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The MIT U.S. Regional Energy Policy (USREP) Model: The Base Model and Revisions

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To this end, the Joint Program brings together an interdisciplinary group from two established MIT research centers: the **Center for Global Change Science (CGCS)** and the **Center for Energy and Environmental Policy Research (CEEPR)**. These two centers—along with collaborators from the Marine Biology Laboratory (MBL) at Woods Hole and short- and long-term visitors—provide the united vision needed to solve global challenges.

At the heart of much of the program's work lies MIT's Integrated Global System Model. Through this integrated model, the program seeks to discover new interactions among natural and human climate system components; objectively assess uncertainty in economic and climate projections; critically and quantitatively analyze environmental management and policy proposals; understand complex connections among the many forces that will shape our future; and improve methods to model, monitor and verify greenhouse gas emissions and climatic impacts.

This reprint is intended to communicate research results and improve public understanding of global environment and energy challenges, thereby contributing to informed debate about climate change and the economic and social implications of policy alternatives.

—Ronald G. Prinn and John M. Reilly,
Joint Program Co-Directors

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The MIT U.S. Regional Energy Policy (USREP) Model: The Base Model and Revisions

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Abstract: The MIT U.S. Regional Energy Policy (USREP) Model has been broadly applied to energy and environmental policy analyses. We provide an overview of the base model, detailed description of the equilibrium structures and main features that drive the dynamic process of the economy growing out to 2050. Given the common features shared between USREP and the MIT Economic Projection and Policy Analysis (EPPA) model, a large part of the description is drawn from EPPA documentation. We also extract from previous literatures the description of several features developed for USREP. The objective of this report is to build a reference point for future development of USREP. Thus revisions to improve the representation of the U.S. economy and energy market are documented in addition to the base model description.

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1. The USREP Model: Overview

The U.S. Regional Energy Policy (USREP) model is a computable general equilibrium model of the U.S. economy designed to analyze energy and environmental policies. It has the capability to assess impacts on regions, sectors and industries, and different household income classes. As in any classical Arrow-Debreu general equilibrium model, our framework combines the behavioral assumption of rational economic agents with the analysis of equilibrium conditions, and represents price-dependent market interactions as well as the origination and spending of income based on microeconomic theory. Profit-maximizing firms produce goods and services using intermediate inputs from other sectors and primary factors of production from households. Utility-maximizing households receive income from government transfers and from the supply of factors of production to firms (labor, capital, land, and resources). Income thus earned is spent on goods and services or is saved. The government collects tax revenue which is spent on consumption and household transfers. USREP is a recursive-dynamic model, and hence savings and investment decisions are based on current period variables.

In the base version of the model, its regional mapping represents the U.S. by 12 regions: New England, New York, North East, South East, Florida, North Central, South Central, Texas, Mountain, Pacific, California, Alaska (see **Figure 1**). The region definition corresponds roughly to electricity power pool regions in which electricity produced in that region can serve any household or industry in that region.

To enhance the capability to analyze policy and regulations at more disaggregated level, other regional mappings are created to take better account of economic regions, power markets (ISO/RTO) regions, GHG policy regions (California, RGGI, WCI), renewable portfolio standard (RPS) policy regions and National Climate Assessment regions. The underlying database for USREP is at the state level, which makes it possible to aggregate to any region definition. However, the wide range in the size of different state economies and the large number of regions can create numerical problems if all 50 states are separately represented. For the latest version of USREP, we developed a region definition with large states separately identified and smaller, contiguous states aggregated into regions that contain 2–5 states each. The new regional mapping aggregates 50 states to 30 regions shown in **Figure 2**.

USREP has been deployed in many studies since its first application in 2009 (Rausch, 2009). With the focus on impact assessment of the U.S. energy and environmental policy, we have explored four main research areas: (1) policy efficiency and equity; (2) fiscal issues; (3) leakage through trade; and (4) air pollution co-benefits. Moreover, applications are extended to evaluate energy and resource under the economic evolution and climate change impact (see **Table 1**).

Table 1. List of USREP Applications and Publications

Study Topic	Publication
ENERGY AND ENIVRONMENTAL POLICY	
Efficiency and Equity	Rausch and Karplus (2014)
	Rausch and Mowers (2012)*
	Rausch (2012)
	Lanz and Rausch (2011)*
	Rausch, Metcalf, and Reilly (2011a)*
	Rausch, Metcalf, Reilly, and Paltsev (2011b, 2010, 2009)
	Rausch and Karplus (2014)
Fiscal Issues	Caron, Cohen, Brown, and Reilly (2018)*
	Jacoby, Montgomery, and Yuan (2018)
	Yuan, Metcalf, Reilly, Paltsev (2017)
	Rausch and Reilly (2015)
Leakage through Trade	Caron, Rausch, and Winchester (2014)
	Caron and Rausch (2013)*
Air Pollution Co-Benefits	Thompson, Rausch, Saari, and Selin (2016, 2014)
ENERGY AND RESOURCE	
Natural Gas	Paltsev, Jacoby, Reilly, Ejaz, Morris, O'Sullivan, Rausch, Winchester, and Kragha (2011)
Water	Blanc, Strzepek, Schlosser, Jacoby, Gueneau, Fant, Rausch, and Reilly (2014)

* Study conducted based on an integrated model that links USREP with a detailed sector model

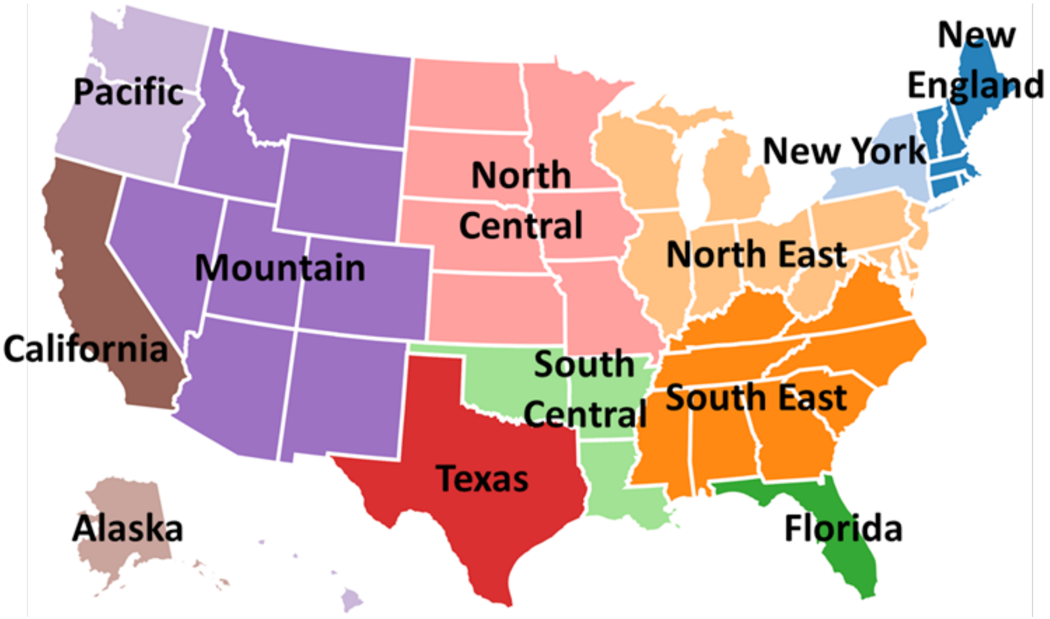

Figure 1. USREP Base Model, Regional Mapping

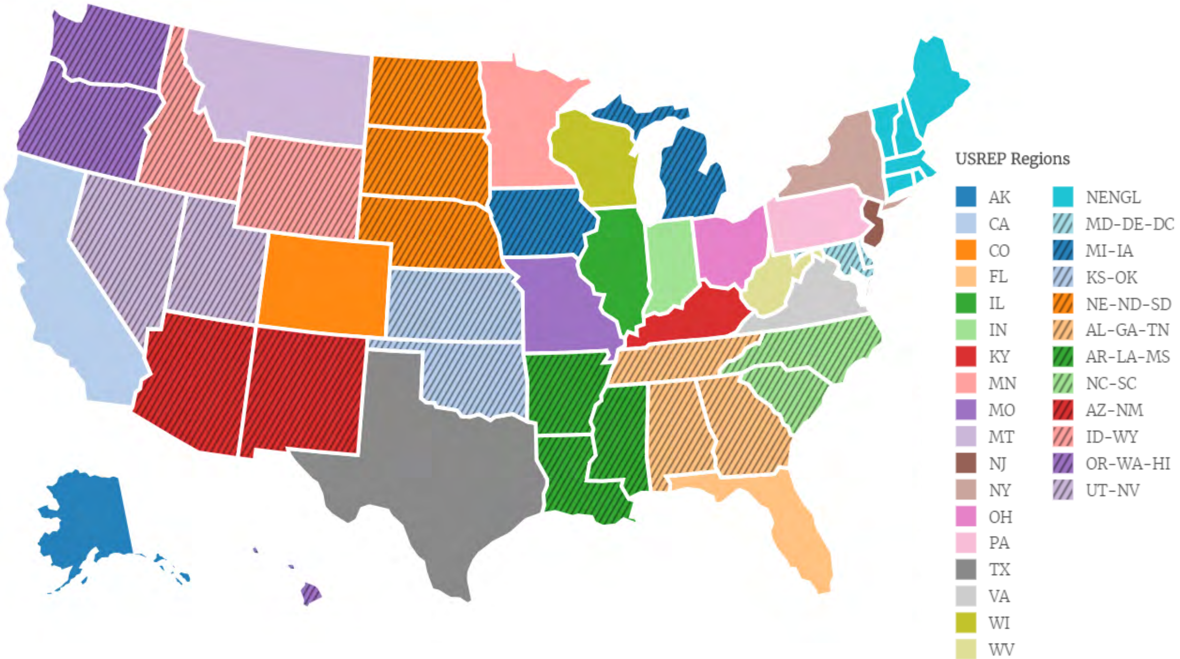

Figure 2. USREP Regional Mapping in the 30-region version

2. USREP Data Sources

USREP is built on a state-level economic dataset of the U.S. economy, called IMPLAN (IMPLAN, 2008) covering all transactions among businesses, households, and government agents for the base year in 2006. To represent historic changes in energy and economic structure, the model is calibrated up to 2015 based on information from Energy Information Administration's Annual Energy Outlooks (see Section 5 for additional information). For the purpose of energy and environmental policy study, we improve the characterization of energy markets in the input-output dataset prepared by IMPLAN by replacing its energy accounts with physical energy quantities and energy prices from Energy Information Administration State Energy Data System (EIA-SEDS, 2009) for the same benchmark year 2006. The final dataset is rebalanced using constrained least-squares optimization techniques to produce a consistent representation of the economy.

The detailed representation of existing taxes captures the existing efficiency loss due to tax interaction, and comprises sector- and region-specific ad-valorem output taxes, payroll taxes and capital income taxes. IMPLAN data has been augmented by incorporating regional tax data from the NBER TAXSIM model (Feenberg and Coutts, 1993) to represent marginal personal income tax rate by region and income class. Using marginal tax rates is important both in terms of better representing the deadweight loss associated with a progressive income tax structure and for estimating the impacts on revenue from these sources when activity levels (tax base for each) are affected by a carbon tax. We approximate the U.S. progressive income tax with an income-specific linear income tax by setting a marginal tax rate for each income class to match marginal tax rates from the TAXSIM model, and then set the intercept so that average tax rates match IMPLAN data at the regional/income class level.

Additional data for the greenhouse gas (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6) emissions are based on the EPA inventory data, including endogenous costing of the abatement of non-CO_2 GHGs (Hyman *et al.*, 2003). Following the approach outlined in Paltsev *et al.* (2005), the model incorporates supplemental physical accounts to link economic data in value terms with physical quantities on energy production, consumption and trade.

Furthermore, the USREP model incorporates demographic data on the population and number of households in each region and income class based on U.S. Census Data (U.S. Census Bureau, 2006). In each region, we model nine households that differ with respect to income. Households of different income levels will consume different bundles of goods, therefore the carbon footprint of households will differ by income class, due both to differences in total consumption and to variation in the carbon intensity (emission per dollar of income) of consumption choices. Households also differ in the share of income coming from wages or capital income.[1] To the extent that richer households, for example, receive a higher proportion of their income from capital, then a carbon tax that lowers the ratio of the interest rate to the wage rate will make higher income households worse off relative to lower income households through the tax's impact on the sources of income.

Data sources used to parameterize the model are listed in **Table 2**. Energy supply is regionalized by incorporating data for regional crude oil and natural gas reserves from U.S. Department of Energy (DOE, 2009), coal reserves estimated by the U.S. Geological Survey (USGS, 2009), and shale oil (Dyni, 2006). Our approach to characterizing wind resource and incorporating electricity generation from wind in the model based on data from the National Renewable Energy Laboratory (NREL, 2010) is described by Rausch and Karplus (2014). Regional supply curves for biomass are derived from data from Oak Ridge National Laboratories (2009) that describes quantity and price pairs for biomass supply for each state.

The standard version of USREP aggregates 509 commodities in the IMPLAN dataset to five energy sectors and six non-energy sectors. The energy sectors include coal (COL), natural gas (GAS), crude oil (CRU), refined oil (OIL) and electricity (ELE). The non-energy sectors include energy-intensive industries (EIS), agriculture (AGR), commercial transportation (TRN), personal transportation (HHTRN), services (SRV) and all other goods (OTH).

Table 2. USREP Data Sources

Data and Parameters	Source
Social Accounting Matrices	Minnesota IMPLAN Group (2008)
Physical Energy Flows and Energy Prices	Energy Information Administration - State Energy Data System (EIA-SEDS, 2009)
Fossil Fuel Reserves and Biomass Supply	U.S. Geological Survey (USGS, 2009) U.S. Department of Energy (DOE, 2009) Dyni (2006) Oakridge National Laboratories (2009)
High-Resolution Wind Data	National Renewable Energy Laboratory - Wind Integration Datasets (NREL, 2010)
Non-CO_2 GHG Inventories and Endogenous Costing	U.S. Environmental Protection Agency (EPA, 2009) Hyman *et al.* (2002)
Marginal Personal Income Tax Rates	NBER's TAXSIM model (Feenberg and Coutts, 1993)
Trade Elasticities	The GTAP 7 Data Base (Narayana and Walmsley, 2008) and own calculation
Energy Demand and Supply Elasticities	MIT EPPA model (Paltsev *et al.*, 2005; Chen *et al.*, 2014)
Passenger Vehicle Transportation	U.S. Department of Transportation (2009) Davis and Boundy (2019)

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[1] We calibrate capital income to households controlling for region and income based on data from IMPLAN. Lacking data on ownership of renewable and depletable resources, we allocate resource income to households in proportion to capital income.

3. USREP Equilibrium Structure

This section provides an algebraic description of the static USREP model and lays out the equilibrium conditions. Following Rutherford (1995b) and Mathiesen (1985), we formulate the equilibrium as a mixed complementarity problem and use the GAMS/MPSGE software Rutherford (1999) and the PATH solver Dirkse and Ferris (1993) to solve for non-negative equilibrium prices and quantities. Our complementarity-based solution approach distinguishes price and demand equations, market clearance conditions, budget constraints, and auxiliary equations. We use constant returns to scale elasticity of substitution (CES) and constant elasticity of transformation (CET) functions to describe production and transformation activities. The model is set up to solve in a 5-year step out to 2050 with the first model year in 2010.[2]

3.1 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 capital k and labor l, depletable and renewable resource factors (indexed by z) and intermediate inputs from other sectors j to maximize profits subject to the constraint of its production technology. Production is modeled assuming constant-elasticity-of-substitution (CES) functions that impose constant returns to scale. By duality and the property of linear homogeneity, optimizing behavior of the representative firm requires that:

$$p_{r,i} = c_{r,i}\left(pa_{r,j}, pl_r, pk, pr_z\right) \qquad (1)$$

where $pa_{r,j}$, pl_r, pk, and pr_z denote prices for domestic output, intermediate inputs, labor, capital, and resource factors, respectively. provides a generic representation of the unit cost function for sector i. Figures B1–B5 provide a schematic overview of the adopted nesting CES structure for conventional production sectors. Figures B7–B11 provide a schematic overview of the adopted nesting CES structure for production with advanced technologies. Zero profits conditions in (1) exhibit complementary slackness with respect to the activity level $y_{r,i}$. For each sector, ad-valorem sector- and region-specific output tax rates, denoted by $to_{r,i}$, enter at the top nest. Region-specific capital income tax rates, denoted by tk_r, and payroll tax rates, denoted by tl_r, enter in the value-added nest. Given input prices gross of taxes, firms maximize profits subject to technology constraints. Firms operate in perfectly competitive markets and sell their products at a price equal to marginal costs.

To illustrate how taxes enter the CES cost functions, consider the pricing equation for the agriculture sector (Figure B2). We write the equations in calibrated share form (Rutherford, 1995a) where ϕ's denote respective benchmark value share parameters and an upper bar refers to the benchmark value of variables. Unit cost function is given by:

$$\frac{(1-to_{r,i})p_{r,i}}{(1-\overline{to}_{r,i})\overline{p}_{r,i}} = \left[\phi_{r,RES,i}\left(\frac{p_{r,RES}}{\overline{p}_{r,RES}}\right)^{1-\sigma_{EVRA}} + \phi_{r,VA,i}\left(\frac{p_{r,VA}}{\overline{p}_{r,VA}}\right)^{1-\sigma_{EVRA}}\right]^{\frac{1}{1-\sigma_{EVRA}}} \qquad (2)$$

where $p_{r,RES}$ denotes the price for the resource-intensive input bundle and the price for the value-added composite, $p_{r,VA}$, is given by:

$$\frac{p_{r,VA}}{\overline{p}_{r,VA}} = \left[\phi_{r,i,L}\left(\frac{(1+tl_r)pl_r}{(1+\overline{tl}_r)\overline{pl}_r}\right)^{1-\sigma_{VA}} + \phi_{r,i,K}\left(\frac{(1+tk_r)pk}{(1+\overline{tk}_r)\overline{pk}}\right)^{1-\sigma_{VA}}\right]^{\frac{1}{1-\sigma_{VA}}} \qquad (3)$$

Elasticities are denoted by σ. Figures A1–A3 provide a list of elasticity parameter used in the model.

By Shephard's Lemma, the demand for good j by sector i is:

$$x_{r,j,i} = y_{r,i}\frac{\partial c_{r,i}}{\partial pa_{r,j}} \qquad (4)$$

and the demand for labor, capital, and resource factors is:

$$ld_{r,i} = y_{r,i}\frac{\partial c_{r,i}}{\partial pl_r} \qquad (5)$$

$$kd_{r,i} = y_{r,i}\frac{\partial c_{r,i}}{\partial pk} \qquad (6)$$

$$rd_{r,z,i} = y_{r,i}\frac{\partial c_{r,i}}{\partial pr_{r,z}} \qquad (7)$$

3.2 Domestic and Foreign Trade

We adopt the Armington (1969) assumption of product heterogeneity for imports and exports. Sectoral output produced in each region is converted through a CET function into goods destined for the regional, national and international markets. The associated unit cost function is given by:

$$\frac{p_{r,i}}{\overline{p}_{r,i}} = \left[\alpha_{r,i,d}\left(\frac{pd_{r,i}}{\overline{pd}_{r,i}}\right)^{1+\eta} + \alpha_{r,i,u}\left(\frac{pdx_{r,i}}{\overline{pdx}_{r,i}}\right)^{1+\eta} + \alpha_{r,i,f}\left(\frac{pdfx_{r,i}}{\overline{pdfx}_{r,i}}\right)^{1+\eta}\right]^{\frac{1}{1+\eta}} \qquad (8)$$

where $pd_{r,i}$, $pdx_{r,i}$, and $pdfx_{r,i}$ denote the price for domestic output, foreign exports, and international exports, respectively, and α's are value shares parameters. All goods are tradable. Depending on the type of commodity, we distinguish three different representations of intra-national regional trade. First, bilateral flows for all non-energy goods (indexed by ne) are represented as "Armington" goods, where like goods from other regions are imperfectly substitutable for domestically produced goods. Second, domestically traded energy goods (indexed by e), except for electricity (indexed by ele), are assumed to be homogeneous products, i.e. there is a national pool that demands domestic

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[2] For 2006–2015, the model is calibrated to economic and energy data from the corresponding Energy Information Administration's Annual Energy Outlooks.

exports and supplies domestic imports. This assumption reflects the high degree of integration of intra-U.S. markets for natural gas, crude and refined oil, and coal. Third, we differentiate six regional electricity pools that are designed to provide an approximation of the existing structure of independent system operators (ISO) and the three major NERC interconnections in the U.S. More specifically, we distinguish the Western, Texas ERCOT and the Eastern NERC interconnections and in addition identify AK, NENGL, and NY as separate regional pools.[3,4] We assume that within each regional pool traded electricity is a homogenous good and that there is no electricity trade between regional pools. In accordance with this market structure we distinguish three prices for intra-national exports:

$$pdx_{r,i} = \begin{cases} pn_{r,i} & if\ i \in ne \\ pnn_i & if\ i \in e,\ i \notin ele \\ pe_{pool} & if\ i \in ele,\ r \in pool \end{cases}$$

Analogously to the export side, we adopt the Armington (1969) assumption of product heterogeneity for imports. A nested CES function characterizes the trade-off between imported (from national and international sources) and locally produced varieties of the same goods. The zero profit conditions that determines the level of Armington production, denoted by $a_{r,i}$, is given by:

$$\frac{pa_{r,i}}{\overline{pa}_{r,i}} = \left[\beta_{r,d,i}\left(\frac{pd_{r,i}}{\overline{pd}_{r,i}}\right)^{1-\sigma_{DM}} + \left(\beta_{r,u,i}\left(\frac{pdx_{r,i}}{\overline{pdx}_{r,i}}\right)^{1-\sigma_{DF}} + \beta_{r,f,i}\left(\frac{pdfm_{r,i}}{\overline{pdfm}_{r,i}}\right)^{1-\sigma_{DF}}\right)^{\frac{1-\sigma_{DM}}{1-\sigma_{DF}}}\right]^{\frac{1}{1-\sigma_{DM}}} \tag{9}$$

where $pdfm_{r,i}$ and β's denotes the price for international imports and respective value share parameters, respectively.

The U.S. economy as a whole is modeled as a large open economy, by specifying elasticities for world export demand and world import supply functions. This specification implies that the U.S. can affect world market prices. Thus, while we do not explicitly model other regions, the simulations include terms of trade and competitiveness effects of policies that approximate results we would get with a full global model.

Solving the model in the GAMS/MPSGE language (Rutherford, 1999) constrains us to employ constant returns to scale functions. To model concave world trade functions, for each region and sector we introduce a fixed factor which enters as an input into a Cobb-Douglas export and import transformation function. A foreign consumer is endowed with the rents from fixed factors and demands foreign exchange. Let $pfix_{r,i}$ and $pfim_{r,i}$ denote the price for the fixed factor associated with export and imports, respectively, and let pfx denote the price for foreign exchange. The pricing equation for international exports of good i by region r is then given by:

$$pfx = pdfx_{r,i}{}^{\gamma_{r,i}} \cdot pfix_{r,i}{}^{1-\gamma_{r,i}} \tag{10}$$

Note that we can calibrate to any price elasticity of foreign demand for exports using the share parameter γ. If $\gamma = 1$, the U.S. cannot affect world prices, i.e. it is a small open economy. Analogously, the pricing equation for imports from international sources is:

$$pdfm_{r,i} = pfx^{v_{r,i}} \cdot pfim_{r,i}{}^{1-v_{r,i}} \tag{11}$$

where $pdfm_{r,i}$ and v denote the price for international imports and a share parameter, respectively.

3.3 Household Behavior

In each U.S. region, households across income classes differ in terms of income sources and expenditure patterns. In region r, a representative agent in income class h chooses consumption, residential and non-residential investment, and leisure to maximize utility subject to a budget constraint given by the level of income . Income is defined as:

$$M_{r,h} = \left(pk \cdot \overline{K}_{r,h} + pl_r \cdot \overline{L}_{r,h}\right) \cdot \left(1 - tinc_{r,h}\right) + pk \cdot \overline{RK}_{r,h} + \sum_z pr_z \cdot \overline{F}_{r,h,z} + TR_{r,h} \tag{12}$$

where $\overline{K}_{r,h}$, $\overline{L}_{r,h}$, $\overline{F}_{r,h,z}$, and $\overline{RK}_{r,h}$ denote the initial endowment of non-residential capital, labor (including leisure time), fossil fuel resources, and residential capital, respectively. $tinc_{r,h}$ and $TR_{r,h}$ denote the region- and household specific marginal personal income tax rate and transfer income, respectively.

Preferences are represented by a CES function where consumption, labor supply, and savings resulted from the decisions of representative households by income class in each region maximizing utility subject to a budget constraint. Figure B6 provides a schematic overview of the adopted nesting structure for household utility. By duality and the property of linear homogeneity, optimizing behavior of households requires that:

$$pw_{r,h} = E_{r,h}\left(pa_{r,i}, pl_r, pk, pinv_r\right) \tag{13}$$

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[3] We identify NY and NENGL as separate pools since electricity flows with contiguous ISOs represent only a small fraction of total electricity generation in those regions. For example, based on our calculation using data provided by ISOs, net electricity trade between ISO New England and ISO New York account for less than 1% of total electricity produced in ISO New England. The interface flows between the New York and neighboring ISOs amount to about 6% of total electricity generation in ISO New York.

[4] The regional electricity pools are thus defined as follows: NENGL, NY, TX, AK each represent a separate pool. The Western NERC interconnection comprises CA, MOUNT, and PACIF. The Eastern NERC interconnection comprises NEAST, SEAST, NCENT, SCENT, and FL.

where $pw_{r,h}$ denotes an utility price index. $pinv_r$ denotes the price for the investment good in region r which is produced with fixed production coefficients according to:

$$\frac{pinv_r}{\overline{pinv}_r} = \sum_i \phi_{r,i,INV} \frac{pa_{r,i}}{\overline{pa}_{r,i}} \tag{14}$$

By Shephard's Lemma, the compensated final demand for good i by household h in region r is given by:

$$d_{r,i,h} = \overline{M}_{r,h} \frac{\partial E_{r,h}}{\partial pa_{r,i}} \tag{15}$$

and leisure, residential and non-residential investment demand are given by:

$$leis_{r,h} = \overline{M}_{r,h} \frac{\partial E_{r,h}}{\partial pl_r} \tag{16}$$

$$rsd_{r,h} = \overline{M}_{r,h} \frac{\partial E_{r,h}}{\partial pk} \tag{17}$$

$$nrd_{r,h} = \overline{M}_{r,h} \frac{\partial E_{r,h}}{\partial pinv_r} \tag{18}$$

3.4 Government

In each region, a single government entity approximates government activities at all levels—federal, state, and local. Government consumption is paid for with income from tax revenue net of any transfers to households. In policy simulations, we adopt the convention to hold government consumption constant. The federal government agent demands regional government goods in fixed proportions:

$$\frac{pg}{\overline{pg}} = \sum_r \psi_r \frac{pgov_r}{\overline{pgov}_r} \tag{19}$$

where ψ_r denotes benchmark value shares, and the regional government good is a CES aggregate of Armington goods whose price is given by:

$$\frac{pgov_r}{\overline{pgov}_r} = \left[\sum_i \xi_{r,i} \left(\frac{pa_{r,i}}{\overline{pa}_{r,i}}\right)^{1-\sigma_{GOV}}\right]^{\frac{1}{1-\sigma_{GOV}}} \tag{20}$$

and where $\xi_{r,i}$ denote value shares parameters. The government budget constraint is given by:

$$\begin{aligned} GOV = & \sum_{r,i} \left(to_{r,i} \cdot p_{r,i} \cdot y_{r,i} + tl_r . pl_r \cdot ld_{r,,i} + tk_r \cdot pk \cdot kd_{r,i}\right) \\ & + \sum_{r,h} tinc_{r,h} \left(pl_r\left(\overline{L}_{r,h} - leis_{r,h}\right) + pk\left(\overline{K}_{r,h} - nrd_{r,h}\right)\right) \\ & - \sum_{r,h} TR_{r,h} - \overline{BOP} \end{aligned} \tag{21}$$

where $\overline{BOP}$ denotes the initial balance of payments (deficit).

3.5 Market Clearing Conditions

The system is closed with a set of market clearance equations that determine the equilibrium prices in the different goods and factor markets. The market clearance condition for Armington goods requires that:

$$a_{r,i} = \sum_j x_{r,i,j} + \sum_h d_{r,i,h} + i_r \cdot \frac{\partial pinv_r}{\partial pa_{r,i}} + g_r \cdot \frac{\partial pgov_r}{\partial pa_{r,i}} \tag{22}$$

By Shephard's Lemma, the two last summands in (22) represent the investment and government demand for good i in region r, respectively. Regional labor markets are in equilibrium if:

$$\sum_{r,h} \left(\overline{L}_{r,h} - leis_{r,h}\right) = \sum_i ld_{r,i} \tag{23}$$

the integrated U.S. capital market clears if:

$$\sum_{r,h} \left(\overline{RK}_{r,h} + K_{r,h}\right) = \sum_{r,i} kd_{r,i} + \sum_{r,h} rsd_{r,h} \tag{24}$$

and equilibrium on resource markets requires that:

$$\sum_{r,h} \overline{F}_{r,h,z} = \sum_i rd_{r,z,i} \tag{25}$$

Balanced intra-national trade for non-energy goods that are traded on a bilateral basis requires that:

$$y_{r,i} \frac{\partial p_{r,i}}{\partial pn_{r,i}} = \sum_{rr} a_{rr,i} \frac{\partial pa_{rr,i}}{\partial pn_{r,i}} \quad , \quad i \in ne \tag{26a}$$

Balanced domestic trade for non-electricity energy goods requires that:

$$\sum_r \left(y_{r,i} \frac{\partial p_{r,i}}{\partial pnn_i} - a_{r,i} \frac{\partial pa_{r,i}}{\partial pnn_i}\right) = 0 \quad , \quad i \in e,\ i \notin ele \tag{26b}$$

and regional electricity trade is in equilibrium if:

$$\sum_{pool} \left(y_{r,i} \frac{\partial p_{r,i}}{\partial pe_{pool}} - a_{r,i} \frac{\partial pa_{r,i}}{\partial pe_{pool}}\right) = 0 \quad , \quad i \in ele,\ r \in pool \tag{26c}$$

Foreign closure of the model is warranted through a national balance-of-payments (BOP) constraint. Hence, the total value of U.S. exports equals the total value of U.S. imports accounting for an initial BOP deficit given by the base year statistics. The BOP constraint thereby determines the real exchange rate which indicates the (endogenous) value of the domestic currency vis-à-vis the foreign currency:

$$\sum_{r,i} \overline{EX}_{r,i} + \overline{BOP} = \sum_{r,i} IM_{r,i} \frac{\partial pdfm_{r,i}}{\partial pfx} \tag{27}$$

where the level of foreign exports, $\overline{EX}_{r,i}$, and foreign imports, $IM_{r,i}$, is determined by conditions (10) and (11).

4. Dynamic Process of USREP

There are five critical features of USREP that govern the evolution of the economy and its energy-using characteristics over time. These are the rate of capital accumulation, population and labor force growth, changes in the productivity of labor and energy, fossil fuel resource depletion, the availability of initially unused "backstop" energy supply technologies. Since the USREP model adopts many features of the MIT EPPA model which represents the global economy, we draw heavily from the model description of EPPA in Babiker *et al.* (2001), Paltsev *et al.* (2005), and Chen *et al.* (2015, 2017).

4.1 The Capital Stock Evolution

The IMPLAN dataset includes an explicit set of accounts that detail the demand for investment by private and public entities for the base year 2006. We assume that the composition of investment includes all inputs to enterprises, fixed investment and inventory sales. We specify an investment sector that produces an aggregate investment good equal to the level of savings determined by the representative agent's utility function. The accumulation of capital is calculated as investment net of depreciation according to the standard perpetual inventory assumption.

Capital stock accounting is often problematic because of empirical measurement issues. It was therefore necessary to calibrate the initial capital stocks. Assuming that the economy is initially on a steady state, we can infer investment level through a regional scale parameter such that investment exactly replaces depreciated capital. In doing so we accepted as being more accurate the initial regional capital flows, and use these flows to impute scale factors that yielded more plausible initial level of investment given observed rates of return for the USREP regions.[5] Given these scale factors we were able to specify the dynamic process of capital evolution.

An important feature in USREP is a distinction between malleable and non-malleable capital. Each regional economy is modeled as having two forms of capital in any period. One portion of the aggregate capital stock is "malleable", in that the mix of inputs with which this type of capital is used can be altered in response to changing relative prices. The other is old, "rigid" capital, for which the proportions of the inputs with which this type of capital is used is fixed. Associated with each type of capital is a sub-model that represents the transformation of primary factors and intermediate inputs into outputs that are treated as perfect substitutes. To be specific, the first sub-model utilizes malleable capital with a CES production technology that allows substitution between inputs whereas the second sub-model characterizes a Leontief production function that captures the industry-specific, non-malleable component of the capital stock that is associated with production that is fixed in its input proportions. The larger the share of sector output that originates in the rigid portion of the production structure, the less substitutable are other inputs for fossil fuels at the level of various sectors and the aggregate economy, and the greater is the inertia of the energy-carbon system. The larger the proportion of aggregated capital that is malleable, the greater are the possibilities for substitution in the short run. The larger the proportion of aggregated capital of the rigid type, the more the initial price response will tend to persist over time.

The dynamic updating of the capital stock in each region and sector is determined by this capital vintaging procedure. New capital installed at the beginning of each period starts out in a malleable form. At the end of the period a fraction of this capital becomes non-malleable and frozen into the prevailing techniques of production. The remaining fraction can be thought of as that proportion of previously installed malleable capital which is able to have its input proportions adjust to new input prices, and take advantage of intervening improvements in energy efficiency driven by the AEEI. As the model steps forward in time it preserves v vintages of rigid capital, each retaining the coefficients of factor demand fixed at the levels that prevailed when it was installed. USREP specifies $v = 1, \ldots, 4$, implemented in the electric power, agriculture, energy intensive, commercial transportation and other industry sectors. This means that the model has 20 region- and sector- and vintage-specific stocks of rigid capital, plus a single aggregate stock of malleable capital that is fungible across U.S. regions.

4.2 Population, Productivity and Labor Supply

From a dynamic perspective, the trade flow and social accounting matrices that underlie USREP's equilibrium structure constitute a single data-point that represents a snapshot of the economies in the model at a point in time. Like many other CGE models in the climate policy arena, USREP relies on assumed exogenous rates of productivity growth from this starting point to drive the increase of endowments of the factors that are not reproducible or accumulable within the model. A key input in this category is labor, whose supply in quantity terms (i.e., physical units of worker-hours) is determined by population demographics and labor force participation decisions, but whose supply in value terms has outstripped the growth in quantity due to the growth in labor productivity.

We do not explicitly represent the sources of this dichotomy within the model. Rather, it is assumed that the inputs of labor to each of the regional economies are augmented by Harrod-neutral technical change. Specifically, for region r and time t, the supply of labor is scaled from its base-year value by an augmentation parameter whose rate of growth represents the combined effect of increased labor input in natural units and chained rates of increase of labor productivity.

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[5] The rate of return is defined as the sum of the rates of interest and depreciation, equal to the ratio of the flow of capital services to the underlying capital stock. Adjusting K0 to be consistent with observed rates of return gives the required scale factor for the capital stock estimates in USREP.

In USREP, labor-augmenting technical change is the key driver of economic growth. We calibrated regional labor productivity growth rates such that the baseline GDP growth matches EIA's Annual Energy Outlook (AEO) 2018 Reference case projection out to 2050. An alternative approach to establish a projection involves extrapolating population and labor productivity growth rates by fitting a logistic function that assumes convergence in growth rates by the end of the century with the 2100 targets for annual labor productivity growth and for population growth set to two and zero percent, respectively.

4.3 The Energy-Saving Technical Change

One of the stylized facts of economic development is that countries tend to use first more, then less energy per unit of GDP as their economies expand from very low to high levels of activity (Schmalensee, Stoker and Judson, 1998). In simulations used to analyze energy or climate policy, it is customary to model these dynamics by means of exogenous time trends in the input coefficients for energy or fossil fuels. We employ such trends in the USREP model to control the evolution of demand reduction factors that scale production sectors' use of energy per unit of output. The rate of growth of these factors is called the autonomous energy efficiency improvement (AEEI), which is a reduced-form parameterization of the evolution of non-price induced, technologically-driven changes in energy demand.

Within USREP, the representation of energy-saving technical change through the AEEI parameter is a way of directly forecasting, on the basis of modelers' assumptions, the effects of innovation on the growth of the economy and its use of energy. The algebraic specification of the regional trends in energy use are separate from the trends in productivity discussed in the foregoing section. However, these trends are jointly chosen by the modelers in constructing USREP's baseline scenario to generate future trajectories of output, energy use and emissions that all appear plausible in the light of history.

Following the approach first outlined in Edmonds and Reilly (1985), we specify an index of energy efficiency that grows over time, whose rate of increase is assumed to be equal to the rate of declines in energy use per unit of output. We differentiate the growth of energy efficiency across sectors according to the assumption that those industries responsible for producing primary energy commodities (coal, crude oil, and natural gas) experience no energy efficiency improvement. The coefficients on energy input to these sectors therefore remain unchanged from their calibrated benchmark values that are derived from the base-year social accounting matrices. For all other sectors and regions in the economy, it is assumed that energy efficiency increases at an equal rate over time. For these sectors, the coefficient on energy input per unit of output by sector and time period is scaled from its benchmark value by the inverse of the energy efficiency improvement rate.

4.4 Natural Resource Inputs

All fossil energy resources are modelled in USREP as graded resources whose cost of production rises continuously as they are depleted. The basic production structure for fossil energy production sectors plus the depletion model and representation of backstop technologies, completely describe fossil fuel production. The resource grade structure is reflected by the elasticity of substitution between the resource and the capital-labor-materials bundle in the production function. The elasticity was estimated based on the distribution of discrete resource grades from the median estimate of resources reported in Edmonds *et al.* (1986), by fitting a long-run constant elasticity supply curve through the midpoints of each of the discrete grade categories in that study.

In the fossil fuel production sectors, elasticities of substitution were then chosen that would generate elasticities of supply that matched the fitted value in the respective supply curves, according to the method developed in Rutherford (1998). Production in any one period is limited by substitution and the value share of the resource, i.e. the technical coefficient on the fixed factor in the energy sector production functions. The resource value shares were determined to represent key differences among regions and fuels. Regions with abundant fuel resources have lower cost of fuel production in capital, labor, materials relative to the market price. By contrast, regions with less accessible resources have higher production costs for the same world price and similar technology.

Table 3 shows the regional fossil fuel reserves. These reserve estimates are scaled to match the U.S. total fuel reserves used in the MIT EPPA model. Over time, energy resources are

Table 3. Fossil Fuel Reserves in 2006 (Quadrillion BTU)

	COAL	NAT. GAS*	CRUDE OIL	SHALE OIL
AK	1915	383	906	
CA		15	220	
FL		2	11	
NY		73		
TX	236	505	387	
SEAST	1489	78	9	32583
NEAST	5784	327	44	25363
SCENT	140	337	251	
NCENT	5927	17	146	
MOUNT	8079	399	165	202718
PACIF	91	4		
USA	24963	2258	2257	

* Includes shale gas resource
Data Sources: USGS (2009), Dyni (2006), DOE (2009), Paltsev *et al.* (2005, 2011).

subject to depletion based on physical production of fuel in the previous period. With USREP solving on a five-year time step we approximate depletion in intervening years by multiplying the output of each fuel sector by a factor of five. This specification captures the major long-run dynamics of resource prices. Fuel price trajectories are driven by the grade structure of the underlying resource base.

4.5 Advanced/Backstop Energy Supply Technologies

Several advanced energy supply options have been specified in USREP. These technologies endogenously enter if and when they become economically competitive with existing technologies. Competitiveness of different technologies depends on the endogenously determined prices for all inputs, as those prices depend on depletion of resources, climate policy, and other forces driving economic growth such as the savings, investment, and the productivity.

Advanced energy supply options represented in the model are summarized in **Table 4**. All technologies produce substitutes for goods and services in each category (electricity, fossil fuel, and personal transport). The unique attributes of these technologies are captured through parameters of the nested CES functions. Each advanced technology is specified with a production structure similar to that of the conventional technology. Shale oil and bio-oil have a similar production structure, with the key difference being that resources for shale oil are the estimated oil content of shale reserves whereas the resource input for bio-oil is land. Moreover, shale oil resources are depletable, although estimated to be very large whereas land is modeled as a non-depletable resource whose productivity is augmented exogenously. Agriculture and biomass electricity also compete for land. Both shale oil and bio-oil use capital, labor, and intermediate inputs from the OTH sector. For oil from shale, the emissions of carbon during the extraction process are estimated to be 20% of the carbon per unit of oil produced. The carbon content of the refined oil produced from shale is assumed to be the same as refined oil from conventional crude. Thus, carbon emissions from production are 20% of the carbon in the oil output. The oil product is assumed homogeneous with crude oil and carbon emitted from combustion is accounted at the point of consumption of refined oil produced from the crude oil.

The coal gasification technology includes intermediates in the top nest as Leontief inputs. The coal input enters at the top level as well, and these are combined with the value added bundle. We assume that the energy conversion efficiency of coal to natural gas is 50% and that the resulting fuel has the same carbon coefficient as natural gas. The efficiency factor, when combined with the differences in

Table 4. USREP Advanced Technologies

TECHNOLOGY	DESCRIPTION
Electricity	
Biomass Electricity	Converts biomass into electricity
Wind and Solar	Converts intermittent wind and solar resources into an imperfect substitute for electricity
Wind with Gas Backup	Jointly builds wind turbines and natural gas generation with gas generation operating at a 7% capacity factor and only used when wind is not sufficient to meet load requirements
Wind with Biomass Backup	Jointly builds wind turbines and biomass generation with biomass generation operating at a 7% capacity factor and only used when wind is not sufficient to meet load requirements
Advanced Gas	Natural gas combined cycle (NGCC)
Advanced Gas with Carbon Capture and Sequestration	Natural gas combined cycle that captures 90% or more of the carbon emissions produced in electricity generation
Advanced Coal with Carbon Capture and Sequestration	Integrated coal gasification combined cycle (IGCC) technology that captures 90% or more of the carbon emissions produced in electricity generation
Advanced Nuclear	Next generation of nuclear power plants incorporating estimated costs of building new nuclear power plants in the future
Fossil Fuel	
Coal Gasification	Converts coal into natural gas
Shale Oil	Extracts and upgrades shale oil resources into crude oil
Biomass Liquids	Converts biomass into refined oil (2^{nd}-generation carbon-free biofuel)
Personal Transport	
PHEV	Plug-In Hybrid Electric Vehicles
BEV	Battery Electric Vehicles

carbon emissions per MMBtu of gas and coal implies that 73% of the carbon in the coal is emitted in the gasification process and 27% remains in the synthesis gas.

Biomass electric and Wind & Solar have a very similar production structure, except that they include an additional fixed factor to slow initial penetration of the technologies as described in more detail in Morris *et al.* (2019). Both use land and a combination of output from the OTH sector, 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% from biomass to the final energy product. This conversion efficiency also assumes that process energy needed for bio-fuel production is biomass. Our main interest in including bio-fuels is to represent a low carbon emissions option. Current biomass production (e.g., ethanol from corn) often uses coal in the distillation process and fossil energy in the production of corn, thus releasing as much or more CO_2 as is offset when the ethanol is used to replace gasoline. There is little reason to represent such a technology option in a climate policy scenario where carbon is priced because its cost would escalate with the carbon price just as would the price of conventional refined oil, and thus it would never be competitive.

Wind and solar are treated as an imperfect substitute to account for their intermittent nature of power supply. In addition, we consider wind generation with backup power supply from flexible and fast ramping natural gas or biomass generating units. With the backup power complementing the wind power intermittency, these two types of wind generation can provide electricity without fluctuation thus are treated as perfect substitutes for all other types of generation.

The three advanced fossil electric generation technologies have a similar structure to one another. These technologies represent: (1) a natural gas combined cycle technology (advanced gas) without carbon capture and sequestration, (2) a natural gas combined cycle technology with carbon capture and sequestration (gas CCS), and (3) an integrated coal gasification technology with carbon capture and sequestration (coal CCS). The production structures for these technologies include separate nests that represent the cost of transmission & distribution (T&D), generation, and sequestration. Separate identification of these components creates greater flexibility in the structure. The gas CCS and coal CCS technology captures 90% of carbon dioxide from combustion.

Specification of advanced technologies must rely on data beyond that contained in National Income and Product Account (NIPA) data because these technologies are not currently used (or used on a very small scale) and thus the production inputs are not identified in standard input-output tables in the 2006 benchmark year. By convention, we set input shares in each technology so that they sum to 1.0. We then separately identify a multiplicative mark-up factor that describes the cost of the advanced technology relative to the existing technology against which it competes in the base year. This markup is multiplied by all of the inputs. For example, the markup of the coal gasification technology in the USA region is 2.0, implying that this technology would be economically competitive at a gas price that is two times that in the reference year (2006) if there were no changes in the price of inputs used either in natural gas production or in coal-gasification production of gas from coal. In USREP simulations, the resulting technology mark-up or relative competitiveness to the conventional technology will adjust to reflect the changes in the price of inputs over time. As with conventional technologies, the ability to substitute between inputs in response to changes in relative prices is controlled by the nesting structure and elasticities of substitution assumed for each technology.

Cost of inputs for the advanced generation technologies shown in **Table 5** are derived from the levelized cost of electricity (LCOE) calculated based on the median estimates of electricity generating costs provided by International Energy Agency (IEA) and Nuclear Energy Agency (NEA). LCOEs include capital recovery required, cost of operations and maintenance, cost of fuel and cost of carbon transportation and storage. The capital recovery required is derived based on "overnight" capital cost, capacity factor and capital recovery charge rate that turns the capital expenditure into annual payments. Detailed steps in calculating the LCOE are provided in Chen *et al.* (2017). In USREP, we assign capital recovery required to capital cost and the fixed and variable operation and maintenance to labor cost of the advanced technologies. Costs of transmission and distribution are divided with one third borne on labor and two thirds on capital.

Along with the top-down approach of representing technologies following Paltsev *et al.* (2005), USREP includes a technology-specific factor (TSF) as a unique resource input for each technology owned by the representative household. The TSF is a latent resource until there is demand for output from the new technology. Once the new technology penetrates, further expansion is dictated by a learning-by-doing function that takes into account investment, knowledge and experience accumulated through productions in the previous periods. The expanded TSF reduces the scarcity rent of the factor and allows the long-run cost of production to fall. Along with its accumulation through a function of additional production in the current period, TSF depreciates to allow for a situation where demand for the technology potentially disappears for some time and then reappears. With depreciation, production capability must be built back up. To continue to allow restart of the technology in later periods, we set the amount of the TSF in any period equal

Table 5. Technology Cost of Advanced Generating Technologies (2006$)

	Pulverized Coal (New)	NGCC	NGCC with CCS	IGCC with CCS	Adv. Nuclear (EA numbers)	Wind	Biomass	Solar	Wind Plus Biomass Backup	Wind Plus NGCC Backup
"Overnight" Capital Cost (*$/kW*)	1,964	942	1,940	3,749	3,919	1,687	3,823	1,445	5,510	2,319
Total Capital Requirement (*$/kW*)	2,278	1,018	1,940	4,499	5,094	1,822	4,434	1,561	5,950	2,504
Capital Recovery Charge Rate	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%
Fixed O&M Costs (*$/kW*)	35.4	27.7	53.8	56.9	64.8	46.1	99.4	23.4	145.5	52.8
Variable O&M Costs (*$/kWh*)	0.003	0.003	0.006	0.005	0.003	0.013	0.005	0.015	0.012	0.013
Project Lifetime (*years*)	20	20	20	20	20	20	20	20	20	20
Capacity Factor	85%	85%	85%	85%	85%	35%	80%	20%	42%	42%
Capacity Factor Wind									35%	35%
Capacity Factor Biomass/NGCC									7%	7%
Operating Hours	7,446	7,446	7,446	7,446	7,446	3,066	7,008	1,752	3,679	3,679
Capital Recovery Required (*$/kWh*)	0.036	0.016	0.030	0.070	0.080	0.069	0.074	0.104	0.188	0.079
Fixed O&M Recovery Required (*$/kWh*)	0.005	0.004	0.007	0.008	0.009	0.015	0.014	0.013	0.040	0.014
Construction Time (*years*)	4	2	2	5	5	2	4	2	2	2
Heat Rate (*Btu/kWh*)	8,740	6,333	7,493	8,307	10,488	-	7,765	-	7,765	6,333
Fuel Cost (*$/MMBtu*)										
Fraction Biomass/NGCC									8.8%	8.2%
Carbon Capture Ratio			90%	95%						
Levelized Cost of Electricity (*$/kWh*)	0.057	0.066	0.099	0.110	0.101	0.098	0.129	0.132	0.243	0.111
Transmission and Distribution (*$/kWh*)									0.01	0.01
Cost of Electricity (*$/kWh*)	0.057	0.066	0.099	0.110	0.101	0.098	0.129	0.132	0.253	0.121

Sources: EIA (2010) with adjustments for changes in prices

to the greater of the depreciated level plus new additions in that period or the initial endowment.

The USREP model includes a technology-rich representation of the personal transport sector and its substitution with purchased modes, which include aviation, rail, and marine transport. Several features were incorporated into the USREP 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 (PHEV) and battery electric vehicle (BEV). Fleet turnover is captured through 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 differences 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 USREP model includes a parameterization of the total miles traveled in both new (0 to 5-year-old) and used (6 years and older) vehicles and tracks changes in travel demand in response to changes in income as well as price per mile. The USREP 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 upfront 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.

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 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 ICE-only vehicle. The ICE fuel economy of the PHEV assumes operation in hybrid (charge-sustaining) mode. 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.

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). 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).

Likewise, we introduce the BEV that runs on battery stored electricity only and is assumed to be 40% more expensive relative to a new ICE vehicle. Both PHEV and BEV are treated as perfect substitute for the ICE-only vehicles. We assume that the base fuel efficiency of PHEV is 25 miles per gallon (MPG) if running on gasoline only and 2.2 miles per kWh if on battery stored electricity only. EV is specified with a base fuel efficiency at 3.3 miles per kWh. In simulations, the fuel efficiency may vary due to price-induced investment in vehicle.

By capturing the projections of VMT, fleet stock turnover, and fuel price-induced investment in fuel efficiency, the vehicle representation in USREP allows us to evaluate the policies such as the U.S. Corporate Average Fuel Economy (CAFE) standards that target improvements in vehicle fuel efficiency given the distinction between newly purchased and pre-existing vehicle stocks in each period. Changes in overall vehicle miles traveled as well as the fuel use and GHG emissions of new and pre-existing vehicles are tracked throughout the dynamic process as the model moves forward.

5. Model Calibration

As customary in applied general equilibrium analysis, we use prices and quantities of the integrated energy-economic dataset for the benchmark year 2006 to calibrate the value share and level parameters in model. Exogenous elasticities determine the free parameters of the functional forms that capture production technologies and consumer preferences. Whenever possible, we adopt the parameterization of the single U.S. region in the EPPA model (Version 6, Chen *et al.*, 2015) and apply to all U.S. regions which has been subjected to extensive sensitivity analysis in Webster *et al.* (2002) and Cossa (2004).

To introduce leisure into the model, we follow Ballard (2000) to calibrate the benchmark value of leisure and the elasticity of substitution between consumption and leisure by specifying compensated and uncompensated labor supply elasticities based on empirical estimates.

To establish a reference case consistent with official projections, we calibrate the model to match GDP growth through 2050 in EIA's AEO2018 Reference case (EIA, 2018) by updating regional labor productivity growth rates. Policies affecting the U.S. energy system and end-use energy efficiency, such as the regional RPS for electric power generation and a national CAFE standards (and a separate CAFE standards for California) for vehicle transportation are represented in our reference case to reflect regulations currently on the books.

6. Policy Instruments

6.1 Emission Cap/Tax

USREP has been engaged in a number of impact analysis of energy and environmental policy proposals to reduce GHG emissions through an emission cap program or an emission tax. Either approach imposes a price on every unit of GHG emissions, raising the cost of fossil fuel consumption. The change in relative prices of fossil fuel to other inputs induces substitution away from carbon-intensive fuels toward low-emission alternatives. In USREP, the emission price is implemented through a permit system. The emission permit is specified as an input of production in fixed proportion to fuel consumption based on emissions per thermal unit. On the permit supply side, instead of directly endowing government or representative household with the emission permits, we introduced an intermediary agency and endowed it with all permits. The agency collects permit revenue and redistributes the revenue to government and household according to a rule described in section 6.2.

An emission cap program sets a limit on emissions thus a fixed number of permits available in the economy. Firms are required to cut emissions to match their permit allocation.

If permit trading is allowed, firms can sell excess permits to other firms, leading to a market determined carbon price equaling the marginal cost of abatement throughout the economy. In USREP, the emission cap policy is modeled by specifying the endowment of number of permits. Depending on policy specification on trading, permit endowment can be defined as sector-specific or region-specific or economy-wide to evaluate cost of emission reduction with efficiency implication. In contrast to the cap policy, an emission tax sets the level of emission price instead of quantity limits on emissions. Although it is a pricing instrument, we can model it through the permit system in USREP by assigning a rationing variable that endogenously adjusts such that the number of permit supply and permit demand in the economy equalizes at the set level of emission price.

6.2 Revenue Recycling and Revenue Neutrality

In USREP, government consumption is calibrated to EIA's AEO 2018 Reference case projection and held constant in the counterfactual scenarios. That is, the change in tax revenue collected by government is offset by a lump sum transfer between government and household. Specifically, an emission cap/tax policy as described in 6.1 may lead to a reduction in total tax revenue collected from personal income, corporate income, payroll taxes and sales taxes. A portion of the carbon revenue collected by the intermediary agency in USREP will be set aside to replace the lost tax revenue such that government revenue is held equal to that in the reference case.

The remaining portion of the carbon revenue is recycled in a form of lump-sum rebate to the household by population weight, as in our default setting. Alternative revenue recycling options are available in USREP to cut rate on taxes, such as payroll taxes, corporate income taxes or personal income taxes. The rate reduction is treated as an endogenous variable acting as a multiplier to adjust the current tax rates.

6.3 Renewable Portfolio Standards (RPS)

The RPS policy sets a minimum share of electricity supply coming from the renewable sources. We adopted the approach illustrated through an MPSGE example by Rutherford.[6] Rutherford's approach creates a RPS permit system giving one permit to renewable generators for every kWh of their electricity output and requiring all electric generators to surrender phi permits for every kWh of generation, where phi is the RPS target. This implementation subsidizes renewable generation sources and imposes a tax on the non-renewable generation by redistributing permit revenue among generators without generating rents outside the electric sector. Moreover, if the electric sector produces more renewable generation than the RPS requirement, the permit supply exceeds permit demand and permit price collapses to zero, reflecting the non-binding RPS constraint.[7]

6.4 Corporate Average Fuel Economy (CAFE)

The CAFE policy regulates the fuel economy of new vehicles with a minimum requirement on how far vehicles travel on a gallon of gasoline. Previous versions of USREP implemented the policy through a subsidy on vehicle capital input to reduce the share of fuel input thus fuel use per mile driven. The vehicle subsidy is financed by raising a lump-sum tax on households proportional to new vehicle purchases, therefore generating a direct income effect.

In the current version of USREP, an alternative approach is adopted by creating a permit system similar to the approach to RPS implementation in the model. On the permit supply side, each new vehicle sales generates α permits, where α is the reciprocal of CAFE standard and in gallons equivalent of fuel use per mile driven. On the permit demand side, each new vehicle sales is required to surrender θ_i permits, where θ_i is the reciprocal of the vehicle type i's fuel economy in gallons equivalent fuel use per mile driven where $i=(ICE, PHEV, BEV)$. Different types of vehicles are associated with different fuel economy. In the case that the fuel economy of ICE vehicle is lower than that of PHEV or BEV, θ_{ICE} for the ICE vehicle is higher relative to θ_{PHEV} and θ_{BEV} of PHEV and BEV. Therefore, each new vehicle sales of BEV can generate an excess permit of $(\theta_{BEV}-\alpha)$ and supply to the permit market. Each ICE vehicle running short of $(\theta_{ICE}-\alpha)$ permit needs to buy from the permit market to fulfill the permit requirement in order to sell the vehicle. By equilibrating the permit supply and demand, the permit market clears with an endogenously determined permit price. In effect, this approach subsidizes BEV and imposes a tax on the production of ICE. The permit system does not generate any rents outside the transport sector and only involves funds transfer within the personal transport sector.

7. Model Revisions and Updates

The USREP model documented in this technical note includes updates to the version of USREP used in a recent published work (Rausch and Reilly, 2015). These updates improve the characterization of the energy market given its development over time and thus strengthen the capability of energy and environmental policy evaluation.

7.1 Technology Vintages

Our treatment of how vintaged capital depreciates through its lifetime is updated. The vintage component of the stock is tracked through 5 vintages, the initial malleable stock and 4 discrete stocks. Once a stock reaches vintage 4, it depreciates at an exponential rate, with any undepreciated stock remaining as part of vintage 4 stock in the next

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[6] http://www.mpsge.org/rps/

[7] This approach obviates the need for a side constraint in MPSGE.

period. Compared with the previous assumption that vintage capital depreciates every period over its lifetime, and fully depreciates after vintage 4, the vintaged capital stock has a longer lifetime. Given the 5-year time step, with the previous assumption the stock was partly retired during each vintage and fully retired after 25-year of service. The new approach allows the vintage stock to retain its full usefulness through 25 years, and then gradually retire. The updates imply that older fleets are allowed to supply more, reducing the demand for investment in new technologies. Only a portion of the stock is vintaged with the malleable portion depreciating exponentially from initial investment. The intuition of this approach is the production capacity of vintaged portion remains unchanged through the first 25 years of service, but to get the full capacity of the total investment of vintaged malleable capital requires additional investment in future years.

7.2 Backstop Technology Markup and Technology Specific Factors

Cost of advanced technologies were calculated based on a markup factor defined as the ratio of the advanced technology's production cost to that of a benchmark technology that currently produces the same product in the region. Previously a uniform markup factor was assumed to apply across regions in the U.S. That approach leads to different costs for the same technology because the price of benchmark technology can differ across regions in the U.S., creating uneven opportunities for the same type of advanced technology to enter the market in different regions. Under a carbon policy, regions with lower cost of existing generation have cheaper low-carbon technologies available for decarbonization whereas regions with higher cost of existing generation have to pay more for adopting the same type of low-carbon technologies. Hence, we updated the technology cost assumption in the latest version of USREP to assume that each type of advanced low-carbon technology costs the same across the U.S. regions except for the fuel input which is calculated based on the regional fuel prices.

We adopt the Technology Specific Factor (TSF) inputs approach used in EPPA and developed by Morris *et al.* (2019). The approach is based on empirical rates of penetration of new technologies. It introduces adjustment costs for rapid expansion of new technology, recognizing that it takes time to develop an industry to fully commercialize it, and that monopoly rents from intellectual property rights (IPR) may accrue and raise the initial cost of the technology. In our global EPPA model we assumed TSF is technology- and region-specific, so that each region must independently develop the capacity to expand the technology. In USREP we assume that the development of the technology in any regions contributes to a national TSF, so that all regions of the US can take full advantage of the development of production capacity for the technology in any region. Compared to the regional TSF, the national TSF will promote higher rate of expansion in advanced technologies as the scarcity rent of TSF declines faster.

Assuming that the TSF costs 1% for advanced generation technology, we calculate the total cost of generation technology by region. **Table 6** shows the regional variation in cost due to differences in regional fuel price. USREP adopts the same approach to representing advanced technologies as in the MIT EPPA model. More details about the advanced technologies can be found in Paltsev *et al.* (2005), Chen *et al.* (2016) and Morris *et al.* (2017, 2019).

Relative to the regional electricity prices by existing technology in the last column, an implied technology cost markup

Table 6. Regional Cost of Generation Technology (2006 cents per kWh)

	Pulverized Coal (New)	NGCC	NGCC w/ CCS	IGCC w/ CCS	Adv. Nuclear (EA numbers)	Wind	Biomass	Solar	Wind Plus Biomass Backup	Wind Plus NGCC Backup
AK	6.1	4.6	7.5	11.5	10.2	9.9	13.1	13.4	25.6	11.5
CA	5.8	6.7	10.0	11.1	10.2	9.9	13.1	13.4	25.6	6.6
FL	6.5	6.7	10.0	12.0	10.2	9.9	13.1	13.4	25.6	7.8
NY	6.4	6.7	10.0	11.8	10.2	9.9	13.1	13.4	25.6	9.4
TX	5.6	6.7	10.0	10.9	10.2	9.9	13.1	13.4	25.6	7.6
NENGL	6.6	6.7	10.0	12.2	10.2	9.9	13.1	13.4	25.6	10.0
SEAST	6.2	6.7	10.0	11.6	10.2	9.9	13.1	13.4	25.6	4.9
NEAST	5.7	6.7	10.0	11.0	10.2	9.9	13.1	13.4	25.6	5.9
SCENT	5.6	6.7	10.0	10.8	10.2	9.9	13.1	13.4	25.6	6.1
NCENT	5.3	6.7	10.0	10.5	10.2	9.9	13.1	13.4	25.6	5.0
MOUNT	5.4	6.7	10.0	10.7	10.2	9.9	13.1	13.4	25.6	5.7
PACIF	5.7	6.7	10.0	11.0	10.2	9.9	13.1	13.4	25.6	5.6
USA	5.4	6.1	9.2	10.4	9.4	9.2	12.1	12.4	23.7	6.2

Table 7. Implied Markups for Advanced Generating Technologies

	Pulverized Coal (New)	NGCC	NGCC w/ CCS	IGCC w/ CCS	Adv. Nuclear (EA numbers)	Wind	Biomass	Solar	Wind Plus Biomass Backup	Wind Plus NGCC Backup
AK	0.53	0.40	0.65	1.00	0.88	0.85	1.13	1.16	2.21	1.04
CA	0.88	1.02	1.53	1.69	1.55	1.50	1.99	2.03	3.88	1.86
FL	0.84	0.86	1.29	1.55	1.31	1.27	1.68	1.72	3.29	1.58
NY	0.68	0.71	1.07	1.26	1.08	1.05	1.39	1.42	2.72	1.30
TX	0.74	0.88	1.32	1.44	1.34	1.30	1.72	1.76	3.37	1.61
NENGL	0.66	0.67	1.00	1.22	1.02	0.99	1.31	1.34	2.55	1.22
SEAST	1.28	1.38	2.07	2.39	2.10	2.03	2.69	2.75	5.26	2.52
NEAST	0.97	1.13	1.69	1.86	1.71	1.66	2.20	2.25	4.30	2.06
SCENT	0.92	1.11	1.66	1.79	1.68	1.63	2.16	2.21	4.22	2.02
NCENT	1.07	1.35	2.03	2.11	2.06	1.99	2.64	2.70	5.16	2.47
MOUNT	0.95	1.17	1.76	1.87	1.78	1.73	2.29	2.34	4.47	2.14
PACIF	1.02	1.19	1.79	1.96	1.82	1.76	2.33	2.38	4.56	2.18
USA	0.88	0.99	1.49	1.68	1.53	1.48	1.96	2.01	3.83	1.84

in the base year can be calculated for each advanced technology by region (see **Table 7**). The markup factor reflects the economic competitiveness of the advanced technology relative to the existing technology. The ratio can vary depending on the changes in input prices, economic condition or policy regime.

7.3 Nuclear and Coal-Fired Generation

We updated the phase-out schedule for nuclear power plants in USREP to be consistent with the generating unit retirement schedule provided by U.S. Environmental Protection Agency (EPA) National Electric Energy Data System (NEEDS) database. Instead of preserving 80% of nuclear generation out to 2050 by the existing plants, the updated phase-out plan calls for faster retirement post 2030. By 2050, less than 10% of present nuclear power supply remains. To keep up with the power sector regulations in recent years, we assume no new coal-fired power plant from 2020 onward. The existing coal-fired power plants represented by the vintaged production in USREP are allowed to operate for their full lifetime as long as they remain economic.

7.4 Energy Delivery Margin

For the energy market, the retail price at the point of consumption is usually higher than the wholesale price at the point of production. The difference lies in the cost of energy delivery from the producers to consumers, i.e., the transmission and distribution of the electric power. To capture the cost difference in the model, we break down the retail energy price into the wholesale price and energy delivery margin which represents the charge of energy delivery service companies. Lacking information on the wholesale prices, we use the minimum retail price across sectors as a proxy for the wholesale price. The delivery margin accounts for the difference between the whole price and retail price paid by each sector. In USREP, the energy delivery margin is modeled as an input in fixed proportion to the energy use. Cost of the delivery margin is determined by the price of services.

7.5 Baseline Calibration

We introduced a routine to calibrate historical years (2010, 2015) to data economic growth, energy prices, energy supply and demand as reported with EIA's official releases. The calibration involves adjustments in (1) labor-augmenting technical change which is assumed as the key driver of economic growth in USREP, (2) autonomous energy efficiency improvement (AEEI) by fuel and by sector to calibrate sectoral emissions and sectoral fuel demand.

To establish a business-as-usual case consistent with official projections, we calibrated the model to match GDP growth through 2050 using projections from EIA's AEO2018 Reference case by updating regional labor productivity growth rates. We also calibrated electricity generation to match the net electric power sector generation in AEO2018. Future energy intensity improvement is driven by estimates derived based on AEO projections and specified as 1.4% per year for the industrial and commercial transportation sectors and 1% per year for the residential and commercial sectors.

In USREP, government collects tax revenues from firms and households then spends it on goods and services. To capture the effect of the progressive income tax structure, we apply marginal tax rates in each income class as estimated by NBER's TAXSIM model (Table 2). The marginal rates, if revenue is unadjusted, collects too much revenue because they fail to account for lower tax rates on inframarginal income. We calibrate the actual revenue to be consistent with tax revenue collected over time consistent with AEO2018 projection, returning excess revenue to households. This lump-sum tax return is held constant in the policy counterfactual to facilitate meaningful comparison.

8. Conclusion

As mentioned in the introduction, the USREP model has been broadly applied to energy and environmental policy analyses. In this document we describe the current configuration of the model, its equilibrium structure, main features of the dynamic process and policy instruments available for economic evaluation, so that the overall model structure and parameterization can be found in one place.

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Appendix A. Elasticity Parameters in USREP

Table A1. Reference Value of Production Sector Substitution Elasticities

Elasticity	Description	Value	Comments
Energy Substitution Elasticities			
σ_{EVA}	Energy - Value Added	0.4–0.5	Applies in most sectors, 0.5 in EIS, OTH
σ_{ENOE}	Electricity - Fuels Aggregate	0.5	All sectors
σ_{EN}	Among Fuels	1.0	All sectors except ELE
σ_{EVRA}	Energy/Materials/Land - Value Added	0.7	Applies only to AGR
σ_{ER}	Energy/Materials - Land	0.6	Applies only to AGR
σ_{AE}	Energy - Materials	0.3	Applies only to AGR
σ_{CO}	Coal - Oil	0.3	Applies only to ELE
σ_{COG}	Coal/Oil - Gas	1.0	Applies only to ELE
Other Production Elasticities			
σ_{VA}	Labor - Capital	1.0	All sectors
σ_{GR}	Resource - All Other Inputs	0.6	Applies to the OIL, COAL, GAS sector, calibrated to match medium run supply elasticity
σ_{NGR}	Nuclear Resource - Value Added	0.04–0.09	Varies by region, calibrated to match medium run supply elasticity
σ_{HGR}	Hydro Resource - Value Added	0.2–0.6	Varies by region, calibrated to match medium run supply elasticity
Armington Trade Elasticities			
σ_{DM}	Domestic - Aggregated Imports	2.0–3.0	Varies by good
		0.3	Electricity
σ_{MM}	National Imports - Int’l Imports	5.0	Non-energy goods
		4.0	Gas, coal
		6.0	Refined oil
		0.5	Electricity
σ_{WS}	Dispathable - Intermittent Electricity	0.03–1.4	Varies by region, calibrated to match supply elasticity
η	Output Produced for Domestic, National, and Int’l Markets	2.0	Elasticity of transformation, uniform for all goods
σ_{GOV}	CES Aggregator for Gov't Production	1.0	

Table A2. Reference Values of Elasticities for Final Demand

Elasticity	Description	Value	Comments
Final Demand Elasticities for Energy			
σ_{EC}	Energy - Non-Energy	0.25	
σ_{EF}	Electricity - Fuels Aggregate	0.4	
Other Final Demand Elasticities			
σ_{CS}	Consumption - Savings	0.0	
σ_{CL}	Consumption/Savings - Leisure	1.0	Calibrated to match labor supply elasticities
σ_{SK}	Residential Invest - Other Invest.	1.0	Calibrated to match labor supply elasticities
σ_{C}	Among Non-Energy Goods	0.25–0.65	
σ_{CT}	Transportation - Other Consumption	1.0	
σ_{PO}	Purchased - Own Transportation	0.2	
σ_{NU}	New - Used Vehicle	0.5	In the Own-Transportation bundle
σ_{NSO}	Service - Other	1.0	In the New Vehicle bundle

Table A3. Reference Values of Elasticities for Advanced Technologies

Elasticity	Description	Value	Comments
σ_{FF}	Fixed Factor - Inputs Aggregate	0.3	All advanced technologies
Fuel Substitutes (Shale Oil, Bio-Oil, Coal Gasification)			
σ_{RVAO}	Resource - Materials/Value Added	0.5	Shale Oil
		0.3–1.2	Bio-Oil: Varies by region, calibrated to match run supply elasticity
σ_{VAO}	Materials - Value Added	0.2	Shale Oil
		1.0	Bio-Oil
		0.0	Coal Gasification
σ_{FVA}	Labor - Capital	0.5	
Electricity Substitutes			
σ_{TDVA}	Labor - Capital in Tran.&Dist	0.5	
σ_{GVA}	Labor - Capital in Generation	0.5	
σ_{SVA}	Labor - Capital in Sequestration	0.5	

Appendix B. Structure of Production and Consumption in USREP

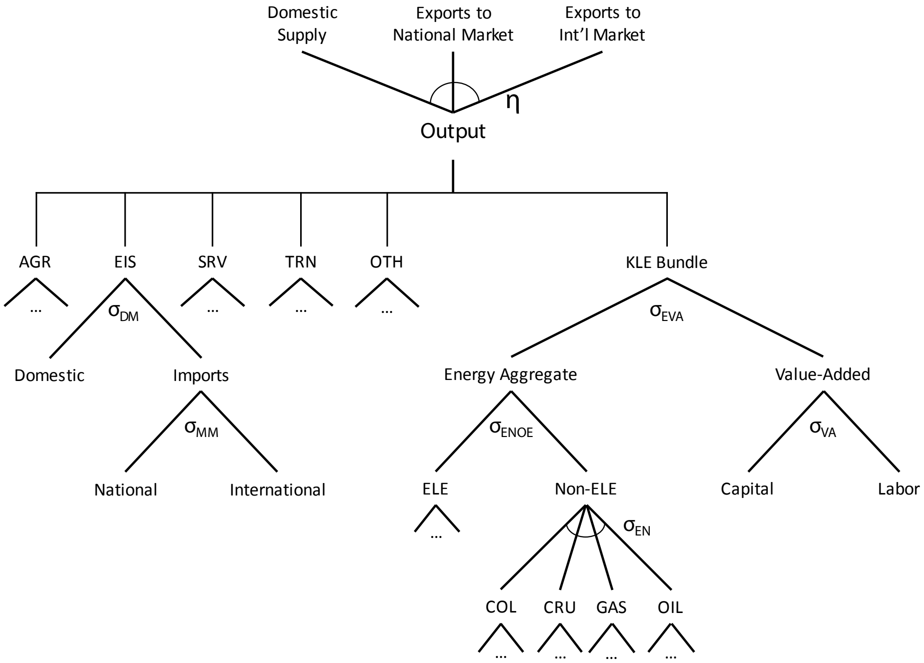

Figure B1. Structure of Generic Production Sectors (Services, Commercial Transportation, Energy Intensive and Other Industries). Vertical lines in the input nest signify a Leontief or fixed coefficient production structure where the elasticity of substitution is zero. Terminal nests with … indicate the same aggregation structure for imported goods as shown in detail for the EIS sector.

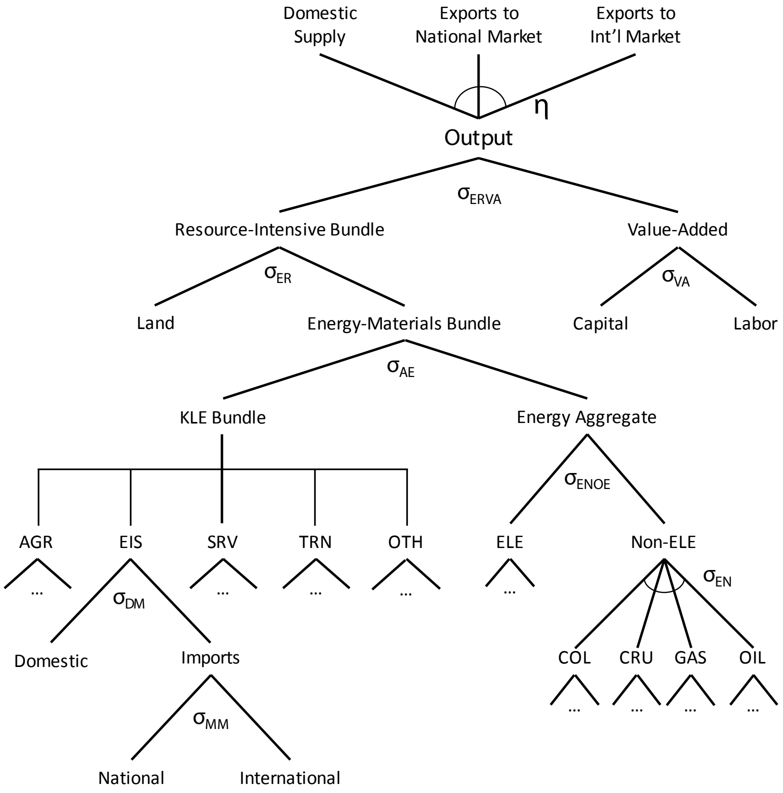

Figure B2. Structure of Agriculture Production

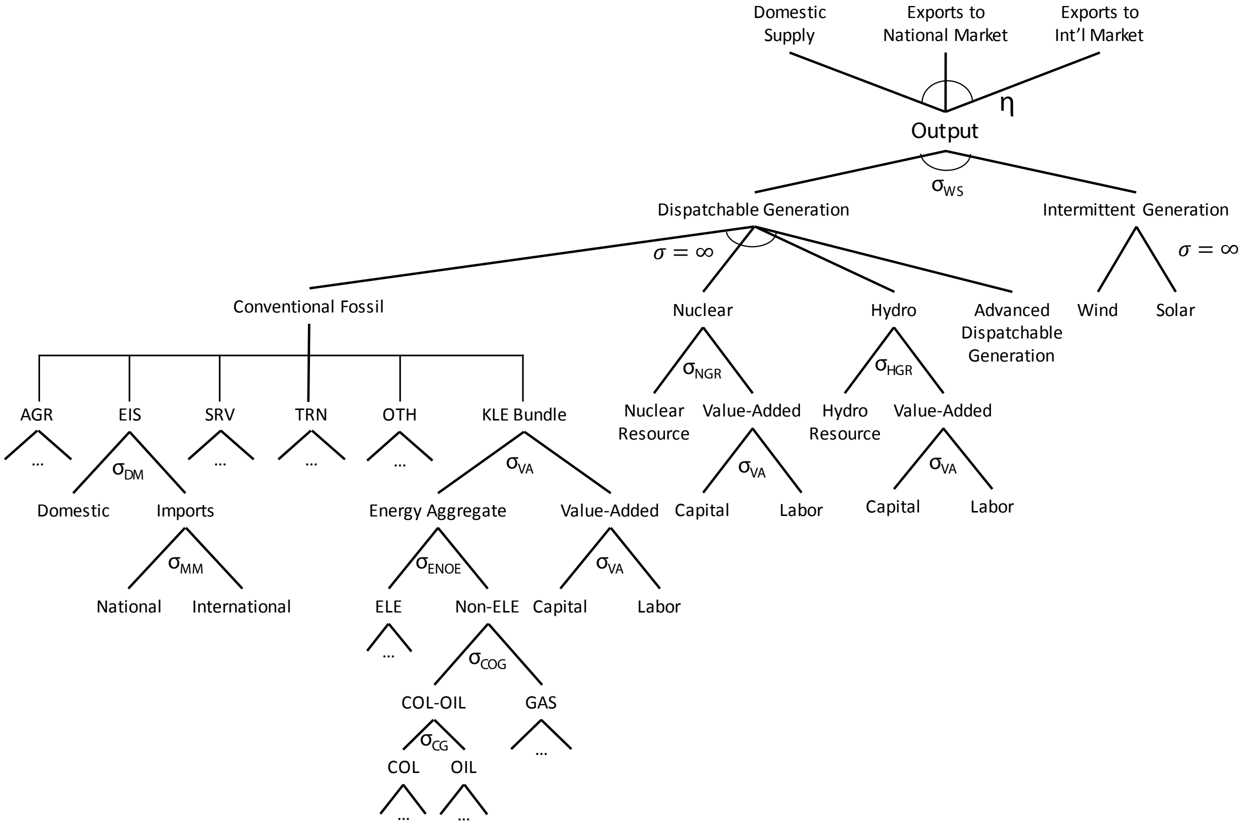

Figure B3. Structure of Electricity Generation

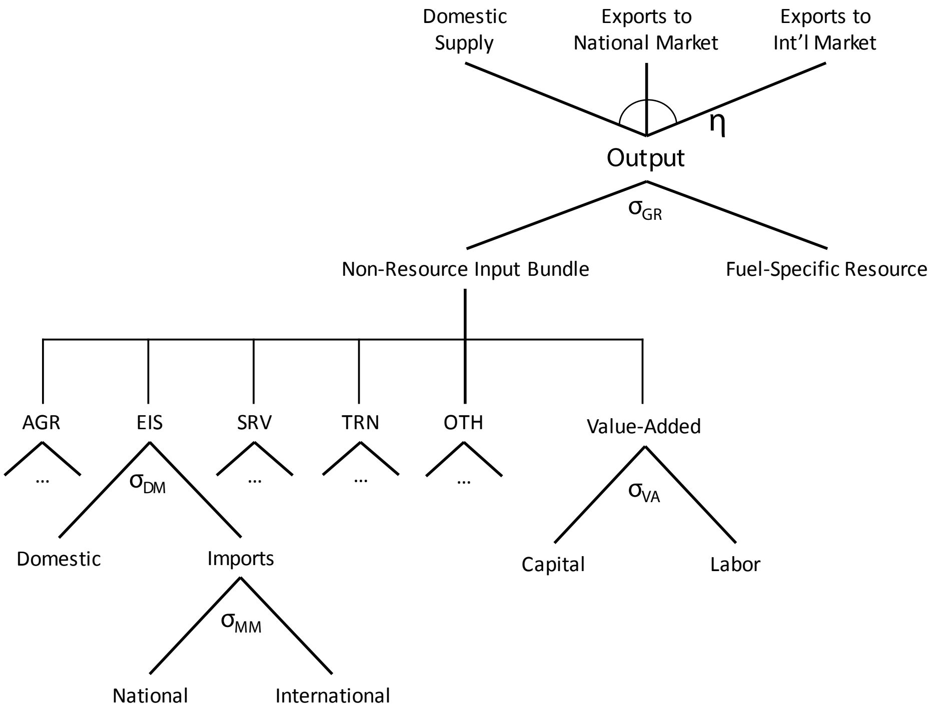

Figure B4. Structure of Primary Energy Production

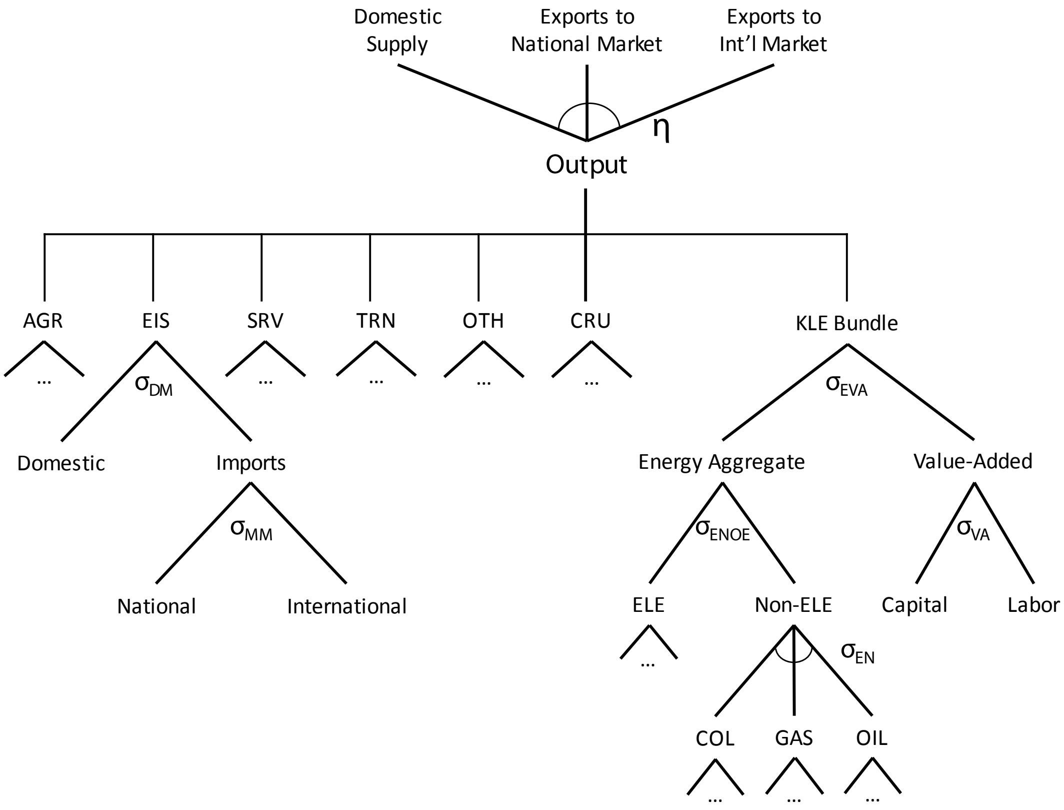

Figure B5. Structure of Refined Oil Production

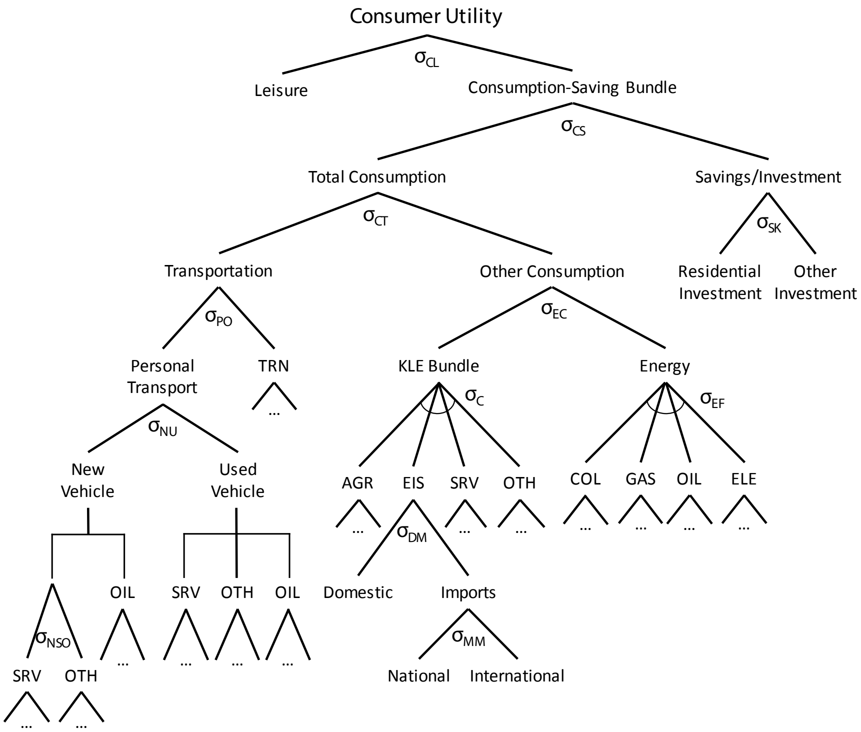

Figure B6. Structure of Household Utility

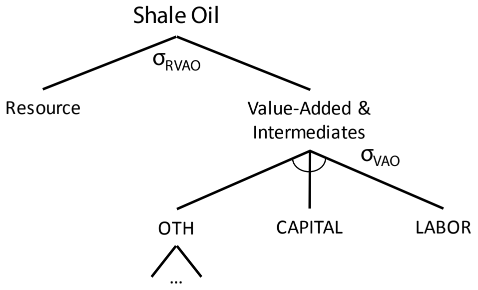

Figure B7. Structure of Shale Oil Production

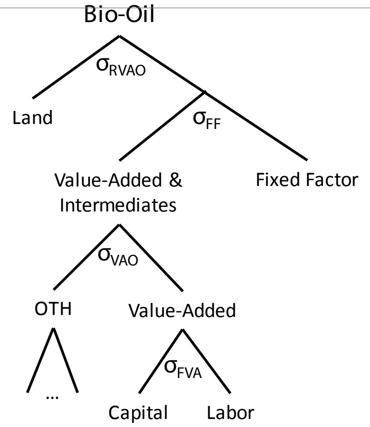

Figure B8. Structure of Bio-Oil Production

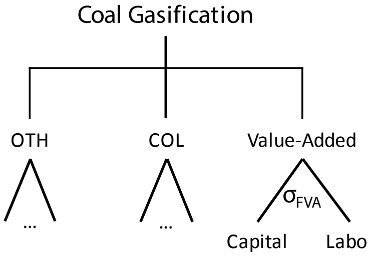

Figure B9. Structure of Coal-Gasification Production

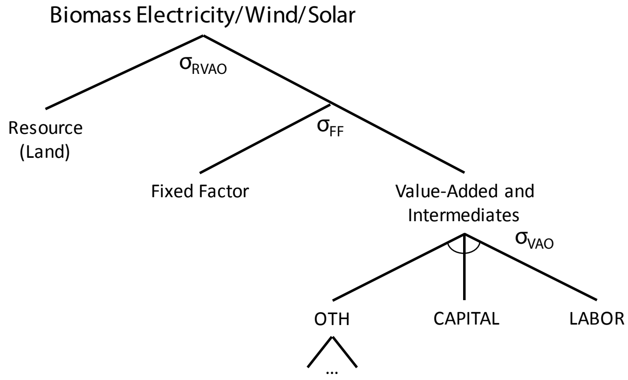

Figure B10. Structure of Biomass Electricity, Wind, and Solar

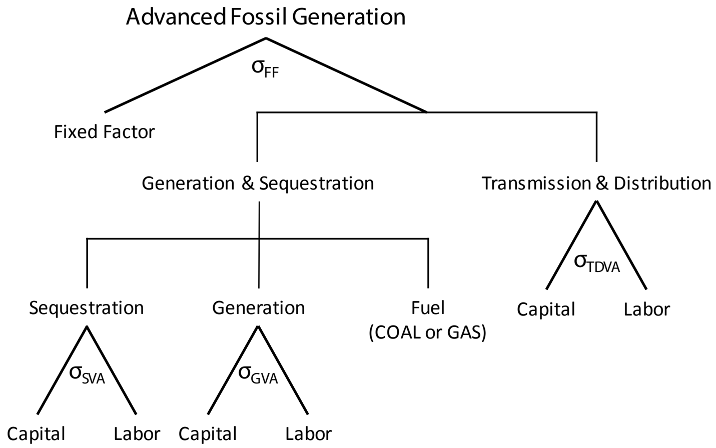

Figure B11. Structure of Advanced Fossil Generation

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