

## VI. Appendix A: Model Methodology

### CEX data organization

Expenditure data is based on the 2007 Consumer Expenditure Survey<sup>71</sup> (CEX). We processed these data using the following steps:

1. In the original CEX data, each response is for a household, income data are annual, and expenditure data are for quarters. We multiply expenditures by 4 to “annualize” these data (see Burtraw et al. 2009). In addition, we removed all incomplete responses (RESPSTAT = 2), all responses where the geographic region was not identified, and all responses with negative values for income, total expenditures, food expenditures, electricity expenditures, total goods expenditures, or total services expenditures.
2. We organize states by the 11 regional groups set out in Burtraw et al.: California, Florida, Mid-Atlantic (Delaware, Maryland, New Jersey, Pennsylvania), Mountains (Arizona, Colorado), New York, Northeast (Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island), Northwest (Idaho, Montana, Oregon, Utah, Washington), Ohio Valley (Illinois, Indiana, Kentucky, Michigan, Missouri, Ohio, West Virginia, Wisconsin), Plains (Kansas, Minnesota, Nebraska, Oklahoma, South Dakota), Southeast (Alabama, Arkansas, District of Columbia, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Virginia), and Texas. Seven states not included in Burtraw et al. were assigned as follows: Alaska (Northwest), Hawaii (Florida), Iowa (Plains), New Mexico (Mountains), North Dakota (Plains), Vermont (Northeast), and Wyoming (Northwest).
3. No responses are attributed to five states in 2007 CEX. For these states we drew data from the regions indicated parenthetically here: Iowa (Plains), New Mexico (Mountains), North Dakota (Plains), Vermont (Northeast), and Wyoming (Northwest).
4. Twelve states had sample sizes of less than 100 in our data set: Arkansas, Delaware, District of Columbia, Kansas, Mississippi, Montana, New Hampshire, North Carolina, Oklahoma, Rhode Island, South Dakota, and West Virginia. We sampled these states’ expenditure data from all responses in their geographic region (e.g., Arkansas expenditure data is sampled from the entire Southeast region).

### Income data

Household income data for the 20<sup>th</sup>, 40<sup>th</sup>, 50<sup>th</sup>, 60<sup>th</sup>, 80<sup>th</sup>, and 95<sup>th</sup> percentile is based on the 2007 American Community Survey.<sup>72</sup> Percentiles were regressed on log income; these regression parameters were used to estimate expected income for the top and bottom of each income decile for each state. These data were then scaled to four-person household sizes by state-decile using household size data from the 2007 CEX. A second linear regression was run for each state with the decile as the independent variable and scaled income as the dependent variable. Coefficients from this regression, by state, were used to estimate the median income in each income decile.

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<sup>71</sup> Bureau of Labor Statistics (2009).

<sup>72</sup> U.S. Census Bureau (2008b).

## Expenditure Data

Expenditure and income responses are scaled to represent a four-person household. The average household size by state-decile is a data point in the original CEX (unscaled) data. For each response, after-tax income was divided by household size and then multiplied by 4; expenditures by category were scaled to maintain their proportion to income. For each state's data, we regress log income separately on each log expenditure category. The median income for each decile in each state is multiplied by the exponential function of the resulting coefficients to estimate the value of each category of expenditures: electricity, household fuels (natural gas and fuel oil), gasoline, air transport, public transportation, food, other goods, and other services. A single scaling factor (2.7) is applied to all expenditure data for the purpose of simultaneously matching two data points: 1) an average propensity to consume of 0.945; and 2) total U.S. CO<sub>2</sub> emissions for 2007, 6,120 million mT. Checking the resulting state-decile expenditures against several other sources of publicly available data, we found good agreement for electricity, household fuels, and gasoline. One of the most important data anomalies was that estimated gasoline expenditures per capita were far below any other state for New York and well above the U.S. mean for the District of Columbia. Adjusting these data for consistency with the pattern seen in other states (which was *not* done in our model) would raise New York and lower D.C. per capita emissions, but would not change the general result that both experience positive net dividends under the scenarios described here.

## Adjusting for Inflation

Data and parameters are adjusted to 2009 dollars using the CPI-U<sup>73</sup> with the following exceptions:

1. Electricity carbon intensities are adjusted to reflect 2009 prices using EIA United States average electricity prices.<sup>74</sup>
2. Gasoline carbon intensities are adjusted to reflect 2009 prices using EIA United States average gasoline prices.<sup>75</sup>

## Carbon Policy Impacts Model

In general terms, our model builds on the methodologies set out in Boyce and Riddle (2007; 2008; 2009) and Burtraw et al. (2009):

$$(1) \quad E = PQ$$

where E = original expenditures (before applying the carbon price), P = price, and Q = quantity of each consumption category purchased. Expenditures are for the median household by state, decile, and consumption category.

$$(2) \quad \frac{\Delta P}{P} = tI$$

where t = carbon price (\$/mT CO<sub>2</sub>), and I = the carbon intensity by consumption category (mT CO<sub>2</sub>/%).

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<sup>73</sup> Bureau of Labor Statistics (2008a), <ftp://ftp.bls.gov/pub/special.requests/cpi/cpi.txt>.

<sup>74</sup> U.S. Energy Information Administration (2010a), [http://www.eia.doe.gov/cneaf/electricity/epm/table5\\_3.html](http://www.eia.doe.gov/cneaf/electricity/epm/table5_3.html).

<sup>75</sup> U.S. Energy Information Administration (2010g), [http://www.eia.gov/dnav/pet/pet\\_pri\\_gnd\\_dcus\\_nus\\_w.htm](http://www.eia.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm).

### Emission Reduction, Interstate Equity, and the Price of Carbon

$$(3) \quad \widehat{E} = PQ + \Delta P \Delta Q = (P + \Delta P)(Q + \Delta Q) = PQ \left(1 + \frac{\Delta P}{P}\right) \left(1 + \frac{\Delta Q}{Q}\right)$$

where  $\widehat{E}$  = after policy expenditures.

$$(4) \quad \widehat{E} = E(1 + tI) \left(1 + \frac{\Delta Q}{Q}\right)$$

$$(5) \quad \frac{\Delta Q^a}{Q} = \varepsilon^d \frac{\Delta P}{P} = \varepsilon^d tI ; \frac{\Delta Q^b}{Q} = \varepsilon^y \frac{\Delta Y}{Y} = \varepsilon^y \frac{netD}{Y}$$

$$(6) \quad \left(1 + \frac{\Delta Q}{Q}\right) = \left(1 + \frac{\Delta Q^a}{Q}\right) \left(1 + \frac{\Delta Q^b}{Q}\right) = 1 + \frac{\Delta Q^a}{Q} + \frac{\Delta Q^b}{Q}$$

ignoring the interaction term.

$$(7) \quad \widehat{E} = E(1 + tI) \left(1 + \varepsilon^d tI + \varepsilon^y \frac{netD}{Y}\right)$$

where netD = net dividend per household by state and decile, summed over consumption categories.

$$(8) \quad R = \widehat{E}tI$$

where R = carbon policy revenue per household by state, decile, and consumption category.

$$(9) \quad D = \frac{k \sum mR}{jn}$$

where D = dividend per person; k = share of revenue returned as dividend; m = number of households by state and decile; j = household carbon policy revenue as share of total revenue; n = total population; and mR is summed over states, deciles, and consumption categories.

$$(10) \quad netD = 4D - \sum_c R$$

where 4D = per household dividend; c = consumption categories; and  $\sum_c R$  = per household carbon policy revenue.

$$(11) \quad C = IE$$

where C = carbon emissions per household by state, decile, and consumption category.

$$(12) \quad \widehat{C} = IP(Q + \Delta Q) = IPQ \left(1 + \frac{\Delta Q}{Q}\right) = IE \left(1 + \varepsilon^d tI + \varepsilon^y \frac{netD}{Y}\right)$$

where  $\widehat{C}$  = after policy carbon emissions.

Because,

$$(13) \quad netD = netD \left( R \left( \widehat{E} (netD) \right) \right)$$

we run the after-policy model in three iterations to approximate a dynamic result.

Iteration 1:

$$(14) \quad \widehat{E}_1 = E(1 + tI) (1 + \varepsilon^d tI)$$

$$(15) \quad R_1 = \widehat{E}_1 tI$$

$$(16) \quad D_1 = \frac{k \sum m R_1}{jn}$$

$$(17) \quad \text{net } D_1 = 4D_1 - \sum_c R_1$$

$$(18) \quad \widehat{C}_1 = IE(1 + tI) (1 + \varepsilon^d tI)$$

Iteration 2:

$$(19) \quad \widehat{E}_2 = E(1 + tI) \left( 1 + \varepsilon^d tI + \varepsilon^y \frac{\text{net } D_1}{Y} \right)$$

$$(20) \quad R_2 = \widehat{E}_2 tI$$

$$(21) \quad D_2 = \frac{k \sum m R_2}{jn}$$

$$(22) \quad \text{net } D_2 = 4D_2 - \sum_c R_2$$

$$(23) \quad \widehat{C}_2 = IE(1 + tI) \left( 1 + \varepsilon^d tI + \varepsilon^y \frac{\text{net } D_1}{Y} \right)$$

Iteration 3:

$$(24) \quad \widehat{E}_3 = E(1 + tI) \left( 1 + \varepsilon^d tI + \varepsilon^y \frac{\text{net } D_2}{Y} \right)$$

$$(25) \quad R_3 = \widehat{E}_3 tI$$

$$(26) \quad D_3 = \frac{k \sum m R_3}{jn}$$

$$(27) \quad \text{net } D_3 = 4D_3 - \sum_c R_3$$

$$(28) \quad \widehat{C}_3 = E(1 + tI) \left( 1 + \varepsilon^d tI + \varepsilon^y \frac{\text{net } D_2}{Y} \right)$$

## Model Parameter Values

### Carbon Intensities

We use carbon intensities for each consumption category that take into account all upstream emissions from materials, manufacture, pre-purchase transportation, and retail and wholesale facilities. Carbon intensities for food, gasoline, air transportation, public transportation, other goods, and other services are based on our work in progress on another study, drawing on EPA’s Greenhouse Gas Inventory, the IMPLAN model data set, and other sources. Intensities are given in mT CO<sub>2</sub>/\$1000 (in 2009\$) in the table below.

Food	Gasoline	Air Transport	Public Transport	Other Goods	Other Services
0.58	3.66	1.26	1.73	0.16	0.15

Carbon intensities for electricity and household fuels vary by state, and are shown in the table below in mT CO<sub>2</sub>/\$1000 (in 2009\$). Electricity emissions intensities are based on data presented in Stanton et al. (2010); carbon intensity for all electricity consumed in each state (including imports) in mT CO<sub>2</sub>/MWh is multiplied by each states’ average retail electricity price. Household fuel emissions intensities are the weighted average of carbon intensities for natural gas and fuel oil where the weights are the shares of natural gas and fuel oil used in each state.<sup>76</sup>

	Electricity	Household Fuels		Electricity	Household Fuels		Electricity	Household Fuels
United States	5.90	5.18	Kentucky	12.70	5.43	Ohio	8.80	5.38
Alabama	6.90	5.49	Louisiana	6.30	5.49	Oklahoma	8.50	5.48
Alaska	4.50	4.79	Maine	2.60	3.23	Oregon	2.50	5.33
Arizona	5.20	5.49	Maryland	7.00	5.06	Pennsylvania	5.30	4.80
Arkansas	6.40	5.49	Massachusetts	4.00	4.45	Rhode Island	3.60	4.36
California	2.90	5.49	Michigan	7.00	5.43	South Carolina	4.20	5.40
Colorado	8.10	5.49	Minnesota	7.90	5.34	South Dakota	6.80	5.31
Connecticut	2.50	4.02	Mississippi	6.00	5.49	Tennessee	8.20	5.46
Delaware	7.90	4.88	Missouri	11.30	5.47	Texas	5.40	5.49
Dist. Columbia	7.00	5.30	Montana	7.80	5.37	Utah	11.30	5.48
Florida	5.70	5.45	Nebraska	8.90	5.47	Vermont	0.60	3.63
Georgia	6.90	5.48	Nevada	5.70	5.44	Virginia	7.10	4.95
Hawaii	3.40	5.49	New Hampshire	2.20	3.72	Washington	2.00	5.32
Idaho	6.40	5.36	New Jersey	3.60	5.12	West Virginia	13.20	5.34
Illinois	5.60	5.48	New Mexico	9.30	5.49	Wisconsin	7.90	5.30
Indiana	11.30	5.44	New York	2.60	4.79	Wyoming	12.10	5.45
Iowa	8.80	5.44	North Carolina	6.20	5.12			
Kansas	9.40	5.49	North Dakota	13.30	5.04			

For electricity emissions, the default carbon intensity values by state are modeled to change dynamically in response to carbon pricing, as discussed below.

<sup>76</sup> U.S. Energy Information Administration (2009c).

**Price Elasticities**

Short-run price elasticities of demand are taken from Boyce and Riddle (2007), and are presented in the table below. We take the average of the price elasticities for natural gas and fuel oil, -0.24, to be the price elasticity of household fuels.

Food	Gasoline	Electricity	Natural Gas	Fuel Oil	Air Transport	Public Transport	Other Goods	Other Services
-0.60	-0.26	-0.20	-0.20	-0.27	-0.25	-0.25	-1.30	-1.00

The price elasticity of demand – for gasoline, electricity, or almost anything else – is smaller in the short run than in the long run.<sup>77</sup> In the short run, consumers respond to the price of gasoline while keeping their current vehicles and travel requirements unchanged; this means that there are very limited opportunities to use less gasoline when prices go up – or to use more when prices drop. In the long run, as the changed prices persist, consumers may buy cars with different fuel efficiency, or even rearrange their lives to require more or less driving; this allows much greater response to a change in fuel prices.

The same is true for prices of other forms of energy, such as electricity. In the short run, consumers respond to electricity prices while keeping their appliances, air conditioning, lighting, and insulation unchanged. In the long run, consumers may also respond by buying different appliances, air conditioning systems, light fixtures, and home insulation; this means that the long-run response to electricity prices is much bigger than the short-run response.

A recent review of hundreds of estimates of gasoline price elasticities from 43 different studies reported a mean short-run elasticity of -.34, and a mean long-run elasticity of -.84 (Brons et al. 2008). A study focused solely on short-run U.S. price elasticity for gasoline found that it had dropped from -.21 to -.34 in 1975-1980, to an unusually low estimate of -.034 to -.077 in 2001-2006 (Hughes et al. 2008). More typical are the findings of a detailed earlier review of international research on gasoline prices, which concluded that short-run price elasticities tend to be between -.2 and -.3, while long-run elasticities tend to be between -.6 and -.8 (Graham and Glaister 2002). Another extensive review, covering hundreds of estimates from dozens of studies performed from 1966 through 1997, found a median of -.23 and a mean of -.26 for the short-run price elasticity of gasoline, and a median of -.43 and mean of -.58 for the long-run price elasticity (M. Espey 1998).

There are fewer research articles on the price elasticity for electricity. One review article found more than 120 estimates of the residential price elasticity of demand in 36 studies, although most of the estimates are from the mid-1980s or earlier (J.A. Espey and Espey 2004). The short-run residential price elasticity for electricity had a median of -.28 and a mean of -.35; the corresponding long-run figures were a median of -.81 and a mean of -.85.

To take account of greater elasticity in fuel and electricity prices over time, we estimate long-run price elasticities by increasing the short-run values for gasoline, electricity, household fuels, air transportation, and public transportation by 50 percent in 2015 and 200 percent in 2020.

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<sup>77</sup> Price elasticities of demand are generally negative, since higher prices lead to smaller purchases. A “smaller” price elasticity means one that is closer to zero, or smaller in absolute value.

## Emission Reduction, Interstate Equity, and the Price of Carbon

### Income Elasticities

We estimate income elasticity of demand using 2007 CEX data for the United States as a whole. Log income was regressed on log expenditures for each category. The resulting coefficients, reported in the table below, are the implied income elasticity of these data.

Food	Gasoline	Electricity	Household Fuels	Air Transport	Other Transport	Other Goods	Other Services
0.32	0.30	0.21	0.23	0.36	0.36	0.56	0.58

### Generator Substitution By Utilities

A price on CO<sub>2</sub> emissions will not only change consumer behavior; it also will cause shifts in the supply of electricity. Lower-carbon sources of electricity will become more economically attractive to utilities, and will be used more. Regional power pools typically “dispatch” (i.e., turn on) generators in increasing order of short-run marginal costs; with a price on carbon, low-carbon generators will move ahead in the dispatch order. The extent of this effect differs from one region to another; accurate calculation requires detailed modeling of individual power pools.

Researchers at Carnegie-Mellon University studied the short-run effects of a carbon price on three power pools, in the Midwest, mid-Atlantic, and Texas (Newcomer et al. 2008). They reported results for three different carbon prices, and for several assumptions about consumer price elasticity. At an elasticity of zero, which “turns off” consumer response and allows observation of pure supply-side response, their results imply an average of 0.06 percent reduction in carbon emissions per dollar of CO<sub>2</sub> price. Of the nine results (three regions at three prices), eight implied ratios between 0.045 percent and 0.078 percent reduction per dollar of carbon price.

In this model, carbon intensities for after-policy expenditures are adjusted for this effect. Every \$1/mT CO<sub>2</sub> in carbon price is translated into a 0.06 percent reduction in every state’s carbon intensity of electricity.

### Energy Efficiency Improvements

In a recent report, energy researchers at Synapse Energy Economics analyzed the costs and technical potential for the elimination of coal and nuclear power from the U.S. electricity system (Keith et al. 2010). Their alternative scenario relies heavily on energy efficiency, wind power, and other renewable energy sources. In a review of recent literature on energy efficiency, they cite estimates of the technical potential for energy savings ranging as high as 3 percent annual reduction in residential electricity use (ibid., p. 61, citing a recent meta-analysis of literature on efficiency). In a review of cost estimates for efficiency measures, they conclude that an average cost of 4.5 cents/kWh saved includes costs borne by customers as well as utilities (p. 63).

**We include an assumed investment in energy efficiency measures from carbon revenues. Investments are allocated to states in proportion to their carbon emissions from electricity. Total investment is capped at the share of revenue for which no state exceeds a 3 percent annual reduction in residential electricity emissions.**