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GTAP-Power Data Base: Version 10

BY MAKSYM CHEPELIEV[a]

This paper documents changes introduced to version 10 of the Global Trade Analysis Project (GTAP) Power (GTAP-Power 10) Data Base construction process relative to the GTAP-Power build stream developed in Peters (2016). First, in Peters (2016) output of the electricity and heat generation sector was split into different technologies using electricity generation data only. We use heat and electricity generation volumes to provide a more representative sectoral split and achieve a better concordance with GTAP 10 Data Base sectoral definitions. Second, we introduce data on country and year-specific shares of transmission and distribution costs in electricity price for 80 countries. In the GTAP-Power 9 Data Base this cost share was assumed to be uniform across all countries and regions. Finally, for every reference year, we update the levelized cost of electricity generation. We first compare GTAP-Power 9 Data Base construction results with and without corresponding changes. We then construct the GTAP-Power 10 Data Base and showcase how it can be used to estimate carbon dioxide emissions embodied in final consumption of electricity generated by different technologies.

JEL codes: C61, D57, D58, L94, Q40.

Keywords: Computable general equilibrium; Disaggregation; Electricity.

1. Introduction

Over the last decade, the role of renewable energy sources has increased dramatically. Between 2010 and 2017, the global share of electricity generated from renewables has grown from 19% to 26% (International Energy Agency (IEA), 2020), while the cost of electricity from solar photovoltaics has fallen by over 70% (Gielen et al., 2019). Major transformations in the electricity generation systems would be further taking place even without additional policy efforts, as according to the International Energy Outlook (Energy Information Administration (EIA), 2019), the share of renewables in the electricity generation would reach 38% by 2050 in their Reference Scenario. Much more substantial policy efforts and energy system transformations would be required to put global economy on the low emission development path, for instance, consistent with keeping global temperature increase below 2°C (Rogelj et al., 2016).

[a] Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University, West Lafayette, IN, 47906 (e-mail: mchepeli@purdue.edu).

Explicit representation of different generation technologies in an economy wide modelling framework, such as computable general equilibrium (CGE) models, is an essential feature for the consistent energy and environmental policy assessment. At the same time, many CGE models do not provide such sectoral details. For instance, prior to version 9, the Global Trade Analysis Project (GTAP) Data Base, widely used by the CGE modelling community had a single electricity and heat generation sector (Aguiar et al., 2019). For the GTAP 9 Data Base, a special version of the GTAP-Power 9 Data Base that split electricity sector into transmission and distribution, and eleven generation technologies was constructed (Peters, 2016).[1] Since then, a new release of the GTAP Data Base, version 10, has been produced (Aguiar et al., 2019), expanding the number of reported sectors from 57 to 65 and adding 2014 reference year.[2] With the updated release of the main GTAP 10 Data Base, there is a need to revise and update the GTAP-Power 10 Data Base construction process, which is the main goal of this paper. In doing so, we do not only implement input data updates, following the process developed by Peters (2016), but also address several limitations identified in the GTAP-Power 9 Data Base.

First, in Peters (2016) output of electricity and heat generation sector of the GTAP 9 Data Base was split into different technologies using electricity generation volumes only. Volumes of heat generation were excluded from this split. While the global average share of heat generation in aggregate electricity and heat production was around 13% in 2014, in some countries, such as Lithuania, Mongolia and Belarus, it was over 65% (IEA, 2015). As most of the heat generation is from gas and coal power plants, application of the electricity generation volumes only for the sectoral disaggregation might misrepresent the generation mix, especially in countries and regions with a high share of centralized heat generation. To address this issue, we use both heat and electricity generation volumes to provide a more representative sectoral split.

Second, in the GTAP-Power 9 Data Base, the share of transmission and distribution costs in the cost of delivered electricity was assumed to be uniform across all countries and regions. This share was set to be 21%, based on the data for United States (EIA, 2013). In reality, due to the differences in electricity grid structure, population density, electricity markets, etc., transmission and distribution costs are highly heterogenous across countries. Even within Europe,

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[1] The GTAP-Power 9 Data Base split electricity sector into the following 11 generation technologies: Nuclear Base Load (NuclearBL), Coal Base Load (CoalBL), Gas Base Load (GasBL), Oil Base Load (OilBL), Hydro Base Load (HydroBL), Wind Base Load (WindBL), Other Base Load (OtherBL), Gas Peak Load (GasP), Oil Peak Load (OilP), Hydro Peak Load (HydroP), Solar Peak Load (SolarP).

[2] The GTAP 10 Data Base reports data for four reference years – 2004, 2007, 2011 and 2014 (Aguiar et al., 2019).

transmission and distribution shares vary from 11.1% in Bulgaria to 54.4% in Slovakia (Eurostat, 2019a; 2019b; 2019c). To capture such difference in the shares of transmission and distribution, we introduce year-specific shares of transmission and distribution costs in electricity prices for 80 countries, representing mostly Europe and Africa, but also including Bhutan, Brazil, China, Nepal, Russia and Ukraine.

Finally, for the levelized cost of electricity generation (LCOE) estimates, the GTAP-Power 9 Data Base relied on the IEA/NEA (2010). The same LCOE estimate was used for each reference year with further adjustments to inflation. The cost of electricity generation changes over time, for renewable generation technologies. In this regard, the LCOE for onshore wind generation has fallen by 23% since 2010 and for solar photovoltaics by 73% (Gielen et al., 2019). To provide a more consistent representation of the LCOE by reference years, we use an updated IEA/NEA (2015) data to derive the LCOE for the 2014 reference year, while using IEA/NEA (2010) for 2004, 2007 and 2011 reference years, as in GTAP-Power 9 Data Base. We also adjust LCOE estimates for all reference years, to include the cost of heat generation to be consistent with the GTAP 10 Data Base sectoral definitions.

The rest of the paper is organized as follows. Section 2 discusses updates introduced to the GTAP-Power 10 Data Base build stream. Section 3 applies these updates to the GTAP-Power 9 Data Base construction process and compares it against the GTAP-Power 9 Data Base constructed by Peters (2016). In this way, the impact of the updated data inputs and procedures are captured without interactions with other data modifications introduced in GTAP 10 Data Base. Section 4 provides an overview of the GTAP-Power 10 Data Base and showcases how it can be used to estimate carbon dioxide (CO_2) emissions embodied in final consumption of electricity generated by different technologies. Finally, Section 5 concludes.

2. Revision of the data inputs

In this section, we discuss changes introduced to the GTAP-Power 10 Data Base construction process compared to the GTAP-Power 9 Data Base construction approach developed in Peters (2016). First, in Peters (2016), output of the electricity and heat generation sector was split intro different technologies using electricity generation data only. We use heat and electricity generation volumes to provide a more representative sectoral split. Second, we introduce data on country and year-specific shares of transmission and distribution costs in electricity prices for 80 countries. In the GTAP-Power 9 Data Base, this cost share was assumed to be uniform across all countries and regions, based on the estimate for the United States. Finally, for every reference year, we update the LCOE estimates. We also adjust LCOE estimates for all reference years to include the cost of heat generation.

2.1 Treatment of the co-generation

In the GTAP 10 Data Base, electricity sector ("ely") includes both electricity and heat generation (Aguiar et al., 2019). This sector combines heat and power plants (CHP), public heat plants, autoproducer heat plants, heat pumps, and CHP and heat plants (McDougall and Lee, 2006).[3] For selected countries, mostly in Eastern and Northern Europe, the share of the heat generation in aggregate electricity and heat production represents over 30%, while the world average share is around 13% (Figure 1).

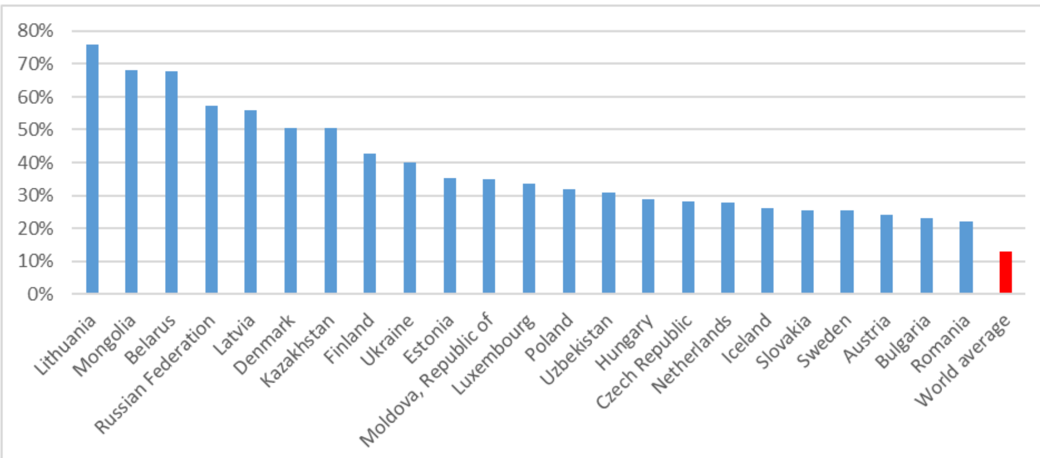

Figure 1. Share of heat generation in aggregate electricity and heat production for selected countries in 2014, %.

Source: IEA (2015).

At the global level, 85% of heat is produced by coal and gas power plants (Figure 2). Though, in a small number of countries, 'Other base load' generation represents the largest share. For instance, this is the case in Switzerland, Norway, Iceland, Brazil and Chile. In the GTAP-Power 9 Data Base construction process, output of the electricity and heat generation sector in GTAP 9 Data Base was split using electricity generation data only. Overall, such an approach did not have a significant impact on the representation of the GTAP 9 Data Base 'ely' sector generation mix. At the same time, for some countries with high shares of heat generation (Figure 1), such assumptions might have led to a substantial misrepresentation of the generation mix. In general, it would lead to the underrepresentation of the gas and oil generation and overrepresentation of other generation activities, in particular, hydro, solar, wind and nuclear – technologies that have a low share of heat generation.

[3] This information is retrieved from the International Energy Agency (IEA). For additional discussions, please refer to McDougall and Lee (2006).

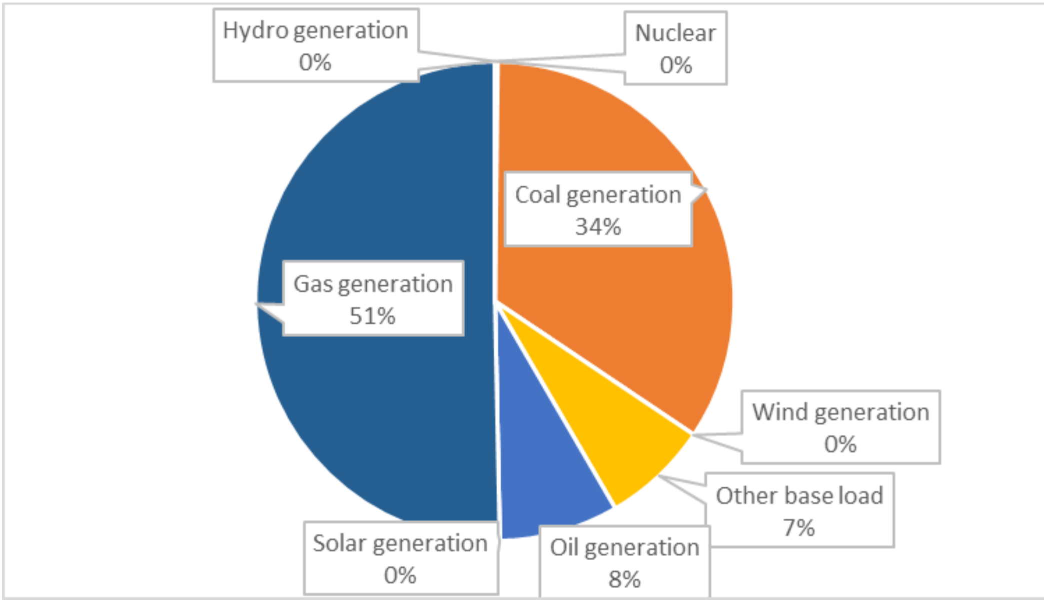

Figure 2. World average shares of heat generation by technologies, %.

Source: IEA (2015).

Therefore, one of the steps introduced in the updated GTAP-Power 10 Data Base build stream includes reliance on the heat generation data by countries and technologies in addition to the electricity generation data. Extended energy balances from International Energy Agency (IEA) are used to derive these data (2015a; 2015b). Such data are collected and processed for all four GTAP 10 Data Base reference years (2004, 2007, 2011 and 2014). For mapping of the heat generation volumes to the GTAP-Power 10 Data Base sectoral classification, we use mappings developed in Peters (2016) and aggregate electricity and heat generation volumes for further processing.

2.2 Transmission and distribution costs

In the GTAP-Power 9 Data Base, a uniform value of transmission and distribution share in the total non-tax value of the electricity and heat generation was used for all countries and regions. This share was assumed to be 21%, based on the data for United States (EIA, 2013). In reality, transmission and distribution shares largely vary between countries, depending on electricity grid structure, population density, specifics of the electricity market structure and other factors. In this paper, we introduce transmission and distribution shares for 80 countries, which correspond to 65 GTAP 10 Data Base regions.[4] In addition to the United States (EIA, 2013; EIA, 2018), transmission and distribution costs data cover

[4] See Appendix A for the country-to-region mappings.

African countries (Trimble et al., 2016), European Union (EU) countries (Eurostat, 2019a) and a number of other countries discussed below. Upon data availability, year-specific transmission and distribution shares are estimated with mapping to the closest GTAP 10 Data Base reference year.[5]

In the case of EU countries, Eurostat (2019a) reports shares of transmission and distribution costs in the electricity price for household and non-household consumers, by different consumption bands for both types of users. For households, we assume that a representative band is the group with annual electricity consumption between 2500 kilowatt-hours (kWh) and 4999 kWh.[6] For non-household consumers, we define a band with 500-1999 megawatt-hours of annual electricity consumption to be representative.[7] For both household and non-household users, Eurostat (2019a) reports data for the second half of each year, covering the 2007-2016 period.[8] First, we subtract the share of transmission and distribution-related losses from the transmission and distribution costs based on the data provided in ENTSO-E (2017). We then estimate a weighted average share of transmission and distribution costs by household and non-household consumers. GTAP 10 Data Base electricity and heat consumption volumes for household and non-household users are applied for weighting transmissions and distribution shares for household and non-household consumers.

Transmission and distribution shares for six additional countries are estimated based on country-specific data sources.[9] In case of Ukraine, data for residential consumers are sourced from NERC (2015) and corresponds to the price structure as of January 2015. Data for non-residential consumers are sourced from NERC (2014) and are available for 2009-2013 timeframe at an annual basis. Weighting of residential and non-residential transmission and distribution cost shares is performed using GTAP 10 Data Base electricity and heat consumption volumes. For China, transmission and distribution shares are based on He et al. (2015). Transmission and distribution shares for Bhutan and Nepal are sourced from Siyambalapitiya (2018). For Nepal, further adjustment for losses is made using ADB (2010). For Russia, transmission and distribution share is sourced from EY (2018) and adjustments for electricity losses are based on WB (2019). Finally, data for Brazil are sourced from NEEA (2008).

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[5] See Appendix A for data availability by year. For instance, in the case of Belgium, we map 2007 data to 2004 and 2007 reference years, 2011 to 2011 and 2014 to 2014.

[6] This is the most representative band according to Eurostat (2019b), as most residential consumers fall into this band.

[7] This is the most representative band for the EU non-household electricity consumers according to Eurostat (2019c).

[8] Starting from 2017 Eurostat is reporting annual average prices.

[9] These countries include Ukraine, China, Bhutan, Nepal, Russia and Brazil.

Appendix A provides estimates of transmission and distribution shares in the total non-tax value of electricity output for selected countries, as well as data availability by years. For other countries and regions, not covered in Appendix A, global average shares are estimated using GTAP 10 Data Base electricity and heat generation volumes as weights.[10]

Figure 3 shows the shares of transmission and distribution in the total non-tax value of electricity output by countries in 2014.[11] These shares are highly variable across countries – from as low as 4% in Seychelles to as high as 56% in Lesotho, with a global weighted average share of around 25.4%.

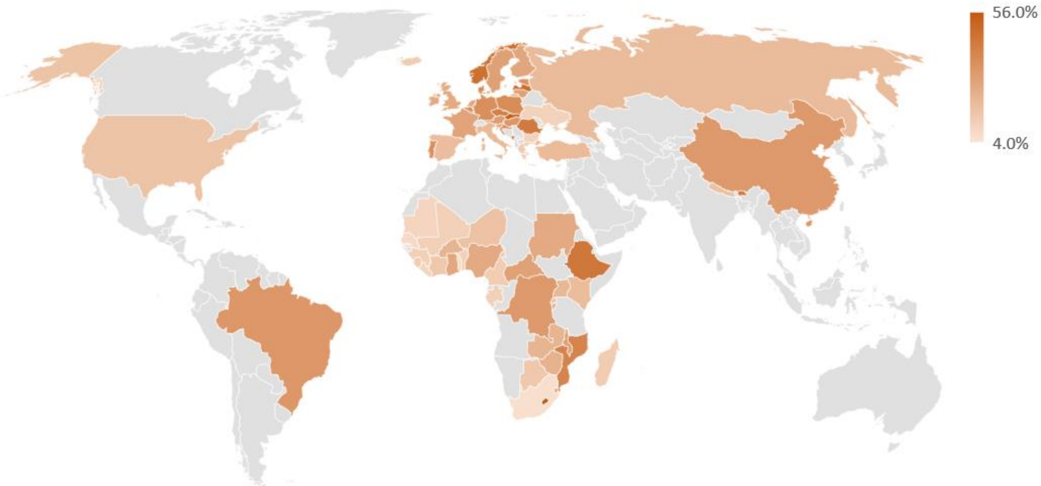

Figure 3. Shares of transmission and distribution in the total non-tax value of electricity output by countries in 2014 (or closest available year).

Notes: Countries colored in grey do not have available data.

Source: Developed by author using EIA (2013), EIA (2018), Trimble et al. (2016), Eurostat (2019a; 2019b; 2019c), ENTSO-E (2017), NERC (2015), NERC (2014), He et al. (2015), Siyambalapitiya (2018), ADB (2010), EY (2018), WB (2019) and NEEA (2008).

2.3 Levelized cost of electricity

To estimate the LCOE for each cost type (i.e. investment, operation and maintenance (O&M), fuel, own-use, and effective tax), for each new sector (e.g., nuclear base load, hydro base load, coal base load, etc.) and region, the GTAP-Power 9 Data Base relied on the IEA/NEA (2010) (Peters, 2016). For the GTAP-Power 10 Data Base update, we use IEA/NEA (2010) to estimate LCOE for 2004, 2007 and 2011 reference years, while IEA/NEA (2015) is used to derive the LCOE

[10] These are weighted average year-specific shares.

[11] For several countries, we do not have 2014 data, in this case we use the closest available year. See Appendix A for data availability by years.

for the 2014 reference year. As in the GTAP-Power 10 Data Base update, we add heat generation to the targeted volumes of the GTAP 10 Data Base electricity and heat sector split, the LCOE for corresponding technologies are added to the set of levelized costs. Appendix B provides the mapping between IEA generation technologies identified in IEA/NEA (2015) and GTAP-Power 10 Data Base sectors. It also identifies countries, for which corresponding technologies are reported by IEA/NEA (2015).

IEA/NEA (2010) and IEA/NEA (2015) have a different country coverage. In particular, there are five countries reported in IEA/NEA (2010) that are not reported in IEA/NEA (2015): Canada, Mexico, Czech Republic, Sweden and Russia. At the same time, IEA/NEA (2015) reports Denmark, Finland, New Zealand, Portugal, Spain and United Kingdom, which are not reported in IEA/NEA (2010). If the LCOE for a given country is reported by only one of the IEA/NEA reports, then it is used to derive the LCOEs for all reference years. To convert reported costs to the USD of the corresponding GTAP-Power 10 Data Base reference year, we use the United States consumer price index (CPI). In cases where several IEA technologies reported for a single country are mapped to the same GTAP-Power 10 Data Base sector, a simple average of the corresponding cost components is estimated.

3. Comparisons for the GTAP-Power 9 Data Base

Before moving to the overview of the constructed GTAP-Power 10 Data Base, we use updated data inputs (Section 2) to produce a GTAP-Power 9 Data Base for 2011 and compare it against the GTAP-Power 9 Data Base constructed by Peters (2016), without updated data inputs. In this way, we can explore the impact of the updated data inputs and procedures, without interactions with other input data modifications (e.g. changes in reference years and sectoral classification).

Introducing heat generation data to the GTAP-Power 9 Data Base build changes the shares of electricity and heat generation technologies at the global level. As most of the heat generation is associated with gas base load generation (labeled "GasBL" in the GTAP-Power 9 Data Base), the share of this technology at the global level increases by 4.6 percentage points (Figure 4). Another technology widely used for heat generation is oil peak generation ("OilP"), its corresponding global share increases by 1.6 percentage points. All other generation technologies experience moderate reductions (between 0.1 percentage points and 1.8 percentage points) in the global electricity and heat generation shares (Figure 4). The combined share of non-fossil fuel generation technologies (NuclearBL, WindBL, HydroBL, OtherBL, SolarP) reduces from 32% (in the GTAP-Power 9 Data Base with initial inputs) to 26.9% (in the GTAP-Power 9 Data Base with updated inputs). This also leads to the reduction in carbon intensity of the fossil fuel-based generation technologies, as electricity volumes generated from fossil fuels increase, while fossil fuel consumption by electricity sector at the country level remains the same.

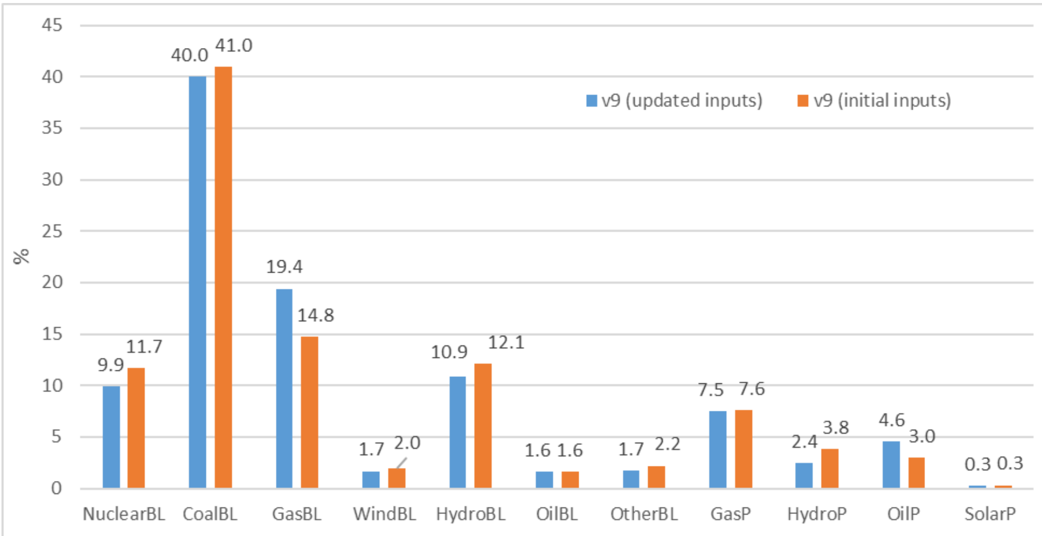

Figure 4. Shares of global electricity and heat generation from different technologies reported in GTAP-Power 9 Data Base for 2011 under different input data assumptions.

Notes: "v9 (updated inputs)" corresponds to the GTAP-Power 9 Data Base developed in this note, using updated data inputs discussed in Section 2; "v9 (initial inputs)" corresponds to the GTAP-Power 9 Data Base developed in Peters (2016).

Source: GTAP-Power 9 Data Base.

Much larger relative changes are observed at the regional level, especially for countries with high shares of heat generation in aggregate electricity and heat production (Figure 5). For instance, in the case of gas base load generation, a number of countries experience at least 20 percentage points increase in corresponding generation technology shares – these include mostly Northern and Eastern European countries. Somewhat lower increases are observed for oil peak generation shares – between 8 percentage points and 15 percentage points for 10 regions with the largest changes (Figure 5). Most Eastern European countries experience large reductions in nuclear generation shares, reaching over 20 percentage points in the case of Ukraine. Reductions in hydro generation shares (both peak and base load) are more uniform around the world (Figure 5).

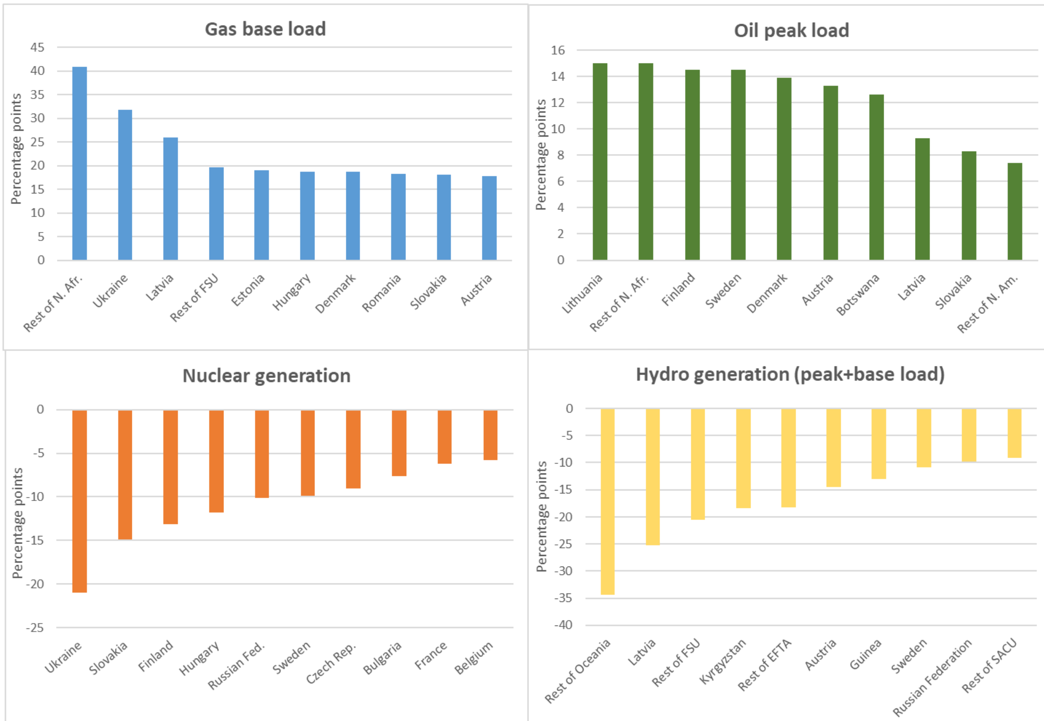

Figure 5. Percentage point change in shares of electricity and heat generation by technologies and regions for 2011 (GTAP-Power 9 Data Base with original inputs vs GTAP-Power 9 Data Base with updated inputs).

Notes: Top 10 regions with the largest change in shares are reported for each technology. Positive change means that the share of corresponding technology is higher in the GTAP-Power 9 Data Base with updated inputs than in the GTAP-Power 9 Data Base with initial inputs.

Source: Estimates by author.

One of the issues identified in the GTAP-Power 9 Data Base was an unusually large input of petroleum products ("p_c") to the electricity transmission and distribution sector ("TnD") in Russia.[12] In particular, the volume of petroleum products used by "TnD" in Russia in 2011 was even larger than "p_c" inputs to the oil peak generation. Using updated data inputs in the new version addresses this issue for all reference years.

Appendix C reports comparisons between the GTAP-Power 9 Data Base constructed by Peters (2016) and the GTAP-Power 9 Data Base with updated data inputs for 2011. The comparison method ranks the differences between the two datasets, in decreasing order, by showing large changes in large values first, based

[12] This issue was identified and reported to the GTAP Center by Larry Liu.

on the entropy measure. The entropy measure is a product of absolute and relative difference (in logarithms).

According to the comparison (Appendix C), the largest change is associated with the reduction of "p_c" use in the "TnD" sector in Russia (corresponding to the issue discussed above). This is followed by an increase in "GasBL" output in Ukraine due to the introduction of heat generation and reduction in "TnD" output in Russia due to the use of country-specific transmission and distribution shares. Other large changes include reductions in hydro peak and base load generation and changes (either increase of decrease) in the transmission and distribution sector output due to the application of country-specific electricity transmission and distribution shares.

There are number of other changes identified by the comparison, caused by the input data updates (e.g. inclusion of the heat generation to the LCOE estimates). These include an increase in the "OilBL" generation in Japan – from less than 1% of the total oil-based generation (in the original GTAP-Power 9 Data Base) to around 12.5% in the GTAP-Power 9 Data Base with updated data inputs. As neither IEA nor EIA data provide the split between base and peak load, such a mix was decided based on initial assumptions and costs by generation technologies (Peters, 2016). Another relatively large difference between two databases is the change in the "p_c" use by "CoalBL" in China. In the case of the GTAP-Power 9 Data Base with updated data inputs, "CoalBL" consumes almost exclusively coal, while relatively larger volume of "p_c" goes to the oil-based power and heat generation.

4. Overview of the GTAP-Power 10 Data Base

Using data inputs described in Section 2 and methodological approach developed in Peters (2016), we construct the GTAP-Power 10 Data Base for all four reference years – 2004, 2007, 2011 and 2014, based on the GTAP 10 Data Base (Aguiar et al., 2019).[13] In this section, we provide a brief overview of the GTAP-Power 10 Data Base and showcase an application that tracks CO_2 emissions embodied in the final consumption of electricity for 2014 reference year.

Looking into the generation mix at the global level, coal and gas power generation contribute almost 66% of total electricity and heat generation (Figure 6). Renewable energy sources (wind, solar, hydro and other base load) contribute around 19.3%, with hydro accounting for almost three quarters of the latter. The mix of electricity and heat generation technologies varies significantly across countries (Figure 7). For instance, in Brazil over 63% of total electricity and heat generation is from hydro, while in South Africa 93% is coal-based. Costs of power and heat generation also significantly differ by countries and technologies.

[13] GTAP 10 Data Base being one of the core data inputs.

Introduction of the country-specific transmission and distribution costs increased this variation relative to the GTAP-Power 9 Data Base (Peters, 2016).

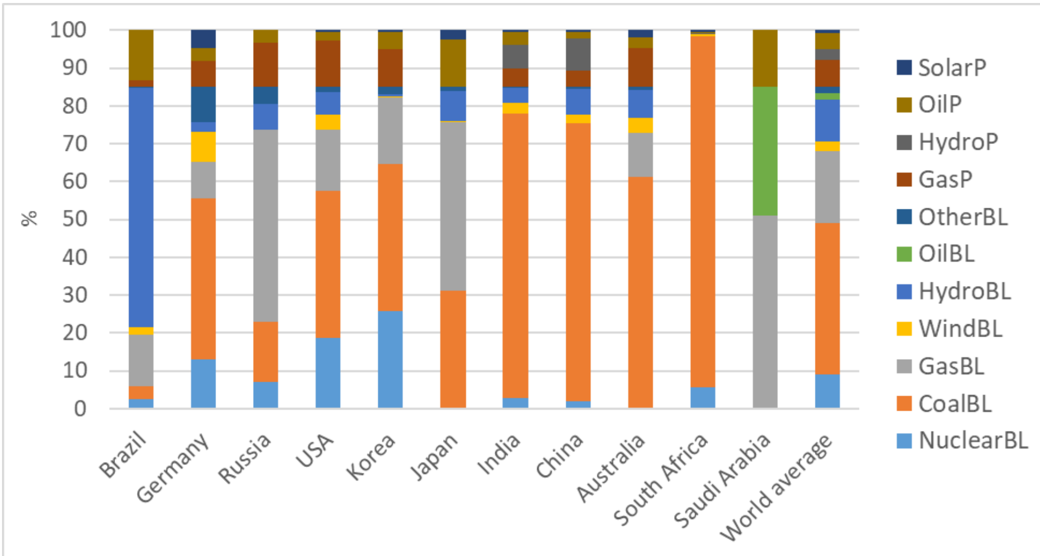

Figure 6. Shares of electricity and heat generation by technologies and selected countries in 2014, %.

Source: GTAP-Power 10 Data Base.

There are other aspects of the GTAP-Power 10 Data Base that can be highlighted. In the rest of this section, we focus on CO_2 emissions embodied in final consumption of electricity generated by different technologies. Following Peters (2008), CO_2 emissions per unit of output by countries and industries are used to estimate emissions associated with final consumption. This method assumes that the production technology is based on fixed proportions (i.e. in a given sector and country, the same production technology is used to produce domestic and exported commodities). For every commodity, total CO_2 emissions associated with fossil-fuels combustion and embodied in final consumption in region r (f_r) are estimated as

$$f_r = F_r(I - A_r)^{-1}c_r \quad (1)$$

where F_r is a vector of country-specific CO_2 emissions per unit of output by industries, I is the identity matrix, A_r is the technological matrix, which represents the industry requirements of domestically produced products in region r and c_r corresponds to the final consumption.

At the global level, around 3.3 gigatons (Gt) of CO_2 emissions are embodied in final domestic electricity consumption by households, which constitutes 11% of the global CO_2 emissions from fossil fuel combustion. Coal generation is by far the largest contributor and, at the global level, accounts for almost 64% of total electricity emissions in final consumption. (Figure 7). Gas-based electricity and heat generation (both base and peak load) accounts for 26.7% of CO_2 emissions embodied in final domestic electricity consumption.

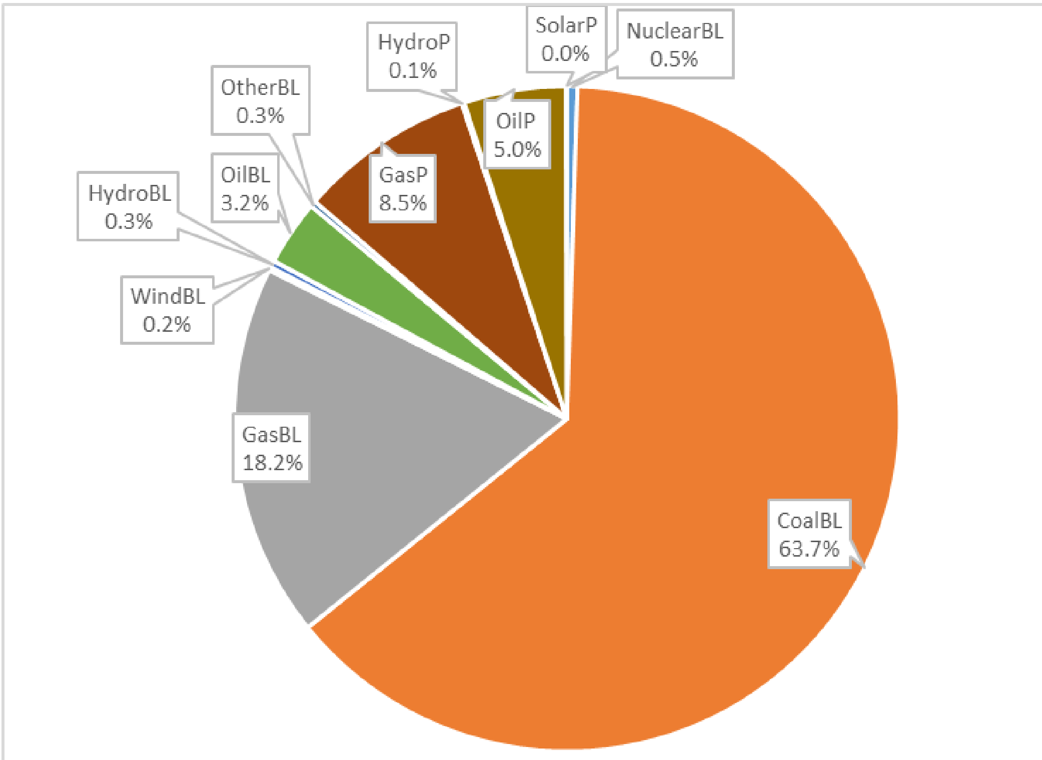

Figure 7. Distribution of the global CO_2 emissions embodied in the final consumption of electricity and heat in 2014 by generation technologies, %.

Source: Author's estimates based on the GTAP-Power 10 Data Base.

In terms of emission intensities, coal generation is by far the dirtiest technology, followed by oil base load generation and gas peak load generation (Figure 8). Hydro base load is the cleanest technology, emitting around 1% of coal base load generation per kWh of generated electricity.

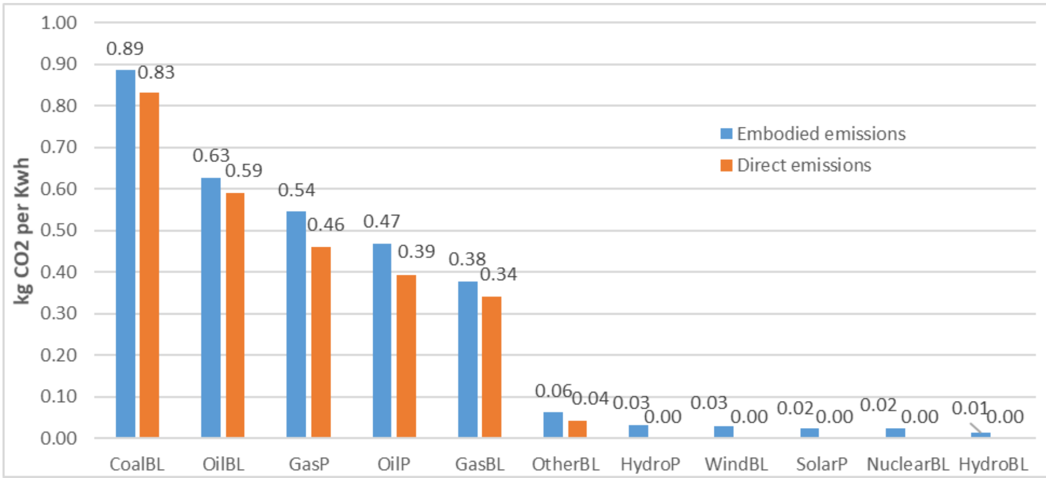

Figure 8. Global average intensities of the CO_2 emissions embodied in the final consumption of domestic electricity and heat in 2014 by generation technologies, kilogram (kg) CO_2 per kWh.

Source: Author's estimate based on the GTAP-Power 10 Data Base.

When only direct emissions from fossil fuel combustion are considered, all renewable generation technologies are carbon neutral (Figure 8), while when we account for the CO_2 emissions embodied in electricity production through the entire value chain, renewable technologies produce between 10 and 30 grams of CO_2 emissions per kWh of generated electricity. Including embodied emissions in the estimates also increases carbon intensity of the fossil fuel-based electricity and heat generation (Figure 8). For gas and oil peak load generations, carbon intensities increase by 18%-19%.

Finally, there is a high variation in intensities of the CO_2 emissions embodied in the final consumption of electricity and heat by countries. For instance, in the case of coal base load generation, CO_2 emissions embodied in the final consumption of domestic electricity and heat vary between less than 0.5 kg per kWh (in Estonia, Finland and Sweden) to over 1.5 kg per kWh (in Zimbabwe and Botswana). While in many cases carbon intensity of the domestic coal-based electricity consumed by households is lower in the developed countries than in the transition economies, it is not the general case. For instance, China's coal generation is less carbon intensive than the one in Australia, Canada and the United States (Figure 9).

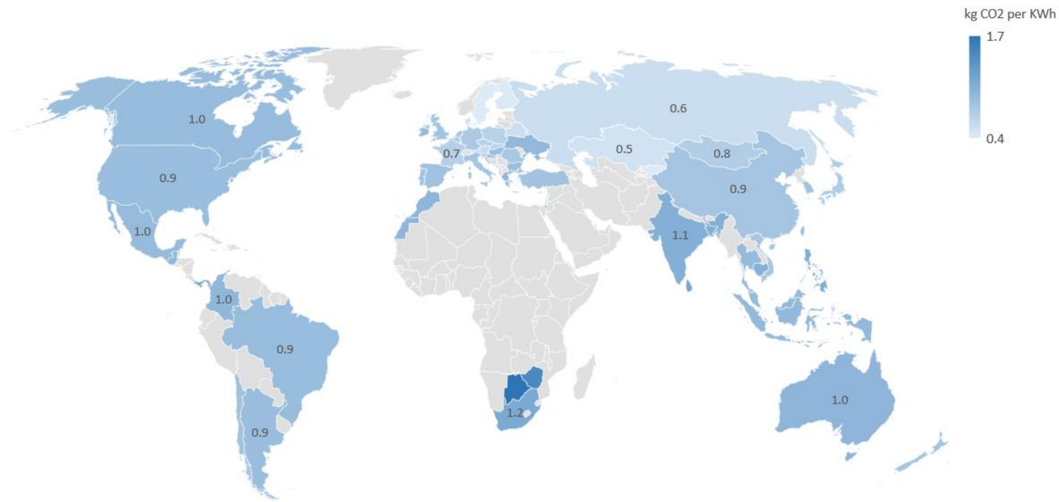

Figure 9. Intensities of the CO_2 emissions embodied in the final consumption of domestic electricity and heat from coal base load generation in 2014 by countries, kg CO_2 per kWh.

Notes: Only individual countries with coal base load generation over 100 gigawatt-hours (GWh) per year are plotted on the map. Countries colored in grey do not have available data or have coal base load generation below 100 GWh per year.

Source: Author's estimate based on the GTAP-Power 10 Data Base.

5. Conclusions

The GTAP-Power 9 Data Base has introduced a transparent approach to the splitting single electricity and heat generation sector of the standard GTAP 9 Data Base into eleven generation technologies and transmission and distribution (Peters, 2016). In this paper, we revise an approach developed in Peters (2016), by addressing several limitations identified in the GTAP-Power 9 Data Base.

First, in the original GTAP-Power 9 Data Base developed by Peters (2016), the output of the electricity and heat generation sector of GTAP 9 Data Base was split using electricity generation data only. In this paper, we added heat generation volumes data to provide a more representative sectoral split and better concordance with GTAP 9 (and 10) Data Base definitions. Introduction of the heat generation data to the GTAP-Power 9 Data Base build changes shares of electricity and heat generation technologies at the global level. As most heat generation is associated with gas base load, share of this technology at the global level increases by 4.6 percentage points (based on the 2011 reference year comparisons). Another technology widely used for heat generation is oil peak load, its corresponding global share increases by 1.6 percentage points. All other generation technologies experience moderate reductions or no significant changes in the global electricity and heat generation mix shares. Much higher adjustments in the generation mix are observed for individual countries. For example, share of gas base load generation in total generation increases by more than 20 percentage points in a number of Northern and Eastern European countries.

Second, we add data on country and year-specific shares of transmission and distribution costs in electricity price. In the GTAP-Power 9 Data Base (Peters, 2016), this share was assumed to be 21%, based on the data for United States (EIA, 2013). In reality, transmission and distribution shares vary across countries, depending on electricity grid structure, population density, specifics of the electricity market and other factors. We have introduced transmission and distribution shares for 80 GTAP 10 Data Base countries, which correspond to 65 GTAP 10 Data Base regions. These shares vary across countries – from as low as 4% in Seychelles to as high as 56% in Lesotho, with global weighted average share of around 25.4%.

Finally, we update the levelized cost of electricity generation and make these data reference year-specific. We use IEA/NEA (2010) to estimate LCOE for 2004, 2007 and 2011 reference years, while IEA/NEA (2015) is used to derive LCOE for the 2014 reference year. We also add LCOE for the co-generation technologies to account for the heat generation costs.

Using this updated approach, we develop the GTAP-Power 10 Data Base. We showcase an application of the newly constructed database by estimating CO_2 emissions embodied in final consumption of electricity generated with different technologies. We show that in terms of emission intensities, coal generation is by far the dirtiest technology, followed by oil base load generation and gas peak load generation. Hydro base load is the cleanest technology, emitting around 1% of coal base load generation per kWh of generated electricity. At the same time, even within the same generation technology emission intensities vary significantly across countries. For instance, in the case of coal base load generation, CO_2 emissions embodied in the final consumption of domestic electricity and heat vary between less than 0.5 kg per kWh (in Estonia, Finland and Sweden) to over 1.5 kg per kWh (in Zimbabwe and Botswana).

While updated data inputs introduced to the GTAP-Power 10 Data Base build stream have helped to address some limitations identified in the GTAP-Power 9 Data Base (Peters, 2016), there are several other improvements that could be introduced to the GTAP-Power Data Base and benefit the modelling community.

As discussed earlier, standard GTAP 10 Data Base (Aguiar et al., 2019) aggregates electricity and heat generation within single sector. In many cases electricity and heat are generated using different technologies, have different shares of transmission and distribution costs, and are not direct substitutes. Splitting of the electricity and heat generation into separate technologies would enable a more consistent assessment of energy and environmental policies, as well as provide additional opportunities for splitting out specific technologies (e.g. heat generation from biomass).

The current version of the GTAP-Power 10 Data Base provides representation of the existing generation technologies only, while in the case of long-term climate energy and environmental modelling, alternative future technologies play a major role. For instance, mitigation scenarios that achieve an ambitious 1.5°C target widely rely on the large-scale application of bioenergy with carbon capture and storage (CCS) (IPCC, 2018). Representation of the cost structure of the alternative (not currently presented on the market) generation technologies in the GTAP-Power Data Base would enable models based on this data to explore a wider range of policy and technological options.

These limitations should be further addressed in the next releases of the GTAP-Power Data Base.

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Appendix A. Electricity transmission and distribution cost shares

Table A.1. Share of the transmission and distribution costs in the total non-tax value of electricity sector output for selected countries, %.

No.	Country code	Country name	Region code	T&D share				Available data years
				2004	2007	2011	2014	
1	aut	Austria	aut	27.9	27.9	27.9	30.8	2011, 2014
2	bdi	Burundi	xec	23.7	23.7	23.7	23.7	2014
3	bel	Belgium	bel	29.3	29.3	34.2	36.2	2007, 2011, 2014
4	ben	Benin	ben	12.0	12.0	12.0	12.0	2013
5	bfa	Burkina Faso	bfa	21.7	21.7	21.7	21.7	2014
6	bgr	Bulgaria	bgr	27.9	27.9	21.7	11.1	2007, 2011, 2014
7	bra	Brazil	bra	33.1	33.1	33.1	33.1	2006
8	btn	Bhutan	xsa	33.2	42.2	42.7	42.7	2015
9	bwa	Botswana	bwa	14.5	14.5	14.5	14.5	2013
10	caf	Central African Republic	xcf	29.3	29.3	29.3	29.3	2014
11	chn	China	chn	32.0	32.0	32.0	32.0	2011
12	civ	Cote d'Ivoire	civ	15.1	15.1	15.1	15.1	2014
13	cmr	Cameroon	cmr	13.4	13.4	13.4	13.4	2014
14	cog	Congo	xcf	31.8	31.8	31.8	31.8	2012
15	com	Comoros	xec	10.7	10.7	10.7	10.7	2012
16	cpv	Cape Verde	xwf	8.9	8.9	8.9	8.9	2012
17	cyp	Cyprus	cyp	14.2	14.2	14.2	16.3	2011, 2014
18	cze	Czech Republic	cze	32.7	32.7	36.7	41.2	2007, 2011, 2014
19	deu	Germany	deu	30.9	30.9	29.0	36.2	2007, 2011, 2014
20	dnk	Denmark	dnk	44.5	44.5	32.5	37.4	2007, 2011, 2014
21	esp	Spain	esp	32.2	32.2	32.2	18.6	2011, 2014
22	est	Estonia	est	35.2	35.2	37.2	33.8	2007, 2011, 2014
23	eth	Ethiopia	eth	45.2	45.2	45.2	45.2	2012
24	fin	Finland	fin	26.1	26.1	25.4	27.2	2007, 2011, 2014
25	fra	France	fra	28.1	28.1	28.1	28.1	2014
26	gab	Gabon	xcf	11.7	11.7	11.7	11.7	2014
27	gbr	United Kingdom	gbr	27.5	27.5	24.7	26.0	2007, 2011, 2014
28	gha	Ghana	gha	26.8	26.8	26.8	26.8	2013

“Continued”.

Table A.1. Share of the transmission and distribution costs in the total non-tax value of electricity sector output for selected countries, %. "Continued".

No.	Country code	Country name	Region code	T&D share				Available data years
				2004	2007	2011	2014	
29	gin	Guinea	gin	11.9	11.9	11.9	11.9	2013
30	gmb	Gambia	xwf	10.1	10.1	10.1	10.1	2014
31	grc	Greece	grc	17.5	17.5	17.5	13.7	2011, 2014
32	hrv	Croatia	hrv	39.4	39.4	34.8	37.2	2007, 2011, 2014
33	hun	Hungary	hun	33.7	33.7	33.1	33.1	2007, 2014
34	irl	Ireland	irl	27.1	27.1	27.1	26.0	2011, 2014
35	isl	Iceland	xef	12.9	12.9	12.9	12.9	2014
36	ita	Italy	ita	20.5	20.5	20.5	20.1	2011, 2014
37	ken	Kenya	ken	19.2	19.2	19.2	19.2	2015
38	lbr	Liberia	xwf	9.7	9.7	9.7	9.7	2014
39	lie	Liechtenstein	xef	46.8	46.8	46.8	46.8	2014
40	lso	Lesotho	xsc	55.7	55.7	55.7	55.7	2010
41	ltu	Lithuania	ltu	42.9	42.9	38.7	29.0	2007, 2011, 2014
42	lux	Luxembourg	lux	29.7	29.7	28.3	29.9	2007, 2011, 2014
43	lva	Latvia	lva	41.5	41.5	39.3	48.8	2007, 2011, 2014
44	mdg	Madagascar	mdg	13.3	13.3	13.3	13.3	2014
45	mli	Mali	xwf	11.5	11.5	11.5	11.5	2014
46	mlt	Malta	mlt	20.1	20.1	12.7	14.2	2007, 2011, 2014
47	mne	Montenegro	xer	39.8	39.8	39.8	40.3	2011, 2014
48	moz	Mozambique	moz	39.8	39.8	39.8	39.8	2014
49	mrt	Mauritania	xwf	9.8	9.8	9.8	9.8	2013
50	mus	Mauritius	mus	12.7	12.7	12.7	12.7	2013
51	mwi	Malawi	mwi	28.5	28.5	28.5	28.5	2014
52	ner	Niger	xwf	16.7	16.7	16.7	16.7	2014
53	nga	Nigeria	nga	26.3	26.3	26.3	26.3	2014
54	nld	Netherlands	nld	21.8	21.8	22.7	26.5	2007, 2011, 2014
55	nor	Norway	nor	47.1	47.1	45.9	47.9	2007, 2011, 2014
56	npl	Nepal	npl	17.0	17.0	17.0	17.0	2014
57	pol	Poland	pol	56.7	56.7	32.8	37.1	2007, 2011, 2014
58	prt	Portugal	prt	12.0	12.0	32.5	36.2	2007, 2011, 2014

"Continued".

Table A.1. Share of the transmission and distribution costs in the total non-tax value of electricity sector output for selected countries, %. "Continued".

No.	Country code	Country name	Region code	T&D share				Available data years
				2004	2007	2011	2014	
59	rou	Romania	rou	39.6	39.6	38.0	43.9	2007, 2011, 2014
60	rus	Russian Federation	rus	19.5	19.5	19.5	19.5	2016
61	rwa	Rwanda	rwa	17.5	17.5	17.5	17.5	2013
62	sdn	Sudan	xec	26.2	26.2	26.2	26.2	2014
63	sen	Senegal	sen	7.9	7.9	7.9	7.9	2013
64	sle	Sierra Leone	xwf	12.6	12.6	12.6	12.6	2012
65	srb	Serbia and Montenegro	xer	25.7	25.7	25.7	25.7	2014
66	stp	Sao Tome and Principe	xcf	9.5	9.5	9.5	9.5	2014
67	svk	Slovakia	svk	42.2	42.2	49.0	54.4	2007, 2011, 2014
68	svn	Slovenia	svn	25.5	25.5	25.5	28.7	2011, 2014
69	swe	Sweden	swe	24.3	24.3	26.3	29.5	2007, 2011, 2014
70	swz	Swaziland	xsc	25.3	25.3	25.3	25.3	2014
71	syc	Seychelles	xec	3.9	3.9	3.9	3.9	2014
72	tgo	Togo	tgo	7.9	7.9	7.9	7.9	2013
73	tur	Turkey	tur	18.1	18.1	18.1	19.8	2011, 2014
74	tza	Tanzania, United Republic of	tza	20.0	20.0	20.0	20.0	2015
75	uga	Uganda	uga	20.6	20.6	20.6	20.6	2014
76	ukr	Ukraine	ukr	15.5	15.5	13.6	10.8	2009, 2011, 2013
77	usa	United States of America	usa	13.4	13.3	15.8	16.5	2004, 2007, 2011, 2014
78	zaf	South Africa	zaf	6.0	6.0	6.0	6.0	2014
79	zmb	Zambia	zmb	21.5	21.5	21.5	21.5	2014
80	zwe	Zimbabwe	zwe	23.0	23.0	23.0	23.0	2012
81	**Weighted average**	24.8	24.7	24.9	25.4	-		

Notes: In the case of data availability for both residential and non-residential users, data years are reported for the type of consumers with the largest number of available years.

Source: Developed by author using EIA (2013), EIA (2018), Trimble et al. (2016), Eurostat (2019), ENTSO-E (2017), NERC (2015), NERC (2014), He et al. (2015), Siyambalapitiya (2018), ADB (2010), EY (2018), WB (2019) and NEEA (2008).

Appendix B. Mapping between generation technologies and sectors

Table B.1. Mapping between IEA generation technologies and GTAP-Power 10 Data Base sectors.

No.	IEA generation technologies	GTAP-Power sector	Reported countries
Nuclear generation			
1	Nuclear – advanced light-water reactor	NuclearBL	China, Japan, Korea, USA, France, Hungary, Finland, UK
2	Nuclear – gen III projects		Belgium
3	Nuclear – light-water reactor		Slovak Republic
Coal base load generation			
4	Coal – ultra-supercritical	CoalBL	China, Japan, Belgium, Netherlands
5	Coal – supercritical pulverised		USA
6	Coal - pulverised		Korea, South Africa, Portugal
7	Coal – hard coal		Germany
8	Coal – lignite		Germany
9	Combined heat and power (CHP) large – coal		Denmark
Gas base load generation			
10	Combined-cycle Gas Turbine (CCGT)	GasBL	China, Japan, Korea, Belgium, France, Germany, Hungary, Netherlands, New Zealand, Portugal, UK
11	CHP medium – natural gas		Denmark
12	CHP large – natural gas		Denmark
13	CHP engine		Spain
14	CHP gas turbine		Spain
Wind base load generation			
15	Onshore wind	WindBL	China, Japan, Korea, USA, Austria, Belgium, France, Germany, Hungary, Italy, Netherlands, South Africa, Denmark, New Zealand, Portugal, UK
16	Offshore wind		Korea, USA, Belgium, France, Germany, Netherlands, Denmark, Portugal, UK
Hydro base load generation			
17	Hydro – non-power dams	HydroBL	USA
18	Hydro – new stream development		USA

19	Large hydro – run of river (Large hydro)		Brazil, Germany, Switzerland, Spain
20	Small hydro – run of river		Austria, Germany, Italy, Switzerland, Spain
21	Large hydro		UK

"Continued".

Table B.1. Mapping between IEA generation technologies and GTAP-Power 10 Data Base sectors. “Continued”.

No.	IEA generation technologies	GTAP-Power sector	Reported countries
Oil base load generation			
22	–	OilBL	–
Other base load generation			
23	Biomass	OtherBL	USA, UK
24	Solar thermal – 12 hrs storage		USA
25	Geothermal – flash steam		USA
26	Geothermal – binary rankine cycle		USA
27	Biogas – engine		Italy, Spain
28	Solid biomass – turbine		Italy
29	Solid waste incineration		Italy, Netherlands
30	Solid waste incineration – turbine		Spain
31	Geothermal		Italy, New Zealand, UK
32	Biomass - turbine		Spain
33	CHP biogas		Austria
34	CHP solid biomass		Austria
35	CHP biomass		UK
36	CHP engine – biogas (digester)		Germany
37	CHP engine – biogas		Germany
38	CHP engine – mine gas		Germany
39	CHP steam turbine – solid biomass		Germany
40	CHP Geothermal		Germany, UK
41	CHP biogas/fermentation		Netherlands
42	Co-firing of wood pellets		Netherlands
43	CHP medium – wood chips		Denmark
44	CHP medium – straw		Denmark
45	CHP large – wood pellets		Denmark
46	Solar thermal (CSP) – molten salt storage		South Africa
Gas peak generation			

Open-cycle Gas Turbine (OCGT)	GasP	Belgium, Germany, New Zealand, UK
Hydro peak generation		
Large hydro – reservoir	HydroP	Switzerland, Portugal, Spain
Small hydro – reservoir		Spain
Large hydro – pumped storage		Switzerland, Portugal

"Continued".

Table B.1. Mapping between IEA generation technologies and GTAP-Power 10 Data Base sectors. "Continued".

No.	IEA generation technologies	GTAP-Power sector	Reported countries
Oil peak generation			
51	–	OilP	–
Solar peak generation			
52	Solar photovoltaic (PV) – large, ground-mounted	SolarP	China, Japan, Korea, USA, France, Germany, Hungary, Italy, Denmark, Portugal, Spain, UK
53	Solar thermal – 6 hrs storage		USA
Discarded technologies			
54	Solar PV – commercial rooftop	Not mapped to the GTAP	China, Korea, USA, Austria, Belgium, France, Germany, Hungary, Italy, Netherlands, Switzerland, Denmark, Portugal, Spain
55	Solar PV – residential rooftop		Japan, Korea, USA, Belgium, France, Germany, Hungary, Italy, Denmark, Portugal, Spain, UK

Source: Developed by author based on IEA/NEA (2015).

Appendix C. A comparison between GTAP-Power 9 Data Base constructed in Peters (2016) and GTAP-Power 9 Data Base with updated data inputs

The comparison program employs an entropy-based methodology developed by Robert McDougall. This method ranks the differences between two datasets, in decreasing order, by showing large changes in large values first. The entropy measure is a product of absolute and relative difference (in logarithms). It is applicable to non-negative data – we focus on usage of commodities as represented in the nonnegative tax-free and tax-paid usage values. This is done in multiple iterations: comparing array elements, array totals, rank 1 sub-totals, rank 2 sub-totals, etc.

For each comparison, all features including array elements, totals and sub-totals are compared, to identify the most divergent feature. The dataset is then re-scaled to eliminate that divergence and then comparisons of all features are carried out again and this process is repeated several times.

Table C.1. Comparisons between GTAP-Power 9 Data Base constructed with initial and updated data inputs (top 20 instances based on the entropy value).

Commodity	Usage	Region	Entropy	Values, mn USD	
				GTAP-Power 9	GTAP-Power 9_upd
p_c_d	TnD	rus	49752	15372	20
GasBL_d	All	ukr	34770	0	8365
TnD_d	All	rus	26433	29117	3644
OilBL_d	All	jpn	26248	0	6314
p_c_d	CoalBL	chn	21691	8881	63
HydroP_d	All	All	21320	74829	29301
All	OilBL	jpn	20280	0	5755
All	HydroP	All	19430	70764	28193
All	GasBL	ukr	18743	0	8331
OilP_d	All	chn	17070	3158	21108
All	OilP	chn	16252	3013	20142
GasP_d	All	jpn	13451	3236	0
All	GasP	jpn	12087	2909	0
GasP_d	All	All	11845	222344	152982
HydroBL_d	All	fra	10920	0	2627
OtherBL_d	All	rus	10488	135	5749
All	GasP	All	10254	204674	142418
All	OtherBL	rus	9843	127	5394
OtherBL_d	All	bra	8330	6262	368
GasBL_d	All	fin	8059	0	1939

Notes: "_d" in the commodity name corresponds to the domestic component; "_m" in the commodity name corresponds to the imported component. "GTAP-Power 9" corresponds to the GTAP-Power 9 Data Base constructed in Peters (2016); "GTAP-Power 9_upd" corresponds to the GTAP-Power 9 Data Base constructed using inputs described in this paper.

Source: developed by author.