j^e \mathbf{z}_i) + \sum_j^{J_e} A_{ij}^e \eta_{ij}^e \\ q_i^{g*}(p_i^g, p_i^e, y_i, z_i^g) &= \sum_j^{J_g} A_{ij}^g(\alpha_j^g + \beta_{1j}^g p_i^g + \beta_{2j}^e p_i^e + \delta_j^g y_i + \gamma_j^g \mathbf{z}_i) + \sum_j^{J_g} A_{ij}^g \eta_{ij}^g \end{aligned} \tag{17}$$

where A_{ij} is the ownership indicator of appliance j in household i. It is equal to 1 if household i uses appliance j in home. The first appliance category is automatically set to 1 for all households to capture the consumption by baseline appliances which are difficult to observe.[4]

[4]Baseline appliances are defined as necessary appliances for most households, such as lighting, heating and cooking.

4.2 Data

The data are drawn from the U.S. Residential Energy Consumption Survey (RECS), which includes detailed information of household's energy consumption, expenditure, characteristics and appliance stocks. The RECS is an annual cross-sectional data set and collects data once every four years. The latest public dataset available is the 2009 RECS. To better capture the variation of energy (electricity and natural gas) prices over time and reduce biasness of the estimation, in addition to the latest 2009 RECS data, 2005 RECS data are also included. We are focusing on households with both positive electricity and natural gas consumption. To decrease the sample bias we exclude households with very low consumptions (<100 kwh electricity and <10 hundred cubic feet natural gas annually). After removing missing values, the full dataset has a sample size of 10164 households. Table 1 presents the sample statistics and data description for the full sample.

There is no price information in the dataset, the only available price information is the average price for each household (total expenditure divided by quantity). Earlier studies on household electricity demand suggest consumers respond to marginal price and apply nonlinear pricing in their analyses (Reiss and White 2005; McRae 2015). Recently, Ito (2014) finds strong evidence that consumers respond to average price rather than marginal price of electricity. It is still unclear whether consumers respond to average price or marginal price when facing nonlinear price schedule of energy, in this paper, we assume consumers respond to average price. Another shortcoming of the RECS data is the lack of detailed household income information. In the 2009 RECS data, income is coded as categorical numbers ranging from 1 to 12 rather than the actual continuous numbers. Although income information in 2005 RECS data is provided by continuous format, it is just converted from the categorical format. Without further information on how the data are converted, we use the mean value of each given income category to approximate household's actual continuous income. For the highest income category which is open-ended, the mean value is estimated by formula given by Parker and Fenwick (1983).[5]

According to the U.S. Energy Information Administration (EIA) (2011), in the year of 2009,

[5]Prices and income are adjusted by Consumer Price Index (CPI), of which year 2009 = 100.

space heating, water heating and air conditioning account for 41%, 18% and 6% of the total energy consumption of each household, which suggest appliances of space heating, water heating and air conditioner must be included in the model. The electricity demand is modeled with 6 distinct appliances: (1) baseline electricity use; (2) additional refrigerators; (3) electric space heating; (4) electric water heating; (5) air conditioning; and (6) electric clothes dryer. The baseline category includes basic electricity use for most households, such as lighting, first refrigerator, it also accounts for other unspecified electrical appliances. For the natural gas demand, 3 distinct appliances are included: (1) baseline natural gas use; (2) natural gas space heating; and (3) natural gas water heating. The baseline category accounts for basic use of cooking and any other unspecified appliances consuming natural gas.

In the U.S., household's energy consumption is heavily influenced by the local weather condition. To capture the effect of local weather on household's energy demand, heating and cooling degree days of each household's residence with base temperature of 65F are included in the model. Previous studies suggest household's characteristics play roles in affecting energy demand (Reiss and White 2005; Alberini, Gans, and Velez-Lopez 2011). In our model, total square feet of housing unit, number of rooms in home, number of bathrooms in home, number of household members, home ownership are included to capture household's characteristics.

4.3 Empirical Strategy

Since electricity and natural gas are priced nonlinearly, households with higher demand for energy will face a higher average price than households with lower demand. In this case, the household level average price is correlated with consumption which suggests average price is endogenous. Not accounting for the endogeneity of price will lead to biased estimates and measurement error (Alberini and Filippini 2011), thus the estimated price elasticities are not accurate. In order to address the endogeneity problem caused by household level average price, instrumental variables are required. A valid instrument will be the state level average prices, since it is correlated with household level average price in certain state, but do not correlate with household consumption. Previous literature also justify the use of state or regional level average price as instruments for household average price (Alberini, Gans, and Velez-Lopez 2011). Due to the data limitation, we cannot identify each household in a certain state but only identify household in one of 9 regions of the U.S. With average price data of each state in 2005 and 2009, we calculated the average price of each region and use the regional average price to instrument the endogenous household average price.

Since average prices are used in this study, identifying the variation of prices over region and time is important to correctly specify the empirical model. Figure 1 and 2 provides an intuitive sense of the price (regional average price) variation over 9 regions and 2 years. The figures intuitively indicate that the price variations of electricity (natural gas) from 2005 to 2009 are about the same size and direction for all 9 regions, which suggests price variations over time are all captured by a year fixed effect. To test this hypothesis, 8 auxiliary regressions are carried out in appendix C. The first 4 auxiliary regressions are used to test the correlation between price (regional average price) and consumption over time; the 5th to 8th auxiliary regressions are used to justify the strength of correlation between price and consumption over region. In the first two auxiliary regressions, electricity consumption is dependent variable, electricity price is the key independent variable. With two-year data and 9 regional observations, difference in difference (DID) approach is carried out to estimate the price coefficient. The regression estimates are presented in table C1, appendix C. The coefficient of electricity price is positive in the first auxiliary regression and not significant in the second auxiliary regression. The positive coefficient of electricity price obeys the law of demand, suggesting regional variation in electricity price does a poor job in capturing consumption variation over time. In the third and fourth auxiliary regressions, dependent variable is natural gas consumption, the key independent variable is natural gas price. Following the similar approach above, DID is used and estimation results justify the negative correlation between regional natural gas consumption and price over time. With results of the 5th to 8th auxiliary regressions which are shown in table C2, appendix C, we find electricity price (regional average price) and consumption has correlation over region but not much regional variation over time; natural gas price and consumption has some regional variation over time but no strong correlation over region. Combining results from all 8 auxiliary regressions, we find regional variation has a minor influence on electricity and natural gas price changes over time, and this finding justifies the exclusion of regional fixed effect in our model. Even though there are regional unobservable factors affecting household energy demand, such effects should be trivial comparing to local weather effects. For instance, if household lives in cold region, more electricity or natural gas will be used in space heating and water heating; if household lives in hot region, more electricity will be used in air conditioning. Other regional unobservables are very unlikely to impact demand significantly since space heating, water heating and air conditioning generally consume the majority of energy (electricity and natural gas) in each household. In this paper, heating degree days (HDD) and cooling degree days (CDD) are used as indicators for local weather conditions to control for regional fixed effects.

4.4 Estimation and Results

The household electricity and natural gas demand equations specified in (17) are linear equations, which can be estimated by instrumental variable approach to deal with the endogenous household level average prices. However, the structure of the composite error term in (17) suggests it is heterogeneous due to different appliance choices. In order to deal with the enodogeneity and heterogeneous error term issues, we employ Two Stage Least Square (2SLS) approach with White's heteroskedasticity consistent covariance matrix. Table 2 presents the 2SLS coefficient estimates of electricity and natural gas demand specified in (17), which accounts for heteroskedasticity. For electricity demand, coefficients of electricity price among additional fridge, space heating, water heating, air conditioner and clothes dryer are all negative which are consistent with the law of demand. The positive coefficient of electricity price for baseline appliances may due to the fact that when facing electricity price increase, household will use less electricity consuming appliances such as air conditioner, and switch to substitutes such as electric fan. The coefficients of natural gas price are positive for additional fridge, water heating, air conditioner and clothes dryer, which suggests a great potential that natural gas is substitute for electricity. For natural gas demand, coefficients of natural gas price are negative for baseline and water heating appliances. The coefficient of electricity price is positive and significant for baseline appliances suggesting they are substitutes for their electric counterparts.

With the potential substitution effects between electricity and natural gas appliances, single equation estimation cannot capture unobservable factors that affect stocks of electric and natural gas appliances. If the unobservable factors influencing stocks of electric and natural gas appliances are correlated across electricity and natural gas equations, estimated coefficients will be biased. To overcome shortcomings of 2SLS single equation estimation, Three Stage Least Square (3SLS) approach is applied to the two-equation system. Results of joint estimation for electricity and natural gas demand are presented in table 3. Comparing coefficient estimates of 3SLS to those of 2SLS, the signs are the same for all coefficients but magnitudes are different, which justifies the specification of two-equation demand system. Considering the effects of household characteristics and local weather condition on electricity and natural gas demand, most of them are just as expected. Table 3 implies that the number of total rooms in housing unit is positively correlated with electricity consumption on baseline, water heating appliance, air conditioner and clothes dryer. The electricity consumption increases in the total square feet of home for space heating appliance and air conditioner. The number of household member is positively associated with all appliances except additional fridge. Electricity consumption of water heating relies heavily on number of bath rooms in home and in terms of local weather conditions, heating degree and cooling degree days both increase baseline consumption while heating degree days increase space heating consumption and cooling degree days increase air conditioner's demand for electricity. For natural gas demand, the number of rooms is positively correlated with baseline and water heating consumption, while the baseline use and space heating are increasing in the total square feet of home and heating degree days. The income effects are small for both electricity and natural gas demand, which is consistent with prior studies.

Table 4 presents own price, cross-price and income elasticities calculated based on estimates from 2SLS, which are close to elasticities calculated from 3SLS estimates in table 5. Since 3SLS estimates account for unobservable factors correlated with both equations, the remainder part of this paper will focus on estimates from 3SLS. The own price elasticity of electricity is -0.384, which is close Reiss and White (2005)'s -0.39 with California data and consistent with most prior studies. We estimate the cross-price elasticity of electricity with respect to price of natural gas as 0.062, which is small and insignificant. The own price elasticity of natural gas is -0.431, slightly larger in magnitude than Davis and Muehlegger (2010)'s -0.278 with U.S. data from 1997 to 2007, and smaller in magnitude than Alberini, Gans, and Velez-Lopez (2011)'s -0.566. The cross-price elasticity of natural gas with respect electricity price is 0.285, which is close to Alberini, Gans, and Velez-Lopez (2011)'s 0.15 with nationwide panel data, suggesting electricity and natural gas are substitutes. In terms of income effect, it is small for both electricity and natural gas, and insignificant for electricity.

To have a comprehensive understanding of the effects of price and income on household energy demand across different income groups, we specify 3 subsamples in terms of household income: low income (with annual household income less than $50,000); middle income (with annual household income no less than $50,000 and less than $100,000); high income (with annual household income no less than $100,000).[6] Own price, cross-price and income elasticities calculated from 3SLS estimates of low, middle and high income subsamples are presented in table 6 to 8. As expected, lower income households are generally more price elastic than higher income households, but there are no big differences in price and income effects across low and middle income households. Specially, for high income households, price effects are not significant for energy goods, but income effects are much larger than lower income households. The comparative larger income effects may due to the potential demand for luxurious energy consuming products.

5 Carbon Tax Incidence Estimates

Carbon tax rates are different from country to country and most of them are set on per metric ton of CO_2 emissions, for instance, Netherlands set carbon tax rate as $20 per metric ton CO_2 in 1996, Norway set carbon tax rate as $15.93 to $61.76 per metric ton in 1991. In order to be consistent with existing carbon taxes, when implementing tax incidence estimation, carbon tax rates are pre-set as amount of dollars per metric ton CO_2 and then convert to percentages of electricity and natural gas prices. According to the U.S. Environmental Protection Agency (EPA)

[6] There are 5234, 3012, and 1918 observations in the low income, middle and high income subsamples respectively

(2015), the use of 1,000 kilowatt-hours of electricity is equivalent to emit 0.69 metric tons of CO_2, and the use of 100 therms (which is approximately equal to 100 hundred cubic feet) of natural gas is equivalent to emit 0.53 metric tons of CO_2. In our full sample, the mean annual household consumption for electricity and natural gas are 9566 kwh and 667 hundred cubic feet, which yields carbon emission of 6.6 and 3.5 metric tons respectively.

5.1 Labor Supply Elasticity

To calculate the excess burden of carbon tax with formula in (15), labor supply elasticity and income elasticity of labor supply are required. Since estimating labor supply elasticities is out of the scope of this paper, these elasticities are cited from previous labor economics literature. Chetty et al. (2011) give comparison of micro and macro labor supply elasticities and recommend an Hicksian elasticities of 0.3 on the intensive and 0.25 extensive margin. Chetty (2012) uses micro and macro evidence on labor supply and gives bounds on elasticities with optimization frictions. By combining empirical estimates from earlier studies, he suggests point estimates of structural Hicksian estimates are 0.33 on the intensive margin and 0.25 on the extensive margin. Following Chetty (2012)'s results, we take 0.30 as compensated labor supply elasticity and 0.08 as uncompensated labor supply elasticity. Income elasticity of labor supply is implicitly provided by the Slutsky decomposition, whose absolute value equals to the difference between the compensated and uncompensated labor supply elasticities. In this paper, we take income elasticity of labor supply as -0.22, which is in the estimated range of Ballard (2000).

5.2 Excess Burden and Cross-price Effects

Prior studies often omit cross-price effects when estimating excess burden or welfare loss. However, omitting cross-price effects may yield significant error if substitution or complementary effects are strong. The expression for excess burden incorporating cross-price effects are presented in formula (15), and to test the strength of cross-price effects between electricity and natural gas, we also estimate a simplified version of formula (15) by setting cross-price effects to zero.

In this paper, we are more interested in how carbon tax will affect household's welfare, so when calculating excess burden with formula (15),elasticities, consumption, prices and income are taken from the "representative" household. The representative household is defined as household with the mean consumption, prices and income in the sample. Since carbon tax will distort labor market and the excess burden heavily relies on labor tax rate, we employ four labor tax groups of 10%, 20%, 30% and 40%, which are similar to U.S. federal income tax rates. To be consistent with existing carbon tax rate in the world, carbon tax rate is set at 10, 30, 50, 70 and 100 dollars per metric ton of CO_2 emission. Table 9 presents the excess burden of carbon tax on a representative household from the full sample. The total annual excess burden on a representative household is increasing dramatically with carbon tax rate. Particularly, with pre-set labor tax rate of 10%, imposing a low carbon tax rate of $10 per metric ton will yield annual excess burden of $3.6 on a representative household; however, imposing a high carbon tax rate of $100 per metric ton will yield annual excess burden as high as $92.155. In addition, excess burden increases steadily with the increase of labor tax rate. At the carbon tax rate of $50 per metric ton, a 10% pre-set labor tax yields an annual excess burden of $30.478 on the representative household while a 40% pre-set labor tax rate increases the excess burden to $70.556.

Figure 3 presents the comparison of excess burden with and without cross-price effects of full sample. The positive cross-price elasticities implying substitution effects between electricity and natural gas, thus omitting cross-price effects will overestimate the excess burden. Some previous studies suggest such cross-price effects are negligible but our results suggest a significant difference if omitting cross-price effects, especially when carbon tax rate is high. For instance, with pre-set labor tax rate of 30%, not accounting for cross-price effects, a $100 carbon tax rate will yield annual excess burden of $178.66, if accounting for cross-price effects, the corresponding excess burden is $145.41, which is 19% smaller than biased estimates.

5.3 Excess Burden on Different Income Groups

Following the same approach as with full sample, we employ information of representative households from low, middle and high income samples to investigate further on the relation between carbon tax and its excess burden. The excess burden of carbon tax on representative households of low, middle and high income samples are in table 10, 11 and 12.[7] Generally, with a low pre-set labor tax rate, higher income households normally have lower excess burden with different carbon tax rate. For instance, with a 10% labor tax rate, at carbon tax rate of \$30 (\$50), the annual excess burden on low, middle and high income representative household is \$14.352 (\$31.397), \$14.347 (\$29.532) and \$13.749 (\$24.950). For a middle level labor tax rate, higher income representative households yield higher excess burden at low carbon tax rate but lower excess burden at high carbon tax rate comparing to lower income representative households. For example, pre-set labor tax rate at 20%, a \$10 carbon tax rate yields annual excess burden of \$5.707, \$6.611 and \$7.977 on low, middle and high income representative households; and a \$100 carbon tax rate yields excess burden of \$122.940, \$115.640 and \$97.697 on low, middle and high income households.

Figure 4 exhibits the carbon tax and its excess burden of full, low, middle and high income samples with different pre-set labor tax rate. At 10% labor tax rate, the excess burden of high income representative households deviate from other income groups, suggesting that high income households are under taxed at such labor tax rate. For a 20% labor tax rate, excess burden for all income groups are close when facing carbon tax rate less than \$60 per metric ton CO_2, but high income households yield less excess burden with relative high carbon tax rate. At 30% labor tax rate, high income households have slightly higher excess burden than middle income households when carbon tax rate is less than \$70, and lower excess burden when carbon tax rate is higher.

5.4 Excess Burden and Spatial Heterogeneity

In addition to income heterogeneity, spatial heterogeneity is also important when evaluating carbon tax policy. Households from different regions face different energy prices (figure 1 and figure 2) and their excess burden with potential carbon tax will differ. To investigate the spatial heterogeneity in excess burden, own-price, cross-price elasticities from the full sample, regional average prices and demands are used when calculating excess burden of each region.[8] Figure 5 shows the carbon

[7]The highest marginal labor tax rates for low, middle and high income households are set at 20%, 30% and 40%.

[8]Ideally, price elasticities should be re-estimated from the regional subsample, but since we have to use regional price to instrument household level average price, subsample provides no variation for our instruments, which makes it impossible to re-estimate elasticities with current instruments. To avoid this difficulty without loss of generality,

tax and its excess burden of 9 regions with different pre-set labor tax rates. Excess burden of all 9 regions are increasing in carbon tax rate but differs significantly in magnitudes. In general, East South Central region yields the largest excess burden while New England region yields the smallest of all 9 regions, and the gap is huge between these two extremes. For instance, with a pre-set 20% labor tax rate, the excess burden on New England and East South Central households are around $85 and $190 respectively when carbon tax rate is $100. Besides, we found regions with approximately 2nd to 6th largest excess burden are West South Central, South Atlantic, West North Central, East North Central and Mountain regions. The excess burden of households in Middle Atlantic, Pacific and West South Central regions are close in magnitudes.

5.5 Excess Burden and Energy Price Variation

The natural gas market is quite unstable and the natural gas price fluctuates frequently in recently years. There is a large decrease in natural gas price after 2008, which will lead welfare gain for households ignoring substitution effects and tax distortion. However, for a taxed good, the price decrease may not always be a good thing if substitution and tax effects are both taken into consideration. In this section, we want to explore how varying natural gas prices contribute to excess burden under different carbon tax rates. In order to give an accurate calculation, we consider demand change and substitution effects when facing varying natural gas prices. Demand estimates from the full sample are used as baseline parameters when calculating excess burden of varying prices. Figure 6 presents the 3-D relation between natural gas price, carbon tax rate and corresponding excess burden of representative household. The range for natural gas price is between 0.8 and 1.8 dollars per hundred cubic feet. We find no evidence that decrease of natural gas price will reduce excess burden. In general, given a low labor tax rate (10%), the excess burden decreases slightly in natural gas price; and given a high labor tax rate (40%), the excess burden increases trivially in natural gas price.

when calculating excess burden for each region, we use the same price elasticities (estimated from the full sample) and different regional price and consumption.

6 Concluding Remarks

In this paper, a model based on general equilibrium framework is developed to investigate consumer's excess burden of carbon tax levied on energy goods (electricity and natural gas). This model incorporates the tax distortion on labor market and gives a more accurate approximation for excess burden estimation accounting for substitution effects between energy goods. It contributes to the literature by providing a new perspective of combining demand estimation and consumer welfare analysis, and gives a more comprehensive explanation on how price changes or tax incidence may affect household energy demand and welfare.

In terms of demand estimation, electricity and natural gas demand models based on appliance stocks are estimated with data from 2005 and 2009 RECS. To deal with the endogenous household level average price and heterogeneous error term issues, 2SLS with white consistent covariance matrix is used. Moreover, to better capture the unobservable factors that are correlated among electricity and natural gas demand equations, 3SLS system estimation is used. From the full sample 3SLS estimation results, own price elasticity of electricity (natural gas) is -0.384 (-0.431), which is consistent with literature (Reiss and White 2005; Alberini, Gans, and Velez-Lopez 2011); cross-price elasticity of electricity (natural gas) with respect to natural gas (electricity) price is 0.062 (0.285), suggesting they are substitutes. In addition to full sample, three subsamples in terms of household income are also used. 3SLS results suggest lower income households are generally more price elastic than higher income households.

Cross-price effects are often omitted by prior studies when estimating excess burden or welfare loss. Comparing household level excess burden of carbon tax with and without cross-price effects among energy goods, we find omitting positive cross-price effects (substitution effects) will overestimate the excess burden, and the bias increases with carbon tax rate. This finding provides strong evidence that cross-price effects among energy goods are not negligible in welfare analyses. Besides, the household excess burden is increasing dramatically with carbon tax rate and increases steadily with the raise of labor tax rate. Carbon tax performs differently on affecting low, middle and high income households. Generally, higher income households have lower excess burden under a low pre-set labor tax rate; for a middle level pre-set labor tax rate, comparing to lower income households, higher income households yield higher excess burden at a low carbon tax rate and lower excess burden at a high carbon tax rate. Spatial heterogeneity is also critical in affecting excess burden and our findings suggest excess burden of all 9 regions are increasing in carbon tax rate but differs in magnitudes. Specifically, East South Central region yields the largest excess burden and New England region yields the smallest of all 9 regions. Considering natural price variation, we find no strong evidence that the small decrease or increase of natural gas price will change household excess burden significantly.

While this paper presents one of the first attempts to evaluate household's excess burden of carbon tax levied on energy goods incorporating both theoretical framework and empirical results, future studies may consider the use of panel data or more detailed dataset. Further, the theoretical framework and methodology of this study can be extended to other topics rather than energy related tax, such as the "sweet tax" on sugar beverages, tax on alcoholic products and cigarettes.

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Table 1
Sample Statistics and Definition of Full Sample

Variable	Definitions	Mean	S.D.
C_e	Annual electricity consumption (kwh)	9566.447	6637.625
C_g	Annual natural gas consumption (100 cubic feet)	667.190	453.375
Price_e	Household level average electricity price per kwh (cents)	12.820	4.142
Price_g	Household level average natural gas price per 100 cubic feet (cents)	130.248	60.297
Ape	Regional level average electricity price per kwh in 2009 (cents)	12.147	2.392
Apg	Regional level average natural gas price per 100 cubic feet in 2009 (cents)	141.302	24.926
Income	Household income in 2009 (dollars)	67532.370	61286.022
Totrooms	Total number of rooms in the housing unit	6.053	2.1555
Totsqft	Total square footage in housing unit	2292.393	1528.426
No. member	Number of household members	2.729	1.536
HDD65	Heating degree days, base temperature 65F	4387.628	2180.464
CDD65	Cooling degree days, base temperature 65F	1250.322	917.280
No. bath	Number of bathrooms in housing unit	1.653	0.756
Year 2009	Data are collected in 2009	0.735	
Region 1	New England (CT, MA, ME, NH, RI, VT)	0.067	
Region 2	Middle Atlantic (NJ, NY, PA)	0.137	
Region 3	East North Central (IL, IN, MI, OH, WI)	0.138	
Region 4	West North Central (IA, KS, MN, MO, ND, NE, SD)	0.138	
Region 5	South Atlantic (DC, DE, FL, GA, MD, NC, SC, VA, WV)	0.095	
Region 6	East South Central (AL, KY, MS, TN)	0.039	
Region 7	West South Central (AR, LA, OK, TX)	0.092	
Region 8	Mountain (CO, ID, MT, UT, WY, AZ, NM, NV)	0.085	
Region 9	Pacific (AK, CA, HI, OR, WA)	0.208	
Own house	Own housing unit or not	0.681	
Add. fridge	Use 2nd refrigerator or more	0.250	
E. S. heating	Use electricity for space heating in home	0.326	
E. W. heating	Use electricity for water heating in home	0.126	
A.C.	Use air conditioners in home	0.733	
Dryer	Use clothes dryer in home	0.798	
N. S. heating	Use natural gas for space heating in home	0.830	
N. W. heating	Use natural gas for water heating in home	0.855	

Table 2
2SLS Estimates of Electricity and Natural Gas Demand

Variable	Electricity						Natural gas		
	Baseline	Add. fridge	S. heating	W. heating	A.C.	Dryer	Baseline	S. heating	W. heating
Constant	−35.067	123.369	270.635***	−114.392	−143.165*	163.258***	199.642***	−333.089***	79.102
	(65.800)	(101.554)	(85.052)	(172.311)	(74.515)	(56.384)	(70.613)	(62.196)	(65.771)
Price_e	2.818	−17.075***	−15.510***	−0.165	−5.503	−21.043***	17.017**	0.946	−4.621
	(4.678)	(6.173)	(5.116)	(9.228)	(4.798)	(4.459)	(6.777)	(3.259)	(4.205)
Price_g	−0.330*	0.650*	0.218	0.322	−0.118	0.602***	−3.611***	1.842***	−0.066
	(0.176)	(0.360)	(0.207)	(0.371)	(0.208)	(0.192)	(1.025)	(0.438)	(0.607)
Income/1000	−0.276	0.639***	−0.252	−0.350	0.540***	0.742***	0.443**	0.104	−0.286
	(0.209)	(0.236)	(0.220)	(0.427)	(0.186)	(0.195)	(0.220)	(0.167)	(0.227)
Totrooms	25.661***	27.031***	−13.507	12.097	19.907***		34.720***	−8.274	16.218**
	(6.591)	(9.993)	(9.098)	(15.439)	(7.461)		(8.774)	(6.833)	(7.270)
Totsqft/10	0.176*	0.080	0.273*		0.450***		0.209**	0.336***	
	(0.104)	(0.149)	(0.153)		(0.114)		(0.092)	(0.104)	
No. member	27.123***	−30.742***	−1.768	62.662***	13.632**	51.635***	−1.117	12.776**	12.972*
	(6.241)	(9.519)	(8.176)	(16.650)	(6.654)	(6.423)	(8.820)	(6.269)	(7.437)
Hdd65/100	2.340***		0.724				2.491***	6.704***	
	(0.302)		(0.524)				(0.610)	(0.507)	
Cdd65/100	12.278***				10.596***		3.247**		
	(1.421)				(1.566)		(1.467)		
No. bath	61.222***			82.810*			−7.121		−8.064
	(11.690)			(48.562)			(24.577)		(25.435)
Own house	−5.995						−7.865		
	(12.275)						(8.843)		
Year 2009	−46.608***						−48.902***		
	(12.158)						(8.147)		

Note: Total observations are 10164. For the electricity demand equation, R^2 is 0.5150. For the natural gas demand equation, R^2 is 0.4443. Asymptotic standard errors in parentheses. *** 1%, ** 5% and * 10% level of significance.

Table 3
3SLS Estimates of Electricity and Natural Gas Two-equation Demand System

Variable	Electricity						Natural gas		
	Baseline	Add. fridge	S. heating	W. heating	A.C.	Dryer	Baseline	S. heating	W. heating
Constant	−23.620	131.971*	256.894***	−114.408	−145.490*	159.579**	188.010**	−338.396***	89.767
	(81.873)	(75.198)	(70.981)	(100.176)	(75.566)	(71.022)	(77.998)	(73.695)	(79.002)
Price_e	2.028	−17.813***	−14.379***	−0.169	−5.694	−21.758***	18.859***	0.478	−5.177
	(5.680)	(5.060)	(4.658)	(6.395)	(5.102)	(5.476)	(6.731)	(4.194)	(3.964)
Price_g	−0.262	0.688***	0.167	0.302	−0.084	0.645***	−3.704***	1.885***	−0.078
	(0.185)	(0.216)	(0.172)	(0.223)	(0.200)	(0.195)	(1.030)	(0.625)	(0.676)
Income/1000	−0.229	0.595***	−0.261	−0.360	0.524**	0.733**	0.428**	0.132	−0.301
	(0.313)	(0.187)	(0.185)	(0.275)	(0.218)	(0.302)	(0.211)	(0.177)	(0.201)
Totrooms	25.185***	25.899***	−12.466*	11.747	20.669***		36.469***	−9.242	15.438**
	(7.106)	(7.006)	(6.685)	(8.814)	(7.417)		(8.103)	(7.248)	(5.999)
Totsqft/10	0.167	0.085	0.272***		0.459***		0.179*	0.370***	
	(0.106)	(0.089)	(0.093)		(0.111)		(0.093)	(0.098)	
No. member	26.904***	−29.196***	−2.281	62.718***	12.614*	52.887***	−1.234	12.296*	13.277*
	(7.930)	(7.119)	(6.652)	(9.958)	(6.919)	(7.780)	(8.966)	(7.242)	(7.299)
Hdd65/100	2.280***		0.781*				2.408***	6.835***	
	(0.348)		(0.462)				(0.621)	(0.501)	
Cdd65/100	11.833***				10.821***		3.394**		
	(1.375)				(1.414)		(1.455)		
No. bath	61.378***			83.915***			−7.590		−7.542
	(9.281)			(22.848)			(16.683)		(16.905)
Own house	−5.573						−7.122		
	(12.986)						(8.891)		
Year 2009	−46.682***						−49.854***		
	(11.729)						(8.085)		

Note: Total observations are 10164, system R^2 is 0.4786. For the electricity demand equation, R^2 is 0.5149, σ^2 is 213718.663. For the natural gas demand equation, R^2 is 0.4428, σ^2 is 114378.024. Asymptotic standard errors in parentheses. *** 1%, ** 5% and * 10% level of significance.

Table 4
2SLS Estimates of Own Price, Cross-price and Income Elasticities of Electricity and Natural Gas with Full Sample

Energy Good	Electricity	Natural gas	Income
Electricity	-0.366^{*}	0.046	0.053
	(0.207)	(0.060)	(0.040)
Natural gas	0.266^{***}	-0.417^{***}	0.029^{***}
	(0.031)	(0.134)	(0.010)

Note: Asymptotic standard errors in parentheses. *** 1%, ** 5% and * 10% level of significance.

Table 5
3SLS Equation System Estimates of Own Price, Cross-price and Income Elasticities of Electricity and Natural Gas with Full Sample

Energy Good	Electricity	Natural gas	Income
Electricity	-0.384^{*}	0.062	0.054
	(0.209)	(0.062)	(0.039)
Natural gas	0.285^{***}	-0.431^{***}	0.028^{***}
	(0.034)	(0.137)	(0.011)

Note: Asymptotic standard errors in parentheses. *** 1%, ** 5% and * 10% level of significance.

Table 6
3SLS Equation System Estimates of Own Price, Cross-price and Income Elasticities of Electricity and Natural Gas with Low Income Sample (less than $50,000)

Energy Good	Electricity	Natural gas	Income
Electricity	-0.454^{*}	0.055	0.011
	(0.253)	(0.058)	(0.047)
Natural gas	0.319^{***}	-0.662^{***}	-0.082^{***}
	(0.052)	(0.102)	(0.019)

Note: Asymptotic standard errors in parentheses. *** 1%, ** 5% and * 10% level of significance.

Table 7
3SLS Equation System Estimates of Own Price, Cross-price and Income Elasticities of Electricity and Natural Gas with Middle Income Sample (between $50,000 and $100,000)

Energy Good	Electricity	Natural gas	Income
Electricity	-0.395^{***}	0.079^{**}	0.038
	(0.116)	(0.039)	(0.140)
Natural gas	0.254^{***}	-0.254	0.062^{*}
	(0.047)	(0.213)	(0.036)

Note: Asymptotic standard errors in parentheses. *** 1%, ** 5% and * 10% level of significance.

Table 8
3SLS Equation System Estimates of Own Price, Cross-price and Income Elasticities of Electricity and Natural Gas with High Income Sample (above $100,000)

Energy Good	Electricity	Natural gas	Income
Electricity	−0.202	0.097	0.130*
	(0.167)	(0.083)	(0.070)
Natural gas	0.292*	−0.271	0.172***
	(0.149)	(0.219)	(0.035)

Note: Asymptotic standard errors in parentheses. *** 1%, ** 5% and * 10% level of significance.

Table 9
Excess Burden of Carbon Tax on Representative Household of Full Sample

Carbon	$\frac{\tau_e}{p_e}$	$\frac{\tau_g}{p_g}$	No cross effects				With cross effects			
tax			$t_l = 0.1$	$t_l = 0.2$	$t_l = 0.3$	$t_l = 0.4$	$t_l = 0.1$	$t_l = 0.2$	$t_l = 0.3$	$t_l = 0.4$
10	0.054	0.041	3.946	6.776	9.489	12.092	3.600	6.437	9.157	11.767
30	0.161	0.122	17.664	26.031	34.052	41.749	14.543	22.975	31.059	38.817
50	0.269	0.203	39.149	52.888	66.061	78.701	30.478	44.400	57.748	70.556
70	0.377	0.285	68.400	87.349	105.520	122.950	51.405	70.712	89.222	106.980
100	0.538	0.407	126.840	153.300	178.660	203.000	92.155	119.340	145.410	170.420

Note: Carbon tax rate is U.S. dollars of per metric ton of CO_2 emission. $\frac{\tau_e}{p_e}$ and $\frac{\tau_g}{p_g}$ are equivalent tax rates on electricity and natural gas converted from given carbon tax rate. A representative household in the full sample has annual income of 67532.370 dollars, and consumes 9566.447 kwh electricity and 667.190 hundred cubic feet natural gas annually.

Table 10
Excess Burden of Carbon Tax on Representative Household of Low Income Sample

Carbon tax	$\frac{\tau_e}{p_e}$	$\frac{\tau_g}{p_g}$	No cross effects $t_l = 0.1$	No cross effects $t_l = 0.2$	With cross effects $t_l = 0.1$	With cross effects $t_l = 0.2$
10	0.054	0.041	3.620	6.031	3.289	5.707
30	0.163	0.122	17.334	24.432	14.352	21.512
50	0.272	0.203	39.681	51.282	31.397	43.173
70	0.380	0.284	70.659	86.583	54.422	70.688
100	0.543	0.406	133.310	155.380	100.180	122.940

Note: Carbon tax rate is U.S. dollars of per metric ton of CO_2 emission. $\frac{\tau_e}{p_e}$ and $\frac{\tau_g}{p_g}$ are equivalent tax rates on electricity and natural gas converted from given carbon tax rate. A representative household in the low income sample has annual income of 26323.438 dollars, and consumes 7899.092 kwh electricity and 604.973 hundred cubic feet natural gas annually.

Table 11
Excess Burden of Carbon Tax on Representative Household of Middle Income Sample

Carbon tax	$\frac{\tau_e}{p_e}$	$\frac{\tau_g}{p_g}$	No cross effects $t_l = 0.1$	No cross effects $t_l = 0.2$	No cross effects $t_l = 0.3$	With cross effects $t_l = 0.1$	With cross effects $t_l = 0.2$	With cross effects $t_l = 0.3$
10	0.054	0.041	4.008	6.954	9.779	3.658	6.611	9.443
30	0.162	0.123	17.499	26.222	34.584	14.347	23.136	31.562
50	0.271	0.205	38.289	52.634	66.388	29.532	44.063	57.993
70	0.379	0.287	66.378	86.193	105.190	49.215	69.392	88.735
100	0.542	0.410	122.200	149.930	176.510	87.172	115.640	142.930

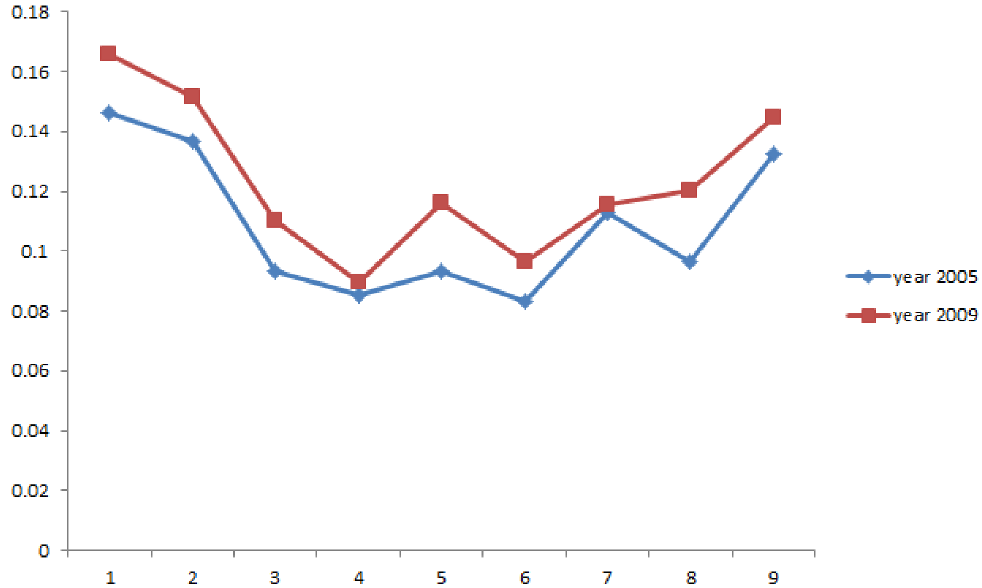
Note: Carbon tax rate is U.S. dollars of per metric ton of CO_2 emission. $\frac{\tau_e}{p_e}$ and $\frac{\tau_g}{p_g}$ are equivalent tax rates on electricity and natural gas converted from given carbon tax rate. A representative household in the middle income sample has annual income of 71379.603 dollars, and consumes 10123.903 kwh electricity and 671.823 hundred cubic feet natural gas annually.

Table 12
Excess Burden of Carbon Tax on Representative Household of High Income Sample

Carbon tax	$\frac{\tau_e}{p_e}$	$\frac{\tau_g}{p_g}$	No cross effects				With cross effects			
			$t_l = 0.1$	$t_l = 0.2$	$t_l = 0.3$	$t_l = 0.4$	$t_l = 0.1$	$t_l = 0.2$	$t_l = 0.3$	$t_l = 0.4$
10	0.052	0.041	4.679	8.469	12.103	15.590	4.176	7.977	11.621	15.118
30	0.156	0.122	18.272	29.554	40.370	50.749	13.749	25.127	36.034	46.501
50	0.260	0.203	37.514	56.168	74.052	91.214	24.950	43.869	62.008	79.412
70	0.364	0.284	62.403	88.311	113.150	136.980	37.778	64.205	89.541	113.850
100	0.520	0.406	110.330	146.890	181.950	215.590	60.073	97.697	133.770	168.380

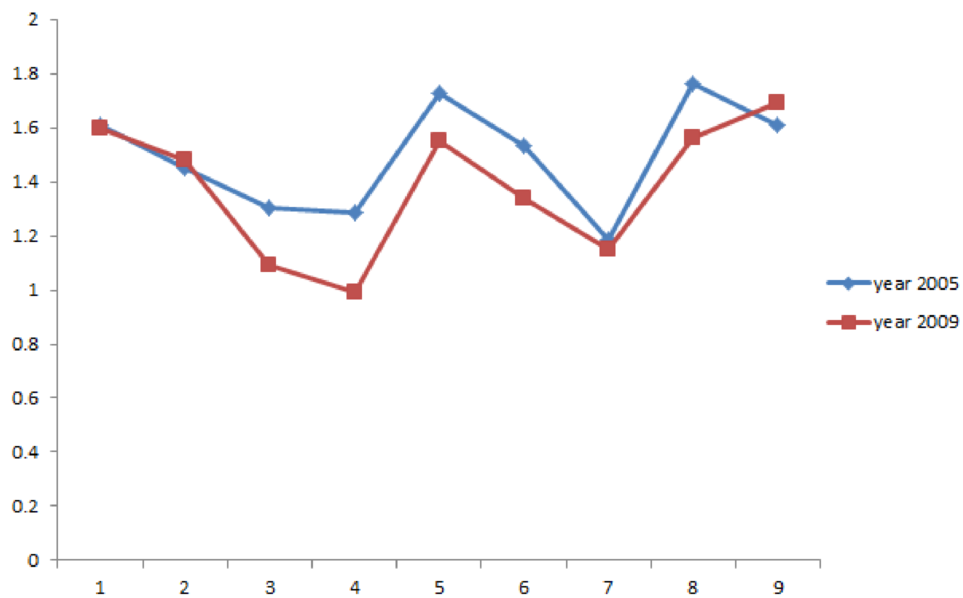
Note: Carbon tax rate is U.S. dollars of per metric ton of CO_2 emission. $\frac{\tau_e}{p_e}$ and $\frac{\tau_g}{p_g}$ are equivalent tax rates on electricity and natural gas converted from given carbon tax rate. A representative household in the high income sample has annual income of 173945.133 dollars, and consumes 13241.045 kwh electricity and 829.698 hundred cubic feet natural gas annually.

Figure 1. Regional Average Price of Electricity in 2005 and 2009



Note: The horizontal axis denotes 9 regions, vertical axis denotes the price in terms of U.S. dollars in 2009.

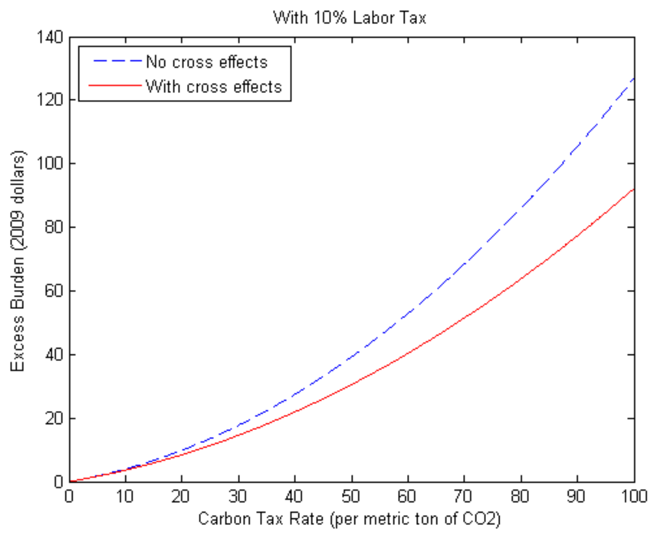
Figure 2. Regional Average Price of Natural Gas in 2005 and 2009



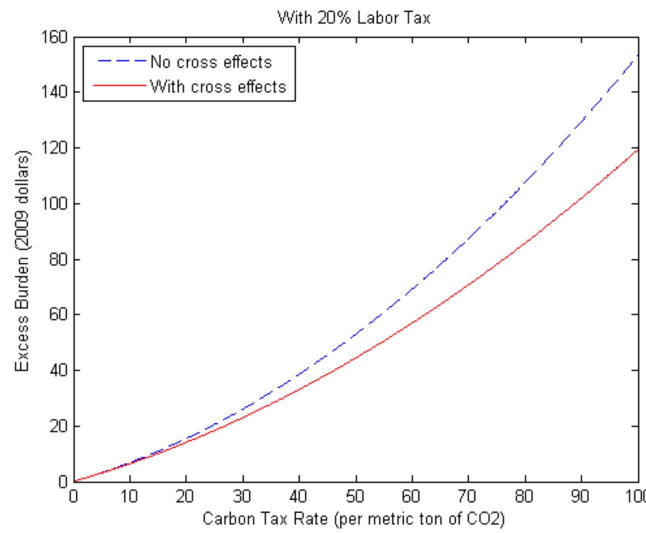
Note: The horizontal axis denotes 9 regions, vertical axis denotes the price in terms of U.S. dollars in 2009.

Figure 3. Carbon Tax and Excess Burden of Full Sample with and without Cross-price Effects under Labor Tax Rate of 10%, 20%, 30% and 40%.

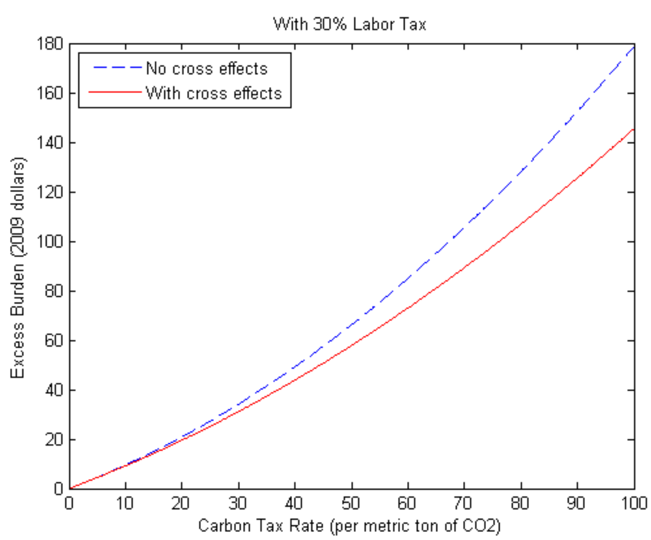
(a)



(b)



(c)



(d)

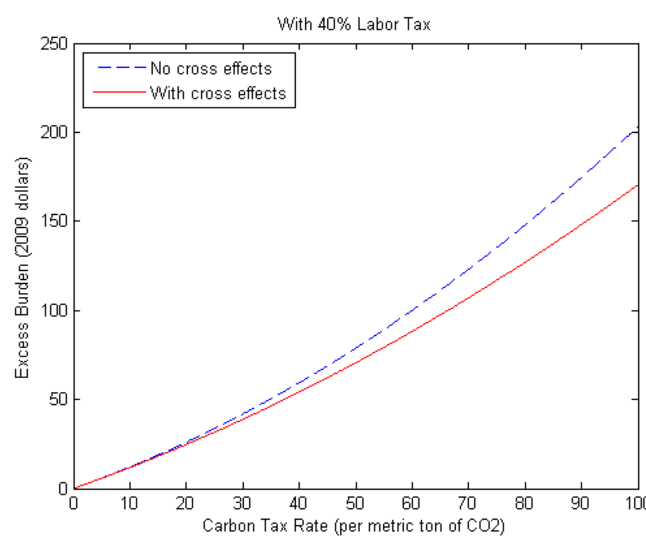
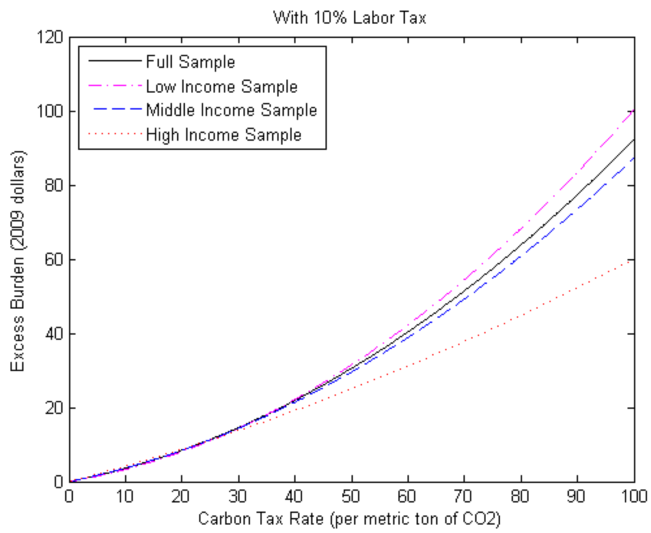
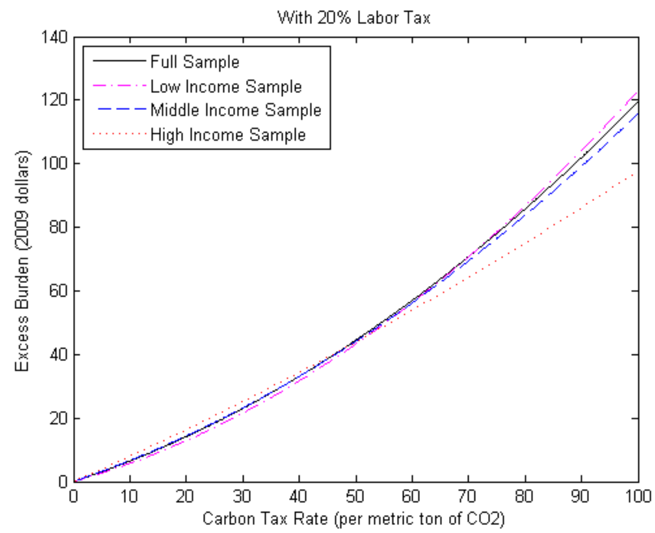


Figure 4. Carbon Tax and Excess Burden of Full, Low, Middle and High Income Samples under Labor Tax Rate of 10%, 20%, 30% and 40%.

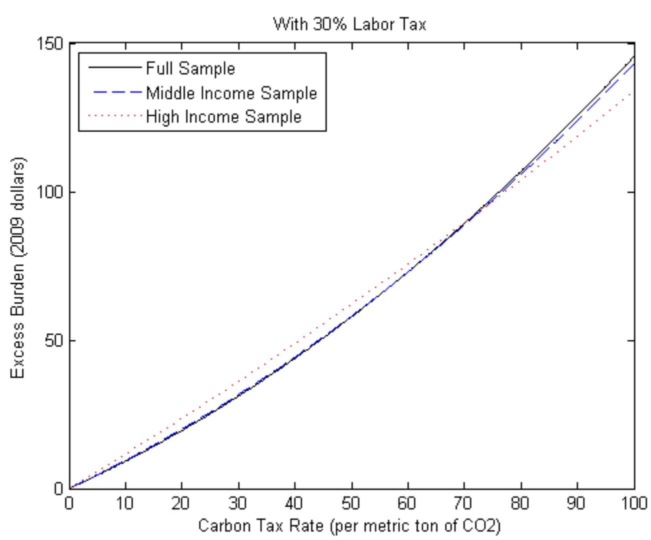
(a)



(b)



(c)



(d)

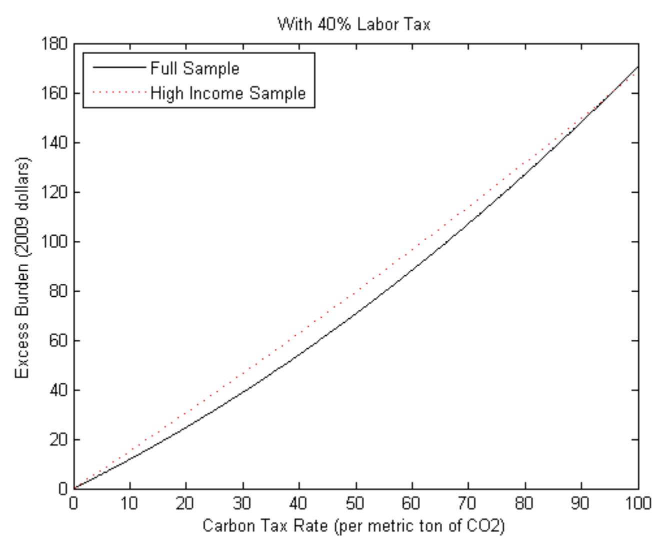


Figure 5. Carbon Tax and Excess Burden of 9 regions under Labor Tax Rate of 10%, 20%, 30% and 40%.

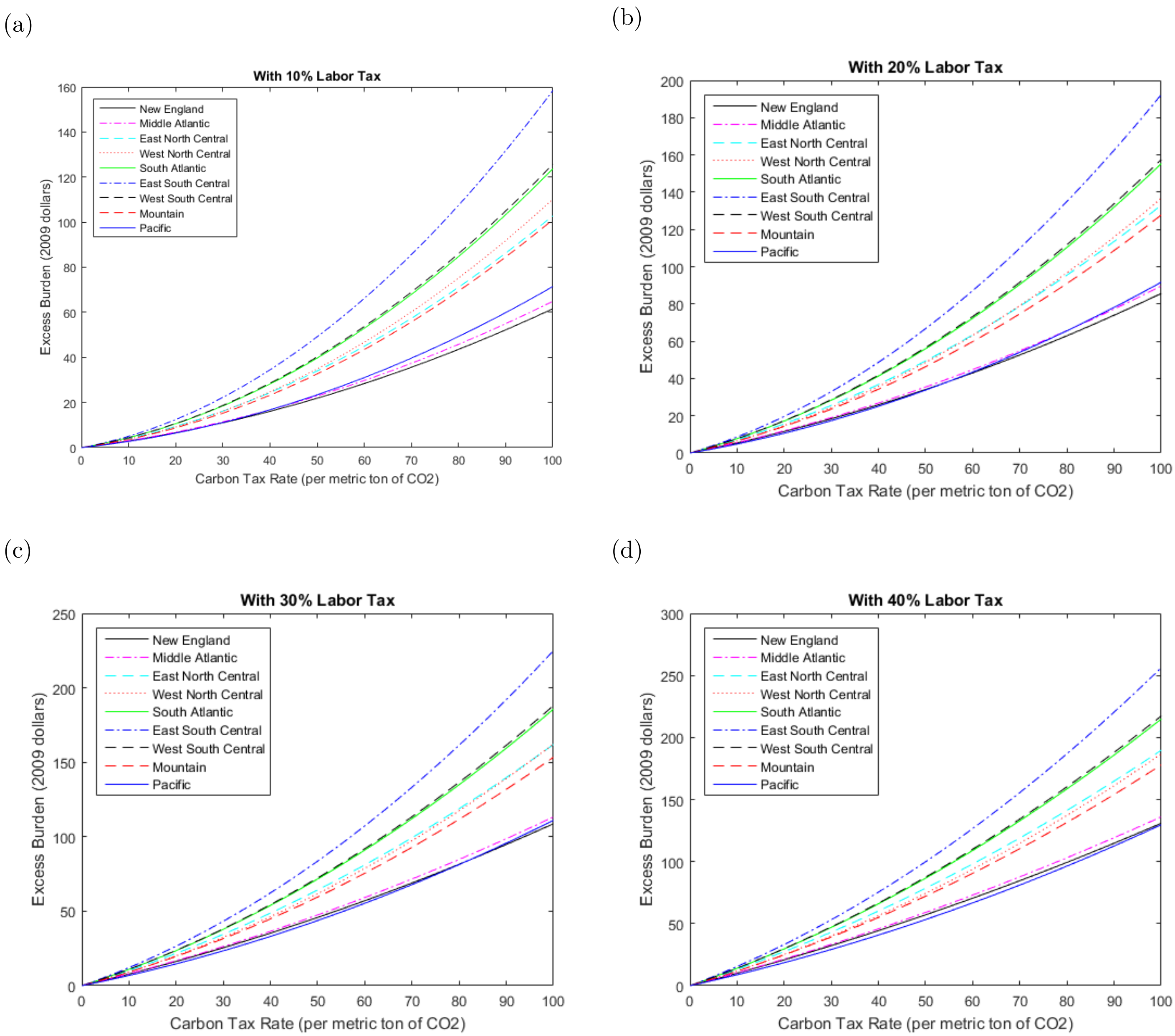
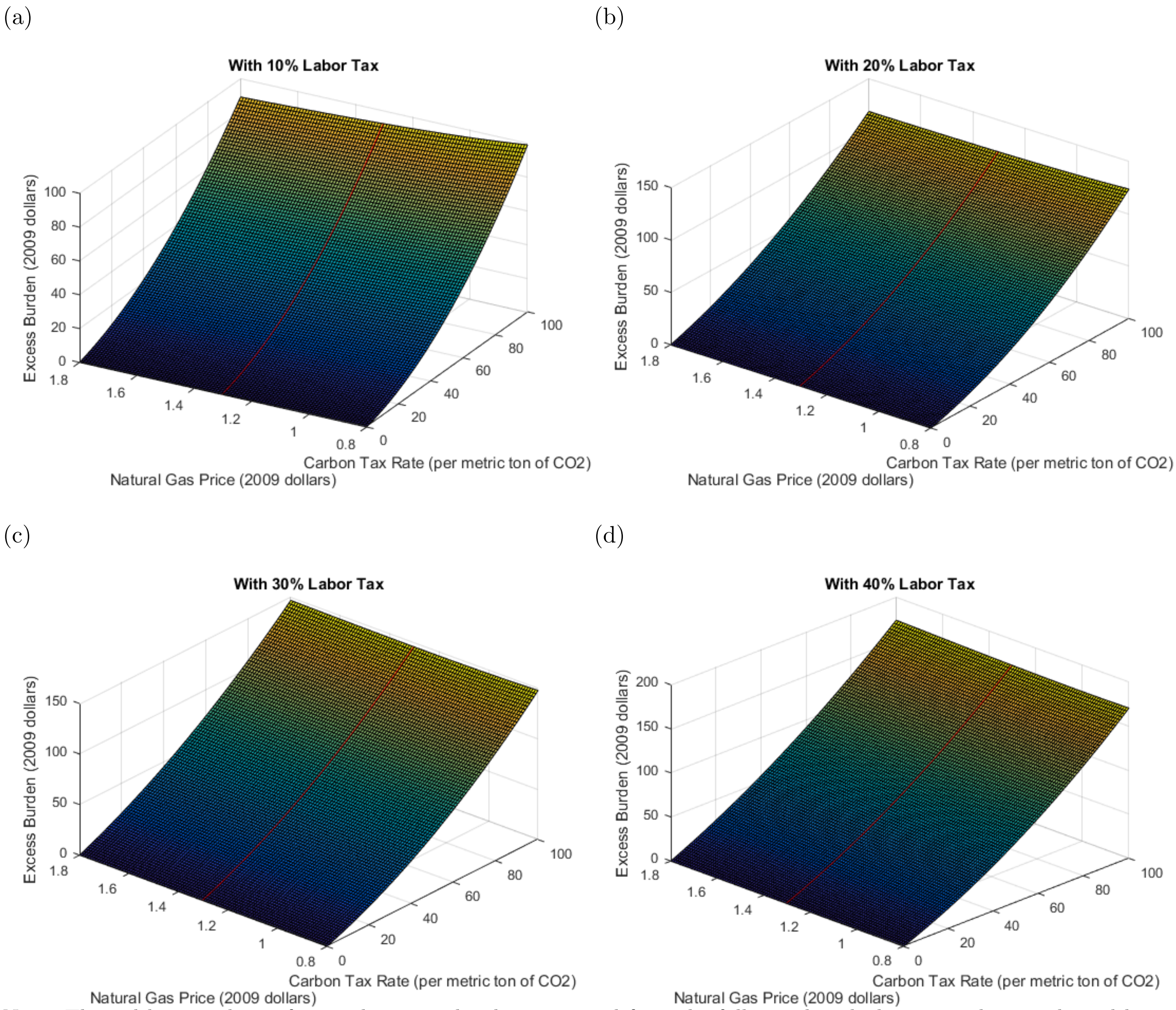


Figure 6. Excess Burden and Varying Natural Gas Prices under Labor Tax Rate of 10%, 20%, 30% and 40%.



Note: The red line on the surface is the excess burden estimated from the full sample, which is equivalent to the red line in Figure 3.

Appendix

A Derivation of First Order Conditions

The first order conditions (FOCs) of equation (5) are

$$\begin{aligned}
\frac{\partial U}{\partial S}\frac{\partial S}{\partial C_e} - \lambda p_e = 0 \\
\frac{\partial U}{\partial S}\frac{\partial S}{\partial C_g} - \lambda p_g = 0 \\
\frac{\partial U}{\partial C_m} - \lambda = 0 \\
\frac{\partial U}{\partial l} - \lambda(1 - t_l) = 0 \\
(1 - t_l)(T - l) + G - p_e C_e - p_g C_g - C_m = 0.
\end{aligned} \tag{A1}$$

The first order conditions (FOCs) of equation (8) are

$$\begin{aligned}
(p_e - t_e) f_e(L_e) - 1 = 0 \\
(p_g - t_g) f_g(L_g) - 1 = 0 \\
f_m(L_m) - 1 = 0 \\
L_e + L_g + L_m = L.
\end{aligned} \tag{A2}$$

B Derivation of Excess Burden Formula

To simplify the derivation process, we take electricity tax t_e as example, the derivation for excess burden of natural gas tax t_g is similar.

B.1 Energy Tax Excess Burden without Income Effect

Substituting FOC conditions from (A1) in equation (11) yields

$$\frac{\partial U}{\partial t_e} = \lambda[p_e \frac{\partial C_e}{\partial t_e} + p_g \frac{\partial C_g}{\partial t_e} + \frac{\partial C_m}{\partial t_e} + (1 - t_l)\frac{\partial l}{\partial t_e}]. \tag{A3}$$

Totally differentiating the production function in equation (7) we have

$$\frac{\partial C_i}{\partial t_e} = \frac{\partial y_i}{\partial t_e} = \frac{\partial F_i}{\partial L_i}\frac{\partial L_i}{\partial t_e}, \tag{A4}$$

substituting $f_i(L_i) = \frac{1}{p_i - t_i}$ in (A4) to get

$$\frac{\partial C_i}{\partial t_e} = \frac{1}{p_i - t_i}\frac{\partial L_i}{\partial t_e}, \ i = e, g, m. \tag{A5}$$

Totally differentiating household's time constraint with respect to t_e yields

$$\frac{\partial L_e}{\partial t_e} + \frac{\partial L_g}{\partial t_e} + \frac{\partial L_m}{\partial t_e} + \frac{\partial l}{\partial t_e} = 0. \tag{A6}$$

Subtracting (A6) from (A3)

$$\frac{1}{\lambda}\frac{\partial U}{\partial t_e} = p_e\frac{\partial C_e}{\partial t_e} + p_g\frac{\partial C_g}{\partial t_e} + \frac{\partial C_m}{\partial t_e} + (1 - t_l)\frac{\partial l}{\partial t_e} - \frac{\partial L_e}{\partial t_e} - \frac{\partial L_g}{\partial t_e} - \frac{\partial L_m}{\partial t_e} - \frac{\partial l}{\partial t_e}, \tag{A7}$$

substituting in (A5) and canceling terms yields

$$\frac{1}{\lambda}\frac{\partial U}{\partial t_e} = t_e\frac{\partial C_e}{\partial t_e} + t_g\frac{\partial C_g}{\partial t_e} + t_m\frac{\partial C_m}{\partial t_e} - t_l\frac{\partial l}{\partial t_e}. \tag{A8}$$

Assume there is no tax levied on other goods (numeraire), so $t_m = 0$, (A8) can be simplified as

$$\frac{1}{\lambda}\frac{\partial U}{\partial t_e} = t_e\frac{\partial C_e}{\partial t_e} + t_g\frac{\partial C_g}{\partial t_e} - t_l\frac{\partial l}{\partial t_e}. \tag{A9}$$

Equation (A9) can be rewritten in terms of elasticities as

$$\frac{1}{\lambda}\frac{\partial U}{\partial t_e} = \frac{t_e C_e}{p_e}\epsilon_e + \frac{t_g C_g}{p_e}\epsilon_{g,e} - \frac{t_l L}{p_e}\epsilon_{L,e}, \tag{A10}$$

Following Goulder and Williams (2003), (A10) can be rewritten in terms of own price elasticity of labor supply which yield

$$\frac{1}{\lambda}\frac{\partial U}{\partial t_e} = \frac{t_e C_e}{p_e}\epsilon_e + \frac{t_g C_g}{p_e}\epsilon_{g,e} - \frac{t_l L}{p_e}\epsilon_L s_e(\theta + 1), \tag{A11}$$

where ϵ_L is the elasticity of labor supply, s_e is the expenditure share of income spent on electricity, and

$$\theta = \frac{\epsilon_{e,L}}{s_e\epsilon_{e,L} + s_g\epsilon_{g,L} + s_m\epsilon_{m,L}} - 1. \tag{A12}$$

To simplify the calculation, we assume all goods and numeraire are average substitutes for leisure, which is equivalent to set $\theta = 0$. In addition, with the assumption of normalized wage rate ($w = 1$), we can approximate income to labor ($Y \approx L$). The final expression for electricity tax excess burden with marginal change is

$$\frac{1}{\lambda}\frac{\partial U}{\partial t_e} \approx \frac{t_e C_e}{p_e}\epsilon_e + \frac{t_g C_g}{p_e}\epsilon_{g,e} - \frac{t_l Y}{p_e}\epsilon_L s_e. \tag{A13}$$

Similarly, the natural gas tax excess burden with marginal change is

$$\frac{1}{\lambda}\frac{\partial U}{\partial t_g} \approx \frac{t_g C_g}{p_g}\epsilon_g + \frac{t_e C_e}{p_g}\epsilon_{e,g} - \frac{t_l Y}{p_g}\epsilon_L s_g. \tag{A14}$$

B.2 Energy Tax Excess Burden With Income Effect

Employing Slutsky equation, (A9) can be expressed as

$$\frac{1}{\lambda}\frac{\partial U}{\partial t_e} = t_e\frac{\partial C_e^h}{\partial t_e} + t_g\frac{\partial C_g^h}{\partial t_e} - t_l\frac{\partial l^h}{\partial t_e} + (t_e\frac{\partial C_e}{\partial G} + t_g\frac{\partial C_g}{\partial G} - t_l\frac{\partial l}{\partial G})(\frac{\partial G}{\partial t_e} - C_e), \tag{A15}$$

where the superscript h denotes derivative of Hicksian demand. Totally differentiate the government budget constraint with respect to t_e yields

$$\frac{\partial G}{\partial t_e} - C_e = t_e\frac{\partial C_e}{\partial t_e} + t_g\frac{\partial C_g}{\partial t_e} - t_l\frac{\partial l}{\partial t_e}, \tag{A16}$$

which equals to the right-hand side of (A9), thus (A15) can be express as

$$\frac{1}{\lambda}\frac{\partial U}{\partial t_e} = t_e\frac{\partial C_e^h}{\partial t_e} + t_g\frac{\partial C_g^h}{\partial t_e} - t_l\frac{\partial l^h}{\partial t_e} + (t_e\frac{\partial C_e}{\partial G} + t_g\frac{\partial C_g}{\partial G} - t_l\frac{\partial l}{\partial G})(\frac{1}{\lambda}\frac{\partial U}{\partial t_e}). \tag{A17}$$

Solving the equation above yields

$$\frac{1}{\lambda}\frac{\partial U}{\partial t_e} = \frac{t_e\frac{\partial C_e^h}{\partial t_e} + t_g\frac{\partial C_g^h}{\partial t_e} - t_l\frac{\partial l^h}{\partial t_e}}{1 - t_e\frac{\partial C_e}{\partial G} - t_g\frac{\partial C_g}{\partial G} + t_l\frac{\partial l}{\partial G}}. \tag{A18}$$

Following previous step and rewriting the equation in terms of elasticities yield to

$$\frac{1}{\lambda}\frac{\partial U}{\partial t_e} = \frac{\frac{t_e C_e}{p_e}\epsilon_e + \frac{t_g C_g}{p_e}\epsilon_{g,e} - \frac{t_l L}{p_e}\epsilon_L s_e(\theta+1)}{1 - \frac{t_e C_e}{Y}\epsilon_{e,Y} - \frac{t_g C_g}{Y}\epsilon_{g,Y} - \frac{t_l L}{Y}\epsilon_{L,Y}}. \tag{A19}$$

To be consistent with previous assumptions, let $\theta = 0$ and $Y \approx L$, (A19) can be simplified as equation (12).

The excess burden formula derived in (A19) applied only for marginal changes in the tax rate. A more general approximation formula for larger tax changes is derived below. Note that comparing to the effect of raising labor tax, the income effect is relative small, thus omitting the second and third terms in the denominator of (A19) will have little effect on the overall excess burden estimation. Then (A19) can be approximated as

$$\frac{1}{\lambda}\frac{\partial U}{\partial t_e} \approx \frac{\frac{t_e C_e}{p_e}\epsilon_e + \frac{t_g C_g}{p_e}\epsilon_{g,e} - \frac{t_l Y}{p_e}\epsilon_L s_e}{1 - t_l\epsilon_{L,Y}}. \tag{A20}$$

We assume linear demand curves for energy goods and labor, and the labor tax remains constant with changes in energy taxes. Integrating (A20) over the changes of electricity tax t_e yields

$$\frac{1}{\lambda}\Delta U_e \approx \int_0^{\hat{t_e}} \frac{1}{\lambda}\frac{\partial U}{\partial t_e} dt_e = \frac{\frac{t_e^2 C_e}{2p_e}\epsilon_e + \frac{t_e t_g C_g}{p_e}\epsilon_{g,e} - \frac{t_e t_l Y}{p_e}\epsilon_L s_e}{1 - t_l\epsilon_{L,Y}}. \tag{A21}$$

B.3 Carbon Tax Excess Burden

Equation (14) can be expressed as

$$\frac{1}{\lambda}\frac{\partial U}{\partial t_c} = \frac{1}{\lambda}\tau_e\frac{\partial U}{\partial t_e} + \frac{1}{\lambda}\tau_g\frac{\partial U}{\partial t_g}. \tag{A22}$$

Employing similar approach in (A20), replacing t_e and t_g with $\tau_e t_c$ and $\tau_g t_c$ in (A20) and the similar excess burden formula for natural gas tax, integrating the right-hand side of (A22) over carbon tax t_c yields

$$\frac{1}{\lambda}\Delta U_c \approx \int_0^{\hat{t_c}} \frac{1}{\lambda}\tau_e\frac{\partial U}{\partial t_e}dt_c + \int_0^{\hat{t_c}} \frac{1}{\lambda}\tau_g\frac{\partial U}{\partial t_g}dt_c, \tag{A23}$$

which leads to the formula of equation (15).

C Auxiliary Regressions

Table C1
Difference in Difference Estimates of Regional Price and Consumption over Time

	Electricity consumption		Natural gas consumption	
Variable	Reg. 1	Reg. 2	Reg. 3	Reg. 4
Constant	-109.319^{**}	-117.480^{**}	-68.953^{***}	-18.004
	(42.425)	(47.757)	(18.255)	(25.006)
Price_e	501.011^{*}	494.927		-358.449^{**}
	(263.420)	(279.02)		(146.100)
Price_g		-80.087	-340.325^{**}	-349.249^{***}
		(159.810)	(109.550)	(83.677)

Note: Asymptotic standard errors in parentheses. *** 1%, ** 5% and * 10% level of significance.

Table C2
Ordinary Least Square Estimates of Regional Price and Consumption

	Electricity consumption		Natural gas consumption	
Variable	Reg. 5 (yr. 05)	Reg. 6 (yr. 09)	Reg. 7 (yr. 05)	Reg. 8 (yr. 09)
Constant	1971.002^{***}	2062.722^{***}	803.301	1045.603^{**}
	(393.100)	(359.400)	(426.850)	316.260)
Price_e	-851.195^{**}	-855.275^{**}		
	(353.630)	(285.95)		
Price_g			-77.294	-208.900
			(283.190)	(225.423)

Note: Asymptotic standard errors in parentheses. *** 1%, ** 5% and * 10% level of significance.