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The MIT Economic Projection and Policy Analysis (EPPA) Model: Version 5

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Abstract: This report documents the version 5 of the MIT Economic Projection and Policy Analysis (EPPA) model. In addition to the updates in economic and population data, the model includes new features such as land use change representation, private vehicles detail, bioenergy production, and power sector representation. We provide an overview of the model with an emphasis on these new features of EPPA.

1. Introduction

The Economic Projection and Policy Analysis (EPPA) model is a multi-region, multi-sector general equilibrium model of the world economy that has been designed to provide future projections of the world economy, its relationship to the environment, and to evaluate energy, agriculture, land use, and pollution policies. Toward that end, it provides details on sectors that contribute to environmental change and that are affected by it (households, energy, agriculture, transportation, energy-intensive industry, etc.). As a full multi-sector model, it includes explicit treatment of inter-industry interactions. These can be important because, for example, while the service sector itself does not emit much in the way of greenhouse gases (GHG), it may require transportation services and other inputs that themselves are GHG intensive, and so it would be a mistake to believe that an economy could simply shift to a service economy and thereby reduce its emissions greatly. Similarly, an economy may not be an intensive GHG emitter but may import intermediate or final goods that, themselves, were GHG-intensive to produce. Thus, it would be misleading to conclude that the world as a whole could easily achieve the apparent low GHG intensity of such a country. The EPPA model therefore keeps track of bi-lateral trade in all goods.

These sectoral and regional interaction features of the model have become more important as discussions around energy, environment, and climate policy have become more complex. For example, if China reduces emissions by shifting away from exports, will that reduce world emissions or simply shift those GHG-intensive activities elsewhere? Are Europe's emissions gains bought at the expense of more emissions abroad? How do energy, pollution, and land policies intersect? Will complex energy policies with multiple objectives achieve them at the lowest cost? Will advancing crop yields, or novel energy technologies create more flexibility to respond to environmental problems? Such questions can be explored with the global economy-wide model like EPPA.

The EPPA model has been in development at the MIT Joint Program on the Science and Policy of Global Change (http://globalchange.mit.edu) for more than two decades. The updates in economic, energy, and emission data, and advances in representation of new technologies, vintaging structure, corresponding physical accounts, and other features have been provided in the more advanced versions. The version 1 of the model is documented in Yang *et al.* (1996), version 2 in Prinn *et al.* (1999), version 3 in Babiker *et al.* (2001), and version 4 in Paltsev *et al.* (2005) in its recursive-dynamic form and in Babiker *et al.* (2008, 2009) in its forward-looking form.

Several new features have been added to the version 5 of the EPPA model (EPPA5) to study: land-use change modeling (Gurgel *et al.*, 2007), plug-in hybrid vehicles (Karplus *et al.*, 2010), air pollution health impacts (Nam *et al.*, 2010; Matus *et al.*, 2012), renewable portfolio standards (Morris *et al.*, 2010), coal-to-liquids conversion (Chen *et al.*, 2011), oil sands production (Chan *et al.*, 2012), shale gas representation (Paltsev *et al.*, 2011; Jacoby *et al.*, 2012), personal transportation details and U.S. fuel efficiency standards for cars (Karplus, 2011; Karplus and Paltsev, 2012; Karplus *et al.*, 2013), gasoline and diesel fleet representation in Europe (Gitiaux *et al.*, 2012), personal transportation pathways in China (Kishimoto *et al.*, 2012), air pollution constraints (Nam *et al.*, 2013), limited sectoral emission trading (Gavard *et al.*, 2011, 2013, 2016), advanced technologies representation (Morris *et al.*, 2014), Paris Agreement pledges (Jacoby and Chen; 2014, 2016), representation of advanced biofuels (Winchester and Reilly, 2015), CO_2 standards for private cars in Europe (Paltsev *et al.*, 2016), irrigated and rainfed crop production (Winchester *et al.*, 2016), and others.

This report brings together the current version of EPPA5 and the many features developed in parallel. The report documents the structure of the model with the components that are retained in the version 5 used for the MIT Joint Program Energy and Climate Outlooks (MIT Joint Program, 2012, 2013, 2014, 2015) and its expanded Food, Water, Energy and Climate Outlook (Chen *et al.*, 2016c). A version 6 of EPPA has been documented in Chen *et al.* (2015, 2016a) with applications reported in Chen *et al.* (2016b), Zhang and Paltsev (2016), and Gurgel *et al.* 2017. Not all features of EPPA5 have yet been incorporated in the released version of EPPA6.

The report is organized in the following way. Section 2 provides an overview of the EPPA model. Section 3 describes equilibrium structures and representation of production, consumption and trade. It also provides a summary of GHG and air pollution emission inventory. Section 4 describes the process of calibration to historic data. Section 5 describes the dynamic process. Section 6 presents the representation of advanced technologies. Section 7 provides the details of linking EPPA to the climate component of the MIT Integrated Global System Modeling (IGSM) framework (Sokolov *et al.*, 2005, Prinn, 2012). Section 8 presents examples of the EPPA model applications to different policy questions.

2. The EPPA Model: An Overview

2.1 Description

The EPPA model is a dynamic multi-sector, multi-region, computable general equilibrium (CGE) model of the world economy with detailed representation of energy technologies, GHG emissions, air pollutants, and land

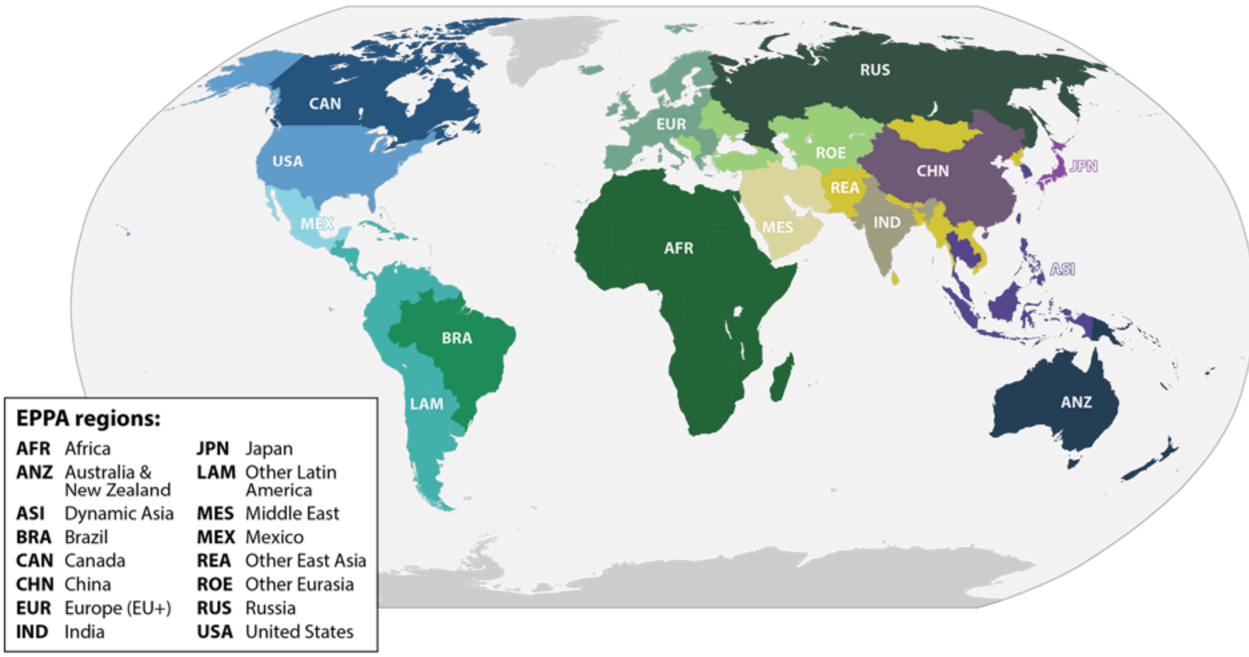

Figure 1. Regions in the EPPA model

use change. To represent the world economy in a base year (2004), the model utilizes the Global Trade Analysis Project (GTAP) dataset (maintained at Purdue University) that provides input-output relationships among economic sectors within a broader social accounting matrix that includes exports, imports, government, investment and household demand for final goods, and the ownership and supply to each sector of labor, capital and natural resources (Narayanan and Welmsley, 2008). From 2005, the model solves in 5-year steps up to 2100. For historical years (2005–2015), model inputs are calibrated so that simulated results approximate macroeconomic data of the International Monetary Fund (IMF, 2016) and energy data of the International Energy Agency (IEA, 2015).

The standard economic specification of the model in billions of dollars of inputs (capital rents, labor, resource rents) and outputs (gross output of each sector and output supplied to each final demand sector) is augmented with accounts in physical terms on energy (exajoules), emissions (tons), land use (hectares), population (billions of people), natural resource endowments (exajoules, hectares) and efficiencies (energy produced/energy used) of advanced technology. These supplemental physical accounts translate economic accounts to corresponding estimates of physical depletion and use of natural resources, technical efficiencies of energy conversion processes and against limits of annual availability of renewable resources such as land availability, and the number of people affected to consider health effects.

Representing the human system of the MIT IGSM framework, the EPPA model provides projections of physical changes such as emissions of GHG (carbon dioxide, CO_2; methane, CH_4; nitrous oxide, N_2O; hydrofluorocarbons, HFCs; perfluorocarbons, PFCs; and sulphur hexafluoride, SF_6), substances with direct climatic impact such as aerosols from sulfates (SO_x), black carbon (BC), and organic carbon (OC), and other pollutants that are important for atmospheric chemistry such as nitrogen oxides (NO_x), carbon monoxide (CO), ammonia (NH_3), and non-methane volatile organic compounds (NMVOCs) or land use by category (crops, pasture, natural grass, natural forests, managed forests) for other components of IGSM, including atmospheric chemistry model and climate and terrestrial ecosystems to produce scenarios of climate and environmental change. Inventories of GHG and air pollutant emissions in EPPA5 are provided in Waugh *et al.* (2011). The EPPA model can also be run in a stand-alone mode, without coupling with other IGSM components, when the focus is the economics and policy of energy, agriculture or emissions.

2.2 Regions and Sectors of the Model

The GTAP data set provides base year information on the input-output structure for regional economies, including bilateral trade flows. The GTAP data are aggregated into 16 regions. **Figure 1** shows the geographical regions that are explicitly represented in the model. The regional aggregation focuses on separately representing large economies such as the US, Europe, China, Japan and then aggregation of smaller countries into regions.

Table 1. Sectors in the EPPA model

Abbreviation	Sector	Abbreviation	Sector
EINT	Energy-Intensive Industries	ELEC: windbio	Wind combined with biofuel backup
OTHR	Other Industries	ELEC: igcap	Coal with CCS
SERV	Services	ELEC: ngcap	Natural Gas with CCS
CROP	Crops	ELEC: anuc	Advanced Nuclear Electricity
LIVE	Livestock	ELEC: ngcc	Advanced Natural Gas
FORS	Forestry	HTRN: ice	Private Transportation: Gasoline Vehicles
FOOD	Food Processing	HTRN: phev	Private Transportation: Plug-in Hybrid Vehicles
COAL	Coal Production	HTRN: ev	Private Transportation: Electric Vehicles
OIL	Oil Production	HTRN: cng	Private Transportation: CNG Vehicles
ROIL	Refining	TRAN	Commercial Transportation
GAS	Natural Gas Production	BIOF: corn	First-Generation Biofuels: Corn
ELEC: coal	Coal Electricity	BIOF: sugar	First-Generation Biofuels: Sugarcane
ELEC: gas	Natural Gas Electricity	BIOF: beet	First-Generation Biofuels: Sugarbeet
ELEC: oil	Petroleum Electricity	BIOF: rapes	First-Generation Biofuels: Rapeseed
ELEC: nucl	Nuclear electricity	BIOF: soyo	First-Generation Biofuels: Soybeen
ELEC: hydro	Hydro Electricity	BIOF: wheat	First-Generation Biofuels: Wheat
ELEC: wind	Wind Electricity	BIOF: palmo	First-Generation Biofuels: Palm Oil
ELEC: solar	Solar Electricity	ABIO	Advanced Biofuels
ELEC: bele	Biomass Electricity	SOIL	Oil Shale
ELEC: windgas	Wind combined with gas backup	SGAS	Synthetic Gas from Coal

The EPPA model explicitly represents interactions among sectors (through inter-industry inputs) and regions (via bilateral trade flows). It simulates production in each region at the sectoral level. The GTAP sectoral data are initially aggregated into 13 sectors (crop, livestock, forestry, food, serives, energy-intensive industries, other industries, coal, oil, refined oil, natural gas, electricity, transportation). Additional data are then used to further disaggregate the electricity and transportation sectors (electricity into coal-based, petroleum-based, natural gas-based, nuclear and hydro power; and transportation into commercial and private vehicles). In addition, the model includes several advanced technology sectors that were not widely deployed in the base year and therefore not represented explicitly in the GTAP data. We refer to them as "backstop technology sectors". They include additional fuels, transportation and electricity technologies. The full list of 40 sectors represented in the EPPA model, including backstop technology sectors, is provided in **Table 1**.

Sectoral output is produced from primary factors including multiple categories of depletable and renewable natural capital, produced capital, and labor (**Table 2**). Intermediate inputs to sectoral production are represented through a complete input-output structure.

Because of the focus on environment, energy, and agriculture/land use, the EPPA model is relatively disaggregated in areas important to these issues. For example, most CGE models limit primary factor endowments to capital and labor, but the EPPA model includes a variety of energy and land resources. Similarly, the model includes details regarding the conversion of primary energy resource endowments to useful energy carriers, and land resources into crops, livestock, and forest products, and then output from crop and livestock sectors into food products.

Table 2. Primary factors in the EPPA model

Capital	Natural Forests	Hydro
Vintaged Capital[a]	Natural Grass	Nuclear
Labor	Coal	Solar
Cropland	Oil	Wind
Pasture	Shale Oil	
Harvested Forests[b]	Natural Gas[c]	

[a] There are five different vintages for each non-malleable portion of the technology-specific capital.

[b] Includes managed forest areas for forestry production as well as secondary forests from previous wood extraction and agricultural abandonment.

[c] For the USA and Canada there is a further disaggregation of natural gas to separately identify conventional gas, shale gas, tight gas, and coal-bed methane resources.

An important feature of the EPPA model is the distinction between malleable and vintaged (i.e., non-malleable) capital. The malleable portion of the capital stock is fully mobile between sectors and technologies. To represent the irreversibility of investments in a particular technology in a particular period of time (e.g., capital invested in a coal power plant cannot be redeployed to solar generation), the EPPA model tracks five different vintages of the non-malleable capital portion. Input share parameters for the production functions for each vintage of capital are determined by the input shares for the period when the capital was put in place. This malleable-vintaged capital formulation means that the EPPA model exhibits a short-run and a long-run response to changes in relative input prices.

2.3 An Overview of the Static Structure of the Model

The EPPA model can be described by a combination of multiple circular flows of goods and services in the economy **(Figure 2)**. A representative consumer in each region provides the supply of primary factor inputs to the producing sectors of the economy, the goods and services produced by each sector, and the disposition of these goods to final consumers (households), who in turn own capital, labor and other resources. Corresponding to this flow of goods and services is a reverse flow of payments. Households receive payments for the services from the producing sectors of the economy for the primary factors. Households then use the income they receive to pay producing sectors for the goods and services consumed. This circular flow ensures that, in any period, the production of goods and services is limited by available resources and that households earn income they spend. Key to representing final consumers is a description of preferences among goods and willingness/ability to substitute one good for another when relative prices change. Similarly, what is essential in representing production sectors is a description of the technology, which determines the shares of different intermediate and primary factors required to produce a unit of output, and the technical ability to substitute among inputs. The sector is simply a technical description of how inputs are converted to outputs, with any profits returned to households as rents or returns on capital and resources. Each

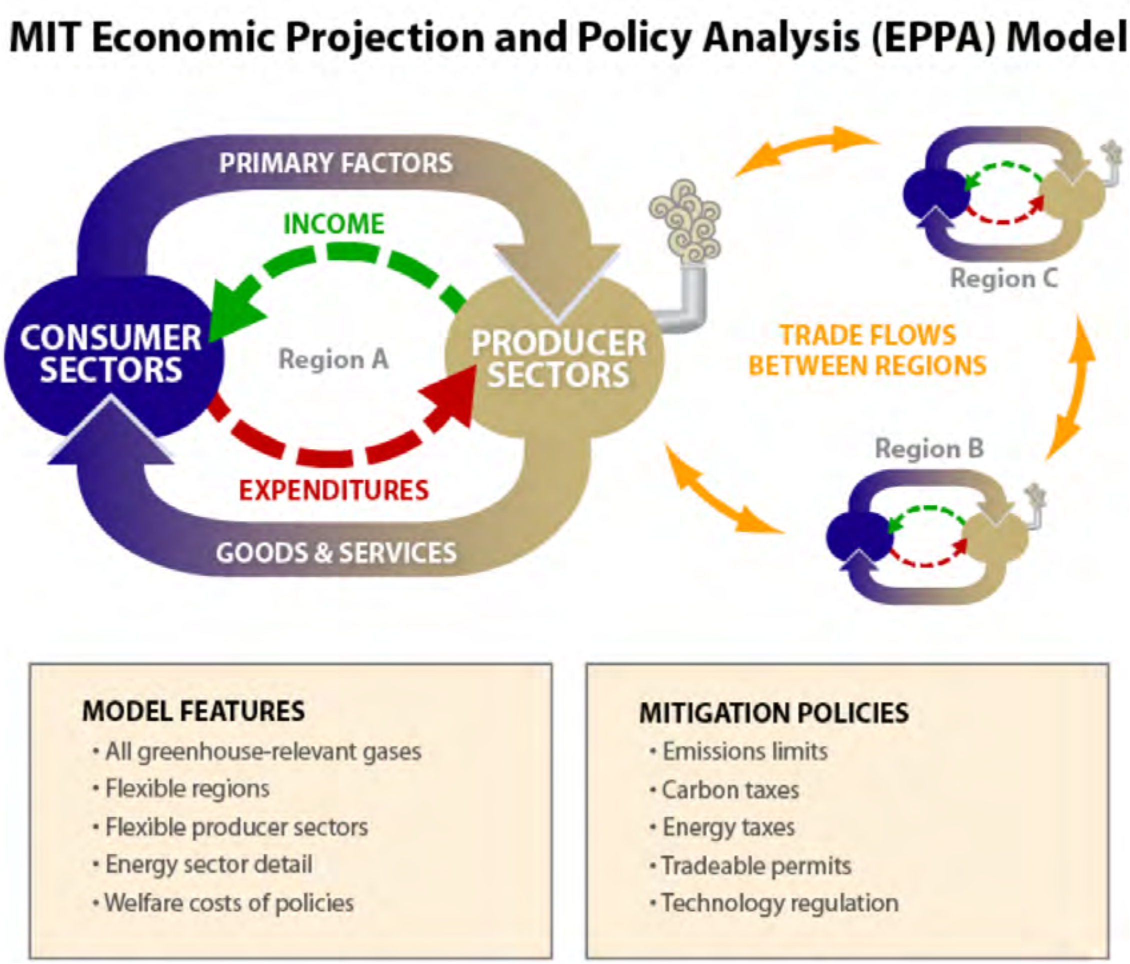

Figure 2. Schematic of the EPPA model

sector is essentially a representative firm, and is solve to maximize profits (and minimize costs) as if in a competitive environment.

Each region must produce and export goods with their domestic resources to trade for goods they import, so that balance is maintained within an economy and among trading regions. In the EPPA model, a few goods (e.g., crude oil, emissions permits, biofuels) are treated as perfect substitutes in global trade. For most goods, however, the model embodies the Armington convention widely used in modeling international trade (Armington, 1969). In this formulation, imported goods from a production sector and region are treated as imperfect substitutes for goods from that sector produced in other regions or domestically. The Armington assumption allows a region to be both an importer and exporter of goods from each sector, reflecting the observed patterns. Where goods are perfect substitutes, there is a single global price. With the Armington assumption, goods from the same sectors but from different regions each have a separate price.

The EPPA model is formulated in the GAMS-MPSGE language (Rutherford, 1999) and in each period it finds a solution that simultaneously clears all markets for goods and primary factors given existing taxes and distortions. A major development in EPPA5 has been extensions to the modeling of a variety of energy, pollution, and land policies. EPPA can evaluate taxes and tax policy, fuel standards such as those applied to vehicles, other credit trading policies such as the Renewable Identification Number (RIN) program that supports renewable fuels in the US, subsidies and other limits or constraints on different sectors, such as phasing out of nuclear or coal, renewable portfolio standards, and other policies.

The main limit in terms of representing policies is the level of aggregation in EPPA. For example, policies directed only at the cement or aluminum industries would be challenging to represent because they are aggregated together in the Energy Intensive industry, although CO_2 emissions calibrated to those from cement production are associated with Energy Intensive industry output. A significant benefit of CGE models is that they facilitate the computation of measures of the total costs of policies simulated within their structure that can easily be compared across different types of policies. These take into account multiple feedbacks on production, income and demand across the full range of industries in an economy. One such measure, common in economic analysis, is the change in economic welfare measured as equivalent variation. Conceptually, this is the amount of income needed to compensate the representative agent for welfare losses suffered as a result of the policy. Welfare costs associated with a cap and trade program can be compared with those from a fuel standard, or renewable portfolio standard, whereas a RIN, Renewable Credit, or Carbon price are not directly comparable.

In most EPPA applications, the cost of a policy is measured by the change in aggregate consumption, and that is because the structure of the standard EPPA is designed to measure welfare changes in equivalent variation. In the versions of the EPPA model that also represent labor-leisure decisions (Nam *et al.*, 2010; Matus *et al.*, 2012), welfare cost calculations include both changes in consumption and leisure. Additional outputs of EPPA simulations are the prices and quantities necessary to calculate other indices of economic well-being that are sometimes of interest in assessing the effects of policies. These include gross domestic product (GDP), sectoral output, commodity and factor prices, and the terms of trade. The model also allows the exploration of different tax settings, sectoral constraints, international trade specifications, subsidies to different technologies, and other policy instruments.

2.4 Dynamic Process

The schematics in Figure 2 provides a highly simplified representation of static (single period) interactions in the model. To simulate forward in time, we specify linkages between static solutions of different periods. The key dynamic links are savings and investment, capital vintaging, population and labor growth, productivity growth (in labor, land and energy), renewable resource limits, depletion of exhaustible resources, and adjustment costs for scaling up backstop technology sectors (Morris *et al.*, 2014). Together these linkages among periods expand or contract the primary factors available with which to produce output in future years. The version of the EPPA model described here is recursive dynamic. It steps forward one period at a time, and solves for each period based on available resources, technologies, consumer preferences, and policy incentives and constraints of that period. The recursive dynamic structure is in contrast to a forward-looking model that solves all periods simultaneously to optimize use of resources through time.

Babiker *et al.* (2009) contrast the results of EPPA when solved as a recursive dynamic and forward-looking model and show that while sectoral and price behavior are similar in two versions, macroeconomic costs are substantially lower in the forward-looking version because it allows consumption shifting as an additional way for an adjustment to the policy. A forward-looking model has great theoretical appeal because agents look forward and anticipate the future, hence the savings behavior is endogenously determined by the model. The approach can be questioned for the longer-term projections (especially for those projecting up to 50–100 years) when in practice the decisions are made at a shorter time horizon, with the future uncertain.

In practice, a forward-looking model solution requires a simultaneous consideration of all periods of time, thereby increasing the dimensionality of the problem. As a result, perfect foresight models must generally include substantially less detail of the economy than a recursive dynamic CGE model. A high degree of sectoral detail (especially in the electric sector) could lead to difficulties in finding a solution because of numerical issues in solving very large problems. A perfect foresight formulation greatly limits our ability to link the model to a relatively complex natural Earth system model as it would need to then be a subroutine of the economic model, solving thousands of times as part of the search for optimal response.

Savings and investment are key to economic growth, as savings provide resources for investment, and investment together with the remained capital from the previous period constitute the capital for the production of the following period. Besides, to better account for the different nature of short-run and long-run substitution possibilities between capital and other inputs, EPPA also considers the capital vintaging process. In short, when there is a change in relative prices, the substitution response in a single period will be a combination of both long-run and short-run substitution possibilities—the former is weighted by output produced by malleable capital (i.e., the capital that can move freely between sectors in pursuing higher rate of return), and the latter is weighted by the output produced by vintage capital (i.e., the "old" capital that becomes sector-specific). The dynamics of capital vintaging process is presented in details in Paltsev *et al.* (2005).

Technical change is another important element of economic growth, represented in the EPPA model as: 1) economy-wide productivity growth (in labor, land and energy) described above 2) specification of backstop technology sectors described in the previous section and subject to adjustment costs associated with scaling them up (Morris *et al.*, 2014), and 3) price-driven changes in inputs of production.

Economy-wide productivity growth in labor, land and energy lowers the cost of production in all sectors/technologies that use these factors directly or indirectly through the use of goods that use them in production. All sectors use labor, capital goods are produced with labor (and other inputs) and also used in all sectors. All sectors use energy, directly or indirectly, and so this productivity trend also lowers the cost of producing all goods. Land, as modeled in EPPA is only used directly in agriculture and biomass energy sectors, but again, indirectly productivity improvement lowers costs in other sectors. For example, productivity improvements in land lower the cost of crop and livestock production. A portion of crops are used to feed livestock, which lowers its cost further. And, as a result, food production costs are lower because the sector uses both crops directly and livestock. All these factor-specific productivity improvements contribute to a lower real of cost of producing goods and an increase in broad measures of economic output such as GDP or welfare.

The backstop technology sectors endogenously enter and expand if or when they become competitive with conventional technology sectors due to changes in relative prices or with policies that favor them. The adjustment cost feature captures both rents and real costs if high demand for the output from the sector suddenly appears due to, for example, a large policy shock (Jacoby *et al.*, 2006; Morris *et al.*, 2014). The input requirements of backstop technology sectors are determined based on estimates of a so-called nth plant, when early learning phenomena have been exhausted. As a result, EPPA generally does not include separate learning-by-doing or technology improvement trends in backstop technology sectors—they benefit from the same economy-wide productivity improvements as other sectors. The adjustment cost specification is based on data for scaling up technology sectors further, once they have reached on the order of a one and one-half percent market share. Given that and the 5-year time steps, the EPPA model is ill-suited to examine the early stages of new technology development from just a few plants when learning can be important, but rather is designed to examine the scaling up of the sector to where it possibly fully replaces conventional sectors.

Adjustment costs are modeled by specifying an initially limited, unique-to-the-sector factor of production, which grows over time with output of the sector. This factor represents the initial limited engineering and technical know-how to expand capacity. It is treated as a capital stock with additions to it determined by the level of output of the sector (i.e., dependent on past investment in the sector). Conventional inputs can be substituted for this limited factor, the rate controlled by an elasticity of substitution. The implications of this formulation are that when the new technology becomes competitive, demand for it will create monopoly rents (that could be associated with patents or intellectual property rights associated with the development) and it will also create adjustment costs as the industry tries to expand rapidly, substituting more conventional inputs but getting reducing marginal increases in output for them. Together these phenomena generate a gradual introduction of the technology and a tendency for the price of its output to be initially above the long-run nth plant cost, falling as the sector expands.

Lastly, by substitution among inputs in the production functions represented in EPPA can be considered, in some sense, technical change. While it is often seen as separate from technical change, its specification is not unrelated to the specification of individual sectors or new technologies. The difficulty of separating technical change from an elasticity response has been well recognized (Diamond *et al.*, 1978; Webster *et al.*, 2008). The structure of the model has direct implications for a choice of elasticity of substitution between the inputs of production. For example, early versions of EPPA had a more aggregated electricity sector, where substitution between fuel inputs and capital implicitly represented a switch, in part, to non-fuel using generation technologies such as hydro, nuclear, wind, or solar. With these now separately represented, the remaining energy generation technology can be more clearly identified with engineering descriptions of technology that converts fossil fuels to electricity, where there are limits to the efficiency with which this can be done. Thus, identifying these explicit technologies constrains the choice of the substitution elasticity between fuels and capital, in combination with exogenous efficiency improvements, so that thermodynamic limits to conversion efficiency are not violated. This same re-evaluation of elasticities was necessary in modeling transportation. In earlier versions of EPPA, household transportation had a single representative vehicle and substitution from fossil energy to other inputs could implicitly represent a shift to a variety of different vehicle technologies. With the explicit introduction of hybrid vehicles, electric vehicles, and other vehicle fuels, the original specification should reflect current internal combustion engine vehicles, and the substitution potential only within that type of power train. Thus, the ability to improve efficiency of fuel use has been informed by engineering studies of the limits to and costs of these improvements.

2.5 Linkage to Physical Quantities

As described in Paltsev *et al.* (2005), the EPPA model is a hybrid economic and physical accounting model. While traditional CGE models measure all their inputs and outputs in monetary values (dollars, euros, yuan, etc), the EPPA model also tracks important physical flows such as emissions of pollutants, depletion of resources, changes in land use, and the efficiency of physical processes such as conversion of fuels to electricity. Similar to earlier versions of EPPA, population growth is exogenous to the model (see Section 4 for details). As mentioned, the EPPA model is a part of the MIT IGSM with the goal to study the Earth as an interacting system which requires the formulation of links between an economic model such as EPPA and other components that go beyond the traditional focus of CGE models. To capture links between resource use and depletion, fuel use and emissions, and land use change and its physical effects requires associating quantities measured in economic units with appropriate physical quantities. This need to link physical and economic changes has driven key developments in EPPA toward what is now a hybrid model—one that operates as a conventional computable general equilibrium model but includes supplemental accounting of the physical and biological variables. Earlier EPPA versions contained such supplemental tables for physical energy use, as they were necessary for accounting of carbon dioxide emissions. They also included accounting of key pollutant emissions. Physical accounting has been extended in EPPA5 to include physical accounting of shifts in land use of the types identified in Table 2.

3. Equilibrium Structure and Representation of Production, Consumption and Trade

The equilibrium structure of EPPA5 is similar to that documented in Paltsev *et al.* (2005). In the following section, we provide a description of the model formulation.

3.1 Equilibrium Structure

All production sectors and final consumption are modeled using nested Constant Elasticity of Substitution (CES) production functions (or Cobb-Douglas and Leontief forms, which are special cases of the CES). The model is solved using the MPSGE modeling language (Rutherford, 1999). The EPPA model is formulated and solved as a mixed complementarity problem (MCP) (Mathiesen, 1985; Rutherford, 1995), where three inequalities must be satisfied: the zero profit, market clearance, and income balance conditions. Using the MCP approach, a set of three non-negative variables is involved: prices, quantities, and income levels.

The zero profit condition requires that any activity operated at a positive intensity must earn zero profit (i.e., value of inputs must be equal or greater than value of outputs). Activity levels y for constant returns to scale production sectors are the associated variables with this condition. It means that either $y > 0$ (a positive amount of y is produced) and profit is zero, or profit is negative and $y = 0$ (no production activity takes place). Specifically, the following condition must be satisfied for every sector in an economy[1]:

$$\text{profit} \geq 0,\ y \geq 0,\ \text{output}^{T}(-\text{profit}) = 0. \quad (1)$$

1 An expression written as $x^T y = 0$ (when $x \geq 0$ and $y \geq 0$) means $x_i\ y_i = 0$, for all $i = 1,\ldots,n$. The variables x_i and y_i are called a complementary pair and are said to be complements to each other.

The market clearance condition requires that any good with a positive price must have a balance between supply and demand and any good in excess supply must have a zero price. Price vector p (which includes prices of final goods, intermediate goods and factors of production) is the associated variable. Using the MCP approach, the following condition must be satisfied for every good and every factor of production:

$$\text{supply}-\text{demand} \geq 0,\ p \geq 0,\ p^{T}(\text{supply}-\text{demand}) = 0 \quad (2)$$

The income balance condition requires that for each agent (including any government entities) the value of income must equal the returns to factor endowments and tax revenue:

$$income = endowment + tax\ revenue. \quad (3)$$

A characteristic of the CES production and consumption structures that are used throughout EPPA is that all inputs (consumption goods) are necessary inputs. Thus, for most markets the above conditions are satisfied with prices, output, income, and consumption of all goods strictly greater than zero, and with supply strictly equal to demand. Falling demand for an input or consumption good will simply mean that the price will fall very low. The exceptions are for those goods that enter as perfect substitutes—such as many of the backstop technology sectors modeled in EPPA. Their prices and output levels are zero until they are economically competitive. In a simple form, the corresponding optimizing problem more typical in to economic theory can be summarized as follows.

Behavior of Firms

In each region (indexed by the subscript r) and for each sector (indexed interchangeably by i or j), a representative firm chooses a level of output y, quantities of primary factors k (indexed by f) and intermediate inputs x from other sectors j to maximize profits subject to the constraint of its production technology. The firm's problem is then:

$$\max_{y_{ri}, x_{rji}, k_{rfi}} \pi_{ri} = p_{ri} y_{ri} - C_{ri}(p_{ri}, w_{rf}, y_{ri}) \ \text{s.t.}\ y_{ri} = \varphi_{ri}(x_{rji}, k_{rfi}) \quad (4)$$

where π and C denote the profit and cost functions, respectively; and p and w are the prices of goods and factors, respectively.

In EPPA, we assume that production is represented by constant elasticity of substitution (CES) technologies that exhibit constant returns to scale (CRTS). These assumptions greatly simplify the firm's problem in (4). First, the linear homogeneity of the cost function implied by duality theory enables us to re-express (4) in terms of the unit cost and unit profit functions. Second, CRTS implies that in equilibrium firms make zero economic profits. Hence, the firm's optimizing behavior implies the equilibrium condition:

$$p_{ri} = c_{ri}(p_{rj}, w_{rf}) \quad (5)$$

where c is the unit cost function.

By Shephard's Lemma, in sector i the intermediate demand for good j is

$$x_{rji} = y_{ri} \frac{\partial c_{ri}}{\partial p_{rj}} \quad (6)$$

and the demand for factor f is

$$k_{rfi} = y_{ri} \frac{\partial c_{ri}}{\partial w_{rf}} \quad (7)$$

Household Behavior

In each region, a representative agent is endowed with the supplies of the factors of production, the services of which may be sold or leased to firms. In each period, the representative agent chooses consumption and saving to maximize a welfare function subject to a budget constraint given by the level of income M:

$$\max_{d_{ri}, s_r} W_{ri}(d_{ri}, s_r) \ \text{s.t.}\ M_r = \sum_f w_{rf} K_{rf} = p_{rs} s_r + \sum_i p_{ri} d_{ri} \quad (8)$$

where s is saving, d is the final demand for commodities, K is the aggregate factor endowment of the representative agent in region r.

Like production, preferences are represented by a CES utility function. By duality and the property of linear homogeneity, for each region there exists a unit expenditure function or welfare price index that corresponds to the configuration in (8), given by:

$$p_{rw} = E_r(p_{ri}, p_{rs}) \quad (9)$$

By Shephard's Lemma, the compensated final demand for goods is given by:

$$d_{ri} = \overline{m}_r \frac{\partial E_r}{\partial p_{ri}} \quad (10)$$

and that for savings is

$$s_r = \overline{m}_r \frac{\partial E_r}{\partial p_{rs}} \quad (11)$$

where $\overline{m}_r$ is the initial level of expenditure in each region.

The system is closed with a set of market clearance equations that determine the equilibrium prices in the different goods and factor markets. Suppressing for simplicity the final demand categories investment, government and foreign trade, these equations are:

$$y_{ri} = \sum_j y_{rj} \frac{\partial C_{rj}}{\partial p_{ri}} + \overline{m}_r \frac{\partial E_r}{\partial p_{ri}} \tag{12}$$

and

$$K_{rf} = \sum_j y_{rj} \frac{\partial C_{rj}}{\partial w_{rf}} \tag{13}$$

The following sections elaborate on the practical implementation of the abstract production and demand structures shown here.

3.2 Production

Production technologies are described using nested CES functions. The nesting structures for most sectors remain unchanged in EPPA5 from EPPA4 (Paltsev *et al.*, 2005), except as they incorporate further disaggregation. Key elasticities of substitution used in EPPA5 are given in **Table 3** and the nesting structure of production sectors is provided in Appendix A.

3.3 International Trade

In general, we maintain the same trade structure as previous EPPA versions. Crude oil is imported and exported as a homogeneous product, subject to tariffs, export taxes, and international transport margins. Given the transportation costs and different products/grades involved, we treat coal, gas, and refined oil as Armington goods. The Armington good assumption is perhaps least justified in the case of gas. Historically, markets for gas were national/regional because of limits to transportation via pipeline, and thus prices in different markets could diverge. Increasingly, transport of liquefied natural gas (LNG) via ship provides the flexibility to direct gas to regional markets based on returns. We have three options for natural gas trade in EPPA5: 1) gas as an Armington good; 2) gas as a globally homogenous good; and 3) gas as a homogenous good within composite regions of EPPA but as an Armington good among these composite regions.

All goods in the model are traded in world markets. Electricity trade is represented but very little trade occurs in the base year data, and it only occurs among regionally contiguous regions. The share-preserving nature of the

Table 3. Reference Values of Production Sector Substitution Elasticities

σ_j	Description	Value	Comments
Energy Substitution Elasticities			
σ_{EVA}	Energy-Value Added	0.4–0.5	Applies in most sectors, 0.5 in EINT, OTHR
σ_{ENOE}	Electricity-Fuels aggregate	0.5	All sectors
σ_{EN}	Among fuels	1.0	All sectors except ELEC
σ_{EVRA}	Energy/Materials/Land-Value Added	0.7	Applies only to CROP, LIVE, FORS
σ_{ER}	Energy/Materials-Land	0.6	Applies only to CROP, LIVE, FORS
σ_{AE}	Energy-Materials	0.3	Applies only to CROP, LIVE, FORS
σ_{CO}	Coal-Oil	0.3	Applies only to ELEC
σ_{COG}	Coal/Oil-Gas	1.0	Applies only to ELEC
Other Production Elasticities			
σ_{VA}	Labor-Capital	1.0	All sectors
σ_{GR}	Resource-All other inputs	0.6	Applies to OIL, COAL, GAS sectors, calibrated to match medium run supply elasticity
σ_{NGR}	Nuclear Resource-Value added	0.04–0.4	Varies by region
Armington Trade Elasticities			
σ_{DM}	Domestic-Imports	2.0–3.0	Varies by good
		0.3	Electricity
σ_{MM}	Among Imports from different regions	5.0	Non-Energy goods
		4.0	Gas, Coal
		6.0	ROIL
		0.5	Electricity

CES function tends to limit expansion of electricity trade, and, realistically given difficulty of transmission, prevents trade from ever occurring among two regions if it is not in the base data. For example, trade in electricity between Japan, Europe, and the US is not possible. The Armington goods specification allows an explicit representation of bilateral trade flows, calibrated to the base year, 2004, such that regions are both exporters and importers of a particular good. Bilateral trade flows involve export taxes, import tariffs, and international transport margins, all of which are explicitly represented in the model.

3.4 Consumption

The EPPA model uses a nested CES structure to describe preferences as well as production, as this specification is compatible with the MPSGE solver. The nesting structure for the household consumption sector in EPPA5 is the same as in EPPA4, which is documented in Paltsev *et al.* (2005). For convenience, it is also provided in Appendix A. The reference values for elasticities in the household sector are provided in **Table 4**.

4. New Features in EPPA5

In addition to updates of the underlying base year economic data to GTAP7 (Narayanan and Walmsley, 2008), and to UN (2013) population projections **(Table 5)**, the major changes in the EPPA5 structure include an introduction of land use change (Gurgel *et al.*, 2007), personal transportation detail (Karplus *et al.*, 2011), detail in the representation of the electricity sector (Morris *et al.*, 2014), and biofuel production (Winchester and Reilly, 2015).

4.1 Land Use Change Representation

In EPPA4 land is an aggregate primary input factor without a supplemental physical account representation. In EPPA5 five different land types are introduced, namely: crop, pasture, managed forest, forest, and natural grass. For the physical land accounting there is an additional land category, "other", which represents land types that are not currently suitable for agriculture or forestry, such as deserts, wetlands, ice sheets, tundra, built areas. In EPPA, it is assumed that such lands will never be suitable for agriculture or forestry in our simulations of the future. Each of the five land types are modeled as a renewable resource whose quantities can be altered through conversion or abandonment to another type. Gurgel *et al.* (2016) provide a detailed discussion of the approach and compares it with other approaches. There has been concern at times that yield growth may plateau but evidence for that is weak (Reilly and Fuglie, 1998). Recent work suggests yield growth trends are subject to structural breaks (Gitiaux *et al.*, 2011), and so apparent plateaus give rise to periods of more rapid growth or vice versa. Average yield improvements of 1% per year are consistent with global yield increases reported by Ray *et al.* (2013, Table 1) and Winchester and Reilly

Table 4. Reference Values for Final Demand Elasticities

σ_j	Description	Value	Comments
	Final Demand Elasticities for Energy		
σ_{EC}	Energy-Other Consumption	0.25	
σ_{EF}	Among Fuels and Electricity	0.4	
σ_{FSO}	ROIL-Services/ Other	0.3	Increases over time
	Other Final Demand Elasticities		
σ_{CS}	Consumption-Savings	0.0	
σ_{C}	Among Non-Energy goods	0.25–0.65	Base year values that among countries, and increase with per capita income
σ_{CT}	Transportation—Other Consumption	1.0	
σ_{PO}	Purchased-Own Transportation	0.2	
σ_{SO}	Services-Other	0.5	In the Own-Transportation bundle

Table 5. Summary of the UN Population Forecast (millions)

Region	2010	2050	2100
USA	309	400	465
CAN	34	45	51
MEX	118	156	140
JPN	127	108	84
ANZ	38	57	65
EUR	522	533	498
ROE	230	256	223
RUS	144	121	102
ASI	506	661	651
CHN	1367	1394	1093
IND	1206	1620	1547
BRA	195	231	195
AFR	1031	2393	4185
MES	211	359	424
LAM	277	380	372
REA	602	837	760

Note: Population Data Source: UN (2013). Description of the EPPA regional abbreviations is provided in **Figure 1**.

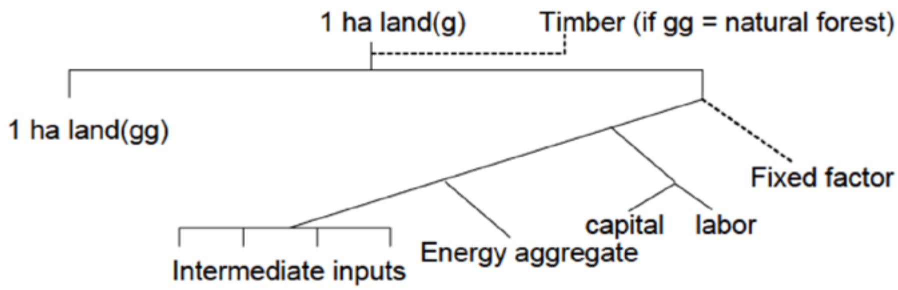

Figure 3. Structure of land transformation functions

(2015).[2] As with other productivity trends, this rate can be varied to understand implications of faster or slower improvement. We also note that in addition to the exogenous productivity growth, substitution of other inputs for land is an additional source of physical yield growth per hectare, endogenously determined by factors that affect the relative price of land and other inputs to agricultural production.

In EPPA5, land is integrated into the CGE framework subject to two requirements: (1) consistency between the physical land accounting and the economic accounting in the general equilibrium setting, and (2) consistency with observations as recorded in the CGE data base for the base year. Failure of the first condition would lead to inconsistencies in the physical accounts, while that of the second would mean that the base year data will be out of equilibrium. Consequently, the model would immediately jump from the base year to the equilibrium state consistent with parameterization of land rents and conversion costs.

The first condition is achieved by assuming that 1 hectare of land of one type is converted to 1 hectare of another type, and through conversion it takes on the average productivity level for that type of land in a given region. The second of these conditions is achieved by observing that in equilibrium the marginal conversion cost of land from one type to another should be equal to the difference in their values. We require that conversions take real inputs through a land transformation function as shown in **Figure 3**. The dashed line at the top indicates a fixed coefficient multi-product production function that produces, in addition to accessible cleared land, a forestry product (i.e. timber and other forestry products) that is a perfect substitute for output of the forestry sector. The fixed factor and the associated elasticity of substitution between it and other conversion inputs allow us to calibrate the conversion response to observed data.

Abandonment of agricultural land with return to natural conditions is allowed in the model. We assume that abandonment occurs at zero cost, and that any prior investments in the abandoned land are fully depreciated—if at some distant date in the future there is reason to convert it back, the full cost of conversion applies.

We use data for land rents provided in Lee *et al.* (2005) for crops, pastures and managed forests. These data are an aggregate rental value for all land of each type. They must be considered "use" values as they come from national economic statistical agencies that represent actual monetary transactions or in the case of land an inferred payment that must be consistent with data on revenue, input costs and returns to other factors. Thus, it is inappropriate to attribute these rental values to lands that are not in current use such as unmanaged forest and grassland. To get per hectare rents the aggregate rental value is divided by the physical quantity of land, but to be comparable to observed rents the physical quantity can include only that land which is used on some regular basis. To separate out unmanaged land that is not producing any current income flow we use the Hurtt *et al.* (2006) data base, which is an elaboration of the underlying physical data used in Lee *et al.* (2005). This data set contains areas of natural grassland and natural forest, as well as other land (tundra, built up land, wetlands, and desert).

While conversion costs from managed forest to cropland and pasture, or from pasture to cropland, is by our equilibrium assumption, equal to the difference in value of these types, we have no information on the "value" of land not currently in use, or any costs of conversion. A particular issue for unmanaged forests is that these by definition include a large stock of standing timber that is potentially very valuable. In contrast, land in the managed forestry sector will be at various stages of a rotation—assuming for simplicity that an optimal rotation is 30 years then only on the order of one-thirtieth of the area is harvested in any one year.

To estimate the land conversion and access costs, and the potential value of unmanaged land, we use data available from Sohngen (2007). He deduces conversion costs from equilibrium conditions under assumptions similar to ours. In particular, he assumes that at the margin the cost of ac-

2 Note that Ray *et al.* (2013) report non-compounding yield improvements, while we specify a (compounding) yield growth rate.

cess to remote timber lands must equal the value of the standing timber stock plus that of future harvests as the forest regrows. He then calculates the net present value using his optimal timber harvest model for each region of the world and for different timber types. Setting the access costs to this value establishes the equilibrium condition that observed current income flow (i.e., rent and returns) from currently inaccessible land is zero because the timber there now and in the future can only be obtained by bearing costs to access it equal to its discounted present value.

We use Sohngen's data, along with some simplifying assumptions, to calculate an average standing stock of timber for each of our regions and the value of the land. In particular, we observe that:

$$NPVofVirginForest = X_0 + \sum_{t=1}^{\infty} \frac{X_t}{(1+r)^t} \tag{14}$$

where X_0 is the value of the standing timber stock on the virgin forest and X_t is the value of future harvests. The value of future harvests is taken to be the value of land once the timber stock is gone: i.e., the value of the land rests in its ability to produce future harvests. We assume that future harvests are some fraction, θ, of X_0, with θ set to 1. Sohngen (2007) also provides the optimal rotation age for these lands.

Assuming optimal rotation once the virgin forest is harvested means that $X_t = 0$ in every year except when there is a harvest. Recognizing this fact allows us to rewrite equation (14) where we define the time period to be of length equal to the optimal rotation, and then make the value of r consistent with that time period length. For example, for an optimal rotation of 30 years, $t=1$ will occur when 30 years have passed, and $t=2$ when 60 years have passed, etc. Assuming an interest rate of 5% per annum means that $r = 1.05^{30} - 1 = 3.32$. This allows us to rewrite equation (14) as:

$$NPVofVirginForest = X_0 + \sum_{t'=1}^{\infty} \frac{\theta X_0}{(1+r)^{t'}} \tag{15}$$

where t' is the time index where a period is of length equal to the optimal rotation for the forest which varies by region. With future harvests held constant (independent of t) and recognizing that the infinite discount factor is just 1/r, equation (15) can be solved for X_0:

$$\frac{NPVofVirginForest}{1+\theta/r} = X_0 \tag{16}$$

This allows us to deduce from the Sohngen (2007) data the value of timber stocks in virgin forests, and for CGE purposes the quantity, in value terms, of timber when it is harvested. The residual value is then the value of future timber harvests—i.e., the value of the land. Sohngen (2007) provides the areas in each type of forest, the NPV, and optimal rotation. Since we have only one "unmanaged" forest land type, we calculate a weighted average among different types for each of our regions. We do not have similar data for natural grassland, which obviously does not have a timber stock on it. We assume that natural grassland rent relative to pasture is the same as rent of natural forest relative to managed forest. The resulting regional land rents by land class are shown in **Table 6**.

To calibrate the land conversion function of natural forests to managed forests in the base year we need to split the forestry output and their land requirements in two: the value of production from managed forest land and the value of production from clearing natural forests. Sohngen (2007) provides information on total hectares occupied by forestry plantations, the annual forest area harvested and changes in the area of forests (plantation and natural) by region. The output share from natural forest areas can be quite large even though the land amount in any one year is small relative to the managed forest area because the timber stock on natural forest land is large: by definition all of it is being harvested that year whereas much of the managed forest land is in some stage of regrowth and not yet ready for harvest. We use these shares to re-benchmark the output of the forestry sector and its land requirements, and also to assign the value of timber production from the conversion of virgin forest.

Table 6. Land Rents per Hectare at Regional Level (2004 US$/ha)

Region	Cropland	Pasture	Managed Forest	Natural Grass	Natural Forest
USA	140.7	73.2	16.2	11.7	2.6
CAN	31.9	46.7	50.4	0.0	8.1
MEX	244.6	46.2	4.6	0.8	0.8
JPN	1936.8	7039.9	99.2	0.0	35.7
ANZ	64.5	6.5	7.3	2.9	3.3
EUR	146.3	280.0	45.1	5.6	0.9
ROE	49.0	13.8	13.1	0.3	0.3
RUS	30.6	32.9	9.9	6.6	2.0
ASI	398.8	752.3	54.6	0.0	19.1
CHN	163.7	121.5	76.3	7.3	4.6
IND	249.6	393.9	17.0	0.0	3.7
BRA	60.9	12.5	1.8	1.1	0.2
AFR	57.4	5.0	4.1	0.4	0.3
MES	162.6	9.0	14.5	7.8	12.5
LAM	139.8	22.6	6.3	2.8	2.9
REA	147.9	50.4	16.0	10.8	11.4

The elasticity of substitution between the fixed factor and other inputs represented in Figure 3 is parameterized to represent observed land supply response in the 1990s to present. We calculate an own-price land supply elasticity for each region in the following manner: We observe the average annual percentage land price increase from 1990 through 2005 and the average annual natural forest area converted to managed land as a percentage of managed land over the same period which allows calculation of the elasticity of supply (εs) using the definition

$$\varepsilon_S = \frac{\%\Delta Q}{\%\Delta P} \qquad (17)$$

where Q and P are land quantity and price, respectively. We follow Hyman *et al.* (2003) to determine the relationship between the elasticity of substitution (σ) and the elasticity of supply:

$$\sigma = \frac{\varepsilon_S}{1-\alpha} \qquad (18)$$

where α is the cost share of the fixed factor.

For the land price changes we consider data from 1990 to 2005 for the US from the Economic Report of the President (2007). Land price data are not easily available in much of the world but because of global commodity trade we expect similar price movements of land globally. Beyond this theoretical argument, evidence that land prices move in parallel internationally are provided by Sutton and Web (1988). Based on this assumption, we use the US percentage price change for all regions. Average annual conversion rates of land over the 1990s are derived from the land cover database of Hurtt *et al.* (2006).

Table 7 presents the parameters associated with the natural forest land parameterization including the share of forest product from managed and natural forests, the share of land converted, our calculated elasticity of supply of land based on equation (17), and the elasticity of substitution from equation (18). While the land supply elasticity is estimated very simply, we note that Sohngen and Mendelsohn (2007) use a land supply elasticity of 0.25 in their forest modeling study, conducting sensitivity analysis for elasticities of 0.13 to 0.38 arguing that these are representative of the range in the literature. The average global response we would get from our regionally varying elasticities is well within this range. Our approach based on observed conversion rates has the advantage of giving us variation in regional response consistent with recent data, and the general observation of a greater willingness to convert land in tropical developing countries than in developed regions.[3]

3 Some regions had virtually no net conversion from natural areas to agricultural in the historical data. For these regions we assigned an elasticity of 0.02.

Table 7. Parameters to Model Natural Land Use Transformation Functions

Region	Share of forestry output from natural forest cleared	Share of natural forest land being cleared from total land used to produce forestry output	Elasticity of land supply	Elasticity of substitution among fixed factor and other inputs
USA	0.10	0.0037	0.02	0.020
CAN	0.01	0.0002	0.08	0.080
MEX	0.08	0.0211	0.30	0.304
JPN	0.01	0.0015	0.02	0.020
ANZ	0.04	0.0219	0.30	0.305
EUR	0.01	0.0013	0.02	0.020
ROE	0.01	0.0020	0.02	0.020
RUS	0.01	0.0001	0.10	0.100
ASI	0.80	0.2141	0.45	0.456
CHN	0.01	0.0005	0.02	0.020
IND	0.07	0.0233	0.03	0.031
BRA	0.24	0.0586	0.36	0.366
AFR	0.10	0.0218	0.50	0.507
MES	0.01	0.0083	0.05	0.050
LAM	0.05	0.0330	0.84	0.860
REA	0.22	0.0709	0.30	0.302

4.2 Private Transportation

The EPPA5 model includes a technology-rich representation of the passenger vehicle transport sector and its substitution with purchased modes, which include aviation, rail, and marine transport. Several features were incorporated into the EPPA model to explicitly represent passenger vehicle transport sector detail. These features include an empirically-based parameterization of the relationship between income growth and demand for vehicle miles traveled (VMT), a representation of slow fleet turnover, and opportunities for fuel use and emissions abatement, including representation of the plug-in hybrid electric vehicle. Where these developments enter into the production nest is described in **Figure 4**. Parameters for the transportation sector representation are provided in **Table 8** and **Table 9**. Fleet turnover is a form of capital vintaging, however, to avoid introducing many new vintages for each vehicle type, we use a simplified structure. The average characteristics of a single used vehicle vintage are updated each period based on new additions to the fleet and retirements. These model developments are described in detail in Karplus *et al.* (2013). Here we briefly summarize the model features that capture heterogeneity in the transportation system across regions.

In an economy-wide analysis of fuel economy standards it is essential to differentiate between the new and used vehicle fleets, given that the current standard constrains only new model year vehicles sold, but energy and emissions depend on characteristics of the total fleet and turnover dynamics. The EPPA model includes a parameterization of the total miles traveled in both new (0 to 5-year-old) and used (6 years and older) vehicles (**Table 9**, column VMT) and tracks changes in travel demand in response to changes in income as well as price-per-mile. The EPPA framework allows explicit specification of substitution between new and used vehicles, for instance. With this specification, when there is a fuel economy standard that raises up-front vehicle cost, the model can capture the fact that households could respond by holding on to their existing vehicles longer or selling their old cars and buying new and more fuel efficient ones with higher prices. This specification captures how consumers respond to changes in relative prices, including those due to the introduction of a fuel economy policy or an increase in the price of fuel given a carbon price. A schematic representation of the detailed production structure for both new and used vehicles are shown in Figure 4.

We represent opportunities to reduce petroleum-based fuel use and emissions by improving the efficiency of the internal combustion engine (ICE-only) vehicle, by substituting compatible fuels, and by reducing travel demand. We also represent similar opportunities for a plug-in hybrid electric vehicle (PHEV), which is modeled as a substitute for the ICE-only vehicle that can run on gasoline in a downsized internal combustion engine (ICE) or on grid-supplied, battery-stored electricity. The PHEV itself is assumed to be 30% more expensive relative to a new internal combustion engine (ICE)-only vehicle. Vehicle characteristics and technology requirements for the PHEV are defined based on a mid-sized sedan, which relies on grid-supplied electricity for 60% of miles-traveled and liquid fuels for the remaining 40%. The ICE fuel economy of the PHEV assumes operation in hybrid (charge-sustaining) mode, while the battery is

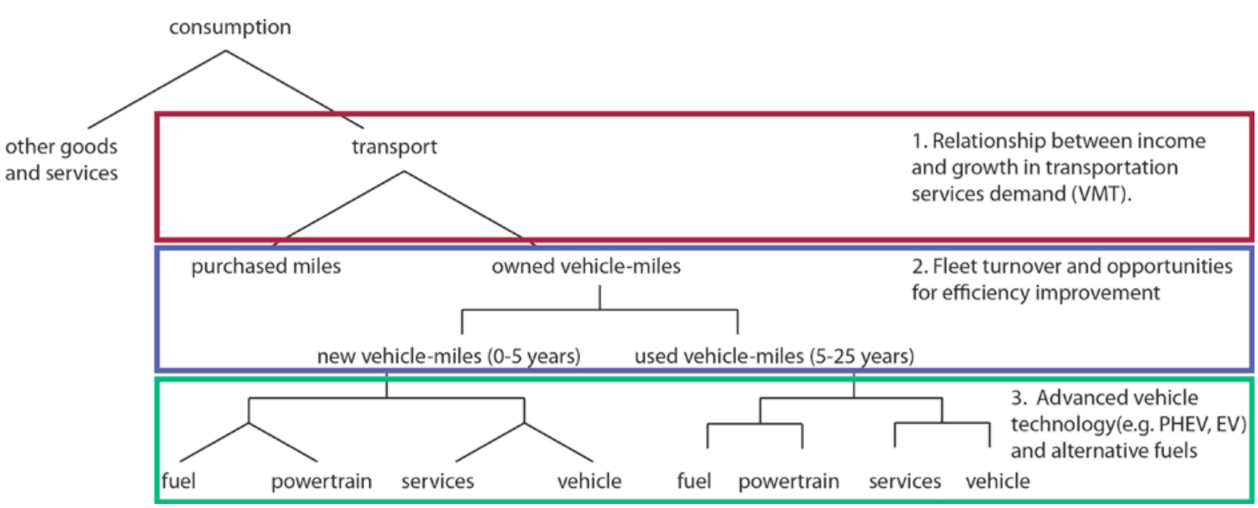

Figure 4. Schematic overview of the passenger vehicle transport sector incorporated into the representative consumer's utility function of the EPPA5 model.

Table 8. Transport sector parameters. Source: Karplus (2011).

Symbol	Description	Value
σ_{TRN}	Households' consumption of transport vs. other goods and services	0.5
σ_{HTRN}	Purchased vs. own-supplied household transport	0.2
σ_{VS}	Services vs. non-powertrain vehicle capital	1
$\sigma_{FE,ICE}$	Fuel vs. vehicle powertrain capital, internal combustion vehicle	0.75
$\sigma_{FE,PHEV}$	Fuel vs. vehicle powertrain capital, plug-in hybrid electric vehicle	0.1
$\sigma_{FE,EV}$	Fuel vs. vehicle powertrain capital, electric vehicle	0.1
$\sigma_{FE,CNGV}$	Fuel vs. vehicle powertrain capital, compressed natural gas vehicles	0.5
$\sigma_{FS,PHEV}$	Refined oil vs. electricity as fuels, plug-in hybrid electric vehicle	0.1
$\sigma_{FF,PHEV}$	Technology specific factor elasticity, plug-in hybrid electric vehicle	0.2
$\sigma_{FF,EV}$	Technology specific factor elasticity, electric vehicle	0.2
$\sigma_{FF,CNGV}$	Technology specific factor elasticity, compressed natural gas vehicle	0.2
$FF_{0,PHEV}$	Initial technology specific factor input share, plug-in hybrid electric vehicle	0.05
$FF_{0,EV}$	Initial technology specific factor input share, electric vehicle	0.05
$FF_{0,CNGV}$	Initial technology specific factor input share, compressed natural gas vehicle	0.01
ES	Expenditure share of transport in total household consumption	
OS	Share of household refined oil consumption used as transport fuel	
FE	On-road average fuel economy, household vehicles	
VDT_N	Annual vehicle distance travelled, household vehicles 0–5 years old	
VDT_V	Annual vehicle distance travelled, household vehicles ≥6 years old	
Stock	Base-year stock of household vehicles	
η_{TRN}	Income elasticity of household transport demand	

Table 9. Household transport region-specific parameters. Source: Karplus (2011).

Region	ES	OS	FE	VMT_N	VMT_V	Stock	η_{TRN}
[0]	[0]	[0]	[miles/gallon]	[miles]	[miles]	[10^6 units]	[0]
AFR	0.053	0.875	23.4	0.1353	0.1997	6.9	0.7
ANZ	0.104	0.992	21.7	0.0388	0.0835	14.9	0.7
ASI	0.068	0.850	19.9	0.1061	0.1812	21.9	0.7
BRA	0.098	0.900	25.5	0.0583	0.0952	20.8	1
CAN	0.129	0.921	21.4	0.043	0.1451	18.2	0.7
CHN	0.042	0.995	22.3	0.3432	0.0144	26.4	5
EUR	0.134	0.855	27.1	0.5986	1.0806	215.6	0.7
IND	0.084	0.900	28.2	0.0445	0.1039	17.4	1
JPN	0.070	0.829	28.8	0.1822	0.1447	76.3	0.675
LAM	0.060	0.854	18.1	0.0458	0.097	11	1
MES	0.090	0.323	15.1	0.0284	0.1029	6.8	1
MEX	0.070	0.862	16.6	0.057	0.1625	16.7	1
REA	0.060	0.443	21.7	0.0129	0.0151	13.9	1
ROE	0.085	0.388	23.9	0.0162	0.0298	27.8	0.85
RUS	0.087	0.990	23.4	0.0654	0.1525	20	0.7
USA	0.104	0.988	20.1	0.962	1.443	200.9	0.7

sized for an all-electric range of 40 miles. As the levelized price per mile of ICE vehicle travel increases over time (with increasing fuel cost and the introduction of efficiency technology), the cost gap is allowed to narrow and may eventually favor adoption of the PHEV, depending on the price impacts of other model dynamics.

We also simulate the ability to reduce the fuel consumption of newly sold PHEVs by investing in efficiency improvements. For the PHEV, we develop a marginal abatement cost curve using the same procedure as was used for the ICE-only vehicle described above, but using the PHEV as the new more efficient "base" vehicle and including opportunities to reduce fuel consumption specific to the PHEV. For instance, mild hybridization of the ICE (e.g., adding a battery to store energy during breaking and using it to assist ICE operation) is included as a fuel consumption reduction opportunity for the ICE-only vehicle, but not for the PHEV, because the PHEV is assumed to have this capability (and it is reflected in the fuel efficiency of miles driven using the ICE). Opportunities to improve the efficiency of the PHEV include improvements such as light weighting, further engine downsizing, and the addition of low rolling resistance tires, among others.

When initially adopted, the PHEV faced increasing returns to scale as parameterized in earlier work, to capture the intuition that development and early deployment are more costly per unit produced until large-scale production volumes have been reached, which also affects its cost relative to the ICE vehicle (Karplus *et al.*, 2010). The PHEV competes against an ICE-only vehicle, which as described above is parameterized to become more efficient in response to rising fuel prices using off-the-shelf technology. As ever larger volumes of PHEVs are introduced, cost of further scaling production will fall accordingly. The model chooses the least cost combination that is capable of achieving standard compliance. The model captures the intuition that the cost and pace of PHEV deployment should depend on when these vehicles become economically viable, stringency of the fuel economy standard, and the rate at which costs decrease as production is scaled up. The results of this analysis are sensitive to the parameterization of these responses, and therefore we have calibrated these responses based on the range of available empirical data (Karplus *et al.*, 2013).

4.3 Power Sector Representation

The GTAP dataset only includes production activities that operated in the benchmark year. As we look to the future, particularly under severe environmental policy constraints energy technologies now not widely in use because they are not currently profitable are likely to become a more important part of the energy mix. These include technologies that do not operate other than in very limited demonstration mode (e.g., power production with carbon capture and storage (CCS)), operate at small scale in the base year (e.g., renewable electricity, biofuel, alternative vehicle technology), or where costs of new version of the technology are much different than those currently operating (e.g., nuclear). To include these we add backstop technology sectors that represent these advanced technologies. In general, the output of a backstop technology sector is represented as a perfect substitute for the output of an existing sector the backstop technology sector competes with.

Since these technologies are not represented in the base economic data, cost data and the production structure for these technologies are based on "bottom-up" engineering estimates available in the literature. By convention, the input share parameters in each are set so that they sum to 1.0, as in conventional technologies. As prices are normalized to 1.0 in our benchmark dataset, cost differences between energy produced from an advanced and the conventional technology for which its substitutes is captured by a markup factor. For each technology, the markup is defined as the cost of advanced production divided by the cost of production from the competing conventional technology. For example, a markup of 1.2 for biofuel production indicates that biofuels are 20% more expensive than conventional fuel in the base year. The markup is multiplied times all of the inputs, except for resource inputs we account for physically.[4] Excluding these ensures that physical relationships such as energy yield per hectare or efficiency of conversion of fuel to electricity are preserved. The mark-up and input share parameters define the advanced technologies over the horizon of the model. The actual relative cost of the advanced and conventional technology after the base year is determined endogenously as the cost of inputs change. For example, land productivity change will affect biofuel costs, depletion of resources will affect crude oil and refined oil product costs, and carbon pricing and other environmental regulations will affect relative costs, as will labor productivity, capital costs, and other input prices.

EPPA5 includes 14 electricity generation technologies: five traditional (coal, natural gas, oil, nuclear, hydro) and nine advanced electricity generation technologies: 1) wind, 2) solar, 3) bio-electricity, 4) wind with natural gas backup, 5) wind with biomass backup, 6) natural gas combined cycle (NGCC), 7) NGCC with carbon capture and sequestration (CCS), 8) coal with carbon capture and sequestration, and 9) advanced nuclear. The

4 To preserve the relationship between physical input (fuels and land) and output (electricity, bioenergy) we exclude the cost share of these when estimating the markup consistent with the literature and do not apply the mark-up to these inputs in the model.

advanced electric generation technologies include an additional technology specific factor (TSF) at the top of the nest that represents adjustment costs, described in Section 2.4. Most of these technologies enter as perfect substitutes for existing technologies, signified by $\sigma = \infty$ at this nest level, with the exception of wind & solar and bio-electricity (as discussed below). These technologies are also vintage, as described in Section 2.4.

The input shares and markups for advanced electricity technologies are determined using a levelized cost of electricity (LCOE) calculation. The LCOE calculation uses data (e.g., from the US Energy Information Administration (EIA), International Energy Agency (IEA) and other sources) for the model base year on overnight capital costs, fixed and variable operation and maintenance costs, fuel costs[5], heat rates, and capacity factors to calculate a cost per kilowatt hour for each generation technology. The costs used in the calculation are for the "nth of a kind" plant for each technology, meaning the costs after learning and adjustments from initial market penetration have taken place. **Table 10** shows an example LCOE table.

The factor inputs vary by technology. The main inputs are capital, labor, fuel, land (for biomass), and technology specific factor. Some technologies further disaggregate capital and labor into capital or labor for transmission and distribution or capital or labor for sequestration.

5 Fuel costs used in the LCOE calculation are a 5-year average around the model base year.

Table 10. Calculating the markups in the EPPA model

		Units	Coal	Coal with CCS	NGCC	NGCC with CCS	Advanced Nuclear	Biomass	Wind	Solar PV	Wind + Biomass	Wind + Gas
[1]	"Overnight" Capital Cost	$/kW	2049	3481	892	1781	3521	3548	1812	5688	5360	2705
[2]	Total Capital Requirement	$/kW	2377	4177	964	1995	4930	4116	1957	6144	5789	2921
[3]	Capital Recovery Charge Rate	%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%
[4]	Fixed O&M	$/kW	25.9	43.5	11.0	18.8	84.8	60.7	28.6	11.0	89.2	39.6
[5]	Variable O&M	$/kWh	0.0043	0.0042	0.0019	0.0028	0.0005	0.0063	0.0000	0.0000	0.0063	0.0019
[6]	Financial Life of Plant	years	20	20	20	20	20	20	20	20	20	20
[7]	Capacity Factor	%	85%	80%	85%	80%	85%	80%	35%	26%	42%	42%
[8]	Operating Hours	hours	7446	7008	7446	7008	7446	7008	3066	2277.6	3679.2	3679.2
[9]	Capital Recovery Required	$/kWh	0.0337	0.0630	0.0137	0.0301	0.0700	0.0621	0.0675	0.2850	0.1663	0.0839
[10]	Fixed O&M Recovery Required	$/kWh	0.0035	0.0062	0.0015	0.0027	0.0114	0.0087	0.0093	0.0048	0.0243	0.0108
[11]	Efficiency of Plant	%	39%	41%	54%	46%	33%	44%	-	-	44%	54%
[12]	Heat Rate	BTU/kWh	8740	8307	6333	7493	10488	7765	-	-	7765	6333
[13]	Fuel Cost	$/MMBTU	1.40	1.40	6.08	6.08	0.63	1.03	-	-	1.03	6.08
[14]	Fuel Cost per kWh	$/kWh	0.0122	0.0116	0.0385	0.0456	0.0066	0.0080	0.0000	0.0000	0.0007	0.0032
[15]	CO_2 Transportation and Storage Cost	$/KWh	-	0.0071	-	0.0036	-	-	-	-	-	-
[16]	Transmission and Distribution	$/kWh	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03
[17]	**Levelized Cost of Electricity**	**$/kWh**	**0.054**	**0.092**	**0.056**	**0.085**	**0.090**	**0.085**	**0.077**	**0.290**	**0.198**	**0.100**
[18]	**Markup Over Coal**		**1.00**	**1.71**	**1.03**	**1.57**	**1.67**	**1.58**	**1.43**	**5.39**	**3.67**	**1.85**

[1] Input, from EIA 2010
[2] [1]+([1]*0.04*y) where y=construction time in years: coal=4, NGCC=2, Coal with CCS=5, NGCC with CCS=3, nuclear=5, wind=2, biomass=4, solar=2, wind with biomass=2, wind with gas=2. For nuclear there is additional cost of ([1]*0.2) for the decomission cost.
[3] =r/(1-(1+r)^(-[6])) where r is discount rate. The discount rate is 8.5% for all technologies.
[4] Input, from EIA 2010
[5] Input, from EIA 2010
[6] Input, assumption
[7] Input, standard assumptions
[8] =8760*[7] (8760 is the number of hours in a year)
[9] =([2]*[3])/[8]
[10] =[4]/[8]
[11] =3412/[12] (3412 is the number of BTUs per 1 kWh of electricity)
[12] Input, from EIA 2010
[13] Input, from EIA data, 5-year average price from 2002-2006
[14] =[12]*[13]/1000000
[15] Assumes $10/tonCO2 for transportation and storage, and carbon contents of 24.686mmtC/Exajoule for coal and 13.7mmtC/EJ for gas
[16] Input, assumption
[17] =[5]+[9]+[10]+[14]+[15]+16]
[18] =[17]/([17] for coal)

[EIA 2010 source refers to Assumptions to the EIA Annual Energy Outlook 2010 Early Release. Note: EIA uses $2008, here they are converted to $2005 (conversion factor from $2008 to $2005 is 0.9218 (from Bureau of Economic Analysis: http://www.bea.gov/))]

The data in Table 10 allows for the calculation of shares of capital, labor (fixed and variable costs of operations and management, O&M) and fuel costs. The shares for technology specific factor and land are outside of the LCOE model and are externally assumed. Therefore, the shares for capital, labor and fuel must be adjusted. The relationship between those three inputs is held constant and their shares are scaled down to account for the shares of technology specific factor and land such that all of the input shares sum to one. These input cost shares are then put into EPPA to define technologies. As the costs of the inputs change endogenously, so too will the cost of the technologies.

The markup for advanced electricity technologies is the measure of the cost of a technology relative to conventional pulverized coal generation in the base year. This is calculated by dividing the LCOE of each technology (row 16 of Table 10) by the LCOE of pulverized coal. The markups for each technology are expressed in row 17 of Table 10. The Coal with CCS markup of 1.46, for example, means that in the base year Coal with CCS is 46% more expensive than pulverized coal. As EPPA works with relative costs and prices, these markups define the cost of each technology in the base year.

We distinguish between renewables at low penetration levels and large scale renewables (see Morris *et al.*, 2010). At lower penetration levels renewables (wind and solar) are an imperfect substitute for other electricity generation technologies (controlled by σ_{EWS}) to reflect the intermittency of the resource and variability in supply from better and more easily accessible sites to those where the resource was less dependable and more remote. The σ_{EWS} parameter allows gradual penetration only as the prices of other generation technologies continue to rise, and tends to limit the share of electricity that can be generated by wind & solar.

We assume that low penetration renewables can be easily integrated into the grid and is at levels where variable resources can be accommodated without significant investment in storage or backup. Treatment of wind as an imperfect substitute implies that increases in the share require an ever higher relative price of conventional electricity to elicit further increases in the share of wind. Thus, the markup we specify is a minimum or entry-level cost, applying only to the first installations of these sources. The specification further implies production can expand to maintain the initial exogenous share as total electricity production increases because expansion of the power sector will provide greater ability to accommodate intermittent renewables without storage or back up. Choice of the substitution elasticity creates an implicit supply elasticity of wind in terms of the share of electricity supplied by the technology. The value chosen for this elasticity results in relatively inelastic supply in terms of wind share, with it reaching at most 15 to 20% of electricity supply in any region, even under relatively tight constraints on carbon that lead to increased cost of generating electricity from fossil energy sources. We implicitly assume that this technology includes some deployment of solar electricity as well.

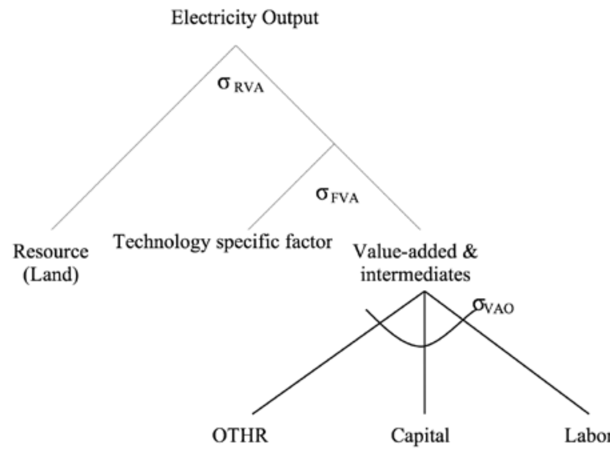

Figure 5. Input Structure for wind and solar

Wind and solar have a very similar production structure (**Figure 5**). Both use land and combination of OTHR, capital, and labor. Note that for the biomass technologies, the production of the biomass and the conversion of the biomass to fuel or electricity is collapsed into this simple nest (*i.e.*, the capital and labor needed for both growing and converting the biomass to a final fuel are combined). These are parameterized to represent a conversion efficiency of 40 percent from biomass to the final energy product. This conversion efficiency also assumes that process energy needed for bio-fuel production is biomass.

At higher penetration, evidence indicates that intermittency of wind and solar becomes a more serious issue, requiring some way of providing dispatchable power. We focus on backup capacity, as it appears less costly than various electricity storage options. We create two new renewable backstop technology sectors: large scale wind with biomass backup and large scale wind with natural gas backup. Large scale wind with biomass or natural gas backup are modeled as perfect substitutes for other electricity because the backup makes up for intermittency of the resource. The additional costs for large scale wind (transmission and storage or backup) are incorporated into the markup costs of the technologies, reflecting the cost of the variable resource. For the wind with backup it is assumed that for every KW installed capacity of wind there is one KW installed capacity of backup (either biomass or natural gas). The backup allows the combined plant to be fully reliable because whenever the wind is not blowing demand can still be met through the backup. It is assumed that the backup is only needed 7% of the time (for the rare occurrences when there is no wind). We also account for the increased costs of transmission and distribution (T&D) from these technologies, assuming an additional $0.03 per kWh for large scale wind plus biomass or natural gas, while the T&D cost for other generation technologies is $0.02 per kWh. The extra $0.01 for large scale wind with backup is assumed to account for the fact that such large scale wind production will mean transmission from sites remote from load centers.

The CES nest structure and input cost shares are shown in **Figure 6** for wind with gas backup and wind with biomass backup (in parentheses). The elasticity of substitution between wind and the backup technology is zero (Leontief), reflecting the requirement of complete backup. The representation of other advanced technologies in EPPA5 is similar to EPPA4 and documented in Paltsev *et al.* (2005).

4.4 Biofuels

Biofuels produced in the benchmark year are implicitly included as agricultural intermediate inputs into the fuel sector in each region. Additional biofuel production beyond this level is represented by advanced technologies in the EPPA model. The model identifies seven first-generation biofuels and a representative cellulosic pathway. First-generation biofuels include ethanol from corn, sugarcane, sugar beet and wheat; and diesel from palm fruit, soybeans and rapeseed/canola.

As noted in Section 2, we include an aggregate crop sector, which is used for food and intermediate inputs into other sectors. To model biofuel production, we include additional production technologies for crops used for biofuel production. For first-generation biofuels, crops specific to each pathway are represented. As these crops are grown in the base year for food and other uses, their production for non-biofuel continues to be captured within the aggregate crops sectors. A representative energy crop is included for our cellulosic pathway.

Benchmark yields for each first generation biofuel crop in each region are calculated as production-weighted averages of observed yields by country from FAOSTAT

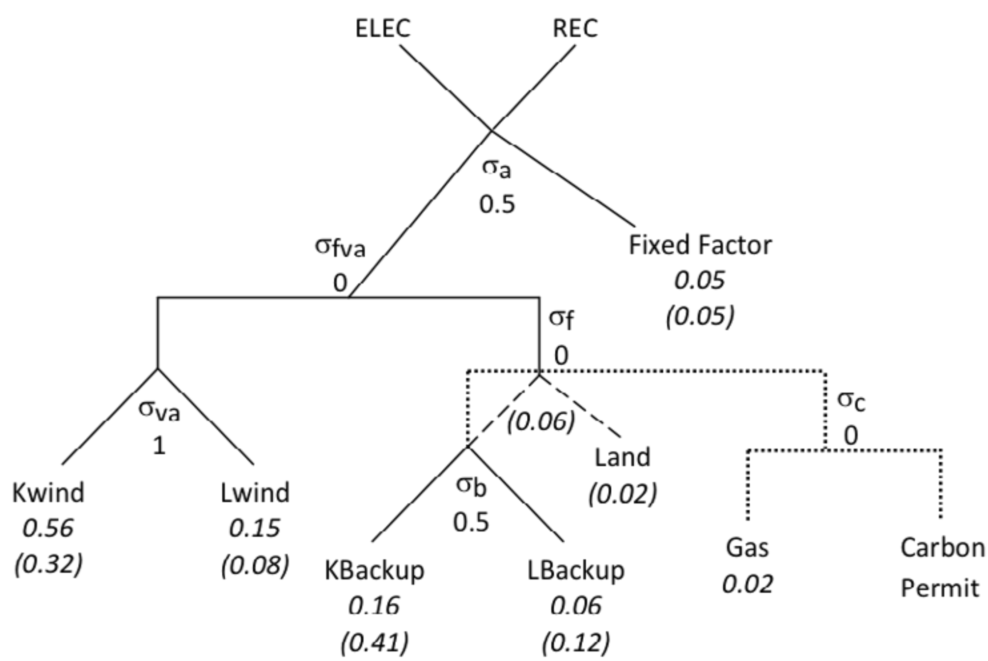

Figure 6. Production Function for Wind with Backup Technologies

Note: Cost share parameters are shown beneath the inputs for wind with gas backup, and in parentheses for wind with biomass backup. K—. and L— are capital and labor, respectively, for the wind generation or for the backup; σj are elasticities of substitution, j indicating the different nests; electricity (ELEC) and renewable electricity credits (REC) are joint outputs. The dashed-line nest with land as an input applies only to biomass backup. The dotted-line nest, with gas and carbon permit, applies only to gas backup.

(2013) and are reported in **Table 11**.[6] Energy crops are not currently produced at large scale, so we assume that the yield for our representative energy crop is 10 dry metric tons per acre (24.7 tons per hectare) in the US and calculate yields for other regions using yield adjustments factors from Gurgel *et al.* (2007). To calculate land costs per gasoline-equivalent gallon (GEG) for each fuel, crop yields are combined with estimates of pounds of feedstock per GEG of fuel and land rents. Our estimates of pounds of feedstock per GEG of fuel are based on a literature survey and are 31.0 for maize, 17.9 for rapeseed, 36.4 for soybeans, 125.0 for sugar beet, 190.7 for sugarcane, 33.2 for wheat, and 42.4 for our representative energy crop. Land rental costs per hectare are calculated using data on total land rents from the GTAP database and land-use estimates from the Terrestrial Ecosystem Model (TEM, see http://ecosystems.mbl.edu/tem/).

The production structure for each biofuel crop is shown in **Figure 7**. Similar to the production structure for the aggregate crop sector in the EPPA model, endogenous yield responses to changes in land prices are represented by substitution possibilities between land for the energy-materials composite (e.g., fertilizer) and between the resource-intensive bundle and the capital-labor aggregate. To calibrate cost functions for biofuels, we combine the land cost estimates above with non-land input cost

6 As FAOSTAT provides yields for palm oil fruit, palm oil per hectare will depend on extraction rates. Guided by statistics from the Malaysian Palm Oil Board (see, http://bepi.mpob.gov.my/), we specify a yield of four metric tons per hectare for East Asia and calculate yields for other regions based on palm oil fruit yields for these regions relative to that for East Asia.

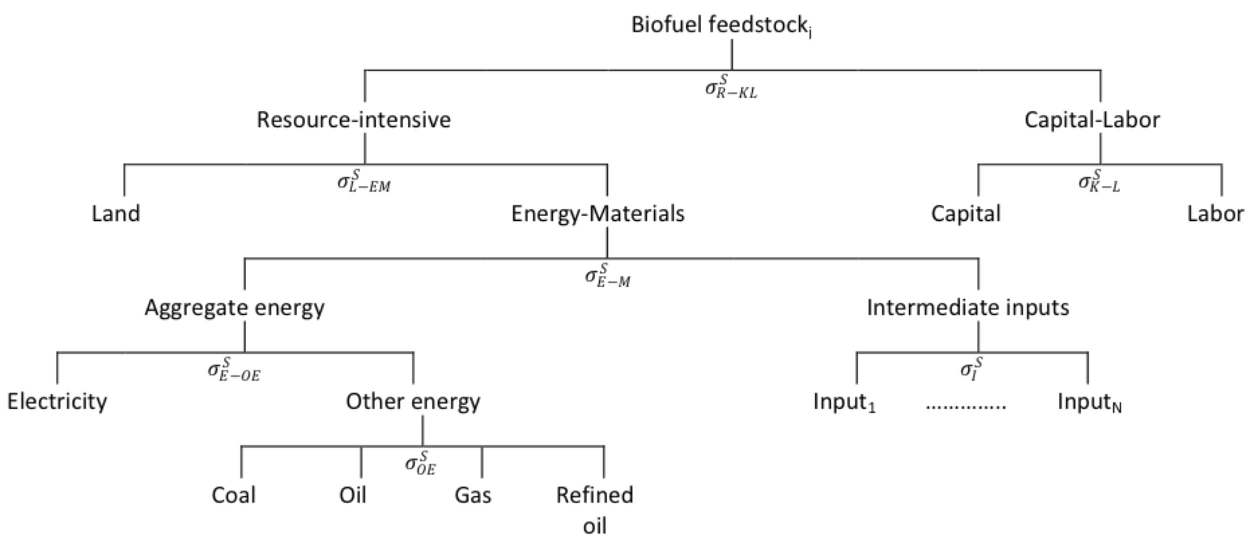

Figure 7. Biofuel crop production (*j* = corn, sugarcane, sugar beet, wheat, palm fruit, rapeseed, soybeans, energy crop)

Table 11. Biofuel crop yields by region, metric tons per hectare per year

	USA	CAN	MEX	BRA	LAM	EUR	RUS	ROE	CHN	IND	JPN	ASI	REA	ANZ	MES	AFR
Corn	9.5	8.5	3.2	3.8	5.9	5.0	2.9	4.8	5.2	2.3	2.6	3.4	3.6	6.2	7.0	1.7
Rapeseed	1.4	1.5	1.3	1.3	2.2	2.5	1.2	1.3	1.9	1.1	1.2	1.2	0.9	1.0	2.1	1.2
Soybeans	2.8	2.3	1.4	2.8	2.9	1.4	0.9	1.4	1.5	1.2	1.6	1.4	1.4	2.4	2.4	1.0
Sugar beet	63.2	55.2	0.0	0.0	76.6	47.0	29.2	35.1	41.3	0.0	64.5	0.0	41.7	0.0	36.8	51.3
Sugar cane	78.0	-	75.4	77.6	78.9	80.3	-	-	71.2	69.0	67.9	68.7	53.5	83.3	86.9	59.0
Wheat	2.7	2.3	5.1	2.2	2.9	3.4	2.1	2.3	4.6	2.7	4.3	3.5	2.5	1.1	2.5	2.0
Palm oil	-	-	12.3	10.6	18.1	-	-	0.0	13.9	-	-	19.0	-	-	-	3.8
Energy grass	24.7															

data for each crop from the GTAP database for first-generation biofuel crops, and Duffy (2008) for our representative energy crop.

As indicated in **Figure 8**, production functions for each biofuel combine inputs of pathway-specific feedstocks and other inputs, including capital, labor and intermediate inputs. A non-zero (and positive) elasticity of substitution between the biofuel feedstock and other inputs ($\sigma^S_{KLI\text{-}C}$) allows producers to respond to relative prices by, at an additional cost, extracting more energy per ton of feedstock. In addition to producing fuel, some processes also produce other products. Output from these sectors is modeled using a joint production function, where fuel and other products are produced in fixed proportions. Co-products represented include distiller's dried grains and solubles for corn and wheat ethanol, electricity for sugarcane ethanol, and meal for soybean and rapeseed diesel. To match the aggregation of agricultural commodities in the EPPA model, all biofuel co-products except electricity are sold as a perfect substitute for output from the "crop" sector.

To calibrate cost functions for first-generation biofuel refining, we source data on costs for each input, which we aggregate to EPPA sectors, from Tiffany and Edman (2003), Shapouri and Gallagher (2003), IEA (2004), Hass *et al.* (2005) and USDA (2006), which we update to reflect total production costs reported by IRENA (2013). Costs estimate for our cellulosic pathway are based on Humbird *et al.* (2011) with, following guidance from industry experts, inflated capital costs.

We assume that conversion technologies are the same in all regions but that the feedstock costs vary regionally according to differences in yields and land rents. **Table 12** reports cost shares (by EPPA sector), markup factors and costs per GEG for each fuel in the region that can produce that fuel at the lowest cost. Feedstock and ultimate total costs are higher in other regions. As the model is solved through times production costs are calculated endogenously based on changes in input prices. To reflect limited possibilities to grow a specific biofuel crop in a particular region, the model contains a series of flags that allows the availability of each pathway in each region to

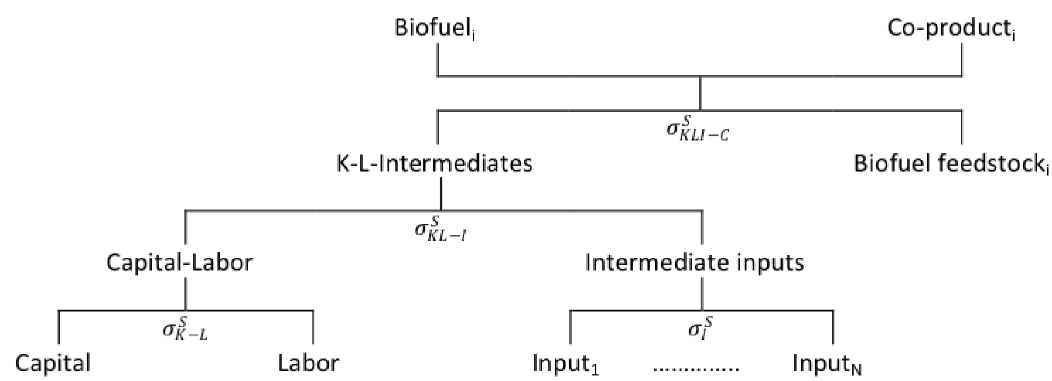

Figure 8. Biofuel production (i = corn ethanol, sugarcane ethanol, sugar beet ethanol, wheat ethanol, palm oil diesel, rapeseed diesel, soybeans diesel, and cellulosic fuel)

Table 12. Biofuel production cost shares and markup factors (2010$)

Input	Corn ethanol	Wheat ethanol	Sugar ethanol	Sugar beet ethanol	Rape diesel	Palm diesel	Soy diesel	Cellulosic biofuel
Feedstock	0.39	0.49	0.27	0.57	0.84	0.77	0.81	0.25
Natural Gas	0.10	0.08	0.00	0.02	0.02	0.00	0.02	0.00
Electricity	0.02	0.02	0.00	0.02	0.01	0.02	0.01	0.00
Energy-intensive industry	0.08	0.07	0.02	0.03	0.06	0.08	0.07	0.10
Other industry	0.03	0.02	0.05	0.03	0.01	0.01	0.01	0.06
Capital	0.35	0.29	0.49	0.27	0.05	0.07	0.06	0.58
Labor	0.03	0.02	0.17	0.09	0.03	0.04	0.03	0.01
Markup	1.20	1.59	1.11	1.60	1.81	1.39	1.81	1.85
Cost per GEG (2010)	2.87	3.79	2.65	3.82	4.33	3.33	4.33	4.41

turned on or off. Similarly, flags are included to switch on and off international trade in biofuels.

To capture mandates for the production of renewable transportation fuel, such as those in the US and the EU, the EPPA model includes permits for different categories of fuel. A simple renewable fuel permit system is depicted in **Figure 9**. One permit is issued for each gallon of renewable fuel produced and retailers of both conventional fuel and renewable fuel are required to purchase α ($0 < \alpha < 1$) permits for each gallon of fuel sold. Under such a system, α, which is set exogenously, determines the share of renewable fuel in total fuel consumption. This procedure can be used to target volumetric biofuel mandates by solving the model iteratively for alternatives values of α.

5. Greenhouse Gas and Air Pollution Emissions

The inventory of non-CO_2 GHGs and traditional air pollutant emissions for the EPPA5 model is provided in Waugh *et al.* (2011). The non-CO_2 GHG species considered include methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). Traditional air pollutants include carbon monoxide (CO), sulfur dioxide (SO_2), nitrous oxides (NOx), ammonia (NH_3), black carbon (BC), organic carbon (OC), and non-methane volatile organic compounds (NMVOCs). Since EPPA5 is also used in connection with other IGSM components to study environmental effects, good agreement with measured GHG concentrations is crucial and we compare bottom-up and top-down estimates to gauge for consistency. Waugh *et al.* (2011) conclude that the EDGAR v4.1 inventory is best suited for benchmarking non-CO_2 GHGs and EDGAR-HTAP is the best for traditional air pollutants in EPPA5 due to good disaggregation between economic sectors and species, and because it provides the closest fit with top-down estimates. **Tables 13–14** provide emission sources for GHGs and air pollutants.

6. Linking With the Climate Component of IGSM

A key linkage between EPPA's emissions output and the climate-chemistry model is an emissions translator.[7] This translator serves to spatially distribute emissions generated by EPPA, predicts emissions of some species that are not handled in EPPA, and includes emissions from some natural sources that are not otherwise incorporated into the Earth system portion of the IGSM, called the MIT Earth Systems Model (MESM).

EPPA categorizes all emissions as either agricultural or non-agricultural. While the economics model works

7 Referred to as the emissions postprocessor in Paltsev *et al.* (2005)

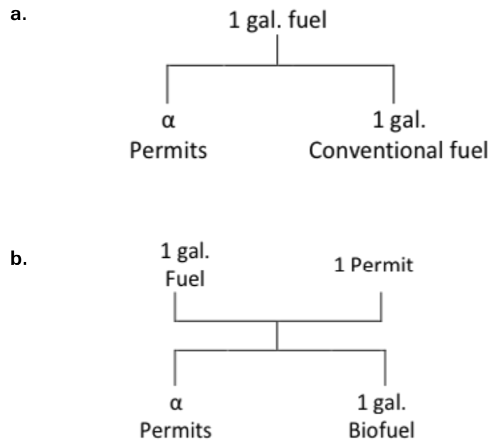

Figure 9. Production and blending of renewable fuel permits into (a) Conventional fuel and (b) Biofuels

with five-year time steps and a regional geographic scale, MESM requires daily emissions on a four-degree latitudinal scale. Therefore, the translator first distributes emissions on a 1x1 degree grid, with non-agricultural emissions distributed based on a population map derived from the Columbia Universities dataset (CIESIN, 2000) and agricultural emissions for each gas distributed based on EDGAR 2.0 emissions inventories for 1990. Any 1°x1° latitude-longitude area that has NOx emissions above a 5 kgN/day/km2 is considered to be an urban area for purposes of the chemistry component of MESM. The 1°x1° emissions are then integrated to yield the latitudinal data. Yearly emissions are linearly interpolated between the five year EPPA time steps, and then evenly distributed over the 365 days of the year.

The following natural emissions are included in the translator: 370 Tg of CO (20 from oceans and the remainder from vegetation), 21 Tg of NO (lightning and other processes), 40 Tg of CH_4 (termites and ocean and other emissions, Prather *et al.*, 2001), and 26 Tg of SO_2 (marine and terrestrial biospheres, Spiro *et al.*, 1992).

Historical CFC11 and CFC12 emissions are based on the Global Emissions Inventory Activity (GEIA) data (McCulloch *et al.*, 2001, 2003) through 2000 and assumed to decline to 0 by 2005 (though research by Fraser and Montzka (2003) indicates that there is a slow release from foam mechanism for CFC11 which leads to continued emissions for 20 years after production).

The translator also does some carbon balancing: because all CH_4 and CO emitted from organic sources (*e.g.*, the agricultural sector) originate from CO_2 that has been sequestered by the ecosystem in the recent past, the translator subtracts the carbon from these sources from CO_2 emitted in that time period. Oxidation in MESM will eventually turn the CO or CH_4 back into CO_2, completing the cycle.

Table 13. Emissions Sources and EPPA Activities for Kyoto Protocol Gases

Gas and Source	EPPA Activity
CO_2	
Coal, oil, and natural gas combustion	Coal, refined oil, and natural gas consumption in all sectors; coal gasification
Cement production	Energy intensive industry production
Deforestation, biomass burning	Agriculture production-TEM
CH_4	
Coal seams	Coal production
Petroleum production	Oil production
Transmissions and distribution losses	Gas consumption
Landfill, wastewater gas	Household consumption
Industrial sewage, paper and chemicals	Energy intensive industry production
Industrial sewage, food processing	Other industry production
Rice, enteric fermentation, manure management, agr. waste, savannah, and deforestation burning	Agriculture production
N_2O	
Adipic and nitric acid production	Energy intensive industry
Refined oil products combustion	Refined oil consumption in all sectors
Coal combustion	Coal consumption in all sectors
Agr. soils, manure management, agr. waste, savannah, and deforestation burning	Agriculture production-TEM
HFCs	
Air conditioning, foam blowing, other	Other industry production
PFCs	
Semi-conductor production, solvent use, other	Other industry production
Aluminum smelting	Energy intensive industry production
SF_6	
Electrical switchgear,	Electricity production
Magnesium production	Energy intensive industry production

Another area of development has been the dynamic linking of land-use change in EPPA with the Terrestrial Ecosystem Model (TEM), a MESM component, which was developed and is maintained at the Marine Biological Labs (MBL), Woodshole, MA (Melillo *et al.* 1993, Felzer *et al.* 2004). This linking was first implemented using a version of EPPA4 containing landuse changes. It was used in studies about the landuse emissions implications of large global biofuels policies (Melillo *et al.* 2009, Reilly *et al.* 2012).

The linkage is accomplished through a downscaling scheme (Wang 2008), which takes EPPAs five-year time step data of land transitions for 16 EPPA regions, and distributes it over a 1/2° x 1/2°. The downscaling uses data of net primary productivity (NPP) from TEM, and temperature and precipitation data provided by MESM at the 1/2° x 1/2° scale, to econometrically estimate the land shares for the five EPPA land use types in each grid cell. This downscaling also uses distances to urban centers, allowing it to place food crops closer to human locales. TEM is then run with these updated shares, and calculates the resulting NPP. The NPP data, aggregated to the EPPA regions and averaged over 5 years, is then fed back to EPPA and is used in updating the land productivity and affects the land transitions decisions. This linkage, via the downscaling, has been transferred to EPPA5, which implements landuse decisions based on economic conditions.

7. Policy Applications

As mentioned in introduction, the EPPA5 model has been applied to study numerous research questions, such as land-use change modeling (Gurgel *et al.*, 2007, 2008), plug-in hybrid vehicles (Karplus *et al.*, 2009), air pollution health impacts (Nam *et al.*, 2009; Matus *et al.*, 2011), renewable portfolio standards (Morris *et al.*, 2010), oil sands production (Chan *et al.*, 2010), coal-to-liquids conversion (Chen *et al.*, 2011), shale gas representation (Paltsev *et al.*, 2011; Jacoby *et al.*, 2011), personal transportation details and U.S. fuel efficiency standards for

Table 14. Emissions Sources and EPPA Activities for Pollutants

Gas and Source	EPPA Activity
SO_2	
Coal, oil, and natural gas combustion	Coal, refined oil & natural gas consumption in all sectors
Non-ferrous metals, iron and steel, chemicals, & cement	Energy intensive industry production
Refinery processes	Refined oil production
Agr. waste, savannah, deforestation, biofuels, uncontrolled waste burning	Agricultural production
Biofuel use in households	Household consumption
NMVOCs	
Coal, petroleum products in transportation, natural gas combustion	Coal, refined oil & natural gas consumption in all sectors
Refinery processes	Refined oil production
Natural gas production processes	Natural gas production
Oil production processes	Oil production
Solvents, other industrial processes	Other industry production
Iron & steel, chemicals	Energy intensive industry production
Biofuel use in households	Household consumption
Agr. waste, savannah, deforestation, biofuels, uncontrolled waste burning	Agricultural production
NO_x	
Coal, oil, and natural gas combustion	Coal, refined oil & natural gas consumption in all sectors
Cement, chemical, iron & steel manufacture	Energy intensive industry production
Refinery processes	Refined oil production
Biofuel use in households	Household consumption
Agr. waste, savannah, deforestation, biofuels, uncontrolled waste burning	Agricultural production
CO	
Coal, oil, and natural gas combustion	Coal, refined oil, and natural gas consumption
Chemical, iron & steel manufacture	Energy intensive industry production
Refinery processes	Refined oil production
Other industrial processes	Other industry production
Biofuel use in households	Household consumption
Agr. waste, savannah, deforestation, biofuels, uncontrolled waste burning	Agricultural production
Black Carbon and Organic Carbon	
Coal, oil, and natural gas combustion	Coal, refined oil, and natural gas consumption
Biomass and waste burning in agriculture	Agricultural production
Biomass burning in households	Household consumption
NH_3	
Manure management and fertilizer use	Agricultural production
Sewage	Household consumption

cars (Karplus, 2011, Karplus *et al.*, 2012, Karplus and Paltsev, 2012), gasoline and diesel fleet representation in Europe (Gitiaux *et al.*, 2012), personal transportation pathways in China (Kishimoto *et al.*, 2012), air pollution constraints (Nam *et al.*, 2012), limited sectoral emission trading (Gavard *et al.*, 2011, 2013, 2016), advanced technologies representation (Morris *et al.*, 2014), Paris Agreement pledges (Jacoby and Chen; 2014, 2016), representation of advanced biofuels (Winchester and Reilly, 2015), CO_2 standards for private cars in Europe (Paltsev *et al.*, 2016), irrigated and rainfed crop production (Winchester *et al.*, 2016), and others. The additions and updates to the model described here have been described in these peer-reviewed publications, so each addition and improvement has been subject to review. This report brings a description of the key elements of the model together so that those interested in the overall model structure and parameterization can find it in one place.

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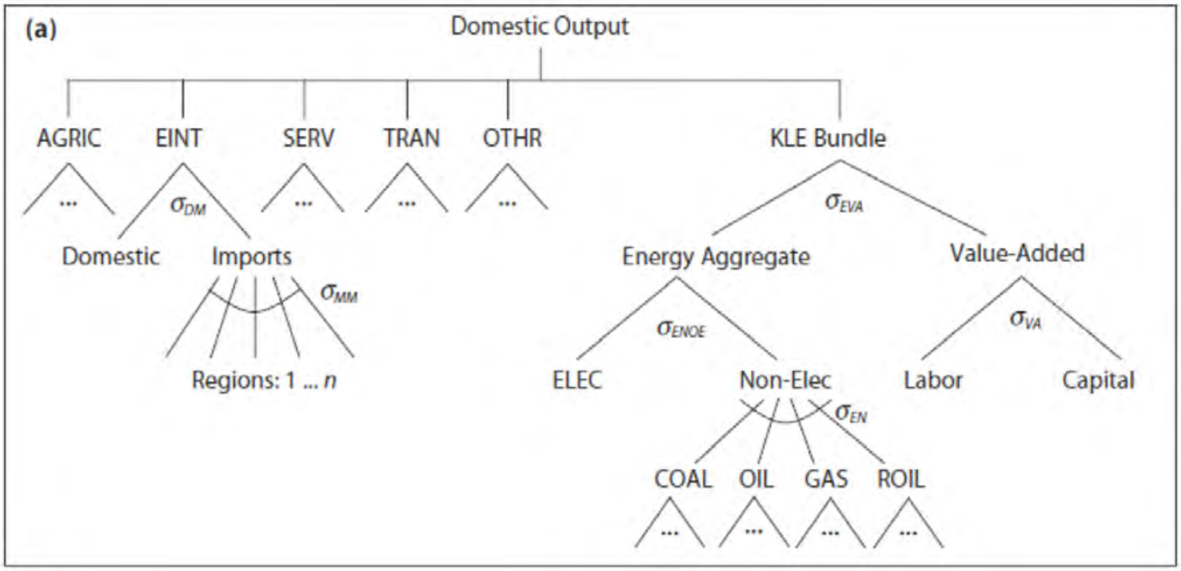
Appendix A. Structure of Production and Consumption in EPPA



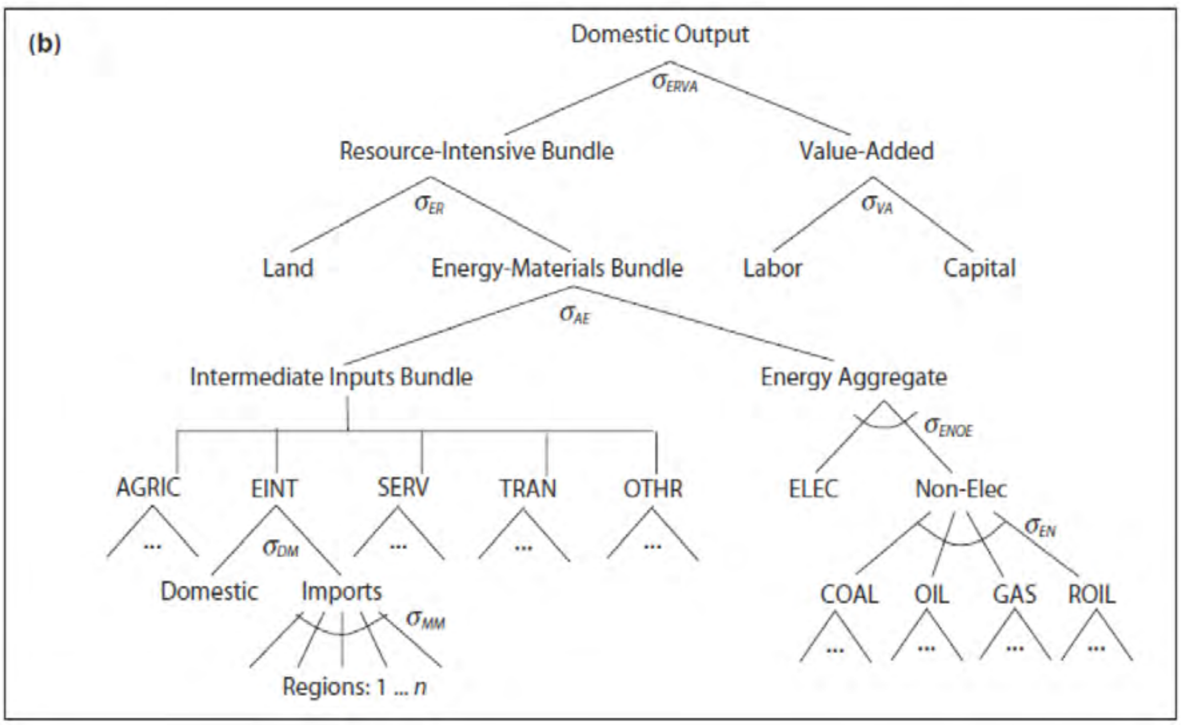


Figure A1. Structure of Production Sectors: (a) Services, Industrial Transportation, Energy Intensive and Other Industries, (b) Crops, Livestock, Forestry (denoted as AGRIC on the figure). Vertical lines in the input nest signify a Leontief or fixed coefficient production structure where the elasticity of substitution is zero. Terminal nests with ... indicate the same aggregation structure for imported goods as shown in detail for the EINT sector. OIL (crude oil) is modeled as an internationally homogenous good (σDM=σMM=∞). [Figure continues on following page].

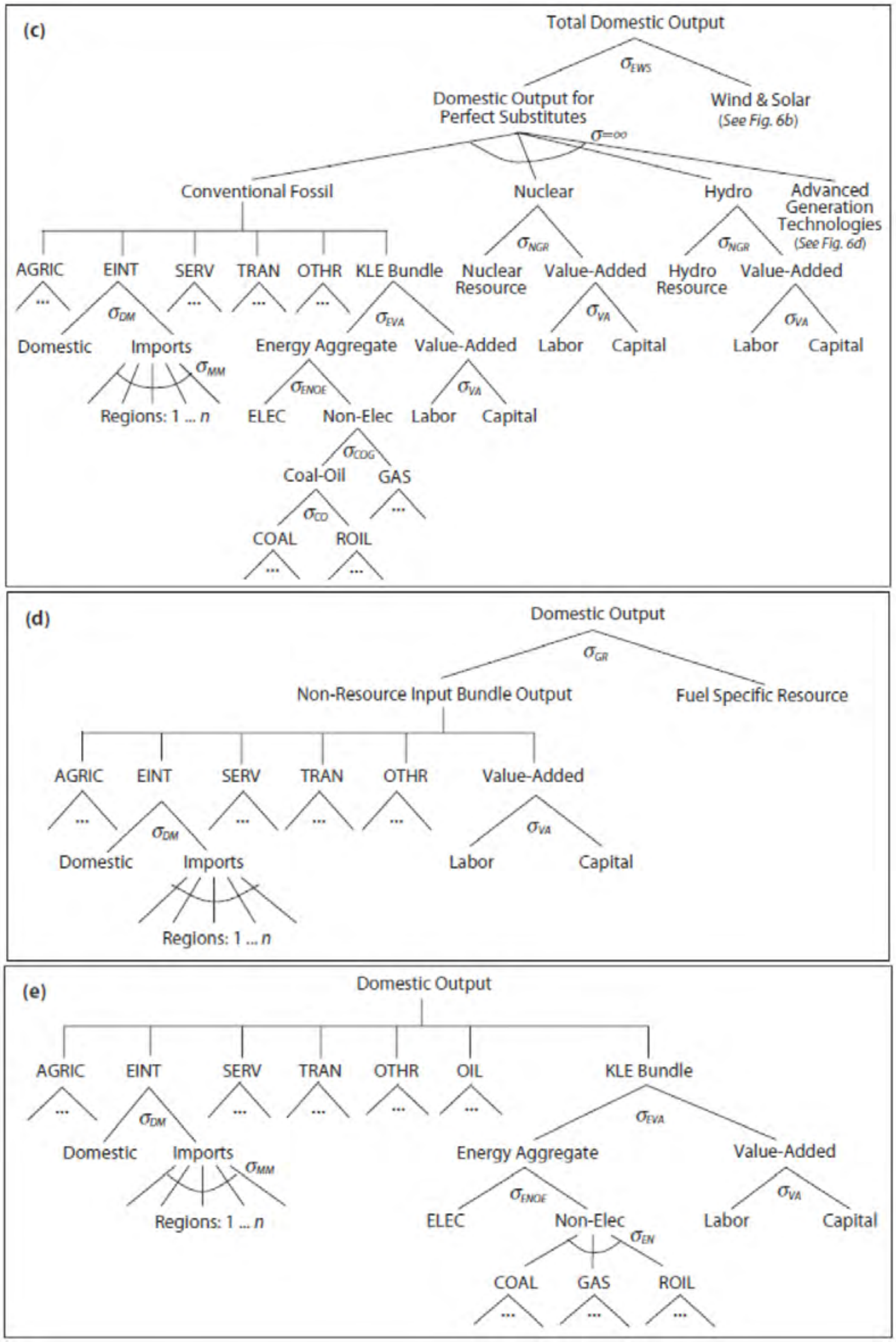


Figure A1. (Continued). Structure of Production Sectors: (c) Electricity, (d) Primary Energy Sectors (COAL, OIL, GAS), (e) the ROIL sector.

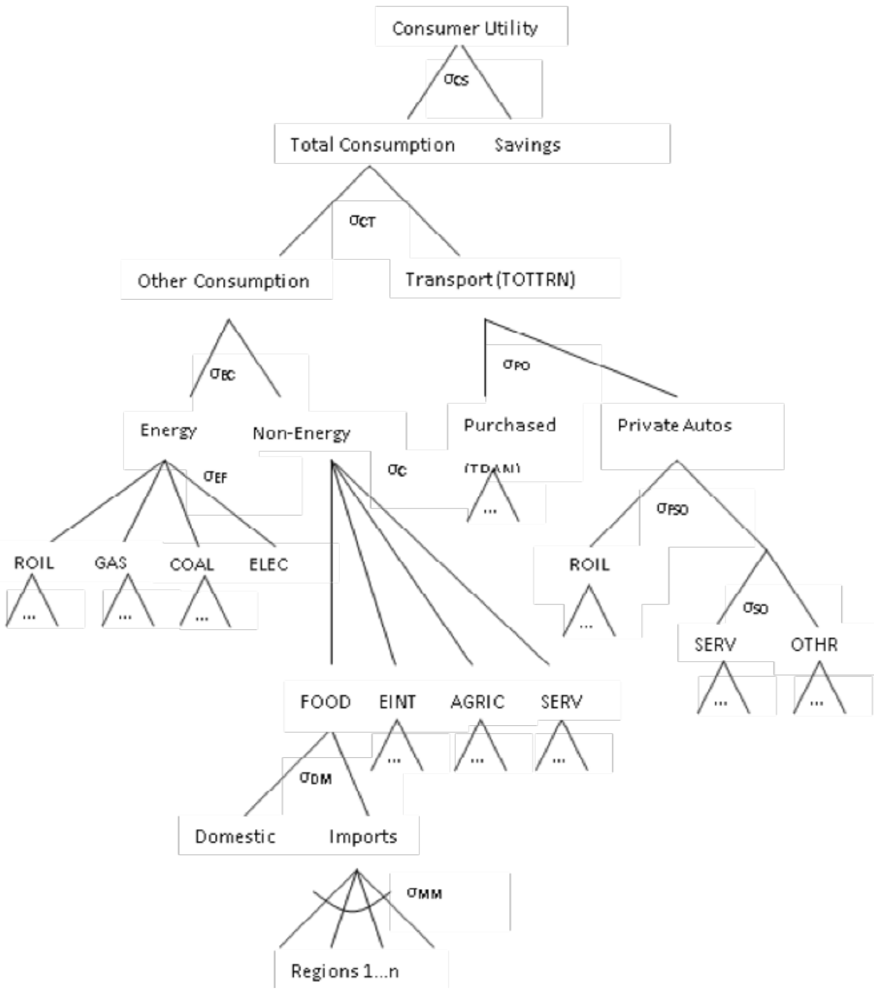


Figure A2. Structure of the household sector. Terminal nests with … indicate the aggregation structure for imported goods, shown in detail for the FOOD sector.

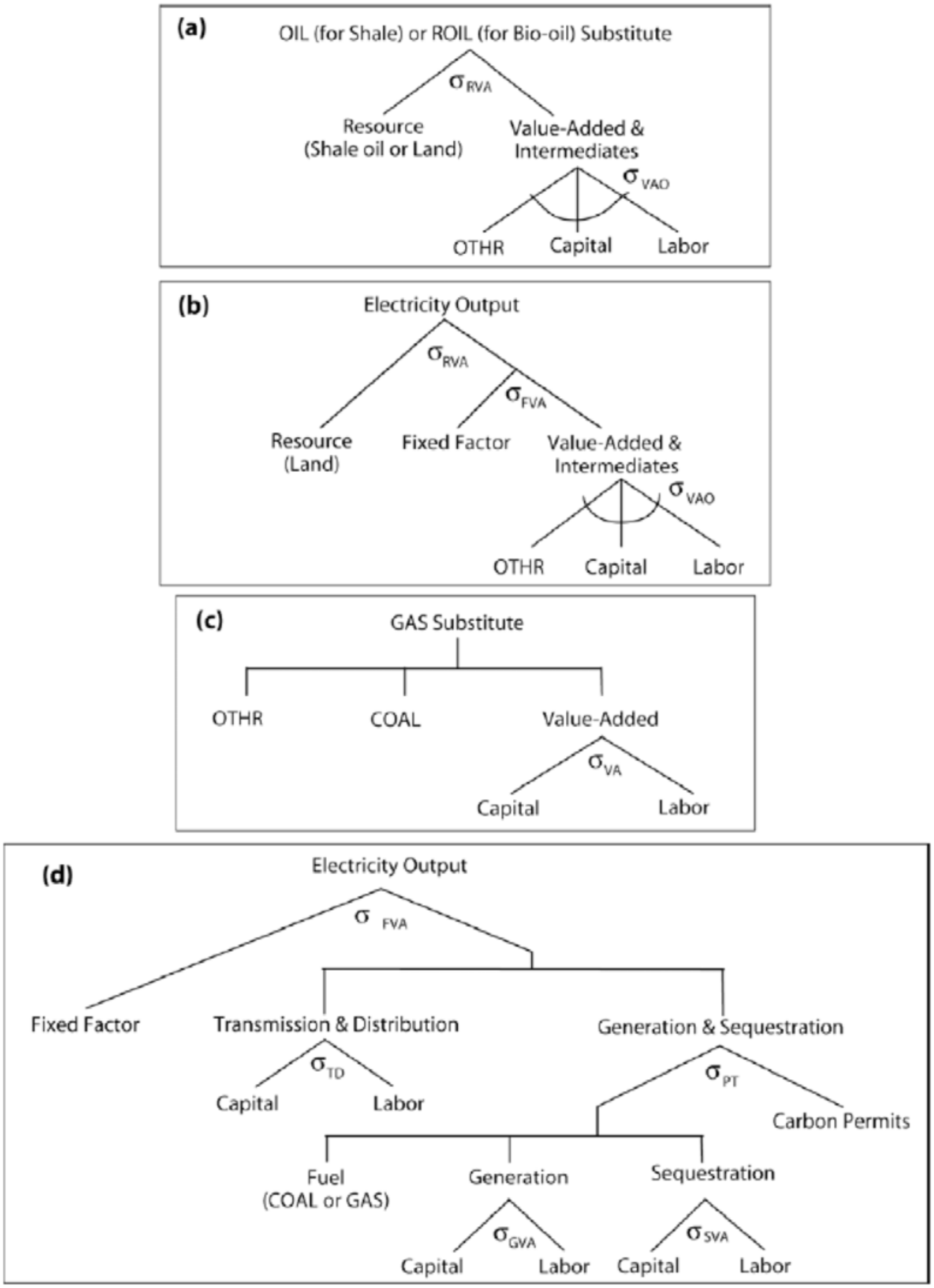


Figure A3. Structure of production for advanced technologies: (a) Shale and Bio-oil, (b) Bio-electric and Wind & Solar, (c) Coal Gasification, and (d) Advanced Fossil Electricity. Vertical lines in the input nest signify a Leontief or fixed coefficient production structure where the elasticity of substitution is zero. Intermediate inputs are a combination of domestic and imports as in other sectors as shown in Figure A1.

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