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Construction and Application of the MEEDE Dataset

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Abstract

We describe the construction of a highly detailed dataset of the US electric sector—the Micro-level Economic and Environmental Detail of Electricity. The dataset represents a unique synthesis of engineering, economic, and environmental data pertaining to electricity generation. These data can support partial or general equilibrium modeling efforts requiring highly detailed depictions of the electric sector. We first provide thorough documentation of the data construction process and a set of descriptive statistics on the data components. We outline how the data can be used to support a partial equilibrium model or integrated into a general equilibrium model. The integrated approach we describe can preserve key environmental and economic features of electricity generation and pollution abatement. It does so while avoiding certain time costs and risks of linked two-model approaches. The integrated approach offers the transparency and economic and environmental realism required of rigorous policy analyses.

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Introduction

This methods report explains the construction and application of a new detailed dataset covering electricity generation in the United States—the Micro-level Economic and Environmental Detail of Electricity (MEEDE). These data provide a full economic and environmental profile of the physical equipment operating on the US electric grid based entirely on public sources. The detailed grid profile offered by the MEEDE data is designed to be an integrated component of An RTI Macroeconomic Analysis System (ARTIMAS™). ARTIMAS contains a computable general equilibrium (CGE) model that, when integrated with the MEEDE data, will enable the detailed assessment of the economic and environmental consequences of different policies on both the electric grid and the broader economy.

CGE models are a common tool for analyzing a wide variety of public policies. These "top-down," economy-wide models provide an experimental laboratory for better understanding the size and distribution of expected economic impacts, but they typically lack the engineering details required to faithfully represent the complexities of certain sectors. In the case of environmental policy analysis, the electricity generation, transmission, and distribution sector frequently demands the most technically detailed treatment. This technical complexity means that the electricity sector is very often independently modeled in "bottom-up" partial equilibrium models that can represent complex engineering features with greater nuance given that they need not accommodate the analytic functional forms used in CGE models.

Broadly speaking, the two categories of models provide mutually exclusive advantages: economy-wide general equilibrium estimates of welfare impacts versus rich representation of the technical and engineering complexities of the electric sector. The obvious question—how can we integrate these approaches to capture the advantages of both—has most often been answered by linking bottom-up and top-down models in some way. Böhringer and Rutherford (2009, p. 1649) offer a typology of such linkages as "soft linked," in which the "consistency and convergence of iterative solution algorithms" may be problematic; "reduced form," in which a highly simplified version of one of the models is employed; or direct linkage, in which the models are combined explicitly through complementarity relations on solution variables.

The Environmental Protection Agency's (EPA's) Integrated Planning Model (IPM) (EPA, 2015b) and the National Renewable Energy Laboratory's (NREL's) Regional Energy Deployment System (ReEDS) (NREL, 2014) model are prominent examples of bottom-up power sector models. Model output from IPM has been used to independently constrain CGE models, and the ReEDS model has been directly linked to the Massachusetts Institute of Technology Joint Program on the Science and Policy of Global Change US Regional Energy Policy model (MIT Joint Program on the Science and Policy of Global Change, 2015). The RTI Applied Dynamic Analysis of the Global Economy (ADAGE™) model (Woollacott, Cai, & Depro 2015) and the NewERA (NERA Economic Consulting, 2015) models are examples of top-down CGE models that iterate with a separate bottom-up electric sector model.

Direct linkages, such as those in RTI ADAGE and NewERA, are achieved by iteratively solving each model while passing certain variables from one model to the other to seed the next model's solve. The iteration is intended to identify a set of values for the variables that both models agree provides a solution, but this convergence of model outcomes is not guaranteed. For greater model simplicity and to avoid the potential pitfalls of iterating models, we employed a different integrated approach designed to fully integrate the MEEDE data into the calibration of the electric sector of the ARTIMAS CGE model. Using this approach, we can capture much of the technical detail commonly omitted from CGE models without the need to iterate with an independent bottom-up model.

The primary challenge in building an integrated model is disaggregating input-output data summarized in macroeconomic accounting to a level of technical, subsectoral detail sufficient to reliably represent existing generation and abatement activity. The MEEDE data are built on public sources that detail the operations on the electric grid at the level of individual boilers and generating units. These data provide a rich characterization of the economic and environmental profiles of the grid's electricity generation and pollution abatement technologies. This richness is necessary to capture the heterogeneity of pollution emissions across multiple pollutants for different electric generating configurations. Emissions from the electricity generating sector are of particular importance given the scale of fossil fuel combustion involved. Data used to calibrate a CGE model will be inconsistent with the aggregate amounts, such as fuel and capital quantities, provided in the sources supporting the MEEDE dataset, thus requiring a reconciliation procedure (e.g., Sue Wing, 2008).

This report describes the methods used in constructing the MEEDE dataset, provides descriptive tables summarizing the dataset variables, and offers a qualitative description of how the dataset can be used to support electric sector modeling and the advantages of these approaches. The Methods section details the MEEDE data construction and its underlying assumptions. It also provides a series of tables that describe the data as they were constructed. The Applications section outlines how the dataset can form the basis of an electric sector model, either as a stand-alone electric sector model or integrated into the ARTIMAS framework. For the latter task, we discuss the key steps to integrating the MEEDE data with macroeconomic data.

Methods

Data provided in national accounts present an aggregated electric generation, transmission, and distribution sector. Capturing the heterogeneity of production and abatement alternatives requires a finer-grain representation, disaggregated along several dimensions to the level of generation-abatement technology types. To achieve this, we integrated Forms EIA-923 and EIA-860 data (Energy Information Administration [EIA], 2013a, 2013b), IPM generation and abatement cost estimates (EPA, 2015b), and EPA emission factors (EPA, 1995) to provide a comprehensive dataset covering 96 percent of electric generation, pollution, and abatement activity on the US grid: the MEEDE dataset.

Engineering

Data Assembly

The MEEDE data rely most heavily on EIA Forms 923 and 860 for the year 2013. Form 923 data record activity levels of electric generating units (EGUs), including fuel use and generation quantities and the cost, ash content, and sulfur content of fuels. Ash content and sulfur content are used to estimate particulate and sulfur emissions rates. The data also contain basic characteristics of each generating unit such as fuel type, prime mover,[1] and location. The Form 923 data provide 39 fuel types, which we collapse to 15 fuel codes.

Data from Form 923 page 1 summarize by fuel code, prime mover, and plant the total quantity of fuel input and electric generation output. From these data we were able to summarize generation by fuel type, prime mover, and region. Table 1 maps fuel types to codes along with the net electricity generation by each type. Table 2 summarizes net generation by fuel code and region.

Form 923 page 3 provides boiler-level detail on the ash and sulfur content, total quantity, and type of fuel inputs. Pollution control equipment can be associated with the boiler(s) it serves using the Form 860 data. Identifying the emissions profile of generation then requires a reliable mapping between boilers and prime movers. This mapping is a many-to-many exercise: one boiler may serve multiple prime movers, or multiple boilers may serve one prime mover. Fortunately, page 3 of the Form 923 data breaks out boiler inputs by plant ID (PID), the prime movers (PMs) they serve, and fuel type (FT).[2] We confirmed that the sum of fuel inputs from page 3 at the PID-PM-FT level equals the sum reported on page 1. This holds with few minor discrepancies.

Table 3 summarizes the unit of observation and variables provided by pages 1 and 3. Summing away the boiler identification (BID) from page 3 produces data equivalent to page 1 at the PID-PM-FT level.

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[1] *Prime mover* refers to the mechanical equipment responsible for converting energy released from fuel combustion into useful energy for doing work (e.g., a turbine).

[2] The Form 860 data refer to a plant "code," which is equivalent to the plant ID referred to here and in the Form 923 data.

Table 1. Net US electric generation by fuel type and code, 2013

Type	Description	Fuel code	Net generation (in thousands of MWh)	Percent of generation
Coal			**1,581,098**	**38.9**
SUB	Subbituminous coal	SUB	752,480	18.5
BIT	Bituminous coal	BIT	732,135	18.0
LIG	Lignite coal	COL	84,924	2.1
WC	Waste/other coal	COL	9,838	0.2
SGC	Coal-derived synthesis gas	COL	1,721	0.0
SC	Coal-based synfuel	COL	0	0.0
ANT	Anthracite coal	COL	0	0.0
Gases			**1,150,558**	**28.3**
NG	Natural gas	GAS	1,123,032	27.6
PG	Propane, gaseous	GAS	15	0.0
LFG	Landfill gas	OGS	10,638	0.3
OG	Other gas	OGS	9,123	0.2
BFG	Blast furnace gas	OGS	3,722	0.1
WH	Waste heat	OGS	2,766	0.1
OBG	Other biomass gas	OGS	1,262	0.0
Nuclear			**789,016**	**19.4**
NUC	Nuclear	NUC	789,016	19.4
Renewables: noncombustion			**456,274**	**11.2**
GEO	Geothermal	GEO	15,775	0.4
SUN	Solar	SOL	8,951	0.2
WAT	Water	WAT	263,851	6.5
WND	Wind	WND	167,697	4.1
Renewables: combustion			**41,543**	**1.0**
WDS	Wood/wood waste solids	BMS	21,606	0.5
BLQ	Black liquor	BMS	18,270	0.4
AB	Agricultural by-products	BMS	959	0.0
OBS	Other biomass solids	BMS	524	0.0
WDL	Wood waste liquids (e.g., black liquor #21)	BML	150	0.0
OBL	Other biomass liquids	BML	35	0.0
Other and wastes			**30,075**	**0.7**
PC	Petroleum coke	OTH	11,892	0.3
OTH	Other	OTH	1,622	0.0
PUR	Purchased steam	OTH	1,161	0.0
SLW	Sludge waste	OTH	206	0.0
MWH	Storage	OTH	0	0.0
MSB	Biogenic municipal solid waste	MSW	7,186	0.2
MSN	Nonbiogenic municipal solid waste	MSW	6,904	0.2
TDF	Tire-derived fuels	MSW	1,104	0.0
Petroleum			**15,227**	**0.4**
RFO	Residual fuel oil	OIL	7,503	0.2
DFO	Distillate fuel oil	OIL	5,272	0.1
SGP	Petroleum coke-derived synthesis gas	OIL	1,433	0.0
JF	Jet fuel	OIL	399	0.0
WO	Waste/other oil	OIL	380	0.0
KER	Kerosene	OIL	240	0.0
Total			**4,063,792**	**100.0**

Abbreviation: MWh = megawatt-hour.

Note: Bold totals may not equal sum of subcomponents because of rounding.

Source: Energy Information Administration (EIA) Form 923.

Table 2. Net generation by fuel code and region, 2013 (in thousands of MWh)

Fuel code		Region										
Code	**Description**	**South Atlantic**	**West South Central**	**East North Central**	**Middle Atlantic**	**Mountain**	**Pacific (CA, OR, WA)**	**East South Central**	**West North Central**	**New England**	**Pacific (AK, HI)**	**Total USA**
GAS	Natural gas and propane	250,934	297,534	57,997	130,548	85,260	145,313	84,800	15,110	52,129	3,421	1,123,047
NUC	Nuclear	197,513	67,215	153,849	156,849	31,431	26,373	80,174	38,429	37,183	0	789,016
SUB	Subbituminous coal	21,639	173,553	185,789	2,301	131,859	10,499	34,434	191,291	681	434	752,480
BIT	Bituminous coal	244,730	2,813	185,719	85,036	69,383	823	134,165	2,575	5,486	1,404	732,135
WAT	Water	16,334	6,310	3,584	26,324	28,964	135,211	28,576	9,746	7,289	1,514	263,851
WND	Wind	1,713	47,036	18,610	6,902	19,285	27,148	47	44,428	1,880	649	167,697
COL	Other coal	2,214	55,771	591	7,824	1,047	0	2,925	25,920	0	191	96,483
BMS	Biomass solids	12,460	5,730	3,219	1,033	564	6,180	5,477	1,237	5,339	118	41,358
OGS	Other gases	3,326	5,379	7,726	3,128	1,281	5,181	482	566	354	87	27,511
GEO	Geothermal	0	0	0	0	3,029	12,471	0	0	0	275	15,775
OIL	Oil and petroleum derivatives	1,562	198	2,032	1,412	210	76	323	290	1,084	8,041	15,227
MSW	Municipal solid wastes	4,782	67	559	4,526	10	646	17	529	3,687	371	15,194
OTH	Miscellaneous other	3,105	6,640	2,233	310	597	158	1,319	167	146	205	14,881
SOL	Solar	654	145	121	566	3,488	3,829	20	3	107	19	8,951
BML	Biomass liquids	0	0	0	66	0	84	0	0	0	35	185
Total		**760,966**	**668,391**	**622,028**	**426,826**	**376,409**	**373,993**	**372,759**	**330,291**	**115,365**	**16,764**	**4,063,792**

Abbreviation: MWh = megawatt-hour.
Source: Energy Information Administration (EIA) Form 923.

Table 3. Meta-summary of EIA Form 923 data, 2013

Form 923 data				
	Observation	**Variables**	**Number of Observations**	**Number of Plants**
Page 1	{ PID, PM, FT }	< Fuel, Generation >	10,315	6,745
Page 3	{ PID, PM, FT, BID }	< Fuel >	6,119	1,448

Abbreviations: BID = boiler identification; EIA = Energy Information Administration; FT = fuel type; PID = plant ID; PM = prime mover.
Note: Observation counts exclude simulated plants.
Source: Energy Information Administration (EIA) Form 923.

We can use the boiler-level fuel data to allocate the generation data from page 1, giving fuel use and estimated generation output data at the PID-PM-FT-BID level.[3] The final column of Table 3 reveals that less than a quarter of generation by plant count is served by boilers (i.e., 1,448 plants relative to 6,745; this is also evident by prime mover in Table 5 in the Data Description section), but nearly half of all generation is provided through the use of boilers (see steam turbines in Table 5).

Pollution control processes and equipment are given control IDs that are associated with plant boilers, meaning environmental control equipment is associated only with steam generation in the Form 860 data. Through this association we can assign environmental control processes and equipment to the boilers represented in Form 923 page 3 boiler data. With the boiler technology characterized, we can then identify what fuel input and electric outputs

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[3] This allocation method for net generation will be inaccurate to the extent that different boilers within the PID-PM-FT tuple operate at different efficiencies.

are traveling through which generation equipment and pollution control technology configurations.

Using the environmental association and equipment datasets from the Form 860 data, we constructed a plant-boiler-level dataset that identifies the type and age of environmental equipment for all available boilers on the grid. Environmental equipment controls include those for sulfur, nitrogen, mercury, and particulates. Given the importance of flue height for local health effects from pollution, we also generated the emissions-weighted average flue height of each boiler (some boilers are served by multiple flues). The Form 860 environmental association file provides the type of environmental equipment installed at each plant and the boilers the equipment serves. The environmental equipment file provides additional attributes for boilers (including boiler age) and some of the control equipment.

The Form 860 data also provide attributes at the generator and plant levels. Age and nameplate capacity by generator are key variables in estimating the cost of generation. Because the final dataset will be summarized at the PID-PM-FT-BID level, we summed nameplate capacity and took a nameplate-weighted average age of the generators at the PID-PM level. The plant file provides a variety of geographic and regulatory location characteristics that are merged with the generator and boiler data at the plant level.

The final engineering dataset summarizes the generation and abatement technologies operating on the grid with plant-, generator-, and boiler-level detail. When applicable, we broke generation out to the boiler level and identified associated environmental equipment. The unit of observation is the PID-PM-FT-BID tuple where the boiler is applicable and PID-PM-FT otherwise. There are 11,271 observations and 64 variables in total. The variables provide detailed information on the geographic and regulatory location of the plants; the ages of combustion, generation, and abatement equipment; the physical and thermal quantities of fuel consumed; and the flues and environmental equipment involved in the combustion of those quantities.

Data Description

The Form 923 data show that, although the natural gas fuel code supports the largest amount of net generation (1,123 million MWh; see Table 2), more electricity is generated in total from coal when aggregating over the different coal types (1,581 million MWh), from Table 1. Table 4 presents the BTU quantities of fuel consumption (grouped by fuel type) and shows how coal also dominates among fossil fuels by heat and pollutant contents. Coal accounts for 62 percent of fossil fuel combustion in electricity generation relative to 33 percent for natural gas in BTU terms (based on totals in the BTU

Table 4. Sulfur, ash, and heat content of fossil fuels for electricity generation, 2013

Fuel code			Pollutant content (%)		BTU (Quadrillion)	Volume/Mass	
	Code	Description	Sulfur	Ash		Quantity	Units
Gas	GAS	Natural gas and propane	0.00	0.00	8.80	1,711	Bn cu ft
	OGS	Other gases	0.00	0.00	0.29	1,368	Bn cu ft
		Weighted Average/Total Quantity	0.00	0.00	9.08	3,079	
Coal	SUB	Subbituminous coal	0.34	5.79	7.91	459	MM short tons
	BIT	Bituminous coal	2.23	10.64	7.54	338	MM short tons
	COL	Other coal	0.98	19.33	1.06	82	MM short tons
		Weighted Average/Total Quantity	1.13	8.91	16.51	878	
Oil	OIL	Oil and petroleum derivatives	0.59	0.00	0.15	18	MM barrels
Other	BMS	Biomass solids	0.00	0.00	0.41	126	MM short tons
	MSW	Municipal solid wastes	0.00	0.00	0.28	30	MM short tons
	OTH	Miscellaneous other	1.40	0.14	0.16	21	MM short tons
		Weighted Average/Total Quantity	0.16	0.02	0.85	177	
Weighted Average/Total Quantity			**0.25**	**1.89**	**25.59**	**4,153**	

Abbreviations: Bn cu ft = billion cubic feet; BTU = British thermal unit; MM = millions.
Note: Numbers may not sum to totals because of rounding.
Source: Energy Information Administration (EIA) Form 923.

column in Table 4). Coal is the primary sulfur- and ash-bearing fuel, and bituminous coal has a higher pollutant content than subbituminous—the two dominant types of coal burned for electricity.

The South Atlantic region has the largest amount of generation nationally; the West South Central and East North Central regions each generate about 15 percent less. About 40 percent of the country's coal generation occurs in these latter two regions and the plurality of natural gas generation occurs in West South Central (26 percent). The majority of oil and petroleum-derived generation occurs in Hawaii. Eighty percent of solar generation occurs on the Pacific Coast or in Mountain states with very little elsewhere. Overall, utility-scale solar contributes only a fraction of a percentage to total generation.

Fuel type–prime mover pairs are another part of the data and do not necessarily identify the overall configuration of a given plant. For example, the Brunot Island generating station in Pittsburgh, Pensylvania, integrates the operation of three combined-cycle combustion prime movers (CT) and one combined-cycle steam (CA) prime mover to provide a total of 340 MW of natural gas–fired combined-cycle generating capacity. Indeed, the pairing of these prime movers is specific to combined-cycle configurations. Identifying technology ensembles such as these is critical for attributing the economic costs of generation in the next section. Table 5 provides a summary of net generation by prime mover and region.

Table 6 summarizes the percentage of net fossil fuel generation that is controlled by each environmental technology. Technologies are grouped by the primary pollutant they are designed to target; however, environmental control technologies influence emissions of multiple pollutants. This is particularly true with respect to mercury. The EIA Form 860 data

Table 5. Net generation by prime mover and region, 2013 (in thousands of MWh)

Prime Mover		Region										
Code	Description	South Atlantic	West South Central	East North Central	Middle Atlantic	Mountain	Pacific (CA, OR, WA)	East South Central	West North Central	New England	Pacific (AK, HI)	Total USA
ST	Steam turbine	497,019	353,643	538,644	272,589	240,526	66,014	263,732	262,667	54,153	7,059	2,556,045
CT	Combined cycle (combustion)	156,210	154,731	34,486	71,857	47,861	76,606	48,947	6,585	22,498	4,411	624,191
CA	Combined cycle (steam)	74,059	64,323	17,070	37,034	26,025	32,954	27,438	3,548	11,793	1,202	295,447
HY	Hydraulic turbine	18,745	6,357	4,454	27,507	29,221	135,007	28,618	9,450	7,658	1,514	268,532
WT	Wind (onshore)	1,713	47,036	18,610	6,902	19,285	27,148	47	44,428	1,880	649	167,697
GT	Gas turbine	12,778	31,961	7,160	9,621	6,344	18,244	3,782	2,184	3,150	1,098	96,323
CS	Combined cycle (single)	824	8,921	2	0	859	11,529	0	636	14,118	0	36,888
IC	Internal combustion (diesel)	1,304	1,289	2,259	1,786	904	2,006	217	454	365	812	11,396
PV	Photovoltaic	552	145	121	566	3,286	3,220	20	3	105	19	8,037
BT	Binary cycle turbines	0	0	0	0	2,072	833	0	0	0	0	2,904
OT	Other	0	33	93	148	181	15	0	41	0	0	510
FC	Fuel cell	173	0	0	0	13	214	0	0	13	0	413
CP	Concentrated solar (storage)	0	0	0	0	89	0	0	0	2	0	91
BA	Battery	0	0	0	0	0	0	0	0	0	0	0
CE	Compressed air (storage)	0	0	0	0	0	0	0	0	0	0	0
PS	Pumped storage	−2,411	−48	−871	−1,184	-256	203	−42	296	−369	0	−4,681
Total		**760,966**	**668,391**	**622,028**	**426,827**	**376,409**	**373,992**	**372,759**	**330,291**	**115,365**	**16,764**	**4,063,792**

Abbreviation: MWh = megawatt-hour.

Source: Energy Information Administration (EIA) Form 923.

Table 6. Environmental controls of fossil fuel generation by region, 2013 (%)

Environmental control technology		South Atlantic	West South Central	East North Central	Middle Atlantic	Mountain	Pacific (CA, OR, WA)	East South Central	West North Central	New England	Pacific (AK, HI)	Total USA
Sulfur Control Technologies												
SP	Spray type (wet) scrubber	32.7	14.9	30.6	21.9	29.9	4.4	39.7	26.5	2.2	0.0	25.3
TR	Tray type (wet) scrubber	11.7	1.1	11.3	7.2	12.7	0.2	3.6	3.8	2.2	0.0	6.9
SD	FGD, dry or semi-dry	2.8	3.3	5.0	2.0	17.0	0.0	1.4	19.9	6.0	0.0	5.9
JB	Jet bubbling reactor (wet) scrubber	3.2	0.9	9.2	0.0	0.0	0.0	3.2	0.0	0.0	0.0	2.6
VE	Venturi type (wet) scrubber	0.1	0.5	0.4	4.9	6.5	0.0	0.0	6.5	0.1	0.4	1.8
DSI	Dry sorbent injection	0.6	0.7	2.5	1.1	0.5	0.3	4.5	0.3	0.0	11.3	1.3
CD	Circulating dry scrubber	1.5	1.5	0.0	0.4	1.3	0.0	0.2	0.7	0.2	0.0	0.8
PA	Packed type (wet) scrubber	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
MA	Mechanical aided type (wet) scrubber	0.7	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.2
SO_x	**Any technology**	**45.9**	**21.3**	**49.6**	**31.3**	**64.6**	**4.7**	**49.0**	**47.9**	**8.5**	**11.7**	**39.5**
Particulate Control Technologies												
EK	ESP, cold side, no flue conditioning	30.5	19.0	51.5	17.5	13.0	6.5	43.9	33.7	8.6	0.0	28.2
EC	ESP, cold side, flue conditioning	9.8	6.9	25.4	12.4	11.6	0.2	9.6	21.0	0.0	0.0	12.3
BP	Fabric filter, pulse	8.6	8.9	10.2	4.6	19.5	0.1	3.0	23.1	7.3	3.2	9.9
BR	Fabric filter, reverse air	3.5	7.4	1.6	1.4	22.9	0.2	2.8	9.4	0.0	11.3	6.0
EW	ESP, hot side, no flue conditioning	5.1	2.3	3.6	0.1	11.5	0.0	10.3	5.3	0.8	0.0	4.7
MC	Multiple cyclone	0.5	0.7	0.3	0.2	1.6	0.0	4.3	0.3	0.2	2.0	0.9
EH	ESP, hot side, flue conditioning	0.0	1.3	1.2	0.3	1.5	0.0	1.9	1.4	0.2	0.0	0.9
BS	Fabric filter, shake and deflate	0.2	2.6	0.0	0.3	0.1	0.0	0.0	1.1	0.0	0.0	0.7
SC	Single cyclone	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PM	**Any technology**	**50.5**	**44.1**	**83.5**	**34.9**	**64.1**	**7.1**	**65.8**	**88.1**	**12.2**	**14.8**	**55.7**
Nitrogen Control Technologies												
LN	Low NO_x burner*	26.8	35.5	39.9	25.5	54.4	14.0	56.4	60.8	13.9	2.8	37.9
SR	Selective catalytic reduction	44.0	14.2	47.9	39.2	12.5	20.3	48.9	18.0	12.7	1.4	31.0
OV	Overfire air*	13.6	27.9	35.1	16.3	28.3	2.6	21.4	52.6	0.7	1.4	24.7
SN	Selective noncatalytic reduction	6.9	6.3	10.0	3.9	0.0	0.4	3.8	9.2	0.8	9.9	5.7
AA	Advanced overfire air*	0.7	2.8	2.6	1.2	9.2	4.2	2.7	13.4	0.1	0.0	3.8
NH3	Ammonia injection*	0.8	2.8	0.6	8.6	1.4	11.4	2.3	0.9	8.3	1.4	2.8
CF	Fluidized bed combustor*	0.5	2.3	0.3	2.5	0.5	0.2	1.1	2.9	0.0	9.9	1.3
LA	Low excess air*	0.1	2.2	0.0	0.6	0.6	0.4	3.5	1.8	0.2	0.0	1.1
FR	Flue recirculation*	0.0	2.5	0.1	0.6	0.2	1.6	0.0	0.1	1.1	0.0	0.7
FU	Fuel reburning*	0.3	0.0	0.0	0.1	0.1	0.0	1.3	0.0	0.0	0.0	0.2
BF	Biased firing*	0.5	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.2
H2O	Water injection*	0.4	0.2	0.1	0.2	0.0	0.2	0.0	0.0	0.6	0.0	0.2
STM	Steam injection*	0.0	0.1	0.0	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.1
NO_x	**Any technology**	**55.1**	**46.4**	**79.3**	**51.3**	**63.2**	**27.8**	**73.7**	**82.4**	**22.9**	**12.7**	**59.4**
Mercury Control Technologies												
ACI	Activated carbon injection*	7.0	12.2	23.9	0.6	18.6	6.5	1.5	18.7	7.3	0.0	11.8
LIJ	Lime injection*	1.8	0.1	0.7	1.3	0.5	0.0	8.0	0.8	0.0	0.0	1.4
Hg	**Any technology**	**8.5**	**12.3**	**24.1**	**2.0**	**18.8**	**6.5**	**8.0**	**19.5**	**7.3**	**0.0**	**13.0**
OT	Other	0.2	0.0	2.1	0.0	1.7	0.0	1.4	3.4	0.0	0.0	1.0
Total fossil fuel generation (MM MWh)		**528.0**	**542.0**	**442.0**	**231.0**	**290.0**	**162.0**	**258.0**	**236.0**	**60.0**	**14.0**	**2,762.0**

Abbreviations: ESP = electrostatic precipitator; FGD = flue-gas desulfurization; Hg = mercury; MM = million; MWh = megawatt-hour; NO_x = nitrogen oxide; PM = particulate matter; SO_x = sulfur oxide.

Notes: Asterisks denote change-in-process controls. Technologies influence multiple pollutants' emissions.

Sources: Energy Information Administration (EIA) Form 923 and Form 860.

identify 33 specific pollution control technologies (and one "other" category). The majority of these are end-of-pipe controls, but, for nitrogen in particular, there are a number of change-in-process controls. These controls rely primarily on changes to how boilers are operated and may require less physical equipment relative to an end-of-pipe technology like a sulfur scrubber or particulate baghouse. Change-in-process technologies are asterisked in Table 6.

Boilers use control technologies in over 1,000 different configurations ranging from no controls to nine control technologies.[4] The prevalence of control technologies varies significantly by region. For example, Pacific and New England states have relatively little of their fossil fuel generation equipped with sulfur, particulate, or nitrogen control technologies, whereas West North Central states have relatively high fractions of fossil fuel generation equipped with these controls.

Although different controls may influence greenhouse gas emissions, no extant controls are targeted specifically for them. Despite the lack of extant greenhouse gas control technologies, modeling within the ARTIMAS system can incorporate potential control technologies such as carbon capture and sequestration given a proper specification of costs. Similarly, new or improved electric technologies can be modeled as "backstop" technologies that become economically viable only in later years.

Economics

Given a full technological and environmental characterization of the grid (see the engineering section above), we specified the economic costs associated with electricity generation and pollution control. We categorized cost components for generation and abatement technologies as either overnight capital or fixed or variable operations and maintenance (O&M) costs. Variable costs exclude fuels and include materials costs such as water and chemical solvents used in operating the generation and control equipment. Fixed O&M costs pertain largely to labor expenses incurred in the daily operations of the plant (EIA, 2013c).

We used generation cost estimates from EIA's Electricity Market Module (EMM; EIA, 2015a; 2015b) and EIA's updated capital cost assumptions (EIA, 2013c). Pollution control cost estimates came from EPA's IPM version 5.13 (EPA, 2013). EIA cost estimates are for new installations of a variety of technologies. Given their new vintage, many technologies' cost estimates include the installation of required pollution control technologies. To estimate the costs of generation alone, we subtracted the IPM cost estimates provided in the model documentation (EPA, 2013) for the included technologies. A generation-only cost estimate enables us to build up the total costs from the generation and pollution control cost components for any configuration that may be operating on the grid.

This approach has some limitations. First, the generation cost estimates are for new installations only. Applying these cost estimates to facilities with a wide variety of vintages leads to an inaccurate assessment of their true costs. True capital costs are likely lower and O&M costs higher than the EIA estimates. Capital costs are reduced through the amortization of overnight costs, which mitigates this limitation, but the overall level is likely still higher than those prevailing at construction time for older-vintage installations. IPM provides vintage-specific fixed O&M costs for generation that are used to increase costs for older installations, which helps address this limitation. This limitation could be further mitigated with better available data; however, such data would likely be proprietary and incomplete.

Second, IPM's pollution control cost estimates are based on retrofitted installations whose costs likely differ from new installations. Two factors address this concern: (1) older installations are more likely to have installed their control equipment as retrofits, making the estimates appropriate, and (2) for new installations, the control equipment costs will still be included in the total costs of the installation; the adjustment for control equipment only shifts costs between generation and control.

Table 7 summarizes the EIA capital and O&M costs for the 26 technology configurations offered in the dataset. These data combine more extensive coverage of configurations from EIA's 2013 capital

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[4] Only one facility uses this many controls, the Trimble County Generating Station in Bedford, Kentucky.

cost update (EIA, 2013c) with more recent estimates from the 2015 release of the EMM (EIA, 2015a). The Generation-only costs columns show the revised costs net of included control equipment as costed from IPM Chapter 5 (EPA, 2013). This adjustment affects all coal technologies, the first half of gas technologies, and biomass combined-cycle configurations. Control equipment cost adjustments vary by technology and category. With the exception of carbon capture and sequestration controls, control cost adjustments for combined-cycle plants are relatively minor (2 to 9 percent difference between generation-only and EIA total costs). Pulverized coal technology costs see significant control cost adjustments upward of 50 percent for capital, 60 percent for fixed O&M, and 90 percent for variable O&M. Carbon capture and sequestration technology accounts for one-third to a half of total costs.

Table 7. Total and generation-only costs for each technology configuration, 2013 (MM 2015$)

Installation attributes			EIA total costs			Generation-only costs		
Configuration	**Capacity (MW)**	**Heat rate (BTU/ MWh)**	**Capital cost ($/MW)**	**Fixed O&M ($/MW-Yr)**	**Variable O&M ($/MWh)**	**Capital cost ($/MW)**	**Fixed O&M ($/MW-Yr)**	**Variable O&M ($/MWh)**
Coal technologies								
Single-unit advanced PC	650	8.80	3.23	0.04	4.47	2.23	0.03	0.50
Dual-unit advanced PC	1,300	8.80	2.92	0.03	4.47	1.99	0.02	0.50
Single-unit advanced PC + CCS	650	12.00	5.23	0.08	9.51	2.23	0.03	0.50
Dual-unit advanced PC + CCS	1,300	12.00	4.72	0.07	9.51	1.99	0.02	0.50
Single-unit IGCC	600	8.70	4.33	0.06	7.22	4.25	0.06	7.09
Dual-unit IGCC	1,200	8.70	3.73	0.05	7.22	3.65	0.05	7.09
Single-unit IGCC + CCS	520	10.70	6.49	0.07	8.44	4.25	0.06	7.09
Gas technologies								
Conventional CC	620	7.05	0.91	0.01	3.60	0.83	0.01	3.47
Advanced CC	400	6.43	1.02	0.02	3.27	0.94	0.01	3.14
Advanced CC + CCS	340	7.53	2.07	0.03	6.78	0.94	0.01	3.14
Conventional CT	85	10.85	0.97	0.01	15.44	0.97	0.01	15.44
Advanced CT	210	9.75	0.67	0.01	10.37	0.67	0.01	10.37
Fuel cells	10	9.50	6.98	0.00	42.97	6.98	0.00	42.97
Nuclear								
Dual-unit nuclear	2,234	0.00	5.37	0.09	2.15	5.37	0.09	2.15
Renewables								
Biomass CC	20	12.35	7.28	0.36	17.49	7.20	0.35	17.36
Biomass BFB	50	13.50	3.66	0.11	5.26	3.66	0.11	5.26
Onshore wind	100	0.00	1.98	0.04	0.00	1.98	0.04	0.00
Offshore wind	400	0.00	6.15	0.07	0.00	6.15	0.07	0.00
Solar thermal	100	0.00	4.05	0.07	0.00	4.05	0.07	0.00
Photovoltaic (small)	20	0.00	4.18	0.03	0.00	4.18	0.03	0.00
Photovoltaic (large)	150	0.00	3.28	0.02	0.00	3.28	0.02	0.00
Geothermal—dual flash	50	0.00	3.50	0.15	0.00	3.50	0.15	0.00
Geothermal—binary	50	0.00	2.45	0.11	0.00	2.45	0.11	0.00
Municipal solid waste	50	18.00	8.27	0.39	8.74	6.99	0.37	3.22
Conventional hydroelectric	500	0.00	2.65	0.02	5.76	2.65	0.02	5.76
Pumped storage	250	0.00	5.29	0.02	0.00	5.29	0.02	0.00

Abbreviations: BFB = bubbling fluidized bed; BTU = British thermal unit; CC = combined cycle; CCS = carbon capture and sequestration; CT = combustion turbine; IGCC = integrated gasification combined cycle; EIA = Energy Information Administration; MW = megawatt; MWh = megawatt-hour; O&M = operations and maintenance; PC = pulverized coal.

Note: Generation-only costs equal EIA total costs less EPA Integrated Planning Model retrofit costs of the EIA technology specification's control equipment.

Sources: EIA (2015a, 2015b) Table 8.2; EIA (2013c) Table 1; EPA (2013c) Chapter 5.

To produce annual capital cost amounts, we amortized overnight capital costs for 30 years at a weighted average cost of capital of 6.1 percent per EMM assumptions (EIA, 2015b). Installations older than 30 years operate with a 7 percent capital cost of life extension (i.e., amortized value of overnight capital times 7 percent) per the average of life extension costs given by IPM (EPA, 2013, Table 4-10).

To apply the EMM cost estimates, we categorized the installations represented in the engineering data constructed in the engineering section above under the set of available configurations from EIA. This categorization allows for costing the generation activity of the installations. Installations were mapped by their PM-FT configuration, of which there are 90, to the 26 EIA configurations. Of the 26 configurations, 18 are active in the EIA data.

Table 8 summarizes the total cost of generation (generation plus controls) for the different plant types by region. Large pulverized coal installations dominate by cost and output, followed by nuclear. The MEEDE dataset's estimated annual cost of operating generation and control equipment in 2013 is $200 billion (2015 dollars) (of which $172 billion is nonfuel costs). These amounts are comparable to IMPLAN data, which give a total cost of electric generation of $212 billion (2015 dollars) for the year 2013 (IMPLAN Group, 2013).

To estimate the total cost of generation including pollution control, we mapped the variety of control technologies identified in the Form 860 data

Table 8. Total and unit costs of generation (in MM 2015$) by plant type and region, 2013

Plant type	Region										Generation cost (MM 2015$)	Net generation (in thousands of MWh)	Unit cost ($/kWh)
	West South Central	South Atlantic	East North Central	Middle Atlantic	Pacific (CA, OR, WA)	Mountain	East South Central	West North Central	New England	Pacific (AK, HI)			
Dual-unit advanced PC	9,588	13,154	13,956	1,758	510	5,891	7,614	5,062	174	0	57,706	1,227,863	0.05
Dual-unit nuclear	3,971	6,974	7,240	5,674	1,859	2,212	2,441	1,848	1,201	0	33,420	789,016	0.04
Single-unit advanced PC	3,979	6,351	5,084	2,521	701	2,972	2,431	3,918	1,226	209	29,392	468,720	0.06
Conventional CC	4,400	5,615	1,759	2,681	2,604	2,128	1,813	639	1,466	127	23,232	796,095	0.03
Conventional hydro.	228	496	98	427	2,551	628	397	176	156	66	5,221	268,532	0.02
Conventional CT	1,722	4,187	2,992	1,304	1,688	1,109	1,114	1,379	429	149	16,074	108,200	0.15
Onshore wind	2,879	140	1,455	612	2,408	1,379	5	2,837	163	56	11,935	167,697	0.07
Municipal solid waste	320	2,262	843	1,765	248	3	133	341	1,512	219	7,647	15,135	0.51
Biomass BFB	657	1,733	417	310	692	121	698	248	698	73	5,646	41,588	0.14
Advanced CC	1,132	2,525	244	339	673	82	5	3	1	144	5,149	158,349	0.03
Geothermal—dual	0	0	0	0	850	88	0	0	0	15	952	13,029	0.07
Photovoltaic	23	156	39	155	364	297	5	1	44	6	1,090	5,096	0.21
Photovoltaic	0	0	0	0	471	247	0	0	0	0	718	3,031	0.24
Single-unit IGCC	0	175	467	0	0	0	0	0	0	0	642	1,979	0.32
Solar thermal	0	298	0	0	232	29	0	0	0	0	558	823	0.68
Geothermal—binary	0	0	0	0	77	142	0	0	0	0	218	2,904	0.08
Fuel cells	0	31	0	0	34	4	0	0	2	0	70	413	0.17
Pumped storage	0	0	0	0	0	0	0	0	0	0	0	−4,681	0.00
Total	**28,898**	**44,097**	**34,592**	**17,545**	**15,959**	**17,329**	**16,656**	**16,453**	**7,074**	**1,064**	**199,669**	**4,063,792**	**0.05**

Abbreviations: BFB = bubbling fluidized bed; CC = combined cycle; CT = combustion turbine; IGCC = integrated gasification combined cycle; kWh = kilowatt-hour; MM = million; MWh = megawatt-hour; PC = pulverized coal.

Notes: Total costs include capital, fixed O&M, and variable O&M.

Source: Micro-level Economic and Environmental Detail of Electricity (MEEDE) dataset.

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(see Table 6) to the smaller set of technologies IPM covers. Depending on the technology, this mapping varies with the type of fuel, the firing configuration of the boiler, and the specific control equipment installations. Table 9 provides the total costs of generation and pollution control. Controlling sulfur oxides requires the greatest expense, and nitrogen oxides and particulate matter control are each less than half the cost of sulfur oxide control. Approximately half of all grid generation (2,219 MM MWh) employs some form of pollution control.

The Form 923 data provide fuel costs and quantities at the PID-FT level. We used local, quantity-weighted average prices for the different fuel types to estimate total fuel costs. The locality of the average varies depending on data availability (i.e., when a state-level average was not available, we took a regional average if available, a national average if not). Given fuel price data and estimates for capital and O&M costs, we fully costed the generation capital, labor, energy, and materials (i.e., KLEM) inputs where we associate fixed O&M with labor and variable O&M with materials. Lastly, we adjusted all costs by regional cost variation factors provided by EIA (2013c, Table 4).

The final step is to estimate the wholesale value of the electricity produced for which we relied on data from the Intercontinental Exchange (Intercontinental Exchange, 2015) as provided by EIA (EIA, 2015c). We used a trade volume–weighted average price by North American Electric Reliability Corporation (NERC) region where hub data are available. Regions without available hub data were assigned the national volume–weighted average price.

Table 9. Costs of generation and pollution control, 2013

Installation attributes		Total costs excluding fuel (MM 2015$)			
Cost component	Net generation (in thousands of MWh)	Total	Capital	Fixed O&M	Variable O&M
Total system costs excluding fuel	4,063,792	172,087	106,186	47,777	18,124
Generation only	4,063,792	150,253	96,696	43,700	9,857
Controls	**1,860,435**	**21,834**	**9,490**	**4,078**	**8,267**
SO_x controls	**1,110,108**	**11,561**	**4,978**	**3,190**	**3,393**
Dry sorbent injection	588,047	727	200	67	460
Limestone forced oxidation scrubber	935,903	8,036	3,113	2,340	2,582
Lime spray dryer scrubber	204,776	3,034	1,693	744	598
PM controls	**1,591,878**	**5,945**	**2,725**	**494**	**2,725**
Electrostatic precipitator (cold side)	1,575,773	1,884	1,445	352	86
Electrostatic precipitator (cold side), with flue gas conditioning	426,893	675	515	127	33
Fabric filter baghouse	464,361	1,476	1,286	152	38
Electrostatic precipitator (hot side)	205,806	613	520	75	18
Electrostatic precipitator (hot side), with flue gas	64,904	210	183	22	5
NO_x controls	**1,667,565**	**3,388**	**1,718**	**381**	**1,290**
Selective catalytic reduction	1,260,254	2,508	1,273	243	993
Selective noncatalytic reduction (fluidized bed)	56,993	211	126	11	74
Selective noncatalytic reduction (tangentially fired)	127,704	262	58	31	172
Low-NO_x burner with advanced overfire air (tangentially fired)	359,849	280	186	58	37
Vertically fired	139,582	89	55	23	11
Low-NO_x burner (wall fired)	587,198	1,627	847	178	601
Low-NO_x burner with overfire air (wall fired)	194,408	698	325	87	287
Hg controls—active carbon injection	**370,419**	**940**	**69**	**13**	**858**

Abbreviations: Hg = mercury; MWh = megawatt-hour; NO_x = nitrogen oxide; O&M = operations and maintenance; PM = particulate matter; SO_x = sulfur oxide.

Notes: Total system cost = cost of generation plus cost of controls. Amounts do not sum across controls because many installations run multiple controls (e.g., selective catalytic reduction with a low-NO_x wall-fired burner).

Source: Micro-level Economic and Environmental Detail of Electricity (MEEDE) dataset.

Table 10 summarizes the wholesale revenue and total costs of electricity generation by region. The data produce good parity between total revenue and costs—estimated revenue is just 2.7 percent below estimated costs nationally. The table indicates considerable regional variation with some highly profitable regions (Mid-Atlantic) and others with revenue shortfalls (Pacific—AK, HI). In the latter case, this is partly due to missing wholesale price data for Alaska and Hawaii, where prices are no doubt higher than the national average from reporting hubs. Similarly, large revenue shortfalls in the regulated South Atlantic markets are likely a result of wholesale electricity prices for the region being higher than the national average.

In all, the economic characterization provides the capital, labor, energy, and materials (KLEM) requirements for operating the electric grid. These costs are produced at the level of individual installations of generation and pollution abatement equipment in true bottom-up fashion. They can be readily summarized at higher-level regional or technology aggregations for modeling applications. In aggregate, the sum of unit-level costs compares reasonably with independent, top-down cost estimates from IMPLAN (IMPLAN Group, 2013) and revenue estimates based on third-party market data (EIA, 2015c).

Environment

The final step is to identify the emissions associated with each observation generated in the previous step. For this step, we relied on data from a variety of EPA sources. We estimated emissions for eight pollutants: four greenhouse gases, three criteria pollutants, and mercury. Emissions were first estimated using emissions factors and control equipment abatement efficiencies from EPA's AP-42 (EPA, 1995) and updated when more current data are available. The AP-42 data form the basis of our estimates of particulate matter and mercury emissions, which we validated in aggregate against secondary sources. We modified mercury emissions factors based on the installation of other control equipment (e.g., particulate matter fabric filters) according to modification factors reported by IPM (EPA, 2013, Table 5-10).

Emissions of sulfur and nitrogen oxides are as reported by the Air Markets Program data provided by EPA's Office of Air and Radiation's Clean Air Markets Division (EPA, 2015a). Emissions of carbon dioxide, nitrous oxide, and methane are as reported by the "Envirofacts" utility of EPA's Greenhouse Gas Reporting Program (EPA, 2015c). Both of these data sources provide unit-level emissions that we summarize at the plant level and allocate

Table 10. Electric wholesale revenue and cost by region, 2013

	Output		Input (MM 2015$)				
Region	Net generation (in thousands of MWh)	Wholesale revenue (MM 2015$)	Total	Capital	Fixed O&M (labor)	Fuel	Variable O&M (materials)
South Atlantic	760,966	36,060	44,097	20,433	9,761	11,062	2,841
W. South Central	668,391	31,406	28,898	18,056	6,136	2,530	2,177
E. North Central	622,028	30,413	34,592	18,090	9,330	4,817	2,355
Middle Atlantic	426,827	23,672	17,545	9,862	5,629	337	1,718
Mountain	376,409	15,506	17,329	9,257	3,006	3,672	1,394
Pacific (CA, OR, WA)	373,992	15,373	15,959	10,267	3,533	232	1,927
E. South Central	372,759	17,543	16,656	7,015	3,741	4,477	1,423
W. North Central	330,291	15,524	16,453	7,894	3,885	3,794	880
New England	115,365	7,920	7,074	4,177	2,309	83	504
Pacific (AK, HI)	16,764	788	1,064	555	231	189	90
Total USA	**4,063,792**	**194,206**	**199,669**	**105,607**	**47,561**	**31,193**	**15,308**

Abbreviations: MM = million; MWh = megawatt-hour; O&M = operations and maintenance.
Source: Micro-level Economic and Environmental Detail of Electricity (MEEDE) dataset.

to the boiler level based on the relative estimates from AP-42 emissions factors. Lastly, fluorinated gas emissions are as reported by EPA's Greenhouse Gas Inventory (EPA, 2015d, Tables 4-98 and 4-102). Fluorinated gases (i.e., SF_6, NF_3, HFCs, and PFCs) are emitted when the electrical equipment associated with transmitting and distributing electricity leaks. Aggregate fluorinated gas (F-gas) emissions are allocated to the generating units in proportion to their net generation.

Table 11 summarizes the US electric sector emissions by pollutant and region. Not all EGUs report emissions within the Air Markets Program data or Greenhouse Gas Reporting Program datasets. We calculated a weighted average emissions rate (lb/MMBTU) by plant and fuel type and applied it to nonreporting units. This calculation increased aggregate emissions by less than 3 percent for nitrogen oxide and sulfur oxide, 4 percent for carbon dioxide, and 12 percent for nitrous oxide and methane relative to the totals reported in the original sources. Table 12 summarizes the US electric sector emissions rates by pollutant and region. There is considerable regional heterogeneity in the emissions rates both within and across pollutants. For example, the West North Central region has both the second highest sulfur emissions rate and a relatively low particulate matter emissions rate. Table 6 shows that West North Central's fraction of generation covered by particulate matter controls is the highest of all regions, while its fraction of generation covered by sulfur controls is at about the 75th percentile and its coal generation relies on dirtier lignite coal (categorized under "other coal") more than other regions (see Table 2).

Table 13 illustrates the impact of control technologies on emissions of sulfur oxides. Among coal-fired generators, 68 percent of generation is covered by some type of sulfur control equipment. Limestone forced oxidation (LSFO) and lime spray dryer technologies are most prevalent. Emissions rates for controlled equipment are between 43 percent (LSFO for other coal) and 87 percent (LSFO for bituminous coal) lower than those for uncontrolled generation. The use of multiple control devices can reduce emissions rates by upward of 90 percent.

The final MEEDE dataset has 11,271 observations and 99 variables. The data provide a variety of plant- level attributes (e.g., latitude and longitude, NERC region, name) and boiler-level attributes (e.g., MMBTU of fuel consumed, emissions rates). Quantitative

Table 11. Electric sector emissions by pollutant and region, 2013

	Output	Criteria and hazardous air pollutants (tons)				Greenhouse gases (MMT CO_2e)				
Region	**Net generation (in thousands of MWh)**	**Sulfur oxides**	**Nitrogen oxides**	**Particulate matter**	**Mercury**	**Total**	**Carbon dioxide**	**Nitrous oxide**	**Methane**	**F-gases**
South Atlantic	760,966	409,579	243,737	233,537	3.7	367.8	364.6	1.4	0.7	1.0
W. South Central	668,391	596,518	265,387	11,172	9.9	390.2	387.4	1.4	0.6	0.8
E. North Central	622,028	953,153	327,940	88,944	9.6	405.8	402.2	1.9	0.8	0.8
Middle Atlantic	426,827	271,942	152,972	262,662	2.3	152.7	151.4	0.6	0.2	0.5
Mountain	376,409	170,435	288,448	16,554	6.1	245.0	242.9	1.1	0.6	0.5
Pacific (CA, OR, WA)	373,992	19,552	21,441	12	0.1	71.9	71.2	0.2	0.1	0.5
E. South Central	372,759	430,603	170,579	3,799	5.5	211.8	209.9	1.0	0.4	0.5
W. North Central	330,291	415,441	251,480	6,469	11.8	230.6	228.6	1.1	0.4	0.4
New England	115,365	16,329	10,383	482	0.1	29.5	29.2	0.1	0.0	0.1
Pacific (AK, HI)	16,764	8,485	3,500	40	0.0	5.0	4.5	0.3	0.2	0.0
Total USA	**4,063,792**	**3,292,037**	**1,735,868**	**623,671**	**49.1**	**2,110**	**2,092**	**9.1**	**4.0**	**5.1**

Abbreviations: MMT CO_2e = million metric tons of carbon dioxide equivalents; MWh = megawatt-hour.

Source: Micro-level Economic and Environmental Detail of Electricity (MEEDE) dataset.

Table 12. Electric sector emissions rates by pollutant and region, 2013

Region	Output	Criteria and hazardous air pollutants (tons/MWh)				Greenhouse gases (tons CO_2e/MWh)				
	Net generation (in thousands of MWh)	Sulfur oxides	Nitrogen oxides	Particulate matter	Mercury	Total	Carbon dioxide	Nitrous oxide	Methane	F-gases
South Atlantic	760,966	0.538	0.320	0.307	0.005	483	479	1.88	0.95	1.26
W. South Central	668,391	0.892	0.397	0.017	0.015	584	580	2.11	0.87	1.26
E. North Central	622,028	1.532	0.527	0.143	0.015	652	647	3.08	1.35	1.25
Middle Atlantic	426,827	0.637	0.358	0.615	0.005	358	355	1.31	0.58	1.25
Mountain	376,409	0.453	0.766	0.044	0.016	651	645	2.83	1.47	1.26
Pacific (CA, OR, WA)	373,992	0.052	0.057	0.000	0.000	192	190	0.49	0.27	1.26
E. South Central	372,759	1.155	0.458	0.010	0.015	568	563	2.60	0.99	1.25
W. North Central	330,291	1.258	0.761	0.020	0.036	698	692	3.44	1.25	1.25
New England	115,365	0.142	0.090	0.004	0.001	256	254	0.80	0.42	1.25
Pacific (AK, HI)	16,764	0.506	0.209	0.002	0.003	299	270	18.72	9.25	1.25
Total USA	**4,063,792**	**0.810**	**0.427**	**0.153**	**0.012**	**519**	**515**	**2.24**	**0.99**	**1.25**

Abbreviations: CO_2e = carbon dioxide equivalents; MWh = megawatt-hour.

Source: Micro-level Economic and Environmental Detail of Electricity (MEEDE) dataset.

Table 13. Coal-fired emissions of sulfur oxide by control type, 2013

Controls	Net generation (in thousands of MWh)	Emissions rate (lb/MMBTU)			Percent reduction from uncontrolled		
		Other coal	Bituminous	Sub-bituminous	Other Coal	Bituminous	Sub-bituminous
No controls	501,069	0.956	1.839	0.634	—	—	—
LSFO	853,948	0.543	0.235	0.085	43.3	87.2	86.6
LSD	160,165	0.427	0.309	0.173	55.3	83.2	72.7
LSD and LSFO	28,452	—	0.321	0.129		82.5	79.7
DSI	14,777	0.346	0.597	0.481	63.8	67.5	24.2
DSI and LSFO	11,478	—	0.243	—	—	86.8	—
DSI and LSD	1,299	—	0.684	—	—	62.8	—
All coal-fired generation	**1,558,411**	**0.506**	**0.253**	**0.117**	—	—	—

Abbreviations: BTU = British thermal unit; DSI = dry sorbent injection; LSD = lime spray dryer; LSFO = limestone forced oxidation; MMBTU = million British thermal units; MWh = megawatt-hour.

Source: Micro-level Economic and Environmental Detail of Electricity (MEEDE) dataset.

boiler-level attributes can be summed over the entire dataset to generate grid totals, whereas plant-level attributes apply to multiple observations. Generator-level attributes (e.g., nameplate capacity, heat rate) also apply to multiple observations. Variable labels indicate the attribute level, units (if quantitative), and data source of each variable.

The MEEDE dataset provides a highly detailed description of the engineering, economic, and environmental attributes and quantities of the US electric grid at the level of individual generating units. The aggregate quantities maintain good fidelity with estimates from secondary sources, suggesting some success in methodology and construction. The final dataset can be used to support economic modeling of the US electric sector. The next section provides brief descriptions of how this modeling can be done in two distinct frameworks.

Applications

Modeling applications will use a much more highly aggregated version of the data. At the very least, we would aggregate to the regional resolution of the model so that plants of identical construction would be summed as one larger facility (but without the economies of scale of a larger facility). This process characterizes model EGUs that can be operated to satisfy model demand for electricity and pollution levels. For example, aggregating the 11,271 observations at the level of plant type; fuel code; and types of nitrogen oxide, sulfur oxide, particulate matter, and mercury controls yields over 600 EGUs, before regionalizing. We are looking for a more parsimonious characterization of the grid.

Grouping on only plant type and fuel code produces 42 EGUs—still quite large given that location and pollution controls remain unaccounted for. Mapping the plant types and fuel codes to smaller sets reduces the number of EGUs to 26. From there we can expand the types to control for the presence of pollution control devices in each of the four categories, generating 114 EGUs. The “nested” production structure of the CGE framework will help mitigate the burden of computing prices and quantities for so many EGUs. A partial equilibrium representation of the grid in a linear programming model may perform less well with this many EGUs, but the data can support such a model equally well.

Partial Equilibrium

The MEEDE data could be used to support a linear programming model of US wholesale electricity markets such as RTI EMA®. Linear programming models provide the mathematical structure for partial equilibrium representations of the electric grid. These models are designed to examine how mid- to long-term policies affecting electricity markets will influence electricity supply decisions, electricity generation costs, electricity prices, and emissions. To estimate these changes, the model determines least-cost combinations of model plants that meet electricity demand on a seasonal and time-of-day basis while satisfying peak demands, limits on emissions, and other grid constraints.

Linear programming models will generally carry more detailed specifications of daily and seasonal patterns in demand, capacity factors, and transmission constraints than general equilibrium models. A key distinction with the partial equilibrium approach to modeling is that aggregate electricity demand is exogenously determined through load curves; however, partial equilibrium models are sometimes iterated with general equilibrium models so that prices and quantities can be determined endogenously.

The MEEDE data can be used to generate a supply curve built up from the separate generation cost and capacities of the model plants. The model will dispatch available model plants economically, minimizing the cost of supply subject to the constraint of meeting a given level of demand. Baseload technologies such as nuclear, hydro, and coal will be dispatched most often, while dispatch of higher-cost technologies like combustion turbines will be reserved for periods of higher-demand quantities and prices. The low cost of baseload technologies is evident in Table 8.

A linear programming model can offer the benefit of more nuanced treatment of the technical constraints faced by grid operators such as transmission and distribution limitations, reserve and reliability considerations, and intra-annual demand patterns. Absent a linkage with a macroeconomic model, these benefits come at the cost of producing partial equilibrium outcomes where general equilibrium consequences may be relevant. For example, substantial climate policy would likely place significant pressure on prices of fossil fuel through channels other than the electric sector. These impacts would be missed in a partial equilibrium analysis. Lastly, the benefits of a linear programming model and a general equilibrium representation of the economy can both be achieved through model linkage. The remaining risk in this approach is that model iterations fail to converge.

General Equilibrium

General equilibrium modeling approaches typically carry far less technical detail than linear programming models. Inconsistencies of top-down data sources relied on for CGE models and bottom-up sources such as the MEEDE data frustrate efforts to incorporate technical detail. We outline a reconciliation process that can be used to bring the two data sources into agreement, enabling technically detailed electric sector representation within the CGE framework.

Macroeconomic input-output data come from national accounts compiled by sources such as the Bureau of Labor Statistics (2012) and Bureau of Economic Analysis (2012) or IMPLAN (IMPLAN Group LLC, 2013) for state-level detail. Even at the highest resolution, only a single "electric power generation, transmission, and distribution" aggregate (North American Industry Classification System 2211) is typically presented; however, IMPLAN has provided some additional detail on generation by fuel type in its most recent release. These data form the basis of the CGE model and must be reconciled with the bottom-up MEEDE dataset.

The model technologies generated from the MEEDE data are assumed to employ a portion of the capital, labor, energy, and materials inputs recorded for the generation-transmission-distribution aggregate sector. Inconsistency between the bottom-up and top-down cost estimates requires that they be reconciled. But reconciliation is particularly problematic for the technologies' fuel uses, where bottom-up data yield totals for the various fuel types that differ markedly from the top-down national accounts data.

We produced a technology-by-input unit-cost matrix of grid generation and specified a mathematical program to minimally revise the matrix entries so that they reconcile with the relative fuel use values given by macro accounts. With the unit-cost shares revised for consistency with the macro data, we can scale the revised matrix by the macro data's fuel-use totals and attribute the remaining capital, labor, energy, and materials to the transmission and distribution subsector. Table 14 provides an example of the unit-cost matrix with technologies defined by fuel type only for parsimony; the actual unit-cost matrix would have far more technologies and break out costs by their association with different generation and abatement activities.

All output of the generation-abatement technologies is purchased by the transmission and distribution subsector at a price equaling the value of inputs to ensure market clearance for the technologies and zero profit for the transmission and distribution subsector. The supporting data preparation for this

Table 14. Example technology-by-input unit-cost matrix, 2013

	Total		Share of total grid inputs %			
Technology	Net generation (in thousands of MWh)	Cost (MM 2015$)	Capital	Labor (Fixed O&M)	Energy (Fuel)	Materials (Variable O&M)
Natural gas and propane	1,121,218	48,927	15.0	4.2	2.6	2.7
Nuclear	789,016	33,420	10.7	5.2	0.9	0.0
Subbituminous coal	754,594	32,405	6.3	3.6	1.2	5.2
Bituminous coal	734,822	40,311	6.8	4.7	1.6	7.1
Water	263,851	5,221	1.2	0.6	0.8	0.0
Wind	167,697	11,935	4.7	1.3	0.0	0.0
Other coal	96,685	4,905	1.4	0.4	0.2	0.3
Biomass solids	41,409	5,570	1.6	1.0	0.1	0.1
Other gases	27,246	1,354	0.4	0.1	0.1	0.0
Geothermal	15,775	1,170	0.3	0.3	0.0	0.0
Municipal solid wastes	15,135	7,647	2.1	1.7	0.1	0.0
Miscellaneous other	14,871	1,549	0.6	0.2	0.0	0.0
Oil and petroleum derivatives	12,338	2,813	0.8	0.4	0.0	0.2
Solar	8,951	2,366	1.1	0.1	0.0	0.0
Biomass liquids	185	77	0.0	0.0	0.0	0.0
Total USA	**4,063,792**	**199,669**	**52.9**	**23.8**	**7.7**	**15.6**

Abbreviations: MM = million; MWh = megawatt-hour; O&M = operations and maintenance.

Source: Micro-level Economic and Environmental Detail of Electricity (MEEDE) dataset.

revision is analogous to that outlined by Sue Wing (2008). We imposed two additional constraints on the revised matrix. The first ensures that the total values of fuel 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 subsector. We based this minimum on ratios of capital and labor to materials inputs for a sample of Regional Transmission Organizations and Independent System Operators. The final revised share matrix can be used to disaggregate the social accounting matrices' electric sector aggregate in a way that will satisfy the accounting requirements of a CGE model.

Discussion

Policy makers require increasing degrees of detail and transparency from full-economy models to assess energy and environmental policies. In the case of policies affecting the electric sector, these modeling efforts must simultaneously capture the rich detail of the electricity sector while identifying impacts on the broader economy. The MEEDE dataset provides unique support for integrating rich electric sector detail into general equilibrium assessments of proposed policies.

The current standard in modeling interactions between the electric sector and the broader economy links two separate models, one partial and one general equilibrium. In this methods report, we discuss our development of a comprehensive database of the electric sector that can support either a partial equilibrium model (with a general equilibrium model linkage) or take an alternative integrated approach. The primary advantage of the integrated approach is that it captures additional environmental and economic details left out of CGE models while avoiding some of the pitfalls of maintaining two models. Whichever approach is taken, either linked or integrated, the MEEDE data can provide a robust characterization of the electric sector to support modeling efforts.

First, when new environmental and economic data are published (e.g., Annual Energy Outlook), modelers must update data and documentation for both models. This task can lead to a perverse result where more time is spent updating models than deploying them for policy analysis. An integrated modeling approach offers potential synergies in the update process. The MEEDE data construction also promises to reduce the cost of alternative technology and spatial aggregations. By building the database from the boiler and unit levels, we can quickly reaggregate to meet alternative details in lieu of rebuilding.

Second, our experience and conversations with peer modelers suggest that linked partial and general equilibrium models often fail to converge to an equilibrium solution. Policies that significantly alter the structure of the energy sector can be particularly problematic, although policy magnitude provides only a limited indication of the likelihood of convergence. By sacrificing some of the finer engineering detail represented in partial equilibrium models, the integrated modeling approach mitigates this risk of nonconvergence while still capturing the rich environmental and economic features required of high-quality policy analysis.

MEEDE's use of publicly available data and rich documentation supports transparency and replication, which are key features of the "citizen-based science" mantra in policy analysis. The inclusion of emissions for eight pollutants (four greenhouse gases, three criteria pollutants, and mercury) enables tracking of multipollutant abatement interactions, which have become a prominent topic in environmental policy analyses. This is particularly true for greenhouse gas policies.

The data stand alone as a unique contribution to analyses of the electric sector. They offer a micro-level characterization of the engineering, economic, and environmental features of the US electric grid. These features are critical for rigorous policy analysis. When used to support a partial equilibrium or integrated general equilibrium model, the data can enable powerful insights into the workings of the electric sector, its relationship to the broader economy, and how environmental policy influences them both.

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