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Towards a disaggregated electric power sector in the GTAP data base

Jeffrey C. Peters
Thomas Hertel

Purdue University
Department of Agricultural Economics
peters83@purdue.edu

1. Introduction and some existing electricity databases in CGE modeling

From 1990 to 2010 electricity output increased 81% worldwide, and approximately 40% of the world's total energy is consumed via the electric power sector (IEA, 2012). Coal and gas alone fueled over 40% and 20% of total world electricity production in 2009, respectively, and global trade of these input fuels has increased faster relative to many other tradable commodities (IEA, 2013; Narayanan, Aguiar, and McDougall, 2012). Technological advancements (e.g., horizontal drilling and hydraulic fracturing) may further expand fossil fuel energy reserves and export opportunities internationally. As a consequence of its prominent role in global fossil fuel combustion, the electricity sector is also responsible for approximately 33% of greenhouse gas emissions, assumed an increasing proportion of total carbon emissions over the last decades (see Figure 1), and as such has been the target of many carbon mitigation policies around the world. Over the last several decades electricity has assumed an increasing proportion of emissions. Electricity-related technologies, policies and their trends such as these beg the question of *how* regional electricity sectors and bilateral energy trade will evolve and, in turn, *what* effects these evolving trade patterns may have on the impacts and incidence of global energy and climate policies.
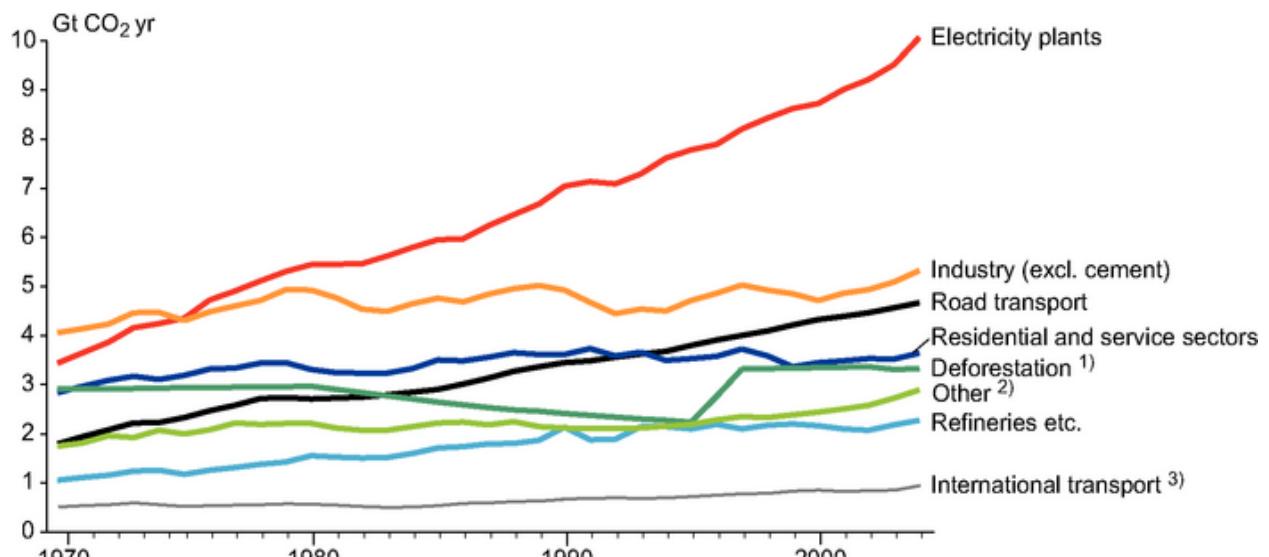
Figure 1: Gigatons of carbon dioxide emissions per year from select sectors (Source: IPCC, 2007)

Computable general equilibrium (CGE) models are often used to provide global policy assessments. However, CGE models aiming to forecast electricity-related technology, policy, and their global implications require a consistent database with disaggregated electricity generating technologies as well as mechanism to address substitutability of generation technologies. Despite this, many CGE models and integrated assessment models treat the electricity sector as an aggregated sector due to a lack of a

consistent database for generating technologies. This is exemplified by the GTAP database for CGE modeling which currently has just one sector ('ely') which encompasses "production, collection and distribution of electricity."

Because electricity from different technologies (e.g., fossil fuels, nuclear, hydro, renewables) are highly substitutable but vary greatly in produced emissions and other impacts, several users of GTAP data have independently disaggregated the electricity sector for their particular research purposes. The assumptions and procedures used in such disaggregation exercises vary across research groups and the limitations in available data inevitably lead to a considerable amount of "educated guesswork", much of which is not properly (or at least not publicly) documented. Table 1 shows how these disaggregation procedures differ in terms of the electricity sectors considered, methodology for disaggregation (where documentation in present), and particular research purposes which may have motivated these decisions.

This paper offers an extension to the GTAP database with a disaggregated electricity sector informed by previous efforts by the GTAP community (and others). The result will be a database to provide greater consistency across researchers modeling the electricity sector. Transmission and distribution is separated from electric power generation technologies. Generation technologies are further disaggregated based on fuel source and the current relevance of the technology globally and in a manner informed by both levelized costs for the technology and relative input shares from the original GTAP data.

Table 1: Example research with disaggregated electricity sector.

Researcher(s)	Electricity Sectors	Method	Example Research Purposes
MIT – Joint Program	coal, gas, oil, nuclear, hydro, biomass, wind & solar, (various advanced technologies)	Subtract nuclear and hydro from GTAP data using engineering cost data, the residual is fossil, other techs are backstop.	Climate change and carbon mitigation policy, future of fuels, future of power technology
JGCRI - Phoenix	coal, gas, nuclear, hydro, oil, biomass, wind, solar, (various advanced technologies)	Positive mathematical programming approach using LCOE and input cost shares (Sue Wing, 2008)	Climate change and carbon mitigation policy
GTEM	coal, oil, gas, nuclear, hydro, waste, biomass, solar, wind, renewables (includes some CCS tech)	"Data on the cost structure of electricity generation."	Climate change and abatement policy, trade analysis, coal-use in Asia
OECD ENV-Linkages	coal, oil, gas, hydro, nuclear, wind & solar, renewable	"…calibrated based on the projections from the IEA's World Energy Outlook"	Climate change and abatement policy
Productivity Commission	coal, oil, gas, biogas, hydro, nuclear, renewables	Combination of output prices for fuels (baseload/peaking) and cost shares of generation technology	

Note: non-exhaustive and summarized based on available documentation. Sources: MIT-EPPA (Paltsev et al., 2005), JCRI-Phoenix (Sue Wing, 2008), GTEM (Pant, 2007), OECD ENV-Linkages (Burniaux and Chateau, 2010), and Productivity Commission (Unpublished email). Most disaggregation processes seem to be un- or weakly documented.

2. Description of the formulation

The primary motivation of this exercise is to provide a common disaggregated electricity sector of the GTAP database informed by the insight, experience, and particular research needs of the previous efforts in the GTAP community in terms of relevant sectors to distinguish, available data, and methodology.

2.1 Relevant subsectors

First, an important distinction should be made between the generation of electricity and the transmission and distribution of electricity. The 'ely' sector in GTAP encompasses all "production, collection and distribution of electricity." In reality, the electricity sector consists of electricity generation units (e.g., power plants) which produce electricity, high voltage transmission lines to transport the electricity over long distances, and lower voltage lines to distribute power to local businesses and residential households. Many of the currently relevant policies, at the time of writing this paper, are directed with respect to generation (or production) and less so with respect to collection and distribution. Also, the cost structure of power generation is much different than the transmission and distribution networks. Therefore, it is necessary to distinguish the electricity generation, which is subject to fuel input shocks and policies, from transmission and distribution of the electricity end product.

Second, electricity generation should be further split into specific generation technologies. There exist many different technologies which transform different fuels to the relatively homogenous product of electricity (e.g., nuclear, gas, oil, coal, renewables). These technologies have very unique cost structures in terms of capital investment, fuel, and operating and maintenance costs which make them more or less competitive in certain economic environments. Furthermore, several policies target specific generating technologies rather than fuel source (e.g., nuclear phase-out, investment in renewables), which necessitates some form of substitutability between technologies (in addition to substitutability between fuel source). The relevant sectors differentiated by both fuel source and significance in the global electricity sector are: nuclear, oil, coal, gas, hydro, solar, wind, and other. While there are many other ways to produce electricity, these tend to have a much lesser penetration or can be likened to one of the other technologies.

Thirdly, there exist many different methods to produce electricity using a particular fuel source (e.g., steam turbine, combustion turbine) which also have unique cost structures in terms of capital investment, fuel, and operating and maintenance costs and are used to fulfill some important operation considerations of the electricity market. Electricity must be delivered to consumers on-demand (i.e., it is very expensive to store) and demand varies by time-of-day, day, and season. As a result, different methods for producing electricity are utilized in response to this changing environment. Figure 2 shows an illustrative example of electricity demand. A certain level (in Megawatts) is required throughout the day (labeled base load) while a higher level is needed for short durations (labeled intermediate and peak load). Figure 3 demonstrates that the total cost of generation is a combination of fixed and variable costs which depend on the fuel source and method. The cost minimizing technology for long durations (i.e., base load demand) may be different for short duration (i.e., peak load demand). The relevant fuel technologies which should include these operational considerations are gas, oil, and hydro power (others are less flexible fuel sources). A base load and peaking sector for each of these fuel technologies are disaggregated as well.
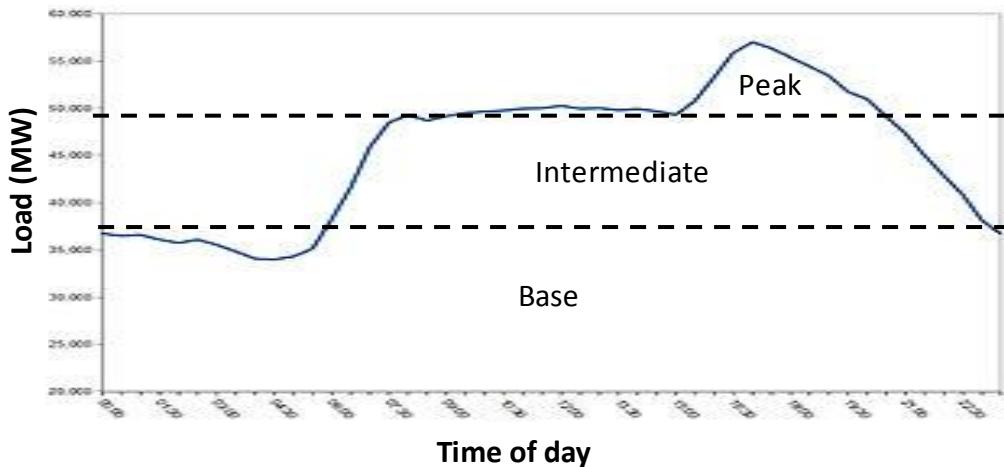

Figure 2: An illustrative example of electricity demand by time-of-day.
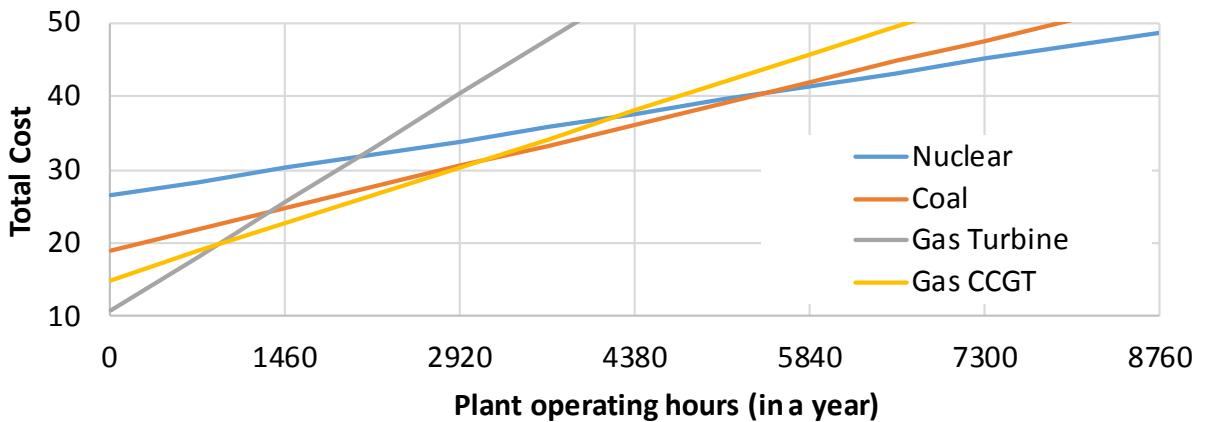
Figure 3: An illustrative example of total cost of generating electricity (fixed and variable)

In recognition of these electricity sector characteristics the original GTAP electricity sector ('ely') is disaggregated to the following sectors: 'TnD', 'NuclearBL', 'CoalBL', 'GasBL', 'HyrdoBL', 'WindBL', 'OilBL', 'OtherBL', 'GasP', 'HydroP', and 'SolarP'. The 'TnD' signifies transmission and distribution, the BL suffix signifies baseload power, and the P suffix signifies peaking power.

2.2 Data and Methodology

Most relevant to this disaggregation effort is the representation of cost share values from input sectors to the final value of the produced sector for each region (see Table 2). Costs are further differentiated based on source (domestic or import) and type (basic or tax). This representation is a normalized version of the GTAP database which the SplitCom application (CITE) uses to split sectors. The methodology in this paper disaggregates the original normalized GTAPv8 database (illustrated by Table 2) to one with 12 distinct electricity sectors (illustrated by Table 3) then brings the normalized representation here to the GTAP database format (i.e., basedata.har).

2.2.1 GTAPv8 Database

The normalized GTAPv8 database provides a full representation of costs (in values) to users for each region divided by source and type (Table 2). Many of the values in the original GTAP database provide insights into the allocation of costs and constraints on total allocations. Also, some reasonable assumptions based on the original database make the mathematical formulation more tractable.

Table 2: The current GTAPv8 database. Note: source, tax, and region dimensions not shown

	User 1	…	User n	Ely
Input 1				
…				
Input n				
ely				
Factor 1				
…				
Factor n				
PTAX				

Table 3: The GTAP database with disaggregated electricity sector into transmission and distribution (TnD) and electric power generating technologies. Note: source, tax, and region dimensions not shown

	User 1	…	User n	TnD	Tech. 1	…	Tech. n
Input 1							
…				COLUMN WEIGHTS			
Input n							
T&D							
Tech. 1		ROW WEIGHTS		CROSS WEIGHTS			
…							
Tech. n							
Factor 1							
…				COLUMN WEIGHTS			
Factor n							
PTAX							

Cost shares in vertical should reflect levelized cost shares of capital, O&M, fuel, etc. from engineering data.

Cost shares in horizontal should reflect relative costs (to other technologies) of capital, O&M, fuel, etc. from engineering data.

Some allocation insights using the GTAPv8 data are used to preserve important features of the electricity sector. First, GTAPv8 fuel input values (e.g., coal, gas, oil) and other generating technology-specific sectors (e.g., fuel transport) are allocated to the corresponding generation technology (e.g., coal to coal power, gas to gas baseload and peaking power). Second, transmission and distribution value in the original GTAPv8 database is assumed to be represented in the original GTAPv8 'ely' sector as own-use. Therefore, the sum of input costs to 'TnD' are represented as such in the disaggregated database. Third, the costs to 'ely' in the original GTAPv8 database must equal the costs across the disaggregated electricity sectors to conserve the market clearance conditions. Finally, to ensure general equilibrium consistency, supply-demand equality constraints are necessary

In addition to allocative insight, several basic assumptions can be made to reduce complexity in the problem without sacrificing the realities of the electricity sector. First, it is assumed that all generation technologies sell electricity to 'TnD' which then sells to the end users. The total value sold to end users is equivalent to the original sales of 'ely' in the original GTAP database. This removes the need to explore the 'Row Weights' in Table 3 as it is derived directly from the original GTAPv8 data values. Second, the input source and type share splits for the disaggregated sectors are assumed identical to the share splits for 'ely' in the original GTAP database. Third, it is assumed that there is no own-use or sales between generating technologies. Sales of generation to 'TnD' are based on a general equilibrium accounting constraint and need not be calculated in the basic problem setup and thus eliminating the 'Cross Weight' sub-matrix shown in Table 3. Therefore, the disaggregation methodology reduces the problem to filling the 'Column Weight' sub-matrix shown in Table 3 for each region using the available data, then extending this to the full matrix for a complete disaggregation.

2.2.2 IEA Energy Balances

Given these foundational insights, assumptions, and constraints, value must be distributed to the 12 disaggregated given available a priori information. Value can be thought of as the product of quantity and cost. The former, in the context of electricity, is measured in electric power with units Watt-hours. The International Energy Administration publishes total GWh generated by fuel sources (LIST) for a large number of regions (150) [CITE]. Beyond providing the first element of value (quantity), the IEA Energy

Balances provides physical clearance constraints (in GWh) for each generating technology by fuel. This is particularly important for generation technologies capable of delivering both baseload and peaking power.

2.2.3   IEA/NEA Levelized Cost of Electricity

The second element of value for the disaggregated sectors is cost. The IEA and Nuclear Energy Administration publish levelized costs of electricity (LCOE) (in USD per GWh) for a collection of both OECD and non-OECD countries for a handful of generation technologies (IEA/NEA, 2010). The levelized costs are broken down into investment, operating and maintenance, and fuel costs. Admittedly, the dataset is sparse and for some technologies the LCOE can vary widely (e.g., hydro, onshore/offshore wind). Simple averages of available LCOE were used to define values for countries and generation technologies lacking in the dataset. There is great opportunity in refining the LCOE dataset using additional sources, region-specific surveys, informed assumptions, and/or statistical methods.

2.2.4   OECD Effective Tax

The Organization for Economic Cooperation and Development (OECD) publishes data on the effective tax on electricity production based on carbon policies which come in many fiscal and regulatory forms (OECD, 2013). However, this data (and other similar) data is not currently included in the disaggregation.

2.2.5   Targets

The mathematical formulation described in the following section allocate values (cost share) of inputs to the 'ely' sector in the GTAPv8 data between a transmission and distribution sector ('tnd') and 11 electricity generation technologies based on the relevant constituents of value (i.e., quantity from IEA data and cost from IEA/NEA data) and important allocative insight, assumptions, and constraints described above. The general intuition underlying the formulation is to target: i) an assumed baseload/peaking power split which is assumed to be 85% baseload, ii) relative costs weighted by GWh across generation technologies to preserve relative cost intensities between technologies, iii) relative levelized costs within a generation technology, and iv) an assumed cost structure for transmission and distribution roughly identical to a similar sector.

3.   Mathematical Formulation

This section defines the primary sets, data, variables, targets, objective function, and constraints in mathematical terms. The formulation ignores the region dimension for ease of understanding; therefore, the formulation below can be thought of as a disaggregation for a single region. Regions are wholly independent from one another and in implementation of the mathematical programming the regions are solved independently in a loop to make the problem tractable.

3.1 Sets

3.1.1 Disaggregated sectors

The full set of the disaggregated sectors:
$$newcom = \{tnd, nuclearbl, coalbl, gasbl, oilbl, hydrobl, windbl, otherbl, gasp, oilp, hydrop, solarp\}$$

The full set of generation technologies:
$$newgen = \{nuclearbl, coalbl, gasbl, oilbl, hydrobl, windbl, otherbl, gasp, oilp, hydrop, solarp\}$$

The full set of baseload generation technologies:
$$baseload = \{nuclearbl, coalbl, gasbl, oilbl, hydrobl, windbl, otherbl\}$$

The fullset of peaking generation technologies:
$$peaking = \{gasp, oilp, hydrop, solarp\}$$

3.1.2 Costs to electricity sectors

The costs to 'ely' in the GTAPv8 database with the exception of 'ely':
$$orgcosts = \{productive\ sectors, endowments, production\ tax\} - 'ely'$$

The full set of costs (including disaggregated sectors) in the disaggregated database:
$$allcosts = \{productive\ sectors, newcom, endowments, production\ tax\} - 'ely'$$

Cost(s) which compose levelized costs of investment in LCOE data:
$$invcost = \{capital\}$$

Cost(s) which compose levelized costs of fuel in LCOE data:
$$fuelcost = \{coa, oil, gas, gdt, p\_c\}$$

Cost(s) which compose levelized costs of production tax in LCOE data:
$$orgptax = \{ptax\}$$

Cost(s) which compose levelized costs of operating and maintenance in LCOE data:
$$omcost = orgcosts - invcost - fuelcost - orgptax$$

3.1.3 Types of levelized costs

The classification of levelized cost of investment, fuel, operating and maintenance, and effective tax respectively:
$$levcost = \{inv, fuel, om, efftax\}$$

3.2 Data

Data (exogenous variables) are signified by a 0 superscript in the mathematical formulation

Levelized costs (investment, fuel, and o&m) data from IEA/NEA:
$$LCOE^0(levcost, newgen)$$

Original GTAPv8 data for cost shares (in values) to the electricity sector ('ely'):
$$x^0(orgcost, 'ely')$$

GWh for each generation type (not split between baseload and peaking) from IEA Energy Balances:
$$gwh^0(newgen^*)$$
*The data is not available for baseload and peaking (e.g., the data provides total gas, total oil, total hydro)

3.3 Variables

Variables (endogenous) are in bold to aid identification in formulation

New costs (in value) to the new electricity sectors (represented by 'Column Weight' sub-matrix in Table 3:
$$x(orgocsts, newcom)$$

The full normalized costs (in value) to all sectors in disaggregated database (represented by the full matrix in Table 3):
$$national(allcosts, allusers)$$
where the set **allusers** is the full set of users in the GTAPv8 database

GWh values for new electricity generating sectors:
$$gwh(newgen)$$

3.4 Targets

3.4.1 Baseload and peaking split

It may be necessary to consider operational characteristics of the electricity. The foremost of these possible considerations is the different markets for baseload and peaking. Drawing a fine line distinguishing baseload and peaking power provision is not feasible. Furthermore the IEA Energy balances dataset does not distinguish between methods of producing electricity for each fuel. Therefore, a target proportion of 85% baseload power is established based on the sparse available data. The proportion is assumed identical for all regions and may be considered a reasonable approximation considering the complexity of the operational characteristic. The following is the mathematical representation of the error between the derived proportion and the target.

$$\frac{\sum_{baseload} gwh(baseload)}{\sum_{newgen} gwh(newgen)} - 0.85 = \varepsilon_{blp}$$

3.4.2 Relative cost intensity *between* technologies

Various generation technologies have unique levelized costs for investement, fuel, O&M, and tax costs. The final database shall preserve the relative cost intensities between the different generation technolgoies. Visualizing the normalized database, this represents the row dimension of the x variable. For example, if in a particular region nuclear produces twice the GWh at twice the levelized cost of investment than another generation technology. The value of investment costs in nuclear power shall be four times the value in the other power sector. This is formalized as a target to allow flexibility with respect to the other targets. The following are mathematical representations of the error for levelized investment, fuel, O&M, and tax costs. The error term is for every cost and generation technology.

$$\frac{LCOE^0(inv, newgen) * gwh(newgen)}{\sum_{newgen}\left(LCOE^0(inv, newgen) * gwh(newgen)\right)} - \frac{x(invcost, newgen)}{x^0(invcost,'ely') - x(invcost, tnd)}$$
$$= \varepsilon_{inv}(invcost, newgen)$$

$$\frac{LCOE^0(om, newgen) * gwh(newgen)}{\sum_{newgen}\left(LCOE^0(om, newgen) * gwh(newgen)\right)} - \frac{x(om, newgen)}{x^0(omcost,'ely') - x(omcost,'tnd')}$$
$$= \varepsilon_{om}(omcost, newgen)$$

$$\frac{LCOE^0(fuel,newgen)*\boldsymbol{gwh}(newgen)}{\sum_{newgen}(LCOE^0(fuel,newgen)*\boldsymbol{gwh}(newgen))}$$
$$-\frac{\sum_{fuelcost}\boldsymbol{x}(fuelcost,newgen)}{\sum_{fuelcost}x^0(fuelcost,'ely')-\boldsymbol{x}(fuelcost,tnd)}=\varepsilon_{fuel}(fuelcost,newgen)$$
$$\frac{LCOE^0(efftax,newgen)*\boldsymbol{gwh}(newgen)}{\sum_{newgen}(LCOE^0(efftax,newgen)*\boldsymbol{gwh}(newgen))}-\frac{\boldsymbol{x}(orgptax,newgen)}{x^0(orgptax,'ely')-\boldsymbol{x}(orgptax,tnd)}$$
$$=\varepsilon_{tax}(orgptax,newgen)$$

3.4.3 Relative levelized costs *within* a generation technology

Similarly the relative levelized cost intensities within a particular generation technology shall be preserved to best match the available engineering data. Visualizing the normalized database, this represents the column dimension of x variable and overlaps the relative cost intensity between technology target, which motivates the targeting technique. The following are mathematical representations of the error between the derived proportion of levelized cost (investment, fuel, O&M, and tax) in total cost to the levelized cost data built from IEA/NEA dataset. The error term is for every generation technology.

$$\frac{\sum_{invcost}\boldsymbol{x}(invcost,newgen)}{\sum_{allcosts}\boldsymbol{x}(allcosts,newgen)}-\frac{LCOE^0(inv,newgen)}{\sum_{levcost}LCOE^0(levcost,newgen)}=\varepsilon_{inv}^{LCOE}(newgen)$$

$$\frac{\sum_{o\_mcost}\boldsymbol{x}(omcost,newgen)}{\sum_{allcosts}\boldsymbol{x}(allcosts,newgen)}-\frac{LCOE^0(om,newgen)}{\sum_{levcost}LCOE^0(levcost,newgen)}=\varepsilon_{o\_m}^{LCOE}(newgen)$$

$$\frac{\sum_{fuelcost}\boldsymbol{x}(fuelcost,newgen)}{\sum_{allcosts}\boldsymbol{x}(allcosts,newgen)}-\frac{LCOE^0(fuel,newgen)}{\sum_{levcost}LCOE^0(levcost,newgen)}=\varepsilon_{fuel}^{LCOE}(newgen)$$

$$\frac{\sum_{orgptax}\boldsymbol{x}(orgptax,newgen)}{\sum_{allcosts}\boldsymbol{x}(allcosts,newgen)}-\frac{LCOE^0(efftax,newgen)}{\sum_{levcost}LCOE^0(levcost,newgen)}=\varepsilon_{tax}^{LCOE}(newgen)$$

3.4.4 Cost structure of transmission and distribution

Currently, not much is known about the specific cost structure of transmission and distribution ('TnD'). However, it is necessary to establish some structure to reasonable allocate the total cost to 'TnD' (assumed to be represented by 'ely' own-use in the GTAPv8 dataset) while simultaneously considering the costs to generation (thus the targeting technique). Lacking specifc information the relative input costs of 'TnD' target the relative input costs of the GTAPv8 communications sector 'cmn' due to the similarity between the product transmitted and the large network spanning an entire region of users (both firms and households). The mathematical formulation of the error follows and is evaluating for each element of the set orgcost.

$$\frac{\boldsymbol{x}(orgcost,'tnd')}{\sum_{orgcost}x^0(orgcost,'tnd')}-\frac{x^0(orgcost,'cmn')}{\sum_{orgcost}x^0(orgcost,'cmn')}=\varepsilon_{tnd}(orgcost)$$

3.5 Objective Function

The objective of this mathematical formulation is to minimize the average squared-error for the four aforementioned targets. Each target is averaged to give equal weighting. Alternatives to the squared-error method (e.g., entropy) may be better suited for this particular formulation and are currently being explored.

$$Minimize_{x(allcosts,newgen),gwh(newgen)}$$

$$\varepsilon_{blp}{}^2 +$$

$$\frac{1}{length(levcost)} \times \left[\frac{\sum_{invcost}\sum_{newgen}(\varepsilon_{inv}(invcost,newgen)^2)}{length(invcost)*length(newgen)} + \frac{\sum_{o_{mcost}}\sum_{newgen}(\varepsilon_{om}(omcost,newgen)^2)}{length(o_{mcost})*length(newgen)} \right.$$
$$\left. + \frac{\sum_{newgen}(\varepsilon_{fuel}(fuelcost,newgen)^2)}{length(newgen)} + \frac{\sum_{orgptax}\sum_{newgen}(\varepsilon_{tax}(orgptax,newgen)^2)}{length(orgptax)*length(newgen)} \right] +$$

$$\frac{1}{length(levcost)} \times \left[\frac{\sum_{newgen}(\varepsilon_{inv}^{LCOE}(newgen)^2)}{length(newgen)} + \frac{\sum_{newgen}(\varepsilon_{om}^{LCOE}(newgen)^2)}{length(newgen)} + \frac{\sum_{newgen}(\varepsilon_{fuel}^{LCOE}(newgen)^2)}{length(newgen)} \right.$$
$$\left. + \frac{\sum_{newgen}(\varepsilon_{tax}^{LCOE}(newgen)^2)}{length(newgen)} \right] +$$
$$\frac{1}{length(orgcost)} \times \sum_{orgcost}(\varepsilon_{tnd}(orgcost)^2)$$

3.6 Constraints

Several of the allocative insights, assumptions mentioned in the previous section enter the formulation as constraints. First, market clearance of the original GTAPv8 values of cost to electricity, no generation own-use, and physical clearance of IEA Energy Balance data on GWh are imposed for some accounting consistency. These are shown below:

Market clearance in GTAP values

$$\sum_{newgen} x(orgcost,newgen) = x^0(orgcost,'ely')$$
$$\sum_{newgen}\sum_{newgen} x(newgen,newgen) = 0$$

Physical clearance in IEA data (sum across baseload and peaking for gas, oil, and hydro)

$$\sum_{load} gwh(load,newgen) = gwh^0(newgen^*)$$

Second, the assumption that transmission and distribution is represented in the GTAPv8 database as 'ely' own-use enters in the following manner:

$$\sum_{allcosts} x(allcosts,'tnd') = x^0('ely','ely')$$

Third, allocative insights related to fuel costs to their corresponding generation technology are also included. Furthermore, the relative fuel use for sectors with multiple fuel costs (i.e., gas and oil) is constrained to have identical proportions for each relevant generating technology. This may be further

refined if the fuel product 'p_c' (petroleum and coal products) is explored in detail. These allocative constraints are as follows:

$$\sum_{cost-gas,gdt} \sum_{gasbl,gasp} x(cost, newgen) = \sum_{gas,gdt} x^0(orgcost, 'ely')$$

$$\sum_{cost-oil} \sum_{oilbl,oilp} x(cost, newgen) = x^0('oil', 'ely')$$

$$\sum_{cost-coa} x(cost, CoalBL) = x^0(coa, 'ely')$$

$$\boldsymbol{gasfuel} = \{gas, gdt, p\_c\}$$

$$\frac{x(gasfuel, 'gasbl')}{\sum_{gasfuel} x(gasfuel, 'gasbl')} = \frac{x(gasfuel, 'gasp')}{\sum_{gasfuel} x(gasfuel, 'gasp')}$$

$$\boldsymbol{oilfuel} = \{oil, p\_c\}$$

$$\frac{x(oilfuel, 'gasbl')}{\sum_{oilfuel} x(oilfuel, 'gasbl')} = \frac{x(oilfuel, 'gasp')}{\sum_{oilfuel} x(oilfuel, 'gasp')}$$

4. An illustrative example of the data in a simplified model

To be completed soon… contact peters83@purdue.edu for questions.

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