Greenhouse Gas Policy in the Electric Sector – Measuring the Costs and Ancillary Benefits

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Abstract

This work leverages a uniquely-constructed dataset of the US electric grid, integrated into a general equilibrium framework, to assess the costs associated with implementing greenhouse gas policies in the US electric sector. Particular attention is paid to the current menu of available generation and abatement technologies and how substitution among those technologies generates both costs and ancillary benefits in meeting policy requirements. Specifically, we find that while gross policy costs associated with $10 - 20\%$ greenhouse-gas abatement in the electric sector are on the order of \$10 Bn., much of that cost is offset by the ancillary benefits of reduced morbidity and mortality arising from lower levels of NOx and SOx as particulate-matter precursors. With only a subset of ancillary benefits considered, greenhouse-gas abatement in the electric sector may well be a "no regrets" policy.

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1 Introduction

The policy imperative for well-specified estimates of pollution abatement costs has driven economic modelers to incorporate increasing degrees of technical realism into their work. A top-down – bottom-up distinction is often offered at first

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approximation, though this distinction has become less stark with increasing emphasis on various hybrid approaches. Top-down, general-equilibrium models offer a richer measure of economy-wide costs but lack the engineering detail of bottom-up models. Methodological differences in the top-down and bottom-up approaches prevent full integration of the two, resulting in hybrid models that constrain one model type with the output of the other, sometimes in an iterative fashion [9,10].[1]

This work develops a novel scheme for integrating bottom-up technological detail in the benchmark specification of a static national CGE model. Leveraging a specially-constructed dataset on the US electric sector, we capture much of the technical detail commonly omitted from CGE models without imposing external constraints from independent bottom-up model output. We take clean-air policy in the United States electricity sector as the object of analysis, though the construction is sufficiently general that it could be expanded to other sectors, pollution media, and regional aggregations provided adequate bottom-up cost data are available. The current iteration of the model includes a greenhouse-gas equivalent (GHGe) pollutant, three criteria pollutants (NOx, SOx, and PM), and one hazardous pollutant (Hg).

The primary challenge in building a model of this type lies in disaggregating input-output data summarized in macroeconomic accounts to a level of technical, sub-sectoral detail sufficient to reliably represent existing generation and abatement activity. Prior work (cf. [13, 16, 19, 20]) has abstracted a generic abatement sector with an independently estimated marginal abatement cost (supply) curve. Yet not all technologies can avail themselves of the same supply of abatement alternatives and, no matter how well articulated the abatement supply costs, this approach will necessarily impose a profile of abatement alternatives that is less sensitive to the general equilibrium effects of the model.

The solution proposed here is to identify and specify extant abatement technologies such that their cost profiles and output levels move with alternative equilibria. This requires "bottom-up" data for unit costs of generation and abatement and a means for reconciling these data with costs given by national accounts. Bottom-up data are available from the Energy Information Administration (EIA; Forms EIA-860 [3] and EIA-923 [4]), which form a partial basis for the Environmental Protection Agency's (EPA) Integrated Planning Model (IPM), and from EPA (IPM cost assumptions [17]). EPA also provide fuel and technology specific emissions factors for the included pollutants (the AP-42 compilation [2]). We adapt a process outlined by Sue Wing [24] to reconcile these bottom-up data with national macroeconomic accounts data from BLS and BEA.[2]

Once having disaggregated data into a social accounting matrix (SAM) split to the appropriate resolution of production-abatement technologies, we con-

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[1] Examples include: the ADAGE model [23], a top-down approach constrained by bottom-up energy data; EPA's IPM [17], a bottom-up model constrained by macro forecasts; the NewERA model [7], a top-down model that iterates with a bottom-up electric sector model.

[2] This process could just as well be done with state-level data (e.g. IMPLAN [5]) as the bottom-up data can be fully disaggregated to the level of the generating unit.

struct a static CGE model that imposes constraints on the ability to substitute across electric technologies (i.e. to capture grid-level generation load “preferences”). Finally, we leverage the CGE model to examine the cost associated with implementing a greenhouse gas rule akin to that recently outlined by EPA. Total welfare costs are considered alongside co-benefits of ancillary abatement of two of the three modeled criteria pollutants (NOx and SOx). This model is ideal for assessing the near-term cost of imposing new clean air policies on the existing electric grid based on a rich characterization of the current menu of electric generation and abatement technologies.

Section two describes the data construction and reconciliation process. Section three outlines the model structure and specification of abatement trade-offs. Section four examines the welfare impacts of the policy experiments and section five concludes.

2 Data Construction and Reconciliation

2.1 Bottom-up Technology Data

Data in national accounts present an aggregated electric generation, transmission and distribution sector. To capture the heterogeneity of production and abatement alternatives, we require a finer-grain representation, disaggregated along several dimensions to the level of production-abatement technology types. To achieve this, we integrate Forms EIA-923 and EIA-860 data [3,4], IPM generation and abatement cost estimates, and EPA emission factors to provide a comprehensive dataset covering 96% of electric generation, pollution, and abatement activity on the US grid: the Pollution, Abatement, and Generation of Electricity (PAGE) dataset (detailed in Appendix A). All data are for the year 2010 where applicable.

Abatement technologies are for four pollutants: oxides of nitrogen and sulfur, particulate matter, and mercury. Emissions rates depend on the generation technology, fuel type, and installed abatement equipment. Mercury emissions depend on installed mercury technologies as well as nitrogen, sulfur, and PM technologies, which provide mercury reduction co-benefits. Both end-of-pipe and change-in-process technologies are included. Table 1 summarizes the abatement technologies represented in the model. As no independently viable installations yet exist, no CO_2 abatement technologies are specified. The model could incorporate “backstop” specification of these technologies if desired, but the current iteration requires carbon abatement to come from adjustments to the level and mix of extant technologies.

Generation-abatement technology aggregates are further identified by prime mover and fuel type. For each aggregate, the PAGE data provide annualized cost estimates for the use of capital, labor, fuel, and electricity for the distinct generation and abatement equipment comprising the technology aggregate. Abatement equipment electric and fuel requirement costs are based on nameplate and heat rate penalties, respectively. Quantity data are provided

Bottom-up Abatement Activity

Model technology	Fraction of Net Generation	Model technology	Fraction of Net Generation
NOx Controls		*Particulate Controls*	
Low NOx burner	20.44%	Cold side	30.15%
Catalytic reduction	19.68%	Fabric filter	7.19%
Overfire air	4.57%	Hot side	4.41%
Noncatalytic reduction	2.75%	Other methods	1.51%
Other change in process	1.73%	Total	43.26%
Fuel reburning	0.00%		
Total	49.18%		
SOx Controls		*Mercury Controls*	
Wet scrubber	65.47%	Activated carbon injection	5.40%
Dry scrubber	3.64%		
Total	69.11%		

Sources: PAGE dataset: Forms EIA-860 and EIA-923.

Notes: Model technologies aggregate EIA technologies.
A significant amount of mercury abatement occurs as a co-benefit of abating other pollutants.

Table 1: Pollution abatement technologies by pollutant

for electric output, abatement and emissions for the four abated pollutants and a greenhouse-gas equivalent (GHGe) comprised of CO_2, CH_4, and N_2O. Table 2 summarizes relevant costs and quantities at the level of fuel type. Table 3 summarizes four technologies at the technology resolution used in the model.

In all, generation-abatement technologies are specified on five characteristics: particulate matter, sulfur, nitrogen, and mercury controls and fuel type. The PAGE data are generated at the plant-technology level allowing for geographic identification for different regional aggregations. For the purposes of the national model presented here, the data are aggregated to the level of generation-abatement technology. A full summary of the data construction process is provided in Appendix A.

2.2 Bottom-up – Top-down Reconciliation

Macroeconomic input-output data come from national accounts compiled by the Bureau of Labor Statistics (BLS) and Bureau of Economic Analysis (BEA) [11, 12]. Benchmark data are taken for the year 2010 in the form of "make" and "use" tables with a 195-industry resolution and transformed into a social accounting matrix (SAM) at a lower resolution. Even at the higher resolution, only a single "electric power generation, transmission, and distribution" aggregate (NAICS 2211) is presented. These data form the basis of the CGE model and must be reconciled with the bottom-up engineering data discussed in the previous

Bottom-up Electric Sector Data

		Generation				**PM**			**GHGe**
	No.	Q (GWh)	K	L	E	Q (MMT)	K	L	Q (MMT)
Coal	58	1,659,000	$ 21,220	$ 7,700	$ 33,800	0.021	$ 11,030	$ 1,490	2,270
Bituminous	23	890,000	$ 6,420	$ 3,600	$ 22,100	0.007	$ 6,520	$ 861	1,140
Sub-bitum.	29	769,000	14,800	4,100	11,700	0.014	4,510	629	1,130
Lignite	6	80,600	500	326	1,360	0.001	572	63	157
Gas	6	973,000	$ 9,790	$ 2,800	$ 35,400	0.007	$ 133	$ 5	476
Nuclear	1	807,000	$ 18,800	$ 1,320	$ 2,080	0.000	$ 0	$ 0	0
Oil	2	17,600	$ 2,460	$ 113	$ 2,210	0.015	$ 476	$ 1	353
Renewables	1	413,000	$ 12,200	$ 1,160	$ 1,350	0.000	$ 0	$ 0	0
Total Grid	68	3,950,200	$ 64,970	$ 13,419	$ 76,200	0.045	$ 12,211	$ 1,559	3,256

		SOx				**NOx**			
	No.	Q (MMT)	K	L	E	Q (MMT)	K	L	E
Coal	58	0.3	$ 12	$ 879	$ 777	0.2	$ 64	$ 32	$ 29
Bituminous	23	1.6	163	10,200	9,360	1.6	1,750	621	1,936
Sub-bitum.	29	1.2	115	7,760	6,740	1.6	818	228	516
Lignite	6	0.3	12	879	777	0.2	64	32	29
Gas	6	0.0	$ 546	$ 27,000	$ 12,500	0.3	$ 1,350	$ 150	$ 425
Nuclear	1	0.0	$ 0	$ 0	$ 0	0.0	$ 0	$ 0	$ 0
Oil	2	0.6	$ 85	$ 3,670	$ 537	0.0	$ 83	$ 1	$ 1
Renewables	1	0.0	$ 0	$ 0	$ 0	0.0	$ 0	$ 0	$ 0
Total Grid	68	3.6	$ 921	$ 49,509	$ 29,914	3.6	$ 4,065	$ 1,033	$ 2,907

Sources: PAGE dataset: Forms EIA-860 and EIA-923, Annual Energy Outlook (generation costs); EPA IPM V.4.10 (abatement costs); EPA AP-42 emissions factors.

Notes: Quantities are given in gigawatthours (GWh) for net electric generation and millions of tons (MMT) of pollutants. Capital (K), labor (L), and energy (E) values are given in $2010 millions. Labor values represent O&M costs. No. counts the number of model technologies.

Energy values inlcude only fuel costs for generation and fuel plus electricity costs for abatement technologies, which impose heat rate (fuel) and capacity (electricity) penalties. PM abatement has no fuel use. Mercury abatement technology costs are not presented, but total $0.68 Bn for all costs (K, L, & E).

Greenhouse gas equivalent (GHGe) emissions include CO2, CH4, and N2O.

Table 2: Electric generation technologies costs & quantities (2010)

section.

The technologies from the bottom-up data are assumed to employ a portion of the capital, labor, and electricity, all of the fuel, and none of the materials from the generation-transmission-distribution (GTD) aggregate of the national accounts. All of the materials and the remainder of the capital, labor, and electricity are then employed by a transmission and distribution sub-sector. Bottom-up cost estimates are incommensurate with values provided in the macro data and must be reconciled. This is particularly problematic for the technologies' fuel uses, whose bottom-up data yield totals for the various fuel types that differ markedly in absolute and relative magnitude from the top-down data from national accounts.[3]

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[3] This is partly a result of differences in data survey methods across the agencies.

Bottom-up -- Top-down Reconciled Model Technologies				
	Fuel: Sub-Bituminous Coal PM: Fabric filter SOx: Dry scrubbed Hg: None		Fuel: Lignite Coal NOx: Low-NOx boiler PM: Cold-side ESP SOx: Wet scrubbed	
	NOx: Non-Cat.	Catalytic	**Hg:** None	Carbon Inject.
Quantities				
Net Generation (GWh)	3,956	7,411	27,600	12,600
Emissions (Tons)				
SOx	30,670	12,504	91,394	45,235
NOx	11,973	14,272	58,512	26,194
PM	67	27	376	186
Hg	0.14	0.16	0.97	0.04
GHGe	9,050,164	10,800,000	53,800,000	24,100,000
Costs ($2010 MM)	$ 133.1	$ 438.0	$ 1568.4	$ 771.2
Generation	$ 52.4	$ 253.9	$ 767.0	$ 378.0
Capital	$ 3.8	$ 117.0	$ 180.0	$ 83.4
Labor (O&M)	20.9	39.1	111.0	50.6
Fuel (HR Pen.)	27.7	97.8	476.0	244.0
SOx Controls	$ 62.7	$ 120.4	$ 542.7	$ 264.2
Capital	$ 0.5	$ 0.9	$ 3.7	$ 1.5
Labor (O&M)	37.1	69.1	274.0	126.0
Fuel (HR Pen.)	3.8	14.4	86.0	49.3
Electricity (Cap. Pen.)	21.3	36.0	179.0	87.4
NOx Controls	$ 10.5	$ 49.7	$ 19.7	$ 8.7
Capital	$ 1.7	$ 19.9	$ 17.3	$ 7.6
Labor (O&M)	7.7	7.0	2.4	1.1
Fuel (HR Pen.)	0.2	6.5	0.0	0.0
Electricity (Cap. Pen.)	0.9	16.3	0.0	0.0
Hg Controls	$ 0.0	$ 0.0	$ 0.0	$ 18.0
Capital	$ 0.0	$ 0.0	$ 0.0	$ 0.7
Labor (O&M)	0.0	0.0	0.0	4.4
Fuel (HR Pen.)	0.0	0.0	0.0	12.9
Electricity (Cap. Pen.)	0.0	0.0	0.0	23.2
PM Controls	$ 7.6	$ 14.0	$ 239.0	$ 102.3
Capital	$ 7.6	$ 14.0	$ 209.0	$ 88.7
Labor (O&M)	0.0	0.0	30.0	13.6

Sources: PAGE dataset: Forms EIA-860 and EIA-923, Annual Energy Outlook (generation costs); EPA IPM V.4.10 (abatement costs); EPA AP-42 emissions factors.
BLS 2010 input-output data and BEA value-add data.

Notes: Technologies are summarized as they actually appear in the model.
The first two differ only in NOx controls and the second only in Hg controls.

Table 3: Summary of costs & quantities for four model technologies

Total Value: $ 173.9 Bn

Bottom-up, Macro-inconsistent

	Fuel Type						
Cost	BIT	SUB	LIG	GAS	NUC	OIL	RNW
K_{GEN}	0.027	0.062	0.002	0.041	0.079	0.010	0.051
K_{PM}	0.027	0.019	0.002	0.001	0.000	0.002	0.000
K_{SOX}	0.001	0.000	0.000	0.002	0.000	0.000	0.000
K_{NOX}	0.007	0.003	0.000	0.006	0.000	0.000	0.000
L_{GEN}	0.015	0.017	0.001	0.012	0.006	0.000	0.005
L_{PM}	0.004	0.003	0.000	0.000	0.000	0.000	0.000
L_{SOX}	0.043	0.033	0.004	0.114	0.000	0.015	0.000
L_{NOX}	0.003	0.001	0.000	0.001	0.000	0.000	0.000
E_{GEN}	0.093	0.049	0.006	0.149	0.009	0.009	0.006
E_{SOX}	0.016	0.009	0.001	0.027	0.000	0.002	0.000
E_{NOX}	0.003	0.001	0.000	0.000	0.000	0.000	0.000
Total	0.239	0.197	0.017	0.351	0.093	0.040	0.062

Sources: PAGE dataset: Forms EIA-860 and EIA-923, Annual Energy Outlook (generation costs); EPA IPM V.4.10 (abatement costs).

Notes: Fuel types define sample technologies. Mercury abatement costs are excluded for this example. The matrix sums to one dollar of electric grid output. The matrix times total value gives nominal input values.

Table 4: Example technology-by-input unit-cost matrix

Drawing on the bottom-up data, we produce a technology-by-input unit-cost matrix of grid generation and minimally revise the matrix entries such that they reconcile with the relative fuel-use values given by macro accounts. We then scale the unit matrix by the fuel use totals from the macro data and remainder a minimum quantity of labor and capital (along with all materials) to the transmission and distribution sub-sector. An example unit cost matrix with technologies defined only on fuel type is presented in Table 4. The actual unit cost matrix used for the model represents approximately 70 technologies (defined on fuel type and abatement technologies). All model technologies are listed in Appendix C.

The unit cost matrix sums to one by construction and all values are positive, hence it is a discrete probability distribution. To measure the extent to which we revise the bottom-up unit cost matrix, we use the Kullback-Leibler divergence, a standard information-theoretic pseudo-metric. We then minimize the divergence between the original and revised unit cost matrices subject to reconciling with the macro data. Both matrices must sum to one to ensure that the divergence measure is well-behaved and that the zero-profit condition on the Social Accounting Matrix (SAM) is met. All output of the generation-abatement technologies is purchased by the transmission and distribution (TD) sub-sector at a price equaling the value of inputs to ensure market clearance for the technologies and zero profit for the TD sub-sector. We first constrain the revised matrix to sum to one unit of output, ensuring no economic profits are reaped. These constraints and a revision process analogous to that described above are outlined by Sue Wing [24].

We impose two additional constraints on the revised matrix. The first ensures that the total values of coal, gas, and oil implied by the revised unit-cost matrix match the values given by the macro data. The second ensures that the values of capital and labor implied by the revised matrix do not exceed what is available to the aggregate electric sector in the macro data, less a minimum amount of labor and capital for the transmission and distribution sub-sector. We base this minimum on ratios of capital and labor to materials inputs for a sample of RTOs and ISOs.[4]

The fuel value constraints are derived from the following identities.

$$\sum_f \sum_c \tilde{\sigma}_{cf} = E_c/\omega_G \tag{1a}$$

$$\sum_f \sum_o \tilde{\sigma}_{of} = E_o/\omega_G \tag{1b}$$

$$\sum_f \sum_g \tilde{\sigma}_{gf} = E_g/\omega_G \tag{1c}$$

where $\tilde{\sigma}$ is the revised unit cost matrix (σ the original, analogous to Table 4), ω_G represents the total dollar value of generation output (e.g. \$174Bn in Table 4) on which the unit cost measures are based, the c, o, and g subscripts denote the subset of technologies (t) relying on coal, oil, and gas, respectively, and the f subscript represents the fuel-use input rows (e.g. E_{GEN} – E_{NOX} in Table 4) of the revised sigma matrix. Taking ratios of the equalities in eqn. (1) will constrain our shares by ratios of the known, fuel values in the macro data (F_c, F_o, F_g). Specifically, we require that:

$$\sum_f \sum_c \tilde{\sigma}_{cf} / \sum_f \sum_o \tilde{\sigma}_{of} = F_c/F_o \tag{2a}$$

$$\sum_f \sum_c \tilde{\sigma}_{cf} / \sum_f \sum_g \tilde{\sigma}_{gf} = F_c/F_g. \tag{2b}$$

Both our benchmark and revised shares are defined positive. We then constrain the ratio of coal to the desired levels of total capital and labor for all technologies.

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[4] Electric transmission and distribution entities that manage the electric grid: Regional Transmission Organizations and Independent System Operators.

For example, given a desired minimum value of capital in the transmission and distribution sub-sector, K_{TD}, and known value of coal, F_c, we require that:

$$\sum_f \sum_c \tilde{\sigma}_{cf} / \sum_k \sum_t \tilde{\sigma}_{tk} \geq \tfrac{F_c}{K_{ETD} - K_{TD}} \tag{3a}$$

$$\sum_f \sum_c \tilde{\sigma}_{cf} / \sum_l \sum_t \tilde{\sigma}_{tl} \geq \tfrac{F_c}{L_{ETD} - L_{TD}} \tag{3b}$$

where l (e.g. L_{GEN} – L_{NOX} in Table 4) and k (e.g. K_{GEN} – K_{NOX} in Table 4) are subsets of labor and capital inputs and L_{ETD} and K_{ETD} are the total amount of electricity-sector labor and capital given by the macro data. Finally, we require zero-profit in generation:

$$\sum_{ti} \tilde{\sigma}_{ti} = 1 \tag{4}$$

In sum, to derive the revised unit-cost matrix we minimize the Kullback-Leibler divergence of the original and revised unit-cost matrices (distributions):

$$D_{KL}(\sigma || \tilde{\sigma}) = \sum_{ti} \sigma_{ti} \ln(\sigma_{ti} / \tilde{\sigma}_{ti}) \tag{5}$$

subject to constraints 2, 3, and 4. All constraints bind. The algorithm is not permitted to revise original zero values at all and is infinitely penalized for revising original non-zero values to zero.

With our revised share matrix, $\tilde{\sigma}$, we can disaggregate the SAM's electric sector aggregate. Drawing on our fuel-value identities (1), our original fuel input values divided by the sum of corresponding fuel input shares in the revised matrix gives the total value of generation, which can be used to scale the share matrix to a matrix of input dollar values consistent with macro data. A sample of four of the sixty-eight technologies produced by this method are summarized in Table 3.

3 Model Structure

3.1 General Structure

We construct a static model with one government and one household agent, a detailed electric sector, and fourteen other sectors, which are summarized in Table 5. A common production structure is shared by the non-resource sectors differing only in the degree of input substitution. Pollution is modeled only within the electric sector.

Producers demand intermediate goods from other sectors and fixed factors from households (i.e. labor and capital) and allocate an equal value (by zero profit) of output to other sectors and final demands (i.e. the household, government, and foreign markets) and investment. Outside the resource-intensive

Sector Inputs ($2010 Bn)

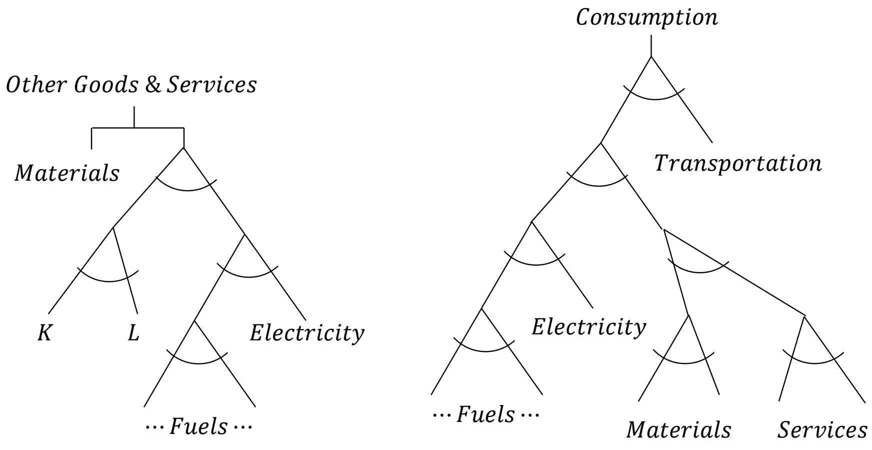
	Value-add			Intermediate		
Sectors	Capital	Labor	Taxes	Energy	Materials	Total
Energy						
Natural gas distribution	87.5	11.0	1.9	294.2	32.3	427.0
Electric T&D (aggregate)	88.3	43.7	37.5	37.3	56.4	263.3
Petroleum and coal prod manuf.	87.4	25.2	23.6	21.8	52.1	210.1
Oil and gas extraction	22.8	11.3	9.7	57.8	17.8	119.4
Coal mining	6.2	3.9	1.0	2.2	7.2	20.5
Total	$ 292	$ 95	$ 74	$ 413	$ 166	$ 1,040
Energy Intensive						
Manufacturing	536.9	846.2	68.9	141.3	2,364.7	3,958.0
Municipal and Infrastructure	151.0	326.4	13.6	48.8	416.1	955.9
Transportation	104.4	197.7	19.6	76.9	263.2	661.7
Mining (non-fuel)	25.5	29.8	3.4	6.7	51.0	116.4
Total	$ 818	$ 1,400	$ 106	$ 274	$ 3,095	$ 5,692
Other						
Services	2,594.4	3,515.1	348.9	142.6	3,946.5	10,547.5
Trade	400.0	831.3	323.1	27.2	620.2	2,201.7
Special Industries	622.9	0.0	137.8	6.0	358.9	1,125.6
Agriculture	79.6	35.0	-0.8	21.1	165.5	300.4
Total	$ 3,697	$ 4,381	$ 809	$ 197	$ 5,091	$ 14,175
Government						
Public Government	235.9	1,293.7	0.0	37.7	567.9	2,135.3
Government Enterprises	10.5	81.6	-6.0	7.2	35.2	128.4
Total	$ 246	$ 1,375	-$ 6	$ 45	$ 603	$ 2,264
Grand Total	$ 5,053	$ 7,252	$ 982	$ 929	$ 8,955	$ 23,171

Sources: BLS 2010 input-output data and BEA value-add data.
Notes: The electric transmission & distribution sector is as presented in national accounts.

Table 5: Summary of SAM sectors

electric, fuel, and agriculture sectors, production technologies aggregate labor and capital, which is traded-off with an energy aggregate of electricity and fuel inputs. The energy-value-add aggregate then enters Leontief with materials (i.e. all other sectoral goods). Figure 1a diagrams the production structure for non-primary-resource sectors (primary-resource sectors are described further below). Imports and domestic production are combined as imperfect substitutes for the goods market via Armington aggregation “production” [8]. Elasticity parameters are based on those in the MIT EPPA model [21] and are summarized in Appendix B.

A representative household constructs welfare from consumption alone, which is funded by the value of endowments of labor, capital, and transfer payments. The entire labor endowment is marketed each period – no leisure value is specified. Benchmark fiscal and balance of payments deficits are endowed to the government agent who makes a lump-sum transfer to the household to cover



(a) Non-primary-resource sectors (b) Consumption good

Figure 1: Production Structures

private debts.

Tax payments accrue to the government agent to offset government expenditure on public goods. The representative household owns the pollution permits and use their proceeds to offset consumption purchases. Permits have no value in the benchmark. A government public good is produced in a Leontief block and government enterprises carry a production structure similar to non-resource private sectors but with attenuated substitution elasticities.

3.2 Consumption

All welfare impacts are borne by the household. Real government purchases are held constant and the consequent deficits of policy-induced changes in government revenue and expenditure are funded by the household. All endowments are owned by the household (i.e. labor and all types of capital). Real investment and net exports are held constant. The household trades-off transportation and all other consumption, which aggregates energy and non-energy goods. Energy goods aggregate fuels and electricity and other consumption aggregates materials and services separately. Figure 1b diagrams the "production" structure for the household consumption good.

3.3 Resource-Intensive Sectors

3.3.1 Electric Generation, Abatement, Transmission & Distribution

The electric sector is built from the bottom up. Its key feature is the micro-specified generation-abatement technologies. Each technology requires a particular mix of capital, labor, fuel, and electricity to operate its generation and abatement equipment (if it runs any). Each technology produces outputs of

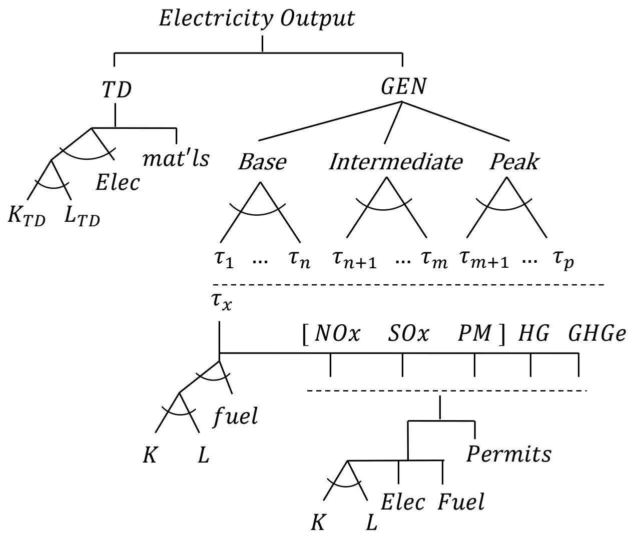


Figure 2: Electric generation, transmission, & distribution production structure

electricity and unabated pollution. Pollution permits are required for the quantities of pollution that each technology's installed abatement equipment cannot abate. Pollution quantities are determined by the specific generation-abatement technology pair and are emitted in fixed relation to the technology's total electric output. This implies that the abatement technology is also run in fixed relation to total electric output. The upper-most nest of the CES production function for a given technology is then a Leontief aggregation of electric generation output, abatement services, and pollution permits (see below the first hashed line in Figure 2).

Given the fixed pollution-generation relationships of the individual technologies, the model's abatement-pollution substitution must occur across technologies, not within. As an example, consider mercury abatement in the context of the second two technologies summarized in Table 3. Here we see how the model's electric clearing house can choose between generation from a lignite-coal-fired generator with a low-NOx boiler, a cold-side electrostatic particulate precipitator, wet-scrubbed desulfurization, and no mercury technology and the same technology with an active-carbon injection mercury control device. The reality such model behavior represents might be a retrofit or new construction, but this distinction is abstracted in the model – a mark of its top-down approach.

The model's electric clearing house then aggregates the output of the discrete generation-abatement technologies into a single electricity good for consumption by other sectors and agents. Substitution across technologies is limited by the load they serve and motivated by changes in relative prices of the labor, capital, environment, and energy inputs required to operate the technologies. The strength of this approach is that it requires full specification of the technology for each productive generation and abatement option, avoiding further abstraction to a generalized abatement service sector. That is, if more abatement is to be done without simply reducing grid output, this approach forces the modeler to articulate specifically by what available technologies it might be achieved. Specifying discrete technologies in this way attenuates the oft-critiqued excessive "smoothness" of the top-down approach without compromising the overall method.

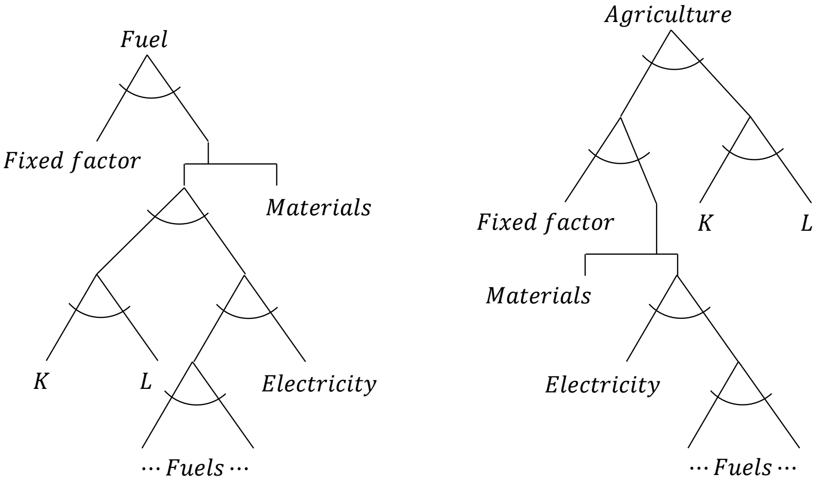
The electric clearing house aggregates these technologies first into base, mid, and peak load "nests." This structure helps preserve the extant technological heterogeneity on the grid and limits the extent to which low-cost, base-load technologies can compete with peak-load technologies whose higher cost is justified by other services they provide to the grid (e.g. fast ramp times). Labor and capital for the TD sub-sector are aggregated with substitution and enter Leontief with materials and the electricity aggregate to produce final electricity output. Figure 2 diagrams the production structure. Hashed horizontal lines indicate that the structure below is repeated for all elements immediately above.

Individual technologies purchase permits from the household. (Permits enter Leontief with abatement in Figure 2, but are just as well considered Leontief to the technology's electric output given the structure.) In this way, the relative costs on which the clearing house chooses its technology portfolio are driven by the technologies' permit requirements, resulting in a higher marginal cost of electricity output. This generates both the substitution and total output effects necessary to reduce GHGe emissions.

3.3.2 Primary-Resource Sectors

In models with constant returns to scale in production, rate limiting of economic growth is imposed primarily by the availability and productivity of fixed factors, the most basic of which are labor and capital. Fuel production is further limited by fixed quantities of raw fuel stocks and limited extraction capacities. Regardless of the output price, only a certain quantity of fuel can be produced in a given period. In a similar way, agricultural production is limited by a fixed quantity of arable land.

To implement this dynamic in the model, fuel producers must draw on a set endowment of technologically feasible fuel inputs and agricultural producers on a set endowment of land capital. The value of these sector-specific factors is deducted from the capital given in the macro data. A similar procedure is completed for renewable and nuclear generation technologies, whose fuel inputs are assumed to be paid in part to capital premia. This offers a mechanism for restricting certain technologies from expanding to levels that are known to be unrealistic in terms of physical or policy constraints not otherwise represented in the model. Figure 3 diagrams the fuel and agriculture sectors' production structures.



(a) Fuel sectors (b) Agriculture sector

Figure 3: Primary-resource sectors production structures

3.4 Policy Design

Pollution permits are the model mechanism for implementing clean-air policies in the modeled electric sector. Permits are only demanded, in a Leontief structure, by the generation technologies. Permits are endowed to the representative household in an amount equal to that required to run the grid in the benchmark. Policies are implemented by reducing the quantity of endowed permits for the pollutant targeted by the policy. Benchmark permit prices are set equal to zero so that generation technologies' costs are not disturbed.

The pollution permits are primarily a modeling tool. In the abstract, they allow the modeler to identify the least expensive means for reaching a target level of emissions given extant technologies. This is an ideal formulation for criteria pollutants and greenhouse gases, for which standards are or would most likely be set according to ambient levels. By contrast, hazardous air pollutant (HAP) policies are typically implemented via a maximum achievable control technologies (MACT). So evaluating a HAP policy (e.g. a mercury rule) would warrant different treatment than criteria pollutants and could be easily accommodated within the model by modifying the various technologies cost structures and emissions factors with reliable cost and performance estimates for the MACT.

Real government expenditures are held fixed without substitution and resulting deficits are borne by the households. Deficits are generated by the interaction of changes in prices and tax revenues. Equivalent variation is then measured by the dollar-quantity change in the household consumption (cf. [22]).

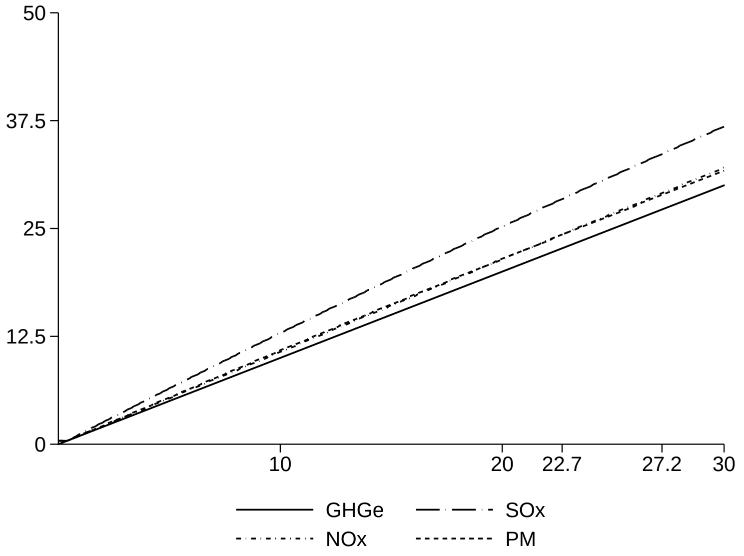


Figure 4: Percent reduction in emissions for targeted & other pollutants

4 Policy Experiments Results & Conclusion

4.1 Static Model Results

Abatement activity of any given pollutant may come with a suite of co-benefits from ancillary abatement of other pollutants. Abatement is achieved both by changing the composition of operating generation and abatement technologies and by reducing the total level of electric output. In both cases, levels of pollutants not targeted by the policy intervention are also subject to change. This ancillary abatement has value and, even absent reliable estimates on the value of abatement benefits for the targeted pollutant, is an important consideration in the cost-benefit assessment of clean-air policies.

As an example of co-abatement under a greenhouse gas policy, consider the first two model technologies presented in Table 3. If greenhouse gas permits are expensive enough, the second technology will be favored to the first for its lower GHGe emissions factor ($1,457$ vs. $2,287$ tons/GWh). The second technology also has a lower NOx emissions factor (1.93 vs. 3.03 tons/GWh). So the greenhouse gas policy has also induced NOx abatement and, in this case, actually led to an equivalent percent decline in NOx and greenhouse gases (36.3%), *ceteris paribus.*

This simplified example has abstracted away from the explicit cost considerations made by the electric clearing house in choosing technologies, but demonstrates how ancillary abatement is likely to come about. Figure 4 demonstrates how this dynamic unfolds in the model by plotting percent reductions in three

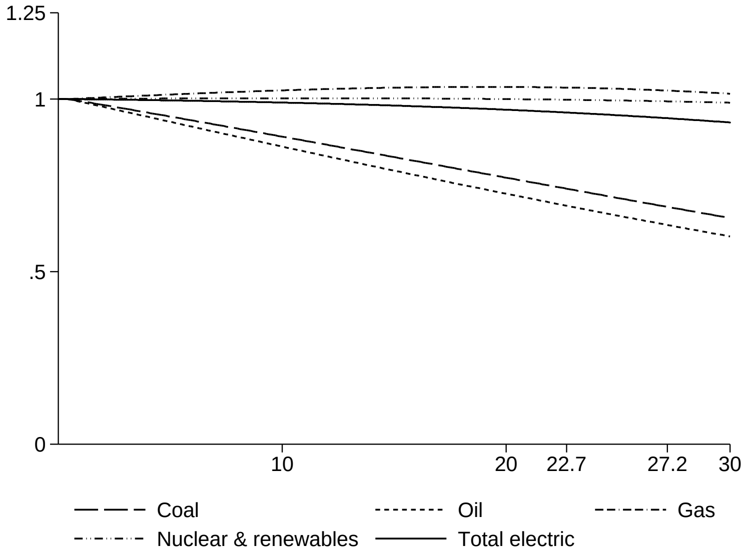


Figure 5: Total and fuel-specific electric output under a GHGe policy

pollutants (NOx, SOx, and PM) for a range percent-reduction policies on greenhouse gases. Most notable here is that all non-targeted pollutants experience *larger* abatement percentages than the targeted greenhouse gases.

Greenhouse gases have no available control technologies in this model so abatement must be achieved through a combination of technology substitution and reduced electric output. Figure 5 presents the changes in output for four technology categories (based on fuel type) and total electric output. Electric output begins its decline immediately after the implementation of the policy driven by sharp declines in coal and oil and offset by larger nuclear, renewable, and gas technologies' output.

The final task is to consider what value certain of the policies ancillary benefits might carry. Here we rely on benefit estimates by Fann, Fulcher, and Hubbell [15] for NOx and SOx as PM precursors. Fann et al. provide dollar estimates of the benefits associated with abating NOx and SOx strictly as a function of their being precursors to particulate matter formation. These benefits arise primarily from reduced mortality and morbidity from a variety of types of illness (e.g. respiratory, cardiac). Fann et al. estimate national benefits for abatement from electric generating unit sources of \$15,000 per ton for NOx and \$82,000 per ton for SOx. Marginal benefits are assumed to be declining in the amount of abatement achieved with a demand elasticity of 5. That is, after 20% ancillary abatement of NO_x or SO_x, additional abatement is assumed to have no further economic benefit. Valuing this particular subset of benefits alongside the welfare costs provides a more comprehensive estimate of the net

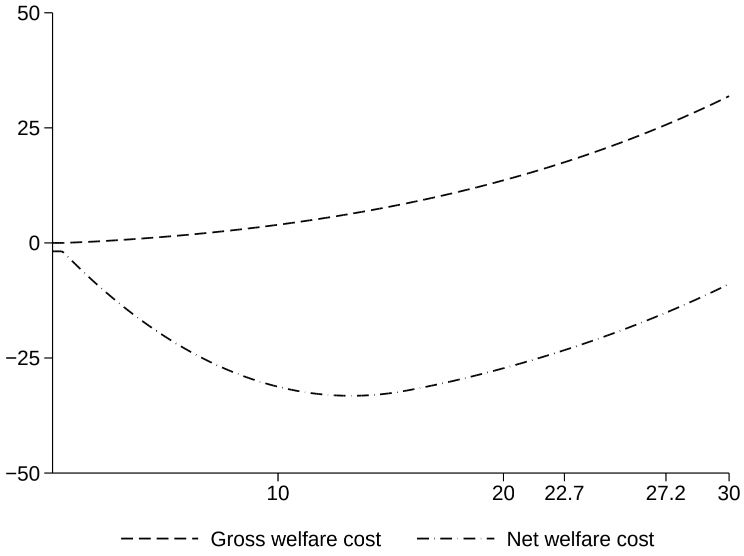


Figure 6: Gross and net welfare cost of an electric-sector GHGe policy

cost of the policy. Figure 6 presents the total and net-of-benefits welfare cost of a greenhouse gas policy.

Considering only the health benefits of NOx and SOx as PM precursors, the net GHGe policy cost is negative through a all 30% of greenhouse gas reductions, suggesting a possible "no regrets" policy window for greenhouse gas abatement in the electric sector. Next we consider alternate modeling scenarios designed to represent plausible constraints on electric-sector compliance that might drive gross policy costs higher.

4.1.1 Alternative estimates

In the above estimates, electric generation technologies' capital is free to be reallocated to other purposes. In reality, reallocations are likely to leave some capital "stranded" in existing relatively "dirty" generating units. To model this behavior, we immobilize a certain fraction of generation and abatement capital by generating separate markets for them. Creating these markets has two primary effects, both of which will drive gross welfare costs higher. First, generation and abatement capital allocated to the new technology-specific markets is no longer free to be reallocated to other purposes. This restricts the supply of capital available to new installations thereby increasing the cost of expanding cleaner generation. Second, as demand for "dirty" capital installations drops, with no alternate uses, the value of this capital falls and households incur losses.

Separate capital markets are created for fossil-fuel generation technologies and pollutant-specific abatement technologies (five new markets). All but a

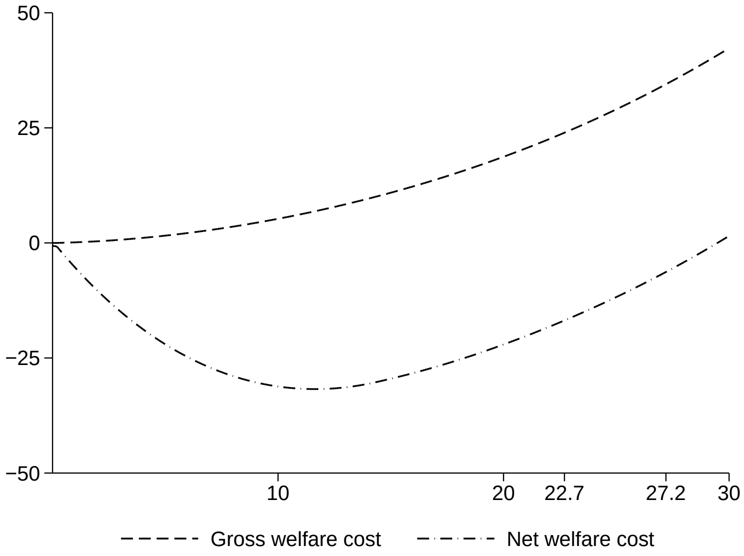


Figure 7: Gross and net welfare costs with “stranded” capital

nominal amount ($1, 000) of capital used by the technologies is designated to its corresponding market. A capital production block aggregates the former amount with the nominal residual drawn from the general capital pool to produce the total quantity of capital used by the technologies. In this way, the initial quantity of capital used by the generation and abatement technologies (less a nominal amount) is left “stranded” within the technologies, though new capital can still be added. The capital production block aggregates technology-specific and general “jelly” capital with an elasticity of 5.

Figure 7 compares gross and net welfare costs associated with greenhouse gas abatement policies with the capital constraint. As expected, welfare costs are higher – 33% higher than without stranded capital at maximum. Welfare costs net of benefits still remain negative until 29.5% GHG abatement. In both scenarios, the NOx and SOx ancillary benefits provide a substantial reduction of gross costs and are $10-20\%$ higher with the capital constraint but converging for higher abatement levels.

Figure 8 shows changes in total and fuel-specific electric output in both scenarios. The capital-constrained scenario has gas generation playing a larger role in absorbing reallocation and greater total generation than the unconstrained scenario. Gas generation with the capital constraint will be relatively cheaper in that fossil-fuel-generation capital is freed from the relatively dirty coal and oil generation with only gas generation to absorb the newly available supply. This dynamic is particularly evident at reductions beyond 15%.

Last, GHGe permit prices are higher in the capital-constrained scenario as

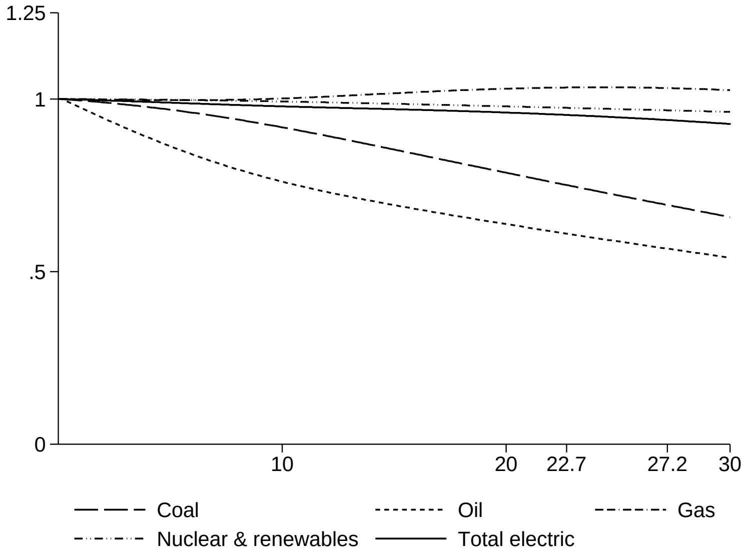


Figure 8: Electric output with "stranded" capital

expected. Prices reach a high of $\$50 - 60$ per ton and are comparable with and without stranded capital. Figure 9 shows permit prices for the range of GHG abatement levels.

5 Conclusion

This work leveraged a uniquely detailed CGE model of the electric sector in the United States to estimate the costs and ancillary benefits of abating air pollution. In particular, we find that, given existing electric generation and abatement technologies, the welfare costs associated with greenhouse-gas abatement are largely offset by the ancillary benefit of NOx and SOx abatement. That is, without considering the direct benefits of GHG abatement, whose valuation can be challenging, net policy costs do not appear to pose an appreciable hurdle for these benefits to clear.

These results give a preliminary indication that multi-pollutant linkages could play a significant role in mitigating, or potentially driving, environmental policy costs. This analysis has not considered what ancillary costs might obtain with a GHG policy. For example, natural gas generation grew in both scenarios considered. Recent opposition to the expansion of natural gas extraction has demonstrated that it may pose unique environmental costs itself that could add to welfare losses from carbon policy. Moreover, we have not considered how the general equilibrium outcomes may influence pollution in other sectors. Again, losses in the natural gas extraction and distribution system are a notable source

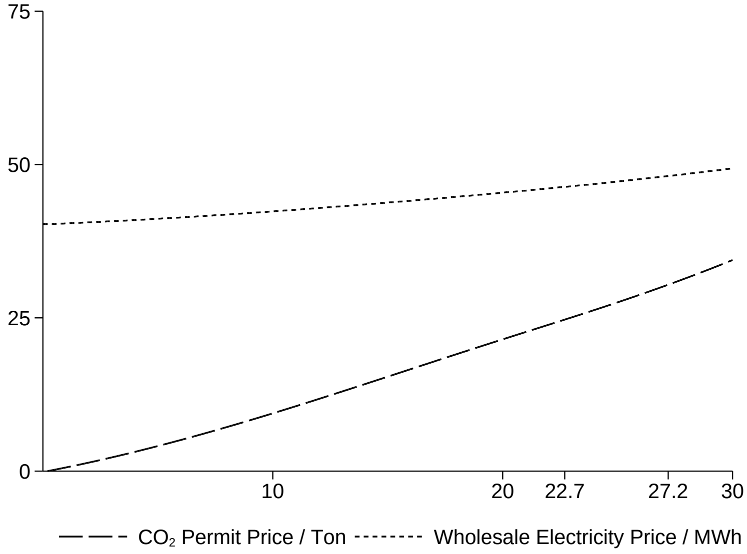


Figure 9: Permit and electricity prices with "stranded" capital

of greenhouse gases, which could offset some gains achieved by a GHGe policy.

Future work could improve the estimates here by adopting a regional or even state-level aggregation scheme, possibly with state-level policy implementation. A more nuanced approach to capital markets and the role of capital vintages in the model might also produce more accurate estimates. While these modifications will likely change the level estimates of policy costs and ancillary benefits, they are not likely to change the central message that multi-pollutant linkages through the technology structure of the electric sector, or other emitting sectors for that matter, are a critical consideration in cost-benefit analysis of clean-air policy.

References

[1] Gross domestic product: Implicit price deflator (GDPDEF). Technical report, Bureau of Economic Analysis, Washington, D.C.

[2] AP 42, Fifth Edition, Compilation of Air Pollutant Emission Factors, Vol. 1. Technical report, Office of Air Quality Planning and Standards, Environmental Protection Agency, Research Triangle Park, NC, 1995.

[3] Form EIA-860. Technical report, Energy Information Administration, Washington, D.C., 2010.

[4] Form EIA-923. Technical report, Energy Information Administration, Washington, D.C., 2010.

[5] State-Level U.S. Data for 2010, 2012.

[6] Electricity, Wholesale Market Data. Technical report, Energy Information Administration, Intercontinental Exchange, Washington, D.C., 2013.

[7] The NewERA Model, 2013.

[8] Paul S. Armington. A Theory of Demand for Products Distinguished by Place of Production. *Staff Papers - International Monetary Fund*, 16(1):159–178, 1969.

[9] Christoph Böhringer and Thomas F. Rutherford. Combining Bottom-up and Top-down. *Energy Economics*, 30(2):574–596, March 2008.

[10] Christoph Böhringer and Thomas F. Rutherford. Integrated Assessment of Energy Policies: Decomposing Top-down and Bottom-up. *Journal of Economic Dynamics and Control*, 33(9):1648–1661, September 2009.

[11] Bureau of Economic Analysis. Gross-Domestic-Product-(GDP)-by-Industry Data, 2012.

[12] Bureau of Labor Statistics. Inter-industry realtionships (Input/Output matrix), 2012.

[13] Rob Dellink, Marjan Hofkes, Ekko van Ierland, and Harmen Verbruggen. Dynamic Modelling of Pollution Abatement in a CGE Framework. *Economic Modelling*, 21(6):965–989, December 2004.

[14] Energy Information Administration. Assumptions to the Annual Energy Outlook 2010 - Electricity Market Module, Report No. DOE/EIA-0554(2010). Technical report, Department of Energy, Washington, D.C., 2010.

[15] Neal Fann, Charles M. Fulcher, and Bryan J. Hubbell. The influence of location, source, and emission type in estimates of the human health benefits of reducing a ton of air pollution. *Air Quality, Atmosphere, & Health*, 2(3):169–176, September 2009.

[16] Reyer Gerlagh, Rob Dellink, Marjan Hofkes, and Harmen Verbruggen. A Measure of Sustainable National Income for the Netherlands. *Ecological Economics*, 41:157–174, 2002.

[17] ICF Resources, LLC. Standalone Documentation for EPA Base Case 2010 (V.4.10), Using the Integraded Planning Model. Technical report, Environmental Protection Agency, 2010.

[18] Stan Kaplan. Power plants: Characteristics and costs, Order code RL34746. Technical report, Congressional Research Service, Washington, D.C., 2008.

[19] O. Kiuila and Thomas F. Rutherford. The Cost of Reducing CO2 Emissions: Integrating Abatement Technologies into Economic Modeling. *Ecological Economics*, 87:62–71, March 2013.

[20] Deborah Vaughn Nestor and Carl A. Pasurka. Environment-Economic Accounting and Indicators of the Economic Importance of Environmental Protection Activities. *Review of Income and Wealth*, 41(3):265–287, 1995.

[21] Sergey Paltsev, John M. Reilly, Henry D. Jacoby, Richard S. Eckaus, James McFarland, Marcus Sarofim, Malcolm Asadoorian, and Mustafa Babiker. The MIT Emissions Prediction and Policy Analysis (EPPA) model: Version 4. Technical Report 125, MIT Joint Program on the Science and Policy of Global Change, Cambridge, MA., 2005.

[22] William A. Pizer and Raymond Kopp. Calculating the Costs of Environmental Regulation. 2003.

[23] Martin T. Ross. Documentation of the Applied Dynamic Analysis of the Global Economy (ADAGE) Model Model. 2008.

[24] Ian Sue Wing. The synthesis of bottom-up and top-down approaches to climate policy modeling: Electric power technology detail in a social accounting framework. *Energy Economics*, 30(2):547–573, March 2008.

Appendices

A Data Construction

A.1 The PAGE Dataset

The Pollution, Abatement, and Generation of Electricity (PAGE) dataset is built on Energy Information Administration (EIA) and Environmental Protection Agency (EPA) data sources. All sources are for 2010 where applicable. Forms EIA-860 and EIA-923 provide a boiler- and abatement-equipment- level summary of 96% of electric generation on the US grid.

A.1.1 Operating Costs

Form EIA-923 data provide generation output and fuel use quantities for each technology installation in the data. Fuel use and electric output quantities are first summarized at the plant-fuel-generator level (approx. 9,300 obs.). Installations of abatement equipment are summarized at the installation-boiler level. The mapping is many-to-many. Some boilers have multiple abatement equipment installations and some installations service multiple boilers.

Cost estimates are capacity-specific. Generating units are categorized on nameplate (NP) capacity as small ($\text{NP} < 300$ MW), medium ($300 \leq \text{NP} < 700$ MW), and large ($\text{NP} \geq 700$ MW). Nameplate data are incomplete. Missing observations are estimated based on prime mover and net generation.

Abatement equipment operating costs are sourced from EPA's IPM [17, Ch. 5]. Fixed capital and O&M costs are specific to the nameplate capacity the installation services. Variable O&M costs are independent of nameplate. O&M costs are allocated entirely to labor, though likely comprise some materials. Heat-rate penalties are valued at a wholesale fuel price and allocated to fuel inputs. Capacity penalties are valued at a wholesale electric price and allocated to electric inputs.

Generation equipment operating costs are sourced from EIA's Annual Energy Outlook [14, Table 8.2]. O&M costs are allocated to labor. AEO technologies are matched to extant grid technologies to assign cost estimates. Cost estimates are adjusted for the "extraordinary rate" of increase in construction costs during the aughts [18, p. 18]. All capital values are amortized at 6.15% over a 20-year life as in IPM [17, Ch. 8].

Fuel price-per-BTU data are provided for fuel purchases made by a subset of installations. Fuel-region quantity-weighted averages are used to estimate the value of the heat-rate penalties of abatement equipment. National averages are used where fuel-region averages are unavailable.

Electricity wholesale prices are provided by trading hub by EIA [6]. Trading hubs are mapped to North American Electric Reliability Corporation (NERC) regions and region-specific volume-weighted average wholesale electricity prices are used to value the capacity penalties imposed by abatement equipment. Missing data for certain regions are approximated from neighboring regions.

All values are adjusted to \$2010 using the Bureau of Economic Analysis "GDPDEF" series [1] for the final PAGE dataset. For the purposes of the model, only relative values enter the bottom-up – top-down reconciliation process.

A.1.2 Emissions

Emissions for oxides of nitrogen and sulfur, particulate matter, mercury, carbon dioxide, nitrous oxide, and methane are estimated. A variety of additional pollutants can be included based on data given in the AP-42 compilation [2]. Carbon dioxide, nitrous oxide, and methane are combined into a single greenhouse-gas equivalent (GHGe) measure based on common global warming potential multipliers. Emissions are driven by a combination of fuel-specific, uncontrolled emissions factors [2] and abatement equipment removal efficiencies (Form EIA-860).

Emissions factors rely on fuel sulfur and ash contents, whose empirical averages are taken from Form EIA-923 fuel-use data. These data are given at the boiler level but do not cover all installations. Fuel-specific sulfur content estimates given by Form EIA-923 documentation are modified by the empirical averages in the Form EIA-923 fuel-use data to generate fuel-region-specific averages (using census regions).

Mercury emissions are particularly sensitive to installations of non-mercury abatement equipment. Mercury emissions are estimated as the product of uncontrolled emissions rates from the EPA AP-42 compilation [2] and emissions modification factors from EPA's Integrated Planning Model [17, Table 5-13]. The modification factors are a function of burner and fuel types plus NOx, SOx, and particulate controls. All other uncontrolled emissions rates are taken directly from the EPA AP-42 compilation [2, Ch. 1] based on fuel type.

Emissions removal efficiencies of the installed equipment are given in the Form EIA-860 data. Where data are missing, abatement-technology averages are applied. These removal efficiencies are used to estimate total abatement and emissions for each installation.

A.1.3 Summary & aggregation

The final dataset then contains capital, labor, fuel, and electricity costs along with electricity and pollution output quantities for each generation and abatement equipment installation on the US grid that is represented in Forms EIA-860 and EIA-923 data – approximately 9,700 installations. The final step in preparing the data for the model is to summarize these values and quantities at a technological resolution sufficiently low for model feasibility.

Collapsing the installations on all technological attributes contained in the dataset produces 173 distinct technologies. To further collapse the data for feasibility, technologies accounting for less than one tenth of one percent of net generation on the grid are collapsed on fuel type, reducing the number of technologies to the final 72 incorporated in the model.

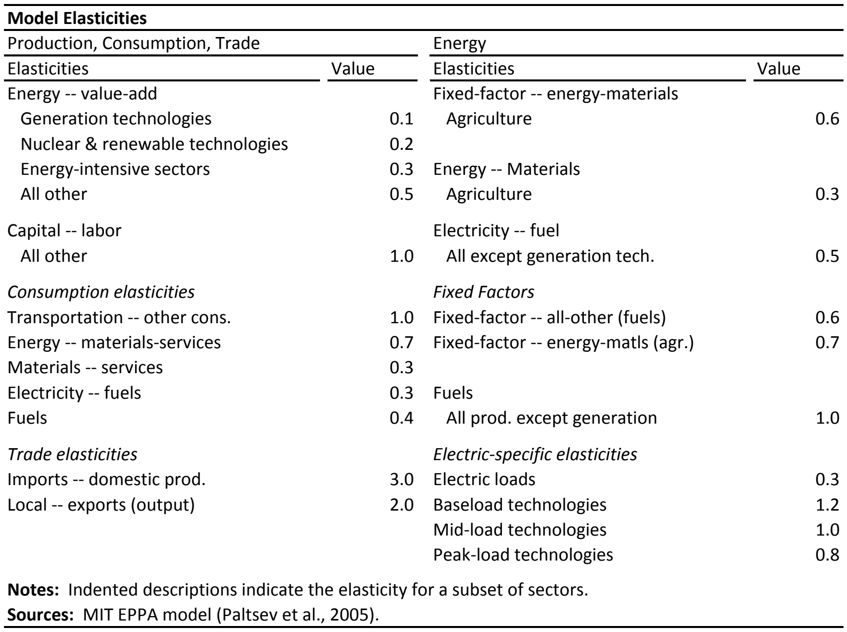
Emissions estimates are accurate to the order of magnitude of independent estimates, though are not exact. For applications where an exact matching is necessary, a balancing procedure that minimally revises the emissions factors ex-post of the value-share revision could be performed in a straightforward way. All model technologies are summarized in Appendix C.

A.2 Social Accounting Matrix

Social Accounting Matrix (SAM) data are from the Bureau of Labor Statistics (BLS) Input-Output data [12]. Standard matrix manipulations are used to generate a SAM from the nominal 2010 I-O accounts. SAM column-row residuals, which are on the order of $\$100,000$, are distributed away by a least-squares minimization. Value-add components are allocated based on Bureau of Economic Analysis (BEA) GDP-by-industry data [11].

B Model Elasticities

Elasticities used in the model are adapted from the MIT EPPA [21] model and are summarized in Figure 10.



Model Elasticities

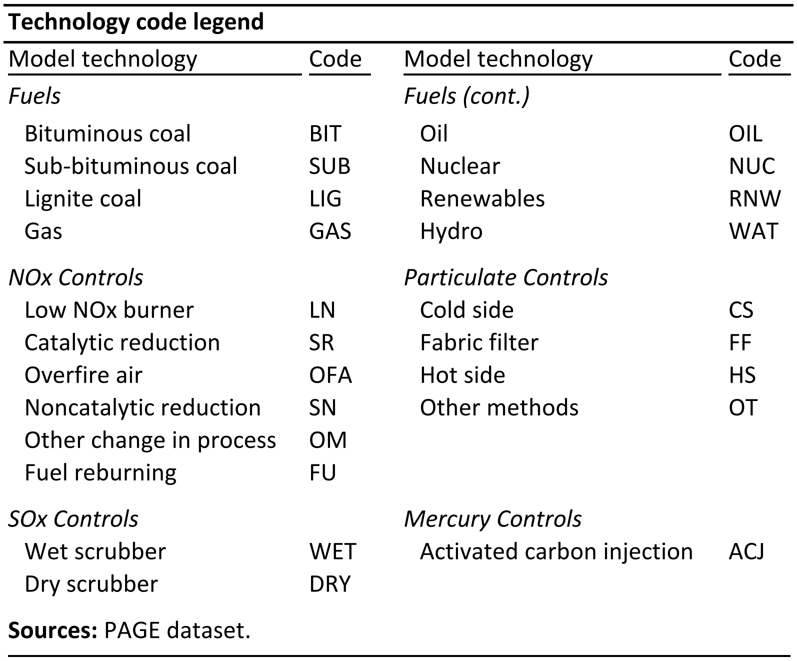
Production, Consumption, Trade		Energy	
Elasticities	Value	Elasticities	Value
Energy -- value-add		Fixed-factor -- energy-materials	
Generation technologies	0.1	Agriculture	0.6
Nuclear & renewable technologies	0.2		
Energy-intensive sectors	0.3	Energy -- Materials	
All other	0.5	Agriculture	0.3
Capital -- labor		Electricity -- fuel	
All other	1.0	All except generation tech.	0.5
Consumption elasticities		*Fixed Factors*	
Transportation -- other cons.	1.0	Fixed-factor -- all-other (fuels)	0.6
Energy -- materials-services	0.7	Fixed-factor -- energy-matls (agr.)	0.7
Materials -- services	0.3		
Electricity -- fuels	0.3	Fuels	
Fuels	0.4	All prod. except generation	1.0
Trade elasticities		*Electric-specific elasticities*	
Imports -- domestic prod.	3.0	Electric loads	0.3
Local -- exports (output)	2.0	Baseload technologies	1.2
		Mid-load technologies	1.0
		Peak-load technologies	0.8

Notes: Indented descriptions indicate the elasticity for a subset of sectors.
Sources: MIT EPPA model (Paltsev et al., 2005).

Figure 10: Elasticities used in CGE model

C Model Technologies

This appendix provides a full list of the 72 technologies that operate within the model. Figure 12 lists each technology with a description of the attributes that define it and a summary of its net generation and GHGe emissions.



Technology code legend

Model technology	Code	Model technology	Code
Fuels		*Fuels (cont.)*	
Bituminous coal	BIT	Oil	OIL
Sub-bituminous coal	SUB	Nuclear	NUC
Lignite coal	LIG	Renewables	RNW
Gas	GAS	Hydro	WAT
NOx Controls		*Particulate Controls*	
Low NOx burner	LN	Cold side	CS
Catalytic reduction	SR	Fabric filter	FF
Overfire air	OFA	Hot side	HS
Noncatalytic reduction	SN	Other methods	OT
Other change in process	OM		
Fuel reburning	FU		
SOx Controls		*Mercury Controls*	
Wet scrubber	WET	Activated carbon injection	ACJ
Dry scrubber	DRY		

Sources: PAGE dataset.

Figure 11: Legend of fuel & technology codes

Model Technologies

No.	Fuel Type	PM	SOx	NOx	Hg	Small Net Gen.	Net Generation (GWh)	Total Cost ($2010 MM)	GHGe Emissions (MMT)
1.	BIT	CS	WET	SR			374,000	$ 26,748	463
2.	SUB	CS	WET	LN			227,000	15,728	328
3.	BIT	CS	WET	LN			190,000	13,968	247
4.	SUB	CS	WET	OFA			79,100	5,526	116
5.	SUB	CS	WET	SR			68,600	5,439	93
6.	BIT	CS	WET	SN			43,300	3,529	57
7.	BIT	HS	WET	SR			42,900	2,620	56
8.	BIT	FF	WET	LN			40,000	2,349	55
9.	SUB	CS	WET	LN	ACJ		37,600	2,626	53
10.	SUB					•	36,100	2,568	57
11.	SUB	HS	WET	LN			35,800	2,271	53
12.	BIT	HS	WET	LN			35,600	2,257	48
13.	SUB	FF	WET	LN			35,400	2,052	50
14.	BIT					•	35,400	2,895	44
15.	SUB	FF	DRY	SR	ACJ		31,800	2,085	45
16.	LIG	CS	WET	LN			27,600	1,568	54
17.	SUB	FF	WET	SR			21,500	1,328	33
18.	LIG					•	19,600	1,122	40
19.	SUB	FF	DRY	LN			18,900	1,073	26
20.	SUB	CS	WET	SR	ACJ		16,900	1,276	24
21.	SUB	FF	WET	OFA			15,400	865	22
22.	SUB	CS	WET	OM			14,000	1,082	21
23.	BIT	FF	DRY	LN			13,800	804	18
24.	BIT	OT	WET	SR			13,600	817	16
25.	SUB	CS	DRY	LN			13,600	870	22
26.	SUB	OT	WET	LN			13,200	795	20
27.	BIT	FF	WET	SN			12,700	802	17
28.	LIG	CS	WET	LN	ACJ		12,600	794	24
29.	SUB	CS	WET	OFA	ACJ		11,500	813	17
30.	SUB	HS	WET	OFA	ACJ		11,500	754	17
31.	BIT	HS	WET	OFA			11,100	520	15
32.	SUB	OT	WET	LN	ACJ		10,700	580	16
33.	BIT	CS	WET	SR	ACJ		10,100	813	12
34.	SUB	CS	WET				10,100	911	16
35.	BIT	FF	WET	SR			9,639	729	12
36.	BIT	CS	WET	OFA			9,304	842	12
37.	BIT	HS	DRY	SR			7,748	473	10
38.	SUB	FF	DRY	SR			7,411	438	11
39.	SUB	HS	WET	OFA			7,247	453	10
40.	SUB	FF	DRY	LN	ACJ		7,183	425	10
41.	LIG	FF	DRY	LN			6,360	244	12
42.	LIG	CSFF	WET	SN	ACJ		6,087	553	11

Model Technologies

No.	Fuel Type	PM	SOx	NOx	Hg	Small Net Gen.	Net Generation (GWh)	Total Cost ($2010 MM)	GHGe Emissions (MMT)
43.	SUB	CS	WET	SN			6,039	505	9
44.	BIT	HS	WET	SR	ACJ		6,036	482	8
45.	BIT		WET	LN			5,855	335	7
46.	BIT	FF	DRY	SN			5,729	380	7
47.	SUB	OT	WET	OFA	ACJ		5,548	300	8
48.	BIT	CS	WET	OM			5,340	602	8
49.	SUB	FF	WET	OM			5,319	355	13
50.	BIT	HS	WET	SN			4,954	377	6
51.	SUB	OT	WET	OFA			4,852	294	7
52.	BIT	FF	WET	OM			4,643	303	7
53.	BIT	CS	WET				4,639	594	7
54.	BIT	CS	WET	SN	ACJ		4,531	454	6
55.	LIG	CS	WET	OFA			4,518	207	9
56.	SUB	HS	DRY	LN			4,287	237	6
57.	SUB	CS	DRY	LN	ACJ		4,254	282	6
58.	SUB	FF	DRY	SN			3,956	133	9
59.	SUB	FF	WET	SN			3,913	265	7
60.	LIG	FF	WET	SR	ACJ		3,907	220	7
61.	GAS		WET				749,000	71,892	422
62.	GAS		WET	SR			147,000	9,175	17
63.	GAS		WET	LN			40,700	3,909	14
64.	GAS		WET	OM			22,200	3,105	14
65.	GAS		WET	OFA			8,829	1,159	6
66.	GAS	CS	WET	OFA			3,894	536	3
67.	GAS					•	1,339	261	1
68.	NUC						807,000	22,200	0
69.	OIL		WET				10,800	5,439	213
70.	OIL					•	6,625	3,761	136
71.	RNW						174,000	3,057	0
72.	WAT						255,000	12,239	0
	Count:	57	64	60	15				
	Total:						3,966,687	$ 257,461	3,247

Notes: Small net generation technologies is a sum of all technologies producing less than a tenth of one percent of net generation. These technology aggregates operate a variety of abatement equipment.

Source: PAGE dataset.

Figure 12: Full list of model technologies