The MIT EPPA6 Model: Economic Growth, Energy Use, and Food Consumption

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Abstract

The MIT Economic Projection and Policy Analysis (EPPA) model has been broadly applied on energy and climate policy analyses. In this paper, we present our newest model: EPPA6-L. Besides adopting the GTAP8 database as the core economic data, EPPA6-L incorporates the latest energy, emissions, and cost estimates from existing studies, and enhances the model structure and implementation to facilitate future extension. With these improvements, the projected business-as-usual CO_2 *emissions in 2100 are lowered by 6.3% compared to the EPPA5 number. We also present how projections for the consumption of crops, livestock, and food products are improved with non-homothetic preference, and how various assumptions for business-as-usual GDP growth, elasticity of substitution between energy and non-energy input, and autonomous energy efficiency improvement may change* CO_2 *emissions and prices.*

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1. INTRODUCTION

The MIT Economic Projection and Policy Analysis (EPPA) model is a computable general equilibrium (CGE) model of the global economy.[1] It has been applied on studying policy impacts, or assessing prospects for new technologies under different scenarios. Recent examples include Jacoby and Chen (2014), Paltsev et al. (2014), Karplus et al. (2013a), Winchester et al (2013), Nam et al. (2013), etc.[2] EPPA can be run at a standalone mode, or it can be coupled with other earth system models of the MIT Integrated Global System Modeling (IGSM) framework for climate policy analyses. Recently, to answer a wider range of questions, in addition to the basic EPPA presented in Babiker et al. (2001) and Paltsev et al. (2005), the model is usually modified to incorporate features with higher resolutions for some technologies or activities, such as detailed representations for: 1) different household transportation technologies; 2) various sources of first generation biofuels; 3) land-use change; 4) refined oil sector; 5) aviation sector; 6) health impacts from pollutants, etc. For instance, the first three features are all included in Paltsev et al. (2014).

While having these features is essential in answering relevant questions, it requires large volumes of additional data and increases the level of model complexity as associated changes are often intertwined with the original model, and therefore sometimes solving the extended model could be numerically challenging. Therefore, to come up with the next generation EPPA with an improved structure and the latest databases, working on a lighter version of the model (which is already complicated due to its multi-regional, multi-sectoral, and multi-period nature) as the starting point turns out to be the most efficient and least error-prone approach. In other words, while developing versions of EPPA6 that have detailed representations for some activities or technologies is underway, this is conducted in a sequential fashion for quality assurance purposes.

In this paper, we present our newest energy-economic model: EPPA6-L (L denotes “light”). EPPA6-L is a lighter version of EPPA, which does not include the aforementioned extended features. At this stage, our focuses are on improving the core model structure and updating databases – both of which will be common features to other versions of EPPA6 under development. Nevertheless, with those improvements and many elaborate treatments inherited from EPPA5, the predecessor of EPPA6-L, the new model is ready for assessing various energy or climate policies. More importantly, it provides a robust platform for the ongoing model development.

The main purpose of this paper is threefold: we first explain the improvements of EPPA6-L over EPPA5 in terms of model structure, data, and assumptions. For instance, we incorporate into EPPA6-L a non-homothetic preference on final consumption to better capture the observed

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[1] While the abbreviation of EPPA is the same as before, we change the model’s full name from “Emissions Predictions and Policy Analysis” to the current one to reflect the broader context of our recent model development and applications.

[2] Readers may refer to the following link for details: http://globalchange.mit.edu/research/publications

differences in regional consumption patterns of crops, livestock, and food products. Adjustments are done carefully to ensure the aggregation condition holds. We also update the main economic data based on the Global Trade Analysis Project Version 8 (GTAP8) database, and revise the regional business-as-usual (BAU) GDP projections according to recent studies. Secondly, we examine the performance of EPPA6-L in terms of GDP impact, energy use, and CO_2 emissions under a sample policy scenario. In particular, we compare combusted CO_2 emissions from EPPA6-L and EPPA5, and decompose sources that account for the different results. Finally, since an important aspect of the model's application is to run century-scale simulations where a huge degree of uncertainty in economic growth and energy use exists, we choose several parameters, including BAU GDP growth rates, autonomous energy efficiency improvement (AEEI), which captures non-price driven changes in energy use over time, and elasticity of substitution between energy and non-energy inputs, to demonstrate how different assumptions for these parameters may change emissions levels and abatement costs.

Two caveats for the application of our model are: firstly, readers shall keep in mind that the model is designed for long-term projections. Short-term fluctuations due to reasons such as business cycles are beyond the scope of our study. Next, while the model can shed light on potential policy impacts that are, without a general equilibrium framework, often overlooked, simulation results are model responses based on pure economic grounds without endogenous considerations for institutional or political factors. In any case, outputs from the model simply represent our best effort for projections with the currently available information and model framework. The model should not be regarded as a crystal ball for the future.

Currently, most relevant studies seem to focus more on the theoretical framework of their models rather than how they are implemented. This paper, on the other hand, also provides readers a clear description for the model structure and how it is enhanced, which are important for understanding, maintaining, or developing a large-scale model for policy assessments. The rest of the paper is organized as follows: Section 2, 3, and 4 introduce the theoretical framework, data, and structure of EPPA6-L, respectively; Section 5 analyzes simulation results for both the reference and policy runs, and conducts sensitivity analyses with various model settings and parameterizations, and Section 6 provides conclusions and directions for future research.

2. THEORETICAL FRAMEWORK

EPPA6-L is a multi-region and multi-sector recursive dynamic computable general equilibrium (CGE) model of the world economy. The recursive approach suggests that consumption, savings, and investment are determined by current period prices. Savings supply fund for investment, and investment plus the remained capital forms the capital for next period's production. EPPA6-L is solved at 5-year per period intervals from 2010 onward up to 2100 to generate scenarios of greenhouse gases (GHGs), aerosols, and other air pollutants emissions from human activities. The model is formulated in a series of mixed complementary problems

(MCP) (Mathiesen, 1985) using the modeling languages of GAMS and MPSGE, which is now a subsystem of GAMS (Rutherford, 1999).

2.1 Static Module

There are three types of agents in each region: household, producers, and government. The household owns primary factors including labor, capital, and natural resources, provides them to producers, receives income of services derived from the utilization of endowments (wage, capital and resource rents) accordingly, pay taxes to the government and get net transfers from it. To maximize utility, the household allocates income for consumption and savings – both of which are derived from the Shephard's Lemma.

Producers (production sectors) transform primary factors and intermediate inputs (outputs of other producers) into goods and services, sell them to other domestic or foreign producers, households, or governments, and receive payments in return. To maximize the profit, each producer chooses the output level, and under the given technology and market prices, hires the cost minimizing input bundle. The government is treated as a passive entity, which simply collects taxes from household and producers to finance government consumption and transfers.

For a typical CGE model, the activities of different agents and their interactions can be described by: 1) zero-profit condition; 2) market-clearing condition; and 3) income balance condition. Zero-profit conditions represent cost-benefit analyses for economic activities. For the household, the activity is the utility, and for each producer, the activity is the output. A typical zero-profit condition expressed in MCP format is:

$$MC - MB \geq 0; Q \geq 0\,; [MC - MB\,] \cdot Q = 0 \tag{1}$$

For instance, if Condition (1) is applied on a production activity, it means that if the equilibrium output $Q > 0$, the marginal cost MC must equal the marginal benefit MB, and if $MC > MB$ in equilibrium, the producer have no reason to produce. Note that $MC < MB$ is not an equilibrium state since Q will increase until $MC = MB$. Other activities such as investment, imports, exports, and commodity aggregation with the Armington assumption (Armington, 1969) also have their own zero-profit conditions.

For each market-clearing condition, it determines the price level based on market demand and supply. A typical market-clearing condition in MCP format is:

$$S \geq D; P \geq 0\,; [S - D\,] \cdot P = 0 \tag{2}$$

Condition (2) states that for each market, if there is a positive equilibrium price P, then P must equalize supply S and demand D. If $S > D$ in equilibrium, then the commodity is free. Similarly, in Condition (2), $S < D$ is not in equilibrium because in this case, P will continue to increase until the market is clear, i.e., $S = D$.

Income-balance conditions specify income levels of household and government that support their spending levels. A typical income-balance condition in MCP format is:

$$E \geq I; E \geq 0 ; [E - I] \cdot E = 0 \tag{3}$$

The expenditure E equals income I always holds in CGE models. In addition, the price of utility for the U.S. is chosen as the numeraire of the model so all other prices are measured relative to it.

Lastly, many CGE models including EPPA use nested Constant Elasticity of Substitution (CES) functions with various inputs to specify production technology as well as preference. CES functions are constant return to scale (CRTS), which means if all inputs are doubled, the output will be doubled as well. Although CRTS makes solving the model easier, it suggests an income elasticity of one for all period. Taking food consumption for instance, existing studies have shown that, as income grows, the expenditure shares on food consumption tend to decrease (Zhou, 2012; Haque, 2005), which suggests an income elasticity of less than one. In previous EPPA, while the consumption shares are adjusted between periods to account for this, the CRTS properties are still kept within a period.

Nevertheless, in EPPA6-L, we are able to take a further step toward a within-period non-homothetic preference. Our strategy is to adopt the approach presented in Markusen (2006), i.e., within the MPSGE framework, applying the setting with a Stone-Geary adjustment, which requires a shift parameter that changes the reference point of consumption from zero (as in the CES case) to the shift parameter level (sometimes the shift parameter is called the "subsistence consumption" of the Stone-Geary system), and the shift parameter is calibrated so the income elasticity can be matched to a given level. Note that for a set of constant shift parameters in the Stone-Geary system, income elasticities will eventually converge to one as income grows. For our research purpose, we recalibrate the shift parameter for each period so the income elasticities can always match specified levels. A caveat for this treatment is that, as previous EPPA that changes consumption shares directly, the consumer's preference is recalibrated over time.[3]
For demonstration purpose, let us consider a utility function U with preference over N commodities indexed by i, and use c_i, c_i^*, and w to represent consumption of commodity i, shift parameter for the consumption of commodity i, and the budget, respectively:

$$u = U(c_1 - c_1^*, c_2 - c_2^*, \dots, c_N - c_N^*) \tag{4}$$

The income elasticity for the consumption of commodity i is defined as:

$$\eta_i = \left(\frac{c_i - c_i^*}{c_i}\right) / \left(\frac{w - \sum_{i=1}^{N} c_i^*}{w}\right) \tag{5}$$

Applying the Engel aggregation, it can be shown (see Appendix) that for a given η_i, the solution for c_i^* that satisfies Equation (5) is:

$$c_i^* = (1 - \eta_i) c_i \tag{6}$$

With Equation (6), we can calibrate the model by choosing c_i^* such that the income elasticity of commodity i is η_i. This strategy allows us to incorporate the existing income elasticity

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[3] This implies that the equivalent variation (EV) can only be used for measuring the within-period welfare change.

estimates for the final consumption of commodities from crops, livestock, and food sectors. For other EPPA sectors that cannot be mapped into those in the existing studies, we apply a uniform income elasticity levels derived from the Engel's Aggregation. The details of EPPA sectors/commodities will be presented in Subsection 2.3.

In addition, since the intermediate inputs of food sector are modeled by a Leontief structure (see Appendix), which suggests that, without further adjustment, crops and livestock inputs to food sector will grow proportionally as food sector expands. We believe this representation could be improved by assuming that for the food production activity, the input shares are updated based on the final consumption trends for crops and livestock. More specific, we update the food sector input shares such that the percentage changes of crops and livestock inputs are represented by the percentage changes of final consumption levels for crops and livestock.

2.2 Dynamic Process

The dynamics of EPPA6-L are determined by both exogenous and endogenous factors. The former include: 1) projections for BAU GDP growth; 2) labor endowment growth; 3) factor-augmented productivity growth; 4) autonomous energy efficiency improvement (AEEI); and 5) natural resource assets. The data needed to calibrate the dynamics will be presented in Section 3. For each region, we assume that the labor endowment increases proportionally to the population growth. Besides, in the BAU simulation, we adjust the factor-augmented productivity levels proportionally (Hicks-neutral adjustment) to match that region's BAU GDP growth profile. The productivity recalibration is done automatically in the BAU run, and the recalibrated productivity levels are treated as given in the policy run (see Section 4 for how it is implemented).

Dynamics determined endogenously include savings, investment, and fossil fuel resource depletion. As in the previous versions of EPPA, savings and consumption are aggregated in a Leontief approach in household's utility function. All savings are used as investment, which meets the demand for capital goods. The capital is divided into a malleable portion KM_t and a vintage non-malleable portion $V_{n,t}$. The dynamics of the malleable capital is described by:

$$KM_t = INV_{t-1} + (1-\theta)(1-\delta)^5 KM_{t-1} \tag{7}$$

In Equation (7), θ is the fraction of the malleable capital that becomes non-malleable at the end of period $t-1$, and INV_{t-1} and δ are investment and depreciation rate, respectively. The newly formed non-malleable capital $V_{1,t}$ comes from a portion of the survived malleable capital from the previous period:

$$V_{1,t} = \theta(1-\delta)^5 KM_{t-1} \tag{8}$$

Compared to earlier versions of EPPA, we improve the vintage dynamics of EPPA6-L with two updates. Firstly, in the original setting of previous EPPA, once a capital stock becomes vintage, it can only have a remained lifespan of 20 years. While this might be a reasonable assumption for some sectors, for others this treatment fails to capture roles of much older capital stocks, which have been in service since decades ago (see Section 4 for an example). Therefore, we now consider the case where part of the vintage capital can survive beyond 20 years. Next, in the previous EPPA, we assume once the capital stock becomes vintage, it continues to depreciate within each period. The issue of this setting is that we apply the notion of economic depreciation, which results from the reduced lifespan rather than decreased productivity, on each following vintage capital stock ($V_{2,t+1}$, $V_{3,t+2}$, $V_{4,t+3}$). However, that would physically depreciate the vintage capital stocks at a stage where their productivity levels are unchanged and therefore, result in over depreciation. To account for these considerations, in EPPA6-L, we only depreciate the vintage capital stock older than 20 years old:

$$V_{2,t+1} = V_{1,t};\ V_{3,t+2} = V_{2,t+1};\ V_{4,t+3} = V_{3,t+2} + (1-\delta)^5 V_{4,t+2} \tag{9}$$

In the above setting, $V_{4,t+3}$ comes not only from $V_{3,t+2}$ but also from $(1-\delta)^5 V_{4,t+2}$, which is the survived vintage capital beyond 20 years old, i.e., $V_{4,t+3}$ represents the sum of vintage capital stocks that are at least 20 years old. With this setting, the roles of remained vintage stocks from decades ago are always considered without the need to create more vintage capital types for later years, which could significantly add the level of model complexity, i.e., in any given period t, there are always only four classes of vintage capital $V_{1,t}$, $V_{2,t}$, $V_{3,t}$, and $V_{4,t}$. **Figure 1** demonstrates the dynamics for capital stock evolution presented in (7), (8), and (9) graphically. To better illustrate the idea, we put “model year” and “vintage year” as the vertical and horizontal axes, respectively, with the former denoting the time period of the model and the latter representing the year when the vintage capital is formed. Therefore, $V_{3,2020}$ for the model year of 2020 was formed in the year 2010. The fact that $V_{4,2025}$ comes from both $V_{3,2020}$ and the survived $V_{4,2020}$ gives an example for the formulation of (9). Vintage capital $V_{n,t}$ is sector specific, and while factor substitution in response to change in relative price is possible for the malleable portion, it is not the case for the non-malleable one.

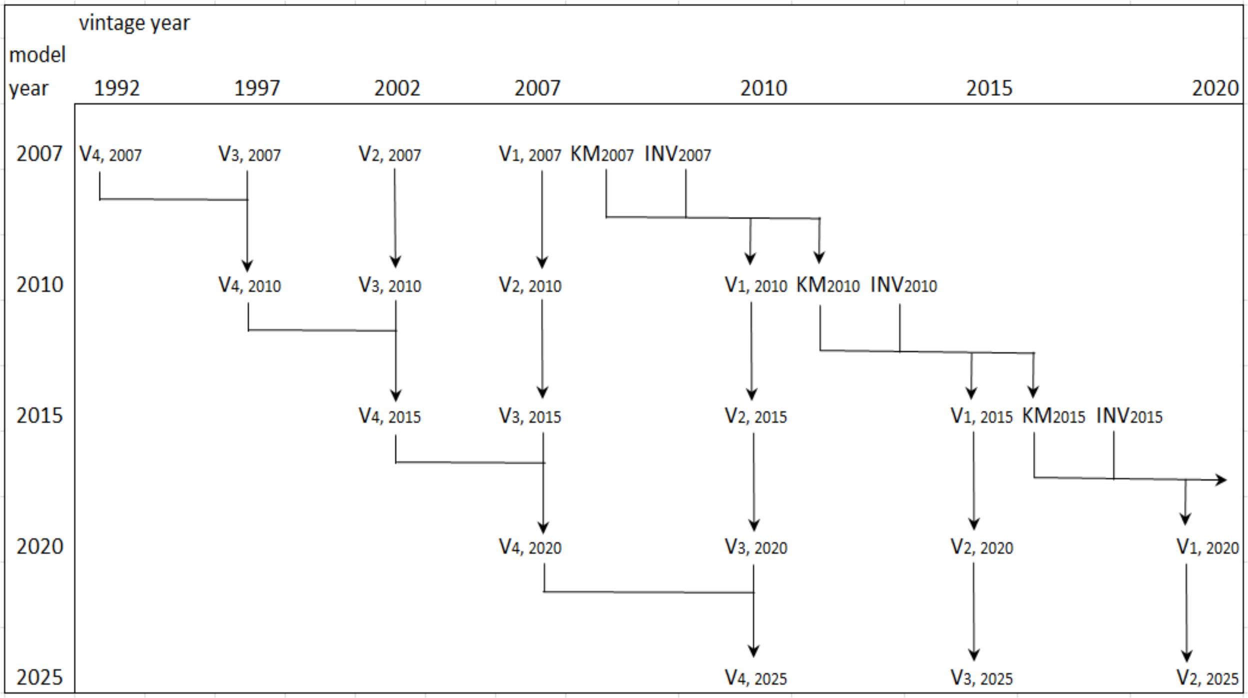

Figure 1. Dynamics for Capital Stock Evolution

In addition, to capture the long-run dynamics of fossil fuel prices, fossil fuel resources $R_{e,t}$ are subject to depletion based on their annual production levels $F_{e,t}$ at period t. Values of $F_{e,t}$ are then multiplied by a factor of five to approximate depletion in intervening years, as EPPA6-L is solved on a five-year time step:

$$R_{e,\,t+1} = R_{e,t} - 5F_{e,t} \tag{10}$$

2.3 Regions, Sectors, and Backstop Technologies

EPPA6-L disaggregates the global economy into 18 regions, including the United States (USA), Canada (CAN), Mexico (MEX), Japan (JPN), Australia-New Zealand-Oceania (ANZ), Europe (EUR), Eastern Europe (ROE), Russia (RUS), East Asia (ASI), South Korea (KOR), Indonesia (IDZ), China (CHN), India (IND), Brazil (BRA), Africa (AFR), Middle East (MES), Latin America (LAM), and Rest of Asia (REA). As shown in **Table 1**, while most of the regions are the same as its predecessor, EPPA6-L separates South Korea and Indonesia from the more aggregated ASI region of EPPA5, and identifies these two countries explicitly to reflect the increasing importance of their economic activities and GHGs emissions in the global economy. Per sectors of the model, the only change in EPPA6-L is that we separate dwelling from EPPA5's other sector, as shown in **Table 2**. With this treatment, we are able to better represent household's energy consumption for heating or cooling.

In addition, based on engineering data (see Section 4 for details), we also consider "backstop technologies" that are new or alternative technology options not presented in GTAP8, as shown in **Table 3**. To produce the same outputs as those from current technologies, backstop technologies are usually more expensive to operate in the base year. Because of this, most backstop technologies have not been operated at all or run at commercial scales so far, but they may become economic in the future if there will be higher fossil fuel prices or policy interventions, etc. The MCP formulation presented in Section 2 is by natural a powerful tool that allows no output from a backstop technology if it is not economic to operate. Under this framework, modelers do not have to assign a very small positive initial output to a backstop technology that is still not economic, a strategy used by some CGE models that unavoidably creates imbalances in SAM. Note that some backstop technologies in Table 3 have been run at nontrivial scales since 2007 mostly due to incentives or support provided by the government. These technologies include wind power, solar power, first generation biofuels, and bio-electricity. We calibrate the model so for historical runs (years 2007 and 2010), the output levels of these technologies match those of the World Energy Outlook from the International Energy Agency (IEA, 2012).

Table 1. Regions in EPPA6-L

EPPA6-L		EPPA5
USA	United States	USA
CAN	Canada	CAN
MEX	Mexico	MEX
JPN	Japan	JPN
ANZ	Australia, New Zealand & Oceania	ANZ
EUR	European Union+[4]	EUR
ROE	Eastern Europe	ROE
RUS	Russia Plus	RUS
ASI	East Asia	ASI
KOR	South Korea	
IDZ	Indonesia	
CHN	China	CHN
IND	India	IND
BRA	Brazil	BRA
AFR	Africa	AFR
MES	Middle East	MES
LAM	Latin America	LAM
REA	Rest of Asia	REA

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[4] The European Union (EU-27) plus Norway, Switzerland, Iceland, and Liechtenstein.

Table 2. Sectors in EPPA6-L

EPPA6-L		EPPA5
CROP	Agriculture - crops	CROP
LIVE	Agriculture - livestock	LIVE
FORS	Agriculture - forestry	FORS
FOOD	Food products	FOOD
COAL	Coal	COAL
OIL	Crude Oil	OIL
ROIL	Refined Oil	ROIL
GAS	Gas	GAS
ELEC	Electricity	ELEC
EINT	Energy-intensive Industries	EINT
OTHR	Other Industries	OTHR
DWE	Ownership of dwellings	-
SERV	Services	SERV
TRAN	Transport	TRAN

Table 3. Backstop Technologies in EPPA6-L

EPPA6-L	
bio-fg	First generation biofuels
bio-oil	Second generation biofuels
synf-oil	Oil shale
synf-gas	Synthetic gas from coal
h2	Hydrogen
adv-nucl	Advanced nuclear
igcap	IGCC w/ CCS
ngcc	NGCC
ngcap	NGCC w/ CCS
wind	Wind
bioelec	Bio-electricity
windbio	Wind power combined with bio-electricity
windgas	Wind power combined with gas-fired power
solar	Solar generation

2.4 Modeling Penetrations of Backstop Technologies

To model the penetration of a backstop technology, previous versions of EPPA have adopted a “technology-specific factor” that is required to operate the backstop technology but may only be available in limited supply especially when the technology is in its earlier stage of introduction. The resource rent of the technology-specific factor goes to the representative household, which is the owner of that factor.

To parameterize the supply of a technology-specific factor turns out to be challenging as very often those backstop technologies we wish to model have not entered the market. Recent work by Morris et al. (2014) provides a theoretical framework to improve the representation for the backstop penetration. The study points out while various factors may contribute to the gradual penetration of a new technology, identifying these factors explicitly and model them separately turn out quite tricky. Thus Morris et al. seeks a simpler formulation that can be parameterized based on observations, and can capture elements of rent and real cost increases due to a policy-induced high demand.

In short, Morris et al. argues that when demand for the output of the backstop technology increases over time, the investment for operating the backstop technology goes up, and so does the supply of technology-specific factor, which may eventually become a nonbinding input for the operation of the backstop technology. The study parameterizes the technology-specific factor supply by the analogue of the nuclear power expansion in the U.S. from its introduction in the late 1960's to the mid-80's when further expansion was hindered by nuclear safety concerns.

More specifically, the study argues that during that period when nuclear power was expanding, it was usually regarded as the next generation technology poised to take over most the base load generation, and therefore the experience of nuclear power expansion may provide a good approximation for representing the expansions of other new technologies. Thus, to model the penetrations of backstop technologies in EPPA6-L, we incorporate the setting and empirical finding of Morris et al. into our model:

$$\begin{aligned} bbres_{bt,t+1} &= \alpha \cdot \left[bout_{bt,t} - (1-\delta)^5 \cdot bout_{bt,t-1}\right] \\ &\quad + \beta \cdot \left[bout_{bt,t}^2 - (1-\delta)^5 \cdot bout_{bt,t-1}^2\right] + bbres_{bt,t} \cdot (1-\delta)^5 \end{aligned} \tag{11}$$

In Equation (11), $bbres_{bt,r,t}$ is the supply of technology-specific factor for technology bt in period t, and $bout_{bt,t}$ is the output of bt in period t. The estimates from Morris et al. are $\alpha = 0.9625$ and $\beta = 1.3129 \cdot 10^{-7}$.[5] In the study Morris et al. also specifies a value of 0.3 for the benchmark substitution elasticity between the technology-specific factor and other inputs, and this is also adopted in EPPA6-L.

3. STRUCTURE

3.1 Social Accounting Matrix, Production, and Consumption

A social accounting matrix (SAM) contains the base year input-output and supply-demand structures of the economy. It provides a consistent picture of production activities, market transactions, and income-expenditure flows between different agents in the economy. As **Table 4** shows, the SAM of each region in EPPA6-L is constructed based on the "micro consistent format" presented in Rutherford (1999) so each row corresponds to a market clearing condition

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[5] The very small estimate for β suggests that the quadratic terms indeed play much less roles in the accumulation of technology-specific factor.

(Condition (2) in Section 2), each column except the last one characterizes the zero profit condition of an activity (Condition (1) in Section 2), and the last column represents the income balance condition of the economy (Condition (3) in Section 2). In Table 4, a variable in blue and italic denotes “output” of each activity, or “supply” of each market, or “endowment” of the economy (those in the last column), and that in red means “input” of each activity, or “demand” of each market. While the first row on top gives the name of each activity (Column 2 to Column 18) and the name of the representative agent (Column 19), the first column on left gives the name of the price index for each market (Row 2 to Row 22). The bottom of the first column (Row 23) is for tax collection.

More specifically, domestic production activities are presented in Columns 2–4, where $XP0$, N_E0, and H_E0 denote outputs by sectors d (all sectors except for nuclear and hydro power), n_e (nuclear power), and h_e (hydro power), respectively. $XDP0$, N_S0, and H_S0 are inputs from domestic production, $XMP0$, N_OT0, and H_OT0 are imported inputs, and these two types of inputs include both energy and non-energy inputs. Domestic produced and imported inputs are aggregated together by the Armington assumption. $LABD$, N_L0, and H_L0 are labor inputs, $KAPD$, N_K0, and H_K0 are capital inputs, and $FFACTD$, N_R0, and H_R0 are other resource inputs, respectively. When CO_2 emissions are priced, the carbon penalty will be reflected by higher prices for energy inputs. For sectors (CROP and EINT) with CO_2 emissions related to production rather than energy consumption, the carbon penalty for emission levels $OUTCO2$ becomes a necessary input. Lastly, TD, TI, and TF are taxes on output, intermediate input, and primary input, respectively.

Columns 5–7 are for activities of capital formation inv, international transportation service yt, and household transportation ($htrn$). The inputs of capital formation include $XDI0$ (domestic produced inputs) and $XMI0$ (imported inputs) with the output $INV0$, which becomes part of next period’s capital stock. The input of international transportation service is denoted by VST, while the output is $\Sigma\Sigma VST$. Household transportation $TOTTRN$ includes the service from privately owned vehicles (which needs inputs from the service sector TSE, from the other sector TOI, and from the refined oil sector TRO), and the service from the purchased transportation $PURTRN$. Taxes paid by this activity is denoted by TP. Columns 8–13 are activities for adding carbon and GHGs penalties to the consumer prices of various energy consumptions. In these columns, $EIND$, $EUSEP$, and ε are sectoral energy use without a carbon penalty, sectoral energy use with a carbon penalty, and emissions coefficient, respectively. Similarly, we have $HEFD$ and $TEFD$ for household non-transport energy use and household transport energy use, both carbon penalty excluded. $HEUSEF$ and $TEUSEF$, on the other hand, denote the same types of energy use with carbon penalty included.

Column 14–17 are activities for Armington aggregation a, trade m, total household consumption z, and welfare (utility) function w, respectively. Armington output $A0$ is the aggregation of domestic produced product $D0$ and imports $XM0$, and the latter comes from exports of other regions $WTFLOW$ plus the international transportation service $\Sigma VTWR$, which is the same as $\Sigma\Sigma VST$. Total household consumption $CONS0$ includes Armington goods (the sum of XDC (domestic produced commodities) and XMC (imported commodities), household transportation $TOTTRN$, and non-transportation energy consumption $ENCE$. Household utility $W0$ is derived from consumption $CONS0$ and saving $INV0$. The government activity $govt$ represents how the government's Armington consumption (sum of domestic produced commodities $XDG0$ and imported commodities $XMG0$) and the associated tax payment TG are converted into the government output $G0$. Column 19 is for the income balance condition of the representative household ra. The total (gross) household income is constituted of net labor income $LABOR$, net capital income $CAPITAL$, resource rents including $FFACT$, N_R, H_R, and the tax payment GRG, while the household expenditure is allocated to purchasing utility $w0$ and spending on government output GRG, which is exogenously determined since the government is treated as a passive entity in EPPA.

On the other hand, Row 2–5 are market clearing conditions for domestic production, loanable fund, international transportation, and household transportation, respectively. Row 6–12 are market clearing conditions for Armington goods, Row 13–15 are market clearing conditions for imports, total household consumption, and utility, respectively. Row 16–20 are market clearing conditions for primary factors (labor, capital, and natural resources), Row 21and Row 22 are market clearing conditions for government service and emissions constraint, respectively, and row 23 presents the resource for tax payment GRG and where it goes.

The CES production and preference structures of EPPA6-L are presented in **Figure 2** and **Figure 3**, respectively. In Figure 2, we take the fossil-based generation as an example, and show how various inputs are aggregated in a nested fashion to represent the generation technology. Components in dashed line denote separate functions. Production structures for other sectors are provided in the Appendix for interested readers. Note that while factor substitution in response to change in relative price is possible for malleable production (production activities using malleable capital), that is not the case for vintage production (production activities using non-malleable capital), i.e., in our model, for each sector, the nest structure for vintage production becomes Leontief. Figure 3 provides the setting for the utility function. In a recursive dynamic framework, savings enter the utility as they can expand the capacity of future production and eventually raise future consumption level.

	d	n_e	h_e	inv	yt	htrn	eid	eid_ ghg	efd_ ghg	tefd_ ghg	edf	tedf	a	m	z	w	govt	ra
pd	*XP0*	*N_E0*	*H_E0*		VST								D0	WTFLOW				
pinv				*INV0*												INV0		
pt					*ΣΣVST*									ΣVTWR				
ptrn						*TOTTRN*									TOTTRN			
pai_c							*EUSEP*	EUSEP										
pai_g	XDP0+ XMP0							*EUSEP*										
paf_g									*HEUSEF*						ENCE			
paf_gh						TRO				*TEUSEF*								
paf_c									HEUSEF		*HEUSEF*							
paf_ch										TEUSEF		*TEUSEF*						
pa	XDP0+ XMP0	N_S0; N_OT0	H_S0; H_OT0	XDI0+ XMI0		TOI; TSE; PURTRN	EUSEP				HEUSEF	TEUSEF	*A0*		XDC+ XMC		XDG0+ XMG0	
pm													XM0	*XM0*				
pu															*CONS0*	CONS0		
pw																*W0*		W0
pl	LABD	N_L0	H_L0															*LABOR*
pk	KAPD	N_K0	H_K0															*CAPITAL*
pf	FFACTD																	*FFACT*
pr		N_R0																*N_R*
pr_h			H_R0															*H_R*
pg																	*G0*	-GRG
pcarb	OUTCO2						EIND*ε				HEFD*ε	TEFD*ε						*CARBLIM*
TAX	TD;TI;TF	TD;TI;TF	TD;TI;TF			TP								TX; TM	TP		TG	*GRG*

Table 4. Social Accounting Matrix of EPPA6-L[6]

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[6] Variables in blue and italic denote output, supply, or endowment, and variables in red denote input or demand.

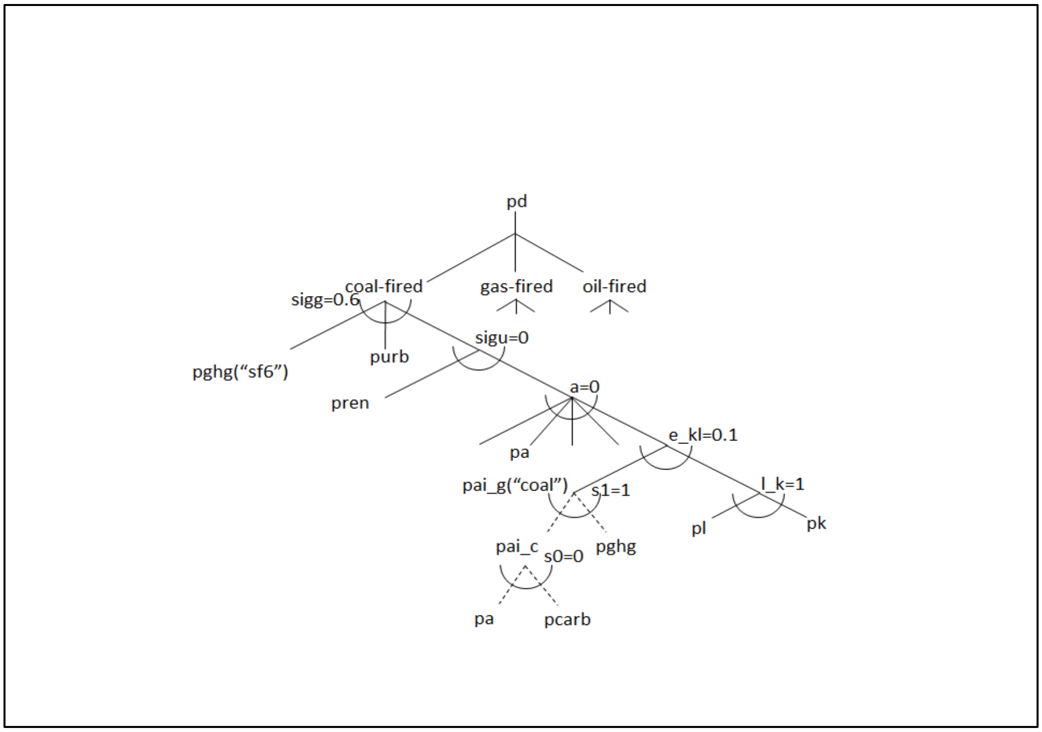

Figure 2. Production Structure for Fossil-based Generation

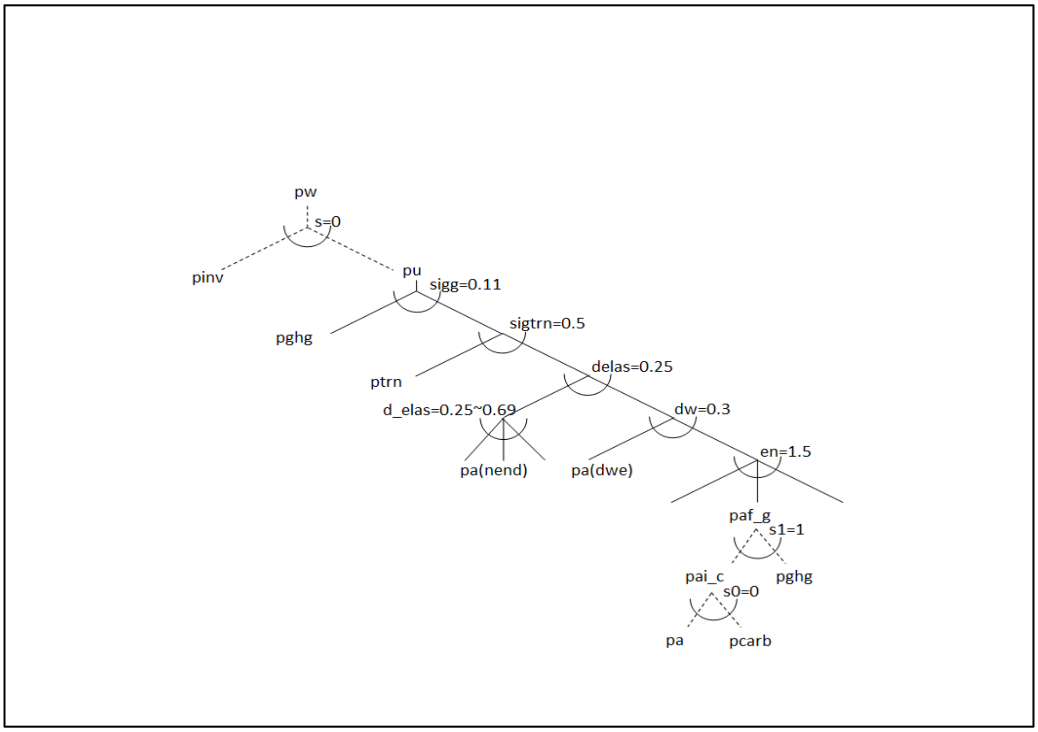

Figure 3. Utility Function

3.2 Other Improvements

In addition to new features documented in Section 2, many improvements of EPPA6-L over the earlier EPPA are under the hood at the implementation levels. Among them are:

1) Simplified model structure:
   We eliminate separated but mostly repeated codes related to the reference and policy runs. Since EPPA6-L will be used extensively with different enhancements, simplifying codes can reduce chances of making programming errors in future model development.
2) Endogenously calibrated Hick's neutral productivity levels:
   In EPPA6-L, modelers only need to specify the BAU GDP growth rates in the reference run, and let the model calculate the implied Hick's neutral productivity levels automatically. After the productivity levels are calculated, for the same reference scenario, the model will replicate the same GDP growth patterns under the given productivity levels. In the past, updating the BAU GDP growth assumption has to be done manually by changing the productivity levels iteratively, which is much less efficient. The new feature greatly facilitates studies such as conducting the sensitivity analysis with various GDP growth scenarios.
3) Explicit treatment for value-added taxes:
   In earlier versions of EPPA, no value-added taxes are presented since they are combined with the net factor income for simplicity. In EPPA6-L, net factor income and value-added taxes are separated so both are presented explicitly. This treatment facilitates studies on tax reform or double dividend issues.
4) Faster solving process:
   Solution information is saved to speed up the process of solving the model again in the future (this is done by using the "savepoint" feature of GAMS). It is worth noting that while this time-saving feature is favorable in most applications, the downside of it is that sometimes using the solution information from the previous run may actually reduce the chance of finding a solution for the current run when one changes some parameter values (such as BAU GDP growth rates) and therefore the model should find a different solution. As a result, the feature can also be turned off in cases such as performing sensitivity analyses with different parameterizations.
5) Ability to stop and restart the model at any intermediate period:
   With this feature, once the restart information is generated from running all time periods previously, one may choose to rerun the model from any intermediate period if there are no changes in the model setting for earlier periods. This feature also makes it easier for EPPA6-L to incorporate feedbacks from other models when EPPA6-L is coupled with other earth system models of IGSM.[7]

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[7] We appreciate inputs from Tom Rutherford on the third feature, and contributions by Tom Rutherford and Qudsia Ejaz on the fourth feature.

Figure 4 provides a bird's eyes view on how different modules of EPPA6-L are executed sequentially. These modules can be classified into the static module on the right (*eppaexec.gms*) and the dynamic module on the left (*eppaloop.gms*). For the static module, the main tasks include: 1) declaring set and parameters; 2) reading data (GTAP8, elasticities, backstop technologies, exogenous trends, GHGs inventories, etc.); and 3) checking accounting balances and model calibration. The core of this module is the static CGE component (*eppacore.gms*). For this component, in addition to zero profit, market clearing, and income balance conditions presented in Section 2, it also includes equations for calibrating the BAU productivity levels mentioned previously. The static component is written in MPSGE, which is a compact, non-algebraic language for building CGE models. MPSGE greatly reduces chances of making programming errors and improves productivity when one would like to change the model settings, such as revising the CES nesting structures for various activities, or making model extensions to have new backstop technologies.[8] Interested readers may refer to Rutherford (1999), Markusen and Rutherford (2004), and Markusen (2013) for details.

The dynamic module, which is written in GAMS, will perform a series of steps to implement the recursive dynamics discussed in Section 2, and these steps include 1) incorporating information about scenario settings (availability of backstop technologies, BAU or policy scenarios, etc.); 2) implementing recursive dynamics (resource evolutions, capital accumulations and vintage capital evolutions, exogenous trends, etc.); 3) solving the model; and 4) saving simulation results for each period.

Figure 5 presents details for the dynamic module. In particular, it shows that for the BAU run, productivity levels are calibrated to match the given BAU GDP projections, which will be illustrated in Section 4. For all other runs, the calculated productivity levels are exogenously given, and the GDP levels are solved endogenously. More specific, if no additional policies beyond BAU are added, with a correct calibration, the model does replicate BAU GDP levels accurately when the productivity levels calculated previously are exogenously assigned.

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[8] Working on MPSGE requires comprehensive understanding of economic theories, mixed complementarity problems, and the language itself. Otherwise it may cost one enormous amount of time before getting something meaningful.

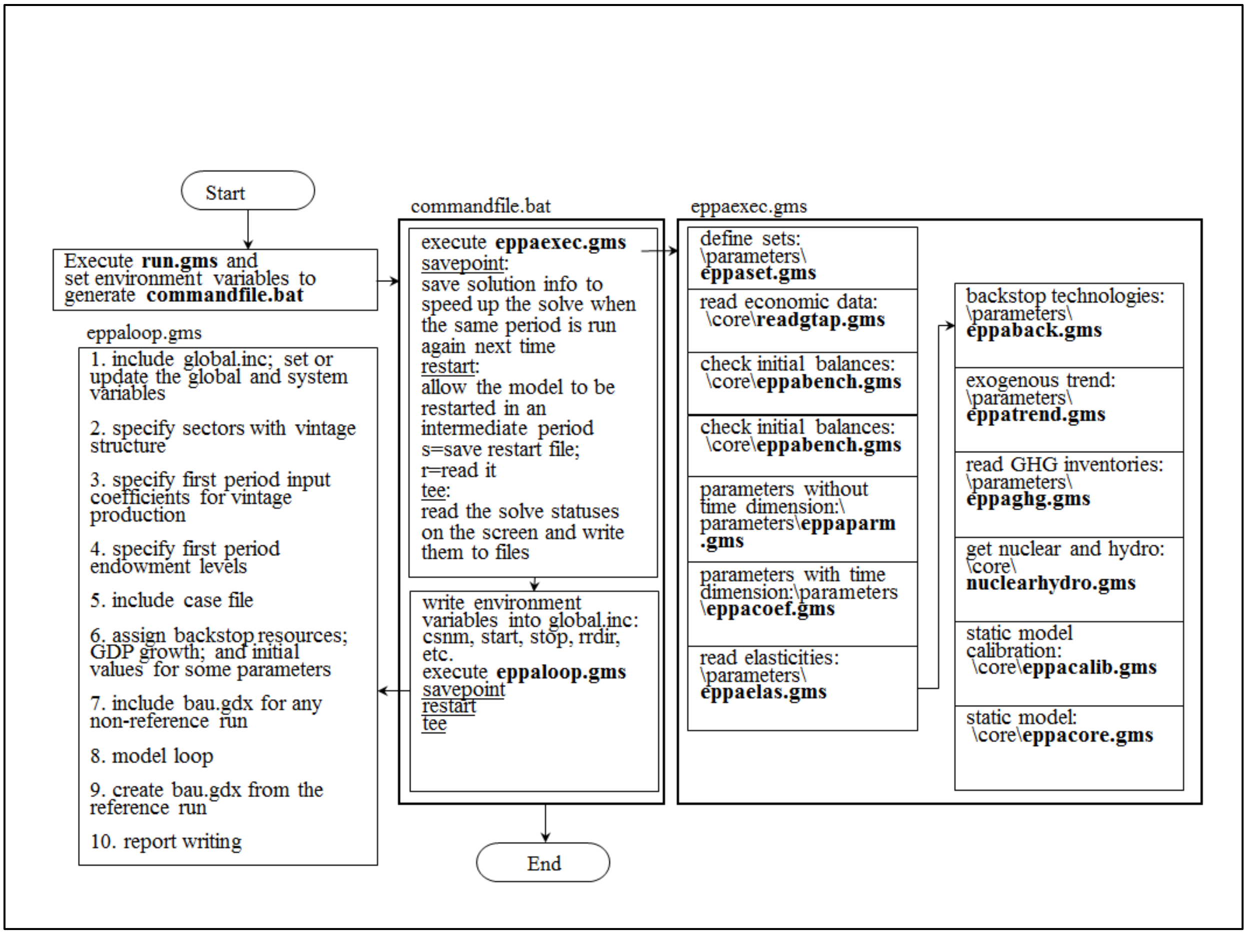

Figure 4. Model Structure: Flow Chart for Running EPPA6-L

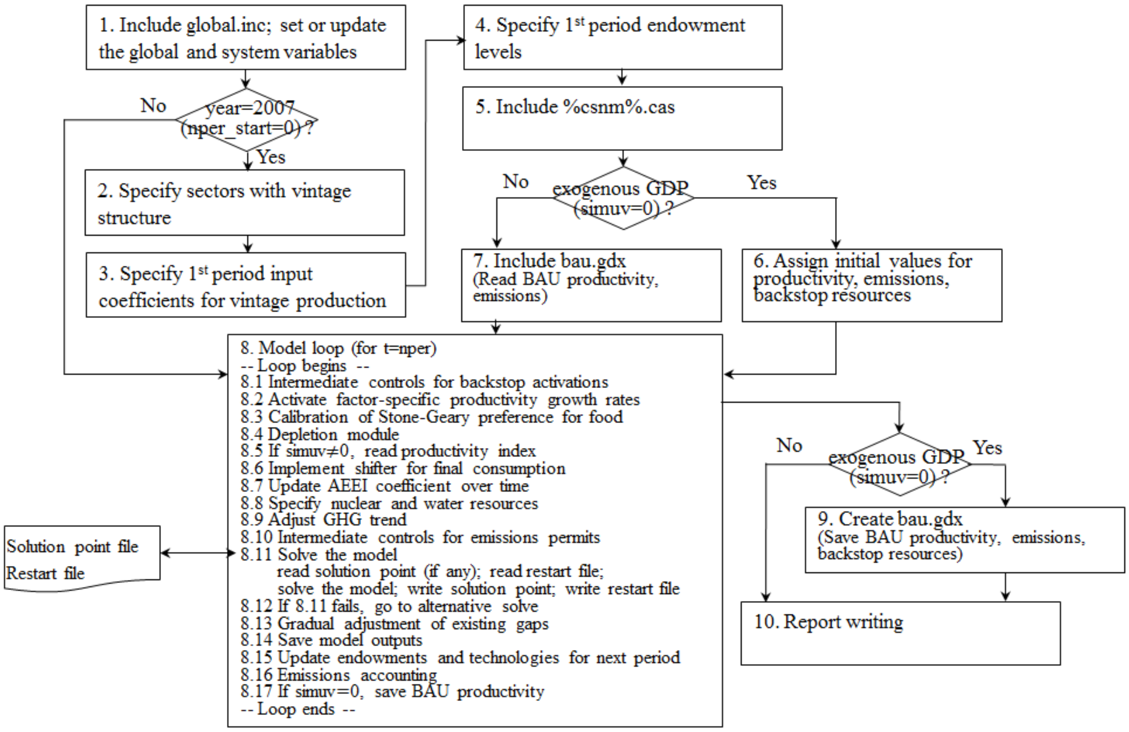

Figure 5. Model Structure: Recursive Dynamics Component

4. DATA

4.1 Economics

The main economic data used in EPPA6-L is GTAP8, the latest GTAP database with the base year 2007. GTAP8 classifies the global economy into 129 regions, 57 sectors (commodities) and 5 types of production factors (GTAP, 2013). For each region, the database provides information such as bilateral trade and input-output structure of each sector, which are key inputs for a global CGE model. While the original GTAP8 data are at a lower level of aggregation, for efficiency and feasibility considerations, global CGE models are often run at more aggregated levels. EPPA6-L aggregates the GTAP8 regions, sectors, and production factors into 18 regions (see Table 1), 14 sectors (see Table 2), and 4 factors (labor, capital, land, and natural resources). The mapping details for regions, sectors, and production factors from GTAP8 to EPPA6-L are provided in Table A1 to Table A3 in the Appendix.

In a CES function, the elasticity of substitution specifies to what extent one input can be substituted for by others under a given level of output when the relative price of inputs changes. For instance, the Armington aggregation for imported and domestic products uses a CES function, and the elasticity of substitution between domestic and imported products controls the degree to which different products differ. In a production activity that uses fossil fuel and others as inputs, the substitution elasticity between fossil fuel and other inputs determines to what level the fossil fuel use can be replaced by other inputs if the price of fossil fuel increases. Similarly, the elasticity of substitution in a utility function characterizes consumer preference, i.e., the substitution possibility between various consumption goods when facing a price change. As shown in **Table 5**, EPPA6-L draws the elasticities of substitution from its predecessor. The elasticity values are based on literature review and expert elicitation conducted by Cossa (2004). While sensitivity analyses using various elasticity values have been conducted extensively by using earlier versions of EPPA (Cossa, 2004; Webster et al., 2002), in this study, we will take the substitution elasticity between energy and non-energy inputs as an example, and demonstrate how sensitive CO_2 emissions and prices are affected by different elasticity levels.

For a dynamic CGE applied on long-term projections, the inter-temporal calibration of regional BAU GDP growth is crucial yet challenging due to factors that subject to uncertainty. For this work, our first step is to incorporate the GDP growth projections presented by the World Economic Outlook (IMF, 2013) up to 2018, the last projection year of that database when this study is conducted. For later years, while the projections of Paltsev et al. (2005) is our starting point, we carefully adjust the regional GDP growth rates to incorporate the latest prospects for long-term economic growth from recent studies, including the World Bank (2013), the United Nations (2012), Gordon (2012), and Empresa de Pesquisa Energética (EPE) (2007). For instance, we raise Africa’s BAU GDP growth projection beyond 2020 to take into account the increased population growth projection published by the United Nations. Lastly, we incorporate into our model the income elasticity estimates for the final consumption levels of CROP, LIVE, and FOOD based on Reimer and Hertel (2004), which was the estimation for An Implicit Direct Additive Demand System (AIDADS). Since the study of Reimer and Hertel was conducted before the base year of our model, In **Table 6**, we readjust those elasticities, which are functions of income and price levels presented in Reimer and Hertel’s study, to account for changes in economic environment.[9]

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[9] Reimer and Hertel (2004) uses the GTAP5 database, which has the base year of 1997.

Table 5. Substitution Elasticities in EPPA6-L

Type of substitution elasticity	Notation	Value
between domestic and imported goods	sdm	1.0–3.0
between imported goods	smm	0.5–5.0
between energy and non-energy (labor-capital bundle) inputs	e_kl	0.6–1.0
between labor and capital	l_k	1.0
between electricity and fossil energy bundle for the aggregated energy	noe_el	0.5
between fossil energy inputs for the fossil energy bundle	esube	1.0
between conventional fossil generations	enesta	1.5
between natural resource and other inputs	esup	0.3–0.5

Source: Cossa (2004)

Table 6. Income Elasticity for Agricultural and Food Products

	CROP	LIVE	FOOD		CROP	LIVE	FOOD
USA	0.08	0.65	0.67	CHN	0.65	1.01	0.88
CAN	0.13	0.61	0.62	IND	0.58	1.11	0.88
MEX	0.50	0.71	0.70	BRA	0.58	0.78	0.75
JPN	0.18	0.60	0.61	AFR	0.63	1.05	0.89
ANZ	0.22	0.59	0.60	MES	0.63	0.83	0.80
EUR	0.16	0.60	0.61	LAM	0.63	0.82	0.79
ROE	0.63	0.82	0.79	REA	0.54	1.16	0.87
RUS	0.56	0.76	0.74	KOR	0.30	0.61	0.61
ASI	0.64	0.86	0.81	IDZ	0.67	1.00	0.88

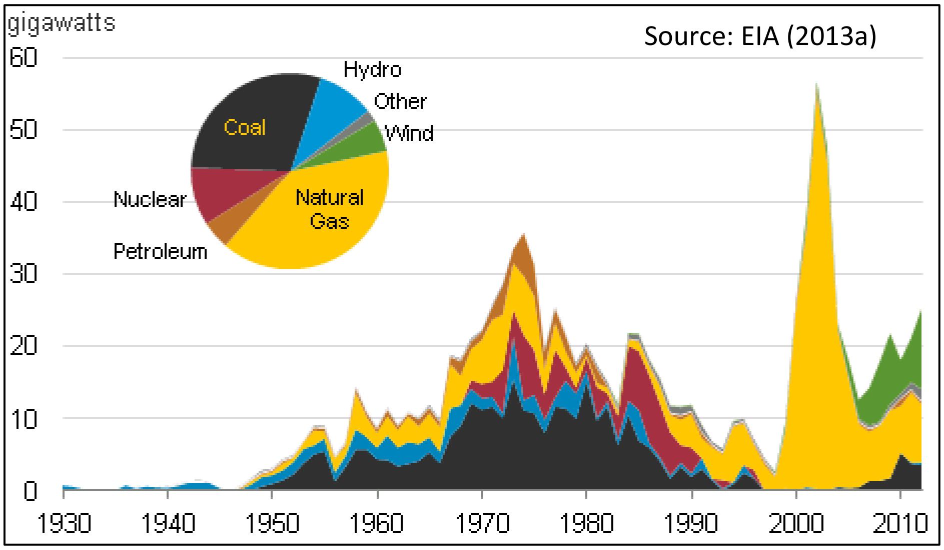
Source: Reimer and Hertel (2004); with adjustments for changes in prices and income levels

4.2 Backstop Technologies

As in previous versions of EPPA, for each backstop technology, we use the "markup" factor to characterize the economics of that technology in the base year. The markup is defined as the ratio of the backstop technology's production cost over that of the current technology that produces the same product. For instance, a markup value of 1.2 means that in the base year, the backstop technology is 20% more expensive to operate than the current technology is. Markups are derived from the engineering data for backstop technologies. For non-power sector backstop technologies (oil shale, synthetic gas from coal, hydrogen, first generation biofuels, second generation biofuels), the markups are derived from Gitiaux et al. (2012) and the previous version of EPPA with price adjustments.

Before discussing the markups for power sector backstop technologies, it is worth noting that power plants in duty are often built decades ago. Taking the power sector in the U.S. for instance, around three quarter of the coal-fired capacity has been in operation for at least 30 years (EIA, 2013), as shown in **Figure 6**. In terms of the levelized cost, the existing coal-fired power plants may be cheaper to operate than those that will adopt the newest designs since in the earlier years, it was easier and faster to get the coal-fired power projects approved due to less environmental considerations, and the emissions standards may be less stringent as well. In the earlier versions of EPPA, markups for power sector backstop technologies are derived by comparing the levelized costs of backstop technologies to that of a planned newest coal-fired power unit, which is likely more expensive to operate than existing coal-fired power plants. Previous versions of EPPA does not consider the potential cost difference between the newest coal fire unit and the existing one, and this suggests that in earlier versions of EPPA, markups for power sector backstop technologies could be underestimated.

To account for this, for power sector backstop technologies (see Table 3 in Section 2 for details), instead of benchmarking on a new coal-fired power unit, we calculate their markups based on the existing coal-fired power plant. To represent the levelized cost of electricity generation for an existing "average" coal-fired power plant, we use the overnight capital cost data from Bechtel Power Corporation (1981). While to represent the base year situation, all costs (levelized capital cost, operating and maintenance (O&M) cost, and fuel costs) are adjusted to the 2007 price levels, we use a seven-year average of fuel costs based on EIA (2013a) to avoid the short-term fluctuation of energy prices. As the third column of **Table 7** shows, in terms of the levelized cost, a new coal-fired unit is around 8% more expensive to operate compared to the existing unit. Markups for different power sector backstop technologies are also presented in that table. The markup and cost structure of each technology are used to calibrate the cost function of that technology, and through the zero-profit condition presented in Section 2, the output level of that technology can be determined.



Source: EIA (2013a)

Figure 6. Power sector capacity in the U.S.

Table 7. Markups for Power Sector Backstop Technologies

	Pulverized Coal built in 1980	New Pulverized Coal	NGCC	NGCC with CCS	IGCC with CCS	Advanced Nuclear (EIA Numbers)	Wind	Biomass	Solar Thermal	Solar PV	Wind Plus Biomass Backup	Wind Plus NGCC Backup
"Overnight" Capital Cost ($/KW)	1775	2196	956	1909	3731	3774	1942	3803	5070	6097	5745	2899
Total Capital Requirement ($/KW)	2059	2548	1033	2138	4477	5284	2098	4411	5476	6584	6205	3131
Capital Recovery Charge Rate (%)	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%
Fixed O&M ($/KW)	27.81	27.81	11.82	20.11	46.58	90.93	30.61	65.03	57.30	11.79	95.64	42.42
Variable O&M ($/KWh)	0.005	0.005	0.002	0.003	0.004	0.001	0.000	0.007	0.000	0.000	0.007	0.002
Project Life (years)	20	20	20	20	20	20	20	20	20	20	20	20
Capacity Factor (%)	85%	85%	85%	80%	80%	85%	35%	80%	35%	26%	42%	42%
(Capacity Factor Wind)											35%	35%
(Capacity Factor Biomass/NGCC)											7%	7%
Operating Hours	7446	7446	7446	7008	7008	7446	3066	7008	3066	2278	3679	3679
Capital Recovery Required ($/KWh)	0.0292	0.0362	0.0147	0.0322	0.0675	0.0750	0.0723	0.0665	0.1887	0.3055	0.1782	0.0899
Fixed O&M Recovery Required ($/KWh)	0.0037	0.0037	0.0016	0.0029	0.0066	0.0122	0.0100	0.0093	0.0187	0.0052	0.0260	0.0115
Heat Rate (BTU/KWh)	8740	8740	6333	7493	8307	10488	0	7765	0	0	7765	6333
Fuel Cost ($/MMBTU)	3.15	3.15	8.18	8.18	3.15	0.50	0.00	2.61	0.00	0.00	2.61	8.18
Fraction Biomass/NGCC (%)											8.8%	8.2%
Fuel Cost ($/KWh)	0.03	0.03	0.05	0.06	0.03	0.01	0.00	0.02	0.00	0.00	0.00	0.00
Levelized Cost of Electricity ($/KWh)	0.07	0.07	0.07	0.10	0.11	0.09	0.08	0.10	0.21	0.31	0.21	0.11
Transmission and Distribution ($/KWh)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03
Cost of Electricity ($/KWh)	0.09	0.09	0.09	0.12	0.13	0.11	0.10	0.12	0.23	0.33	0.24	0.14
Markup Over New Pulverized Coal	0.92	1.00	0.98	1.34	1.43	1.23	1.11	1.33	2.47	3.59	2.64	1.50
Markup Over Coal built in 1980	1.00	1.08	1.06	1.44	1.55	1.33	1.20	1.44	2.67	3.89	2.85	1.62

4.3 Energy Use and Emissions

While GTAP8 has included energy use data from IEA (Narayanan et al., 2012), to incorporate IEA's latest updates, we recalibrate the historical energy use in the model based on the World Energy Outlook (IEA, 2012a). We also use IEA's data of combusted CO_2 emissions associated with energy consumption (IEA, 2012b). For CO_2 emissions related to cement production, which accounts for around 4.5% of world's non-land-use-related CO_2 emissions, we draw the data from Boden et al. (2010). In EPPA6-L, CO_2 emissions related to land-use change are exogenously assigned based on the RCP8.5 scenario developed by Riahi et al. (2007) and presented by the Intergovernmental Panel on Climate Change (IPCC).

EPPA6-L also considers non-CO_2 GHGs emissions and urban pollutants emissions. The non-CO_2 GHGs included in the model are: methane (CH_4), perfluorocarbon (PFC), sulfur hexafluoride (SF_6), and hydrofluorocarbon (HFC), and the urban pollutants considered are carbon monoxide (CO), volatile organic compound (VOC), nitric oxide and nitrogen dioxide (NO_x), sulfur dioxide (SO_2), black carbon (BC), organic carbon (OC), and ammonia (NH_3). Most of the base year non-CO_2 GHGs and urban pollutants are drawn from the Emissions Database for Global Atmospheric Research (EDGAR) Version 4.2 (European Commission, 2013).[10] Two exceptions are BC and OC, which are based on Tami Bond (2000).

For later years, energy use levels are determined endogenously by factors such as the patterns of economic growth, technological change (both AEEI and price-driven), and relevant energy or emissions policies. In EPPA6-L, we consider the case of no AEEI trend in refined oil sector, a 1% per year of AEEI improvement for all other sectors except for the power sector. We assume a 0.3% per year of AEEI improvement for power sector as previous EPPA, which leads to an efficiency of conversion from fuels to electricity that approaches 0.5 by the end of the century in the BAU scenario. Energy use levels will also determine the remained fossil fuel reserves. In EPPA6-L, while estimates for oil and gas reserves are from the U.S. Geological Survey as the previous version of EPPA, we also incorporate into the model the revised outlook for the growing output of shale gas production due to the technology break through that makes more shale resources available (EIA, 2013). Estimates for coal reserves, on the other hand, are from the World Energy Council. Interested readers may refer to the details in Paltsev et al. (2005).

5. REFERENCE AND POLICY SIMULATIONS

In EPPA6-L, the regional BAU GDP growth projections have been revised, and the changes will in turn affect the CO_2 emissions through energy consumption, which will be illustrated in this section. Since the introduction of Stone-Geary preference on food consumption is new to the model, we compare results between food consumption levels with the Stone-Geary preference and those without that. Lastly, we provide sensitivity analyses on CO_2 emissions and CO_2 prices under various growth assumptions, AEEI levels, and elasticities of substation between energy use and capital-labor bundle.

5.1 Economic Growth

Based on the regional GDP projections presented in IMF's World Economic Outlook (see Section 3 for details), regional GDP growth rates are in general higher than the EPPA5 numbers before 2020, and therefore, the global GDP growth projections for the next decades are increased, as shown in **Figure 7(a)**. For years around the middle of the century, projections for the global GDP growth rates are somewhat lower than those of EPPA5 due to reduced GDP growth projections for developed regions, including USA and EUR, and for the last half of the 21st century, the global GDP growth rates eventually approximate EPPA5's levels because of the higher growth in AFR. Under the new projection, the global GDP level for 2020 is 1.8% higher than that of EPPA5, and the levels for 2050 and 2100 are 1.0% and 4.2% lower than those of EPPA5, respectively, as shown in **Figure 7(b)**. Overall, compared to EPPA5, while regional

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[10] We would like to thank Kyung-min Nam and Anna Agarwal for preparing the data.

GDP projections are revised, EPPA6-L does not have a much different view in terms of the global GDP growth.

Note that the BAU GDP growth of EPPA6-L is calibrated to the scenario where in USA and EUR, expansions of coal-fired power are limited and as a result, coal-fired power outputs will not exceed their 2010 levels. This is different from EPPA5, where the BAU GDP growth is mapped to an unlimited coal-fired power expansion for all regions. The treatment for coal-fired power in EPPA6-L is pretty much in line with the BAU projections of IEA (2012) and EIA (2013b), and we believe it better represents the reality.

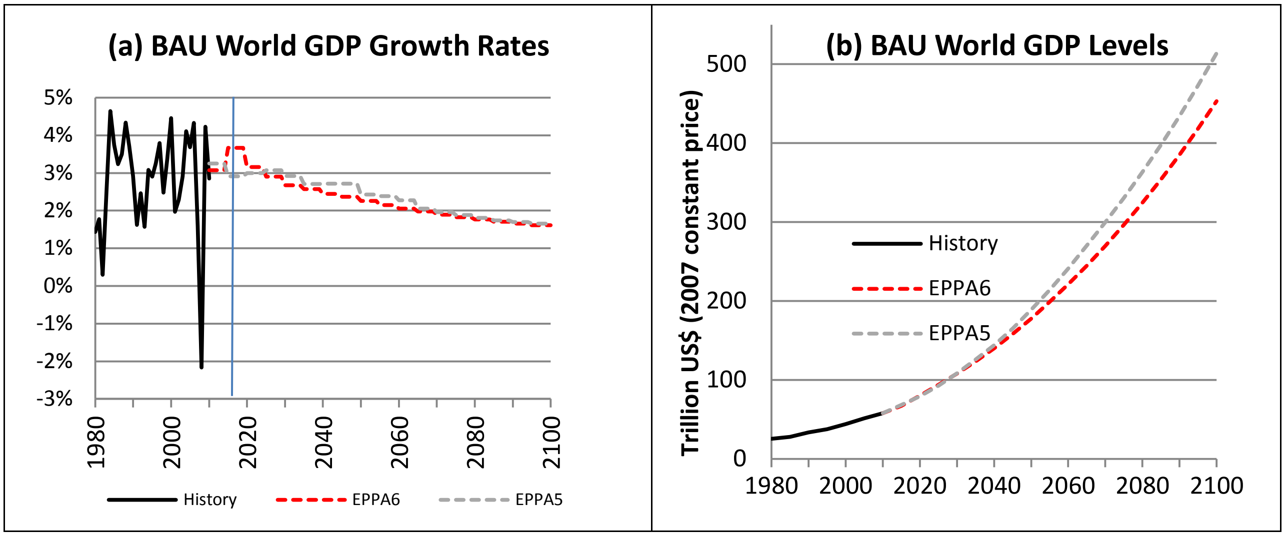

Figure 7. BAU World GDP Growth Projection

5.2 GDP and Energy Use

Let us consider a sample policy that, for each region, uses a carbon tax to cut combusted CO_2 emissions to half of the 2000 levels by 2050, and then stay at the 2050 levels up to 2100. The policy begins from 2015 onward and the targets before 2050 are linearly interpolated. Compared to the stylized 550 ppm stabilization policy presented in Paltsev et al. (2005), the sample policy we consider is much more stringent.[11] While the policy may look quite ambitious and politically hard to achieve in reality, testing the more extreme scenario can let us examine the model performance in terms of solvability. If the model solves under this extreme case, finding solutions for less stringent targets are usually less of a problem. The simulation results are presented in **Figure 8**, which shows that the sample policy would induce a 12%–14% reduction in GDP per period from 2050 onward. A caveat for the exercise is that simulations for policy impact, by nature, may vary due to factors such as the uncertainties in BAU long-term productivity growth (which in turns affects the economic growth), technology advancement, etc.

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[11] See Figure 19 in Paltsev et al. (2005).

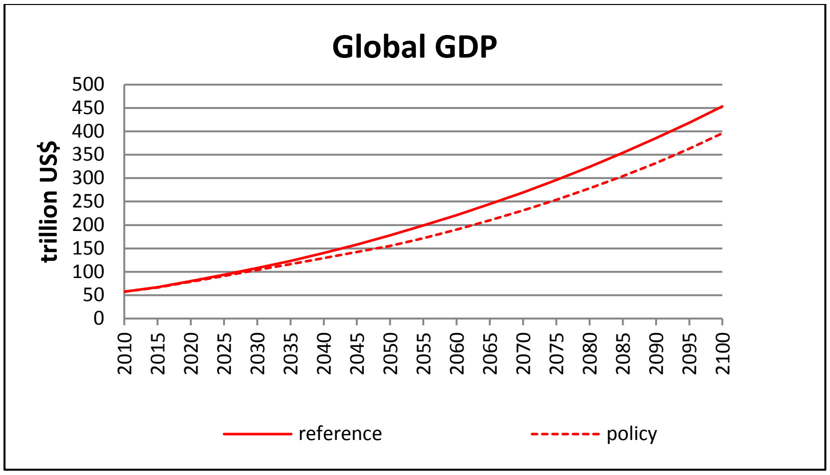

Figure 8. Global GDP: BAU vs. Policy

Since energy use patterns are closely related to emissions, we present model outputs for total primary energy demand (TPED) levels in **Figure 9(a)** (for the BAU case) and **Figure 9(b)** (for the policy case). For the BAU simulation, compared to the 2010 level, the global GDP level increases by almost 7 times (from around $58 trillion to $453 trillion in 2007 US dollar) by the end of the 21st century. The global TPED increases at a much slower pace by 137% (from 496 EJ in 2010 to 1176 EJ in 2100) due to energy efficiency improvement and changes in industrial structure. Nevertheless, the projection shows that the global economy during the same period will continue to rely heavily on fossil fuels with an increasing share of gas (23% to 30%) and decreasing shares of coal (29% to 23%), while the share of oil remains almost unchanged (34% to 33%). Overall, the share of fossil fuels decreases slightly (87% to 85%). Under this scenario, the roles of hydro, biofuels, and other renewables (wind and solar) do not change much over time, but the simulation finds a rising share of nuclear power (4% to 7%).

With the sample policy, results shown in Figure 9(b) suggest that a drastic cut in fossil fuels consumption is needed to achieve the policy goal (from 432 EJ in 2010 to 186 EJ in 2100). Under this scenario, as expected, the roles of hydro, biofuels, and other renewables become more important, with the sum of shares rising from about 8% in 2010 to 35% in 2100. Additionally, the share of nuclear power also increases up to 22% in 2100 from around 4% in 2010.

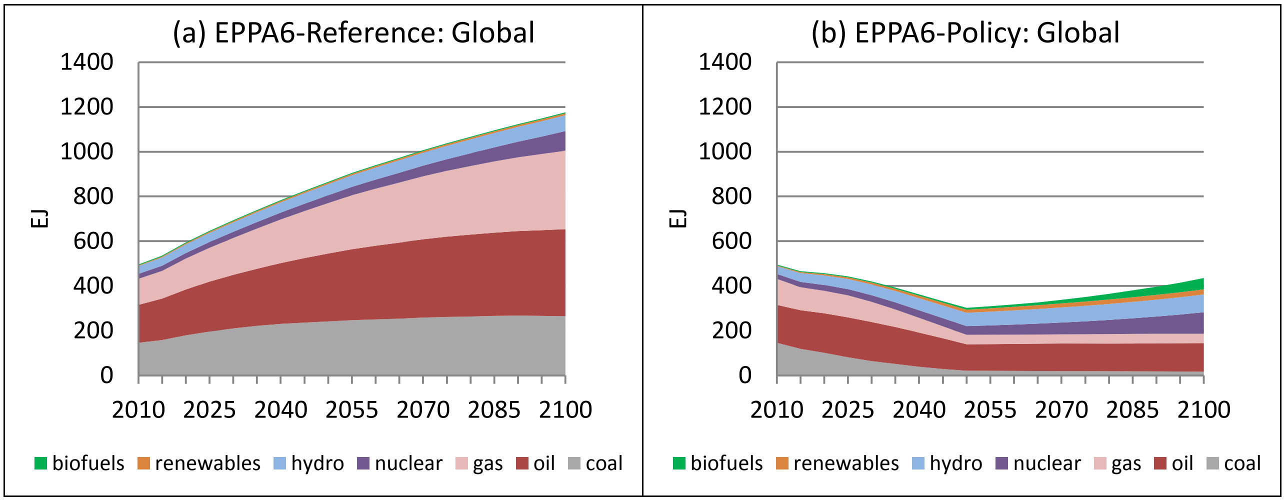

Figure 9. Total Primary Energy Demand: BAU vs. Policy

5.3 Emissions

Figure 10(a) presents the BAU combusted CO_2 emissions of EPPA6-L. The emissions, which increase by 123% by 2100 compared to the 2010 levels, are directly related to the consumption of fossil fuels that increases by 133% during the same period. The slightly slower growth path of the emissions is a result of the moderate shift from coal to gas, as discussed previously.

Figure 10(b) presents the comparison of projections for the BAU combusted CO_2 emissions between EPPA6-L and EPPA5. Over the century, EPPA6-L has a slightly lower emissions projection due to lower global GDP levels. By 2100, the gap between emissions projections of the two models reaches the maximum–emissions projection of EPPA6-L is roughly 6% lower than the EPPA5 number for that year. Figure 10(b) decomposes the gap. In short, changes in several key assumptions that may account for the gap are: 1) BAU GDP growth assumption; 2) markup factor for coal-fired power; and 3) the caps that limit the coal-fired power capacities in USA and EUR at their 2010 levels. The decomposition shows that, if we keep these assumptions the same between EPPA6-L and EPPA5, the emissions difference is relatively small (comparing cases B and A in Figure 10). One major factor that is responsible for the projection difference is the revised GDP growth assumption of EPPA6-L (comparing cases C and B), and while incorporating the markup on coal-fired power only slightly lowers the projection (comparing cases D and C), capping the coal-fired capacities in USA and EUR at their 2010 levels constitutes another main reason for the projection difference (comparing cases E and D).

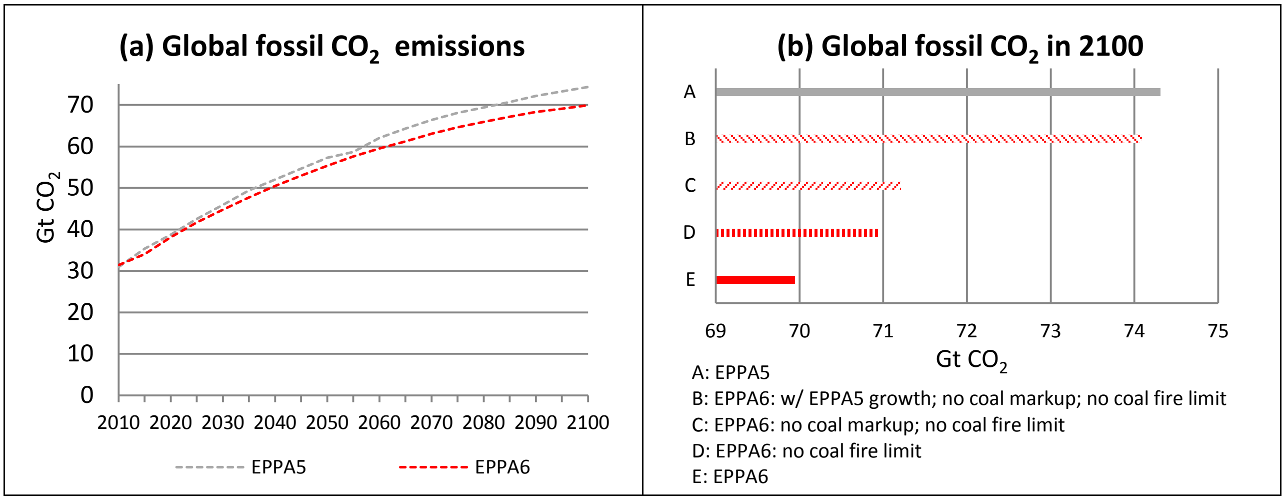

Figure 10. BAU World GDP Growth Projection

5.4 Final Consumption for Food and Agricultural Products

Consumptions for food and agricultural products are closely related to production activities of agricultural sectors (CROP and LIVE), which may induce land-use changes and result in GHGs implications. To improve our projections, we incorporate into our model the income elasticity estimates for the final consumption of CROP, LIVE, and FOOD from Reimer and Hertel. As mentioned in Section 4, the estimates have been adjusted to reflect the economic environment of our base year.

It is worth noting that, as illustrated in Section 2, since the labor endowment (and population) of the representative consumer increases over time, the representative consumer of the model is indeed an aggregated consumer, which means that, on top of the income elasticity estimates for an individual η_i presented in Equation (5), income elasticities for the model's representative consumer, denoted by η_i', should take into account the population growth. Taking total derivatives on aggregate consumption and budget to decompose changes and rearranging terms, we have:

$$\eta_i' = \frac{\eta_i \frac{dw}{w} + \frac{dpop}{pop}}{\frac{dw}{w} + \frac{dpop}{pop}} \qquad (12)$$

In Equation (12), w is the budget (see Section 2) and pop is the population index of each region with the base year level normalized to unity (the regional index is dropped for succinctness). Besides using Reimer and Hertel's income elasticity estimates, for comparison purpose, we also present results based the estimates from USDA (2013), and those with a pure CES setting. **Table 8** presents the income elasticity estimates of USDA, which are based on the International Comparison Program (ICP) data across 144 countries.[12]

Figure 11(a) to **Figure 11(i)** demonstrate the BAU projections for final consumption per capita as GDP per capita grows over time, starting from 2010 up to 2050. The results show that, with income elasticity adjustments, global food and crop consumption projections are lowered compared to those with a pure CES setting, which we believe overestimate the consumption levels as it fails to take into the empirical evidence of smaller income elasticities for food consumption. Using Reimer and Hertel's estimates, global food consumption projection in 2050 is 15% lower compared to the case with a pure CES setting. Furthermore, the projection will be more than 22% lower if the USDA data were used, as shown in Figure 11(a). Note that except for the income elasticity of crop consumption, USDA data in general have lower income elasticity numbers compared to those of Reimer and Hertel (a comparison between Table 8 and Table 6 would confirm this). On the other hand, for global crop consumption (Figure 11(b)), using the Reimer & Hertel estimates and those of USDA produce similar projections, which are around 27% lower than the pure CES projection in 2050. This comes from the fact that both studies have quite similar estimates for the income elasticities of crop consumption. Lastly, as Figure 11(c) shows, the projection for global livestock consumption based on Reimer and Hertel's estimates are very close to those with a pure CES setting, as Reimer and Hertel's income elasticity estimates for livestock products are generally higher (see Table 6 in Section 4). Using USDA's income elasticity estimates again produce lower projections (24% lower in 2050 compared to the other two cases).

Projections at the regional levels are presented for USA and CHN, as shown in Figure 11(d) though Figure 11(i). In short, comparisons can reveal that 1) income elasticities adjustments tend to lower projections for food, crop, and livestock consumption levels; 2) USA has lower growth rates for the consumption levels of these products compared to those of CHN, since USA has lower income elasticity estimates; and 3) except for crop consumption in USA, projections based on USDA estimates are lower as the underlying elasticity numbers of USDA are lower.

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[12] We approximate the elasticity levels of 2007 for our model by the USDA data, which are for the year 2005.

Table 8. Income Elasticity for Agricultural and Food Products from USDA

	CROP	LIVE	FOOD		CROP	LIVE	FOOD
USA	0.210	0.260	0.346	CHN	0.617	0.654	0.775
CAN	0.315	0.369	0.477	IND	0.621	0.660	0.782
MEX	0.440	0.506	0.646	BRA	0.517	0.571	0.704
JPN	0.324	0.380	0.492	AFR	0.561	0.622	0.752
ANZ	0.380	0.452	0.588	MES	0.456	0.534	0.666
EUR	0.283	0.385	0.503	LAM	0.501	0.562	0.699
ROE	0.488	0.563	0.697	REA	0.601	0.644	0.772
RUS	0.443	0.532	0.672	KOR	0.428	0.479	0.600
ASI	0.461	0.514	0.641	IDZ	0.572	0.621	0.757

Source: USDA (2013)

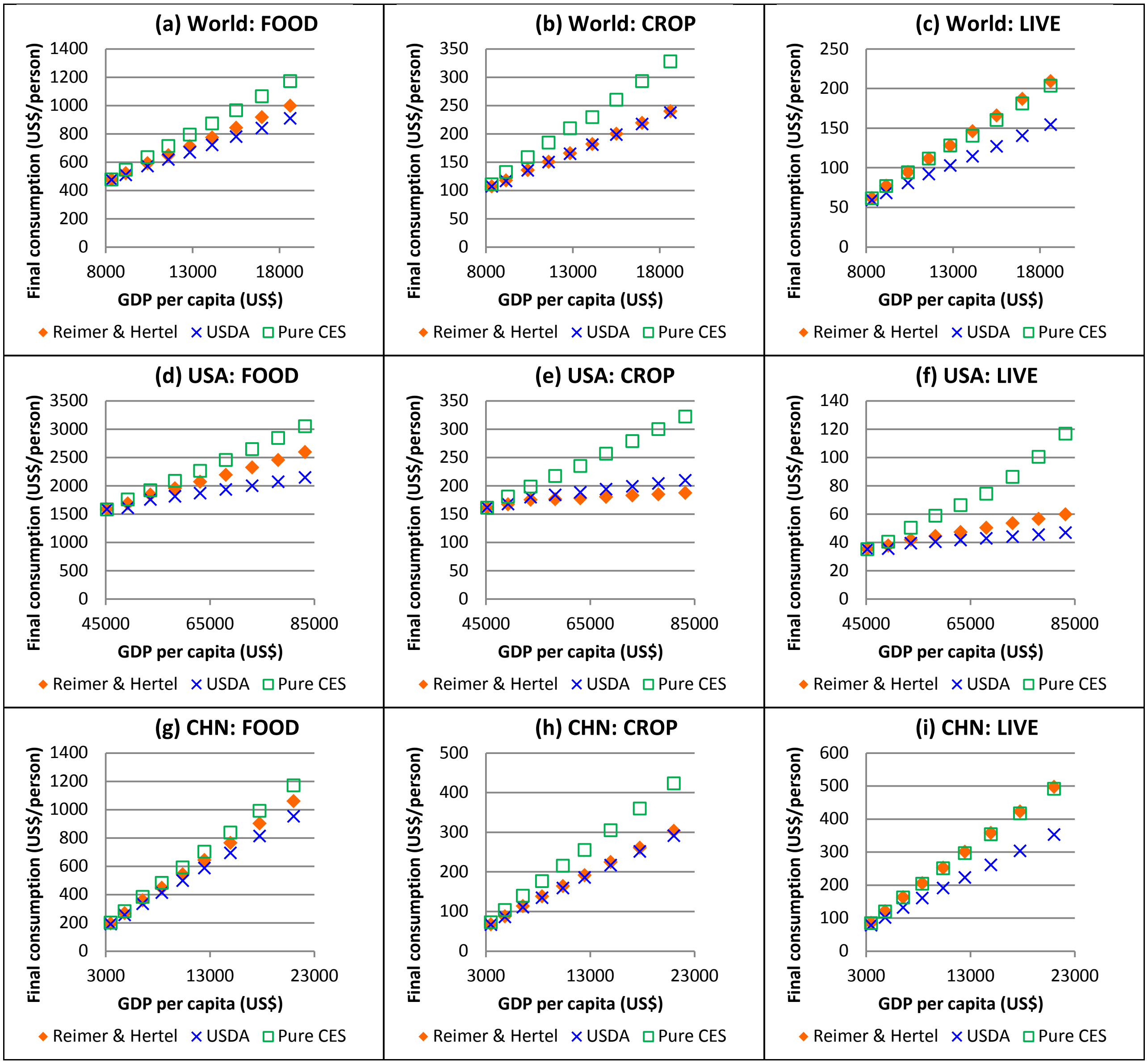

Figure 11. Final Consumption Projections for Food, Crop, and Livestock Products

5.5 Sensitivity Analyses

Long-term projections for future emissions and CO_2 prices are closely related to energy use levels, which are in turn determined by many other parameters with values that may be subject to uncertainty. For instance, Paltsev et al. (2005) and Webster et al. (2003) point out that economic growth is one of the most important drivers for energy use and emissions, and Webster et al. (2008) finds that the main sources of uncertainty in CO_2 prices come from energy demand parameters, including substitution elasticities between energy and non-energy (capital and labor) inputs and AEEI. While an extensive uncertainty analysis is beyond the scope of this paper, to explore the performance of EPPA6-L, we present the sensitivity analysis with various assumptions in: 1) BAU GDP growth; 2) AEEI; and 3) elasticities of substitution between energy and non-energy inputs.

For all three different types of parameters, we consider a 20% range of deviation from the values used in EPPA6-L. In **Figure 12**, we use "base" to denote the adoption of parameter values with the original EPPA6-L numbers, "high" means the considered parameter value is 20% higher than the base level, and "low" can be interpreted following the same logic.[13] As Figure 12 shows, the projected BAU global combusted CO_2 emissions in 2050 are most sensitive to elasticities of substitution between energy and non-energy inputs. For instance, holding other two parameter values at their base levels, if we normalize the global emissions to one, the range of emissions due to different elasticity levels is in [0.81, 1.17], and ranges of emissions due to various GDP and AEEI assumptions are in [0.88, 1.11] and [0.92, 1.08], respectively. Emissions are least sensitive to the AEEI assumption due to the "rebound effect" of efficiency improvement. More specific, the non-price driven efficiency improvement lowers demand for energy and thus the energy price, but the cheaper price encourages energy use and so the overall energy saving and reduced emissions are not as high as expected. Applying the same rationale in a reverse direction explains the result for a decrease in AEEI.

Figure 13 presents BAU combusted CO_2 emissions and CO_2 prices under the sample policy for selected regions. We find that up to 2030, deviations of emissions projections from the base case (the original setting) are mostly within 10%. The only exception is the case of CHN under extreme substitution elasticities, which result in slightly higher deviations from the base case (in the range of [0.87, 1.13] if we normalize the base case emissions level in 2030 to one). It is not a surprise that longer term projections are subject to greater levels of uncertainty. Besides, as previously found, distinct AEEI levels have the smallest effect on BAU emissions. Also, changes in BAU GDP growth have higher impacts on CHN's emissions since the base case GDP growth levels of CHN is the highest.

Figure 13 also presents the projected CO_2 prices for selected regions under the sample policy. The higher CO_2 prices of EUR may be resulted from the fact that EUR is less carbon intensive from the beginning, and therefore it may be harder to further decarbonize. If we use the emissions to GDP ratio as the proxy for the average carbon intensity level of economic activities, the base year number of EUR is 0.21Kg/US$, which has been much lower than those for USA (0.41 Kg/US$) and CHN (1.69 Kg/US$). Similarly, we also observe that CHN, which as been most carbon intensive among the three regions from the beginning, has the lowest projected CO_2 prices over time.

The projected CO_2 prices may also change due to uncertainties in those parameters considered. While the uncertainty in AEEI continues to play minimum roles in CO_2 prices, changes in substitution elasticities will have higher impacts on CO_2 price projections. In particular, higher elasticity levels makes it easier to switch from burning fossil fuels that incurs carbon penalty to

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[13] For instance, a "high" GDP growth represents the annual GDP growth rate is 20% higher, a "low" AEEI means the annual autonomous efficiency improvement rate is 20% lower, etc., compared to numbers with the "base" scenario (the original setting).

using other non-energy inputs, while a lower elasticity levels makes the switch for avoiding the carbon penalty trickier. The finding is consistent to Webster et al. (2008), and suggests that careful research to characterize the ability of energy and non-energy switch is crucial in reducing the uncertainty in CO_2 price projections.

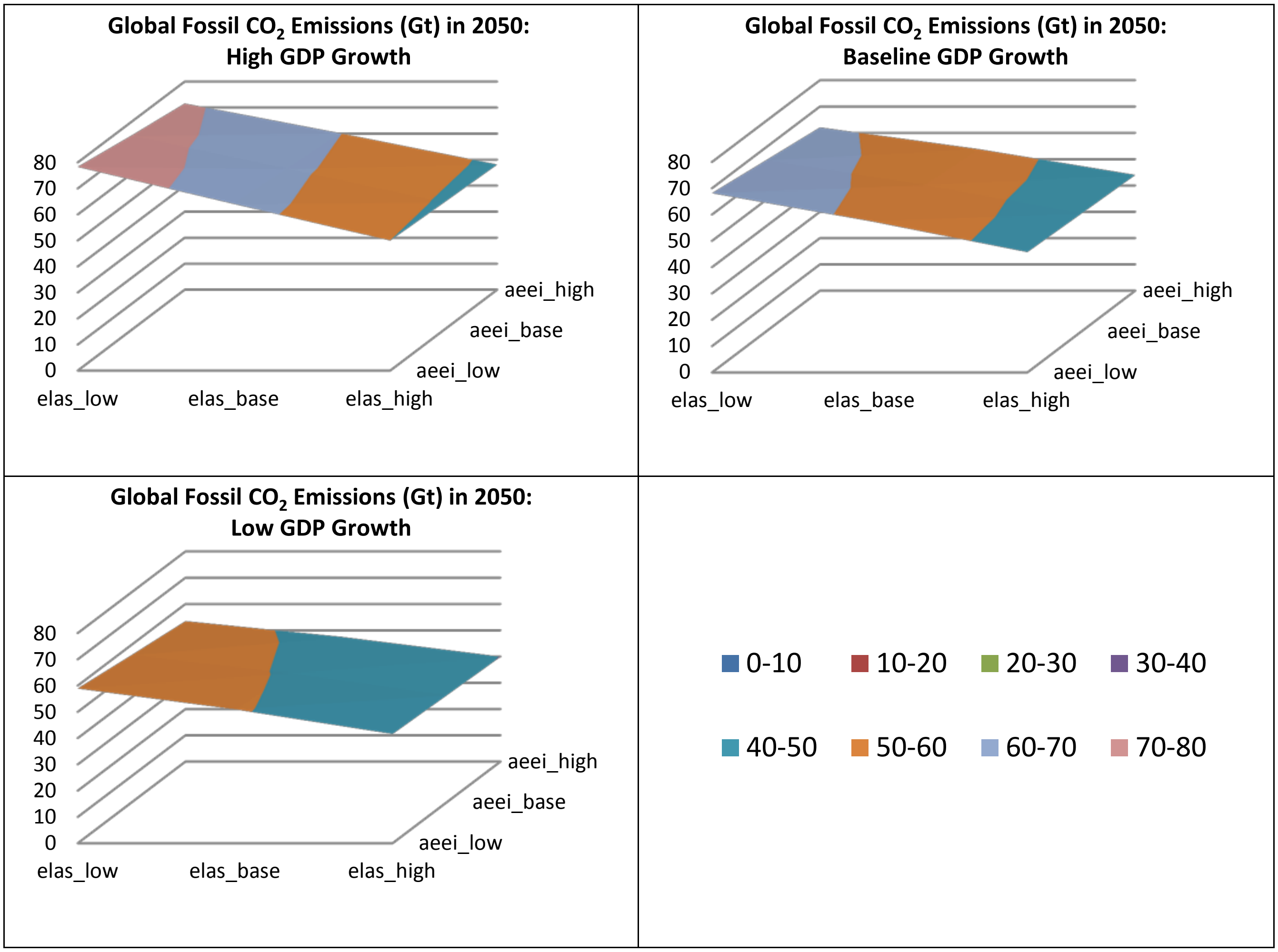

Figure 12. BAU Global Combusted CO_2 Emissions Under Different Assumptions

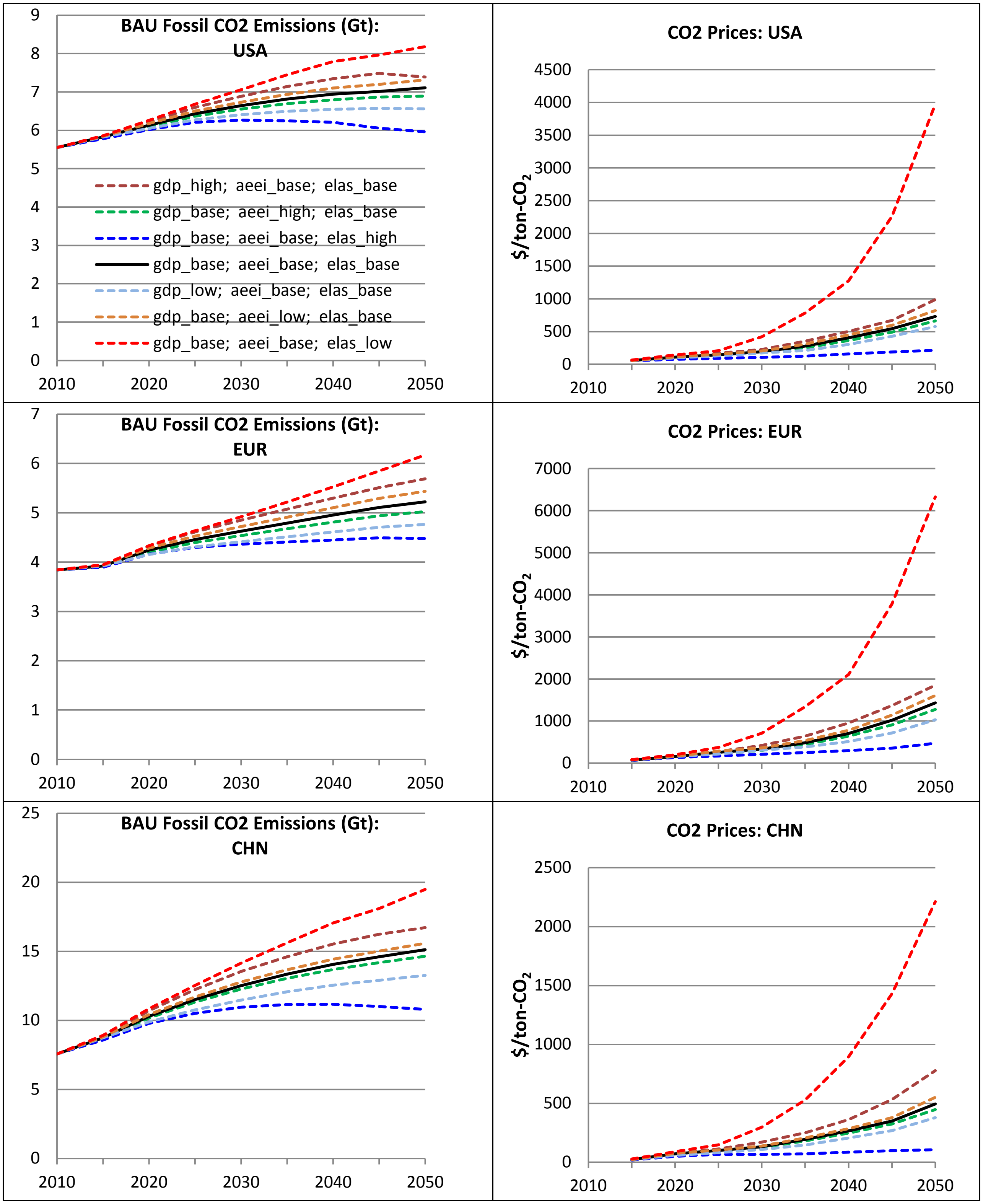

Figure 13. BAU Combusted CO_2 Emissions and CO_2 prices Under the Sample Policy

6. CONCLUSIONS

Large scale energy-economic CGE models have been used extensively for various policy analyses. In addition, they are often crucial components of various integrated assessment frameworks, which are used for studying interdisciplinary questions with broader contexts. However, in many cases, perhaps due to the lack of transparency, explaining and comparing model results could be challenging even for researchers. This study aims at bridging this gap by providing details for the data, structure, features, and improvements of EPPA6-L.

Besides, any long-term projection from an energy-economic model would inevitably involve distinct aspects of uncertainty, including factors such as (but not limited to) economic growth, autonomous energy efficiency improvement, and substitution elasticity between energy and non-energy inputs. As a result, in this study, we pick up these three parameters as an example to demonstrate how changes in their values may affect CO_2 emissions levels and prices. We also explore the implications of adopting non-homothetic preferences on the projections for food and agricultural products' consumption, which are also crucial as numerous studies have found the evidence against the assumption of an income elasticity of one for the consumption of these products.

Therefore, this paper contributes to the literature of presenting model development for a global energy-economic CGE model, which is often overlooked but is critical for supporting policy implications drawing from the model simulations. Furthermore, for many recent integrated assessment studies, incorporating more details, pursuing higher resolutions, and linking different models all seem to be appealing strategies as expansive considerations are expected to deliver more comprehensive and fruitful insights. The increasing complexity, on the other hand, has made the maintenance of a large-scale model more and more challenging. Because of this, the importance of presenting a careful illustration for model development cannot be over-emphasized. We believe future studies with comparable efforts for other models will be valuable as well.

Based on EPPA6-L, the developments of several EPPA6 versions are underway, including: 1) *EPPA6 with a comprehensive representation for land-use change*: following the framework developed by Gurgel et al. (2007), economic incentives for land-use conversions as well as CO_2 emissions from the land-use changes will be considered; 2) *EPPA6 with details for first generation biofuels*: as presented by Gitiaux et al. (2012), different biofuels production activities will be identified, and each of which has its own land-use and carbon footprint implications, 3) *EPPA6 with refined oil sectors details*: as Choumert et al. (2006), the single refined oil product of GTAP8 will be disaggregated into different petroleum products with various uses and emissions factors, and 4) *EPPA6 with household transportation details*: based on Karplus et al. (2013b), household owned-supplied transportation (service from private automobiles) will be disaggregated by age and powertrains to improve policy analyses such as fuel efficiency requirements on automobiles.

APPENDIX

A-01:

Show that Equation (6) is the solution to equation (5), i.e., given the budget constraint $\sum_{i=1}^{N} c_i = w$, for any $i = 1,2,\dots,N$, $c_i^* = (1-\eta_i)c_i$ is the solution for $\eta_i = \left(\frac{c_i - c_i^*}{c_i}\right) / (\frac{w - \sum_{i=1}^{N} c_i^*}{w})$ when the vector of η_i is given.

Step 1:

Following the definition for η_i, we have:

$$\frac{\eta_i}{\eta_j} = \frac{\left(\frac{c_i - c_i^*}{c_i}\right) / (\frac{w - \sum_{i=1}^{N} c_i^*}{w})}{\left(\frac{c_j - c_j^*}{c_j}\right) / (\frac{w - \sum_{j=1}^{N} c_j^*}{w})} = \frac{\left(\frac{c_i - c_i^*}{c_i}\right)}{\left(\frac{c_j - c_j^*}{c_j}\right)} \tag{A01}$$

Rearrange terms, we can get:

$$\frac{c_j - c_j^*}{c_i - c_i^*} = \frac{\eta_j c_j}{\eta_i c_i} \tag{A02}$$

Step 2:

Equation A02 suggests that the candidate for the solution can be $c_i^* = (1-\eta_i)c_i$. We need to verify this is indeed the case, i.e., we need to show that $c_i^* = (1-\eta_i)c_i$ satisfies Equations A01 and A02. It is straightforward to show that A02 is satisfied. Let us plug $c_i^* = (1-\eta_i)c_i$ into the right hand side of Equation A01. We have:

$$\frac{c_i - c_i^*}{c_i} = \frac{c_i - (1-\eta_i)c_i}{c_i} = \eta_i \tag{A03}$$

Since from the budget constraint we have $\sum_{i=1}^{N} c_i = w$, and $\sum_{i=1}^{N} \frac{c_i}{w}\eta_i$ =1 is just the Engel's Aggregation, thus:

$$\frac{w - \sum_{i=1}^{N} c_i^*}{w} = \frac{w - \sum_{i=1}^{N}(1-\eta_i)c_i}{w} = \frac{w - \sum_{i=1}^{N} c_i + \sum_{i=1}^{N} \eta_i c_i}{w} = \sum_{i=1}^{N} \frac{c_i}{w}\eta_i = 1 \tag{A04}$$

As a result, the numerator of the right hand side of A01 is equal to η_i. Similarly, the denominator of A01's right hand side is η_j. Therefore $c_i^* = (1-\eta_i)c_i$ is the solution to the problem.

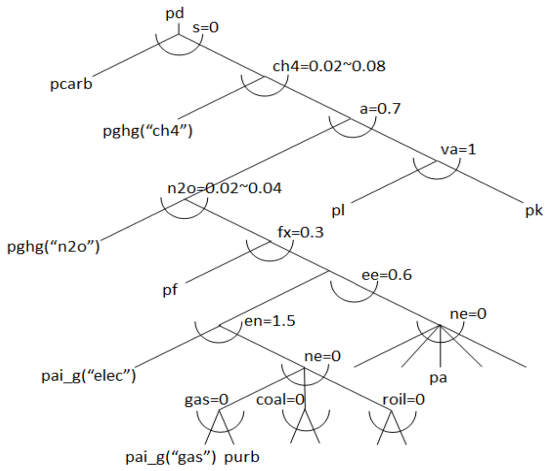

Figure A1. Production Structure for CROP, LIVE, and FORS

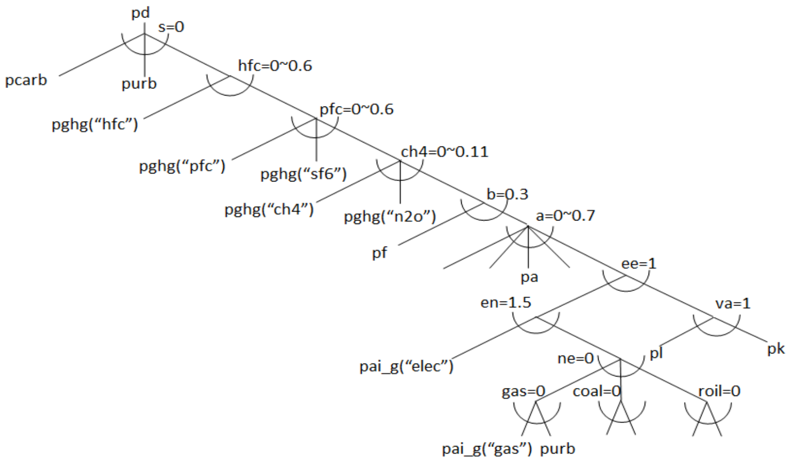

Figure A2. Production Structure for FOOD, OTHR, SERV, TRAN, and DWE

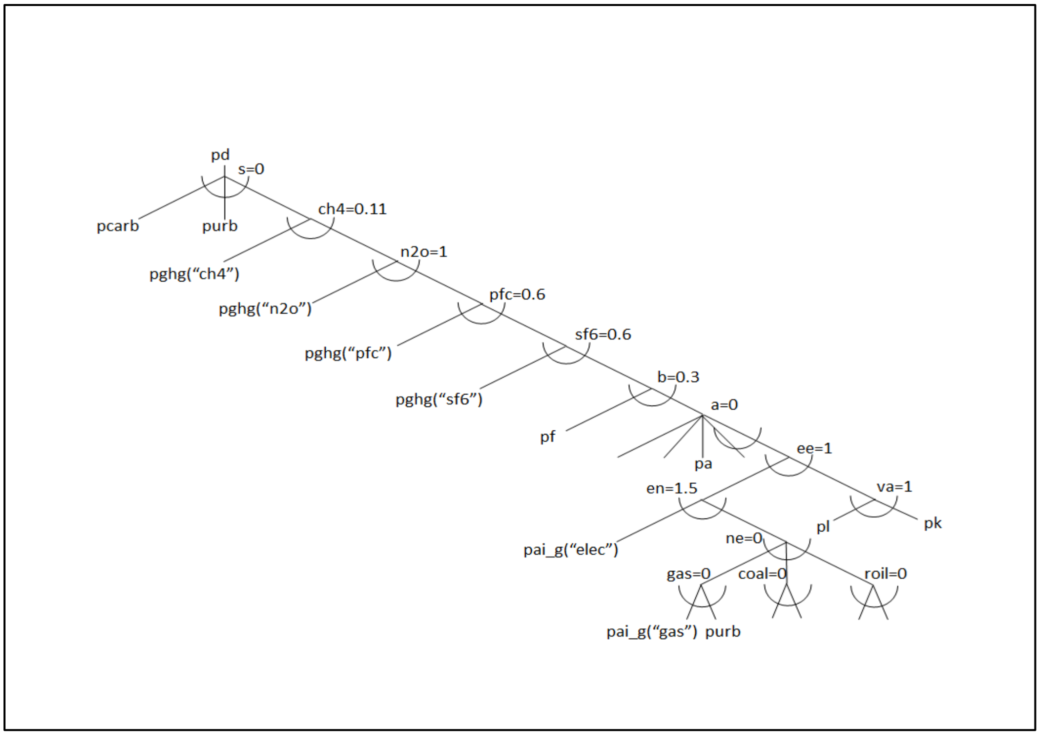

Figure A3. Production Structure for EINT

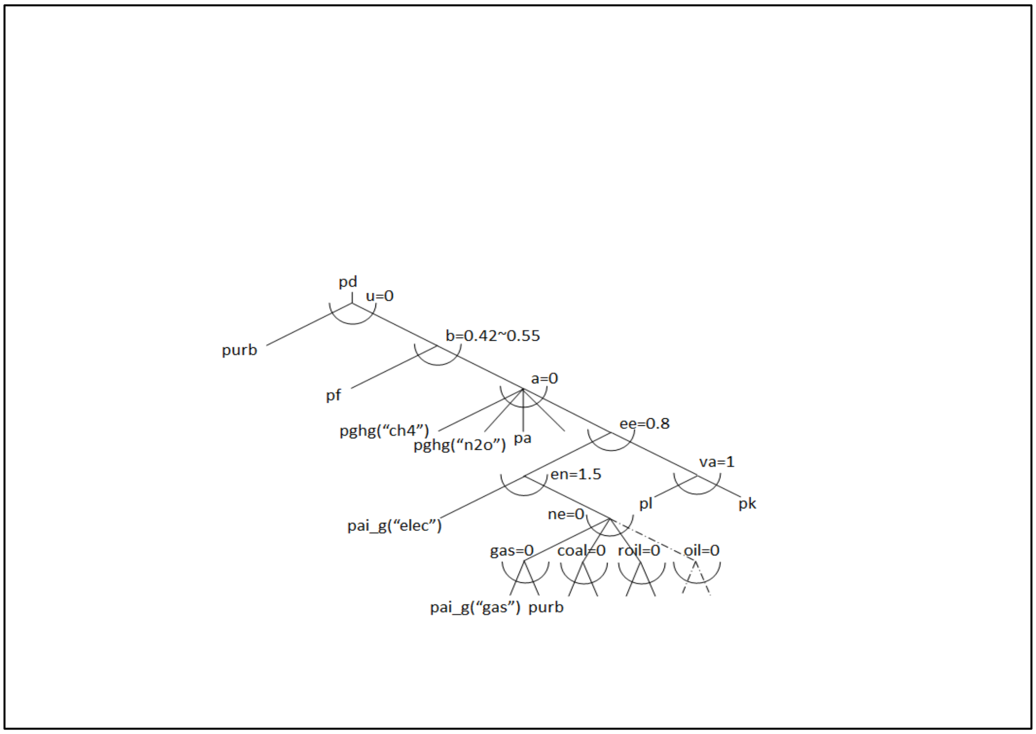

Figure A4. Production Structure for COAL, OIL, ROIL, and GAS

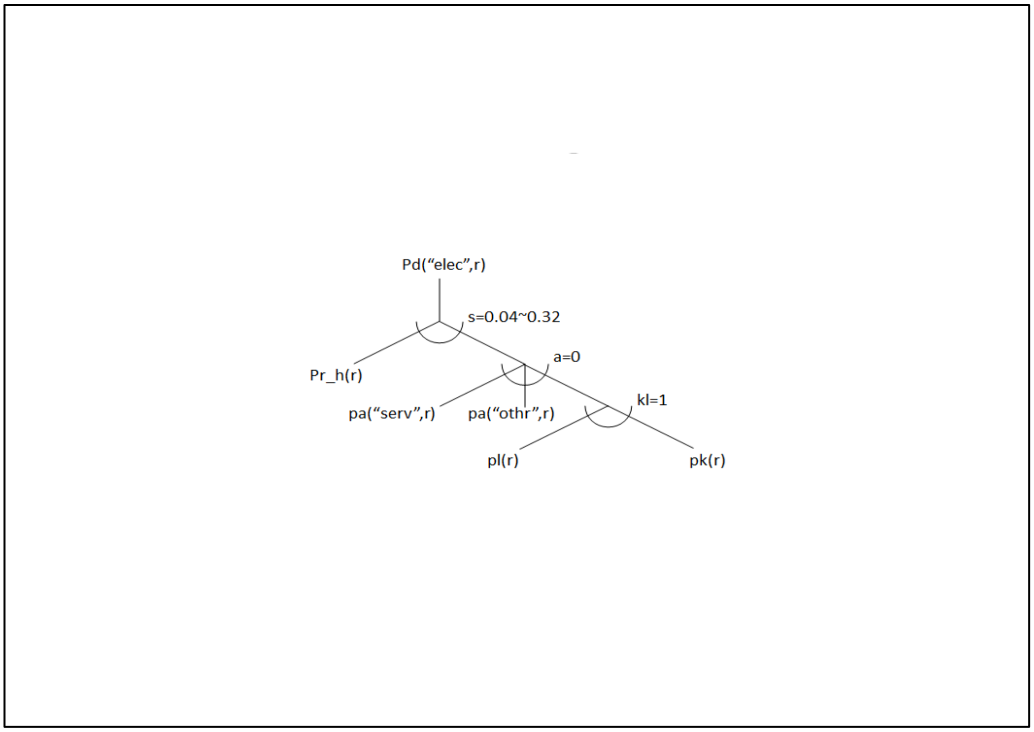

Figure A5. Production Structure for Hydro and Nuclear Generation

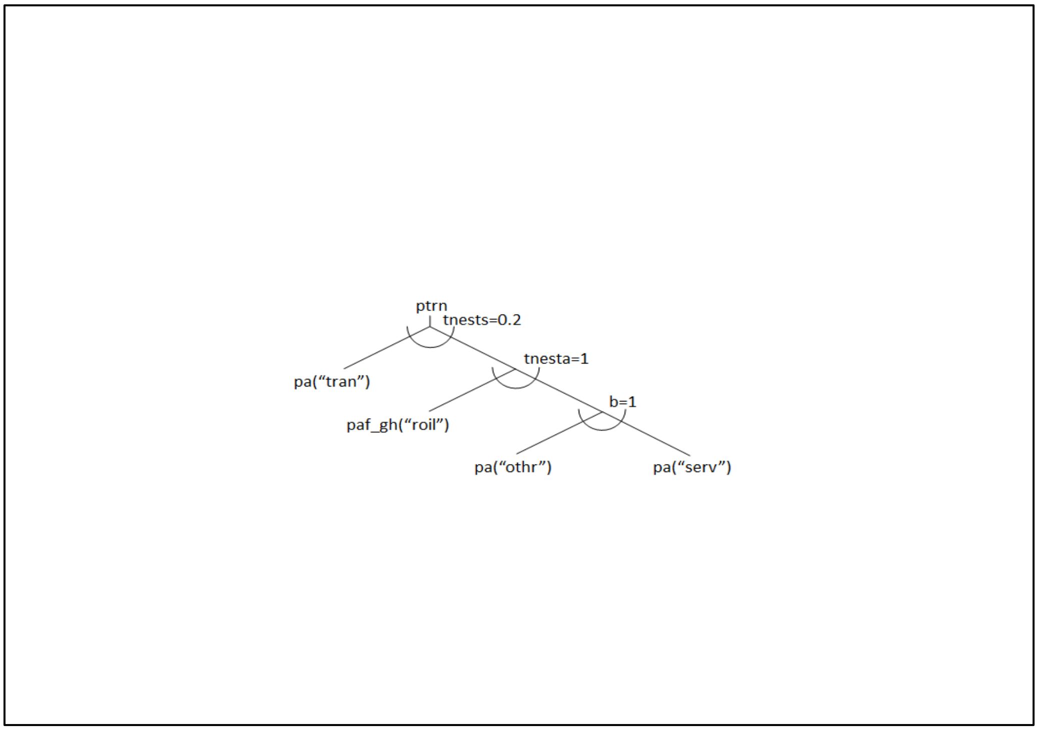

Figure A6. Household Transportation

GTAP8 region	EPPA6 region	GTAP8 region	EPPA6 region
Albania	ROE	Mongolia	REA
United Arab Emirates	MES	Mozambique	AFR
Argentina	LAM	Mauritius	AFR
Armenia	ROE	Malawi	AFR
Australia	ANZ	Malaysia	ASI
Austria	EUR	Namibia	AFR
Azerbaijan	ROE	Nigeria	AFR
Belgium	EUR	Nicaragua	LAM
Bangladesh	REA	Netherlands	EUR
Bulgaria	EUR	Norway	EUR
Bahrain	MES	Nepal	REA
Belarus	ROE	New Zealand	ANZ
Plurinational Republic of Bolivia	LAM	Oman	MES
Brazil	BRA	Pakistan	REA
Botswana	AFR	Panama	LAM
Canada	CAN	Peru	LAM
Switzerland	EUR	Philippines	ASI
Chile	LAM	Poland	EUR
China	CHN	Portugal	EUR
Cote d'Ivoire	AFR	Paraguay	LAM
Cameroon	AFR	Qatar	MES
Colombia	LAM	Romania	EUR
Costa Rica	LAM	Russian Federation	RUS
Cyprus	EUR	Saudi Arabia	MES
Czech Republic	EUR	Senegal	AFR
Germany	EUR	Singapore	ASI
Denmark	EUR	El Salvador	LAM
Ecuador	LAM	Slovakia	EUR
Egypt	AFR	Slovenia	EUR
Spain	EUR	Sweden	EUR
Estonia	EUR	Thailand	ASI
Ethiopia	AFR	Tunisia	AFR
Finland	EUR	Turkey	ROE
France	EUR	Taiwan	ASI
United Kingdom	EUR	Tanzania United Republic of	AFR
Georgia	ROE	Uganda	AFR
Ghana	AFR	Ukraine	ROE
Greece	EUR	Uruguay	LAM
Guatemala	LAM	United States of America	USA
Hong Kong	CHN	Venezuela	LAM
Honduras	LAM	Viet Nam	REA
Croatia	ROE	South Central Africa	AFR
Hungary	EUR	Rest of Central America	LAM
Indonesia	IDZ	Caribbean	LAM
India	IND	Central Africa	AFR
Ireland	EUR	Rest of East Asia	REA
Iran Islamic Republic of	MES	Rest of Eastern Africa	AFR
Israel	MES	Rest of Eastern Europe	ROE
Italy	EUR	Rest of EFTA	EUR
Japan	JPN	Rest of Europe	ROE
Kazakhstan	ROE	Rest of North America	LAM
Kenya	AFR	Rest of North Africa	AFR
Kyrgyzstan	ROE	Rest of Oceania	ANZ
Cambodia	REA	Rest of South Asia	REA
Korea Republic of	KOR	Rest of South African Customs Union	AFR
Kuwait	MES	Rest of Southeast Asia	REA
Lao People's Democratic Republic	REA	Rest of South America	LAM
Sri Lanka	REA	Rest of Former Soviet Union	ROE
Lithuania	EUR	Rest of the World	ANZ
Luxembourg	EUR	Rest of Western Africa	AFR
Latvia	EUR	Rest of Western Asia	MES
Morocco	AFR	South Africa	AFR
Madagascar	AFR	Zambia	AFR
Mexico	MEX	Zimbabwe	AFR
Malta	EUR		

Table A1. Regional Mapping from GTAP8 to EPPA6-L

GTAP8 sector	EPPA6 sector	GTAP8 sector	EPPA6 sector
paddy rice	CROP	wood products	OTHR
wheat	CROP	paper products - publishing	EINT
cereal grains nec	CROP	petroleum - coal products	ROIL
vegetables - fruit - nuts	CROP	chemical - rubber - plastic products	EINT
oil seeds	CROP	mineral products nec	EINT
sugar cane - sugar beet	CROP	ferrous metals	EINT
plant-based fibers	CROP	metals nec	EINT
crops nec	CROP	metal products	EINT
bo horses	LIVE	motor vehicles and parts	OTHR
animal products nec	LIVE	transport equipment nec	OTHR
raw milk	LIVE	electronic equipment	OTHR
wool - silk-worm cocoons	LIVE	machinery and equipment nec	OTHR
forestry	FORS	manufactures nec	OTHR
fishing	LIVE	electricity	ELEC
coal	COAL	gas manufacture - distribution	GAS
oil	OIL	water	OTHR
gas	GAS	construction	OTHR
minerals nec	OTHR	trade	SERV
bo meat products	FOOD	transport nec	TRAN
meat products	FOOD	water transport	TRAN
vegetable oils and fats	FOOD	air transport	TRAN
dairy products	FOOD	communication	SERV
processed rice	FOOD	financial services nec	SERV
sugar	FOOD	insurance	SERV
food products nec	FOOD	business services nec	SERV
beverages and tobacco products	FOOD	recreational and other services	SERV
textiles	OTHR	public admin - and defence - education - health	SERV
wearing apparel	OTHR	ownership of dwellings	DWE
leather products	OTHR		

Table A2. Sectoral Mapping from GTAP8 to EPPA6-L

GTAP8 production factor	EPPA6 production factor	
Skilled labor	L	Labor
Unskilled labor	L	Labor
Capital	K	Capital
Land	Lnd	Land
Natural resources	FFA	Natural resource (fixed factor)

Table A3. Mapping of Production Factor from GTAP8 to EPPA6-L

Acknowledgments

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