

GTAP-E-Power: An Electricity-detailed Economy-wide Model

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Global economic analysis of energy and climate policy often uses an aggregate representation of the electricity sector (e.g., GTAP-E). However, disproportionate technological progress and policies across different generating technologies requires a more detailed representation that identifies and allows for substitution between generating technologies. GTAP-E-Power extends the GTAP-E model to include transmission and distribution as well as substitution between nuclear, coal, gas base load, gas peak load, oil base load, oil peak load, hydro base load, hydro peak load, wind, solar, and 'other' power. Electric power substitution is represented with a nested additive constant elasticity of substitution which, opposed to the traditional constant elasticity of substitution, ensures that the sum of demands for generation from each technology is equal to total demand for electricity generation. The primary purpose of GTAP-E-Power is to serve as guidance for implementing the GTAP-Power Data Base in a computable general equilibrium model with substitution between electricity generating technologies to inform economic, energy, and climate policy.

JEL codes: C68, D58, L94, Q47, Q56

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1. Introduction

Electric power is a critical component of international energy-economy – promoting economic growth by consuming resources and producing potentially harmful emissions. As such, policymakers have identified the electric power sector as a key mechanism to maintain economic growth while simultaneously offsetting emissions. Political intractability for explicitly pricing carbon emissions (e.g. a carbon tax) has led to policies designed to discourage or promote specific

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generating technologies. For example, in the United States emission regulation is used to discourage investment in coal power while investment tax credits for wind and solar are designed to promote renewable capacity expansion.

Computable general equilibrium (CGE) modeling is widely-used to explore global economic analysis of energy and climate policy both as standalone (e.g., Burniaux and Truong, 2002) or as part of integrated assessment models (e.g., Kriegler et al. 2014). However, limited electricity sector detail hinders the ability of many of these models to address emerging questions related to technology-specific policies and productivity change.

Analyzing technological change or policies specific to individual generating technologies in a CGE framework requires two elements. First, the technologies must be identified in an electricity-detailed database. For example, the GTAP-Power Data Base (Peters, 2016) extends version 9 of the Global Trade Analysis Project (GTAP) Data Base (Aguiar et al., 2016) by disaggregating the 'ely' sector to include transmission and distribution, nuclear, coal, gas base load, gas peak load, oil base load, oil peak load, hydro base load, hydro peak load, wind, solar, and other power generating technologies. Second, the CGE model must allow for these generating technologies to substitute with one another in the ultimate production of electricity (termed here as "electric power substitution" or simply "power substitution"). Electric power substitution has been introduced in CGE models in a variety of ways (e.g. Paltsev et al., 2005; Sue Wing, 2011; Capros et al. 2013; Arora and Cai, 2015; Château et al. 2014); however, there is no consensus regarding an ideal representation or even if one method is superior to another.

The primary contribution of this article is GTAP-E-Power, which introduces electric power substitution in the widely-used and freely-available GTAP-E model (Burniaux and Truong, 2002; McDougall and Golub, 2007). Another contribution is the implementation of an additive constant elasticity of substitution (termed ACES) specification in the power sector that ensures the sum of inputs (measured in GWh) sums to the total output (also in GWh).¹ The ACES specification has an intuitive appeal over the widely-used constant elasticity of substitution (CES) which does not have this additive property and is seen by many as a weakness of

¹ Dixon and Rimmer (2006) implement the ACES specification for labor and Giesecke et al. (2013) implement it for land. van der Mensbrugghe and Peters (2016) discuss technical differences between the CES and CET and the ACES and additive constant elasticity of transformation (ACET) formulations and their implications for economic modeling. This article has the first implementation of the specification for electricity using the GTAP framework.

the CES specification (Sue Wing, 2006; Fujimori et al., 2014). In doing so, this article supports and enhances electricity-detailed modeling in the CGE community.

The remainder of the article is organized as follows. Section 2 reviews existing approaches for modeling electric power substitution both indirectly via capital-energy and energy fuel substitution and directly via electric power substitution. The advantages and disadvantages of several power substitution representations are evaluated in general terms. Section 3 reviews key features of GTAP-E and then introduces a nested ACES electric power substitution specification into the GTAP-E model using insights from the review in Section 2, creating the GTAP-E-Power model.² Section 4 first compares the result resolution of GTAP-E-Power to GTAP-E by repeating a global carbon tax experiment from McDougall and Golub (2007) updated with several hard targets from the Paris Agreement. Second, GTAP-E-Power is used to simulate and analyze how regional differences drive sensitivity to a renewable power subsidy. Finally, the effects of a nuclear moratorium in the United States, European Union, and Japan are simulated to demonstrate the expanded capabilities of power substitution in analyzing technology-specific regulatory policies. Each simulation highlights important insights that are inaccessible using a CGE model with an aggregate electricity sector with only capital-energy and interfuel substitution. Section 5 highlights limitations of the GTAP-E-Power model and charts a path forward for researchers to conduct their own analysis with the model. Section 6 concludes.

2. Review of Existing Approaches

2.1 Foundations in capital-energy and interfuel substitution

In many CGE models specific electricity generating technologies are not identified. Instead, there is an aggregate electricity sector that purchases capital, fuels, and other inputs for production. While generating technologies are not specifically identified, some substitution may still occur indirectly via interfuel substitution (e.g. coal, oil, gas) and/or capital-energy substitution (e.g. capital improvements or fuel versus non-fuel based technologies). Interfuel substitution may serve well for fuel-based technologies; however capital-energy substitution is incapable of distinguishing non-fuel-based technologies (e.g. nuclear, hydroelectric, wind, solar, geothermal power) which constitute 32% of global power generation. Rapid progress in several emerging technologies as well as specific policies designed to help them penetrate (e.g. investment tax credits) or

² The files for the GTAP-E-Power version to replicate results reported in the paper are available at https://www.gtap.agecon.purdue.edu/private/secured.asp?Sec_ID=1123.

shut them down (e.g. nuclear moratoriums) are not easily implementable in CGE models with only capital-energy and interfuel substitution, limiting the utility of these models in today's energy and environmental policy landscape.

2.2 Electric power substitution

Recognizing the limitation of aggregate electricity sector modeling, several researchers have directly incorporated substitution between electricity generating technologies in CGE models, which requires both identification of specific generating technologies in a CGE database and an economic representation of how these technologies substitute in the production of electricity. The focus of this section is on alternative representations of power substitution in CGE models.

While capital-energy and interfuel substitution are widely studied in econometric literature, econometric work lags behind in electric power substitution. With few exceptions, the representations are neither econometrically estimated nor validated against historical observations nor compared to alternatives.³ This has resulted in a multitude of different ways to represent power substitution without clear consensus in academic literature as to what may be a preferred method or even whether a single method may be preferred over another. Therefore, the relative advantages and disadvantages of a breadth of alternative representatives are reviewed.

Table 1 shows the nested production structure for electricity production in several prominent CGE models. The illustrations depict the substitution nests in the standard fashion in CGE literature. For example, Arora and Cai (2015) describe electricity as demanding 'O&M and distribution' in fixed proportion with a virtual (*in italics*) generation good in the first-level nest. In the second-level nest, generating technologies substitute according to a constant ratios of elasticity of substitution (CRESH) formulation, termed a "technology bundle" approach. The CRESH parameter is calibrated to estimates of capital-energy and interfuel substitution. Alternatively, Sue Wing et al. (2011) describe electricity production as a CES substitution between 'transmission & distribution' and 'electricity generation' activities in the first nest. In the second level-nest for generation, base, intermediate, and peak load substitute according to a CES formulation and in the third level nest specific technologies substitute via CES to produce each load type. As is the case for many CGE models, the CES parameter values are assumed rather than estimated, calibrated, or validated.

³ In the absence of econometric estimations or validations all the different representations reviewed in this work must be considered equally valid (or invalid).

Table 1. A subset of computable general equilibrium research that incorporates substitution between electricity generating technologies.

Researcher(s)	Simplified nested production structure of electricity production
MIT – Joint Program (Paltsev et al. 2005, pg. 19, 37)	<p>Electricity</p> <p>$\swarrow \searrow$ CES > 0</p> <p>Output of perfect substitutes Wind & Solar</p> <p>$\swarrow \searrow$ CES = ∞</p> <p>Conventional fossil*, Nuclear, Hydro, Various advanced generation technologies</p>
JGCRI - Phoenix (Sue Wing, 2011, pg. 30–31)	<p>Electricity</p> <p>$\swarrow \searrow$ CES = 0.7</p> <p>Transmission & Distribution Generation</p> <p>$\swarrow \searrow$ CES = 1</p> <p>Base Load Intermediate Load Peak Load</p> <p>$\swarrow \searrow$ CES = 4 $\swarrow \searrow$ CES = 4 $\swarrow \searrow$ CES = 4</p> <p>Coal, Nuclear, Hydro, Biomass, Natural Gas, Refined Oil, IGCC, Geothermal NGCC Solar, Wind, Natural Gas, Refined Oil, NGCC</p>
GEM-E3 (Capros et al. 2013, pg. 43, Annex VIII)	<p>Electricity</p> <p>$\swarrow \searrow$ CES = 0</p> <p>Distribution Technologies</p> <p>$\swarrow \searrow$ CES = 0</p> <p>Coal, Gas, Oil, Nuclear, Hydro, Biomass, Solar, Wind, CCS Coal, CCS Gas</p>
GTEM/CTEM (Arora and Cai, 2015, pg. 545–547)	<p>Electricity</p> <p>$\swarrow \searrow$ CES = 0</p> <p>O&M and Distribution Generation</p> <p>$\swarrow \searrow$ CRESH = many parameters</p> <p>Coal, Gas, Oil, Nuclear, Hydro, Wind, Solar, Biomass, Waste, and Other Renewables</p>
OECD ENV-Linkages (Château et al. 2014, pg. 23, 32)	<p>Electricity</p> <p>$\swarrow \searrow$ CES = 5</p> <p>Fossil-fuel based*, Hydro & Geothermal, Nuclear, Solar & Wind, Biomass & Waste</p>

*The conventional fossil sector in Paltsev et al. (2005) and fossil-fuel based sector in Château et al. (2014) have capital-energy and interfuel substitution rather than substituting technologies.

Notes: This is not an exhaustive list of research efforts. Production structures are summarized based on available documentation and simplified for illustrative purposes. Some sectors may be renamed for comparability. Nesting below basic electricity sub-sectors excluded.

These two examples (along with the others in Table 1) illustrate the wide variety of possible representations of power substitution in CGE models. None of the methods can be said to truly be preferred. Instead they can be said to be useful for particular purposes. Returning to the same two methods discussed previously, the CRESH ("technology bundle") approach of Arora and Cai (2015) is more general than CES (i.e., CES is a special case of CRESH); however, in the absence of empirical support (as currently the case in power substitution) the simpler theory (i.e. CES) may be preferred according to the principle of Occam's razor (Italianer, 1986 pg. 310). Preference, in this case, may depend on the availability of data. Preference may also be dependent on the research question. The representation in Sue Wing (2011), because of the base, intermediate, and peak load differentiation, can answer research questions pertaining to the load characteristics of technologies, where the other models listed in Table 1 would not be useful. In fact, many electricity researchers find load type to be an important aspect of substitutability. Table 2 contains a non-exhaustive list of basic advantages and disadvantages of each of the models reviewed in Table 1.

There are other models not listed in Table 1 that represent electricity substitution, but merit brief mention. The Global Climate Assessment Model (GCAM) assumes no substitution between existing technologies, but uses a nested logit choice model for new installations. The logit choice model is often seen as an advantage over CES and CRESH, because it preserves additivity of GWh between inputs and total production (Fujimori et al. 2014). Peters and Hertel (2017) implement ACES substitution for existing technologies and a logit choice model for new installations, albeit only in a partial equilibrium model.

Further, hybrid top-down, bottom-up models or "linked" models may use a bottom-up representation of electricity (e.g. richly-detailed least cost optimization) to pass quantity information to a top-down CGE model which then passes price data back, solving iteratively (e.g. Manne and Wene, 1992; Böhringer, 1998; Böhringer and Rutherford, 2008). These alternate representations are highly useful because of their ability to capture technological detail, capacity changes, as well as regional difference in electricity markets, policy, and regulation (Adams et al. 2014), but are less common in CGE models and may be unfamiliar to some CGE researchers.

2.3 A path forward

It is clear that identifying an ideal method for representing electric power substitution for CGE modeling would be premature at this point in time. Rather, the researcher should select (or create) the most relevant representation for the question at hand. This point motivates the creation of a CGE model that is

available to GTAP subscribers so that researchers can adjust a model with electric power substitution to their particular research problem. The following section describes how GTAP-E-Power is constructed upon the GTAP-E foundation for precisely this purpose.

Table 2. A non-exhaustive list of advantages and disadvantages of different representations of electric power substitution in CGE modeling.

Researcher(s)	Advantages and disadvantages of power substitution
MIT – Joint Program	<p>Advantages:</p> <ul style="list-style-type: none"> - Substitution may account for some operational considerations (e.g., intermittent renewables, base versus peak power) <p>Disadvantages:</p> <ul style="list-style-type: none"> - Several parameters may not be easily estimated or calibrated currently due to a lack of historical observations (e.g. <i>Perfect Substitutes</i> versus Wind & Solar nest) - Capital-fuel and inter-fuel substitution remains for fossil fuel power - CES does not preserve GWh additivity
JGCRI - Phoenix	<p>Advantages:</p> <ul style="list-style-type: none"> - Substitution nests account for base and peak load markets <p>Disadvantages:</p> <ul style="list-style-type: none"> - CES does not preserve GWh additivity
GEM-E3	<p>Advantages:</p> <ul style="list-style-type: none"> - Simple and straight forward analysis - Parameters can be easily calibrated or estimated with few data <p>Disadvantages:</p> <ul style="list-style-type: none"> - Simplistic substitution does not account for operational considerations (e.g., base versus peak capable technologies) - CES does not preserve GWh additivity
GTEM/CTEM	<p>Advantages:</p> <ul style="list-style-type: none"> - CRESH allows different elasticities between technologies <p>Disadvantages:</p> <ul style="list-style-type: none"> - CRESH does not preserve GWh additivity - CRESH requires many parameters (10 technologies x 10 technologies)
OECD ENV-Linkages	<p>Advantages:</p> <ul style="list-style-type: none"> - Simple and straight forward analysis - Parameters can be easily calibrated or estimated with few data <p>Disadvantages:</p> <ul style="list-style-type: none"> - Simplistic substitution does not account for operational considerations (e.g., base versus peak capable technologies) - CES does not preserve GWh additivity - Does not distinguish between transmission and distribution which can be a large component of electricity sector - Capital-fuel and inter-fuel substitution remains for fossil fuel power

3. GTAP-E-Power

GTAP-E is a version of the GTAP model that includes capital-energy and interfuel substitution and is widely-used to analyze global energy and climate policy. The GTAP-E model is freely-available to subscribers to GTAP. As such, it is an ideal foundation to introduce electric power substitution to promote electricity-detailed analysis in the CGE community.

GTAP-Power is used as the initial data base. GTAP-Power is a disaggregation of the GTAP data base that splits electricity ('ely') into transmission and distribution ('TnD') as well as 11 generating technologies: nuclear, coal, gas base load, gas peak load, oil base load, oil peak load, hydro base load, hydro peak load, wind, solar, and 'other' power generating technologies. The data base is constructed by minimizing the deviation between the total value implied by levelized cost and production data for each technology such that the total value is equal to the original GTAP value for general equilibrium consistency. Peters (2016) documents GTAP-Power in its entirety. Appendix C is a step-by-step guide to create additional headers needed to fit the GTAP-Power Data Base to the GTAP-E-Power format.

In this procedure, a virtual electricity good, which is a composite of several goods, replaces the GTAP-E electricity sector. A virtual generation good, base load good, and peak good are added to the GTAP-E framework to represent substitution between the GTAP-Power technologies listed above. These virtual goods are simply aggregations of the actual produced goods in the database (e.g. nuclear, coal). The first section explains how these technologies produce the virtual electricity good, and the subsequent section explains how it fits into the GTAP-E framework.

3.1 Incorporating electric power substitution

The wide variety of alternative ways to represent electric power substitution was shown in Section 2, while Table 1 showed that there is currently no single path forward. Instead, the researcher should use a representation that is well-suited to their data and research question or one that performs well compared to historical observation. One of the major purposes of this particular work is to provide the CGE community with a tool and guidance to conduct electricity-detailed CGE modeling. Therefore, the purpose of this section is three-fold: i) provide guidance in justifying a particular representation, ii) provide guidance in constructing nested substitution in the accompanying GTAP-E-Power software, and iii) introduce the ACES formulation to electricity substitution in a GTAP model.

Figure 1 shows the representation of power substitution in GTAP-E-Power which guides the discussion in the following sections.

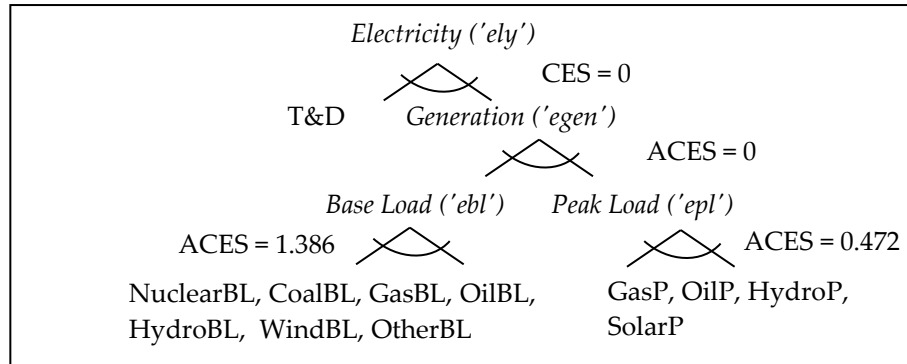


Figure 1. Nested electric power substitution in GTAP-E-Power. Virtual sub-products are denoted in italics.

3.1.1 Generation, Transmission, and Distribution

The electricity sector is composed of generation (i.e. production), transmission, and distribution to firms and households. Transmission and distribution are similar activities in that they require similar materials to meet a similar objective (i.e. delivering generating electricity to customers). These two activities are treated as a single service sector (transmission and distribution, T&D) that is demanded in fixed proportion (Leontief) with a virtual generation good (Figure 1). That is, if electricity demand increases 5%, generation must increase 5% and T&D services must increase 5%. T&D is represented in the same way as all the other firms, while generation is the final product of electric power substitution.

3.1.2 Base and Peak Load

A unique characteristic of the electricity sector is that supply must meet demand instantaneously. Demand can fluctuate greatly throughout the day, week, and season. Generating technologies have technical limitations that prevent them from instantaneously adjusting utilization to meet these fluctuations. For instance, coal power plants cannot adjust utilization easily in response to prevailing daily demand, resulting in the common classification as "base" load, meaning it can provide a base amount of generation during the day, but is not competitive in meeting demand spikes or "peak" demand. On the other hand, gas and oil power are able to adjust operations quickly and are competitive in meeting the peak demand. Depending on the prevailing fuel prices, these fuels may even be competitive with base load technologies (e.g. inexpensive gas in the United States).

is leading substitution to gas power).⁴ This characteristic of electricity generation leads to the separation of technologies into virtual base load (BL) and peak (P) nests. NuclearBL, CoalBL, GasBL, OilBL, HydroBL, WindBL, and OtherBL substitute within the base load nest, while GasP, OilP, HydroP, and SolarP substitute within the peak load nest (Figure 1).

The virtual base and peak power goods are demanded in fixed proportion (Leontief). That is, the load profile of electricity demand is independent of the relative price between base and peak load.

3.1.3 Electricity Generating Technologies

In both the base-peak nest and within each of those nests, the units of measure are identical (i.e. GWh), and the sum of electricity demanded from each individual technology and total electricity demanded should be equal. CES substitution, as is used in many of the examples in Table 1, does not have this additive property. Instead, GTAP-E-Power uses the ACES formulation pioneered by Dixon and Rimmer (2006) for labor and Giesecke et al. (2013) for land.

As opposed to cost minimization in CES, ACES minimizes the (dis)utility of cost. The disutility of costs can be interpreted in the electricity sector as a combination of average cost and various costs of reliability in meeting the complex nature of demand (Peters and Hertel, 2017). In the context of electricity, the disutility reflects the fact that the average cost of generation is an incomplete representation of costs faced by the electricity system operator. In addition to generation, the operator faces the costs of day-ahead and balancing operating capacity reserves, reactive services, synchronous condensing, and black start services which focus on the reliability of supply and are a function of the technologies used to generate electricity in the system. The system operator problem for base load power is formulated as follows:

$$\min_{q_t^g} U^B = \left[\sum_{\forall t \in B} (p_t^g \cdot q_t^g)^\rho \right]^{1/\rho} \quad (1)$$

subject to:

$$Q^B = \sum_{\forall t \in B} q_t^g \quad (2)$$

⁴ Fuels are often combusted using different technologies to meet the two types of demand (e.g. steam turbine, combustion turbine, combined cycle).

where B is the set of base load technologies, q_t^g is the quantity of generation from technology t , p_t^g is the price of generation for technology t , Q^B is the total generation of base load power, U^B is the disutility of base load supply, and ρ is a parameter. The same formulation is used for peak load technologies.

The constraint, equation (2), ensures that the ACES formulation preserves the additive property in electric power substitution, seen by many as a limitation in CES representations (Sue Wing, 2006; Fujimori et al. 2014), without significant theoretical departure from the popular cost-minimizing CES formulation (van der Mensbrugghe and Peters, 2016).⁵

Peters and Hertel (2017) use an identical power substitution representation in a partial equilibrium analysis of the United States, estimate the substitution parameters using prices and generation data from 2002–2012, and use ACES substitution parameters of 1.386 and 0.472 for base and peak load nests, respectively; these values are the default parameters for all regions in GTAP-E-Power.

3.2 Integrating with the GTAP-E foundation

Both the GTAP and GTAP-E model are widely documented.⁶ This section details how the power substitution described in Section 3.1 integrates with key elements of the GTAP-E model (i.e. generating technology production and firm, household, and government demands).

3.2.1 Production for each generating technology

One of the foremost defining features of GTAP-E is that industries are able to substitute capital and energy as well as fuels for production, as shown in Figure 2. For instance, here, energy-intensive industries can make capital improvements to increase energy efficiency. They can also shift fuel usage (i.e. coal, oil, gas, or electricity) based on prevailing prices. The GTAP-E specification is used for all productive sectors in GTAP-E-Power, but has an important interpretation in the context of electricity generation technologies.

Generation changes are determined by utilization, expansion, and their interdependency (Peters and Hertel, 2017). Utilization is driven by two mechanisms: dispatchability and electric power substitution. The latter is a sector-wide parameter and was explored in section 3.1. The former, dispatchability, is

⁵ The GTAP-E-Power code (i.e. gtap.tab) contains instructions to switch between a CES and ACES representation.

⁶ Hertel (1997) describes the fundamental equations of the GTAP model. Burniaux and Truong (2002) and McDougall and Golub (2007) document the GTAP-E model.

technology-specific and pertains to the ability of a technology to adjust utilization with existing capacity.

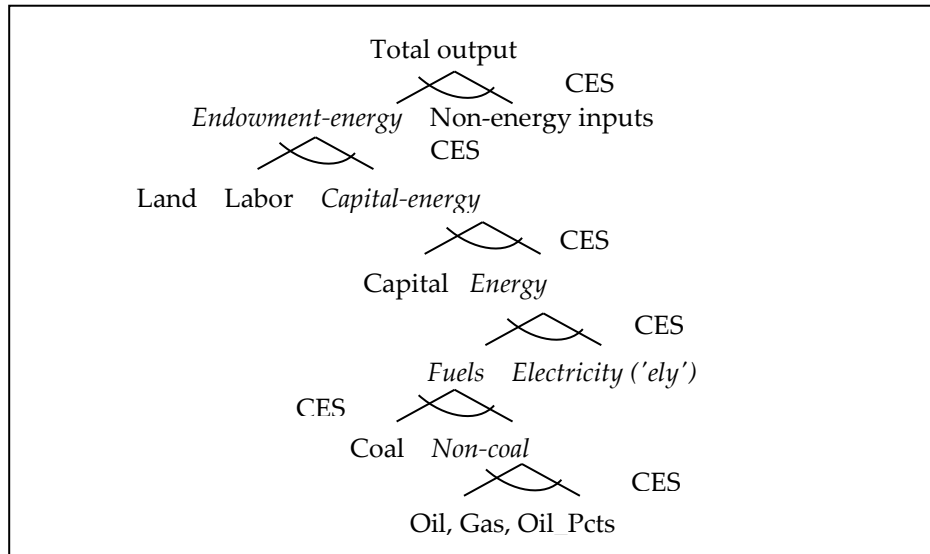


Figure 2. Production structure for industries in GTAP-E and GTAP-E-Power.

Source: Burniaux and Truong (2002, pg. 31).

Dispatchable technologies can substitute additional operating and fuel costs in lieu of constructing additional capital (i.e. capacity). A non-dispatchable technology cannot adjust utilization and can only expand generation by increasing capacity. Technical limitations prevent several technologies from adjusting generation given fixed capacity. For instance, Peters and Hertel (2017) show that fuel-based technologies have adjusted annual capacity factor from 2002–2012 in response to prevailing economic conditions, while other technologies like nuclear, hydroelectric, wind, and solar have not (and cannot easily from a technological point-of-view).

This concept guides the endowment-energy and capital-energy parameter values selected for each of the generating technologies. In a static model like the model described here, dispatchable technologies (i.e. CoalBL, GasBL, OilBL, GasP, OilP and OtherBL) have non-zero CES parameter values in both the endowment-energy and capital-energy nest. The endowment-energy nest represents the ability to substitute labor for capital. Dispatchable technologies can increase production by increasing labor (e.g. more production equates to longer hours and overtime). Therefore, the default endowment-energy CES parameters for dispatchable technologies are set to the same parameter for energy-intensive industries.

Similarly, greater dispatchability of a technology corresponds with greater capital-energy substitution. The default capital-energy CES parameter for GTAP-E-Power is set to 1.0 for gas- and oil-fired power, 0.5 for CoalBL, and 0.1 for OtherBL to reflect relative dispatchability of these technologies. Non-dispatchable technologies (i.e. NuclearBL, HydroBL, WindBL, HydroP, and SolarP) have zero values in the endowment-energy nest and do not have significant energy demand which means, absent changes in capital productivity, capital is demanded in fixed proportion to demand. That is, the only changes in generation for non-dispatchable technologies must be driven by capacity retirements or expansion.

3.2.2 Firm demand

One of the novelties of the GTAP-Power Data Base is that firms demand individual technologies as opposed to an aggregate national electricity good. The purpose is to allow for certain firms (e.g. manufacturing) to demand more base load type technologies, consistent with 24 hour production, and allow others (e.g. services) to demand more peak load type ones, say during business hours. The current version of the GTAP-Power Data Base (accompanying the GTAP 9 Data Base) assumes that firms demand equal shares of each technology, because of the lack of reasonable data internationally, but it is the more flexible and general method. GTAP-E-Power is capable of leveraging this aspect of the GTAP-Power Data Base, but at the expense on computation complexity and time.

All firms demand electricity in the manner described in Figure 1. Because in the GTAP-Power Data Base that accompanies the GTAP 9 Data Base, firms demand equal shares of each technology, the results would be identical to the more commonly-implemented case where firms are assumed to demand an aggregate electricity good with generating technologies as activities.

3.2.3 Household and government demands

Similar to firms, households and governments may demand specific technologies. For example, some electricity providers in the United States offer options to customers to purchase renewable electricity. Also, household solar is a rapidly growing industry in the United States.

Also, similar to firm demand, household and government demands for electricity are in the same share as production and the nested demand structure is identical to production. However, the GTAP-E-Power offers a starting point to alter this assumption.

4. Simulations with GTAP-E-Power

GTAP-E-Power leverages the disaggregated electricity sector data from the GTAP-Power Data Base with the electric power substitution described above. This section describes three simulations which demonstrate the usefulness of GTAP-E-Power via: i) expanded clarity in power sector results compared to GTAP-E and ii) further capabilities in electricity-detailed CGE modeling. First, a 16 sector, 20 sector, 8 factor aggregation of the GTAP-Power Data Base is implemented in the GTAP-E-Power model and compared to the equivalent GTAP-E construction (i.e. one without specific generating technologies and power substitution).⁷ Next, the GTAP-E-Power model is used to test the efficacy of renewable subsidies around the world as well as the impact of nuclear moratoriums in several countries; both of these simulations are not feasible with CGE models with only capital-energy and interfuel substitution. These three simulations highlight the expanded research possibilities unleashed by introducing electric power substitution in CGE modeling. The simulations also highlight some pitfalls and peculiarities of electricity modeling using CGE that should be addressed for some research purposes.⁸

4.1 Expanded electricity result resolution

Burniaux and Truong (2002) and McDougall and Golub (2007) use GTAP-E to simulate carbon permit trading to meet the Kyoto Protocol targets. Similarly, the simulation in this section replaces countries' Kyoto Protocol carbon dioxide reduction targets with the Intended Nationally Determined Contributions (INDCs) pledged to meet the Paris Agreement (UNFCCC, 2016). Only countries and regions with specific reduction targets are considered in this analysis (Table 3). Countries that did not pledge a specific target (e.g. India and China pledged reduction in carbon *intensity*, South Africa pledged to plateau then decline) as well as ad hoc groupings of countries with a smattering of targets (e.g. 'MENA', 'RoW') are assumed not to have any reduction target for this particular simulation. The targets, converted to reductions from 2011 levels (the base year for the GTAP-Power Data Base) and shown in the right column of Table 3, are used as shocks to simulate pledged proportional emission reductions in 2011 via the CO₂ quota mechanism in the GTAP-E and the GTAP-E-Power model – which simulates a cap-

⁷ The exact region and sector mappings are shown in Appendix A and B, respectively.

⁸ The simulations can be reproduced by installing the EPower9.zip version archive from https://www.gtap.agecon.purdue.edu/private/secured.asp?Sec_ID=1123.

and-trade system. These countries comprise only 44.8% of 2011 global CO₂ emissions; including a target for India and China would cover 75.5% (EIA, 2016).

The purpose of this simulation is to show that GTAP-E-Power provides expanded result resolution in simulations that have previously been explored using GTAP-E. GTAP-E-Power has all the basic modeling capabilities of GTAP-E. The departure in the two models is power substitution in the GTAP-E-Power model. The main result, shown in Table 4, is the effective cost per ton of CO₂ in the no permit trade and world trade scenarios. The cost of CO₂ is inversely related to the power substitution possibility. That is, as the elasticities of substitution increase, the cost per ton of CO₂ decreases, echoing the need for properly estimated, calibrated, and/or validated elasticities.

Table 3. Simulating the Paris Agreement in GTAP-E and GTAP-E-Power.

Region	Brief description	Intended Nationally Determined Contributions (INDC)	Reduction from 2011 levels
USA	USA	28% from 2005 levels	21.22%
EUx	Europe Union and interior countries	40% from 1990 levels	35.87%
XE	Rest of Europe	-	-
CA	Central Asia	-	-
RUS	Russian Federation	25% from 1990 levels	11.40%
JPN	Japan	26% from 2013 levels	22.38%
CAN	Canada	30% from 2005 levels	22.64%
ANZ	Australia, New Zealand, Rest of Oceania	26% from 2005 levels	28.27%
MENA	Middle East and North Africa	-	-
EXLA	Energy exporters in Latin America	-	-
EXAs	Energy exporters in Asia	-	-
CHINA	China and Hong Kong	-	-
IND	India	-	-
NGA	Nigeria	-	-
ZAF	South Africa	-	-
RoW	Rest of the world	-	-

Source: UNFCCC (2016), EIA (2016), and author calculations.

Notes: EUx is simply referred to as the European Union in the text, but does include non-EU some countries (see Appendix A). If there is no target, there is no cap.

The Paris Agreement shocks in Table 3 are imposed on the GTAP-E and GTAP-E-Power models. Table 4 compares the marginal cost of achieving the Paris Agreement based on the INDCs with no inter-sector or inter-region permit trading and with worldwide permit trading.

One interesting result is the difficulty, measured by a high CO₂ cost, the European Union may face meeting their aggressive Paris Agreement target without permit trading, \$204 per ton CO₂. While some of the difficulty can be attributed to the aggressive target, it may also be due to less opportunity to shift away from high-emitting coal power. Coal comprises only 25% of total generation in the European Union, whereas it is over 40% higher in the United States.

From another perspective, when world trade of carbon permits is allowed, China, India, and South Africa reduce emissions greatly because their coal-intensive electricity sector offers greater opportunity to reduce emissions.

Also, both the GTAP-E and GTAP-E-Power results show that allowing trading of carbon permits will reduce the cost of CO₂ for every country with a quota and provides opportunity for non-quota countries to reduce emissions rather than increase, as in the no permit trading case.

Table 4. Proportional changes in emissions and marginal costs of meeting Intended Nationally Determined Contributions of the Paris Agreement with worldwide CO₂ permit trading.

Region	GTAP-E		GTAP-E		GTAP-E-Power		GTAP-E-Power	
	No permit trade		World permit trade		No permit trade		World permit trade	
	Total CO ₂ (%)	USD per ton CO ₂	Total CO ₂ (%)	USD per ton CO ₂	Total CO ₂ (%)	USD per ton CO ₂	Total CO ₂ (%)	USD per ton CO ₂
USA	-21.22	40.45	-7.17	10.01	-21.22	36.22	-7.82	10.23
EUx	-35.87	241.98	-3.36	10.01	-35.87	203.99	-4.01	10.23
XE	3.41	-	-5.87	10.01	-0.18	-	-6.46	10.23
CA	3.71	-	-9.73	10.01	1.73	-	-9.36	10.23
RUS	-11.40	24.09	-6.24	10.01	-11.40	15.71	-8.75	10.23
JPN	-22.38	122.44	-2.82	10.01	-22.38	109.66	-3.00	10.23
CAN	-22.64	50.60	-6.63	10.01	-22.64	45.14	-7.49	10.23
ANZ	-28.27	89.89	-5.35	10.01	-28.27	83.49	-5.37	10.23
MENA	2.05	-	-8.41	10.01	1.47	-	-8.11	10.23
EXLA	1.25	-	-11.46	10.01	1.28	-	-11.73	10.23
EXAs	1.79	-	-5.84	10.01	1.57	-	-6.46	10.23
CHINA	0.36	-	-17.56	10.01	0.06	-	-15.98	10.23
IND	0.07	-	-30.97	10.01	-0.10	-	-31.07	10.23
NGA	1.12	-	-4.06	10.01	1.09	-	-4.25	10.23
ZAF	2.97	-	-23.69	10.01	0.35	-	-18.61	10.23
RoW	1.99	-	-4.47	10.01	1.31	-	-5.65	10.23
TOTAL	-10.06		-10.71		-10.39		-10.71	

Sources: GTAP-E versions GTAPE9 and GTAP-E-Power version EPOWER9; experiments: wtr and notr; results: gco2t, gco2tw, and NCTAXB.

Notes: The imposed emission quotas are in **bold** in the no permit trade scenarios. The same quotas are imposed in the world permit trade scenarios.

The results in Table 4 show that the ACES parameter values used in GTAP-E-Power happen to produce roughly similar results as GTAP-E. The marginal costs of meeting the Paris Agreement targets is slightly lower in GTAP-E-Power, which suggests that introducing power substitution makes the electricity slightly more flexible than with only capital-energy and interfuel substitution. However, it is important to note that these parameter values (contained in the default GTAP-E-Power parameters files, default.prm and wtr_p.prm) are adopted from Peters and Hertel (2017) where they are calibrated and validated for the United States, but not for other regions. Specification, parameterization, and calibration should be driven by a specific research questions, and these steps remain the responsibility of the individual researcher.

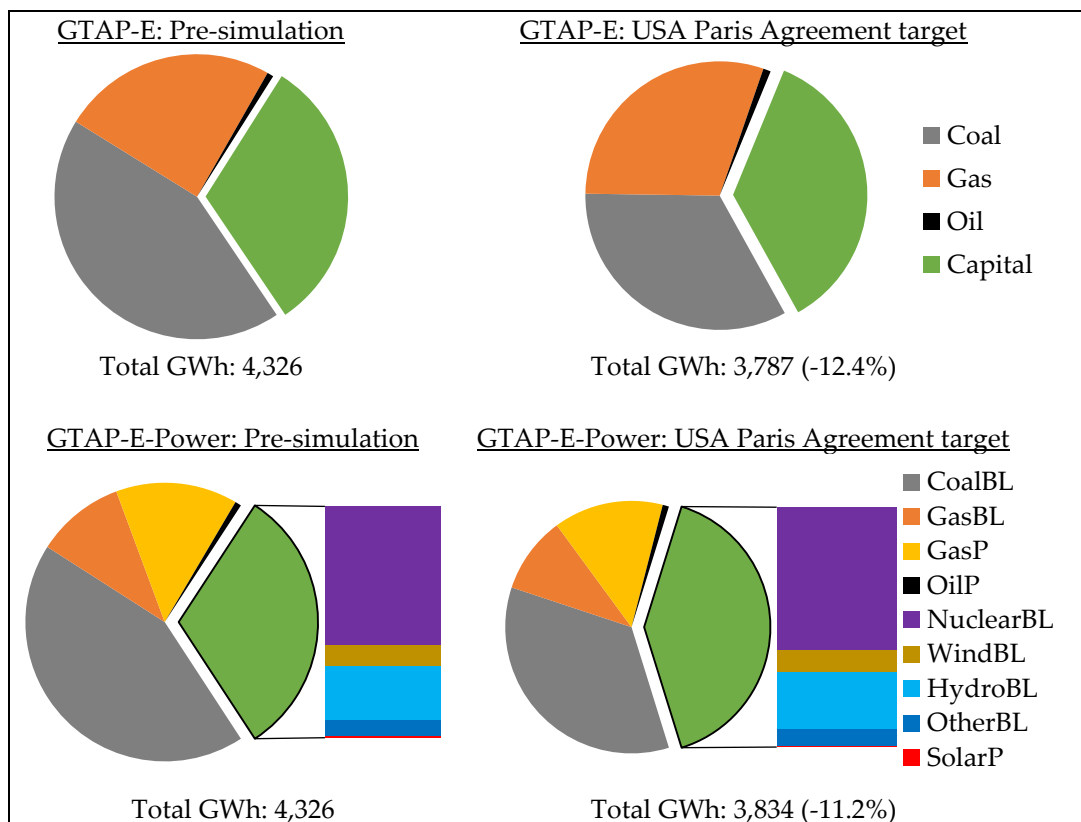


Figure 3. Comparison of result clarity: pre- and post-simulation electricity generation results for USA Paris Agreement targets using GTAP-E and GTAP-E-Power.

Sources: GTAP-E versions GTAPE9 and GTAP-E-Power version EPOWER9; experiment: notr; results: qf(i,"ely",r) and qo(i,r).

While Table 4 shows that GTAP-E-Power encompasses the modeling capabilities of GTAP-E, Figure 3 shows that GTAP-E-Power enhances electricity-detail compared to GTAP-E.

Comparing the electricity generation results of GTAP-E-Power to GTAP-E reveals two key points. First, GTAP-E-Power offers greater result resolution in the evolution of the electricity sector. Recall that GTAP-E has interfuel substitution via coal, oil, and gas inputs to electricity and capital-energy substitution for the electricity sector as a whole. Therefore, we cannot see precisely which technologies play a role in the non-fuel base technologies that are broadly lumped within the capital sector.

Second, most of the substitution in GTAP-E occurs between coal- and gas-fired power rather than between fossil fuels and renewables (represented implicitly through energy-capital substitution). This may be because capital-energy substitution in GTAP-E was meant to represent efficiency gains rather than introduction of renewable technologies.⁹ GTAP-E-Power, however, projects both coal to gas power substitution as well as the emergence of renewable substitutes. The greater flexibility also reduces the effect on total electricity price and the electricity sector contracts less (-11.2%) than in GTAP-E (-12.4%).

These two points reiterate the importance of specifying, calibrating, and validating the GTAP-E-Power in order to explore these results in greater depth.

4.2 Expanded electricity capabilities

4.2.1 Differential policy impacts due to region-specific attributes

As environmental policy has shifted focus from global taxation to more politically-tractable subsidies and regulation for specific sources, the electricity sector has been identified as one of those key sources. For instance, the United States, various European, and other countries offer production and investment tax credits for renewable generating technologies. The magnitude and scale of these interventions vary widely by region. Further, one method for reducing global emissions would be for developed countries to invest in renewable power technologies in developing countries, where they are otherwise cost prohibitive. Several developing countries' INDCs acknowledge that reducing emissions at high levels is contingent on the help from the international community. This

⁹ In 2002, the time of initial publication of GTAP-E, wind and solar constituted a very small portion of total generation while nuclear and hydroelectric power are highly constrained by regulation and resource availability, respectively.

simulation asks in which regions would a “solar and wind” subsidy make the most impact on local emissions.

A 50% output subsidy is implemented for each region separately, and the percentage change in regional CO₂ emissions and the impact on GDP are shown in Figure 4.¹⁰ Leakage is not reported in that the emission results only consider the region where the subsidy is implemented rather than global emissions.

Figure 4 shows a large difference in the emissions elasticity of GDP (i.e. the ratio of percentage change in regional CO₂ emissions and percentage change in GDP) in response to the wind and solar subsidy. The United States has an emissions elasticity of GDP of 51.4 while Japan has an elasticity of only 2.1. The larger elasticity implies that the policy could potentially generate larger emission reductions per percentage of GDP and would be considered a more effective policy measure compared to regions with lower elasticities.

Table 5 shows these elasticities as well as the nominal cost to GDP (in USD) per ton of CO₂ eliminated from production for each region and the regional attributes that drive the efficacy of wind and solar subsidies.

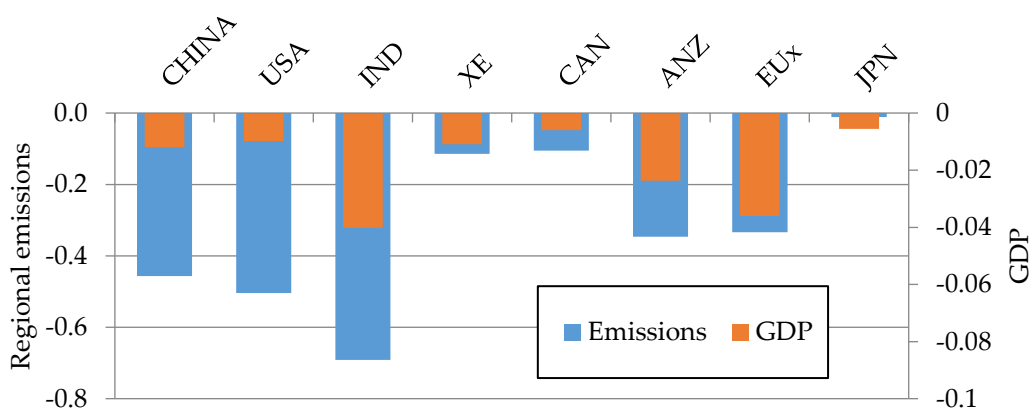


Figure 4. Regional CO₂ emission reductions GDP changes in response to a 50% output subsidy for wind and solar power.

Sources: GTAP-E-Power version EPower9; exp. renewsubs; results: gco2t and qgdp. Simulations were conducted for each region separately. Results ordered left to right by lowest to highest cost per ton of CO₂ reduction.

The nominal GDP cost of emission reduction is the absolute measure of the CO₂ elasticity of GDP. The elasticity is driven by both the numerator, which measures the ability for solar and wind to displace high-emitting power sources, especially coal, and the denominator which measures the effect of the subsidies on GDP.

¹⁰ CA, RUS, MENA, EXLA, EXAs, NGA, ZAF, and RoW have smaller shares of wind and solar and are dropped from the results presented here.

Table 5. CO₂ reduction cost (measured in GDP) of a 50% wind and solar output subsidy.

	2011 USD per ton of CO ₂	CO ₂ /GDP Elasticity	Wind and solar power	Fossil fuel power	Coal power	Electricity -intensive output
CHINA	\$26.88	38.5	1.5%	81.2%	78.9%	19.7%
USA	\$59.16	51.4	2.9%	68.4%	43.3%	6.6%
IND	\$61.66	17.2	2.4%	79.6%	66.8%	10.1%
XE	\$154.55	10.5	0.8%	64.4%	37.8%	10.8%
CAN	\$193.93	17.5	1.6%	23.4%	12.2%	9.0%
ANZ	\$257.09	14.6	2.9%	78.5%	56.2%	11.0%
EUx	\$534.77	9.3	6.6%	48.1%	24.5%	8.8%
JPN	\$2,786.97	2.1	0.9%	77.5%	25.2%	8.9%

Sources: GTAP-Power and GTAP-E-Power version EPower9; exp: renewsubs; results: gco2t and qgdp. Author's calculations.

The numerator (the blue bar in Figure 4) will be greater when wind and solar are competitive in the initial equilibrium, and there is sufficient fossil fuel (especially coal) power to replace. Table 5 shows that this the case. High shares of wind and solar combined with high shares of fossil fuels (especially coal) correlate with the large CO₂ reductions in China, India, the United States, the European Union, and Australia & New Zealand in Figure 4. Note that, despite the highest share of wind and solar, the emission reduction opportunities in the European Union are offset by less fossil fuel power to replace. Similarly, Canada has the fewest existing fossil fuel plants of the regions shown here, and the effect on total emissions from the subsidy is low. The emission impact is low in XE and Japan because of the low existing shares of wind and solar.

Switching focus to the denominator, the elasticity will be higher when the subsidy will have a smaller impact on the rest of the economy. The wind and solar subsidy is effectively a subsidy on electricity where the effective electricity subsidy is larger where wind and solar constitute a large share (i.e. more of the subsidy is passed on to the electricity price). Therefore, although the calculation of GDP is complex, one indicator of GDP sensitivity is the size of electricity-intensive sectors in the region. Regions with large shares of wind and solar as well as dominant electricity-intensive sectors would raise the impact of the policy intervention – decreasing allocative efficiency and reducing GDP. Figure 4 shows that GDP decreases the most in the European Union, India, and Australia & New Zealand. The impact on GDP is less in other regions where the share of wind and solar, and therefore effective subsidy on electricity, are low (i.e. China, XE, Canada, and

Japan) or where electricity-intensive sector constitute a smaller share of total regional output (i.e. the United States).

The regional efficacy of the solar and wind subsidy is dependent on the technological mix of electricity generation as well as the electricity-intensity of the economy. This analysis shows that Japan, the European Union, Canada, and Australia & New Zealand may have a greater opportunity for investing in wind and solar in developing countries compared to their own region. Extrapolated outside this analysis, the best destinations for investing in these renewable technologies would be in coal power reliant countries like China and India where these renewables will be competitive (e.g. high quality solar or wind resources). Further, that strategy may not be effective for some developed countries like the United States where subsidies may actually be more effective at reducing emissions at home.

4.2.2 Global impacts of regional policy: nuclear moratoriums

The previous simulation focused on technology-specific fiscal policy, but technology-specific regulations are also becoming increasingly prevalent. One such regulation is nuclear moratorium and phase-out which aims to halt new construction and phase-out old nuclear plants, respectively. This simulation explores the CO₂ emission cost as well as cost to regional household utility of a nuclear moratorium in the United States, European Union, and Japan in meeting the Paris Agreement targets.

European countries (e.g. France) view nuclear power as a critical technology in their electricity mix; however, several other European Union and interior (EUx) countries have already implemented a nuclear moratorium and/or phase-out (e.g. Austria, Belgium, Germany, Italy, Sweden, Switzerland). These selective moratoriums may prevent expansion in nuclear power in the region as a whole. Across the Atlantic, a strong anti-nuclear movement and additional state regulation along with inexpensive natural gas has stifled expansion in nuclear power, despite no explicit state or national moratoriums. Moving across the Pacific, in response to the Fukushima-Daiichi nuclear disaster in 2011 Japan shut down all of its nuclear power, but has since lifted the shut down with the plan to decrease the generation share of nuclear power from 30% to 20%. To reflect these regulations in GTAP-E-Power, the production of electricity from nuclear power (NuclearBL) is not permitted to change from 2011 levels in the United States, European Union, and Japan – i.e., NuclearBL output is treated exogenously, replaced by an endogenous output tax in these regions to ensure this condition is held, similar to a quota. This assumption breaks the strict requirements of a general equilibrium result (i.e. quantities are no longer completely endogenous),

but shows how these increasing prevalent technology-specific regulations can be analyzed in GTAP-E-Power and other global economics models.

Imposing the nuclear moratoriums in GTAP-E-Power should make it more difficult for the affected regions to meet their Paris Agreement target by eliminating a low-emitting generating technological option. The cost of carbon should increase in the moratorium regions and the household utility should decline from the deadweight loss of the effective tax needed to ensure no expansion. Table 6 shows the impact of the nuclear moratoriums in terms of nuclear output, emissions, carbon cost, and household utility for each region.

Table 6. Achieving the Paris Agreement targets: the cost of nuclear moratoriums in the United States, European Union, and Japan without carbon permit trade.

Region	Base Case				Nuclear Moratoriums				Δ
	Nuclear power (%)	Total CO ₂ (%)	USD per ton CO ₂	HH Utility (U)	Nuclear power (%)	Total CO ₂ (%)	USD per ton CO ₂	HH Utility (U)	
USA	12.89	-21.22	36.22	-0.16	0	-21.22	37.77	-0.16	-0.002
EUx	19.40	-35.87	203.99	-1.27	0	-35.87	210.77	-1.32	-0.051
XE	0.14	-0.18	-	0.20	-0.60	-0.11	-	0.17	-0.025
CA	1.91	1.73	-	-1.41	-9.13	1.80	-	-1.41	-0.007
RUS	9.44	-11.40	15.71	1.73	8.97	-11.40	15.84	-1.74	-0.006
JPN	25.04	-22.38	109.66	-0.32	0	-22.38	113.71	-0.35	-0.021
CAN	4.73	-22.64	45.14	-0.40	3.47	-22.64	45.27	-0.40	0.000
ANZ	0	-28.27	83.49	-0.51	0	-28.27	83.68	-0.51	0.004
MENA	-0.93	1.47	-	-1.36	-20.77	1.50	-	-1.37	-0.010
EXLA	0.13	1.28	-	-0.35	-0.18	1.32	-	-0.35	-0.002
EXAs	0	1.57	-	-0.24	0	1.59	-	-0.23	0.003
CHINA	-0.67	0.06	-	0.05	-0.94	0.09	-	0.05	0.001
IND	-0.39	-0.10	-	0.20	-0.79	-0.06	-	0.20	-0.002
NGA	0	1.09	-	-0.98	0	1.12	-	-0.98	-0.006
ZAF	-0.16	0.35	-	0.13	-6.79	0.57	-	0.13	0.005
RoW	-0.02	1.31	-	-0.04	-1.39	1.37	-	-0.04	-0.002
TOTAL		-10.39				-15.86			

Sources: GTAP-E-Power version EPower9; experiments: notr and ntr-0nuc; results: qo, gco2t, gco2tw, NCTAXB, and u.

Notes: Nuclear power moratorium shocks for USA, EUx, and JPN and emission targets are shown in bold. CA, MENA, EXLA, and ZAF have modest amounts of nuclear power. ANZ, EXAs, and NGA have no nuclear power.

Table 6 supports the initial hypothesis. The moratorium on nuclear power in the United States, European Union, and Japan increases the negative impact of the Paris Agreement on utility in the countries. This is primarily because the technology is eliminated as an option to shift away from fossil fuels. In fact, the

moratorium affected countries' depressed economies extend the negative impact to other countries as well. On the positive side, the effect of the moratoriums on the cost of CO₂ is small relative to effect from the Paris Agreement targets themselves (less than 5% of the contribution to total cost in most regions). This lends some creditability to the viewpoint that the risks of nuclear power may outweigh the benefits, measured here as a cost. However, these costs would increase if nuclear power was removed completely from the mix rather just halting new construction, as simulated here.

Next, the same moratoriums are explored with carbon permit trading. Carbon permit trading should allow for moratorium-affected regions to offset the cost buying permits from countries that do not have a moratorium and can expand all low-emitting technologies more freely.

Table 7. Achieving the Paris Agreement targets: the cost of nuclear moratoriums in the United States, European Union, and Japan with worldwide carbon permit trade.

Region	Base Case				Nuclear Moratoriums				Δ
	Nuclear power (%)	Total CO ₂ (%)	USD per ton CO ₂	HH Utility (U)	Nuclear power (%)	Total CO ₂ (%)	USD per ton CO ₂	HH Utility (U)	ΔU
USA	4.63	-7.82	10.23	-0.08	0	-7.63	10.32	-0.08	0.001
EUx	2.38	-4.01	10.23	-0.07	0	-3.91	10.32	-0.08	-0.003
XE	3.00	-6.46	10.23	0.06	2.93	-6.50	10.32	0.06	-0.003
CA	7.50	-9.36	10.23	-0.22	6.00	-9.42	10.32	-0.21	0.003
RUS	5.94	-8.75	10.23	-0.27	5.92	-8.80	10.32	-0.27	0.003
JPN	3.17	-3.00	10.23	-0.01	0	-2.95	10.32	-0.01	-0.002
CAN	1.91	-7.49	10.23	-0.14	1.55	-7.54	10.32	-0.14	0.000
ANZ	0	-5.37	10.23	-0.07	0	-5.41	10.32	-0.07	0.001
MENA	7.31	-8.11	10.23	-0.31	4.38	-8.17	10.32	-0.31	0.002
EXLA	3.71	-11.73	10.23	-0.17	3.69	-11.80	10.32	-0.17	0.000
EXAs	0	-6.46	10.23	0.06	0	-6.51	10.32	0.06	0.002
CHINA	19.67	-15.98	10.23	0.08	19.79	-16.07	10.32	0.08	0.001
IND	8.21	-31.07	10.23	0.31	8.21	-31.18	10.32	0.31	0.003
NGA	0	-4.25	10.23	-0.27	0	-4.28	10.32	-0.27	0.002
ZAF	24.77	-18.61	10.23	0.24	23.91	-18.70	10.32	0.24	0.003
RoW	3.63	-5.65	10.23	0.03	3.49	-5.70	10.32	0.03	0.000
TOTAL		-10.71				-10.71			

Sources: GTAP-E-Power version EPower9; experiments: wtr and wtr-0nuc; results: qo, gco2t, NCTAXB, and u.

Notes: Nuclear power moratorium shocks for USA, EUx, and JPN are shown in **bold**. CA, MENA, EXLA, and ZAF have modest amounts of nuclear power. ANZ, EXAs, and NGA have no nuclear power.

Table 7 shows that allowing worldwide trade of carbon permits helps offset much of the cost of the nuclear moratoriums in the United States, European Union and Japan. The European Union and Japan are still hurt by the policy, but by a smaller amount. The United States is roughly unaffected. Interestingly the rest of Europe (XE) is still hurt, presumably from the deeper economic connections to the European Union and lack of energy exports to gain from the higher cost of CO₂.

The trade of carbon permits helps reduce the impact of these region-specific policies. The cost of CO₂ only increases \$0.09 from \$10.23 to \$10.32 per ton of CO₂. This raises the cost of carbon across all countries and benefits the more flexible electricity sectors (i.e. those countries without similar moratoriums).

GTAP-E-Power expands the result resolution of models that only have capital-energy and interfuel substitution. Previously represented as capital inputs to electricity in GTAP-E, changes in nuclear, hydroelectric, wind, and solar power are easily analyzed. Technology-specific progress and policies, such as renewable subsidies and nuclear moratoriums shown in this section, can be simulated in a straightforward manner. The electricity sector detail in GTAP-E-Power is a powerful tool; however, additional detail requires additional care in designing the experiments and interpreting the results.

5. Known limitations

The detailed representation of electric power substitution in GTAP-E-Power merits discussion about several limitations in modeling key aspects of the electricity sector. None of these limitations are exclusive to GTAP-E-Power, but rather apply to electricity-detailed CGE modeling in general.

First, in GTAP-E-Power transmission and distribution is demanded in fixed proportion with total generation. However, technologies have different locational constraints that affect the cost allocation between transmission and generation. For example, utility-scale solar is often deployed on inexpensive land far from the demand. Steam turbines, on the other hand, must have inexpensive access to water. GTAP-E-Power may not be able to address the full range of questions related to transmission and distribution.

Second, the specification of electric power substitution discussed in Section 3.1 uses previously calibrate parameters, but is not validated in a robust manner that helps lend confidence in the reliability of the numerical results. That is, the model provides a platform for studying electricity relevant policy using a GTAP-based model, but specification, parameterization, and calibration should be driven by a specific research questions and therefore, remains the responsibility of the individual researcher.

Third, the single substitution mechanism – i.e. nested substitution in generation terms – may not adequately represent the realities of the electricity sector. Peters and Hertel (2017) suggest that the simplistic CES and ACES specifications used here, and in many other studies, do not differentiate the two distinct mechanisms for adjusting electricity generation: short-run capacity utilization and longer-run expansion. A single elasticity of substitution may confuse short- and long-run scenarios, because that elasticity may increase with the time period of the analysis. In the short-run, substitution is limited by existing capacity (no capital expansion); however, moving to the long-run equilibrium as capacity is replaced, only operational considerations (e.g. base versus peak load) constrain perfect substitution. Therefore, the elasticity of substitutions chosen in the GTAP-E-Power specification should be a function of the simulation time horizon.

Along a similar vein, GTAP-E-Power is a static model and cannot straightforwardly map out trajectories, an increasingly common capability of IAMs which can help address "invest now" versus "invest later" renewable energy strategies. Introducing dynamics that track capital accumulation in electric power can differentiate lumpy, long-term capacity and short-run capacity utilization changes. However, in practice, capital does not map precisely to capacity in dynamic CGE models of electric power, and the models are calibrated to generation changes rather than to capacity utilization and expansion mechanisms that are described above. Also, incorporating dual substitution mechanisms or dynamics both require additional data and limiting assumptions. Still, the lack of dual mechanisms for generation changes and dynamics are major limitations of the GTAP-E-Power model.

6. Conclusions

GTAP-E-Power leverages the GTAP-E-Power Data Base in the commonly used GTAP-E model. Electric power substitution between base and peak load generating technologies combined with transmission and distribution allows CGE modelers to explore the role of electric power in the global economy. The base-peak separation and the implementation of the ACES specification overcome key limitations of other static electricity-detailed CGE models.

Electric power substitution allows for greater resolution and clarity of the response of capital-intensive generating technologies to policy and technology shocks. Further, increasingly common technology-specific policy and uneven productivity advances are easily studied in the GTAP-E-Power model.

The GTAP-E-Power model is a versatile tool for electricity-detailed CGE modeling that can add necessary resolution to global policy analysis. The

representation of electric power substitution can be calibrated with existing global electricity generation data and does not require strong assumptions that are required by more complex representations or dynamic CGE models. The next step of research is to capture the dual mechanisms of generation change (i.e. capacity and utilization) in the GTAP framework; however, this requires data that is yet to be identified.

Combined with qualitative electricity expertise, the GTAP-E-Power model supports quantitative global economic analysis of electric power policy and technology. Appendix C details a list of steps to produce an alternate aggregation of the GTAP-E-Power model.

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Appendix A. Regional Aggregation

GTAP-E-Power region	Brief description	GTAP 9 region
USA	USA	usa
EUx	Europe Union and interior countries	aut, bel, cyp, cze, dnk, est, fin, fra, deu, grc, hun, irl, ita, lva, ltu, lux, mlt, nld, pol, prt, svk, svn, esp, swe, gbr, che, nor, bgr, hrv, rou
XE	Rest of Europe	xef, alb, blr, ukr, xee, xer
CA	Central Asia	kaz, kgz, xsu, arm, aze, geo
RUS	Russian Federation	rus
JPN	Japan	jpn
CAN	Canada	can
ANZ	Australia, New Zealand, Rest of Oceania	aus, nzl, xoc
MENA	Middle East and North Africa	bhr, irn, isr, jor, kwt, omn, qat, sau, tur, are, xws, egypt, mar, tun, xnf
EXLA	Energy exporters in Latin America	mex, col, ecu, per, ven
EXAs	Energy exporters in Asia	idn, mys, vnm
CHINA	China and Hong Kong	chn, hkg
IND	India	ind
NGA	Nigeria	nga
ZAF	South Africa	zaf
RoW	Rest of the world	kor, mng, twt, xea, brn, khm, lao, phl, sgp, tha, xse, bgd, npl, pak, lka, xsa, xna, bol, bra, chl, pry, ury, xsm, cri, gtm, hnd, nic, pan, slv, xca, dom, jam, pri, tto, xcb, ben, bfa, cmr, civ, gha, gin, sen, tgo, xwf, xcf, xac, eth, ken, mdg, mwi, mus, moz, rwa, tza, uga, zmb, zwe, xec, bwa, nam, xsc, xtw

Appendix B. Sectoral Aggregation

GTAP-E- Power sector	Brief description	GTAP 9 sector
Agriculture	Agriculture, forestry, and fishing	pdr, wht, gro, v_f, osd, c_b, pfb, ocr, ctl, oap, rmk, wol, frs, fsh
Coal	Coal mining	coa
Oil	Oil extraction	oil
Gas	Natural gas extraction and distribution	gas, gdt
Oil_Pcts	Refined oil and coal products	p_c
TnD	Transmission and distribution of electricity	GTAP-Power sector (formerly 'ely')
NuclearBL	Nuclear power	GTAP-Power sector (formerly 'ely')
CoalBL	Coal-fired power	GTAP-Power sector (formerly 'ely')
GasBL	Gas-fired power in base load	GTAP-Power sector (formerly 'ely')
WindBL	Wind power	GTAP-Power sector (formerly 'ely')
HydroBL	Hydroelectric power in base load	GTAP-Power sector (formerly 'ely')
OilBL	Oil-fired power in base load	GTAP-Power sector (formerly 'ely')
OtherBL	Other power	GTAP-Power sector (formerly 'ely')
GasP	Gas-fired power in peak load	GTAP-Power sector (formerly 'ely')
HydroP	Hydroelectric power in peak load	GTAP-Power sector (formerly 'ely')
OilP	Oil-fired power in peak load	GTAP-Power sector (formerly 'ely')
SolarP	Solar photovoltaic and thermal power	GTAP-Power sector (formerly 'ely')
En_Int_Ind	Energy intensive industries	omn, crp, nmm, i_s, nfm
Oth_Ind	Other (non-energy intensive) industries	cmt, omt, vol, mil, pcr, sgr, ofd, b_t, tex, wap, lea, lum, ppp, fmp, mvh, otn, ele, ome, omf
Services	Services	wtr, cns, trd, otp, wtp, atp, cmn, ofi, isr, obs, ros, osg, dwe

APPENDIX C. Creating a version of the GTAP-Power database to fit the GTAP-E-Power model

The following steps can be used to create the GTAP-E-Power data files (i.e. basedata.har, sets.har, and default.prm) with the purpose of creating an alternate regional and/or sectoral aggregation. A license to the GTAP Data Base is required.

- 1) Using GTAPAgg2 choose GTAP-Power and desired year as the source data.
- 2) Create an aggregation file. The aggregation file used in the version described in this article is located in the version archive as GTAPEPower.agg.
- 3) Create the new database and save in a new version folder within the GTAP directory (with other GTAP model versions). (e.g. GTAP\MyPower)
- 4) Extract the .zip file with the new database into a new folder titled "GTAPAggFile". (e.g. GTAP\MyPower\GTAPAggFile)
- 5) Move GTAPEHeaders.cmf, GTAPEHeaders.tab, and makeheaders.bat from the EPower9_supp_files folder (e.g. GTAP\ EPower9_supp_files into the new version folder (e.g. GTAP\MyPower)
- 6) Move default_e.prm and sets_e.har into the GTAPAggFile folder.
- 7) Run (double-click) on makeheaders.bat.
- 8) Updated GTAP-E-Power data files should appear in the new version folder (e.g. GTAP\MyPower): basedata.har, baseview.har, co2.har, default.prm, gsdvole.har, and sets.har.
- 9) Note that the default.prm parameters must be checked and changed manually, because they are specific to the new aggregation.
- 10) Because the RunGTAP/GEMPACK solvers have difficulties with the large number of zeros in the GTAP-Power database, the zeros in the following basedata.har headers must be replaced by a small number (1E-10).

EVFA, TVOM, VDEP, VDFA, VDFM, VDGA, VDGM, VDPA, VDPM, VFM, VIFA, VIFM, VIGA, VIGM, VIMS, VIPA, VIPM, VIWS, VTMFSD, VXMD, VXWD, DFNC, DGNC, DPNC, IFNC, IGNC, IPNC, CODP, COIP, CODG, COIG, CODF, and COIP.

To do this: highlight the header, right-click, select "Change values" then select "Replace zeros by small number", and replace zeros with 1E-10 and press "OK". Be sure to save after.

- 11) Copy all file extensions (.tab, .min, etc.) with the name "gtap", "decomp" and "gtapview" from EPower9_supp_files folder to new version folder (e.g. GTAP\ EPower9_supp_files to GTAP\MyPower).
- 12) Copy the SaveSims folder from the EPower9_supp_files folder to new version folder.
- 13) Open RunGTAP.
- 14) Select the "Version" tab and select "New".
- 15) Click "Next" then create "New aggregation" and type in the name of the new folder (e.g. GTAP\MyPower). Click "Next", locate basedata.har, sets.har, and default.prm in that folder, then click "Next" then "Finish".
- 16) Don't worry! There will be an error. Select the "Version" tab and select "Modules".
- 17) Click on the empty box in the "Main model" row and "TAB file" column in the "Version-specific settings". Select "stored in version folder" then highlight "GTAP.TAB" and press "OK".
- 18) Click on the empty box in the "Welfare Decomp" row and "TAB file" column in the "Version-specific settings". Select "stored in version folder" then highlight "DECOMP.TAB" and press "OK".
- 19) Solve the model for a numeraire shock.
- 20) Check the solution.
- 21) To make any changes in the model you should modify the gtap.tab file in the version folder (not the main GTAP model!). Note: the gtap.tab file documents the modifications made to the GTAP-E model in order to introduce power substitution. The comments are meant to help the design of alternate representations of power substitution.